FCNC and Top Quarks

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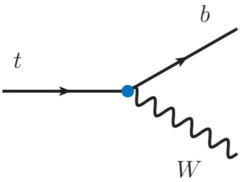
With W. Altmannshofer, M. Blanke, S. Gori, P. Uttayarat, J. Zupan

What are we looking at?

- Top FCNC modes
  - $t \to ch$
  - $t \to cZ$
  - $t \to c\gamma$
  - $t \to cg$
- The modes with $c \to u$

The Challenge

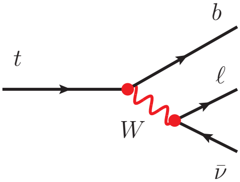
- Top quark has unsuppressed decay width $t \to bW$



$$\Gamma_t \approx \frac{g_2^2}{64\pi} \frac{m_t^2}{M_W^2} |V_{tb}|^2 \, m_t$$

$$\Rightarrow \frac{\Gamma_t}{m_t} \simeq 10^{-2}$$

- Compare to B-meson decay: 3-body + CKM suppression

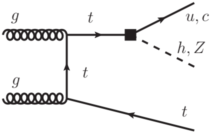


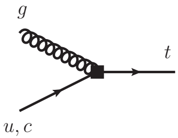
$$\Gamma_{B\to c\ell\nu} \approx \frac{g_2^4}{384\pi} \frac{1}{16\pi^2} \frac{m_b^4}{M_W^4} |V_{cb}|^2 \, m_b$$

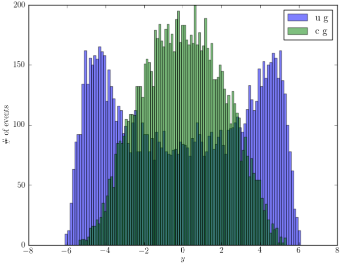
$$\Rightarrow \frac{\Gamma_{B_d}}{m_{B_d}} \simeq 8 \times 10^{-13}$$

The Good News

- In theories addressing naturalness there is non-trivial flavor structure
- Top often most sensitive to NP modifications
- Top FCNC in both production and decay are important
- Can distinguish between $t \to c$ and $t \to u$ from production!
- What about indirect constraints?







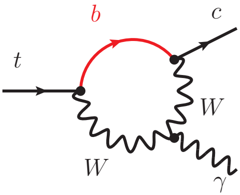
Outline

- Top FCNCs in the Standard Model
- Operator analysis and indirect constraints
- Predictions in concrete models
- A look at 100 TeV

Everything is work in progress!

Top FCNCs in the Standard Model

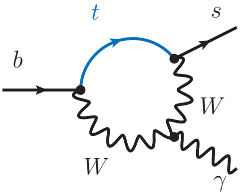
- Top FCNCs are loop, CKM, and GIM suppressed



$$\mathcal{A}_{t\to c\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_b^2}{M_W^2}V_{tb}V_{cb}^*$$

$$\Rightarrow \text{Br}(t \to c\gamma)_{\text{SM}} \simeq 5 \times 10^{-14}$$

- Compare to B-meson decay: Hard GIM breaking by m_t



$$\mathcal{A}_{b\to s\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_t^2}{M_W^2}V_{tb}V_{ts}^*$$

$$\Rightarrow \text{Br}(b \to X_s\gamma)_{\text{SM}} \simeq 3.15 \times 10^{-4}$$

Standard-Model Predictions

[Aguilar-Saavedra, hep-ph/0409342]

$$\begin{aligned} \mathrm{Br}(t \to c\gamma) &\simeq 5 \times 10^{-14}\,, & \mathrm{Br}(t \to u\gamma) &\simeq 4 \times 10^{-16} \\ \mathrm{Br}(t \to cg) &\simeq 5 \times 10^{-12}\,, & \mathrm{Br}(t \to ug) &\simeq 4 \times 10^{-14} \\ \mathrm{Br}(t \to cZ) &\simeq 1 \times 10^{-14}\,, & \mathrm{Br}(t \to uZ) &\simeq 8 \times 10^{-17} \\ \mathrm{Br}(t \to ch) &\simeq 3 \times 10^{-15}\,, & \mathrm{Br}(t \to uh) &\simeq 2 \times 10^{-17} \end{aligned}$$

$$\frac{\mathrm{Br}(t \to uX)}{\mathrm{Br}(t \to cX)} \simeq \left|\frac{V_{ub}}{V_{cb}}\right|^2 \simeq 0.008$$

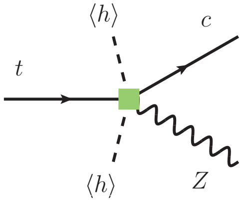
Any observation would be a clear signal of new physics!

