Single-top couplings: SM predictions, anomalous couplings, FCNC

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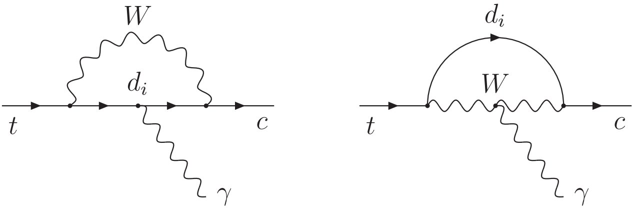
2^{nd} CMS single-top workshop

Outline

1. FCNC in the SM
2. EFT and effective Lagrangian
3. LO and NLO review of FCN anomalous couplings

FCNC in the SM

SM prediction of FCNC is small: GIM suppressed (unitarity of CKM matrix).



$\sum_i V_{ti} \times V_{iq} \simeq 0$, non-zero because quarks are not mass degenerate

SM predictions for top FCNC BRs

F. del Aguila, J. A. Aguilar-Saavedra and R. Miquel, Phys. Rev. Lett. **82** (1999) 1628 [hep-ph/9808400]

J. A. Aguilar-Saavedra, Acta Phys. Polon. B **35** (2004) 2695 [hep-ph/0409342]

$t \to uZ$	$t \to u\gamma$	$t \to ug$	$t \to uH$	$t \to cZ$	$t \to c\gamma$	$t \to cg$	$t \to cH$
8×10^{-17}	3.7×10^{-16}	3.7×10^{-14}	2×10^{-17}	1×10^{-14}	4.6×10^{-14}	4.6×10^{-12}	3×10^{-15}

BSM predictions for top FCNC BRs

J. A. Aguilar-Saavedra, Acta Phys. Polon. B 35 (2004) 2695 [hep-ph/0409342]

BR	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

Current BR limits

BR (BSM decay)	Best limits in the single top	Best limits in the $t\bar{t}$	Best limit
g – c – t	• 0.016% (ATLAS-CONF-2013-063 @ 8TeV) • 0.034% (CMS-TOP-14-007 @ 7TeV)		**0.016%**
g – u – t	• 0.0031% (ATLAS-CONF-2013-063 @ 8TeV) • 0.035% (CMS-TOP-14-007 @ 7TeV)		**0.0031%**
Z – c – t	11.4% (CMS-TOP-12-021 @ 7 TeV)	• 0.05% (CMS-TOP-12-037 @ 7+8TeV) • 0.73% (ATLAS:JHEP90(2012) @ 7TeV)	**0.05%**
Z – u – t	0.51% (CMS-TOP-12-021 @ 7 TeV)		
h – c – t		• 0.56% (CMS-HIG-13-034 @ 8TeV) • 0.79% (ATLAS:JHEP06(2014) @ 7+8TeV)	**0.56%**
h – u – t			
γ – c – t	0.182% (CMS-TOP-14-003 @ 8TeV)		**0.182%**
γ – u – t	0.016% (CMS-TOP-14-003 @ 8TeV)		**0.016%**

Limits obtained at Tevatron, LEP and HERA are not competitive.

EFT intro

The top-quark couplings can be parametrised in an effective field theory.

The SM Lagrangian is extended by gauge-invariant (non-renormalisable) operators, obtained by integrating out heavy modes

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

One could consider any term, $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)^n$

Here we consider only dimension 6 operators, the first non-vanishing terms in $1/\Lambda$ expansion

FCNC has no interference with SM, that starts from $\left(\frac{C_i O_i}{\Lambda^2}\right)^2$

Possible interference between FCNC; not more than 1 coupling per diagram

Not all possible dim-6 operators that one can write are independent

Redundant operators can be reduced by using equation of motions and other relations due to gauge invariance

