Contributions from flavour changing effective operators to the physics of the top quark at LHC

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TOP 2006, 12/1/06

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Outline

- Effective operator formalism.
- Operator set chosen.
- Processes of single top production at LHC via FCNC's.
- Cross section expressions.

- New physics "generated" in extensions of the standard model would manifest itself at lower energy scales in the form of effective operators of dimension superior to 4.

- Complete list of dimension 5 and 6 effective operators: Buchmüller e Wyler, *Nucl. Phys.* B268 (1986) 621.

- Dimension 5 operators violate baryon/lepton number.

Dimension 6 operators: a great many of them….

We are interested in processes of single top production via flavour changing neutral currents (FCNC's) at the LHC.

EFFECTIVE OPERATOR FORMALISM

$$\mathcal{L} = \mathcal{L}^{SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

All terms are invariant under the SM gauge group; ☹ is the energy scale of new physics.

To select among the many dimension 6 terms, we employed some physical selection criteria:

- The operators must contribute to FCNC's involving the top quark and the strong interaction, with impact on single top production.

- They must not have sizeable contributions to physics below the TeV scale, so as to not ruin the successful predictions of the SM.

- Try to expand on the many works already done in this area.

Some references of previous work in this field:

T. Han, K. Whisnant, B.L. Young and X. Zhang, *Phys. Lett.* **B385** (1996) 311;

T. Han, M. Hosch, K. Whisnant, B.L. Young and X. Zhang, *Phys. Rev.* **D55** (1997) 7241;

K. Whisnant, J.M. Yang, B.L. Young and X. Zhang, *Phys. Rev.* **D56** (1997) 467;

M. Hosch, K. Whisnant and B.L. Young, *Phys. Rev.* **D56** (1997) 5725;

T. Han, M. Hosch, K. Whisnant, B.L. Young and X. Zhang, *Phys. Rev.* **D58** (1998) 073008;

K. Hikasa, K. Whisnant, J.M. Yang and B.L. Young, *Phys. Rev.* **D58** (1998) 114003.

F. del Àguila and J.A. Aguilar-Saavedra, *Phys. Rev.* **D67** (2003) 014009.

T. Tait and C. P. Yuan, *Phys. Rev.* **D63**, (2001) 014018;

D. O. Carlson, E. Malkawi, and C. P. Yuan, *Phys. Lett.* **B337**, (1994) 145;

G. L. Kane, G. A. Ladinsky, and C. P. Yuan, *Phys. Rev.* **D45**, (1992) 124;

T. G. Rizzo, *Phys. Rev.* **D53**, (1996) 6218;

T. Tait and C. P. Yuan, *Phys. Rev.* **D55**, (1997) 7300;

A. Datta and X. Zhang, *Phys. Rev.* **D55**, (1997) 2530;

E. Boos, L. Dudko, and T. Ohl, *Eur. Phys. J.* **C11**, (1999) 473;

D. Espriu and J. Manzano, *Phys. Rev.* **D65**, (2002) 073005.

DIMENSION SIX TOP-GLUON OPERATORS

The dimension six operators that survive our criteria are only two,

$$\mathcal{O}_{uG} = \; i\,\frac{\alpha_{ij}}{\Lambda^2}\left(\bar{u}^i_R\,\lambda^a\,\gamma^\mu\,D^\nu\,u^j_R\right)G^a_{\mu\nu}$$

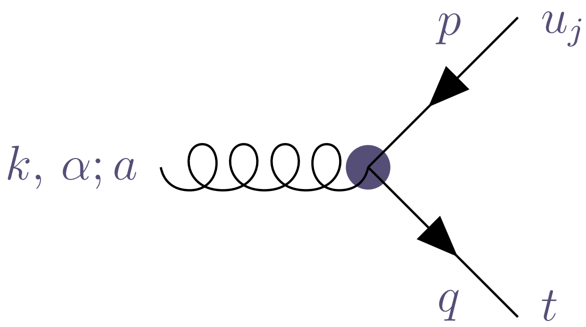
$$\mathcal{O}_{uG\phi} = \; \frac{\beta_{ij}}{\Lambda^2}\left(\bar{q}^i_L\,\lambda^a\,\sigma^{\mu\nu}\,u^j_R\right)\tilde{\phi}\,G^a_{\mu\nu} \quad .$$

and after spontaneous symmetry breaking, we are left with a lagrangean for new physics given by