Model-Independent Bounds

- $\Lambda \gg v$ – use expansion in v/Λ
- EFT description of NP above the electroweak scale
  [Buchmüller, Wyler Nucl.Phys.B268; Grzadkowski et al., JHEP 1010 (2010) 085]
- $SU(2)$ symmetry provides additional relations

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}^u_{LL} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{Q}_2 \gamma^\mu \sigma_a Q_3)$$
$$\mathcal{O}^h_{LL} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_2 \gamma^\mu Q_3)$$
$$\mathcal{O}^h_{RR} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{c}_R \gamma^\mu t_R)$$



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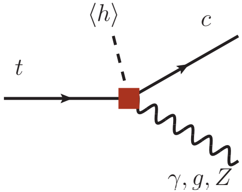
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i$$

$$\begin{aligned}
\mathcal{O}_{RL}^{B} &= g_1(\bar{Q}_2\sigma^{\mu\nu}t_R)H \quad B_{\mu\nu} \\
\mathcal{O}_{RL}^{W} &= g_2(\bar{Q}_2\sigma^{\mu\nu}\sigma^a t_R)H \quad W^a_{\mu\nu} \\
\mathcal{O}_{RL}^{G} &= g_3(\bar{Q}_2\sigma^{\mu\nu}T^A t_R)H \quad G^A_{\mu\nu} \\
&+ \quad (L \leftrightarrow R)
\end{aligned}$$



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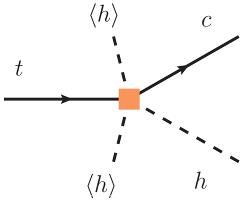
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\mathcal{C}_i}{\Lambda^2} \mathcal{O}_i$$

$$\mathcal{O}^h_{RL} = (H^\dagger H)(\bar{c}_R Q_3) H^c$$
$$\mathcal{O}^h_{LR} = (H^\dagger H)(\bar{Q}_2 t_R) H$$



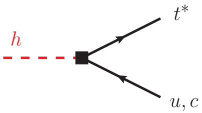
Associated Higgs production

- For each of the decays
  - $t \to cZ$, $t \to c\gamma$, $t \to cg$, $t \to ch$
- there is an associated decay
  - $t \to cZ^* h$, $t \to c\gamma h$, $t \to cgh$, $t \to ch^* h$
- If dominated by one operator, associated decay completely fixed
- If more operators, can give additional information
- BRs naively suppressed by $1/16\pi^2 \sim 10^{-2}$
  - Out of reach for LHC
  - Maybe at 100 TeV?
  - Could also look at $ug \to tZh$, $ug \to t\gamma qh$, $ug \to thh$, $tu \to hh$

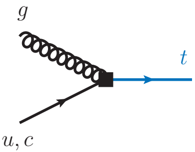
Direct and Indirect Constraints

- Effective couplings are not only probed by rare top decays:

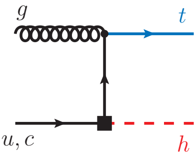
Higgs decays



Single top production



Single top + Higgs production



Direct Bounds – LHC

Process	Br Limit	Search	Dataset
$t \to Zq$	5×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.7 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
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to \gamma u$	1.6×10^{-4}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to \gamma c$	1.8×10^{-3}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to hq$	7.9×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV
$t \to hq$	5.6×10^{-3}	CMS $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	19.5 fb^{-1}, 8 TeV

in many cases experimental bounds can still improve by ~ 1 order of magnitude at the LHC

Implications for NP Scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\mathcal{C}_i}{\Lambda^2} \mathcal{O}_i$$

Operators that are only weakly constrained by indirect probes

	$t \to c$	$t \to u$
SU(2) dipole $\mathcal{O}_{LR}^{W}$	$\Lambda \gtrsim 0.75$ TeV	$\Lambda \gtrsim 0.75$ TeV
SU(3) dipole $\mathcal{O}_{RL}^{G}$	$\Lambda \gtrsim 4.0$ TeV	$\Lambda \gtrsim 5.8$ TeV
Higgs penguin $\mathcal{O}_{RL}^{h}$	$\Lambda \gtrsim 0.73$ TeV	$\Lambda \gtrsim 0.73$ TeV

Current experimental constraints already probe the TeV scale!

