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Exotic signals of heavy scalar bosons through vectorlike quarks

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PRD96, 055041

Longitudinal polarization enhancement in $h \to VV$

- $V = W^{\pm}, Z$
- Longitudinal polarization of a massive gauge boson

$$\varepsilon_L^\mu \propto \frac{p_V^\mu}{m_V}$$

- When $m_h \gg m_V$, $\Gamma(h \to V_L V_L)$ is dominant:

$$\Gamma(h \to V_L V_L) \propto m_h^3.$$

The same thing happens when a new heavy scalar boson decays **only radiatively**?

General setup

- Consider a $\mathcal{J}^{\mathcal{PC}} = 0^{++}$ scalar particle S.
- S-V-V vetex:

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

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- Helicity amplitudes for the decay $S \to VV'$

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

Crucial condition for the longitudinal enhancement

- The dimensionless amplitudes $\mathcal{T}_{\lambda_1\lambda_2}$

$$
\begin{aligned}
\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}
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- Required!

$$2\mathcal{A}+\mathcal{B} \neq 0$$

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- Required!

$$2\mathcal{A} + \mathcal{B} \neq 0$$

- In the SM,

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

Model with a singlet scalar S

- CP-even singlet scalar boson S_0
- The most general scalar potential of the Higgs doublet H and S_0

$$
\begin{aligned}
V(H, S_0) &= -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \boxed{\frac{a_1}{2} S_0 H^\dagger H + \frac{a_2}{2} S_0^2 H^\dagger H} \\
&\quad + 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 .
\end{aligned}
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- No tree level coupling of S_0 with the Higgs boson:

$$a_1^{\mathrm{tree}} = 0 = a_2^{\mathrm{tree}} .$$

- No tree level S-V-V and S-h-h.

Model with 3 VLQ multiplet

- VLQs: 1 doublet and 2 singlets

$$\mathcal{Q}_{L/R} = \begin{pmatrix} \mathcal{U}' \\ \mathcal{D}' \end{pmatrix}_{L/R}, \quad \mathcal{U}_{L/R}\,, \quad \mathcal{D}_{L,R}.$$

- The Yukawa terms of VLQs

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

Mass matrices of VLQ

- The VLQ mass matrix $\mathbb{M}_F$ and the mixing matrix is

$$\mathbb{M}_F = \begin{pmatrix} M_{\mathcal{Q}} & \frac{Y_F v}{\sqrt{2}} \\ \frac{Y_F v}{\sqrt{2}} & M_F \end{pmatrix}, \quad \mathbb{R}_{\theta_F} = \begin{pmatrix} c_{\theta_F} & -s_{\theta_F} \\ s_{\theta_F} & c_{\theta_F} \end{pmatrix}.$$

VLQ coupling in mass eigenstates

- h-F-F

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

Suppressed couplings for diagonal when $\theta_F \ll 1$.

VLQ coupling in mass eigenstates

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Suppressed couplings for diagonal when $\theta_F \ll 1$.

- *V-F-F*

$$\begin{aligned}
\hat{g}_{ZF_1F_1} &= \bar{g}^v_{\mathcal{Q}} c^2_{\theta_F} + \bar{g}^v_F s^2_{\theta_F}\,, \quad \hat{g}_{ZF_2F_2} = \bar{g}^v_{\mathcal{Q}} s^2_{\theta_F} + \bar{g}^v_F c^2_{\theta_F}\,,\\
\hat{g}_{ZF_1F_2} &= \left(\bar{g}^v_{\mathcal{Q}} - \bar{g}^v_F\right) s_{\theta_F} c_{\theta_F}\,,\\
\hat{g}_{W\mathcal{U}_1\mathcal{D}_1} &= c_{\theta_\mathcal{U}} c_{\theta_\mathcal{D}}\,, \quad \hat{g}_{W\mathcal{U}_1\mathcal{D}_2} = c_{\theta_\mathcal{U}} s_{\theta_\mathcal{D}}\,,\\
\hat{g}_{W\mathcal{U}_2\mathcal{D}_1} &= s_{\theta_\mathcal{U}} c_{\theta_\mathcal{D}}\,, \quad \hat{g}_{W\mathcal{U}_2\mathcal{D}_2} = s_{\theta_\mathcal{U}} s_{\theta_\mathcal{D}}\,,
\end{aligned}$$

Suppressed for off-diagonal when $\theta_F \ll 1$.

$$\boxed{\bar{g}^v_{\mathcal{F}} = \tfrac{1}{2} T_3^{\mathcal{F}} - s^2_W Q_{\mathcal{F}}}$$

Effects of the VLQ loops

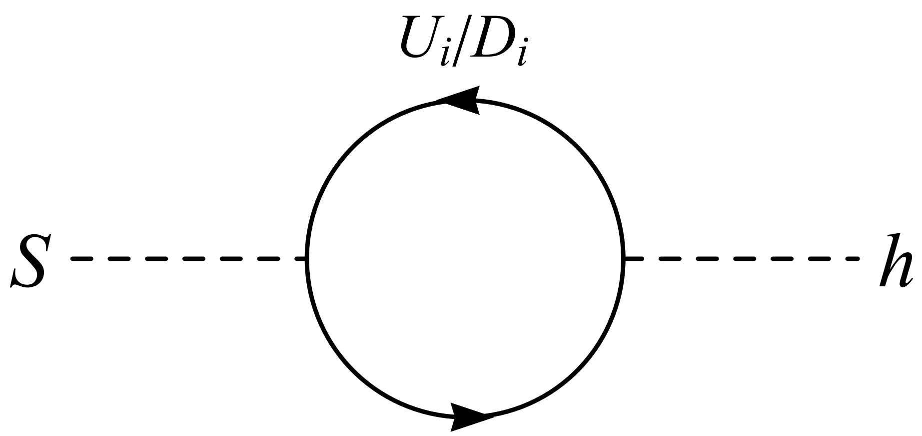
1. S-h mixing
2. Loop corrected Higgs modifiers
3. Radiative decays of S

S-h mixing

- Though the VLQ loops

$$\mathbb{M}^2_{hS} \equiv \begin{pmatrix} 2\lambda v^2 & \delta M^2_{Sh} \\ \delta M^2_{Sh} & M^2_{SS} \end{pmatrix},$$

where $M^2_{SS} = b_2$.



