New decay modes of VLQ at the LHC

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Introduction and Motivation

- Almost 150 fb^{-1} and 180 fb^{-1} of data have collected during Run II.
- No significant deviations from the SM have been recorded.
- Most of common scenarios BSM are restricted.
- Yet, it is important to study the connection beween top and Higgs sector.
- Most of the current data may help to understand the nature of hierarchy problem.

SM+VLQ+Scalar

- Gauge eigenstates in the top sector by $\widetilde{t}_L$, $\widetilde{t}_R$ and T.
- Mass eigenstates that are to be denoted by t and t'.

The Lagrangian for this model before EW symmetry breaking (EWSB) can be written as

$$\mathcal{L}_{\rm kin} \supset \bar{T}\left(i\not{D} - M\right)T + \frac{1}{2}\left(\partial_\mu S\right)\left(\partial^\mu S\right) - \frac{1}{2}m_S^2 S^2, \qquad (1)$$

$$\mathcal{L}_{\rm int} \supset -\lambda_S^a S\,\bar{T}_L T_R - \lambda_S^b S\,\bar{T}_L \widetilde{t}_R - \widetilde{y}\left(\bar{Q}_L \widetilde{H}\right)\widetilde{t}_R - \lambda_1\left(\bar{Q}_L \widetilde{H}\right)T_R - m_2 \bar{T}_L \widetilde{t}_R + \text{h.c.} \qquad (2)$$

- where the SM Higgs doublet is denoted by H.
- The SM Yukawa coupling for the top quark is here denoted by $\widetilde{y}$ and Q_L is the left-handed quark doublet of the third generation.
- The couplings $\lambda_S^{a,b}$ are real if S is a scalar and purely imaginary if S is a pseudoscalar.

SM+VLQ+Scalar

After EWSB, we have a mass matrix

$$\mathcal{L}_t \supset \begin{pmatrix} \bar{\widetilde{t}}_L & \bar{T}_L \end{pmatrix} \begin{pmatrix} m_{\widetilde{t}} & m_1 \\ m_2 & M \end{pmatrix} \begin{pmatrix} \widetilde{t}_R \\ T_R \end{pmatrix} + \text{h.c.}, \tag{3}$$

$$\begin{pmatrix} t_{L,R} \\ t'_{L,R} \end{pmatrix} = \begin{pmatrix} c_{L,R} & -s_{L,R} \\ s_{L,R} & c_{L,R} \end{pmatrix} \begin{pmatrix} \widetilde{t}_{L,R} \\ T_{L,R} \end{pmatrix} , \tag{4}$$

where $\{t, t'\}$ are the mass eigenstates and the mixing angles are given by

$$\tan(2\theta_L) = \frac{2\left(m_{\widetilde{t}} m_2 + M m_1\right)}{M^2 - m_{\widetilde{t}}^2 - m_1^2 + m_2^2} , \quad \tan(2\theta_R) = \frac{2\left(m_{\widetilde{t}} m_1 + M m_2\right)}{M^2 - m_{\widetilde{t}}^2 + m_1^2 - m_2^2} . \tag{5}$$

The mass eigenvalues m_t and $m_{t'}$ are found by computing the eigenvalues. Focusing on the mixing terms yields

$$\kappa_L^S = \left(\lambda_S^a s_L c_R + \lambda_S^b s_L s_R\right)^* , \quad \kappa_R^S = \lambda_S^a c_L s_R - \lambda_S^b c_L c_R , \tag{6}$$

while for the coupling to the top we have

$$\kappa_t = \text{Re}\left(-\lambda_S^a s_L s_R + \lambda_S^b s_L c_R\right) , \quad \widetilde{\kappa}_t = \text{Im}\left(-\lambda_S^a s_L s_R + \lambda_S^b s_L c_R\right) . \tag{7}$$