Dim-6 operators - EW

Among all the 59 possible operators, 14 contribute to top-quark EW anomalous couplings W. Buchmuller, D. Wyler, Nucl.Phys. B268 (1986) 621

$$O_{\phi q}^{(3,ij)} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}_{Li}\gamma^\mu \tau^I q_{Lj}) \,,$$
$$O_{\phi q}^{(1,ij)} = i(\phi^\dagger D_\mu \phi)(\bar{q}_{Li}\gamma^\mu q_{Lj}) \,,$$
$$O_{\phi\phi}^{ij} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu d_{Rj}) \,,$$
$$O_{\phi u}^{ij} = i(\phi^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu u_{Rj}) \,,$$
$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I \,,$$
$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I \,,$$
$$O_{uB\phi}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu} u_{Rj})\tilde{\phi}\, B_{\mu\nu} \,,$$

$$O_{Du}^{ij} = (\bar{q}_{Li}\, D_\mu u_{Rj})\, D^\mu\, \tilde{\phi} \,,$$
$$O_{\bar{D}u}^{ij} = (D_\mu \bar{q}_{Li}\, u_{Rj})\, D^\mu\, \tilde{\phi} \,,$$
$$O_{Dd}^{ij} = (\bar{q}_{Li}\, D_\mu d_{Rj})\, D^\mu\, \phi \,,$$
$$O_{\bar{D}d}^{ij} = (D_\mu \bar{q}_{Li}\, d_{Rj})\, D^\mu\, \phi \,,$$
$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^\mu \tau^I D^\nu q_{Lj} W_{\mu\nu}^I \,,$$
$$O_{qB}^{ij} = \bar{q}_{Li}\gamma^\mu D^\nu q_{Lj} B_{\mu\nu} \,,$$
$$O_{uB}^{ij} = \bar{u}_{Ri}\gamma^\mu D^\nu u_{Rj} B_{\mu\nu} \,,$$

Only three operators (up to flavour indices) contribute to strong interactions,

$$O_{uG\phi}^{ij} = (\bar{q}_{Li}\lambda^a \sigma^{\mu\nu} u_{Rj})\tilde{\phi}\, G_{\mu\nu}^a \,,$$

$$O_{qG}^{ij} = \bar{q}_{Li}\lambda^a \gamma^\mu D^\nu q_{Lj} G_{\mu\nu}^a \,,$$
$$O_{uG}^{ij} = \bar{u}_{Ri}\lambda^a \gamma^\mu D^\nu u_{Rj} G_{\mu\nu}^a \,.$$

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$$O_{uG\phi}^{ij} = (\bar{q}_{Li}\lambda^a \sigma^{\mu\nu} u_{Rj})\tilde{\phi}\, G_{\mu\nu}^a\,,$$

REDUNDANT

$$O_{qG}^{ij} = \bar{q}_{Li}\lambda^a \gamma^\mu D^\nu q_{Lj} G_{\mu\nu}^a\,,$$
$$O_{uG}^{ij} = \bar{u}_{Ri}\lambda^a \gamma^\mu D^\nu u_{Rj} G_{\mu\nu}^a\,.$$

Dim-6 operators - Higgs

The operators that contribute to the $H - f - f'$ interaction are

$$O_{u\phi}^{ij} = (\phi^\dagger \phi)(\bar{q}_{Li} u_{Rj} \tilde{\phi}) \,,$$
$$O_{\phi q}^{(3,ij)} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}_{Li} \gamma^\mu \tau^I q_{Lj}) \,,$$
$$O_{\phi q}^{(1,ij)} = i(\phi^\dagger D_\mu \phi)(\bar{q}_{Li} \gamma^\mu q_{Lj}) \,,$$
$$O_{\phi u}^{ij} = i(\phi^\dagger D_\mu \phi)(\bar{u}_{Ri} \gamma^\mu u_{Rj}) \,,$$