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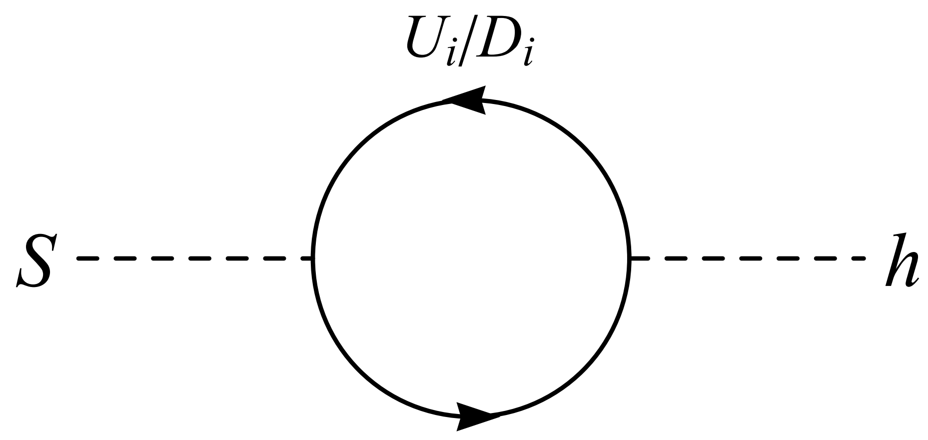

- At one loop level,

$$\delta M^2_{Sh} = -\frac{y_S N_c}{4\pi^2} \sum_F \sum_i y_{hF_iF_i} M^2_{F_i} \left[4(\tau^S_{F_i} - 1) g(\tau^S_{F_i}) - 4\tau^S_{F_i} + 5\right],$$

S-h mixing

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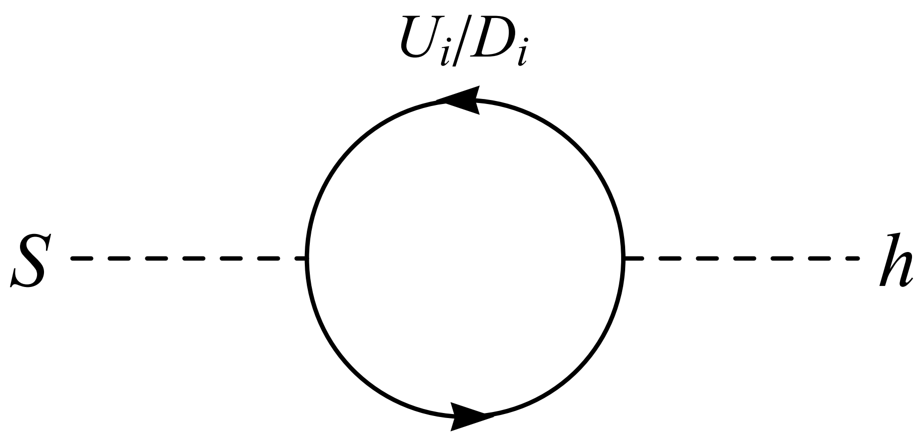

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- Note

$$\text{if } M_{F_1} = M_{F_2}, \quad \delta M^2_{Sh} = 0 \Longleftarrow \boxed{y_{hF_1F_1} = -y_{hF_2F_2}}$$

Modified Higgs couplings

1. Through the S-h mixing to all κ_i.
2. Through new triangle diagrams for κ_g and κ_γ.

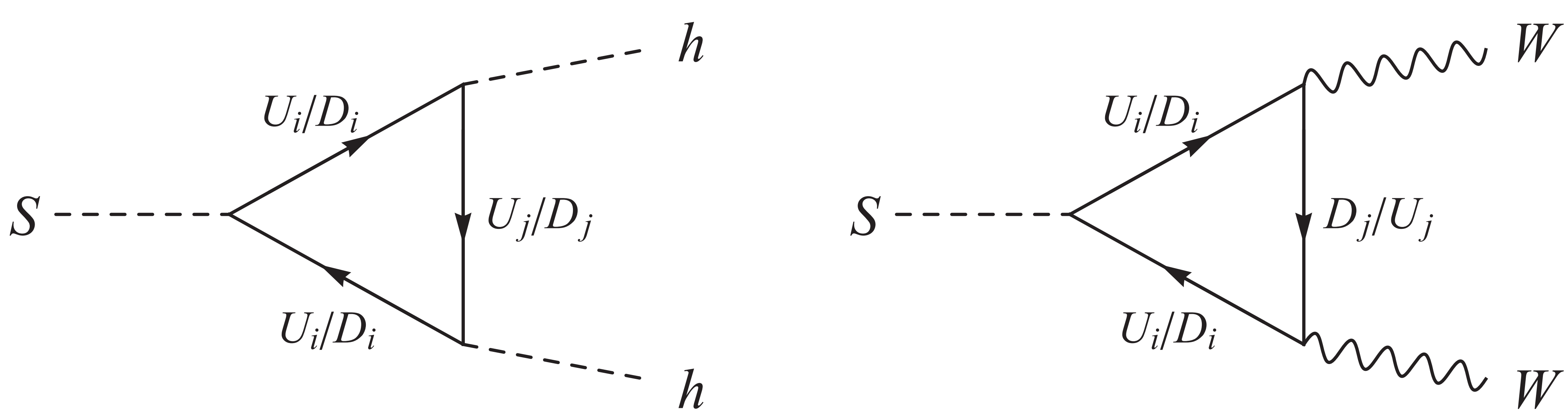
- Both corrections are suppressed when $M_{F_1} \simeq M_{F_2}$.

Radiative decays of S (i)

- The decay into a top pair is through the S-h mixing

$$\Gamma(S \to t\bar{t}) = s_\eta^2\, \Gamma(h_{\rm SM} \to t\bar{t})\Big|_{m_{h_{\rm SM}}=m_S},$$

- Decay into hh and VV are from the SS-h mixing and the VLQ triangle diagrams:



Radiative decays of S (ii)

- Decay into hh

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

where

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

Radiative decays of S (iii)

- Decay into VV, governed by $\mathcal{A}$ and $\mathcal{B}$

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where

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

where $g_W = g$, $g_Z = g/c_W$, and η is the S-h mixing angle.

