Explaining the HERA Anomaly Without Giving Up R-parity Conservation

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(April, 1997)

We point out that in extended supersymmetric models such as supersymmetric left-right models, it is possible to have leptoquarks that explain the HERA high $Q^2$ anomaly without giving up R-parity conservation. The leptoquarks belong to vectorlike $(2,2,\pm\frac{2}{3},3\alpha^3)$ representations of $SU(2)L\times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$ (denoted by $G_{2213}$). Considerations of D-terms imply that the only phenomenologically viable model is the one where the leptoquark couples to positrons and the up quark. Unlike the R-parity violating scenario, the leptoquarks are accompanied by new superpartners, the leptoquarkino which leads to many interesting signatures in other collider experiments. At Tevatron, pair productions of the leptoquarkino will give rise to dilepton signals very distinct from the top productions. These models can lead to unification of gauge coupling constants at a scale of around $10^{10}$ GeV implying that grand unification group is not of the usual $SU(5)$ or $SO(10)$ types but rather an automatically R-parity conserving $SU(2)_L \times SU(2)_R \times U(1)$ model recently proposed by one of the authors (R. N. M.) which leads to a stable proton.

OITS-627 UMD-PP-97-108 OSURN-325

If the high $Q^2$ anomaly observed recently in the $e^+p$ scattering by the H1 [4] and the ZEUS [2] collaborations is confirmed by future data, it will be an extremely interesting signal of new physics beyond the standard model. A very plausible and widely discussed interpretation of this anomaly appears to be in terms of new scalar particles capable of coupling to $e^+u$ or $e^+d$ of scalar leptoquarks [1] with mass around 200 GeV. Alternative interpretations based on contact interactions [5] or a second $Z'$ [6] have been proposed, but attempts to construct models that lead to the desired properties seem to run into theoretical problems.

The leptoquark must be a spin zero color triplet particle with electric charge 5/3 or 2/3. The latter electric charge assignment makes it possible to give a plausible interpretation of the leptoquark as being the superpartner of the up-like quark [1] of the minimal supersymmetric standard model (MSSM) provided one includes the R-parity violating couplings of the type $\lambda Q L d^c$ to the MSSM (where $Q,L$ denote the quark and the lepton $SU(2)_L$ doublets and $u^c,d^c,e^c$ denote the $SU(2)_L$ singlets [1]). There are however very stringent upper limits on several R-parity violating couplings: for instance, if in addition to the $\lambda'$ term described above, one adds the allowed $\lambda''u^c d^c d^c$ terms to the superpotential, then it leads to catastrophic proton decay unless $\lambda'\lambda'' \leq 10^{-24}$ [1]. There are also stringent limits on $\lambda_{111}' \leq 10^{-4}$ [1] from neutrinoless double beta decay, which forces the leptoquark to be $\bar{c}$ or $\bar{t}$ rather than the obvious choice $\bar{u}$. Furthermore, within such a framework, the lightest supersymmetric particle (LSP) is no more stable and therefore, there is no cold dark matter (CDM) candidate in such theories. In view of the fact providing a natural CDM candidate was long considered an attractive feature of the supersymmetric models, it may be worthwhile to consider extensions of the MSSM which incorporate the leptoquark without giving up R-parity conservation (and hence the idea of LSP as a natural CDM candidate). It is the goal of this letter to report on the results of such a study.

The class of supersymmetric theories where R-parity conservation is automatic can provide an absolutely stable LSP that can act as the CDM candidate. We will therefore use them as a typical framework for studying the consequences of leptoquarks incorporated into such theories while at the same time maintaining automatic R-parity conservation. Minimal versions of such theories are based on the gauge group $SU(2)_L \times U(1)_{B-L}$ or $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with usual assignments for the quarks and leptons. We will consider the latter left-right symmetric gauge group. The quark doublets $Q \equiv (u,d)$ and $Q' \equiv (u',d')$ transform as doublets under the $SU(2)_L$ and $SU(2)_R$ groups respectively and similarly the lepton doublets $L \equiv (\nu,e)$ and $L' \equiv (\nu',e')$ respectively. The $SU(2)_R$ gauge symmetry breaking is achieved via the $B-L$ non-singlet isoriplets $\Delta^c \equiv (1,3,-2)$ and $\Delta^c \equiv (1,3+2)$ and their left-handed counterparts added to maintain left-right symmetry (the numbers in the parenthesis denote the $SU(2)_L,SU(2)_R$ and $U(1)_{B-L}$ quantum numbers). The standard model symmetry is broken by the bi-doublet fields $\phi(2,2,0)$.