The last 3 can be decomposed in $i + j$ and $i - j$ ($i < j$) components

J. A. Aguilar-Saavedra, Nucl. Phys. B **821**, 215 (2009) [0904.2387]

$$O_{\phi q}^{(3,i+j)} \equiv \frac{1}{2}\left[O_{\phi q}^{(3,ij)} + (O_{\phi q}^{(3,ji)})^\dagger\right] \,, \qquad O_{\phi q}^{(3,i-j)} \equiv \frac{1}{2}\left[O_{\phi q}^{(3,ij)} - (O_{\phi q}^{(3,ji)})^\dagger\right] \,,$$
$$O_{\phi q}^{(1,i+j)} \equiv \frac{1}{2}\left[O_{\phi q}^{(1,ij)} + (O_{\phi q}^{(1,ji)})^\dagger\right] \,, \qquad O_{\phi q}^{(1,i-j)} \equiv \frac{1}{2}\left[O_{\phi q}^{(1,ij)} - (O_{\phi q}^{(1,ji)})^\dagger\right] \,,$$
$$O_{\phi u}^{i+j} \equiv \frac{1}{2}\left[O_{\phi u}^{ij} + (O_{\phi u}^{ji})^\dagger\right] \,, \qquad O_{\phi u}^{i-j} \equiv \frac{1}{2}\left[O_{\phi u}^{ij} - (O_{\phi u}^{ji})^\dagger\right] \,.$$

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~~$O_{\phi q}^{(1,i-j)} \equiv \frac{1}{2}\left[O_{\phi q}^{(1,ij)} - (O_{\phi q}^{(1,ji)})^\dagger\right] ,$~~

~~$O_{\phi u}^{i-j} \equiv \frac{1}{2}\left[O_{\phi u}^{ij} - (O_{\phi u}^{ji})^\dagger\right] .$~~

This shift affects the relation of some of the dim-6 EW operators on the previous slide

Effective Lagrangian

Dim-6 operators can be simplified by means of e.o.m and equalities, both for on- and off-shell particles. Equivalent interaction Lagrangian, with scalar, γ^μ and $\sigma^{\mu\nu}$ terms only, can be written J. A. Aguilar-Saavedra, 0811.3842 and 0904.2387

$$
\begin{aligned}
\mathcal{L} \;=\; & -\sum_{q=u,c}\Big[g_s\,\frac{\kappa_{gqt}}{\Lambda}\,\bar{t}\,\sigma^{\mu\nu}\,T_a\big(f^L_{Gq}P_L + f^R_{Gq}P_R\big)\,q\,G^a_{\mu\nu} \\
& + \frac{g}{\sqrt{2}c_W}\,\frac{\kappa_{zqt}}{\Lambda}\,\bar{t}\sigma^{\mu\nu}\,\big(f^L_{Zq}P_L + f^R_{Zq}P_R\big)\,q\,Z_{\mu\nu} \\
& + \frac{g}{4c_W}\,\zeta_{zqt}\,\bar{t}\,\gamma^\mu\,\big(f^L_{Zq}P_L + f^R_{Zq}P_R\big)\,q\,Z_\mu \\
& + e\,\frac{\kappa_{\gamma qt}}{\Lambda}\,\bar{t}\,\sigma^{\mu\nu}\,\big(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R\big)\,q\,A_{\mu\nu} \\
& + \frac{1}{\sqrt{2}}\bar{t}\,\kappa_{Hqt}\,\big(f^L_{Hq}P_L + f^R_{Hq}P_R\big)\,q\,H\Big] + \mathrm{h.c}
\end{aligned}
$$

$q = t$ $\Rightarrow$ top anomalous couplings: ttZ, $tt\gamma$, ttg, ttH
$q = u/c$ $\Rightarrow$ top FCNC: ztq, γtq, gtq, Htq
Validity: OK for production of SM bosons both on- and off-shell
Limitation: Heavy particles only in loops $\Rightarrow$ No 4f operators

Partial widths and NLO

J. J. Zhang et al., Phys. Rev. D **82**, 073005 (2010) [1004.0898]

Top-quark partial widths $\forall q = u,\, c$ ($\Gamma_{tot} = \Gamma_1 + \Gamma_{mix}$)

$\Gamma(t \to qV/S)$ (MeV) / 0.1 TeV^{-1}	Γ_0	Γ_1	Γ_{tot}	Γ_1/Γ_0	Γ_{tot}/Γ_0
$\Gamma(t \to qg)$ (via κ_{gqt})	3.61	3.94	-	1.09	-
$\Gamma(t \to q\gamma)$ (via $\kappa_{\gamma qt}$)	0.20	0.18	0.16	0.91	0.82
$\Gamma(t \to qZ)$ (via κ_{Zqt})	0.163	0.148	0.153	0.91	0.94

QCD NLO: enhance $\Gamma(t \to qg)$ by $\mathcal{O}(10\%)$, reduce $\Gamma(t \to qZ/\gamma)$ by same amount. On top, operator mixing can change partial top-quark partial widths by another $\mathcal{O}(10\%)$.

