# *Top FCNCs in extended Higgs sectors*

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June 18, 2018

Based on

**arXiv:1806.02836**

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# Introduction

- Many reasons to go beyond the SM, *viz.* gauge hierarchy, neutrino mass, dark matter, baryon asymmetry etc.
- Processes mediated via Flavour Changing Neutral Currents (FCNCs) are very rare within the SM $\rightarrow$ any experimental signature $\rightarrow$ evidence for new physics
- FCNCs in top production are lucrative $\rightarrow$ copious production of top quarks in high energy hadron colliders $\rightarrow$ large number of rare FCNC events expected despite small decay rate
- Large mass of top quark connects it to the EWSB sector where new physics may be lurking around

# Top FCNC searches

- Numerous searches:

  $t \to \gamma c\ (u)$: $\mathcal{B}(t \to \gamma c\ (u)) < 1.7\ (0.13) \times 10^{-3}$ [8 TeV, CMS]

  $t \to gc\ (u)$: $\mathcal{B}(t \to gc\ (u)) < 4.1\ (0.2) \times 10^{-4}$ [7 + 8 TeV, CMS]

  $t \to Zc\ (u)$: $\mathcal{B}(t \to Zc\ (u)) < 2.4\ (1.7) \times 10^{-4}$ [13 TeV, CMS and ATLAS]

  $t \to hc\ (u)$: $\mathcal{B}(t \to hc\ (u)) < 2.2\ (2.4) \times 10^{-3}$ [13 TeV, ATLAS]

- All the above searches assume a Standard Model (SM) particle spectrum $\to$ possibility of other particles lurking around the EW scale to which tops might decay $\to$ Scalar singlets, $S$
- Production of such $S$ strongly constrained $\to$ Near-precise Higgs couplings measurement and $W$-mass measurement
- For a mixing angle $0.2 < \sin\theta < 0.35 \to$ wide range of singlet mass allowed

# Motivation for top FCNCs via scalars

- Scalar particles produced by well motivated models $\rightarrow$ NMSSM, CHMs, xSM etc.
- Such scalars induce significantly larger FCNCs compared to the Higgs mediated FCNCs [Zhang, Maltoni, 2013]
  - top FCNCs mediated by new scalar singlets generally suppressed by one less power of heavy physics scale
  - Scalar singlet can have larger decay width into cleaner $\ell^+\ell^-$, $b\bar{b}$ and $\gamma\gamma \rightarrow$ model dependent statement
  - In models like CHMs, Higgs mediated FCNCs forbidden at the leading order [Agashe, Contino, 2009]
- Top FCNCs mediated by such singlet scalars may well be within the reach of the LHC

# Flavour constraints

- Presently no constraints on $t \to qS$
- Possible to have strong constraints from $D^0 - \bar{D}^0$ oscillations
- Constraints as products of two $S$ Yukawas, *viz.*, $Y_{ct}$ and $Y_{ut}$ (also $Y_{uc}$) $\to$ $|Y_{ut}Y_{ct}|$, $|Y_{tu}Y_{tc}| < 7.6 \times 10^{-3}$, $|Y_{tu}Y_{ct}|$ $|Y_{ut}Y_{tc}| < 2.2 \times 10^{-3}$ and $\sqrt{|Y_{ut}Y_{tu}Y_{ct}Y_{tc}|} < 0.9 \times 10^{-3}$ [Harnik, Kopp, Zupan, 2012]
- To circumvent such issues $\to$ fall back on scenarios where $Y_{ut}$ is negligible $\to$ model dependent

# Model independent framework: Effective Lagrangian

- In this talk → scrutinise reach of HL-LHC for top FCNCs in top-pair produced events
- We consider one of the tops to have standard leptonic decay and the other to decay as $t \to Sc, S \to b\bar{b}\ (\gamma\gamma)$
- Current experimental searches tailored for the SM-like 125 GeV Higgs → new searches needed for varying scalar masses → careful treatment of backgrounds
- We consider a scenario where SM is augmented by a gauge singlet, $S$ having a mass $m_S$ in the EW regime
- At low energies, the relevant Yukawa Lagrangian is

$$\mathcal{L} = -\overline{\mathbf{q_L}}\left(\mathbf{Y} + \mathbf{Y}'\frac{|H|^2}{f^2} + \tilde{\mathbf{Y}}\frac{S}{f}\right)\tilde{H}\mathbf{u_R} + \text{h.c.}$$

