Possible Method in Some Extensions of the Standard Model to Produce and Detect Higgs Bosons at Hadron Colliders

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If an SU(2)-singlet quark (we call it D) with mass on the weak scale exists, for which there is some motivation, it can have a large decay to a normal quark plus a Higgs boson, e.g., $D \rightarrow b+H^0$. If $M_D \lesssim 150$ GeV, this converts present-day hadron colliders from being unlikely to detect Higgs bosons into useful Higgs-boson factories, sensitive for $M_{H^0} \lesssim M_Z$.

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If physics at the scale of a few hundred GeV and below is described by the minimal standard model, or conventional supersymmetric generalizations, finding a neutral Higgs boson or showing that one does not exist is difficult.[1] At the CERN e^+e^- collider LEP a search is eventually possible up to $M_H \lesssim 35$ GeV for $\sqrt{s} \lesssim 100$ GeV; as $\sqrt{s}$ is increased up to 200 GeV a search will be possible up to $M_H \lesssim 80$ GeV. At hadron colliders (CERN, FNAL) the low production rates and the backgrounds from other standard-model processes make it nearly impossible to discover or exclude H^0.

In this Letter we point out that, for one way in which physics beyond the standard model could occur, the hadron colliders become useful sources of Higgs bosons, with large production rates up to kinematical limits, and good signatures. We have in mind adding to the standard model one (or three, one for each family) $SU(2)_L$-singlet quark with $Q=-\frac{1}{3}$; such quarks are often called vectorlike since their left-handed and right-handed states have the same SU(2) transformations. We have previously[2] studied such a theory, showing that it could describe a world where quark electroweak and mass eigenstates coincided for the three light families. That approach led[2] to a new view of the origin of the Kobayshi-Maskawa (KM) matrix, an interpretation of the u-d mass inversion, and some other interesting phenomenological possibilities. Further study[3,4] has confirmed the viability of such an approach. Such vectorlike quarks occur naturally in the fermion representations of E_6 models.[5]

Since the vectorlike quarks are not in $SU(2)_L$ doublets, they do not couple directly to W's. They decay by mixing with the down-type quarks b, s, and d. This forces[6] them to have flavor-changing neutral decays in addition to charged-current decays. The effects of interest to us here arise because the decays $D \rightarrow bZ$ and $D \rightarrow bH$ (and/or $D \rightarrow sZ$, $D \rightarrow sH$) occur as often as $D \rightarrow tW, cW$ if $M_D > M_W$, giving rise to copious production of H. If $M_H < M_D < M_{W,Z}$ the decay $D \rightarrow bH$ can be the dominant D decay.

In the following we will speak for simplicity of a singlet object D, but we will present numerical estimates as if there were a D for each light family, as could arise from E_6 representations. The mass of D is relevant for kinematical reasons—as D gets heavier too few are produced to provide a useful number of H. As we will see below, at FNAL production rates are satisfactory up to $M_D \sim 150$ GeV. At future hadron colliders (Large Hadron Collider, Superconducting Supercollider) similar arguments hold, with sensitivity up to much larger M_D and M_H; this could provide a crucial method for studying intermediate mass Higgs bosons at such colliders.[7]

It has previously been understood that physics beyond the standard model makes detecting Higgs bosons considerably easier. Barger *et al.*[8] have emphasized that the η_Q $^1S_0$ quarkonium state from a fourth family has a large branching ratio $\eta_Q \rightarrow ZH$ which provides a good production rate and signature. This has been further studied[9] by Gunion and Kunszt. Nandi has studied[10] the decays $Z' \rightarrow ZH$ of a new Z', again finding a useful rate and signature. Haeri, Soni, and Eilam have studied[11] the one-loop decay $b' \rightarrow bH$ for a fourth-generation quark and emphasize that the rate is perhaps as large as a few percent. Our mechanism has different motivations and characteristics. In particular, the decay to H could be the dominant decay of D, and finding the signature of interest could provide the simultaneous discovery of D and H^0.