We augment this model by including the leptoquark fields. Demanding that the lepto-doublets couple to $e^+d$ or $e^+u$ leads to the conclusion that they must belong to the multiplet $(2,2,4/3,3)$ (denoted $\Sigma_{QL^c}$) and $(2,2,-4/3,3^*)$ (denoted by $\Sigma_{QL^c}$). Each of these multi-
plets have four scalar fields and four fermion fields which will be denoted in what follows by the obvious subscript corresponding to their couplings. We denote the four scalar leptoquarks as $\Sigma_{ue}, \Sigma_{ue^c}, \Sigma_{de} \text{ and } \Sigma_{de^c}$ and their fermionic partners (to be denoted by a tilde on the corresponding scalar field). Writing down the most general superpotential, one can easily convince oneself that the resulting theory maintains the property of R-parity conservation. Thus the lightest neutralino LSP will be stable in this model and can serve as the cold dark matter.

Before discussing the application of this model to explain the HERA anomaly, let us first discuss the mass spectrum of the model. The superpotential for this model will have a direct mass term of the form $M_0 \Sigma \Sigma$ which will imply that the fermionic fields in the leptoquark multiplet will have a masses $M_0$ prior to symmetry breaking. There may be other contributions to these masses from radiative corrections which will split the degeneracy implied by the above mass term.

As far as the scalar leptoquark states are concerned, their masses will receive several contributions: first a direct common contribution from the $M_0$ term given above. After symmetry breaking, the D-terms of the various gauge groups will contribute. There is also soft SUSY breaking contribution along with the radiative correction. Assuming that the SU(2)$_R$ symmetry is broken by the vev’s $< \Delta^c_1 > = v_1, < \Delta^c_2 > = v_2$ and the SU(2)$_L$ symmetry is broken by the two $\phi$ vev’s as $\text{diag} < \phi_u > = (0, v \sin \beta)$ and $\text{diag} < \phi_d > = (v \cos \beta, 0)$, we can write the masses for the various scalar leptoquarks as follows:

$$M_{\Sigma_a}^2 = M_0^2 + (I^a_{R2R} g_{2L}^2 - B - L g_{B-L})(v_1^2 - v_2^2) + \frac{g_{2L}^2 v^2 I_{3L}}{4} \cos 2 \beta + \Delta_{m}^2 + \text{Radiative correction}$$

(1)

$\Delta_{m}^2$ is the soft SUSY breaking contribution. The values of the $I^a_{R}$ and $B - L$ are given in Table I:

| states      | $I^a_{R}$ | $B - L$ | $I_{3L}$ |
|-------------|----------|---------|----------|
| $u^c e$     | $\frac{1}{3}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ |
| $u^c \nu$  | $\frac{1}{3}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ |
| $u e^c$    | $-\frac{1}{3}$ | $\frac{1}{3}$ | $\frac{2}{3}$ |
| $d e^c$    | $-\frac{1}{3}$ | $\frac{1}{3}$ | $\frac{2}{3}$ |

TABLE I. The $I_{SR}$ and $B_L$ quantum numbers of the various leptoquark states

The radiative correction can be positive or negative. From table I and Eq.(1), we see easily that if $v_1 < v_2$, then the lightest leptoquark state is the first entry in the table I which corresponds to the conjugate of $\Sigma_{ue^c}$ since $g_{2L}^2 \Delta_{m} > 2 g_{2L}^2 - L$ in the left-right models. Furthermore, interestingly enough for this choice of vev’s, assuming the combined $\Delta_{m}^2 + \text{Radiative correction}$ to be smaller than the the D-term, the leptoquarkino states are heavier than the lightest leptoquark state. We assume their masses to be in the range of 300 to 400 GeV. In a subsequent section we will obtain a lower bound on the leptoquarkino mass from the present collider data.

