Leptoquarks and vector-like strong interactions
at the TeV scale

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Abstract

In a vector-like extension of the minimal standard model with mirror fermions
leptoquarks can be bound states of fermion-mirror-fermion pairs held together by
a new strong interaction at the TeV scale. The small couplings of leptoquarks to
light fermion pairs arise due to mixing. The large $Q^2$ event excess at HERA and
also the high $E_T$ jet excess at Tevatron can potentially be explained.
1 Introduction

The recently reported excess of deep-inelastic $e^+p$ events at the HERA experiments H1 [1] and ZEUS [2] is an unexpected deviation from the predictions of the minimal standard model. As has been observed in several theoretical papers [3], a possible explanation can be a resonating leptoquark state in the positron-quark channel. The existence of such states can be due, among others, to a new strong gauge interaction above the presently explored energy range.

In the vector-like extension of the standard model with three mirror fermion generations [4] one can naturally implement strong interactions at some scale of the order of 1-10 TeV. In fact, if the mirror fermions have masses of the order of 200 GeV or higher, the renormalization of the corresponding Yukawa couplings towards higher energies implies strong interactions at such scales. This follows from the renormalization group equations investigated in ref. [5]. Since the motivation for the vector-like extension of the standard model is based on the difficulty of non-perturbatively defining chiral gauge theories, theoretical consistency requires that any new gauge interaction should be vector-like.

In the present letter a simple example based on a strongly interacting U(1) Higgs model is exploited. For definiteness, let us denote the new charge by $X$. The vacuum expectation value breaking this new $U(1)_X$ symmetry is assumed to be of the order of several TeV. The advantage of $U(1)$ is its simplicity and the fact that it does not require the introduction of further new fermionic states. Other possibilities based on larger gauge groups are also conceivable, but are not considered here. The existence of a new strong $U(1)$ interaction in the TeV range has been proposed for the explanation of HERA data in the recent paper of Babu et al. [3]. Here this idea is implemented in the vector-like extension of the standard model. As we shall see, this allows to explain the smallness of the leptoquark coupling by relating it to the smallness of the fermion-mirror-fermion mixing.

2 Quantum numbers

In order to introduce the new $U(1)_X$ interactions in the extended standard model with three mirror pairs of fermion generations, it is advantageous to define a basis of fermion fields where the vector-like nature of the gauge interactions becomes explicit. Let us denote the fermion fields in an SU(2) doublet by $\psi^{(A)}_{L,R}(x)$ and the corresponding mirror fermion fields by $\chi^{(A)}_{L,R}(x)$. The indices $L, R$ denote chiralities and $A = 1, 2$ stands for the doublet index. Since, for instance, $\chi^{(A)}_R(x)$ has the same quantum numbers as $\psi^{(A)}_L(x)$, the vector-like gauge couplings act on the combinations

$$\rho^{(A)}(x) \equiv \psi^{(A)}_L(x) + \chi^{(A)}_R(x) , \quad \sigma^{(A)}(x) \equiv \chi^{(A)}_L(x) + \psi^{(A)}_R(x) . \quad (1)$$

