Radiative decays of a singlet scalar boson through vector-like quarks

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Sin Kyu Kang

(Seoul-Tech)

In collaboration with Kingman Cheung, Jeonghyeon Song, Yeo Woong Yoon

Outline

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Introduction

- 13 TeV LHC data → more solidifying the Standard Model, and no signal for new physics.
- Usual way to explain the absence of new signal is to push new particles out of the LHC reach, or to introduce hidden sectors.
- If either is the case, a clue on new physics can be searched through radiative corrections mediated by new particles or the linking to the hidden sector.
- We aim at proposing new signals for a heavy scalar boson generated only through loop effects, which are *so significant* to be useful in the search for a new heavy scalar boson.

Introduction

- How can loop effect be significant ?

→When heavy particles running in the loop non-decouple, so that the amplitude is substantially enhanced.

- Non-decoupling means that the suppression of loop effects due to large mass of mediator is compensated by the increased coupling.
- In the SM, the process $h \to \gamma\gamma$ shows non-decoupling of t.

→ Since t Yukawa coupling is $\frac{m_t}{v}$, t contribution to the amplitude is of the form $\frac{m_t}{v}\frac{1}{16\pi^2}\frac{1}{m_t}$

- We study a possibility that loop induced decay rate of a new heavy scalar can be enhanced.

Model

- On top of the SM, we introduce a singlet scalar boson S_0,

  VLQ doublets $Q_{L/R} = \begin{pmatrix} U'_{L/R} \\ D'_{L/R} \end{pmatrix}$, VLQ singlets $U_{L/R}$, $D_{L/R}$

- Scalar potential :

$$V(H, S_0) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} S_0 H^\dagger H + \frac{a_2}{2} S_0^2 H^\dagger H$$
$$+ b_1 S_0 + \frac{b_2}{2} S_0^2 + \frac{b_3}{3} S_0^3 + \frac{b_4}{4} S_0^4.$$

- Minimization : $v = \langle h^0 \rangle = 246$ GeV,

$$\langle S_0 \rangle = 0, \qquad \mu^2 = \lambda v^2 \qquad b_1 = -\frac{v^2}{4} a_1$$

Model

- Yukawa interactions for VLQs :

$$-\mathscr{L}_Y = S_0\left[y_{\mathcal{Q}}\bar{\mathcal{Q}}\mathcal{Q} + y_{\mathcal{U}}\bar{\mathcal{U}}\mathcal{U} + y_{\mathcal{D}}\bar{\mathcal{D}}\mathcal{D}\right] + M_{\mathcal{Q}}\bar{\mathcal{Q}}\mathcal{Q} + M_{\mathcal{U}}\bar{\mathcal{U}}\mathcal{U} + M_{\mathcal{D}}\bar{\mathcal{D}}\mathcal{D}$$
$$+\left[Y_{\mathcal{D}}\bar{\mathcal{Q}}_L H\mathcal{D}_R + Y'_{\mathcal{D}}\bar{\mathcal{Q}}_R H\mathcal{D}_L + Y_{\mathcal{U}}\bar{\mathcal{Q}}_L\widetilde{H}\mathcal{U}_R + Y'_{\mathcal{U}}\bar{\mathcal{Q}}_R\widetilde{H}\mathcal{U}_L + H.c.\right]$$

- VLQ mass matrix :

$$\mathbb{M}_F = \begin{pmatrix} M_{\mathcal{Q}} & \frac{Y_F v}{\sqrt{2}} \\ \frac{Y_F v}{\sqrt{2}} & M_F \end{pmatrix}$$

diagonalized by

$$\mathbb{R}_{\theta_F} = \begin{pmatrix} c_{\theta_F} & -s_{\theta_F} \\ s_{\theta_F} & c_{\theta_F} \end{pmatrix}$$

Model

- Mass eigenvalues & mixing angles

$$M_{F_1,F_2} = \frac{1}{2}\left[M_{\mathcal{Q}} + M_F \mp \sqrt{(M_F - M_{\mathcal{Q}})^2 + 2Y_F^2 v^2}\right]$$

$$s_{2\theta_F} = \frac{\sqrt{2}Y_F v}{M_{F_2} - M_{F_1}},$$

- Gauge interactions

$$\mathscr{L}_{\text{gauge}} = eA_\mu \sum_F \sum_i Q_F \bar{F}_i \gamma^\mu F_i + g_Z Z_\mu \sum_F \sum_{i,j} \hat{g}_{ZF_iF_j} \bar{F}_i \gamma^\mu F_j$$
$$+ \frac{g}{\sqrt{2}}\left[W^{+\mu} \sum_{i,j} \hat{g}_{W\mathcal{U}_i\mathcal{D}_j} \bar{\mathcal{U}}_i \gamma_\mu \mathcal{D}_j + H.c.\right].$$