$H = [\phi^+, (h+\phi^0)/\sqrt{2}]^t$ → SM-like Higgs doublet, $\mathbf{q_L}$ ($\mathbf{u_R}$) → left- (right-) handed) quarks, $\mathbf{Y}, \mathbf{Y}'$, and $\tilde{\mathbf{Y}}$ → arbitrary flavour matrices, $f \gtrsim \mathcal{O}(\text{TeV})$ → heavy physics scale

# Summarising possible models

- In the absence of effective operators
  - $Sf\bar{f}$ negligible and occurs at one-loop if $S$ isn't a pseudoscalar
  - In such cases, $Sf\bar{f}$ coupling proportional to the *vev* of $S$ $\rightarrow$ mixing with SM-like Higgs $\rightarrow$ severe constraints from current Higgs measurements
  - FCNC currents further suppressed by GIM mechanism $\rightarrow$ $\mathcal{B}(t \rightarrow Sc)$ expected to be orders of magnitude smaller than $\mathcal{B}(t \rightarrow hc)$ which is predicted to be smaller than $10^{-13}$ [Mele, Petraca, Soddu, 1998]
- We are looking at scenarios with $S$ being around the EW scale and also have heavier new states
  - In CHMs, $S$ is a pNGB, whereas $f$ refers to the scale of the strong sector
  - In NMSSM, $S$ serves as the bosonic sector of the additional singlet, whereas $f$ refers to the other SUSY resonances
  - In models with strong EW phase transitions, $S$ is a new scalar with mass around the EW scale, for the phase transition to occur, whereas $f$ is the scale with the new sources for CP violation

# Summarising possible models (continued)

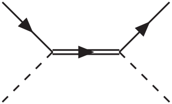
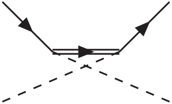
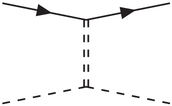
| Field | Relevant Lagrangian | Diagram | $\tilde{\mathbf{Y}}_{ij}/f^2$ |
|---|---|---|---|
| $Q = (1,2)_{1/6}$ | $L_Q = -m_Q \overline{Q} Q + (\alpha_i^Q \overline{Q} S q_L^i$ $+ \tilde{\alpha}_j^Q \overline{Q} \tilde{H} u_R^j + \text{h.c.})$ |  | $\dfrac{\alpha_i^Q \tilde{\alpha}_j^Q}{m_Q}$ |
| $U = (1,1)_{2/3}$ | $L_U = -m_U \overline{U} U + (\alpha_i^U \overline{U} H q_L^i$ $+ \tilde{\alpha}_j^U \overline{U} S u_R^j + \text{h.c.})$ |  | $\dfrac{\alpha_i^U \tilde{\alpha}_j^U}{m_U}$ |
| $\Phi = (1,2)_{1/2}$ | $L_\Phi = -\frac{1}{2} m_\Phi^2 \Phi^2 + (\alpha_{ij}^\Phi \overline{q_L^i} \tilde{\Phi} u_R^j$ $+ \kappa S \Phi^\dagger H + \text{h.c.})$ |  | $\dfrac{\alpha_{ij}^\Phi \kappa}{m_\Phi^2}$ |

Table : Single field extensions of the SM supplemented with $S$ that induce the FCNC of interest at low energy at tree level. The numbers in parenthesis and the subscript denote the $SU(3)_c$ and $SU(2)_L$ representations and the hypercharge, respectively. From the top left and clockwise, the different diagram legs represent $q_L^i$, $t_R^j$, $H$ and $S$, respectively.