The QCD NLO correction to $\Gamma(t \to qH)$ has been recently evaluated

C. Zhang et al. Phys. Rev. D **88**, 054005 (2013) [1305.7386]

$$\frac{\alpha_s \Gamma_1}{\Gamma_0} = 0.018 - 0.049 \frac{C_{uG}}{C_{u\varphi}}$$

Enhance $\Gamma(t \to qH)$ by $\mathcal{O}(2\%)$, but could be $\mathcal{O}(10\%)$ due to operator mixing.

REVIEW OF ANOMALOUS COUPLINGS

Wtb anomalous coupling

J. A. Aguilar-Saavedra et al. Eur. Phys. J. C **50**, 519 (2007) [hep-ph/0605190]

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \mathrm{H.c.}$$

with

$$\delta V_L = C_{\phi q}^{(3,3+3)*}\frac{v^2}{\Lambda^2} \qquad \delta g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}$$

$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2} \qquad \delta g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

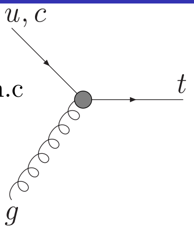
In the SM, $V_L = V_{tb} \simeq 1$ and $V_R = g_L = g_R = 0$. Non-zero V_R, g_L, g_R would alter the W helicity from the top decay:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\ell}^{*}} = \frac{3}{8}(1+\cos\theta_{\ell}^{*})^2\,F_L + \frac{3}{8}(1-\cos\theta_{\ell}^{*})^2\,F_R + \frac{3}{4}\sin^2\theta_{\ell}^{*}\,F_0$$

SM	F_L	F_R	F_0
LO	0.297	$3.6\,10^{-4}$	0.703
NLO	0.304	0.001	0.695

gqt anomalous coupling: $pp \to t$

$$\mathcal{L} = -\sum_{q=u,c}\left[\sqrt{2}\, g_s\, \frac{\kappa_{gqt}}{\Lambda}\, \bar{t}\,\sigma^{\mu\nu}\, T_a \left(f^L_{Gq} P_L + f^R_{Gq} P_R\right) q\, G^a_{\mu\nu}\right] + \text{h.c}$$



with $(u:\ i=1,\ c:\ i=2)$

$$\frac{\kappa_{gqt}}{\Lambda} f^L_{Gq} = \frac{2}{g_s} C^{3i*}_{uG\phi} \frac{v m_t}{\Lambda^2}$$

$$\frac{\kappa_{gqt}}{\Lambda} f^R_{Gq} = \frac{2}{g_s} C^{i3}_{uG\phi} \frac{v m_t}{\Lambda^2}$$

$\sigma(pb)/0.1$ TeV^{-1}	κ_{gct}	κ_{gut}
$pp \to t$	86.7	398
$pp \to t\gamma$ (*)	1.3	6.8
$pp \to th$	0.064	0.49
$pp \to t\ell\ell$ (**)	0.030	0.33
$pp \to t\nu\nu$	0.052	0.59

These couplings enter into any single-top process at the LHC. This topology though is the most sensitive: if coupling non zero, it will be seen here

NLO: MEtop generator can generate events with "matched effective NLO-QCD" precision (soft/collinear approx.): k-factors? 1303.5485