Effects of VLQ Loops

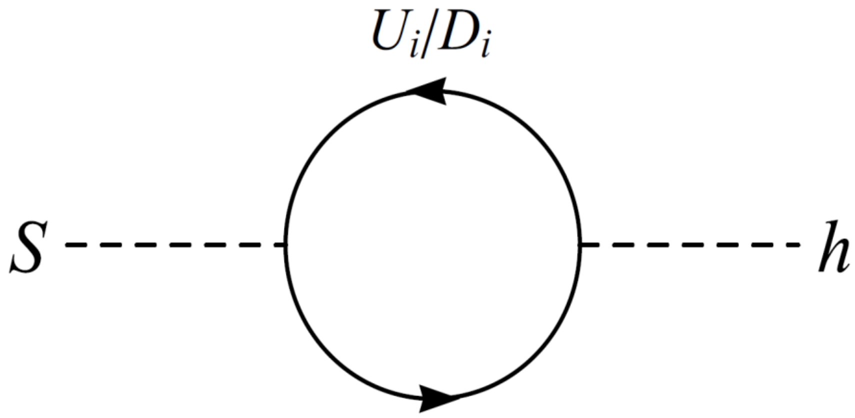
- To see how loop induced decay rate of S_0 can be enhanced, we take a limiting scenario where S_0 has no tree level coupling with the SM higgs :

$$a_1^{tree} = 0 = a_2^{tree}$$

- VLQs play the messenger connecting S_0 to SM higgs
- 2 radiative phenomena :
  - radiative generation of $S_0 - h$ mixing
  - radiative decays of S_0 into SM particles

Effects of VLQ Loops

(1) Radiative generation of $S_0 - h$ mixing



- 1-loop Mixing mass squared term

$$\tau_{F_i}^S = \frac{m_S^2}{4m_{F_i}^2}$$

$$\delta M_{Sh}^2 = -\frac{y_S N_c}{4\pi^2} \sum_F \sum_i y_{hF_iF_i} M_{F_i}^2 \left[4(\tau_{F_i}^S - 1) g(\tau_{F_i}^S) - 4\tau_{F_i}^S + 5\right]$$

$$g(\tau) = \begin{cases} \sqrt{\tau^{-1} - 1} \arcsin \sqrt{\tau} & \text{if } \tau \leq 1; \\ \frac{\sqrt{1-\tau^{-1}}}{2} \left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right] & \text{if } \tau > 1\,. \end{cases}$$

Effects of VLQ Loops

- Since $y_{hF_1F_1} = -y_{hF_2F_2}$, δM_{Sh}^2 is suppressed when $M_{F_1} \approx M_{F_2}$
- Scalar mass-squared matrix

$$M_{hS}^2 \equiv \begin{pmatrix} M_{hh}^2 & \delta M_{Sh}^2 \\ \delta M_{Sh}^2 & M_{SS}^2 \end{pmatrix}$$

- Mass eigenvalues and mixing angles여기에 수식을 입력하십시오.

$$m_{h,S}^2 = \frac{1}{2}\left(M_{hh}^2 + M_{SS}^2 \mp \sqrt{(M_{SS}^2 - M_{hh}^2)^2 + 4(\delta M_{Sh}^2)^2} \right)$$

$$s_{2\eta} = -\frac{2\,\delta M_{Sh}^2}{m_S^2 - m_h^2},$$

$h = c_\eta h_0 - s_\eta S_0$ → 125 GeV scalar boson

Effects of VLQ Loops

- Loop induced decays of h into gg and $\gamma\gamma$ have additional loop contributions from VLQs.
- In the SM :

$$\mathcal{L}_{\text{Higgs}} = \kappa_g c_g^{\text{SM}} \frac{h}{v} G^{a\mu\nu} G^a_{\mu\nu} + \kappa_\gamma c_\gamma^{\text{SM}} \frac{h}{v} F^{\mu\nu} F_{\mu\nu}$$

$$c_g^{\text{SM}} \equiv \frac{\alpha_s}{16\pi} A_{hgg}^{\text{SM}}, \quad c_\gamma^{\text{SM}} \equiv \frac{\alpha_e}{8\pi} A_{h\gamma\gamma}^{\text{SM}}$$

(A. Djouadi, Phys.Rpt.457(2008))

- Contributions from VLQs :

$$\mathcal{A}_{hgg}^{\text{VLQ}} = \sum_F \sum_i y_{hF_iF_i} \frac{v}{M_{F_i}} A_{1/2}(\tau^h_{F_i}),$$

$$\mathcal{A}_{h\gamma\gamma}^{\text{VLQ}} = \sum_F \sum_i N_C Q^2_{F_i} y_{hF_iF_i} \frac{v}{M_{F_i}} A_{1/2}(\tau^h_{F_i}),$$

$$F = \mathcal{U}, \mathcal{D}, \; i = 1, 2, \; \tau^i_j = m_i^2/(4m_j^2)$$

Effects of VLQ Loops

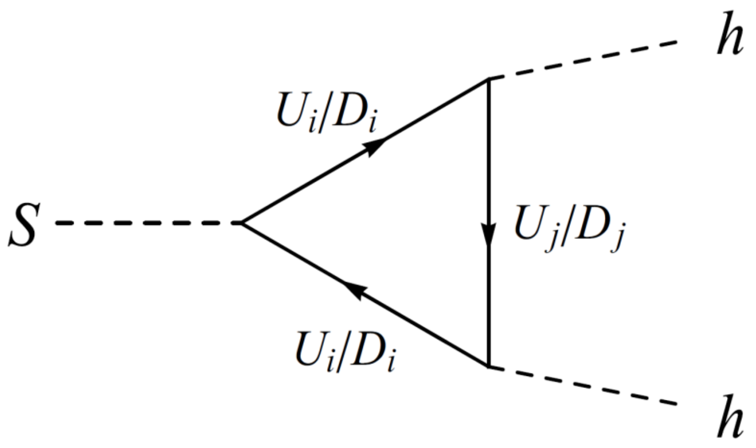
- Contributions to $\kappa_{g,\gamma}$

$$\kappa_{g,\gamma} = \frac{c_\eta A^{SM}_{hgg,h\gamma\gamma} + s_\eta A^{VLQ}_{hgg,h\gamma\gamma}}{A^{SM}_{hgg,h\gamma\gamma}}$$

- Similar to δM^2_{Sh}, $A^{VLQ}_{hgg,h\gamma\gamma}$ are enhanced for large $|M_{F_1} - M_{F_2}|$.