# Model independent framework: Effective Lagrangian

- The flavour matrices from the Effective Lagrangian are not aligned in general $\rightarrow$ FCNCs can occur in the EW phase
- Various new physics effects come about $\rightarrow$ top flavour-violating effects, *viz.*, $t \rightarrow hc$ and $t \rightarrow Sc$ $\rightarrow$ latter dominates as former is further suppressed by $1/f$ and in many UV-complete models, $\mathbf{Y}, \mathbf{Y}'$ are approximately aligned
- After EWSB

$$\mathcal{L} = -\frac{v}{\sqrt{2}}\left[\overline{\mathbf{q_L}}\mathbf{Y}\left(1+\frac{h}{v}\right)\mathbf{u_R} + \frac{S}{f}\overline{\mathbf{q_L}}\tilde{\mathbf{Y}}\mathbf{u_R} + \mathcal{O}\left(\frac{1}{f^2}\right)\right] \supset \tilde{g}\,\frac{m_t}{f}\overline{t_L}Sc_R + \text{h.c.},$$

$m_t \sim 173$ GeV and $\tilde{g}$ is $\mathcal{O}(1)$.

# Branching ratios

- One obtains

$$\Gamma(t \to Sc) = \frac{\tilde{g}^2}{32\pi}\frac{v^2}{f^2} m_t \left(1 - \frac{m_S^2}{m_t^2}\right)^2$$

For a benchmark point with $f \sim 1$ TeV and $\tilde{g}$ is $\mathcal{O}(1)$, one obtains
$\mathcal{B}(t \to Sc) \sim \Gamma(t \to Sc)/\Gamma_t^{\rm SM} \sim 0.03$ with $\Gamma_t^{\rm SM} \sim 1.4$ GeV

- Final rate also depends on the decay of $S$ to SM particles $\to$ motivated by CHMs, we consider the following couplings of $S$ to fermions and photons $\frac{m_\psi}{f} S\bar{\psi}\psi$ and $\frac{c_\gamma \alpha}{4\pi f} S F_{\mu\nu}\tilde{F}^{\mu\nu}$, $c_\gamma$ is $\mathcal{O}(1)$
- In the regime $m_S \gg m_\psi$, one obtains

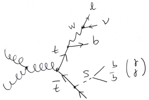
$$\Gamma(S \to \psi\psi) = \frac{N_c}{8\pi}\frac{m_\psi^2}{f^2} m_S \quad \text{and} \quad \Gamma(S \to \gamma\gamma) = \frac{c_\gamma^2 \alpha^2}{64\pi^3 f^2} m_S^3$$

- Thus, $\mathcal{B}(S \to \gamma\gamma)/\mathcal{B}(S \to \overline{\psi}\psi) \sim \frac{\alpha^2}{\pi^2}(m_S/m_\psi)^2$
- Suppression factor driven by $\alpha$ can be partially compensated by $m_S$
- Contrary to $\mathcal{B}(h \to \gamma\gamma) \sim 2 \times 10^{-3}$ in SM, $\mathcal{B}(S \to \gamma\gamma)$ is model-dependent and can be much larger

# LHC prospects for $t \to Sc, S \to b\bar{b}$

Three Benchmark Points (BP), each including $m_S = 20, 50, 80, 100, 120, 150$ GeV

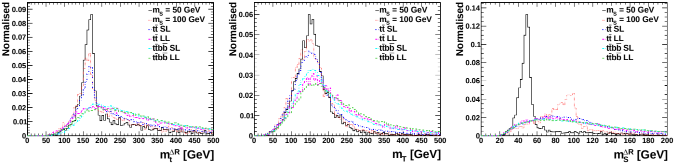
$$\text{BP 1}: \quad \tilde{g} = 1.0\,, \quad f = 2\ \text{TeV} \quad \Longrightarrow \quad \mathcal{B}(t \to Sc) \sim 10^{-3} - 10^{-2}\,;$$
$$\text{BP 2}: \quad \tilde{g} = 1.0\,, \quad f = 10\ \text{TeV} \quad \Longrightarrow \quad \mathcal{B}(t \to Sc) \sim 10^{-4} - 10^{-3}\,;$$
$$\text{BP 3}: \quad \tilde{g} = 0.1\,, \quad f = 2\ \text{TeV} \quad \Longrightarrow \quad \mathcal{B}(t \to Sc) \sim 10^{-5} - 10^{-4}$$