Next we write the relevant Lagrangian, and then discuss the phenomenological implications in some detail.

The D-quark interactions.— In Ref. 2 the down-type quark mass matrix was taken to have the form

$$\begin{pmatrix} \Delta & m' \\ m & M \end{pmatrix}, \tag{1}$$

where columns are labeled by d_R, D_R and rows by $\bar{d}_L, \bar{D}_L$. We take $m, m' \ll M$ since M is unrelated to the electroweak breaking and can be much larger. Each element can be 1×1 or 3×3 depending on the family structure; m and m' are 1×3 and 3×1 if appropriate. Some constraints on elements of m occur from known values of the elements of the KM matrix. The nondiagonal D interactions are described at leading order in m'/M by

$$\mathcal{L} = \frac{g_2}{\sqrt{2}} \frac{m'}{M} W_\mu^\dagger \bar{u}_L \gamma^\mu D_L - \frac{g_2}{2\cos\theta_W} \frac{m'}{M} Z_\mu \bar{d}_L \gamma^\mu D_L - \frac{m'}{v} H^0 \bar{d}_L D_R + \text{H.c.} \tag{2}$$

No other terms involving the Higgs field and D occur because D is an $SU(2)_L$ singlet. The term with the Higgs field is proportional to m' because m' arises from a Yukawa coupling times a vacuum expectation value, while the W,Z terms are proportional to m' because the fermion mass eigenstates introduce flavor-changing charged and neutral currents. If u,d represent flavor vectors there is an implied sum with $m'\bar{u}_L$ and $m'\bar{d}_L$ replaced by $m_i'\bar{u}_{Li}$ and $m_i'\bar{d}_{Li}$, respectively. v is the usual Higgs vacuum expectation value. The vertices generated have model-dependent factors (neglecting the mixing with the first generation which is proportional to m_1'):

$$\begin{aligned} &DtW \sim g_2 m_3'/\sqrt{2}M, \\ &DcW \sim g_2 m_2'/\sqrt{2}M, \\ &DbZ \sim g_2 m_3'/2\cos\theta_W M, \\ &DsZ \sim g_2 m_2'/2\cos\theta_W M, \\ &DbH^0 \sim g_2 m_3'/2M_W, \\ &DsH^0 \sim g_2 m_2'/2M_W. \end{aligned} \tag{3}$$

The mixing parameters m_2', m_3' are not especially constrained by experiment[3] and cannot be calculated without a better knowledge of the underlying theory. M is approximately the D mass. We have assumed that D mixes most strongly with the heavier quarks. Fortunately, in practice results will depend on the two parameters, M and m_2'/m_3', and branching ratios only on M (summing over light quarks and neglecting their masses).

Phenomenology.— The quantities of interest here are the branching ratios. Then (neglecting m_q) it follows from Eq. (2)[12] that

$$\begin{aligned} \Gamma(D\to Wq) &\simeq \frac{\alpha_2}{8} \frac{m'^2}{M^2} \frac{(M^2-M_W^2)^2}{M^3} \left[1+\frac{M^2}{2M_W^2}\right], \\ \Gamma(D\to Hq) &\simeq \frac{\alpha_2}{32} \frac{m'^2}{M^2} \frac{(M^2-M_H^2)^2}{MM_W^2}. \end{aligned} \tag{4}$$

$\Gamma(D\to qZ)$ is obtained from $\Gamma(D\to qW)$ by replacing M_W by M_Z and by dividing the whole expression by $2\cos^2\theta_W$. What happens can be seen in Table I.

The signature in all cases is two hard isolated leptons (one a ν for W) plus four (parton) jets; if $m_H > 10$ GeV, H will decay mainly to $b\bar{b}$. While backgrounds are not negligible, they do not dominate such a signal.