SM+VLQ+Scalar

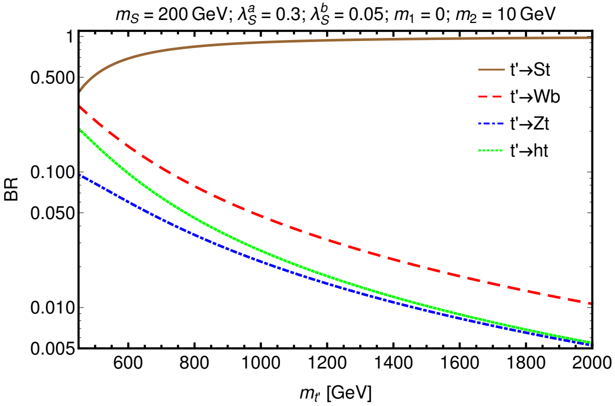

Figure : BRs of t' as a function of the mass for a specific parameter point.

- $t' \to S\, t$ channel has a BR of almost 100%.

2HDM + VLQ. See Bouzid's Talk

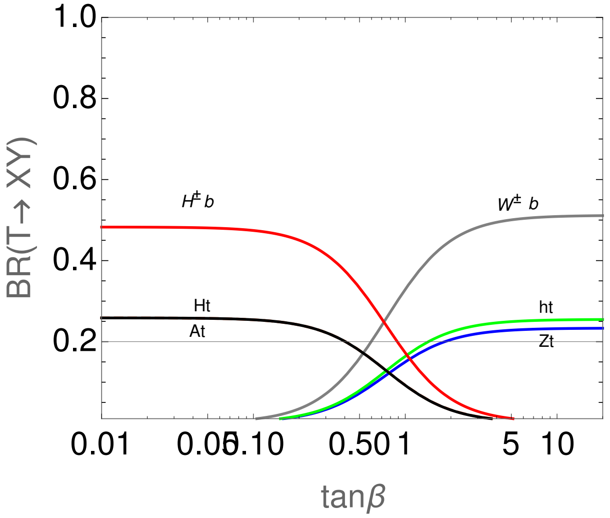

Figure : BRs of t' as a function of the mass for a specific parameter point.

- $t' \to S\, t$ channel has a BR of almost 50%.

Composite Higgs Model

The SM Higgs $\mathcal{H}$ field in this model is a bi-doublet of $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, which together with a singlet S forms the five dimensional anti-symmetric irrep of Sp(4),

$$\mathcal{H} \oplus S \equiv \begin{pmatrix} H^{0*} & H^{+} \\ -H^{+*} & H^{0} \end{pmatrix} \oplus S \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) = \mathbf{5}. \qquad (8)$$

The fermionic sector also consists of a bi-doublet and a singlet in the **5** of Sp(4),

$$\Psi \equiv \begin{pmatrix} T & X \\ B & T' \end{pmatrix} \oplus \widetilde{T} \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) = \mathbf{5}. \qquad (9)$$

The new fermions mix with the third family quarks of the SM. the Lagrangian becomes

$$\mathcal{L} = y_L f\,\mathrm{tr}\left(\bar{Q}_L \Sigma \Psi_R \Sigma^T\right) + y_R f\,\mathrm{tr}\left(\Sigma^* \bar{\Psi}_L \Sigma^\dagger \widetilde{t}_R\right) - M\,\mathrm{tr}\left(\bar{\Psi}_L \Psi_R\right) + \text{ h.c.} \qquad (10)$$