- $t\bar{t}$ production with one top decaying leptonically and the other as $t \to Sc, S \to b\bar{b}$
- $b$-tagging efficiency chosen as 70%, $c(\ell) \to b$ mistag rate has been taken as 10% (1%)
- Demanding final state: 3 $b$-tagged jets, at least one additional jet and one isolated lepton
- Basic cuts: $p_T(j) > 30$ GeV, $p_T(\ell) > 10$ GeV and Lepton isolation: total hadronic activity around lepton with cone radius 0.2, less than 10% of its $p_T$

# LHC prospects for $t \to Sc, S \to b\bar{b}$

- Most dominant background: semi-leptonic $t\bar{t}b\bar{b}$ production
- Other background: leptonic $t\bar{t}b\bar{b}$ production
- Fake backgrounds: semi-leptonic (leptonic) $t\bar{t}$ merged up to one extra matrix element (ME) parton, $Wb\bar{b}$ and $Zb\bar{b}$ merged up to two extra ME partons, $W/Z$ decaying leptonically $\to$ Flat NLO $K$-factors included for signal and backgrounds
- We look for closest pair (in $\Delta R$) of $b$-tagged jets and reconstruct top mass ($m_t^{\Delta R}$) with the additional hardest jet
- Transverse mass reconstructed with the remaining $b$-tagged jet



# LHC prospects for $t \to Sc, S \to b\bar{b}$

| Cuts | 20 GeV | 50 GeV | 80 GeV | 100 GeV | 120 GeV | 150 GeV |
|---|---|---|---|---|---|---|
| Basic | 0.014 | 0.050 | 0.051 | 0.056 | 0.063 | 0.063 |
| $\lvert\eta_{(b,\ell,j)}\rvert < 2.5$ | 0.83 | 0.88 | 0.86 | 0.87 | 0.86 | 0.82 |
| $\Delta R$(all pairs) $> 0.4$ | 0.96 | 0.94 | 0.93 | 0.93 | 0.94 | 0.94 |
| $\lvert m_t^{\Delta R} - m_t\rvert < 50$ GeV | 0.29 | 0.63 | 0.57 | 0.55 | 0.49 | 0.41 |
| $m_T < 200$ GeV | 0.72 | 0.56 | 0.87 | 0.85 | 0.83 | 0.74 |

Table : Efficiency after each cut for the six signal benchmark points.

| Cuts | $t\bar{t}$ (SL) | $t\bar{t}$ (LL) | $Wb\bar{b}$ | $Zb\bar{b}$ | $t\bar{t}b\bar{b}$ (SL) | $t\bar{t}b\bar{b}$ (LL) |
|---|---|---|---|---|---|---|
| Basic | 0.0038 | 0.0016 | 0.00032 | 0.00016 | 0.11 | 0.073 |
| $\lvert\eta_{(b,\ell,j)}\rvert < 2.5$ | 0.78 | 0.69 | 0.74 | 0.71 | 0.90 | 0.85 |
| $\Delta R$(all pairs) $> 0.4$ | 0.95 | 0.94 | 0.95 | 0.95 | 0.96 | 0.91 |
| $\lvert m_t^{\Delta R} - m_t\rvert < 50$ GeV | 0.49 | 0.32 | 0.27 | 0.33 | 0.31 | 0.28 |
| $m_T < 200$ GeV | 0.80 | 0.58 | 0.56 | 0.70 | 0.63 | 0.53 |

Table : Efficiency after each cut for the six dominant backgrounds. SL (LL) denotes semi (di)-leptonic decays.

