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Exotic signals of heavy scalar bosons through vectorlike quarks

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In an extension of the SM with an additional singlet scalar field S and vector-like quarks, we study the condition of the radiative enhancement of a heavy scalar boson decay into a massive gauge boson pair. Focusing on the loop effects, we assume that S is linked to the standard model world only through loops of vector-like quarks. The radiative effects are the mixing with the Higgs boson and the loop-induced decays into hh, WW, ZZ, gg, and $\gamma\gamma$. The critical condition for the longitudinal polarization enhancement is the large mass differences among vector-like quarks.

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1. Introduction

One of most unique features of a heavy scalar boson is the longitudinal polarization enhancement in its decay into $VV(V=W^\pm,Z)$ since the longitudinal polarization vector is proportional to p_V^μ/m_V in the high energy limit. We answer the question of whether the same thing happens at loop level in a new physics model with a singlet scalar S and vector-like quarks (VLQs) [1]. Theoretically, a singlet scalar is important in the context of Higgs portal models [2] and VLQs also appear in many new physics models [3, 4].

In order to find the condition for the longitudinal polarization enhancement, we first write the most general coupling of S to a pair of gauge bosons in the CP-conserving framework as

$$S(p)V_\mu(p_1)V'_\nu(p_2)\,:\,m_S\left[\mathscr{A}\,g_{\mu\nu}+\mathscr{B}\,\frac{p_{2\mu}p_{1\nu}}{m_S^2}\right]. \tag{1.1}$$

Then the longitudinal polarization enhancement occurs when $2\mathscr{A}+\mathscr{B}\neq 0$.

2. Model with a singlet scalar and vector-like quarks

We consider a simple extension of the SM by introducing a CP-even singlet scalar boson S_0, a VLQ doublet $\mathscr{Q}_{L/R}$, two VLQ singlets $\mathscr{U}_{L/R}$ and $\mathscr{D}_{L/R}$ with $SU(3)_c\times SU(2)_L\times U(1)_Y$ quantum numbers of $(\mathbf{3},\mathbf{1},-2/3)$. The scalar potential without tree-level mixing between S_0 and h_0 is

$$V(H,S_0)\,=\,-\mu^2H^\dagger H+\lambda(H^\dagger H)^2+b_1S_0+\frac{b_2}{2}S_0^2+\frac{b_3}{3}S_0^3+\frac{b_4}{4}S_0^4. \tag{2.1}$$

Our choice of the vacuum as $(v_0,x)=(v,0)$, where x is the vacuum expectation value of S_0, eliminates the tadpole term of S_0. And minimization conditions lead to $\mu^2=\lambda v^2$ and $b_1=0$. The Yukawa terms of VLQs with the singlet S_0 and the SM Higgs doublet H as well as their mass terms are

$$\begin{aligned}-\mathscr{L}_Y\,=\,&y_SS_0\left[\bar{\mathscr{Q}}\mathscr{Q}+\bar{\mathscr{U}}\mathscr{U}+\bar{\mathscr{D}}\mathscr{D}\right]+M_{\mathscr{Q}}\bar{\mathscr{Q}}\mathscr{Q}+M_{\mathscr{U}}\bar{\mathscr{U}}\mathscr{U}+M_{\mathscr{D}}\bar{\mathscr{D}}\mathscr{D}\\&+\left[Y_{\mathscr{D}}\bar{\mathscr{Q}}_LH\mathscr{D}_R+Y_{\mathscr{D}}\bar{\mathscr{Q}}_RH\mathscr{D}_L+Y_{\mathscr{U}}\bar{\mathscr{Q}}_L\widetilde{H}\mathscr{U}_R+Y_{\mathscr{U}}\bar{\mathscr{Q}}_R\widetilde{H}\mathscr{U}_L+H.c.\right].\end{aligned} \tag{2.2}$$

The Yukawa couplings of VLQs with the Higgs boson mix the VLQ doublet and singlets. In terms of mass eigenstates, the Higgs couplings are

$$y_{hF_1F_1}\,=\,-y_{hF_2F_2}\,=-\frac{Y_F}{\sqrt{2}}s_{2\theta_F},\quad y_{hF_1F_2}=y_{hF_2F_1}\,=-\frac{Y_F}{\sqrt{2}}c_{2\theta_F}. \tag{2.3}$$

The opposite sign of $y_{hF_1F_1}$ and $y_{hF_2F_2}$ cancels the VLQ contribution to κ_g.