In the standard model $\rho^{(A)}(x)$ is an SU(2) doublet and $\sigma^{(A=1,2)}(x)$ are two SU(2) singlets. On the $(\rho, \sigma)$-basis the Yukawa couplings to the standard Higgs doublet scalar field are off-diagonal and parity violating. The gauge invariant Dirac-masses of these fields are, respectively,
\(\mu_L\) and \(\mu_R^{(A=1,2)}\). They are responsible for the L-handed, respectively, R-handed mixings of fermions with mirror fermions and, therefore, must be small in order to be consistent with experiment. (For a recent summary of viable mixing schemes and the discussion of possible small universality violations due to mixing see ref. [3].) The other indices besides the doublet index \(A\) are suppressed in (1): in general we have \(\rho^{(AcK)}(x)\) and \(\sigma^{(AcK)}(x)\) with generation index denoted by \(K = 1, 2, 3\) and the colour index \(c\) defined in such a way that \(c = 1, 2, 3 \equiv q\) stand for SU(3) colour and \(c = 4 \equiv l\) for the corresponding lepton. On the \((\rho, \sigma)\)-basis the SU(3) \(\otimes\) SU(2) \(\otimes\) U(1) gauge interactions are explicitly vector-like. The new vector-like U(1) gauge interaction can generally be defined by the charges \(X^{(AcK)}_\rho\) and \(X^{(AcK)}_\sigma\). SU(3) \(\otimes\) SU(2) invariance implies that the X-charges are the same for \(c = 1, 2, 3\) and \(X^{(AcK)}_\rho\) is independent of \(A\). It is plausible that the lightest bound states are X-neutral, therefore, in order to produce fermion-antifermion bound states with leptoquark quantum numbers, one has to postulate that \(X^{(AcK)}_\rho\) and/or \(X^{(AcK)}_\sigma\) be the same for \(c = q\) and \(l\). Therefore, we have the freedom to choose \(X^{(K)}_\rho\) and/or \(X^{(AK)}_\sigma\).

An important feature of the leptoquark interpretation of the HERA data is that leptoquarks must couple, to a very good approximation, diagonally to the three generations of quarks and leptons [3]. This can be achieved by assuming different X-charges for the three fermion generations. A possible simple choice is then to assign a single charge value within the generations: \(X^{(K)} = X^{(AK)}_\rho\). In this case every U(1) multiplet can be paired up with any other in its generation, giving 256 bound states per generation, if one counts isospin and colour components separately. Among these states there will be isosinglets, isodoublets and isotriplets and as colour multiplets we have singlets, triplets, antitriplets and octets. It is also possible to introduce models with less states which are still sufficient to explain the large \(Q^2\) deviations from the standard model observed at HERA:

- **\(\rho\)-model**: taking only \(X^{(K)}_\rho \neq 0\) and \(X^{(1K)}_\sigma = X^{(2K)}_\sigma = 0\);

- **down-type \(\sigma\)-model**: taking \(X^{(2K)}_\sigma\) \(\neq 0\) and \(X^{(1K)}_\sigma = X^{(K)}_\rho = 0\).

Choosing \(A = 2\) in the second case here is, of course, motivated by the required existence of a leptoquark in the \(e^+d\)-channel, which contributes to \(e^+p\)-scattering. In the first model there are isosinglet and isotriplet bound states and the number of states per generation is 64. In the second one we have only isosinglets and 16 states per generation. The SU(3) \(\otimes\) SU(2) \(\otimes\) U(1) quantum numbers of the expected light bound states in the down-type \(\sigma\)-model are summarized in table [4]. In case of the SU(2) quantum numbers one has to have in mind that the light fermion states are mixtures of the original chiral fermions with their mirror fermion partners. This results in an apparent SU(2)_L symmetry violation, if compared to the standard model.

Concerning spin-parity, in analogy with para-positronium, a plausible assumption for the lightest fermion-antifermion bound states is \(J^{PC} = 0^{-+}\). Other bound states, as \(J^{PC} = 1^{--}\) vector bosons, are expected to have masses in the TeV range. The large mass gap between vector and pseudoscalar states might be a consequence of an approximate global chiral symmetry,
similarly to QCD. Nevertheless, in general, it is not much known about the dynamical spectrum of strongly interacting U(1) Higgs models with fermions. Future lattice simulations could help in this respect.