# LHC prospects for $t \to Sc, S \to b\bar{b}$

Final cut: $0.8\, m_S < m_S^{\Delta R} < m_S + 10$ GeV

| $m_S$ [GeV] | Signal | $t\bar{t}$ (SL) | $t\bar{t}$ (LL) | $Wb\bar{b}$ | $Zb\bar{b}$ | $t\bar{t}b\bar{b}$ (SL) | $t\bar{t}b\bar{b}$ (LL) |
|---|---|---|---|---|---|---|---|
| 20 | 8.2 | 0.12 | 0.037 | 0.017 | 0.0094 | 4.0 | 1.5 |
| 50 | 110 | 1.8 | 0.35 | 0.093 | 0.056 | 37 | 17 |
| 80 | 140 | 3.4 | 0.60 | 0.080 | 0.070 | 51 | 24 |
| 100 | 120 | 3.7 | 0.59 | 0.066 | 0.062 | 49 | 24 |
| 120 | 96 | 3.1 | 0.47 | 0.052 | 0.042 | 41 | 19 |
| 150 | 51 | 1.4 | 0.23 | 0.025 | 0.019 | 22 | 11 |

Table : Efficiencies ($\times 10^4$) after the final cut.

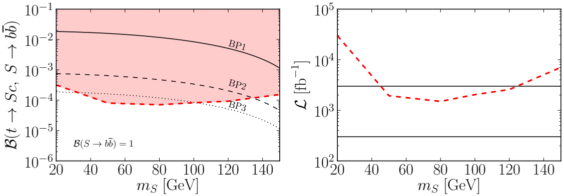



Figure : Left) Branching ratios that can be tested in the $b\bar{b}$ channel. Superimposed are the theoretical expectations in the three BPs. Right) Luminosity required to test $\mathcal{B}(t \to St, S \to b\bar{b}) = 10^{-4}$. Superimposed are $\mathcal{L} = 300$ fb$^{-1}$ and 3000 fb$^{-1}$.

# LHC prospects for $t \to Sc, S \to \gamma\gamma$

- Final state: at least two jets with one being $b$-tagged, one isolated lepton and two isolated photons (same isolation criteria used for photons)
- Photons required to have $p_T > 10 GeV$ and $|\eta| < 2.5$
- Dominant backgrounds: semi-leptonic (di-leptonic) $t\bar{t}h$ and the QCD-QED $t\bar{t}\gamma\gamma$
- $W\gamma\gamma$ merged up to two hard ME partons, also considered $\to$ despite having $\mathcal{O}(1)$ pb cross-section, it reduces drastically after all cuts
- Selection cuts up to the transverse mass are almost identical but for the final cut, due to the much sharper di-photon resolution, we demand a narrow window of 3 GeV around the scalar mass

# LHC prospects for $t \to Sc, S \to \gamma\gamma$

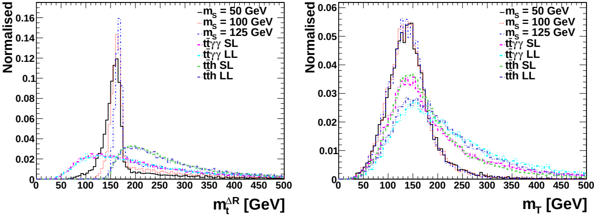



Figure : Left) The reconstructed top mass from the hardest two photons and the hardest jet. Right) The transverse mass $m_T$.

| $m_S$ [GeV] | Signal | $t\bar{t}\gamma\gamma$ (SL) | $t\bar{t}\gamma\gamma$ (LL) | $t\bar{t}h$ (SL) | $t\bar{t}h$ (LL) |
|---|---|---|---|---|---|
| 20 | 760 | 13 | 5.5 | 0.15 | 0.20 |
| 50 | 1100 | 27 | 9.9 | 0.40 | 0.25 |
| 80 | 1000 | 19 | 6.8 | 0.45 | 0.35 |
| 100 | 940 | 13 | 5.0 | 0.20 | 0.25 |
| 120 | 740 | 6.4 | 3.5 | 0.25 | 0.35 |
| 125 | 660 | 5.0 | 2.6 | 570 | 240 |
| 150 | 280 | 2.3 | 1.1 | 0.00 | 0.00 |

Table : Efficiencies ($\times 10^4$) after the final cut, $|m_{\gamma\gamma} - m_S| < 3$ GeV.