$$\begin{aligned}\mathcal{L} \;&=\; \alpha_{tu}\,\mathcal{O}_{tu} + \alpha_{ut}\,\mathcal{O}_{ut} + \beta_{tu}\,\mathcal{O}_{tu\phi} + \beta_{ut}\,\mathcal{O}_{ut\phi} + \text{h.c.}\\ &=\; \frac{i}{\Lambda^2}\left[\alpha_{tu}\,(\bar{t}_R\,\lambda^a\,\gamma^\mu\,D^\nu\,u_R) + \alpha_{ut}\,(\bar{u}_R\,\lambda^a\,\gamma^\mu\,D^\nu\,t_R)\right]G^a_{\mu\nu} \;+\\ &\quad\; \frac{v}{\Lambda^2}\left[\beta_{tu}\,(\bar{t}_L\,\lambda^a\,\sigma^{\mu\nu}\,u_R) + \beta_{ut}\,(\bar{u}_L\,\lambda^a\,\sigma^{\mu\nu}\,t_R)\right]G^a_{\mu\nu} \;+\; \text{h.c.}\end{aligned}$$

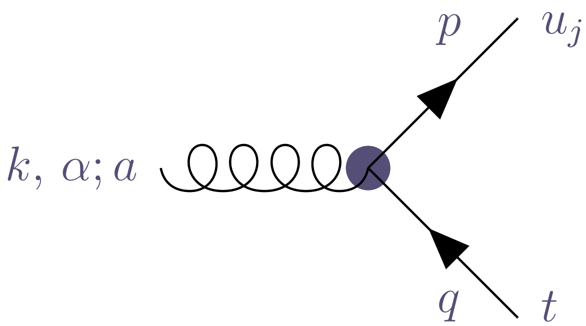
CHROMOMAGNETIC MOMENTUM OPERATORS

This lagrangean generates new vertices, namely



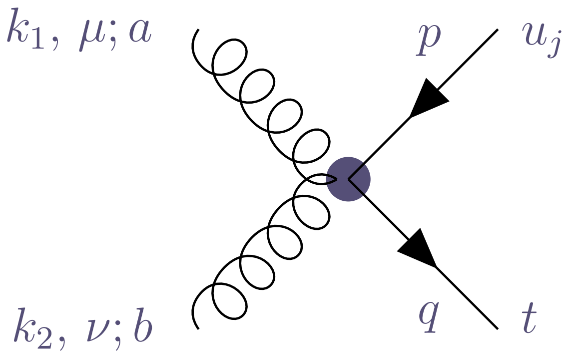
$$\frac{\lambda^a}{\Lambda^2}\left[\gamma_\mu\gamma_R(\alpha_{tj}p_\nu + \alpha^*_{jt}q_\nu) + v\,\sigma_{\mu\nu}\left(\beta_{tj}\gamma_R + \beta^*_{jt}\gamma_L\right)\right]$$

$$(k^\mu\, g^{\nu\alpha} - k^\nu\, g^{\mu\alpha})$$



$$\frac{\lambda^a}{\Lambda^2}\left[\gamma_\mu\gamma_R(\alpha_{jt}p_\nu + \alpha^*_{tj}q_\nu) + v\,\sigma_{\mu\nu}\left(\beta_{jt}\gamma_R + \beta^*_{tj}\gamma_L\right)\right]$$

$$(k^\mu\, g^{\nu\alpha} - k^\nu\, g^{\mu\alpha})$$



$$\frac{i\,g_s}{\Lambda^2}\Big[\lambda^c\, f_{abc}\Big\{\gamma_\mu\gamma_R(-\alpha_{tj}p_\nu + \alpha^*_{jt}q_\nu) + \gamma_\nu\gamma_R(\alpha_{tj}p_\mu - \alpha^*_{jt}q_\mu)$$

$$+2v\,\sigma_{\mu\nu}\left(\beta_{jt}\gamma_R + \beta^*_{tj}\gamma_L\right)\Big\}\Big] +$$

$$\frac{g_s}{2\Lambda^2}\Big[(\not{k}_1 g_{\mu\nu} - k_{1\nu}\gamma_\mu)\,\gamma_R\,\Big(\lambda_a\lambda_b\alpha_{tj} + \lambda_b\lambda_a\alpha^*_{jt}\Big) +$$

$$(\not{k}_2 g_{\mu\nu} - k_{2\nu}\gamma_\mu)\,\gamma_R\,\Big(\lambda_b\lambda_a\alpha_{tj} + \lambda_a\lambda_b\alpha^*_{jt}\Big)\Big]$$