A side remark on validity of EFT

- What is the value of Λ?
  - Integrate out NP at Λ
  - For EFT to be valid need large scale separation (cf. $m_b \ll M_W$ in B physics)
  - (And no new fields below Λ – e.g. 2HDM??)
- For indirect bounds from precision observables, clearly $\Lambda \gg v$
- For collider bounds $\Lambda \gg m_{\text{inv}}$ should be determined dynamically [Englert, Spannowsky, arxiv:1408.5147]
- Even more relevant at 100 TeV collider

Indirect Constraints – B physics

[Fox, Ligeti, Papucci, Perez, Schwartz, arxiv:0704.1482]

- Constraints from $b \to s\gamma$, $b \to s\ell\ell$, $b \to c/u\ell\nu$, $\Delta F = 2$
- Recent $B_d \to \mu^+\mu^-$ not yet included
- Strongest constraint on left-handed Z penguin $\mathcal{O}^h_{LL}$ – tree-level contributions
- Right-handed dipoles and right-handed Z penguin $\mathcal{O}^W_{LR}$, $\mathcal{O}^B_{LR}$, $\mathcal{O}^h_{RR}$ only weakly constrained by B physics

Indirect Constraints – B physics

[Fox, Ligeti, Papucci, Perez, Schwartz, arxiv:0704.1482]

Operator	$\text{Br}(t \to cZ)_{\text{max}}$	$\text{Br}(t \to c\gamma)_{\text{max}}$	Scale
$\mathcal{O}^u_{LL}$	7.1×10^{-6}	–	3.9 TeV
$\mathcal{O}^h_{LL}$	3.5×10^{-7}	–	8.3 TeV
$\mathcal{O}^W_{RL}$	3.4×10^{-5}	1.8×10^{-5}	2.6 TeV
$\mathcal{O}^B_{RL}$	8.4×10^{-6}	4.8×10^{-5}	2.0 TeV
$\mathcal{O}^W_{LR}$	4.5×10^{-3}	2.3×10^{-3}	0.8 TeV
$\mathcal{O}^B_{LR}$	5.6×10^{-3}	3.2×10^{-2}	0.4 TeV
$\mathcal{O}^u_{RR}$	1.4×10^{-1}	–	0.3 TeV

- With 100fb^{-1} LHC will be sensitive to BRs of $\mathcal{O}(10^{-5})$

Indirect Constraints – B physics

[Fox, Ligeti, Papucci, Perez, Schwartz, arxiv:0704.1482]

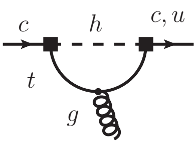
Operator	$\text{Br}(t \to uZ)_{\text{max}}$	$\text{Br}(t \to u\gamma)_{\text{max}}$	Scale
$\mathcal{O}_{LL}^{u}$	1.6×10^{-5}	–	3.2 TeV
$\mathcal{O}_{LL}^{h}$	6.4×10^{-7}	–	7.2 TeV
$\mathcal{O}_{RL}^{W}$	4.1×10^{-5}	2.1×10^{-5}	2.5 TeV
$\mathcal{O}_{RL}^{B}$	1.2×10^{-4}	6.7×10^{-4}	1.1 TeV
$\mathcal{O}_{LR}^{W}$	3.2×10^{-3}	1.6×10^{-3}	0.8 TeV
$\mathcal{O}_{LR}^{B}$	1.0×10^{-3}	5.9×10^{-3}	0.6 TeV
$\mathcal{O}_{RR}^{u}$	1.4×10^{-1}	–	0.3 TeV

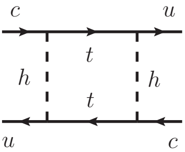
- With 100fb^{-1} LHC will be sensitive to BRs of $\mathcal{O}(10^{-5})$

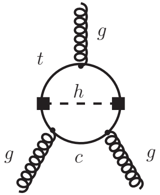
Indirect Constraints – EDMs and D physics

[Gorbahn, Haisch, JHEP06 (2014) 033]

Observable	Coupling	Present bound	Future Sensitivity
d_n	$\lvert \mathrm{Im}\, Y_{tc} Y_{ct} \rvert$	5.0×10^{-4}	1.7×10^{-6}
d_n	$\lvert \mathrm{Im}\, Y_{tu} Y_{ut} \rvert$	4.3×10^{-7}	1.5×10^{-9}
$\Delta \mathcal{A}_{CP}$	$\lvert \mathrm{Im}\, Y_{ut}^{*} Y_{ct} \rvert$	4.0×10^{-4}	–
$D - \bar{D}$ mixing	$\sqrt{\lvert \mathrm{Im}\, Y_{tc}^{*} Y_{ut}^{*} Y_{tu} Y_{ct} \rvert}$	4.1×10^{-4}	1.3×10^{-4}