Effects of VLQ Loops

(2) Radiative decays of $S \to hh$



Coupling of shh : $m_S C$

S-h mixing

$$\mathcal{C} = \frac{y_S N_c}{4\pi^2} \sum_F \sum_{i,j} y^2_{hF_iF_j} \mathcal{C}_T(m_h, m_S, M_{F_i}, M_{F_j}) + \frac{3m_h^2}{v m_S} s_\eta$$

- For $m_h \ll m_S$ & $M_{F_1} \approx M_{F_2}$, $\quad \tau = m_S^2/(4M_\mathcal{F}^2)$

$$\Delta_F = M_{F_j} - M_{F_i}$$

$$\sqrt{\tau}\,\mathcal{C}_T = 2 + (1 - 2\tau^{-1}) f(\tau) - 2g(\tau) + \left(\frac{\Delta_F^2}{M_\mathcal{F}^2}\right)\left[\frac{8\tau^2 + 49\tau - 48}{12\tau(1-\tau)} + \frac{(\tau^3 + 12\tau^2 - 26\tau + 16) g(\tau)}{4\tau(1-\tau)^2}\right]$$

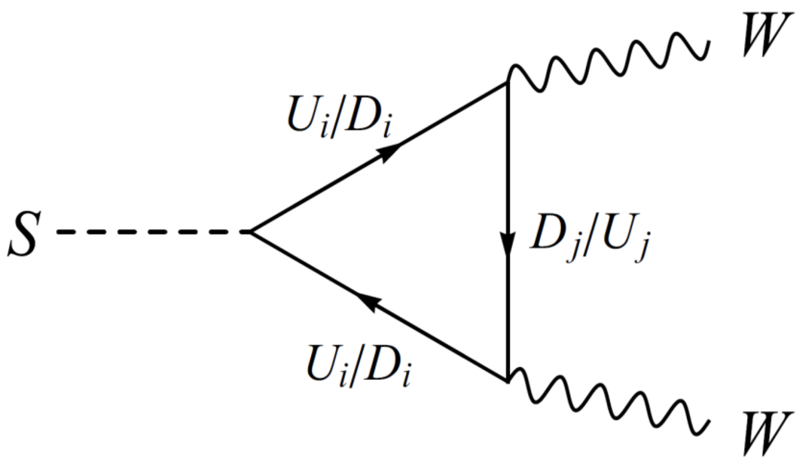
- C is not suppressed by taking large m_S if $y_S, Y_{U,D} \sim 1$
- $\Gamma(S \to hh)$ ($\propto m_S |C|^2$) increases with Δ_F

Effects of VLQ Loops

(3) Radiative decays of $S \to VV$

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

S-h mixing



$$\mathcal{A}_{WW} = \frac{g^2 y_S N_c}{8\pi^2}\sum_{i,j}\left[\hat{g}^2_{W\mathcal{U}_i\mathcal{D}_j}\mathcal{A}_T(m_W, m_S, M_{\mathcal{U}_i}, M_{\mathcal{D}_j}) + \{\mathcal{U}\leftrightarrow\mathcal{D}\}\right] + \frac{2m_W^2}{v m_S}s_\eta,$$

$$\mathcal{B}_{WW} = \frac{g^2 y_S N_c}{8\pi^2}\sum_{i,j}\left[\hat{g}^2_{W\mathcal{U}_i\mathcal{D}_j}\mathcal{B}_T(m_W, m_S, M_{\mathcal{U}_i}, M_{\mathcal{D}_j}) + \{\mathcal{U}\leftrightarrow\mathcal{D}\}\right],$$

$$\mathcal{A}_{ZZ} = \frac{g_Z^2 y_S N_c}{4\pi^2}\sum_{i,j}\left[\hat{g}^2_{Z\mathcal{U}_i\mathcal{U}_j}\mathcal{A}_T(m_Z, m_S, M_{\mathcal{U}_i}, M_{\mathcal{U}_j}) + \{\mathcal{U}\leftrightarrow\mathcal{D}\}\right] + \frac{2m_Z^2}{v m_S}s_\eta,$$

$$\mathcal{B}_{ZZ} = \frac{g_Z^2 y_S N_c}{4\pi^2}\sum_{i,j}\left[\hat{g}^2_{Z\mathcal{U}_i\mathcal{U}_j}\mathcal{B}_T(m_Z, m_S, M_{\mathcal{U}_i}, M_{\mathcal{U}_j}) + \{\mathcal{U}\leftrightarrow\mathcal{D}\}\right],$$