Four-fermion operators

These operators are not independent; using the full gauge invariance of the theory, we may apply the fermion equations of motion and obtain the following relations:

$$\mathcal{O}^{\dagger}_{ut} = \mathcal{O}_{tu} - \frac{i}{2}(\Gamma^{\dagger}_{u}\,\mathcal{O}^{\dagger}_{ut\phi} + \Gamma_{u}\,\mathcal{O}_{tu\phi})$$

$$\mathcal{O}^{\dagger}_{ut} = \mathcal{O}_{tu} - i\,g_s\,\bar{t}\,\gamma_{\mu}\,\gamma_R\,\lambda^a\,u\,\sum_i(\bar{u}^i\,\gamma^{\mu}\,\gamma_R\,\lambda_a u^i + \bar{d}^i\,\gamma^{\mu}\,\gamma_R\,\lambda_a\,d^i)$$

four-fermion contact terms

These relations tell us that, as long as we include the four-fermion operators, we have TWO relations between the operators and can therefore set TWO coupling constant to ZERO.

We will consider THREE different types of four-fermion terms:

Type 1 : $$\mathcal{O}_{u_1} = \frac{g_s\,\gamma_{u_1}}{\Lambda^2}\,(\bar{t}\,\lambda^a\,\gamma^\mu\,\gamma_R\,u)\,(\bar{q}\,\lambda^a\,\gamma_\mu\,\gamma_R\,q)\;+\;\text{h.c.}$$

Type 2 : $$\mathcal{O}_{u_2} = \frac{g_s\,\gamma_{u_2}}{\Lambda^2}\left[(\bar{t}\,\lambda^a\,\gamma_L\,u')\,(\bar{u}''\,\lambda^a\,\gamma_R\,u)\;+\;(\bar{t}\,\lambda^a\,\gamma_L\,d')\,(\bar{d}''\,\lambda^a\,\gamma_R\,u)\right]\;+\;\text{h.c.}$$

Type 3 : $$\frac{g_s\,\gamma^*_{u_3}}{\Lambda^2}\left[(\bar{t}\,\lambda^a\,\gamma_L\,u)\,(\bar{d}'\,\lambda^a\,\gamma_L\,d'')\;-\;(\bar{t}\,\lambda^a\,\gamma_L\,d)\,(\bar{d}'\,\lambda^a\,\gamma_L\,u'')\right]\;+\;\text{h.c.}$$

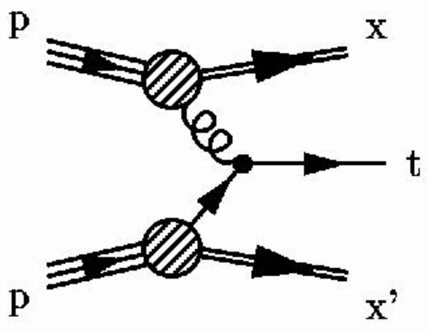
We also considered identical terms for the second generation (with couplings α_{ct} , β_{tc}, etc.)

These new vertices allow extra contributions for rare top decay channels, such as $t \to c\, g$ and $t \to u\, g$. The corresponding top width is given by

$$\Gamma(t \to ug) = \frac{m_t^3}{12\pi\Lambda^4}\left\{ m_t^2\, |\alpha_{ut} + \alpha_{tu}^*|^2 + 16\, v^2\, \left(|\beta_{tu}|^2 + |\beta_{ut}|^2\right) \right. +$$
$$\left. 8\, v\, m_t\, \mathrm{Im}\left[(\alpha_{ut} + \alpha_{tu}^*)\, \beta_{tu}\right] \right\}$$

(a similar expression for the width of the c-quark decay)

Direct top production



The new vertices allow for the production of a single top quark at the partonic level. The resulting cross section is very easy to obtain:

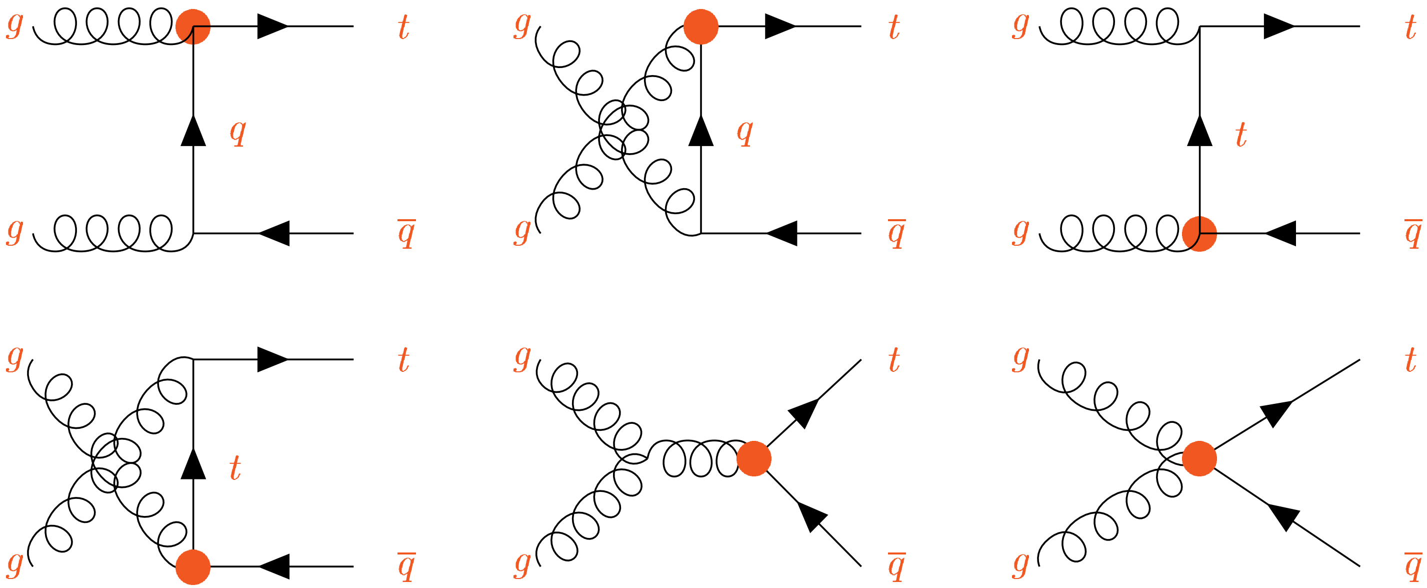
$$\sigma(pp \to t) = \sum_{q=u,c} \Gamma(t \to q\,g) \frac{\pi^2}{m_t^2} \int_{m_t^2/E_{CM}^2}^{1} \frac{2\,m_t}{E_{CM}^2\,x_1} f_g(x_1)\, f_q(m_t^2/(E_{CM}^2\,x_1))\, dx_1$$

IT IS PROPORTIONAL TO THE PARTIAL WIDTHS OF THE RARE DECAYS OF THE TOP QUARK.

After integration on the CTEQ6M parton density functions, we obtain

$$\sigma(pp \to g\,q \to t) = \left[10.51\, BR(t \to u\,g) + 1.70\, BR(t \to c\,g)\right] |V_{tb}|^2\; 10^4 \text{ pb}$$

Gluon-gluon fusion



The calculation is hellish, but the final result is remarkably simple:

$$\frac{d\,\sigma(g\,g \to t\,\bar{u})}{dt} = -\frac{g_s^2}{4\,m_t^3}\,\frac{F_{gg}}{u\,t\,s^3\,(s+t)^2\,(s+u)^2}\,\Gamma(t \to u\,g)$$

$$\frac{d\sigma(g\,g \to t\,\bar{u})}{dt} = -\frac{g_s^2}{4\,m_t^3}\,\frac{F_{gg}}{u\,t\,s^3\,(s+t)^2\,(s+u)^2}\,\Gamma(t \to u\,g)$$

