A SCENARIO FOR CONTACT INTERACTIONS AT HERA

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ABSTRACT

The four fermion contact interactions, required to explain the anomalous HERA result, could come from the exchange of new heavy (probably composite) resonances. Depending on their charges and quantum numbers, one gets different scenarios and finds that many of these configurations are unsuitable. For example, new neutral resonances seems to be disfavored by the data coming from the TEVATRON, LEP 2 and atomic parity violation. These experiments allow only few helicity combinations that cannot arise from neutral currents in a natural way. On the contrary, a global large symmetry $SU(8) \times SU(8)$ (which is contained in $SU(16)$) embeds some lepto-quarks of spin 1 that could give suitable four fermion interactions (compatible with all other experiments) if these resonances are the lightest new (probably composite) states with a mass comparable to the scale of the contact interactions.

Introduction

In this paper we will try to discuss the nature of the physics that could explain the anomalous excess observed by the two collaboration ZEUS and H1 at HERA [1]. An explanation could be the real production of a light squark or a scalar lepto-quark [2, 3, 4, 5, 6, 7, 8] with a small coupling with the electron and down quark. In the squark case one assumes a $R-$parity violating scenario [9]. However, even if this seems the most realistic interpretation, the possibility of new four fermion contact interactions [2, 10] cannot be ruled out, in particular if the existence of a peak around 200 GeV is not confirmed by the experiments. These interactions are severely constrained both from atomic parity violation and from collider physics at the Tevatron and LEP 2 [2, 10, 11, 12]. As a result, only few helicity combinations are allowed and the nature of the physics that could generate them is very restricted. We will see that it is not easy to find a simple scenario. First we analize the possibility that the contact terms come from new neutral currents; we will see that they cannot give a satisfactory interpretation of the helicity structure of the contact terms that appears to emerge when all the constraints are taken into account. On the contrary, all the lepto-quarks of the adjoint of a global $SU(8) \times SU(8)$ (with spin 1) contained in a $SU(16)$ global symmetry, could potentially give the correct contact terms, with the needed helicity structure and the correct overall and relative signs.

Contact interactions

The four fermion interactions are usually parametrized in the following way [13]

$$\eta_{ij}\frac{4\pi}{\Lambda^2}\bar{\psi}_i\gamma^\mu\psi_i \ \bar{\psi}_j\gamma_\mu\psi_j \tag{1}$$

where $i, j = e_L, e_R, u_L, u_R, ...$ are left handed and right handed components of the standard fermions.

Adding new physics to the standard model lagrangian can potentially affect the precision measurements at the Z_0 peak [14], in particularly if this new physics breaks the electroweak symmetry. For example, a $SU(2)$ violating contact term $\bar{e}_R u_L \ \bar{u}_L e_R$ (without a similar $\bar{e}_R d_L \ \bar{d}_L e_R$ term) can arise if the fermions exchange a scalar $SU(2)$ doublet, and the two component (up and down) have very different mass. However if we we split the masses in this scalar doublet, the electroweak parameter ε_1 would get a significant contribution which roughly goes as

$$\frac{\alpha}{4\pi s_W^2}\frac{(M_u - M_d)^2}{M_W^2} \tag{2}$$

(M_u, M_d are the masses of the up and down scalar in the doublet). Since ε_1 is in agreement with the Standard model within an accuracy of the per mill level, we easely realize that the splitting could be at most of the order of $w-$boson mass which is certainly not enough to explain a difference in the scale of the two contact terms of the order of the TeV (if we require that the down quark contact interaction is suppressed compared with the up quark one). In general, a $SU(2)$ breaking operator would be suppressed by a power of the Higgs vev v_{HIGGS}^2 (if we want

chirally invariant contact interactions we have only an even number of fermion $SU(2)-$doublets and scalar doublets), which give the scale of the contact interaction

$$\frac{v^2_{HIGGS}}{\Lambda^4}. \tag{3}$$

Thus the scale Λ has to be much closer to the weak scale and should be visible.

Hereafter we will assume that the physics responsible for the new contact interactions preserves the $SU(2) \times U(1)$ symmetry.