The condition for the longitudinal enhancement

- Asymptotically

$$2\mathcal{A}_T + \mathcal{B}_T \sim \mathcal{O}\left(m_V^2/m_S^2\right) \text{ if } \Delta_F = 0$$

- Mass differences in VLQ and thus multi VLQs are crucial to longitudinal polarization enhancement.

Benchmark point

- We consider

$$M_{\mathcal{Q}} = M_{\mathcal{U}} = M_{\mathcal{D}}, \quad Y_{\mathcal{U}} = 0, \quad Y_{\mathcal{D}} \text{ varies.}$$

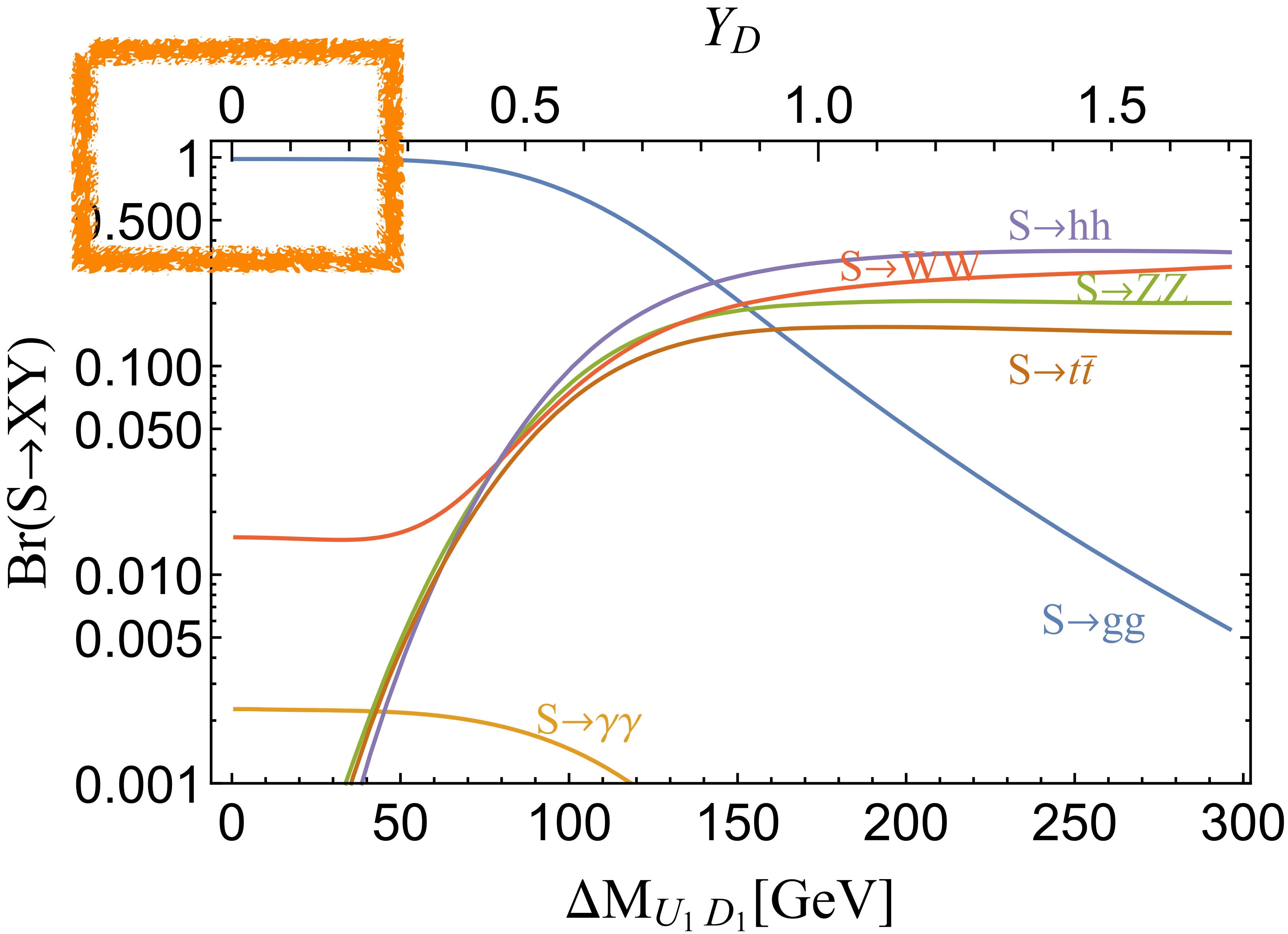
$M_{\mathcal{D}_2}$

$M_{\mathcal{U}_1} = M_{\mathcal{U}_2}$

$M_{\mathcal{D}_1}$

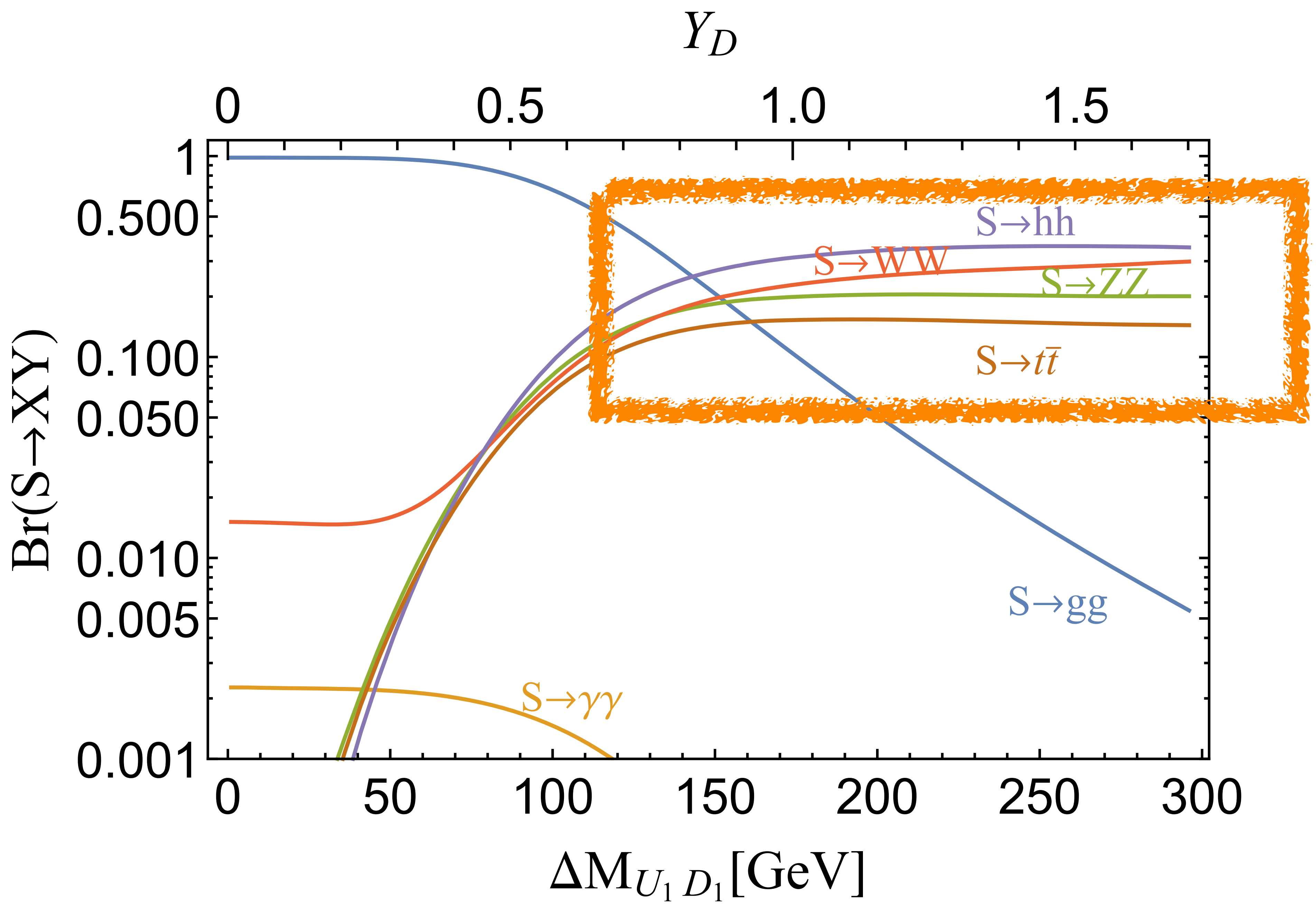
$$\boxed{M_{\mathcal{D}_1} = 0.6 M_S}$$

Branching ratios of S



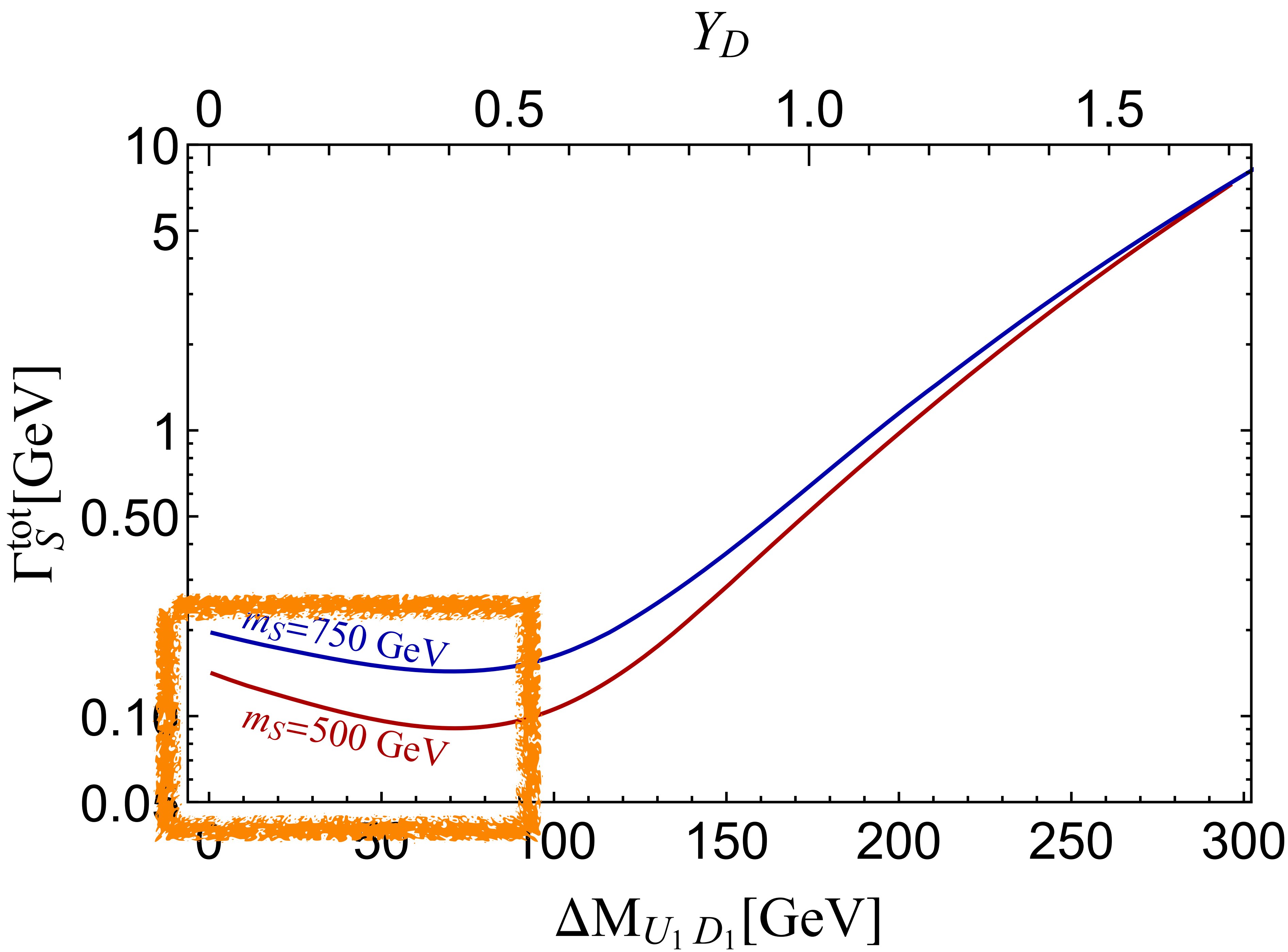
W/ mass degeneracy, the decay into gg is dominant.