Composite Higgs Model

we can write the part of eq. (10) concerning top partners as

$$\mathcal{L}_{\text{tops}} = -\begin{pmatrix} \bar{\tilde{t}}_L & \bar{T}_L & \bar{T'}_L & \bar{\tilde{T}}_L \end{pmatrix} \left(\mathcal{M} + h\mathcal{I}_h + S\mathcal{I}_S \right) \begin{pmatrix} \tilde{t}_R \\ T_R \\ T'_R \\ \tilde{T}_R \end{pmatrix} + \text{ h.c.} \quad (11)$$

where the mass and Yukawa matrices are given by

$$\mathcal{M} = \begin{pmatrix} 0 & y_L f \cos^2\left(\frac{\theta}{2}\right) & -y_L f \sin^2\left(\frac{\theta}{2}\right) & 0 \\ \frac{y_R f}{\sqrt{2}} \sin\theta & M & 0 & 0 \\ \frac{y_R f}{\sqrt{2}} \sin\theta & 0 & M & 0 \\ 0 & 0 & 0 & M \end{pmatrix}$$

$$\mathcal{I}_h = \begin{pmatrix} 0 & -\frac{1}{2} y_L \sin\theta & -\frac{1}{2} y_L \sin\theta & 0 \\ \frac{y_R}{\sqrt{2}} \cos\theta & 0 & 0 & 0 \\ \frac{y_R}{\sqrt{2}} \cos\theta & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Constraints from $\gamma\gamma$ and γZ

We assume t' decays at 100% rate as $t' \to S\,t$. For S, we consider all the possible bosonic decay channels necessary to ensure gauge invariance in the CHM[1],

$$S \to \{\gamma\,\gamma, Z\,\gamma, WW, ZZ\}. \tag{12}$$

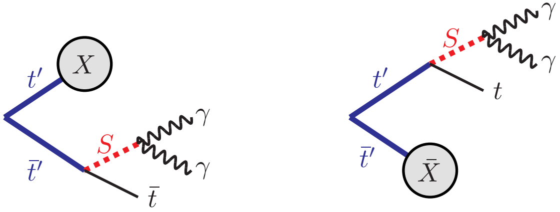

Figure : Pair production of t' with the decay of one branch into $t(S \to \gamma\,\gamma)$ and inclusive decay for the other.

[1] Note that additional decays are present for the 2HDM+VLQ case, specifically, $b\bar{b}$ and $t\bar{t}$, which are then simulated for the corresponding signal.

Constraints from $\gamma\gamma$ and γZ

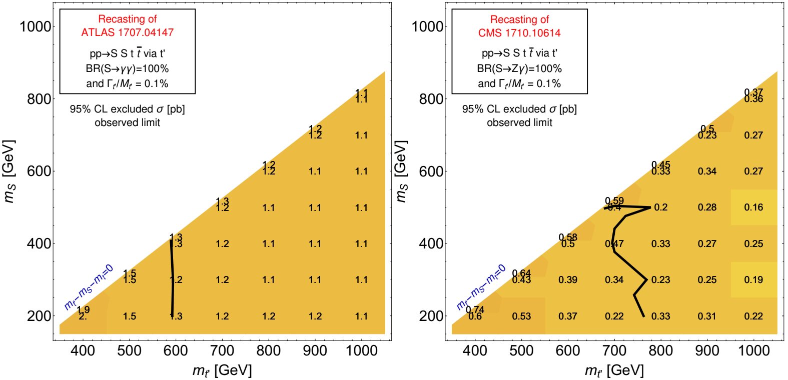

Figure : Upper limits on the cross section in the $m_{t'}$ vs m_S plane for the $\gamma\gamma$ (left panel) and $Z\gamma$ channels (right panel) from the recast of the ATLAS and CMS search, respectively. The solid black lines represents the bounds on the two masses obtained by comparing the upper limits with the pair production cross section of t' at NLO+NNLL computed through HATHOR under the assumption of 100% BRs for both t' and S in the respective channels and in the narrow width approximation (NWA).