Effects of VLQ Loops

(3) Radiative decays of $S \to VV$

- For $m_V \ll m_S$ & $M_{F_1} \approx M_{F_2}$,

$$\sqrt{\tau}\,\mathcal{A}_T = 1 + (1-\tau^{-1})f(\tau) + \left(\frac{\Delta_F^2}{M^2}\right)\left[-\frac{1}{4} + \frac{(3\tau-4)f(\tau)}{4\tau^2} + \frac{(\tau^2+4\tau-8)g(\tau)}{4\tau(\tau-1)}\right]$$

$$\sqrt{\tau}\,\mathcal{B}_T = -2 - 2(1-\tau^{-1})f(\tau) + \left(\frac{\Delta_F^2}{M^2}\right)\left[\frac{5}{2} + \frac{(8-5\tau)f(\tau)}{2\tau^2} - \frac{(\tau^2+12\tau-16)g(\tau)}{2\tau(\tau-1)}\right]$$

- Sizable mass difference of VLQs are crucial to generate & to enhance the radiative decays of S into VV.

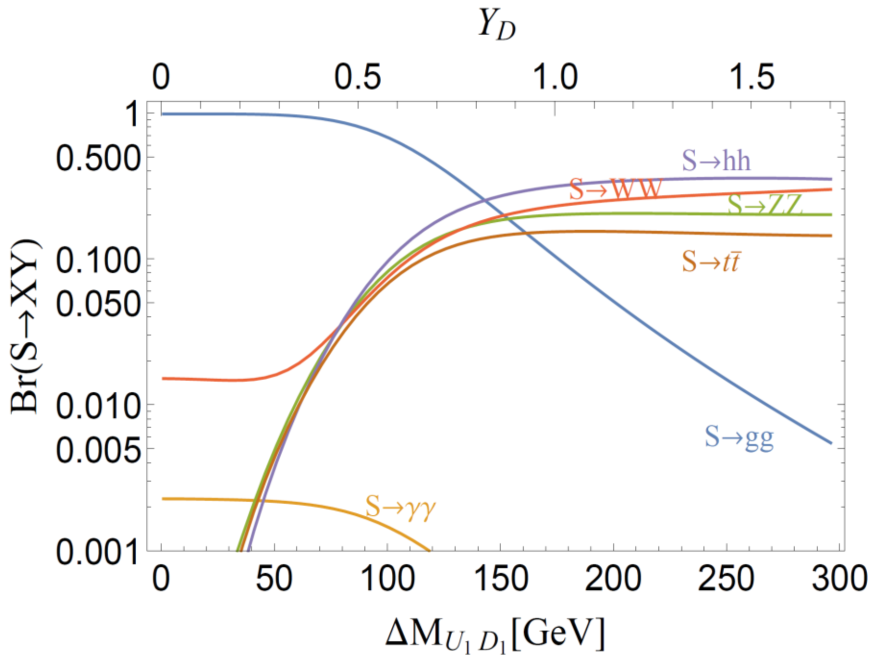
- Yukawa couplings of VLQs with SM higgs are crucial to obtain sizable mass difference of VLQs.

Numerical Results

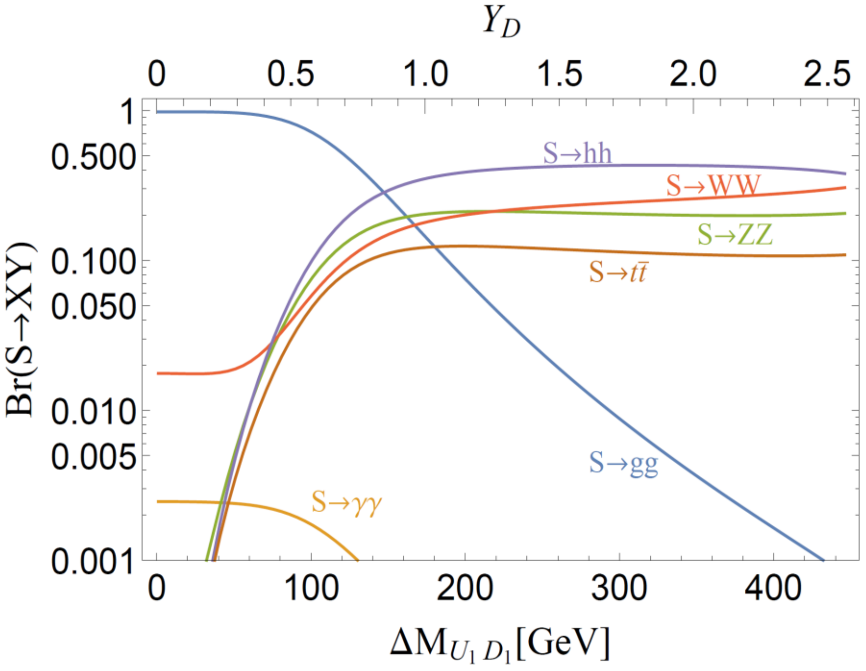
- model parameters in the analysis : $y_S,\ m_S, Y_{U/D}\ , M_Q,\ M_U, M_D$
- Consider a simple benchmark parameter space :

$$M_Q = M_U = M_D, \quad Y_U = 0, \quad Y_D \text{ varies}$$

- Branching ratios of radiative decay of S



(a) $m_S = 500$ GeV



(b) $m_S = 750$ GeV

$$M_{D_1} = 0.6\, m_S$$

$$\Delta M_{U_1 D_1} \sim Y_D v$$

Numerical Results

- Exclusion region in $(\Delta M_{U_1 D_1}, y_S)$

  - we impose Higgs precision data : (ATLAS & CMS, '15)

$$\kappa_V = 0.97 \pm 0.06 \;\; \kappa_g = 0.81^{+0.13}_{-0.10} \;\; \kappa_\gamma = 0.90^{+0.10}_{-0.09}$$