# LHC prospects for $t \to Sc, S \to \gamma\gamma$

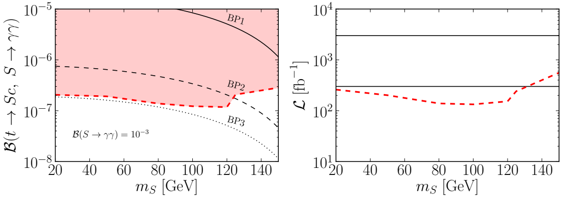



Figure : Left) Branching ratios that can be tested in the $\gamma\gamma$ channel. Superimposed are the theoretical expectations in the three BPs. Right) Luminosity required to test $\mathcal{B}(t \to St, S \to \gamma\gamma) = 10^{-6}$. Superimposed are $\mathcal{L} = 300$ fb$^{-1}$ and 3000 fb$^{-1}$.

The kink shows the regime for $m_S = m_h = 125$ GeV. Here the SM backgrounds are much larger and hence a larger integrated luminosity is required to probe the same BR

# HE-LHC prospects for $t \to Sc, S \to \gamma\gamma$

- The increase in cross-section for the dominant background $t\bar{t}\gamma\gamma$ at the 27 TeV (100 TeV) collider is $\sim 4$ ($\sim 40$) times that from the 14 TeV numbers.
- Similar factors hold for the signal cross-section
- Assuming 10 ab$^{-1}$ of luminosity and similar efficiencies, one expects an increase in significance by $4/\sqrt{4} \times \sqrt{10/3} \sim 3.7$ ($40/\sqrt{40} \times \sqrt{10/3} \sim 11.5$) for the 27 TeV (100 TeV) collider $\to$ An order of magnitude improvement in the bound of $\mathcal{B}(t \to Sc, S \to \gamma\gamma)$
- Similar improvements should hold for $\mathcal{B}(t \to Sc, S \to b\bar{b})$

# Summary and conclusions

- Flavour violating top decays into singlet scalars mediated by heavy physics at scales $f \gtrsim \mathcal{O}(\mathrm{TeV})$ dominate over the ones involving SM-like Higgs $\rightarrow$ Latter (former) proceeds via dimension 6 (5) operators and are hence suppressed by $1/f^2$ $(1/f)$ $\rightarrow$ Also $S$ can be much lighter than Higgs and corresponding top decay can be kinematically enhanced
- We studied top-pair production with one top decaying leptonically and the other decaying via $t \rightarrow Sc, S \rightarrow b\bar{b}$ $(\gamma\gamma)$ with 20 GeV $< m_S <$ 150 GeV
- For $S \rightarrow b\bar{b}$ we have the best bound at $m_S \sim$ 80 GeV, being able to probe $\mathcal{B}(t \rightarrow Sc, S \rightarrow b\bar{b})$ at 95% CL with 3 ab$^{-1}$ luminosity $\rightarrow$ reach smaller than about a factor of 5 for lower masses because at much lower masses the two $b$-jets might not be fully resolved and one might have to resort to fat jets in the boosted regimes $\rightarrow$ For heavier masses the closest $b$-tagged jets might not peak exactly around $m_S$ (wrong pairing)
- For the $t \rightarrow Sc, S \rightarrow \gamma\gamma$ analysis, one can probe $\mathcal{B}(t \rightarrow Sc, S \rightarrow \gamma\gamma) \gtrsim 10^{-7}$ at 95% CL with same integrated luminosity
- In models where $\mathcal{B}(S \rightarrow \gamma\gamma) \sim 1$, one can probe a heavy new physics scale of $\sim$ 50 TeV
- An order of magnitude improvement in the bound for $\mathcal{B}(t \rightarrow Sc, S \rightarrow \gamma\gamma)$ upon going to 100 TeV colliders with 10 ab$^{-1}$ luminosity