Constraints from $\gamma\gamma$ and γZ

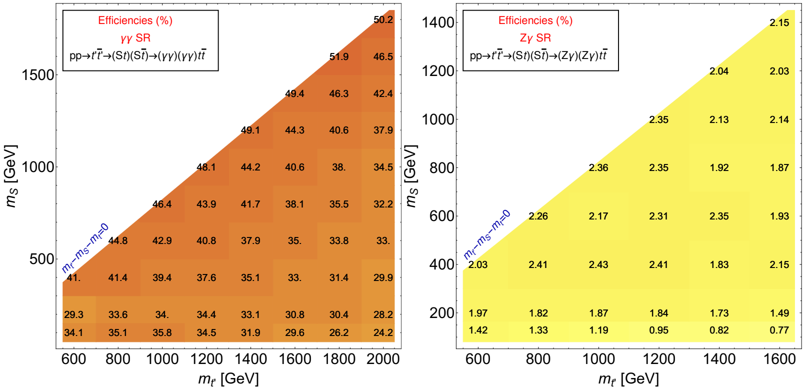

Figure : Left: Efficiencies for the $\gamma\gamma$ SR for the signal decay channel $S(\rightarrow\gamma\gamma)S(\rightarrow\gamma\gamma)$. Right: Efficiencies for the $Z\gamma$ SR for the signal decay channel $S(\rightarrow Z\gamma)S(\rightarrow Z\gamma)$.

Interpretation

The expected number of background events in one of the signal regions $\mathrm{SR} \in \{\gamma\gamma, Z\gamma\}$, B_{SR}, is given by

$$B_{\mathrm{SR}}(m_S, m_{t'}) = L\, \sigma_{B_{\mathrm{SR}}} \epsilon_{B_{\mathrm{SR}}}(m_S, m_{t'}) \qquad (13)$$

with L the integrated luminosity, and $\sigma_{B_{\gamma\gamma}} = 74.0\,\mathrm{pb}$ and $\sigma_{B_{Z\gamma}} = 4.58\,\mathrm{pb}$ our best estimate of the total background cross section for the $\gamma\gamma$ and $Z\gamma$ signal regions, respectively, and $\epsilon_{B_{\mathrm{SR}}}$ the efficiency after all cuts in the corresponding SR.

The number of background events can be extracted for arbitrary values of m_S and $m_{t'}$ by interpolating the data.

m_S [GeV]	$\sigma_{B_{\gamma\gamma}} \epsilon_{B_{\mathrm{SR}}}(m_S)$ [pb]
100	0.0146
200	0.00144
400	8.41×10^{-4}
600	1.82×10^{-4}
800	5.23×10^{-5}
1000	2.14×10^{-5}
1200	7.64×10^{-6}
1400	3.10×10^{-6}

Table : The background cross section times efficiency $\sigma_{B_{\gamma\gamma}} \epsilon_{B_{\gamma\gamma}}(m_S)$ (in pb)

Interpretation

The number of expected signal events for each SR is given by

$$S_{\mathrm{SR}} = L\,\sigma(m_{t'})\,\left(\sum_{X,Y} \epsilon_{\mathrm{SR}}^{Y,X}\mathrm{BR}_{S\to X}\mathrm{BR}_{S\to Y}\right), \tag{14}$$

where $\epsilon_{\mathrm{SR}}^{Y,X}$ is the final efficiency in appropriate signal region SR for the signal sample with decay $(S \to X)(S \to Y)$ with $X, Y \in \{\gamma\,\gamma, Z\,\gamma, WW, ZZ\}$. (In these expressions we assume the validity of the NWA and assume 100% BR $t' \to S\,t$ and $\bar{t}' \to S\,\bar{t}$.) we estimate the significance by employing the formula:

$$z = \sqrt{2}\left\{(S+B)\ln\left[\frac{(S+B)(B+\sigma_b^2)}{B^2+(S+B)\sigma_b^2}\right] - \frac{B^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 S}{B(B+\sigma_b^2)}\right]\right\}^{1/2}, \tag{15}$$

that is obtained by using the "Asimov" data-set into the profile likelihood ratio.