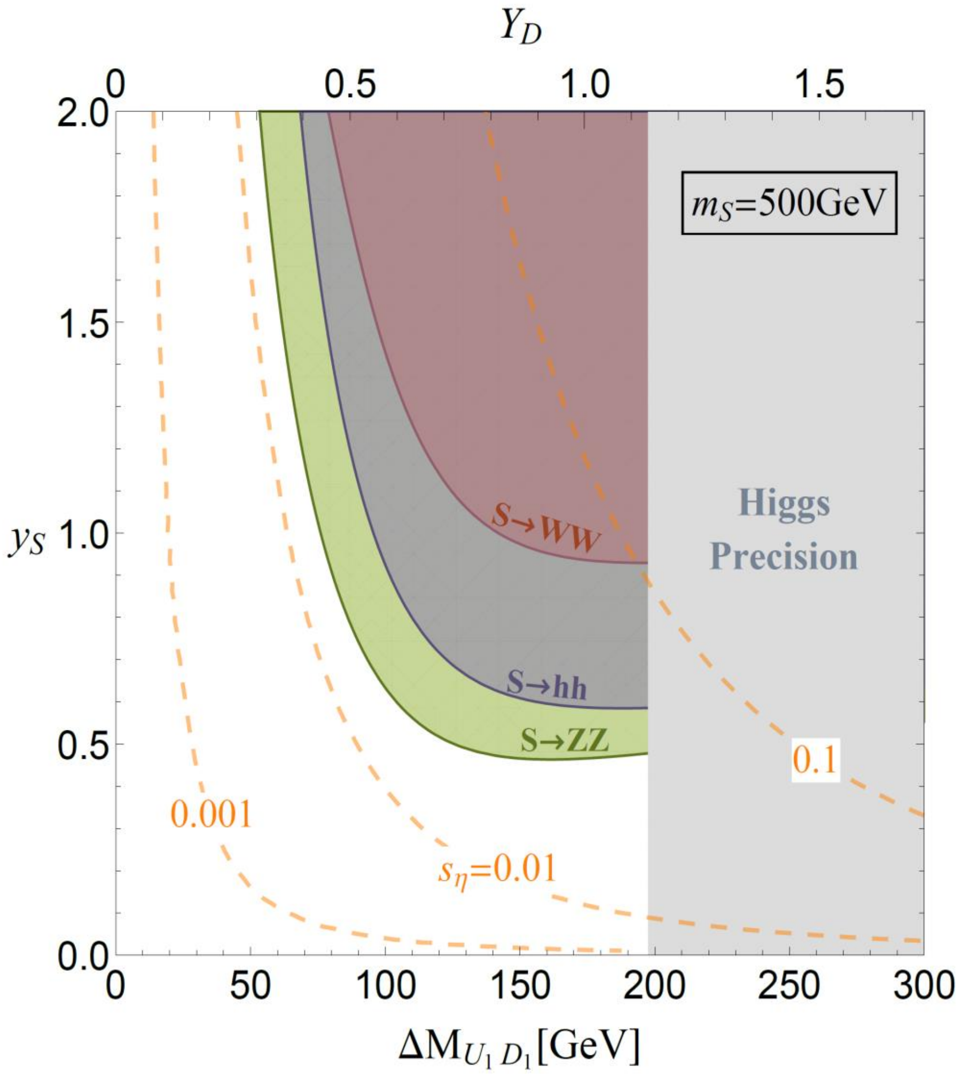
$$\kappa_\tau = 0.87^{+0.12}_{-0.11},\; \kappa_b = 0.57^{+0.16}_{-0.16}$$