Branching ratios of S



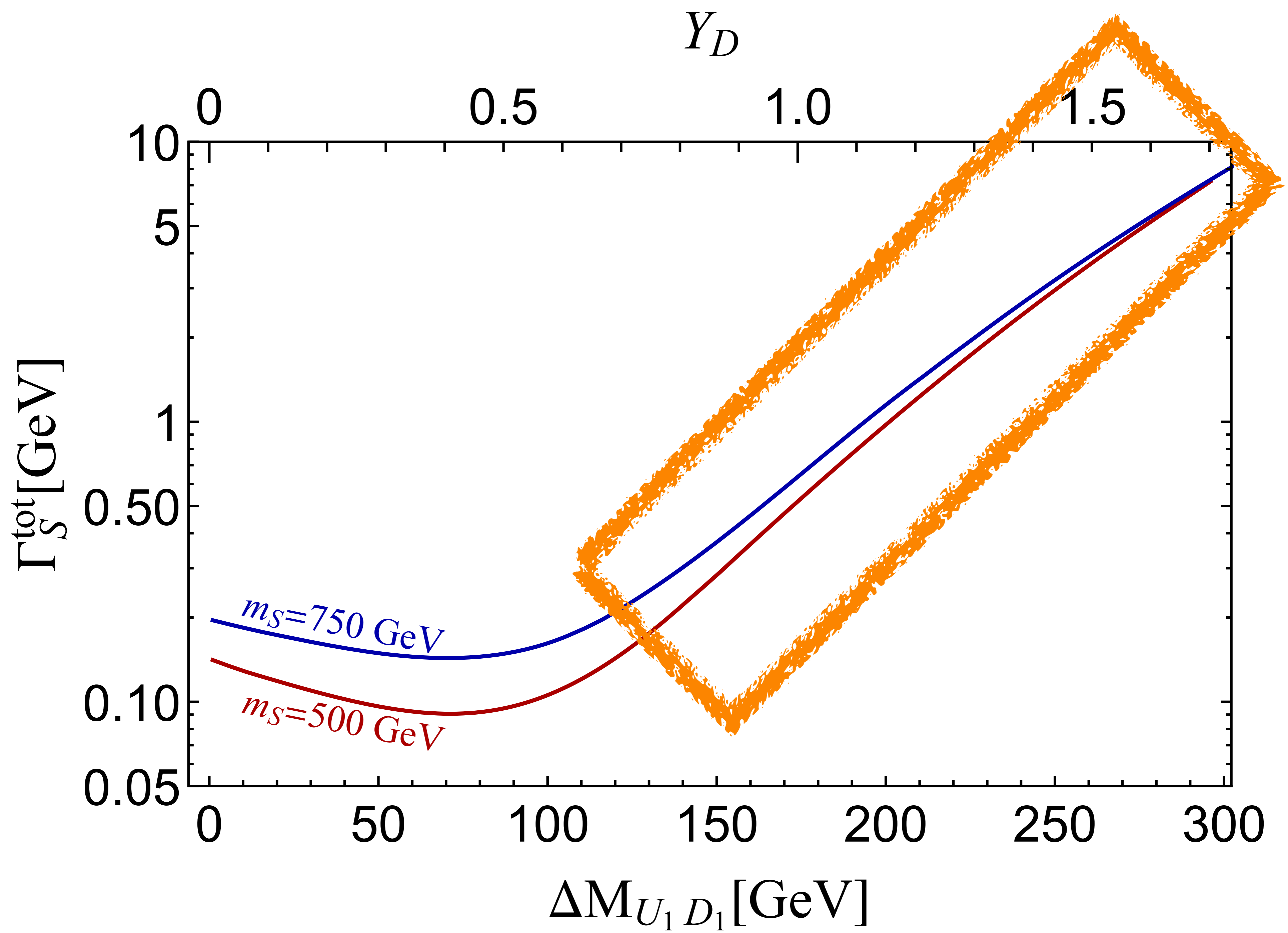
W/ mass differences, decays into hh,WW,ZZ are all significant