3. The effects of the VLQ loops

In this model, the VLQs play the role of messengers between the SM particles and S through loops. There are two kinds of VLQ loop effects. First, the radiatively generated S-h mixing is via

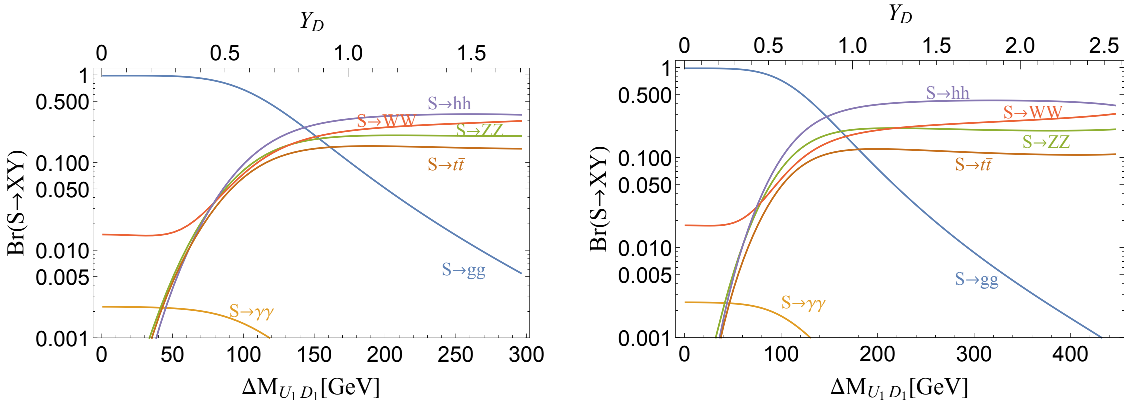
$$\delta M_{Sh}^2\,=\,-\frac{y_SN_c}{4\pi^2}\sum_F\sum_{i=1,2}y_{hF_iF_i}M_{F_i}^2\left[4(\tau_{F_i}^S-1)g(\tau_{F_i}^S)-4\tau_{F_i}^S+5\right], \tag{3.1}$$

where $\tau^i_j = m_i^2/(4m_j^2)$, and $g(\tau)$ is referred to Ref.[1]. Note that δM^2_{Sh} vanishes if $M_{F_1} = M_{F_2}$ since $y_{hF_1F_1} = -y_{hF_2F_2}$. Significant S-h mixing requires sizable mass difference between F_1 and F_2.

The second effect of the VLQ loops is the radiative decay of S into $t\bar{t}$, gg, $\gamma\gamma$, WW, ZZ, and hh. The decay of S into a top quark pair is only through the S-h mixing. The radiative decays of S into gg, $\gamma\gamma$, and $Z\gamma$ are suppressed since they do not have longitudinal polarization enhancement. $S \to hh$ is also important: $\Gamma(S \to hh)$ increases with ΔM_F. The VLQ loops also generate the decay of S into VV $(V = W, Z)$. The asymptotic behavior of $2\mathscr{A} + \mathscr{B}$ is

$$2\mathscr{A} + \mathscr{B} \longrightarrow \mathscr{O}\left(\frac{m_V^2}{m_S^2}\right) \text{ if } \Delta M_F = 0.$$