Turning to the couplings of the leptoquarks $\Sigma$ and $\Sigma$ to quarks and leptons, it is given by the superpotential:

$$W_{ij} = \lambda_{ij}(\Sigma Q_i L_j + \Sigma Q_i L_j^c)$$

(2)

(where $i, j$ are generation indices). Let us assume for simplicity that $\lambda_{ij}$ are diagonal in the mass eigenstate basis for the quarks and leptons. Explanation of the HERA high $Q^2$ anomaly seems to require $\lambda_{11} \approx 0.05$ which we will assume from now on and mass of the scalar field $\Sigma$ (assumed to be $\Sigma_{ue^c}$ from the above mass arguments) around 200 GeV. As far as the other couplings go, they will be strongly constrained by the present experimental upper limits on the low energy processes such as $\mu \rightarrow e \gamma, \tau \rightarrow e \gamma$ etc. which will arise at the one loop level from the exchange of $\Sigma$ and $\Sigma$. There are also tree level diagrams which can lead to rare processes such as $K \rightarrow \pi^- e^+$. These processes imply an upper limit of $\lambda_{23} \leq 2 \times 10^{-3}$. The most stringent upper limit on $\lambda_{32}$ comes from the upper limit on the process $K^0 \rightarrow \mu^+ e^-$ and yields $\lambda_{32} \leq 2 \times 10^{-4.5}$. Turning to $\lambda_{33}$, the most stringent limits arise from the present upper limit on the branching ratio for the process $\tau \rightarrow e \gamma$ which the 1996 Particle data tables give as $\lesssim 1.1 \times 10^{-4}$ [4]. This implies a weak upper limit on $\lambda_{33} \leq 0.2$. Thus the third generation leptoquark coupling $\lambda_{33}$ could in principle be comparable to $\lambda_{11}$. If the efficiency for the detection of $\tau$ leptons at HERA were comparable to the detection efficiency for electrons, that could also severely limit $\lambda_{33}$. Finally we also note that such a value for $\lambda_{11}$ is also consistent with the present data on the parity violation in atomic physics. Thus it appears that our leptoquark couplings are consistent with all known low energy data. It is clear from the above discussion that the leptoquarks do not respect $\mu - e$ universality.

The existence and properties of the leptoquarkino provides a new and unique signature for our model as compared to all other proposals to explain the HERA anomaly. To see this note that in hadron colliders, we can produce pairs of leptoquarkinos at the same rate as the $t \bar{t}$ pair due to identical color content. Moreover, due to R-parity conservation the leptoquarkino decay leads to a missing energy signal as follows: $\Sigma \rightarrow e^+ \tilde{u} \bar{u}$ with $\tilde{u} \rightarrow u + \chi^0$ or $\Sigma \rightarrow u + e^+ \chi^0$. In both the cases we have $e^+ + \tilde{u}$ plus missing energy in the final state. If the $\lambda_{33}$ coupling is comparable to $\lambda_{11}$ as is allowed, then the branching ratio for leptoquarkino decay
to electrons will be 50%. This signal is similar to the top signal at the Tevatron with one crucial difference. The dilepton branching ratio from the leptoquark pairs is 100% compared to only 10% from the top pairs. There will be no $\mu^+\mu^-$ events. The branching ratio to $e^+e^-$ will be 25% compared to only 1% from the top. The present observations should therefore lead to lower limits on the mass of the lightest leptoquarkino pairs. Thus an excess of dilepton pairs over that expected from the top productions, or an excess in $e^+e^-$ channel over $\mu^+\mu^-$ will be a clear signal of leptoquark productions at Tevatron. In addition, leptoquarks will also give rise to harder leptons and larger missing energy events. In Fig. 1, we plot the cross section for the leptoquarkino pair production.

We see that for the present combined Tevatron data of about 200 pb$^{-1}$, there would be 6 events of type $e^+e^-jj$ plus missing energy for $M_{\text{Leptoq}} = 250$ GeV, assuming a detection efficiency of 0.2 for the $e^+e^-$ mode. At present CDF collaboration has only one such event$^{[2]}$, and the D0 collaboration has also 1 event$^{[3]}$. Using these two events, and the the cross sections given in Fig. 1, we obtain a lower bound on the leptoquarkino mass of about 290 GeV (assuming the detection efficiency to remain 0.2 for the higher masses). Any evidence for an excess of dielectron events would be interpretable in terms of this new leptoquarkino. We urge the CDF and D0 collaboration to look for such excess, and also to look for any dilepton event in which the lepton $P_T$ or missing energy do not fit the top productions. The recent CDF analysis$^{[4]}$ shows that the leptoquarkino mass bound at 95% CL is 210 GeV assuming the branching ratio is 1. In this model however the branching ratio is less than 1, since the leptoquark can also decay into the top quark and the $\tau$ lepton.