Total decay width of S



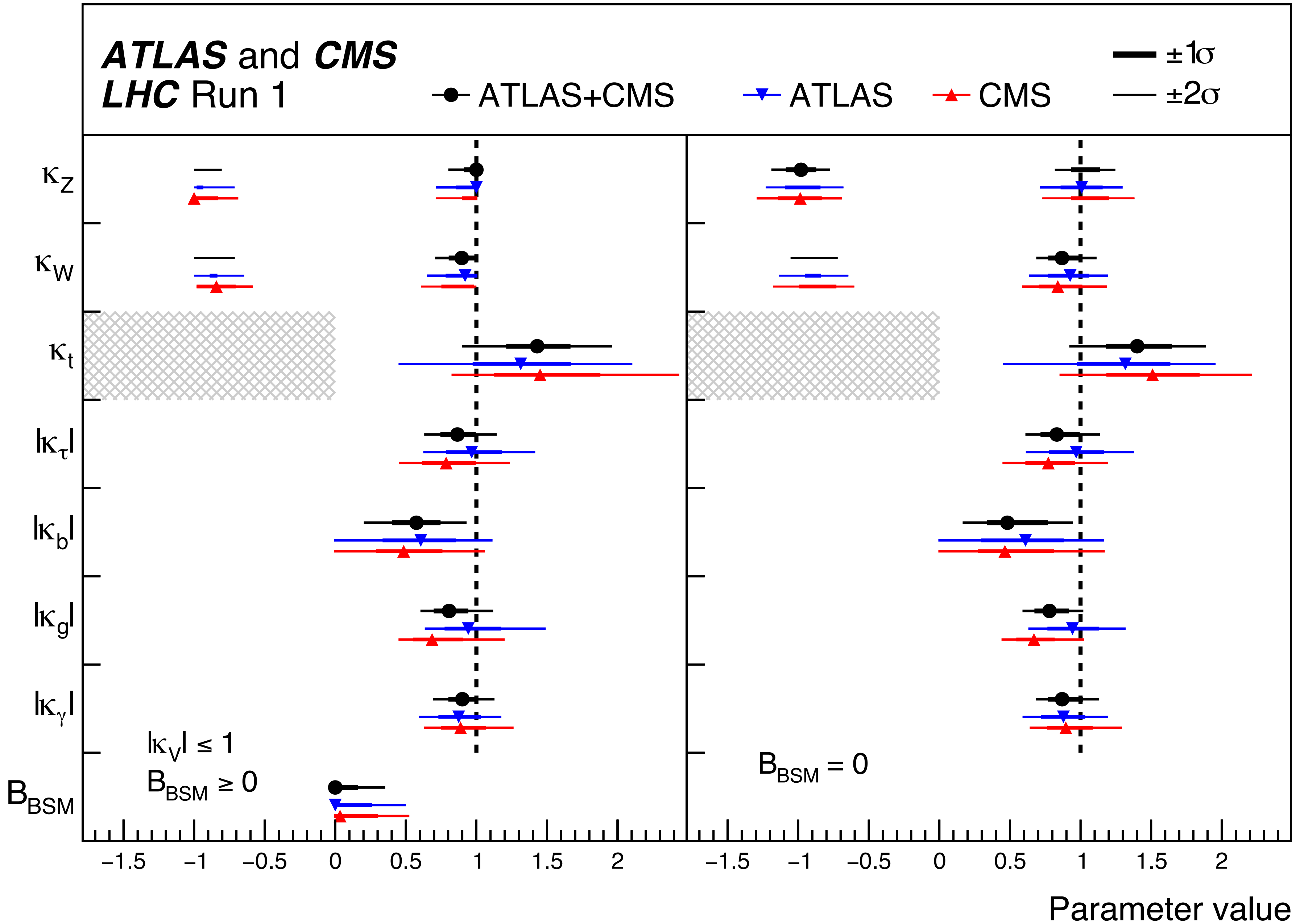
W/ the fixed lightest VLQ mass,
increasing mass difference mean increasing VLQ masses

Total decay width of S

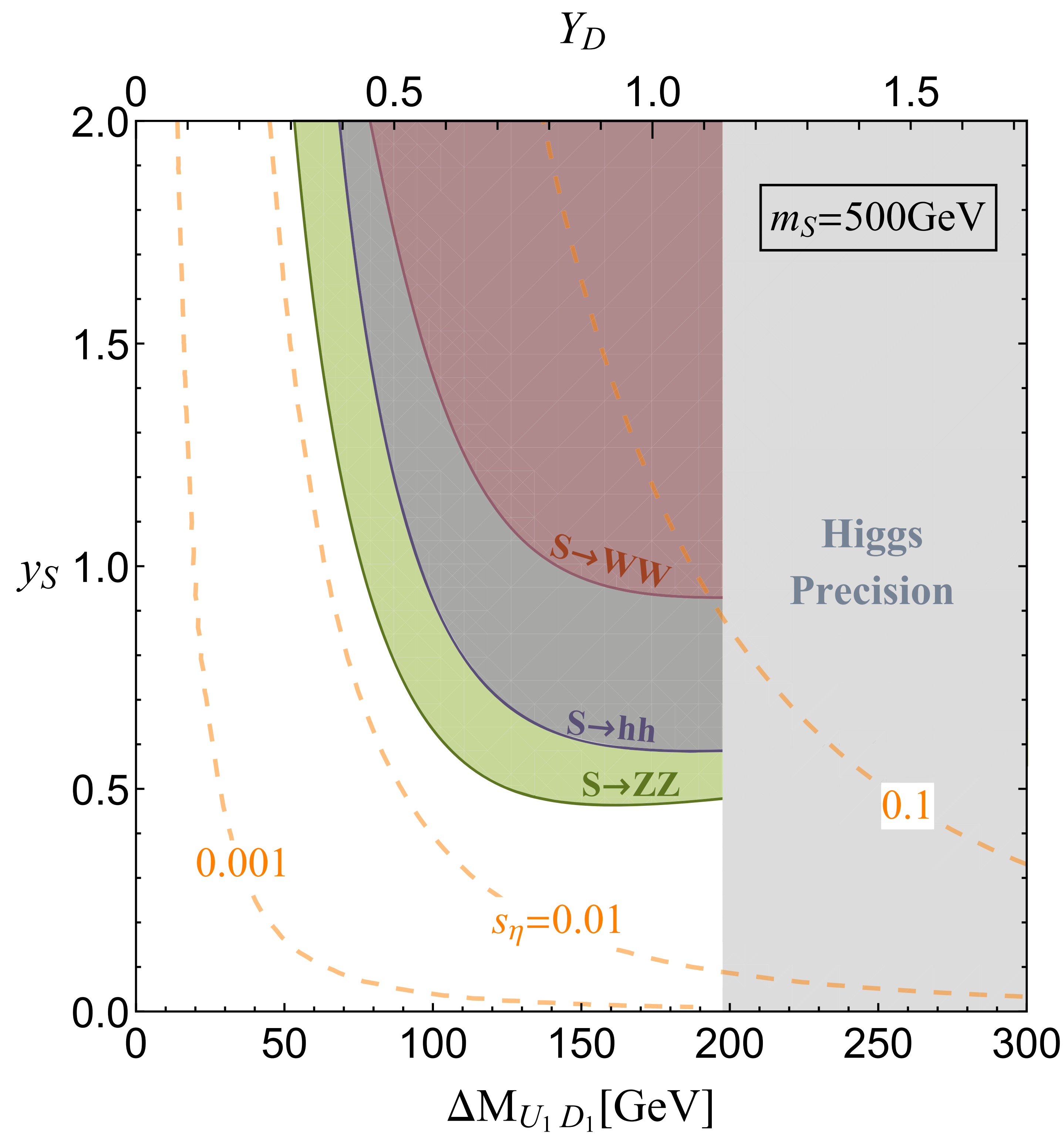


Even with increasing VLQ mass,
longitudinal polarization enhancement dominates the decay