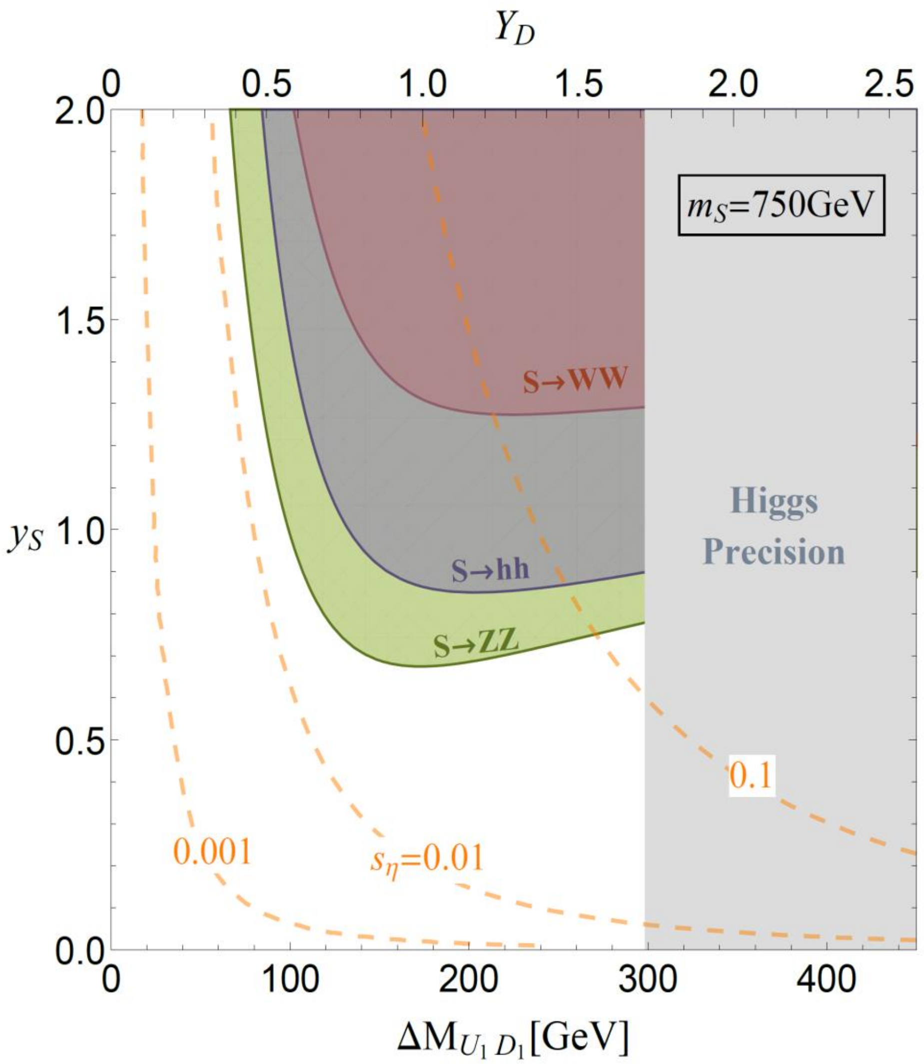
  - For the heavy scalar search with $m_S = 500(750)$ GeV, the observed 95 %CL upper bounds on σB at 8 TeV are WW: 200(40) fb / ZZ: 43(12) fb / hh: 107.6(34) fb.

  - Consider heavy scalar search channels of dijet and W(Z)γ

Numerical Results

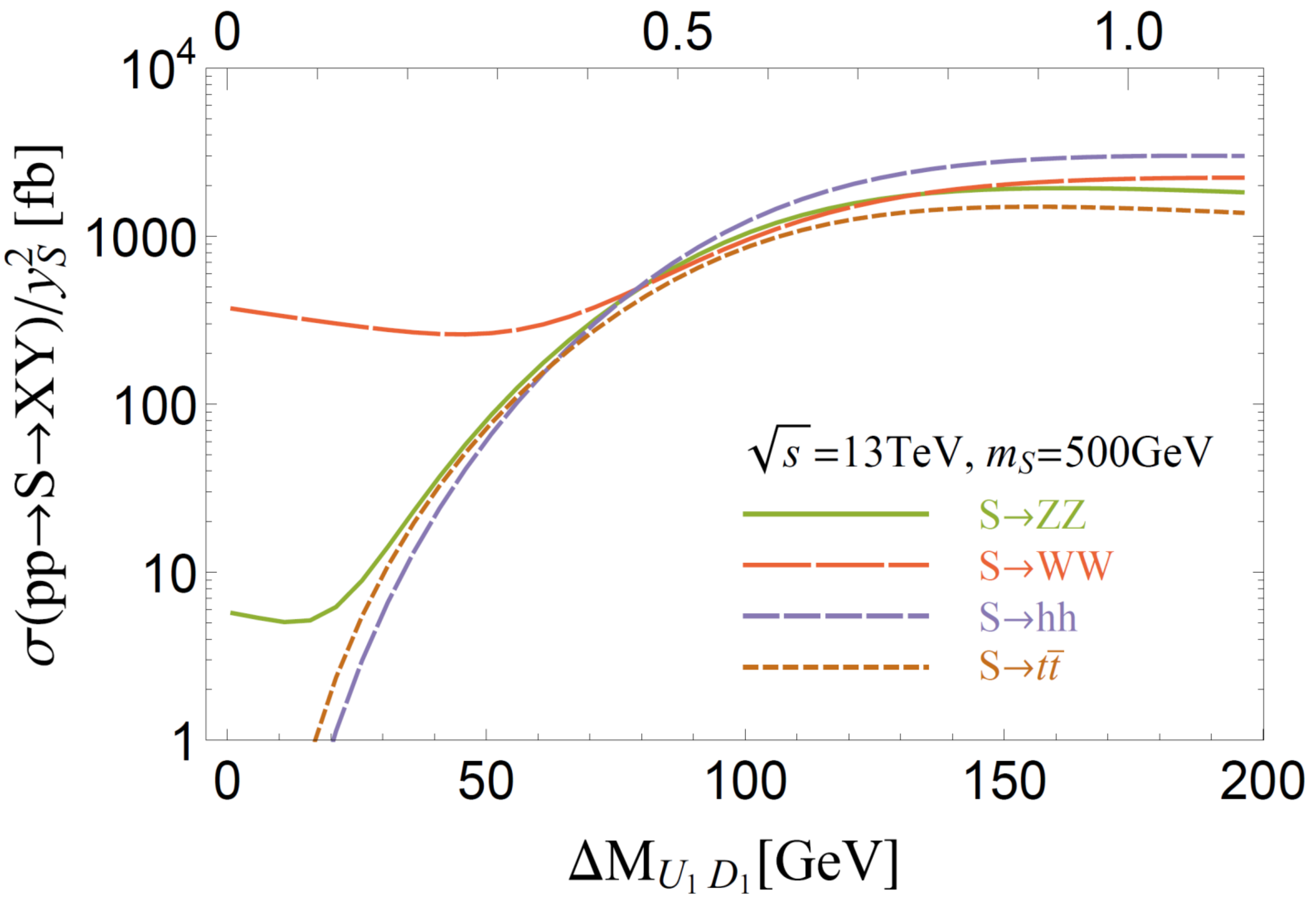
- Exclusion region in $(\Delta M_{U_1 D_1}, y_S)$