Previous analyses [2, 10] have shown that only few four fermion contact interactions could explain the excess observed at HERA: limits coming from the tevatron in similar processes ($q\,\bar{q} \to e^+\,e^-$) and atomic parity violation are strong. HERA suggests the following flavor and helicity content (see ref. [2, 10] for a more detailed discussion)

$$\bar{e}_L\gamma^\mu e_L \ \bar{u}_R\gamma_\mu u_R, \quad \bar{e}_R\gamma^\mu e_R \ \bar{u}_L\gamma_\mu u_L \tag{4}$$

in order to get a sizable contribution in the relevant kinematical region, while the tevatron suggests that the other helicity contribution (LL and RR have to be suppressed). To avoid the constraints from atomic parity violation we preserve parity, and adding $SU(2)$ gauge invariance, we are obliged to introduce the down quark contribution

$$\bar{e}_L\gamma^\mu e_L\bar{d}_R\gamma_\mu d_R, \quad \bar{e}_R\gamma^\mu e_R\bar{d}_L\gamma_\mu d_L. \tag{5}$$

The full lagrangian becomes[1]

$$\text{iL} = \frac{4\pi\text{i}}{(3 \text{ TeV})^2} \quad (\bar{L}_L\gamma^\mu L_L(\bar{u}_R\gamma_\mu u_R + \bar{d}_R\gamma_\mu d_R)$$
$$+\bar{e}_R\gamma^\mu e_R \ \bar{Q}_L\gamma_\mu Q_L). \tag{6}$$

where $\bar{L}_L\gamma^\mu L_L$ is the $SU(2)$ invariant combination of two lepton doublets (the same for Q_L). This appears to be the most realistic scenario that could explain the HERA excess: all the terms have the same scale $3 \ TeV$ to avoid parity violation and to preserve gauge invariance, and the overall phase in front of the parenthesis is $+$i, otherwise this term would constructively interfere with the standard model amplitude in $\bar{q} + q \to e^+ + e^-$, leading to an unacceptable rate of production of lepton pairs at the TEVATRON.

The nature of the new physics

In this section we discuss the nature of the physics that could generate the contact interactions of the type in eq.(6). If these interactions are mediated by new heavy (probably composite)

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[1]Note that four fermion contact interactions that induce charged current processes are strongly constrained [15].

resonances then it should be possible to describe the interaction as the product of the matrix elements of operators J as below

$$\frac{1}{\Lambda^2} < q|J_i|q > < e|J^i|e > \tag{7}$$

or

$$\frac{1}{\Lambda^2} < e|J_i|q > < q|J^i|e > \tag{8}$$

where the sum over i takes into account any possible lorentz structure of the operators J (scalar,...). Firstly we analyze the former case when the interaction is due to neutral currents *i.e.* this new interaction is mediated by the exchange of few neutral particles. A realistic consequence of this scenario is the existence of the following similar interactions

$$\frac{1}{\Lambda^2} < e_{L,R}|J_i|e_{L,R} > < e_{L,R}|J^i|e_{L,R} > \tag{9}$$

and $$\tag{10}$$

$$\frac{1}{\Lambda^2} < q_{L,R}|J_i|q_{L,R} > < q_{L,R}|J^i|q_{L,R} > . \tag{11}$$

Then we get a relation between the scales of contact interactions of different processes (purely leptonic processes Λ_{ee}, mixed Λ_{eq}, etc.):

$$\Lambda_{eq}^2 \simeq \Lambda_{ee}\Lambda_{qq} \tag{12}$$

This relation has to be compared with the limits [11, 12] coming from LEP2 and TEVA-TRON (to obtain roughly the limit on the parity conserving Λ_{LL+RR}^{ll} we have multiplied $\Lambda^2 = \sqrt{2}\Lambda_{RR}^2$, see ref.[11]). Namely[2]

$$\Lambda^{ll} >\sim 4.4 \ TeV \quad \Lambda^{qq} >\sim 1.6 \ TeV \tag{13}$$

and applying the above relation we also get

$$5.6 \ TeV >\sim \Lambda^{ll} >\sim 4.4 \ TeV. \tag{14}$$

for $\Lambda^{qq} = 1.6 \ TeV$ and

$$6.9 \ TeV >\sim \Lambda^{ll} >\sim 4.4 \ TeV. \tag{15}$$

for $\Lambda^{qq} = 1.3 \ TeV$

In practice this new contact interaction is very close to the limit of both LEP 2 and the TEVATRON and will be certainly seen in the next future.

These constraints become even harder to avoid when we also try to obtain the helicity structure in eq.(6), which is rather unnatural and unclear in the context of pure neutral currents [16, 17]: the existence of LR and RL helicity without the LL and RR one, requires at least two neutral bosons, the first coupled only to e_L and q_R the second only to e_R and q_L; these

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[2]Assuming lepton universality.

couplings, their signs and the masses of these bosons have to be chosen in order to guarantee the compatibility with the constraints (14) and at the same time have to give the correct lagrangian (6).

