Top quark rare decays

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The top FCNC era

- Flavor violation in the top sector is poorly constrained, but one of the most likely flags of new physics.
- The LHC is a top factory, already making considerable progress improving top FCNC measurements, with much more to come.
- Future colliders have comparable sensitivity in certain top FCNC channels.
- The era of top FCNC has arrived!

The top FCNC charge

The charge for Snowmass:

- Does the top quark decay to exotic final states? SM-like or BSM-like? How well can these decays be measured/constrained at hadron and lepton colliders?
- What sensitivity needs to be reached for these decays in order to have a significant impact on models of physics beyond the SM?

Effective lagrangian for top FCNC

$$\mathcal{L}_{\text{eff}} = \frac{v}{\Lambda^2}\left(b^Z_{LR}\mathcal{O}^Z_{LR} + b^\gamma_{LR}\mathcal{O}^\gamma_{LR} + b^g_{LR}\mathcal{O}^g_{LR}\right) + \frac{v^2}{\Lambda^2}\left(a^Z_L\mathcal{O}^Z_L + a^h_{LR}\mathcal{O}^h_{LR}\right) + L \leftrightarrow R + h.c.$$

Dimension 5

$$\mathcal{O}^Z_{LR} = \frac{2e}{\sin 2\theta_W}(\bar{q}_L\sigma^{\mu\nu}t_R)Z_{\mu\nu}$$

$$\mathcal{O}^\gamma_{LR} = e(\bar{q}_L\sigma^{\mu\nu}t_R)F_{\mu\nu}$$

$$\mathcal{O}^g_{LR} = g_s(\bar{q}_L\sigma^{\mu\nu}T^a t_R)G^a_{\mu\nu}$$

Dimension 4

$$\mathcal{O}^Z_L = \frac{2e}{\sin 2\theta_W}(\bar{q}_L\gamma^\mu t_L)Z_\mu$$

$$\mathcal{O}^h_{LR} = (\bar{q}_L t_R)h$$

Look for $t \to Zq, t \to gq, t \to \gamma q, t \to hq$

Motivated signals

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	$\lesssim 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\lesssim 10^{-5}$	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	$\lesssim 10^{-4}$

- SM rate is tiny due to GIM suppression, so any signal is an indication of new physics.
- Motivated new physics scenarios can generate branching ratios as large as 10^{-4}-10^{-5} consistent with direct limits on new states.
- Correlations among different signals allows differentiation of various scenarios.

Current limits

Process	Br Limit	Search	Dataset
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV
$t \to gu$	5.7×10^{-5}	ATLAS $qg \to t \to Wb$	2.05 fb^{-1}, 7 TeV
$t \to gc$	2.7×10^{-4}	ATLAS $qg \to t \to Wb$	2.05 fb^{-1}, 7 TeV
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV

- Current limits set by a combination of LHC searches and older limits from Tevatron, HERA.
- LHC beginning to overtake existing limits from previous experiments, though some channels await dedicated LHC search results (e.g., $t \to \gamma q$).
- Current sensitivity at the level of 10^{-4}, though there is substantial reach in $t \to gq$ from single top production.

LHC projections

Process	Br Limit	Search	Dataset	Source
$t \to Zq$	2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	ATLAS ESG
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	ATLAS ESG
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	ATLAS ESG
$t \to \gamma q$	3×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	ATLAS ESG
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell q X$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell q X$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.

- 14 TeV LHC capable of setting limits as far down as 10^{-6} in certain channels.
- Expect a factor of ~2-3 improvement in going to high luminosity.

LHC projections

- The "ATLAS ESG" limits are based on the ATLAS projections for the European Strategy Group. These should be updated by dedicated ATLAS studies of 14 TeV sensitivity by Minneapolis.
- "Extrapolated" limits are preliminary, based on naive theory scaling of relevant cross sections and luminosity from current searches at 7 and 8 TeV. These estimates will be refined by the ATLAS and CMS groups responsible for the relevant 7 and 8 TeV searches by Minneapolis, but no additional dedicated studies underway.
- If additional resources are available, dedicated 14 TeV studies of $t \to hq, t \to gq$ would be extremely useful.

ILC projections

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 500 GeV	TESLA study
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 500 GeV	TESLA study
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	TESLA study
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	TESLA study

- The ILC offers useful complementarity to the LHC, particularly for FCNC involving photons and Z bosons.
- The greatest sensitivity arises in single top channels, which can be probed even at $\sqrt{s} = 250$ GeV; allows useful probe of top physics at the earliest stage of ILC operation.
- In contrast to LHC, can differentiate between different Lorentz structures and hence dim-4 or dim-5 operators.

ILC projections

- The "TESLA study" limits are based on '01 TESLA studies at $\sqrt{s} = 500$ GeV that in turn form the basis for sensitivity estimates in the ILC RDR.
- "Extrapolated" limits are based on a conservative rescaling of e^+e^- studies at $\sqrt{s} = 192$ GeV to the first stage of ILC operation at $\sqrt{s} = 250$ GeV and could be substantially improved by a dedicated study.
- Given that searches for top FCNC in single top production would provide useful sensitivity to new physics in the top sector during the initial stages of ILC operation, a dedicated study would be extremely useful.

Summary

- Rare decays of the top can be measured down to the 10^{-6} level at the LHC and ILC.
- The LHC provides coverage of all top FCNC modes.
- The ILC provides comparable sensitivity to modes involving photons or Z bosons, with the capacity to probe the Lorentz structure of the coupling.
- Even operating at 250 GeV, the ILC can set meaningful limits on rare decays via single top production.
- If additional resources are available before the Minneapolis meeting, dedicated study of $t \to Zq, t \to \gamma q$ at 250 GeV ILC and dedicated study of $t \to hq, t \to gq$ at 14 TeV LHC would be extremely useful.