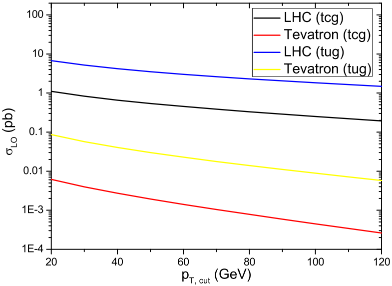
gqt anomalous coupling: $pp \to tj$

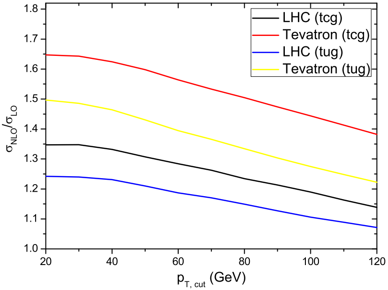
The gqt anomalous coupling can also affect the single-top + jet production

J. Gao et al. Phys. Rev. D **80**, 114017 (2009) [0910.4349]

Inclusive cross sections

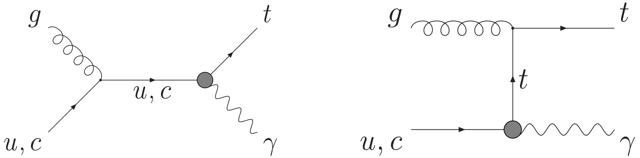
FCNC coupling	tug (LO)	tug (NLO)	tcg (LO)	tcg (NLO)
LHC $(\frac{\kappa/\Lambda}{0.01\mathrm{TeV}^{-1}})^2$ pb	6.77	8.41	1.10	1.49





LO cross sections and NLO k-factor as a function of the jet p_T cut

γqt anomalous coupling: $pp \to t\,\gamma$



$$\mathcal{L} = -\sum_{q=u,c}\left[e\,\frac{\kappa_{\gamma qt}}{\Lambda}\,\bar{t}\,\sigma^{\mu\nu}\left(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R\right)q\,A_{\mu\nu}\right] + \text{h.c}$$

with $(u:\ i=1,\, c:\ i=2)$

$$\frac{\kappa_{\gamma qt}}{\Lambda}f^L_{\gamma q} = \frac{1}{e}\left[s_W C^{3i*}_{uW} + c_W C^{3i*}_{uB\phi}\right]\frac{v m_t}{\Lambda^2}$$

$$\frac{\kappa_{\gamma qt}}{\Lambda}f^R_{\gamma q} = \frac{1}{e}\left[s_W C^{i3}_{uW} + c_W C^{i3}_{uB\phi}\right]\frac{v m_t}{\Lambda^2}$$

$\sigma(fb)/0.1$ TeV^{-1}	κ_{gct}	κ_{gut}	$\kappa_{\gamma ct}$	$\kappa_{\gamma ut}$
$pp \to t\gamma$ (*)	1300	6800	19	150
$pp \to t\ell\ell$ $(**)$	30	330	0.27	2.3

(*) $p_T(\gamma) > 1$ GeV; $(**)$ $M(\ell\ell) > 10$ GeV

Selecting a real photon in the final state can single out this coupling

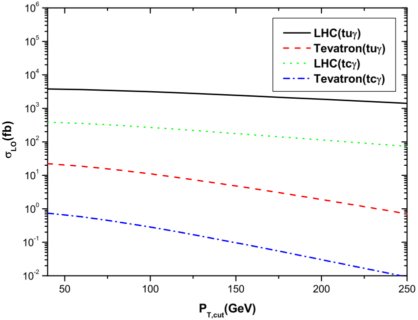
γqt anomalous coupling: $pp \to t\,\gamma$ @ NLO

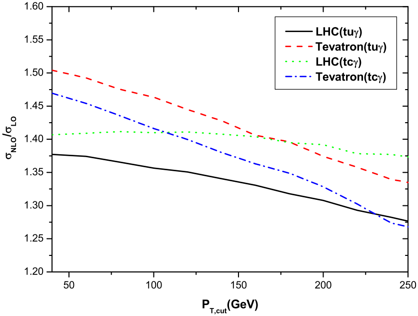
Cross sections for $pp \to t\,\gamma$ have been evaluated at NLO (for γqt only)

Y. Zhang et al. Phys. Rev. D **83**, 094003 (2011) [1101.5346]

Inclusive cross sections with $p_T^\gamma > 40\mathrm{GeV}$ and $|\eta^\gamma| < 2.5$