Therefore we believe that purely neutral currents cannot explain the HERA excess. On the contrary (as will become clearer after), new heavy lepto-quarks could more naturally explain the helicity structure of these contact terms in (6) and at the same time the absence of similar signals in the $e^-\ e^+ \to e^-\ e^+$ and $q\ \bar{q} \to q\ \bar{q}$ channels.

First, let us analyze the possibility of a new scalar lepto-quark exchange. A scalar $SU(2)-$doublet which interacts with the electron and the up quark through a Yukawa interaction $\lambda \Phi \bar{e}_L u_R$ will introduce the amplitude

$$-\lambda^2 \bar{e}_L u_R \frac{\mathrm{i}}{\mathrm{P}^2 - \mathrm{M}_\Phi^2} \bar{u}_R e_L \tag{16}$$

and after a Fierz rearrangement (and neglecting P^2) can be written

$$-\lambda^2 \frac{\mathrm{i}}{\mathrm{M}_\Phi^2} \bar{e}_L \gamma^\mu e_L \quad \bar{u}_R \gamma_\mu u_R. \tag{17}$$

Note that the phase of this amplitude is $-\mathrm{i}$, with opposite sign with respect (6). This is a general result for a scalar exchange, the Yukawa coupling enters the amplitude through the square $|\lambda|^2$ and the sign is only determined by the overall phase of the propagator of the internal particle which is $-\mathrm{i}/\mathrm{M}_\Phi^2$ for a scalar. This gives a constructive interference with the standard model amplitude at the TEVATRON (and destructive at HERA): it increases the rate of production of a pair of leptons at the TEVATRON to an unacceptable level (if the size is large enough to explain HERA).

We therefore consider the possibility of a heavy spin 1 particle exchange (much heavier than the lower bound coming from the TEVATRON direct searches). In such case, we need the following set of currents

$$\begin{aligned} J^\mu &= \bar{e}_L \gamma^\mu (u_R)^c, \ \overline{(e_R)^c} \gamma^\mu u_L \\ &\quad \bar{e}_L \gamma^\mu (d_R)^c, \ \overline{(e_R)^c} \gamma^\mu d_L \end{aligned} \tag{18}$$

in order to satisfy all the constraints from gauge invariance, atomic parity violation, LEP 2 and TEVATRON. $SU(3) \times SU(2) \times U(1)$ gauge invariance implies that the spin 1 resonances coupled to the above currents have to be $(3, 2, 5/6)$ and $(\bar{3}, 2, -1/6)$ (plus their hermitian conjugate). Obviously these currents do not commute with the $SU(3) \times SU(2) \times U(1)$ generators, since they carry color and charge and the commutation relations

$$\left[T_{SM}^a, T_{NEW}^b \right] = f^{abc} T_{NEW}^c \qquad T_{SM} \in SU(3) \times SU(2) \times U(1) \tag{19}$$

(where the f^{abc} are fixed by the quantum numbers $(3, 2, 5/6)$ and $(\bar{3}, 2, -1/6)$ of the currents J^μ).

The obvious origin for new (conserved) currents is the existence of a new symmetry involving the fermions: a global (or local) transformation of the fields is associated with a set of Noether

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currents J^μ, which are conserved if this transformation is a symmetry of the lagrangian, *i.e.* the action is invariant under this transformation. Let us see if our currents can be identified as the Noether currents of a global (or local) symmetry. If so, they satisfy a Lie algebra which can be represented by some matrices which transform as the adjoint of a symmetry group

$$\left[T^a_{NEW}, T^b_{NEW} \right] = f^{abc} T^c_{NEW} \tag{20}$$

where the T_{NEW} contains the generators of our lepto-quark plus additional generators needed to close the algebra. Since all our lepto-quarks carry some charges, none of them can be identified with the Cartan subalgebra which is neutral, we have to add new generators to close the algebra, and one can easely verify that the minimal scenario is embedding the above lepto-quarks into the **45** adjoint of $SO(10)$ (since we need two type of lepto-quark, with hypercharge $-5/6$ and $1/6$).

Now, if we embed all the first generation of standard fermions into a **16** of this group we easily realize that the same lepto-quarks needed to generate the contact terms at HERA will make the proton disastrously unstable. To avoid this problem, one could introduce the exact conservation of a quantum number that forbids proton decay and would be forced to enlarge the representation of the standard matter to include new fermions (carrying baryon number); they should also have a mass very close to weak scale due to their chiral nature. Therefore, in the next section, we will consider a larger global group to embed our lepto-quarks, without additional light fermions and still keeping the proton stable.