Check with the Higgs precision data

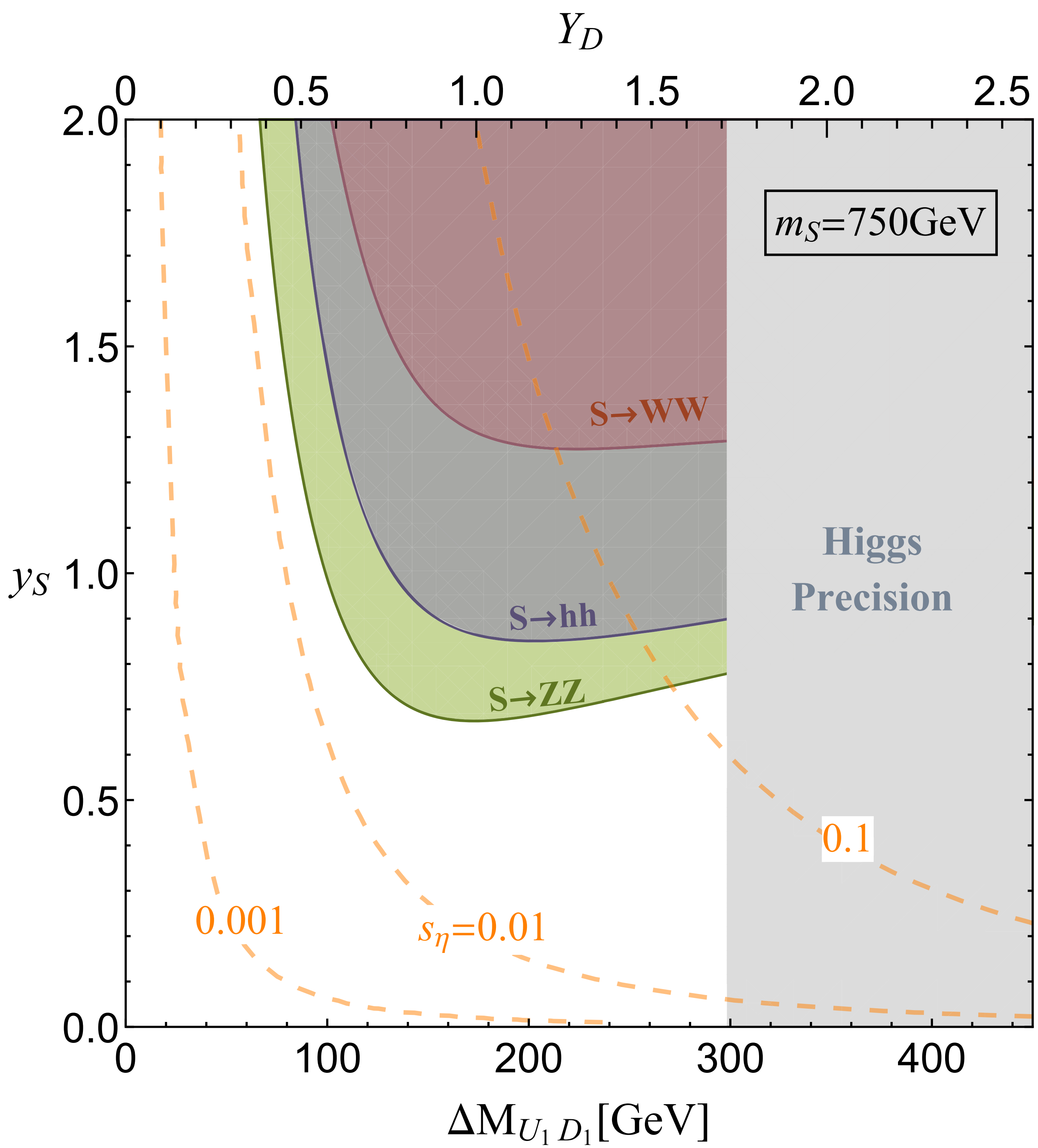


Current VLQ search constraints for $m_S = 500$ GeV



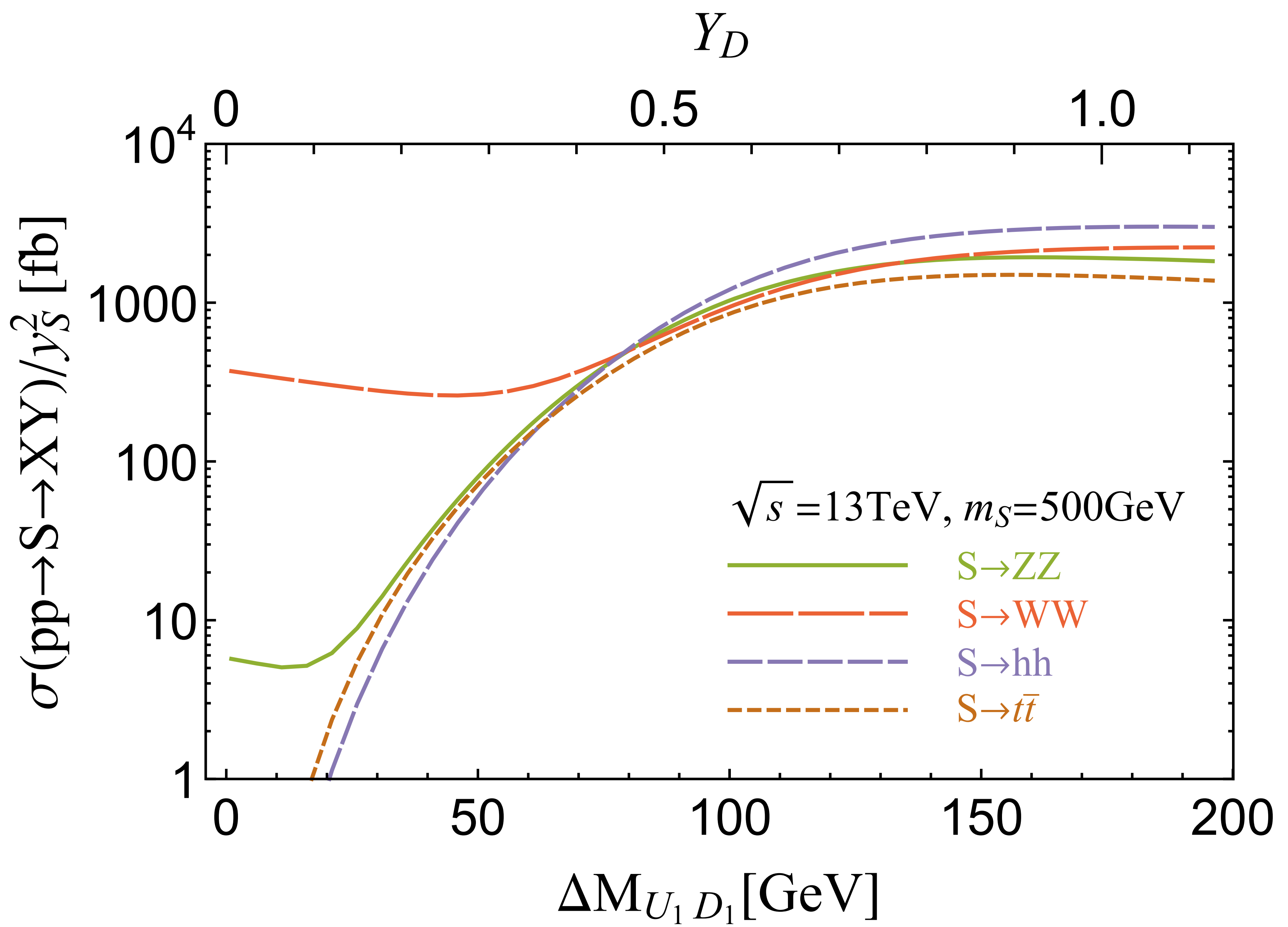
8 TeV constraints from WW, hh, ZZ

Current VLQ search constraints for $m_S = 750$ GeV



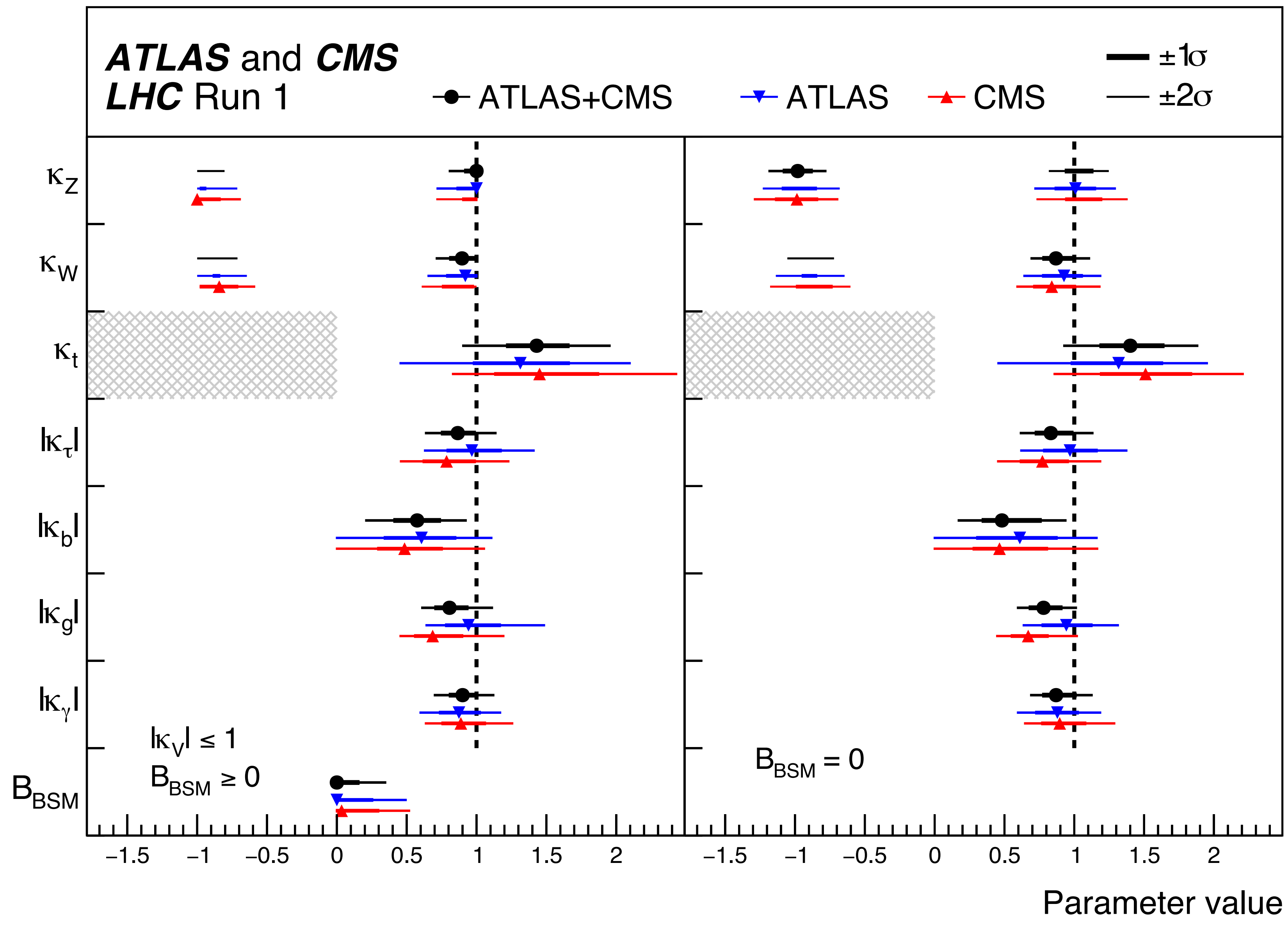
8 TeV constraints from WW, hh, ZZ

Prospect at the 13 TeV LHC



Conclusions

- Longitudinal polarization enhancement in the heavy scalar boson decay into a massive gauge boson pair can happen even at loop level.
- In a new physics model with one singlet scalar boson and three LQ multiplets, the crucial condition for the enhancement is sizable mass differences among VLQs.
- The WW and ZZ channels for a heavy scalar boson can be very efficient.


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
κZ
κW
κt
|κτ|
|κb|
|κg|
|κγ|
BBSM
|κV| ≤ 1
BBSM ≥ 0
BBSM = 0
−1.5
−1
−0.5
0
0.5
1
1.5
2
Parameter value