FCNC coupling	$tu\gamma$ (LO)	$tu\gamma$ (NLO)	$tc\gamma$ (LO)	$tc\gamma$ (NLO)
LHC $(\frac{\kappa/\Lambda}{0.3\mathrm{TeV}^{-1}})^2$ pb	3.78	5.16	0.386	0.537





LO cross sections and NLO k-factor as a function of the photon p_T cut

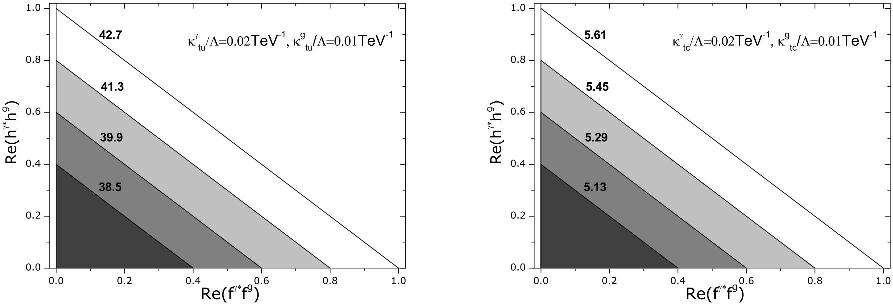
Mixing in $pp \to t\,\gamma$ @ NLO

The gqt and γqt anomalous couplings can mix and affect $\sigma(pp \to t\,\gamma)$

Y. Zhang et al. Phys. Rev. D **83**, 094003 (2011) [1101.5346]

Inclusive cross section with mixing (for $Re(g_{gL}g^*_{ZL}) = Re(g_{gR}g^*_{ZR}) = 1$)

FCNC coupling	tuV (LO)	tuV (NLO)	tcV (LO)	tcV (NLO)
LHC $\left(\frac{\kappa/\Lambda}{0.01\mathrm{TeV}^{-1}}\right)^2$ fb	27.8	42.7	3.13	5.61



$f\,(h)$ are the vector(axial) couplings

zqt anomalous couplings: $pp \to t+$ MET

$$\mathcal{L} = -\sum_{q=u,c}\Big[\frac{g}{\sqrt{2}c_W}\frac{\kappa_{zqt}}{\Lambda}\,\bar{t}\sigma^{\mu\nu}\left(f^L_{Zq}P_L + f^R_{Zq}P_R\right) q\, Z_{\mu\nu}$$
$$+ \frac{g}{4c_W}\,\zeta_{zqt}\,\bar{t}\,\gamma^\mu\left(f'^L_{Zq}P_L + f'^R_{Zq}P_R\right) q\, Z_\mu\Big] + \text{h.c}$$

Via $pp \to t\,Z$ with $Z \to \nu\nu$. LO cross sections

$\sigma(fb)/0.1$ TeV^{-1}	κ_{gct}	κ_{gut}	κ_{zct}	κ_{zut}	ζ_{zct}	ζ_{zut}
$pp \to t\nu\nu$	52	593	4.1	34	21	149

Cross section at NLO (for undecayed Z) from B. H. Li et al. Phys. Rev. D **83**, 114049 (2011) [1103.5122]

FCNC coupling	tuZ (LO)	tuZ (NLO)	tcZ (LO)	tcZ (NLO)
LHC $(\frac{\kappa/\Lambda}{0.01\text{TeV}^{-1}})^2$ (fb)	6.4	9.0	0.5	0.7
	tug (LO)	tug (NLO)	tcg (LO)	tcg (NLO)
LHC $(\frac{\kappa/\Lambda}{0.01\text{TeV}^{-1}})^2$ (fb)	141	180	7.6	10.8
	tuV (LO)	tuV (NLO)	tcV (LO)	tcV (NLO)
LHC $(\frac{\kappa/\Lambda}{0.01\text{TeV}^{-1}})^2$ (fb)	147	188	8.1	11.5