So far we have discussed the signals of leptoquarkinos in the usual SUSY theories. If however the supersymmetry breaking is communicated to the observable sector by the SM gauge interation$^{[13]}$, the signal is different. Let us first consider the case when neutralino is the NLSP in these models. The leptoquarkino decays into a spositron and $u$ quark (squarks masses are large in these models). The spositron decays (100%) into a positron and a neutralino and the neutralino then decays (100%) into a hard photon and a gravitino. Consequently the final state in the leptoquarkino pair production process has $e^+e^-\gamma jj$ plus missing energy without any SM background. If lighter stau is the NLSP and neutralino is the NLNLSP, spositron decays (100%) into a positron and a neutralino and the neutralino then decays (100%) into a $\tau$ and a lighter stau. The lighter stau then decays into a tau and a gravitino. Consequently the final state in the leptoquarkino pair production process in the Tevatron has $e^+e^-2\tau^+2\tau^-jj$ 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.

One could also look for the signals of leptoquarkino production in $e^+\gamma$ colliders. The leptoquark or leptoquarkino can be singly produced in such a collider. The scalar leptoquark will be produced in the association of an antiquark$^{[1]}$. As discussed before in the usual SUSY theories, the leptoquark further decays into a quark and a positron with the final state consisting of positron +jets. The leptoquarkino however will be produced along with a squark. This leptoquarkino will then decay into a lepton and a squark. The final state has electron +jets+missing energy. The missing energy part will then disentangle the leptoquarkino signal. 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 $e^+e^-$ collider the signal for this leptoquarkino would be jets + missing energy, since a squark anti-squark pair will be produced from a $t$ channel exchange of leptoquarkino. The exchange of a $t$ channel leptoquark however gives rise to jets without any missing energy. It is not possible for LEPII to see the signal of leptoquarkino due to the large squark mass. A higher energy machine is needed for that purpose. A detailed study of the discovery prospects of the leptoquarkino in different colliders will be presented elsewhere.

Another important implication of our model is that there does not seem to any operator which can give a non-negligible charged current signal at HERA. Thus observation of charged current like events above background at HERA will be an evidence against this model.

Let us now discuss the possible implications of the existence of a low mass leptoquark supermultiplet for uniﬁcation. We will assume that the physics immediately beyond MSSM (i.e. in the TeV region) is described by a supersymmetric left-right symmetric model (SUSYLR) with the addition of the leptoquark multiplets described above. The evolution of the gauge couplings depend not only on the individual beta functions but also on the nature of the final unification group which determines the normalizations of the various gauge couplings at low energies. For instance, if we envision embedding the SUSYLR group within a simple group such as $SO(10)$ or $SU(16)$ etc, the properly normalized weak hypercharge, $I_Y$ is given by the familiar formula $I_Y = \sqrt{\frac{3}{5}} \times Y$ and the properly normalized $B-L$ charge $I_{BL}$ is given by $I_{BL} = \sqrt{\frac{3}{5}} \times (B-L)$. This leads to the matching formula for the weak hypercharge coupling to be $\alpha^{-1}_{I_Y} = \frac{3}{5} \times (B-L)$ at $M_R$. Evolving our model with this kind of unification leads to a unification scale of about $10^{15.5}$ GeV assuming that at the $W_R$ scale, we have two bidoublets, right handed triplets of type $(1, 3, -2, 1) + (1, 3, +2, 1)$ without their left-handed partner in addition to the aforementioned leptoquark multiplets. This is therefore unacceptable since it will lead to catastrophic proton decay via the exchange of gauge bosons that violate baryon number in the $SO(10)$ models. We therefore consider a different kind of embedding of SUSYLR into an $SU(5) \times SU(5)$
SU(5) × SU(5) embedding of SUSYLR with leptoquarks