Interpretation: SM+VLQ+S

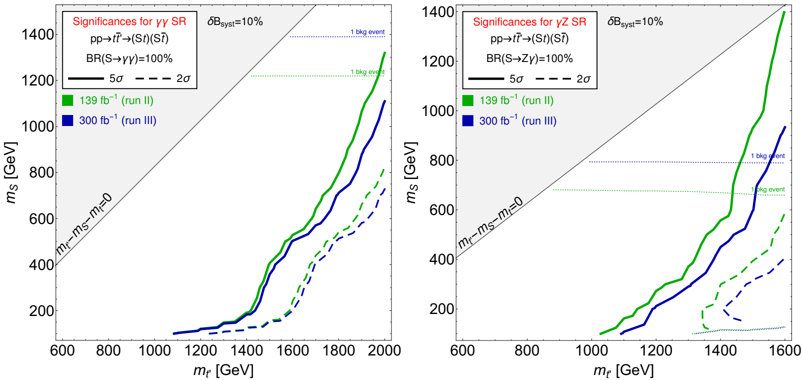

Figure : LHC optimal reach for different LHC luminosities for the $\gamma\gamma$ SR (left) and $Z\gamma$ SR (right). The solid lines correspond to the 5σ discovery reach, while the dashed lines correspond to the 2σ exclusion reach. The dotted lines identify the region with 1 irreducible background event, where the contribution of fake rates can become relevant.

Interpretation: SM+VLQ+S

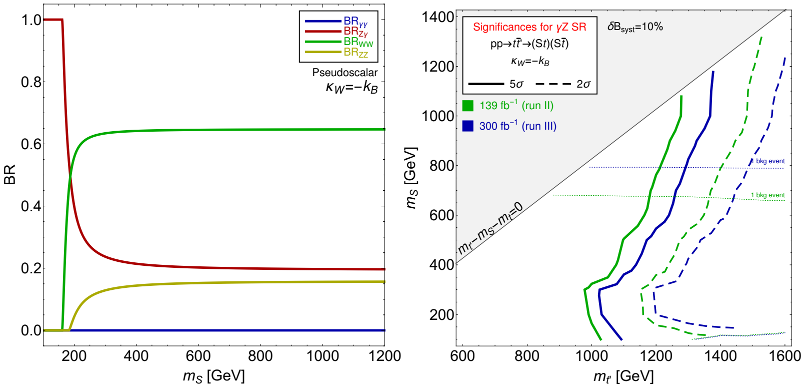

Figure : Left panel: BRs of S resonance into EW bosons for the pseudoscalar case ($\kappa_B = \kappa_W = 0$) in the photophobic S case ($\tilde{\kappa}_B = -\tilde{\kappa}_W$). Right panel: LHC reach for different LHC luminosities; the meaning of contours is the same as in last slide.

Interpretation: SM+VLQ+S

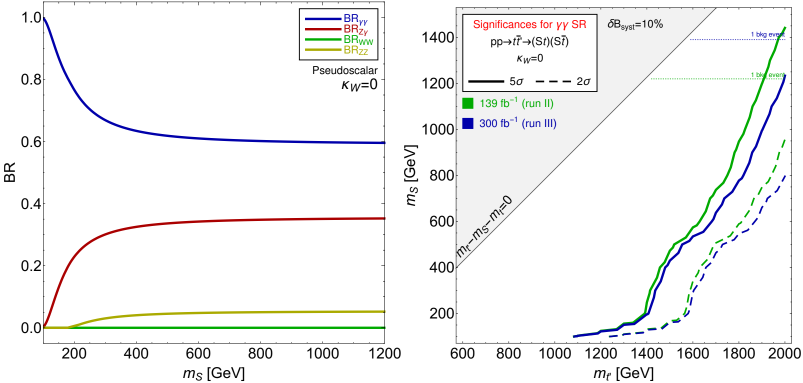

Figure : Left panel: BRs of S resonance into EW bosons for the pseudoscalar case ($\kappa_B = \kappa_W = 0$) in the W-phobic case ($\tilde{\kappa}_W = 0$). Right panel: LHC reach for different LHC luminosities; the meaning of contours is the same as before.