zqt vs γqt

Relation of zqt couplings to Dim-6 ones, with $(u: \; i=1, \, c: \; i=2)$

$$\zeta_{zqt}\, f'^{L}_{Zq} = \left[C^{(3,i+3)}_{\phi q} - C^{(1,i+3)}_{\phi q}\right] \frac{v^2}{\Lambda^2}$$

$$\zeta_{zqt}\, f'^{R}_{Zq} = -\left[C^{i+3}_{\phi u}\right] \frac{v^2}{\Lambda^2}$$

$$\frac{\kappa_{zqt}}{\Lambda} f^{L}_{\gamma q} = \left[c_W C^{3i*}_{uW} - s_W C^{3i*}_{uB\phi}\right] \frac{v^2}{\Lambda^2}$$

$$\frac{\kappa_{zqt}}{\Lambda} f^{R}_{\gamma q} = \left[c_W C^{i3}_{uW} - s_W C^{i3}_{uB\phi}\right] \frac{v^2}{\Lambda^2}$$

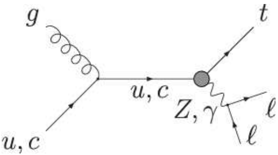
Recall $\kappa_{\gamma qt}$:

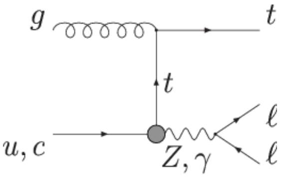
$$\frac{\kappa_{\gamma qt}}{\Lambda} f^{L}_{\gamma q} = \frac{1}{e}\left[s_W C^{3i*}_{uW} + c_W C^{3i*}_{uB\phi}\right] \frac{v m_t}{\Lambda^2}$$

$$\frac{\kappa_{\gamma qt}}{\Lambda} f^{R}_{\gamma q} = \frac{1}{e}\left[s_W C^{i3}_{uW} + c_W C^{i3}_{uB\phi}\right] \frac{v m_t}{\Lambda^2}$$

At LO, they are independent. $pp \to t\,\gamma$ and $pp \to t\,Z$ can be combined to reconstruct the Dim-6 operators

γqt–zqt anomalous couplings: $pp \to t\,\ell^+\,\ell^-$ $(\ell = e,\ \mu,\ \tau)$





$$
\begin{aligned}
\mathcal{L} \;=\; & -\sum_{q=u,c}\Bigg[\frac{g}{\sqrt{2}c_W}\frac{\kappa_{zqt}}{\Lambda}\,\bar{t}\sigma^{\mu\nu}\left(f^L_{Zq}P_L + f^R_{Zq}P_R\right) q\, Z_{\mu\nu} \\
& + \frac{g}{4c_W}\,\zeta_{zqt}\,\bar{t}\,\gamma^{\mu}\left(f'^L_{Zq}P_L + f'^R_{Zq}P_R\right) q\, Z_{\mu} \\
& + e\,\frac{\kappa_{\gamma qt}}{\Lambda}\,\bar{t}\,\sigma^{\mu\nu}\left(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R\right) q\, A_{\mu\nu}\Bigg] + \text{h.c}
\end{aligned}
$$

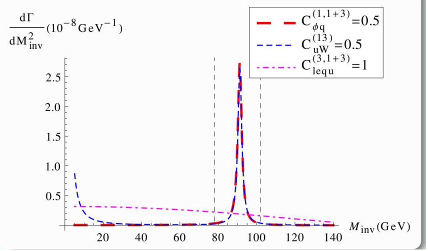
$\sigma(pb)(fb)/0.1$ TeV^{-1}	K_{gct}	K_{gut}	$K_{\gamma ct}$	$K_{\gamma ut}$	K_{zct}	K_{zut}	ζ_{zct}	ζ_{zut}
$pp \to t\ell\ell$ (**)	30	330	0.27	2.3	2.0	17	10	75

(**) $M(\ell\ell) > 10$ GeV

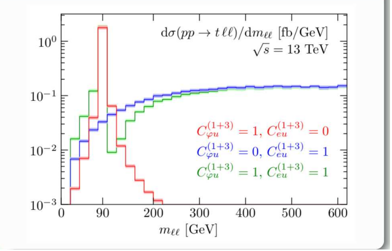
So far, photon and Z in the final state (either on- or -off shell).
However, new bosons could also give similar final state (i.e. FCN Z').
If heavy, their interactions can be contracted and give rise to 4-fermion operators, which are not included here.