First let us briefly recapitulate the fermion assignments of the model: they belong to the \((5 + \bar{10}, 1) + (1, 5 + \bar{10})\) multiplet for every generation. One therefore needs a weak singlet vectorlike pair of \(D, U\) quarks and a heavy weak singlet vectorlike charged lepton \(E^\pm\). The lefthanded \((\bar{5}, 1)\) multiplet then consists of \((D_1^e, D_2^e, D_3^e, e^-, \nu_e)\) whereas the righthanded multiplet \((1, 5)\) is given by \((D_1, D_2, D_3, e^+, \nu^e)\). The assignments to the \(10\) dimensional representations are easily obtained \[17\]. For instance, the fermion assignment in \((10, 1)\) representation is given by

\[
\begin{pmatrix}
0 & U^c_3 & -U^c_5 & u_1 & d_1 \\
-U^c_3 & 0 & U^c_5 & u_2 & d_2 \\
U^c_3 & -U^c_1 & 0 & u_3 & d_3 \\
-u_1 & -u_2 & -u_3 & 0 & E^+ \\
-d_1 & -d_2 & -d_3 & -E^+ & 0
\end{pmatrix}
\]

and similarly for the \((1, \bar{10})\) multiplet which contains the other chirality states for the above fields arranged exactly the same way. The Higgs mechanism of the model is implemented by multiplets of type \((5, \bar{5}) + (\bar{5}, 5)\) and they lead to the vectorlike quarks and leptons acquiring mass at the unification scale. This leaves the low energy theory to be the usual SUSYLR model. The SUSYLR symmetry is broken down to MSSM by the Higgs multiplets of type \((1, 15) + (15, 1)\) which also leads to the see-saw mechanism for neutrino masses. Below the \(W_R\) scale the theory is MSSM with the important difference that now the R-parity violating couplings are automatically absent. In order to accomodate the leptoquarks in this model, we include the multiplets \((5, 10) + (10, 5)\). We assume that below the GUT scale, only members of these multiplets that remain light are the leptoquarks discussed above.

Turning to unification with leptoquarks in this model, we first note that since \(U(1)_{B−L}\) and \(SU(3)_c\) now emerge from two different \(SU(5)\)'s and that there are more fermions in the fundamental representation of the GUT group than the \(SO(10)\) case, the normalization of the low energy couplings are totally different from the previous case. For instance, now \(I_Y = \sqrt{\frac{2}{16}}(\frac{2}{3})\) and \(I_{BL} = \sqrt{\frac{1}{16}}(\frac{2}{3})\); furthermore, \(I_a = \sqrt{\frac{2}{3}}(I_{aL} + I_{aR})\) where \(a\) denotes \(SU(3)_c\) or \(B - L\) generators. Because of this unification profile is now very different; however with the same field content at \(M_R\) as above, we find a unification scale of \(10^9\) GeV in the one loop approximation.

In conclusion, we have suggested an alternative leptoquark interpretation of the HERA high \(Q^2\) anomaly within an extension of the MSSM in such a way that R-parity conservation is maintained automatically. The superpartner of the leptoquark, the leptoquarkino in this model leads to many interesting and testable predictions in present and future hadronic as well as in the future e-gamma colliders. At Tevatron, the pair productions of these leptoquarkinos give rise to very distinctive signal, namely opposite sign dilepton events of the type ee, e\(\tau\), \(\tau\tau\) accompanied by dijets plus missing energy, but no events of \(\mu\mu\) type. If the leptoquarkino is not too much heavier than the “HERA leptoquark”, then these events will be observable in the present or upgraded Tevatron. It is possible that one excess event in the dilepton channel containing a \(\tau\), as reported by the CDF collaboration, could be due to the production of a leptoquark or leptoquarkino. Although clearly more data is needed before definitive conclusion can be drawn.

The work of B. D has been supported by a DOE grant no. DE-FG06-854ER-40224; the work of R. N. M. has been supported by NSF grant no. PHY-9421386 and the work of S. N. has been supported by DOE grant no. DE-FG02-94ER40852.
TABLE II. The grand unification scale, the intermediate scale and the strength of the unified couplings at the grand unified scale are shown for different numbers of bidoublets. $\alpha_{GA}$ is the unified coupling for one SU(5) group and $\alpha_{GB}$ is the unified coupling for the other SU(5) group.

| nbidoublets | $M_I$(GeV) | $M_G$(GeV) | $\alpha_{GA}$ | $\alpha_{GB}$ |
|-------------|------------|------------|---------------|---------------|
| 5           | $10^4$     | $10^{7.11}$| 5.12          | 2.29          |
| 6           | $10^4$     | $10^{7.83}$| 4.05          | 3.46          |
| 7           | $10^{4.75}$| $10^{7.01}$| 4.25          | 4.25          |

FIG. 1. Cross section for the production of leptoquarkino pair at Tevatron energy against the leptoquarkino mass.