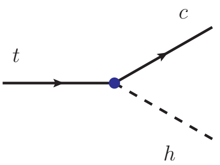
What to expect in specific models

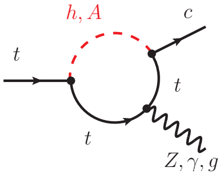
2HDM

- Two Higgs doublets with completely generic Yukawa couplings:

$$\mathcal{L} \supset (y_u)_{ik}\ H_2 \bar{Q}_i U_k + (\tilde{y}_u)_{ik}\ H_1^\dagger \bar{Q}_i U_k + (y_d)_{ik}\ H_1 \bar{Q}_i D_k + (\tilde{y}_d)_{ik}\ H_2^\dagger \bar{Q}_i D_k$$

- Large flavor-violating couplings of the SM-like Higgs are possible





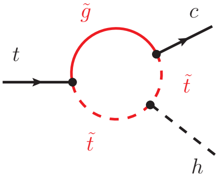
$$\text{Br}(t \to ch) \lesssim 10^{-2}\,, \qquad \text{Br}(t \to cZ) \lesssim 10^{-6}\,,$$

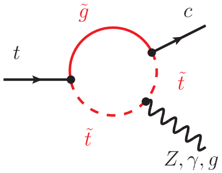
$$\text{Br}(t \to cg) \lesssim 10^{-5}\,, \qquad \text{Br}(t \to c\gamma) \lesssim 10^{-7}\,.$$

[Atwood, Reina, Soni, hep-ph/9609279]

MSSM with general FV

- In MSSM, FCNC only at loop level (as in SM)
- But, new contributions from soft SUSY breaking terms (δ_{LR})





$$\mathrm{Br}(t \to ch) \lesssim 6 \times 10^{-5}\,, \qquad \mathrm{Br}(t \to cZ) \lesssim 10^{-6}\,,$$
$$\mathrm{Br}(t \to cg) \lesssim 3 \times 10^{-5}\,, \qquad \mathrm{Br}(t \to c\gamma) \lesssim 5 \times 10^{-7}\,.$$

[Cao et al., hep-ph/0702264]

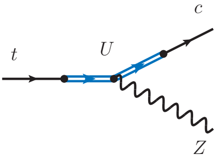
- Gluino mass 200 GeV $\to$ 1 TeV $\Rightarrow$ factor 10 reduction of BRs
- $\mathrm{Br}(t \to ch/Z/\gamma/g)$ all comparable and small

RS Flavor

- Flavor structure from profiles of zero modes in 5th dim.
- Need to solve tension between large top mass and EWPO
- Find, e.g., [Agashe et al., hep-ph/0606293]

$$\mathcal{L}^t_{\mathrm{FC}} \supset \left(g_1 \bar{t}_R \gamma_\mu c_R + g_2 \bar{t}_L \gamma_\mu c_L\right) Z^\mu$$

with $g_{1,2} \sim 10^{-4} \times (3\,\mathrm{TeV}/m_{KK})^2$

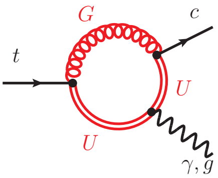


- $t \to ch/Z$ at tree level
- BRs 10^{-5} – 10^{-4} possible

RS Flavor

- Radiative processes require a chirality flip
- Dipole operators give

$$\mathrm{BR}(t \to c\gamma,\, cg) \sim 10^{-9,-10} \times (3\,\mathrm{TeV}/m_{KK})^2$$



- $t \to c\gamma/g$ at loop level
- BRs much larger than in SM, but still out of reach for LHC

Comparison

[1] Atwood, Reina, Soni hep-ph/9609279 [2] Cao et al. hep-ph/0702264

[3] Agashe, Contino 0906.1542; Azatov et al. 0906.1990; Casagrande et al. 1005.4315

see also Snowmass Top Quark Working Group Report 1311.2028

	2HDM[1]	MSSM[2]	RS[3]
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Combining the information from the various decay modes would allow to distinguish the underlying new-physics models

A look at 100 TeV

- Increased cross sections
  - $\sigma(t\bar{t}) \approx 30\,\text{nb}$ at 100 TeV
  - $\sigma(t\bar{t}) \approx 250\,\text{pb}$ at 8 TeV
- Charm content of proton increases
  - $\sigma(ug \to tZ)/\sigma(cg \to tZ) = 7\,(19)\%$ at 13 (100) TeV
- Do we still have up/charm separation?
- Different backgrounds
  - E.g. $\sigma(t)_{\text{SM}}/\sigma(t)_{\text{utG}} = 30\,(200)$ at 8 (100) TeV
- Need more quantitative analysis

  [Altmannshofer, Blanke, Brod, Gori, Uttayarat, Zupan; work in progress]

Summary

- The observation of rare top decays would be a clear signal of new physics
- Current limits already probe the TeV scale
- Many models predict branching ratios within reach of the LHC
- Study opportunities at a 100 TeV collider