The qualitative behaviour of the coupling strengths of light fermion-antifermion bound states to different types of fermions can be inferred from the fermion-mirror-fermion mixing structure. In general, one can expect that the strongly bound (pseudo-)scalar states are dominantly coupled with a strong Yukawa-coupling of the order \( O \) to their constituent fermions represented by the \( \rho \), respectively, \( \sigma \)-type fields in eq. (1). The chiral components of fermion \( \psi^{(AcK)}(x) \), respectively, mirror fermion \( \chi^{(AcK)}(x) \) fields are mixtures of the mass eigenstates, denoted by \( \xi^{(AcK)}(x) \) for the light states and \( \eta^{(AcK)}(x) \) for the heavy states, respectively. The mixing relations are:

\[
\psi_{L,R}^{(AcK)}(x) = \xi_{L,R}^{(AcK)}(x) \cos \alpha_{L,R}^{(AcK)} + \eta_{L,R}^{(AcK)}(x) \sin \alpha_{L,R}^{(AcK)},
\]

\[
\chi_{L,R}^{(AcK)}(x) = -\xi_{L,R}^{(AcK)}(x) \sin \alpha_{L,R}^{(AcK)} + \eta_{L,R}^{(AcK)}(x) \cos \alpha_{L,R}^{(AcK)}.
\]  

The mixing angles in the L-handed, respectively, R-handed sector are denoted here by \( \alpha_{L}^{(AcK)} \) and \( \alpha_{R}^{(AcK)} \). The universality constraints on the \( W \)- and \( Z \)-boson couplings imply that these mixing angles are small: \( |\alpha_{L,R}^{(AcK)}| \approx O(10^{-2}) \). (For the moment we are concentrating on the first generation. For the other generations the experimental bounds on the mixing angles are weaker.)

Omitting again colour- and generation-indices as in eq. (1), for isospin indices \( A, B = 1, 2 \) we have in the small mixing angle limit, for instance:

\[
(\bar{p}^{(A)}(x)\gamma_5\bar{p}^{(B)}(x)) \approx \alpha_{R}^{(A)} \left( \xi_{R}^{(A)}(x)\xi_{L}^{(B)}(x) \right) - \alpha_{R}^{(B)} \left( \xi_{L}^{(A)}(x)\xi_{R}^{(B)}(x) \right) + \alpha_{L}^{(A)} \left( \eta_{L}^{(A)}(x)\eta_{R}^{(B)}(x) \right) - \alpha_{L}^{(B)} \left( \eta_{R}^{(A)}(x)\eta_{L}^{(B)}(x) \right) - \left( \bar{\sigma}^{(A)}(x)\gamma_5\bar{\sigma}^{(B)}(x) \right) \approx \alpha_{L}^{(A)} \left( \bar{\xi}_{R}^{(A)}(x)\xi_{R}^{(B)}(x) \right) - \alpha_{L}^{(B)} \left( \bar{\xi}_{L}^{(A)}(x)\xi_{L}^{(B)}(x) \right) + \alpha_{R}^{(A)} \left( \bar{\eta}_{R}^{(A)}(x)\eta_{R}^{(B)}(x) \right) - \alpha_{R}^{(B)} \left( \bar{\eta}_{L}^{(A)}(x)\eta_{L}^{(B)}(x) \right),
\]

Table 1: The SU(3) \( \otimes \) SU(2) \( \otimes \) U(1)_Y quantum numbers of the light fermion-mirror-fermion bound states \( \Phi_{c_1c_2}^{(K)} \) \( \propto (\bar{\sigma}_{c_1}^{(2K)}\gamma_5\sigma_{c_2}^{(2K)}) \) in the down-type \( \sigma \)-model.

| c_1 | c_2 | SU(3) | SU(2) | \( Q = \frac{1}{2}Y \) |
|-----|-----|-------|-------|---------------------|
| e e | 1   | 1     | 0     |                     |
| d e | 3   | 1     | -2/3  |                     |
| e d | 3   | 1     | 2/3   |                     |
| d d | 1 \( \oplus 8 \) | 1 | 0 |                     |

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Figure 1: Virtual quark-mirror-quark resonance ($\Phi_{qq}$) contributions in $s$-channel (a) and $t$-channel (b) to $q\bar{q}$ scattering. Heavy mirror quarks are denoted by $Q$.