Numerical Results

- Cross sections of production and decay of S



Conclusion

- We have investigated possible new signals for a heavy scalar boson generated only through loop effects, which are so significant to be useful in the search for a new heavy scalar in a simple extension of the SM with a singlet S and VLQs.
- We have shown that the mixing between S and h can be radiatively generated, and the radiative decays of S generated via the $S-h$ mixing & triangle VLQs loops can be enhanced.
- We found that the most required condition for enhancing the $S-h$ mixing as well as the radiative decays of S into WW, ZZ and hh is the sizable mass difference of VLQs.
- The persistent searches for a heavy scalar at the future LHC are of importance in constraining new particles that appear at loop level.

Introduction

- When a scalar boson is heavy enough, its decay into a massive gauge boson pair has a special feature.
- In the SM, the partial decay rate of $h_{SM} \to V_L V_L$ is proportional to m_h^3/v^2, while that of $h_{SM} \to V_T V_T$ is proportional to $\frac{v^2}{m_h}$.
- The heavier higgs boson is, the more dominant $h_{SM} \to V_L V_L$ will become. → longitudinal polarization enhancement
- We wonder whether the same thing happens when a new heavy scalar boson decays only radiatively.
- To answer this question, we consider a simple extension of the SM where a singlet scalar and vector-like quarks are introduced.

Model

- Mass eigenvalues & mixing angles

$$M_{F_1,F_2} = \frac{1}{2}\left[M_{\mathcal{Q}} + M_F \mp \sqrt{(M_F - M_{\mathcal{Q}})^2 + 2Y_F^2 v^2}\right]$$

$$s_{2\theta_F} = \frac{\sqrt{2}Y_F v}{M_{F_2} - M_{F_1}},$$

- Gauge interactions

$\bar{g}^v_{\mathcal{F}} = \frac{1}{2}T_3^{\mathcal{F}} - s_W^2 Q_{\mathcal{F}}$ for $\mathcal{F} = \mathcal{Q}, \mathcal{U}, \mathcal{D}$.

$$\mathscr{L}_{\text{gauge}} = eA_\mu$$

$$+\frac{g}{\sqrt{}}$$

$$\hat{g}_{ZF_1F_1} = \bar{g}^v_{\mathcal{Q}} c^2_{\theta_F} + \bar{g}^v_F s^2_{\theta_F}, \quad \hat{g}_{ZF_2F_2} = \bar{g}^v_{\mathcal{Q}} s^2_{\theta_F} + \bar{g}^v_F$$

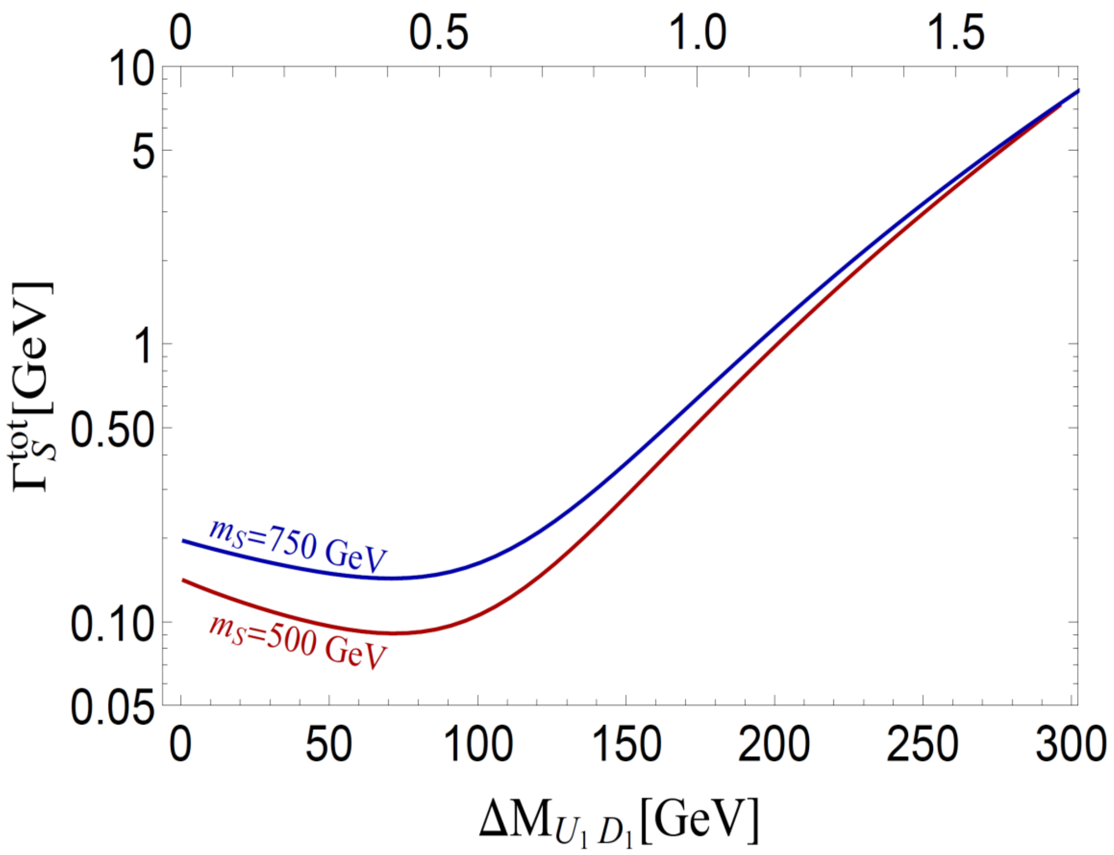
$$\hat{g}_{ZF_1F_2} = \left(\bar{g}^v_{\mathcal{Q}} - \bar{g}^v_F\right) s_{\theta_F} c_{\theta_F},$$

