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On the small contribution to the Z^0 width of a new and elusive vector-like down quark singlet

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Abstract

We discuss the *small* contribution of a new vector-like down quark singlet to the Z^0 hadronic width. Such a particle could be somewhat elusive, in particular at large hadron colliders, for it might be hidden in the hadronic background. It is also possible for appropriate values of the new (mass) parameters that this vector-like quark could be detected in missing transverse momentum distributions for pure hadronic events, as well as in dilepton mass distributions for events with no missing transverse momentum.

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No discrepancy with the minimal standard model has still been found [1,2]. However, if a new vector-like down quark singlet with a mass $m_D < \frac{M_Z}{2}$ exists, its contribution to the Z^0 width is so small ($\sim 0.1 - 1\%$) that with the present experimental accuracy it may not be distinguished at the Z^0 resonance. When more statistics is available, it may be detected at e^+e^- colliders after a detailed analysis of the hadronic events. It may be also detected at large hadron colliders, but with a dedicated search, different from that followed to find the top quark [2].

A new *vector-like down quark singlet* D (of the expected type in E_6 models [3]) contributes to the Z^0 width [4]

$$\Gamma(Z^0 \rightarrow D\bar{D}) = (1 + \frac{\alpha_s}{\pi}) \frac{\alpha_s^2}{9c_W^2} (1 - 4\frac{m_D^2}{M_Z^2})^{\frac{1}{2}} (1 + 2\frac{m_D^2}{M_Z^2}) M_Z. \quad (1)$$

Then

$$\Gamma(Z^0 \rightarrow D\bar{D}) = 22.4(5.4) \text{ MeV} \quad (2)$$

for $\alpha_s(M_Z) = 0.12$, $\alpha(M_Z) = (128)^{-1}$, $s_W^2 = 1 - c_W^2 = 0.23$, $m_D = 30(45)$ GeV and $M_Z = 91$ GeV [1]. From now on we will assume that there are three of such new quarks (one per family) with a mass equal to 45 GeV and then an increase of 16 MeV in the predicted (hadronic) Z^0 width.

Although the D coupling to the Z^0 is small, the D decays are characteristic and its mass can be bound by a detailed analysis. This vector-like quark could decay through W, Z, H [5]. (In fact, a new vector-like quark can be distinguished from a sequential one by its neutral to charged decay ratio [6]. This is large for the former and negligible for the latter.) However, depending on the values of the new (mass) parameters there are two possible scenarios. (i) If the Higgs is lighter than the D quark, $m_H < m_D$, then the decay $D \rightarrow q, H$ is the only two-body decay, with [4]

$$\Gamma(D \rightarrow q, H) = \frac{\alpha}{32s_W^2} \frac{|m_i|^2 (m_D^2 - m_H^2)^2}{m_D^2 m_D M_W^2}, \quad (3)$$

where we neglect the final q mass (except later for the top quark mass) everywhere for simplicity. (We are only interested in an estimate because the arbitrariness in

the choice of the mass parameters is more important and it is what will dictate the physics.) The ratios $\frac{m_i}{m_D}$ are (arbitrary) small mixing angles fixing the interaction Lagrangian [5] (in obvious notation):

$$L = \frac{1}{2} W_\mu^+ \bar{u}_L \gamma^\mu (CKM)_{ij} \frac{m_i}{m_D} D_L - \frac{g}{2W} Z_\mu \bar{d}_L \gamma^\mu \frac{m_i}{m_D} D_L - H \bar{d}_L \frac{m_i}{m_D} D_R + h.c. \quad (4)$$

At this point an important worry is the possibly large flavor-changing neutral currents in the standard sector. However, the new mixing angles can be as small as needed, i.e. $\frac{m_i}{m_D} < 2 \times 10^{-5}$ from $K_L^0 \rightarrow \mu^+ \mu^-$, etc [7], because they are arbitrary and common to all vertices mixing the D with the standard quarks. Thus a proper power of these mixing angles suppresses the new contributions to standard processes; whereas new processes like D decays are suppressed by analogous factors but they are also enhanced by large m_D powers (see, for instance, Eq. (3)). Theoretically these mixing angles are naturally small for they are of the order of a standard down quark mass over m_D , $\frac{0.01-0.5}{45}$. (ii) If the Higgs mass is of the order of (or larger than) the gauge boson masses, $m_H \sim M_{W,Z}$, then the new D quark has only three-body decays and those mediated by virtual bosons W^* , Z^* are often dominant. In standard notation and neglecting larger $\frac{m_D}{M_{W,Z}}$ powers [8] we find

$$\Gamma(D \rightarrow q_i W^* \rightarrow q_i f \bar{f}) = \frac{G_F^2 m_D^5}{192 \pi^3} \frac{|m_i|^2}{m_D^2} \left(1 + \frac{3}{5} \frac{m_D^2}{M_W^2}\right) C_f^W, \quad (5)$$

where C_f^W is 1(3) for leptons (quarks), and

$$\Gamma(D \rightarrow q_i Z^* \rightarrow q_i f \bar{f}) = \frac{G_F^2 m_D^5}{192 \pi^3} \frac{|m_i|^2}{m_D^2} \left(1 + \frac{3}{5} \frac{m_D^2}{M_Z^2}\right) C_f^Z, \quad (6)$$

where

$$\begin{aligned} C_\nu^Z &= \frac{1}{4}, \\ C_e^Z &= \frac{1}{4} - s_W^2 + 2s_W^4, \\ C_u^Z &= \frac{3}{4} - 2s_W^2 + \frac{8}{3}s_W^4, \\ C_d^Z &= \frac{3}{4} - s_W^2 + \frac{2}{3}s_W^4. \end{aligned} \quad (7)$$