These relations express the obvious fact that $\rho\rho$- and $\sigma\sigma$-bound states are predominantly composed of a light fermion and its heavy mirror fermion partner. Therefore, the expected Yukawa-couplings in the first generation are of the order

$$\lambda_{\Phi\xi\eta} \simeq \mathcal{O}(1), \quad \lambda_{\Phi_{qq},\Phi_{qq}} \simeq \mathcal{O}(10^{-2}) .$$

(5)

This is in an order of magnitude agreement with the leptoquark coupling $\lambda_{\Phi} \simeq 0.04$ required for the explanation of HERA data [3].

In general, a qualitative prediction of models as the ones discussed here is, besides leptoquarks, the existence of bound states with lepton-antilepton and quark-antiquark quantum numbers (see e.g. table [3]). Since at the scale of the new strong interaction the SU(3) colour coupling and other standard model couplings are not very strong, it is expected that the masses of $\Phi_{ll}$ and $\Phi_{qq}$ are not much different from the mass of $\Phi_{lq}$. This has interesting implications for the possibility of production at high energy colliders. At LEP2 the $\Phi_{ll}$ resonance is an interesting candidate, whereas at the Tevatron especially the states with colour could be produced. Besides the colour triplet $\Phi_{lq}$, also colour octet states of the type $\Phi_{qq}$ should be pair produced. Their decays produce jet pairs, therefore a $\Phi_{qq} \Phi_{qq}$ pair decays predominantly to four jets.
3 Consequences for mirror fermions

The existence of leptoquarks and other similar fermion-mirror-fermion bound states has important consequences for the phenomenology of mirror fermions, too. The fermion-mirror-fermion bound state, in general denoted by \( \Phi \), has lower mass than the sum of masses of the corresponding fermion \( f \) and mirror fermion \( F \), therefore the \( F \rightarrow f \Phi \) decay may be kinematically possible and goes via the strong coupling \( \lambda_{\Phi \xi \eta} = \mathcal{O}(1) \). If the mass deficit is large enough, this is a fast dominant decay, because the decay amplitudes via electroweak vector bosons are suppressed by mixing angles \( \alpha \approx \mathcal{O}(10^{-2}) \).

As an example, let us consider the decay of the heavy mirror \( d \)-quark \( (D) \) into a leptoquark \( (\Phi_{de}) \) plus electron \( (e^-) \) within the down-type \( \sigma \)-model of table [I]. The coupling \( \lambda_{\Phi De} \) for \( \Phi_{de}(\bar{t}_R D_L) \) is expected to be of the order \( \lambda_{\Phi De} = \mathcal{O}(1) \). The decay width for zero electron mass is

\[
\Gamma_{D \rightarrow \Phi_{de}e} = \frac{M_D \lambda^2_{\Phi De}}{32\pi} \left(1 - \frac{M^2_{\Phi}}{M^2_D}\right)^2.
\]

(6)

For \( M_D = 300 \text{ GeV} \) and \( M_{\Phi} = 200 \text{ GeV} \) this gives \( \Gamma_{D \rightarrow \Phi_{de}e} \approx 1 \text{ GeV} \). This has to be compared to the decay widths to electroweak vector bosons which are of the order of MeV [4]. In addition to these decays, the mirror quarks may also have similar decays into quarks plus quark-mirror-quark bound states (in general \( \Phi_{qq} \), in the model of table [I] \( \Phi_{dd} \)).