C. Zhang, TOP 2014

Lepton pair inv. mass distribution in $t \to ull$:

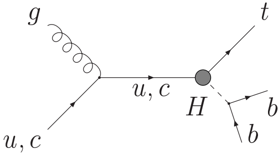


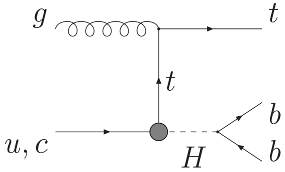
$pp \to tll$ 13 tev, nlo+ps (preliminary)



Here, C_{eu} is 4f coupling: small but non-negligible around Z peak, dominant outside

Hqt anomalous couplings: $pp \to t\,H$





$$\mathcal{L} = \sum_{q=u,c} \frac{1}{\sqrt{2}} \left[\bar{t}\, \kappa_{Hqt} \left(f^L_{Hq} P_L + f^R_{Hq} P_R \right) q\, H \right] + \text{h.c}$$

with $(u:\ i=1,\ c:\ i=2)$

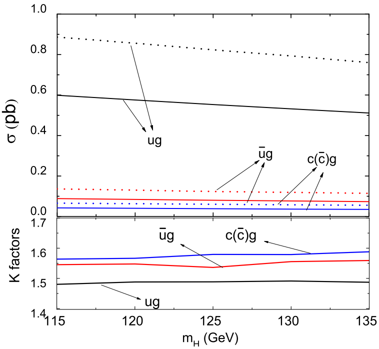
$$\frac{\kappa_{Hqt}}{\Lambda} f^L_{Hq} = \frac{3}{2} C^{3i*}_{u\varphi} \frac{v^2}{\Lambda^2}$$

$$\frac{\kappa_{Hqt}}{\Lambda} f^R_{Hq} = \frac{3}{2} C^{i3}_{u\varphi} \frac{v^2}{\Lambda^2}$$

$\sigma(fb)/1$ (TeV^{-1})	κ_{gct}	κ_{gut}	κ_{Hct}	κ_{Hut}
$pp \to tH$	6.4	49	9.2	74

Hqt anomalous couplings: $pp \to t\,b\bar{b}$ @ NLO

Y. Wang et al. Phys. Rev. D **86**, 094014 (2012) [1208.2902]



Cross sections after cuts:

$M_H = 125$ GeV	σ_{LO} [fb]	K_{pro}	K_{tot}
$\kappa_{Hut} = 0.2$	6.64	1.22	1.11
$\kappa_{Hct} = 0.2$	0.428	1.40	1.00

K_{pro}: NLO QCD k-factor only for production

K_{tot}: k-factor also including NLO QCD correction to decay

However, $O^{ij}_{uG\phi} = (\bar{q}_{Li}\lambda^a\sigma^{\mu\nu}u_{Rj})\tilde{\phi}\,G^a_{\mu\nu}$ gives $Htqg$ vertex: to be included in QCD real corrections!

Conclusions

- LO couplings: reduced number of independent operator: minimal set of independent couplings in effective Lagrangian
- EFT: NLO mix couplins $\Rightarrow$ “one-coupling-at-a-time” not justified
- However, not all signatures are equally sensitive. If non-zero, some couplings will appear sooner than others
- gqt at LHC appears in all signature, and mix with all couplings
- Global fit desirable, but what could be done meanwhile?
- gqt will be seen first in top-alone final state.
- If a signal in any other final state is observed, but not in top-alone, then gqt negligible
- 4f operators. To be included in $t \to q\ell\ell$, small contamination at Z peak. Account as sistematic error in zqt exclusion?
- Regarding Higgs, $Htqg$ to be included in signal when at NLO or $+1j$ (Notice: it is not the case for all other couplings, all $Vtqg$ are reabsorbed in Effective Lagrangian)

Thank You