Interpretation: 2HDM + VLQ

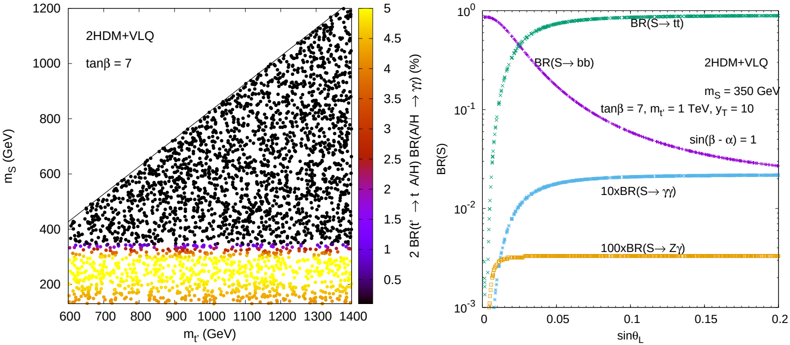

Figure : Left: $2\ \sigma \times \mathrm{BR}(t' \to tA/H) \times \mathrm{BR}(A/H \to \gamma\gamma)$ in the 2HDM+VLQ over the plane (m_t', m_S), where $m_S = m_H = m_A$, for the following inputs parameters: $\sin(\beta - \alpha) = 1$, $m_h = 125.09\,\mathrm{GeV}$, $m_{H^\pm} = 600\,\mathrm{GeV}$, $\tan\beta = 7$, $m_{12}^2 = m_S^2/(\cos\beta \sin\beta)$, $y_T = 10$ and $0.05 \le s_L \le 0.1$. Right: BRs of the H, A states in the 2HDM+VLQ as a function of s_L for the following inputs parameters: $m_{t'} = 1\,\mathrm{TeV}$, $\sin(\beta - \alpha) = 1$, $m_h = 125.09\,\mathrm{GeV}$, $\tan\beta = 7$, $m_{12}^2 = m_S^2/(\cos\beta \sin\beta)$ and $y_T = 10$.

Interpretation: 2HDM + VLQ

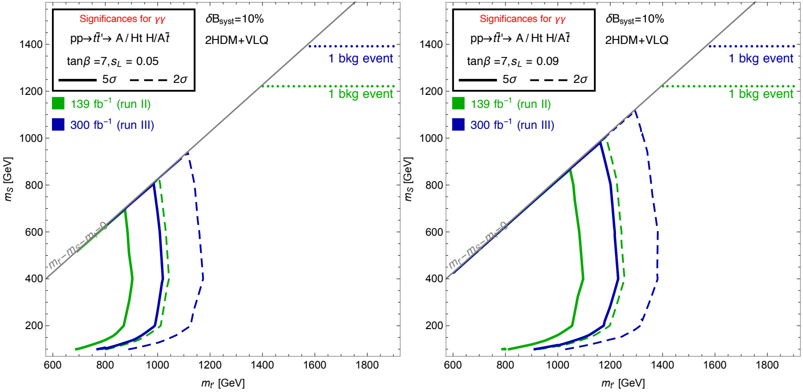

Figure : Significances in the 2HDM+VLQ with for the inputs parameters of figure 9 with the exception of and $s_L = 0.05$ (left) and $s_L = 0.09$ (right). The coding colour is the same as before.

Conclusion

- ATLAS and CMS analyses have primarily been carried out the signatures of VLQs under the assumption that these VLQ decay into SM particles only.
- It may be very useful to for $t' \to t+$ object, where this object could be either fundamental or composite.
- We have assumed in this talk an exemple of spin-0 fundamental states.
- Discovery reach and exlusion regions are presented in two-models by assuming spin-0 state decaying into $\gamma\gamma$ and γZ.
- Results are presented for Run II and Run III
- Limits on t' mass are extracted in the simplied models.

Thank you