Similarly, \( \Phi \) also plays an important rôle in the production of heavy mirror fermions both in lepton-quark and quark-quark scattering. Let us consider, as an example, quark-antiquark scattering relevant at Tevatron. The important \( s \)-channel and \( t \)-channel contributions are shown, respectively, by figures [I]a and [I]b. The amplitudes for \( q\bar{q} \rightarrow q\bar{Q} \) or \( q\bar{q} \rightarrow Q\bar{q} \) are proportional to the couplings \( \lambda_{\Phi \xi \xi} \lambda_{\Phi \xi \eta} \approx \mathcal{O}(10^{-2}) \). This has to be compared to the production amplitudes via electroweak vector bosons which have an additional suppression by an electroweak coupling. Particularly important is the \( t \)-channel contribution to the process \( q\bar{q} \rightarrow Q\bar{Q} \) in figure [I]b, because it has only couplings \( \lambda_{\Phi \xi \eta} = \mathcal{O}(1) \). Similar mirror fermion production mechanisms are also effective in \( e^+e^- \) scattering, where the rôle of \( \Phi_{qq} \) is played by \( \Phi_{ee} \) and in the \( t \)-channel also by \( \Phi_{eq} \). In \( ep \)-scattering only \( \Phi_{eq} \) is relevant: either in the \( s \)-channel or in the \( u \)-channel.

It is an important qualitative feature of this model based on fermion-mirror-fermion bound states that the couplings to light fermion pairs are suppressed by small mixing angles (see eq. (3)). This implies that fermion-mirror-fermion bound state exchanges are important for heavy mirror fermion production, but are suppressed by factors of about \( \mathcal{O}(10^{-3}) \)-\( \mathcal{O}(10^{-4}) \) in light fermion scattering.

It is an interesting question, whether the processes mediated by the quark-mirror-quark resonances could contribute to the high-\( E_T \) jet cross section excess observed at the Tevatron [7]. A potentially relevant contribution can arise from the decay products of mirror quarks produced by the mechanisms with virtual \( \Phi_{qq} \) bosons shown by figure [I]. For instance, the differential cross section of the process \( q\bar{q} \rightarrow Q\bar{Q} \) corresponding to the Feynman graph in
The unknown mirror quark mass $M_Q$ is expected to be above 200 GeV, if the present interpretation of the observed high $Q^2$ anomaly at HERA by leptoquark resonances is correct. As discussed above, the coupling $\lambda_{\Phi Qq}$ is expected to be of the order $\lambda_{\Phi Qq} = \mathcal{O}(1)$. Compared to the heavy quark production parton cross sections in QCD \cite{8} the ratio of total parton cross sections is roughly given by the ratio of couplings $(\lambda_{\Phi Qq}/g_s)^4$, where $g_s$ is the QCD coupling. For instance, for $\lambda_{\Phi Qq}/g_s \simeq 3$ we have a total parton cross section resulting from (7) which is by two orders of magnitude larger than those from heavy quark pair production processes in QCD. This is large enough to give a significant contribution to the single jet inclusive cross section above 200 GeV and can compete with interpretations based on modifications of the parton distributions (see, for instance, \cite{9}). However, the cascade decays $Q \rightarrow \Phi_{qq} + jet \rightarrow jet + jet + jet$ produce multi-jet signature characteristics, which distinguish these final states from usual QCD ones. In QCD-like final states some virtual loop contributions involving $Q$, $\Phi_{qq}$ and the coupling $\lambda_{\Phi Qq}$ could also be relevant. Another contribution to high-$E_T$ can come from a process as in figure 1a with on-shell $\Phi_{qq}$ resonance and virtual $Q$. This would contribute to the cross-sections of $W$ or $Z$ plus jets. The evaluation of these different possibilities requires a detailed study, which goes beyond the scope of this letter.

In summary, the assumption of a new strong interaction at the TeV scale in the vector-like extension of the standard model with mirror fermions can produce resonances in fermion-mirror-fermion channels. These new states can potentially explain the recently observed high $Q^2$ and high $E_T$ event excesses compared to the predictions of the minimal standard model. The small mixing between fermions and mirror fermions naturally leads to small couplings of these new resonant states to light fermion pairs.

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