4. Numerical Results



(a) $m_S = 500$ GeV (b) $m_S = 750$ GeV

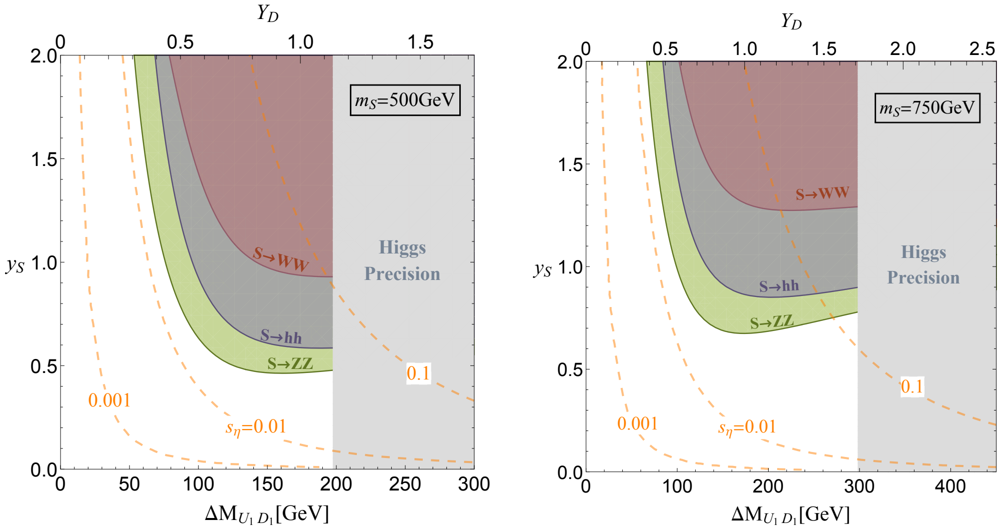
Figure 1: Branching ratios of the radiative decays of the singlet scalar S with mass $m_S = 500, 750$ GeV as functions of $\Delta M_{\mathscr{U}_1\mathscr{D}_1} (\equiv M_{\mathscr{U}_1} - M_{\mathscr{D}_1})$ in the benchmark scenario.

We take a benchmark parameter line of

$$M_{\mathscr{Q}} = M_{\mathscr{U}} = M_{\mathscr{D}}, \quad Y_{\mathscr{U}} = 0, \quad Y_{\mathscr{D}} \text{ varies}, \tag{4.1}$$

which implies that $\mathscr{D}_1$ becomes the lightest VLQ and $\Delta M_{\mathscr{U}_1\mathscr{D}_1} = \Delta M_{\mathscr{D}_2\mathscr{U}_1} = (1/2)\Delta M_{\mathscr{D}_2\mathscr{D}_1}$ where $\Delta M_{ij} \equiv M_i - M_j$. Figure 1 shows the branching ratios of S as functions of $\Delta M_{\mathscr{U}_1\mathscr{D}_1}$ for $m_S = 500, 750$ GeV and $M_{\mathscr{D}_1} = 0.6 m_S$. When $Y_{\mathscr{D}} = 0$, the singlet scalar S decays into gg almost 100%. As $Y_{\mathscr{D}}$ increases, the decay modes of hh, WW, ZZ and $t\bar{t}$ become significant: the hh mode is as important as gg when $Y_{\mathscr{D}} \simeq 0.8$. The next dominant are into WW, ZZ, and $t\bar{t}$.

Now we present the current constraints on this model from the Higgs precision data [6], as well as the heavy Higgs boson searches in the WW [7, 8], ZZ [9], and hh [10]. The other heavy scalar search channels give weaker constraints. The parameter space of $\Delta M_{\mathscr{U}_1\mathscr{D}_1} \gtrsim 200\,(300)$ GeV for $m_S = 500\,(750)$ GeV is excluded by the Higgs precision data, irrespective of y_S. Among the heavy Higgs search constraints at the LHC, the ZZ channel puts the strongest bound due to its clean signal. The parameter space with large y_S and large $Y_{\mathscr{D}}$ is excluded. We also present the contours of the S-h mixing angle, s_η, by dashed (orange) lines. In most parameter space, s_η should be less than about 0.01 (0.05) for $m_S = 500\,(750)$ GeV.



(a) $m_S = 500$ GeV (b) $m_S = 750$ GeV

Figure 2: The constraints in the parameter space of $(\Delta M_{\mathscr{U}_1\mathscr{D}_1}, y_S)$ from the current LHC Higgs data as well as the $\sqrt{s} = 8$ TeV searches for a heavy Higgs decaying into WW, ZZ, and hh.

5. Conclusions

In a new physics model with a singlet scalar field S, one VLQ doublet and two VLQ singlets, we find the condition for the longitudinal polarization enhancement of a heavy scalar boson in its decay into $S \to WW/ZZ$ at loop level. Through the Yukawa couplings of VLQs, the VLQs generate radiatively the S-h mixing as well as the decays of S into gg, WW, ZZ, and hh. The condition for enhancing the radiative decay rates of S into WW, ZZ and hh is the large mass differences of VLQs. The enhancement can be very large huge, by one order of magnitude.

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