Let us discuss in turn both cases. Assuming $m_H = 36$ GeV ($M_W = 80$ GeV) and $m_1' = m_2' = m_3' = m_3'$ and knowing that the top quark is heavy [2] (note that present m_t bounds are modified little when the decay $t \rightarrow DW^{(*)}$ is also considered), it follows from Eqs. (3), (5-7) that the decay ratio is

$$W^*/Z^*/H = 5/2/214 \quad (8)$$

and the decay mode fraction for $D\bar{D}$ events (assuming that the Higgs decays entirely into $b\bar{b}$) is

$$q\bar{q}b\bar{b}b\bar{b}/\nu\bar{\nu}q\bar{q}b\bar{b}/e\bar{e}q\bar{q}b\bar{b} = 1620/8/6/1. \quad (9)$$

(We neglect fractions much smaller than 10^{-3} .) As a consequence, the discovery of a D quark at e^+e^- would require, besides measuring an enhanced hadronic width, a detailed study of jet events with a proper mass reconstruction. Concerning the search for a vector-like quark at hadron colliders, although the $D\bar{D}$ cross section is large [9] (for one D quark with a mass $m_D = 45$ GeV and transverse momentum $p_{t,D}^{D,\bar{D}} > 10$ GeV)

$$\sigma(S\bar{p}\bar{p}S, \text{ Tevatron} \rightarrow D\bar{D}) = 0.3, 5.2 \text{ nb}, \quad (10)$$

the isolation of the dominant (hadronic) decays requires a dedicated analysis.

In the other case ($m_H \geq M_{W,Z}$), the (mass) parameters m_i' are constrained by present top quark searches at large hadron colliders, due to the large ratio of D decays mediated by W^* , Z^* . In fact, $m_1' \sim m_2' \sim m_3' = m_3'$ is already excluded. Using Eq. (10) and assuming

$$W^*/Z^*/H^* = 2/1/1, \quad (11)$$

we find that the $\nu\bar{\nu}q\bar{q}q\bar{q}$ cross section is 0.02 (0.43) nb at the $S\bar{p}\bar{p}S$ (Tevatron), above present top quark limits [2]. e^+e^- colliders can not be definite in this case for the D quark sample at the Z^0 peak is more than one order of magnitude smaller than the bottom quark sample, $\sim \frac{18}{39}$, and there is not enough statistics accumulated to distinguish the D from the b quark events. However, the limit $m_3' \gg m_{1,2}' \sim 0$ has

not been excluded yet at any large collider. In this case the D mixes mainly with the third family, then the W^* channel is forbidden because $m_t > m_D$ and D can decay through Z^* , H^* only. Assuming as in Eq. (11)

$$Z^*/H^* = 1/1, \quad (12)$$

we obtain for the dominant mode fractions

$$q\bar{q}q\bar{q}q\bar{q}/\nu\bar{\nu}q\bar{q}q\bar{q}/e\bar{e}q\bar{q}q\bar{q}/e\bar{e}\nu\bar{\nu}q\bar{q} = 722/170/28/3. \quad (13)$$

The signatures are the same at any large collider. For e^+e^- the $D\bar{D}$ cross section corresponding to a contribution to the Z^0 width of 16 MeV is 0.29 nb at the Z^0 pole, which translates into 49 (8) pb for the $\nu\bar{\nu}q\bar{q}q\bar{q}$ ($e\bar{e}q\bar{q}q\bar{q}$) signal in Eq. (13). These events differ from those giving the standard signature of a light Higgs. They have hadrons in both hemispheres with one jet plus missing energy (a charged lepton pair) opposite to the other three jets. In any case, Eq. (13), which fixes the ratio among the different modes, must be consistent with the experiment. At large hadron colliders a search of $\nu\bar{\nu}q\bar{q}q\bar{q}$ ($e\bar{e}q\bar{q}q\bar{q}$) events with the correct kinematics can already put strong limits on this case. The events $e\bar{e}q\bar{q}q\bar{q}$ are particularly interesting because they can be fully reconstructed

$$m_D \sim M_{e\bar{e}jet} \sim M_{3jet}. \quad (14)$$

The dilepton invariant mass $M_{e\bar{e}}$ is centered ~ 23 GeV for $m_D = 45$ GeV, and there is no missing transverse momentum. However, the Drell-Yan background may be important in this mode.

A discussion of the importance of a heavy new vector-like quark for detecting the (intermediate mass) Higgs at hadron colliders was stressed elsewhere [5]. Here we have analysed the implications of a lighter new vector-like down quark singlet, in particular at e^+e^- colliders, discussing also the possibility of a light Higgs. In this case and as a byproduct, if a new D quark exists, this analysis gives new signatures for searching the standard Higgs.

Summarizing, in this paper we have explored the possibility of explaining a value of the Z^0 hadronic width slightly larger than the value predicted by the minimal standard model with a heavy top quark. We have observed that a new vector-like down quark singlet has as small contribution to the Z^0 width as to compete with the expected experimental precision. In fact, if it is not by its characteristic decays, a unique D quark of 45 GeV (contributing, according to Eq. (2), ~ 5 MeV to the Z^0 width) can not be unambiguously established at the Z^0 resonance, where the expected precision is ~ 10 MeV.

For this D quark mass we have discussed two scenarios. In one case, the Higgs is assumed to be lighter than the D quark. This possibility can be excluded at LEP when the Higgs mass bound is pushed up appreciably. Whereas in the other case, the Higgs is assumed to be heavier than the D quark. This second possibility can be strongly constrained by an appropriate search using in particular (present) hadron collider data.

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