$SU(8) \times SU(8)$, $SU(16)$ **and** $SU(15)$ **global symmetries**

We will discuss the simplest scenario with a $SU(8) \times SU(8)$ global symmetry, plus a discrete symmetry P which exchanges the left-handed and right-handed fermions (all these generators are contained in $SU(16)$); one can apply similar arguments for $SU(15) \supset SU(7) \times SU(8)$.

We divide the 16 fermions[3] in two multiplets of 8 fermions: the first contains all the left-handed quarks, the right-handed electron and the right-handed neutrino; the second contains all the right-handed quarks and the left-handed leptonic doublet. Each $SU(8)$ acts on its multiplet.

Now we will write a mass term for all the spin 1 boson of the adjoint of this group: first, we introduce an invariant mass term M_0^2 which does not break the whole symmetry group. All the bosons are degenerate with mass M_0. Then we break the group $SU(8) \times SU(8)$ without breaking the discrete symmetry P: each $SU(8)$ is broken into $SU(6) \times SU(2) \times U(1)$; therefore we expect that all the bosons of the unbroken generators remain with mass M_0 since they would be massless for $M_0 = 0$. On the contrary we expect that the broken generators would have a squared mass $M_0^2 + M_1^2$. Here we assume that the sign in front of the mass term M_1^2 which split the states in the multiplet (breaking the $SU(8)$ symmetry) is negative: the lepto-quarks would be the lightest particles with squared mass $M_0^2 - M_1^2$.

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[3]Including the right-handed neutrino.

Once we have written the above masses for the particles, we will have that the lepto-quarks which transform as the $(6,2)$ under the unbroken $SU(6) \times SU(2) \times U(1)$ that acts on the left-handed quarks (as well as the lepto-quarks acting on the right-handed quarks) are the lightest and degenerate states since also the discrete symmetry P is unbroken[4].

These lepto-quarks transform as the $(3,2,5/6)$ and $(\bar{3},2,-1/6)$ under $SU(3) \times SU(2) \times U(1)$. For instance, the $(3,2,5/6)$ are coupled with e_R and u_L, d_L and give the following interaction

$$-\lambda^2 \frac{\mathrm{i}}{\mathrm{M}^2} \overline{(e_R)^c} \gamma^\mu u_L \quad \bar{u}_L \gamma_\mu (e_R)^c. \tag{21}$$

This will give one of the needed contact terms (6) after a Fierz rearrangement. In the same way, all the other lepto-quarks will give all the contact interactions (6) needed to explain HERA without affecting all the other measurements. Here we have not addressed the problem to generate the CKM matrix in the above framework, as a simplifying (and *ad hoc*) assumption we could say, for instance, that the Cabibbo angle is mainly due to a mixing in the up quark sector, in which case the lepto-quarks would induce FCNC only in the D_0 decay, where the limits are much less stringent. A complete understanding of the flavor physics certainly demand further work.

Conclusions

In this paper we have tried to understand the possible nature of the physics that generates the four fermion contact interaction needed to explain the HERA excess. Even if the explanation of a new light resonance as a squark or a light scalar lepto-quark appears to be the simplest and more realistic scenario, it is not ruled out that the anomalous excess is due to new four fermion contact interaction; in particular if the cluster of events around 200 GeV observed by one of the experiments is not confirmed. Since the number of contact terms is very restricted and only few helicities are allowed, finding a simple scenario is certainly not an easy task. However, we have proceeded without prejudice, and at each step we have chosen the simplier (to our opinion) direction. We have emphasized that new neutral currents cannot provide a satisfactory explanation, because they should affect $e^+ e^- \to e^+ e^-$ and $q\bar{q} \to q\bar{q}$ channels , and because the helicity structure needed (LR and RL) can only unnaturally arise from purely neutral currents. On the contrary it appears to us that these problems could find a simplier explanation if the new contact interaction come from the exchange of new lepto-quark at the TeV region.

We have tried to identify the J_μ currents coupled to this new particles as the Noether currents of a new global symmetry. In the minimal case of a $SO(10)$ symmetry, the corresponding lepto-quarks make the proton unstable and additional baryonic fermions (with an unnatural pattern of masses) are required to conserve exactly the baryonic number. On the contrary, a larger symmetry, as $SU(8) \times SU(8) \subset SU(16)$ acting on the first generation of the standard fermions contains the lepto-quarks of spin 1 and with quantum number $(3,2,5/6)$ and

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[4]These symmetries are obviuosly broken by gauge interactions and fermion masses.

$(\bar{3}, 2, -1/6)$ with respect $SU(3) \times SU(2) \times U(1)$; these lepto-quarks do not make the proton unstable. If these are the lightest new states they would give the four fermion interactions (6), with the correct helicity structure and the correct overall and relative signs.

Acknowledgements

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