The production of D quarks is the same as for any color triplet, from the constituent process $gg\to D\bar{D}$. The cross section[13] at FNAL for producing a quark with $m_D \simeq 150$ GeV is about 30 pb, assuming three degenerate D quarks; for $m_D \simeq 100$ GeV the cross section is an order of magnitude larger. An integrated luminosity of 5 pb^{-1} will give about 150 $D\bar{D}$ pairs for $m_D \simeq 150$ GeV. Depending on what fraction of the $D\to qW$ and $D\to qZ$ decays can be used as a trigger, that means that $m_D \simeq 150$ GeV is at or somewhat above the upper limit of D masses that can be detected with 5 pb^{-1}. As the integrated luminosity increases, of course the accessible m_D increases. The accessible range of m_H is determined by the decay kinematics. As m_H increases $B(D\to qH)$ decreases, but the useful trigger rate increases, so the useful fraction of events drops slowly. Probably events with m_H up to about $\frac{3}{4}$ of m_D can be detected. Thus if this mechanism should be available it will be possible to search for Higgs bosons up to $m_H \gtrsim m_Z$ at hadron collid-

TABLE I. Branching ratios for $D\to qW$, qZ, and qH and fraction of $D\bar{D}$ pairs with easily detectable signatures. We defined $F_W = 2\times2/9\times B(D\to qW)\times B(D\to qH)$ to be the fraction of $D\bar{D}$ pairs triggered by $W\to e\nu$ or $W\to\mu\nu$ and $F_Z = 2\times0.06\times B(D\to qZ)\times B(D\to qH)$ to be the similar fraction for $Z\to E^+e^-$ or $Z\to\mu^+\mu^-$; $F_{\text{tot}} = F_W + F_Z$ is the total fraction triggered. It is a conservative assumption for these numbers to neglect the corrections due to a non-negligible m_t. If m_t is large a dependence on m_2'/m_3' appears, enhancing the Z and the H branching ratios. This will be discussed in Ref. 7.

M (GeV)	M_H (GeV)	$B(D\to qW)$	$B(D\to qZ)$	$B(D\to qH)$	F_W	F_Z	F_{tot}
150	92	0.59	0.26	0.15	0.040	0.004	0.044
150	60	0.52	0.24	0.24	0.056	0.006	0.062
100	60	0.51	0.07	0.42	0.096	0.004	0.100

ers in the near future.

If a new heavy quark Q (D or b' or $\cdots$) is discovered it is essential to know how to distinguish a vectorlike quark from a fourth-generation one or a t quark in order to know whether to expect $Q \rightarrow q + H$ decays. That is done[6] by determining whether the flavor-changing neutral-current decays $Q \rightarrow q + Z$ occur; for a quark in an $SU(2)_L$ doublet (t quark or new family) the charged-current decays are the only ones allowed at tree level so they totally dominate, while for a vectorlike quark the neutral flavor-changing decays will be large, at least a few percent.

Our examples above were for the best case, and perhaps the most likely one, $M > M_Z$ and $M > M_H$. If $M < M_{W,Z,H}$ then the W,Z,H are virtual and our arguments basically hold; the signature is somewhat less good because the lepton-pair mass is spread out rather than unique, but it is still a useful signature. If $M_H < M < M_W$, then $D \rightarrow qH$ is two-body, while $D \rightarrow qW, qZ$ are three-body, so $D \rightarrow qH$ totally dominates; the signature is not very useful, but the events are there. If $M_W < M < M_H$, the decays to H are suppressed.

We conclude by emphasizing again that the existence of a vectorlike quark would not only allow hadron colliders to discover such a new object, but would allow them simultaneously to discover or exclude a Higgs boson of mass nearly up to that of the vectorlike quark. That contrasts greatly with the situation in the standard model or in a minimal supersymmetric theory, where a hadron collider is poorly suited for finding Higgs scalars and surely cannot exclude them.

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