$$\hat{g}_{W\mathcal{U}_1\mathcal{D}_1} = c_{\theta_{\mathcal{U}}} c_{\theta_{\mathcal{D}}}, \quad \hat{g}_{W\mathcal{U}_1\mathcal{D}_2} = c_{\theta_{\mathcal{U}}} s_{\theta_{\mathcal{D}}},$$

$$\hat{g}_{W\mathcal{U}_2\mathcal{D}_1} = s_{\theta_{\mathcal{U}}} c_{\theta_{\mathcal{D}}}, \quad \hat{g}_{W\mathcal{U}_2\mathcal{D}_2} = s_{\theta_{\mathcal{U}}} s_{\theta_{\mathcal{D}}},$$

Numerical Results

- Total decay rate of S



- For 0< $\Delta M_{U_1 D_1}$ < 75 GeV, Γ_S^{tot} decreases as $\Delta M_{U_1 D_1}$ increases
- For $\Delta M_{U_1 D_1}$ > 75 GeV, , Γ_S^{tot} increases with $\Delta M_{U_1 D_1}$

We consider a $\mathcal{J}^{\mathcal{PC}} = 0^{++}$ scalar particle S which has a mass m_S and a momentum p^μ. In the CP-conserving framework, the most general coupling of S to a pair of gauge bosons and that to a pair of the Higgs bosons can be parameterized by

$$
\begin{aligned}
S(p)V_\mu(p_1)V'_\nu(p_2) \,:\, & m_S \left[\mathcal{A}\, g_{\mu\nu} + \mathcal{B}\,\frac{p_{2\mu}p_{1\nu}}{m_S^2}\right], \\
Shh \,:\, & m_S\, \mathcal{C},
\end{aligned}
\tag{2.1}
$$

where $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$ are dimensionless.

We write the helicity amplitudes for the decay $S \to VV'$ as

$$
\langle V_\mu(p_1, \lambda_1) V'_\nu(p_2, \lambda_2) | S(P) \rangle \equiv m_S \mathcal{T}_{\lambda_1 \lambda_2}, \tag{2.2}
$$

$$\mathcal{T}_{++} = \mathcal{T}_{--} = -\mathcal{A},$$

$$\mathcal{T}_{00} = \begin{cases} \dfrac{m_S^2}{4m_V^2}(2\mathcal{A}+\mathcal{B}) - (\mathcal{A}+\mathcal{B}), & \text{if } m_V \equiv m_{V_1} = m_{V_2} \neq 0; \\ 0, & \text{if } m_{V_1} = 0 \text{ or } m_{V_2} = 0, \end{cases}$$

and the other helicity amplitudes are zero. The partial decay rates are

$$\Gamma(S \to VV') = \frac{1}{\mathcal{S}} \frac{\beta_{VV'}}{16\pi} m_S \sum_{\lambda_1,\lambda_2} |\mathcal{T}_{\lambda_1\lambda_2}|^2 ,$$

$$\Gamma(S \to hh) = \frac{\beta_{hh}}{32\pi} m_S \, |\mathcal{C}|^2 ,$$

When a scalar particle is heavy enough, its decay into a massive gauge boson pair VV ($V = W^{\pm}, Z$) has a special feature. The condition $m_S \gg m_V$ makes $\mathcal{T}_{00}$ greatly enhanced if $(2\mathcal{A} + \mathcal{B}) \neq 0$. The SM Higgs boson, if its mass is greater than $2m_V$, has

$$\mathcal{A}^{h_{\mathrm{SM}}} = \frac{2m_V^2}{vm_h}, \quad \mathcal{B}^{h_{\mathrm{SM}}} = 0. \tag{2.5}$$

The partial decay rate of $h_{\mathrm{SM}} \to V_L V_L$ is proportional to the cube of m_h while that of $h_{\mathrm{SM}} \to V_T V_T$ is inversely proportional to m_h. The heavier the Higgs boson is, the more dominant $h \to V_L V_L$ will become. Another significant decay rate $\Gamma(h \to t\bar{t})$ is linearly proportional to m_h. The Higgs boson decay into $V_L V_L$ is dominant in the total decay rate. This is called the longitudinal polarization enhancement.