with

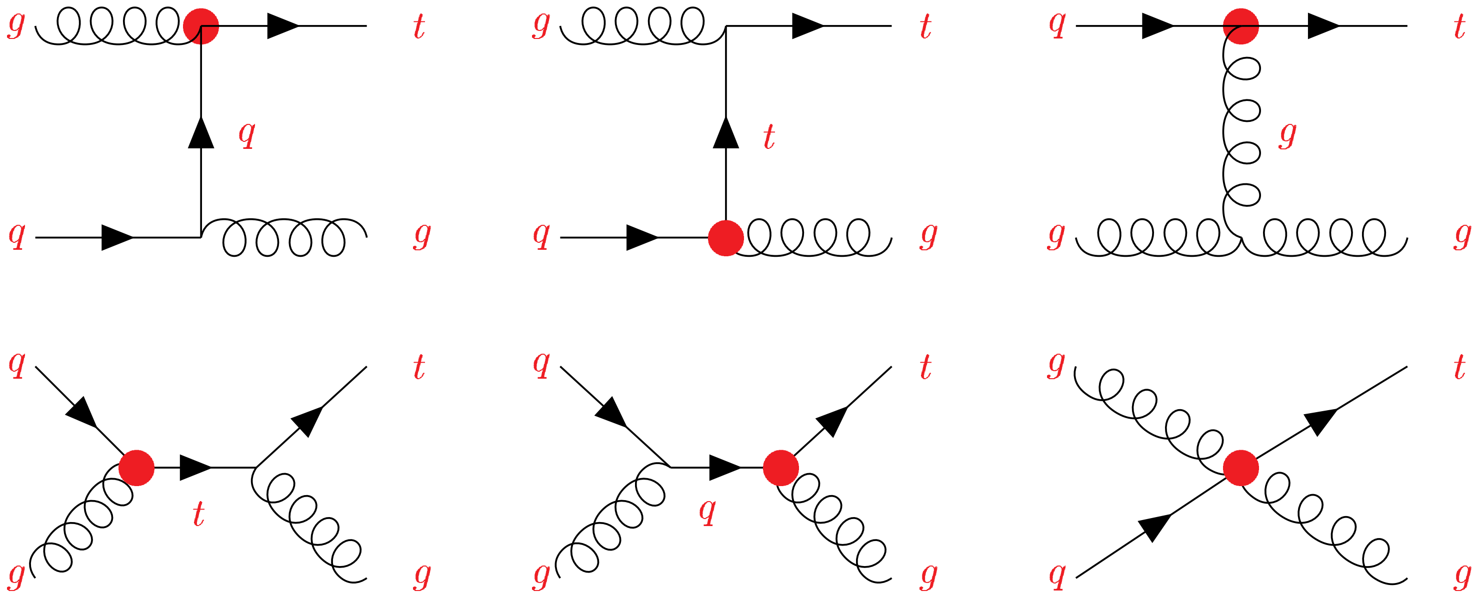
$$F_{gg} = 4\,s^2 t\,(s+t)^3\,(s^2+2\,s\,t+2\,t^2) + s\,(s+t)^2\,(4\,s^4+11\,s^3\,t+48\,s^2\,t^2+52\,s\,t^3+18\,t^4)\,u$$
$$+2\,(s+t)\,(10\,s^5+27\,s^4\,t+69\,s^3\,t^2+90\,s^2\,t^3+45\,s\,t^4+9\,t^5)\,u^2$$
$$+(s+t)\,(44\,s^4+115\,s^3\,t+203\,s^2\,t^2+162\,s\,t^3+36\,t^4)\,u^3$$
$$+2\,(26\,s^4+85\,s^3\,t+135\,s^2\,t^2+99\,s\,t^3+27\,t^4)\,u^4+4\,(2\,s+t)\,(4\,s^2+9\,s\,t+9\,t^2)\,u^5$$
$$+2\,(4\,s^2+9\,s\,t+9\,t^2)\,u^6$$

After PDF integration, we obtain

$$\sigma(p\,p \to g\,g \to t\,\bar{q}) = [0.98\,BR(t \to u\,g) + 0.98\,BR(t \to c\,g)]\,|V_{tb}|^2\,10^4\ \text{pb}$$

Again, the cross section is proportional to the branching ratios for the rare top decays.

Gluon-quark fusion



We obtain

$$\sigma(p\,p \to g\,q \to g\,t) = \left[43.98\,BR(t \to u\,g) + 6.78\,BR(t \to c\,g)\right] |V_{tb}|^2\ 10^4 \text{ pb}$$

DIRECT:

$$\sigma(pp \to gq \to t) = [10.51\, BR(t \to ug) + 1.70\, BR(t \to cg)]\, |V_{tb}|^2\, 10^4 \text{ pb}$$

GLUON-GLUON

$$\sigma(pp \to gq \to gt) = [43.98\, BR(t \to ug) + 6.78\, BR(t \to cg)]\, |V_{tb}|^2\, 10^4 \text{ pb}$$

GLUON-QUARK

$$\sigma(pp \to gq \to gt) = [43.98\, BR(t \to ug) + 6.78\, BR(t \to cg)]\, |V_{tb}|^2\, 10^4 \text{ pb}$$

- **In the SM, the branching ratio of $t \to c\,g$ is expected to be of the order of 10^{-10}.**

- **But in other models (2HDM, SUSY), that value may increase by as much as 4 orders of magnitude!**

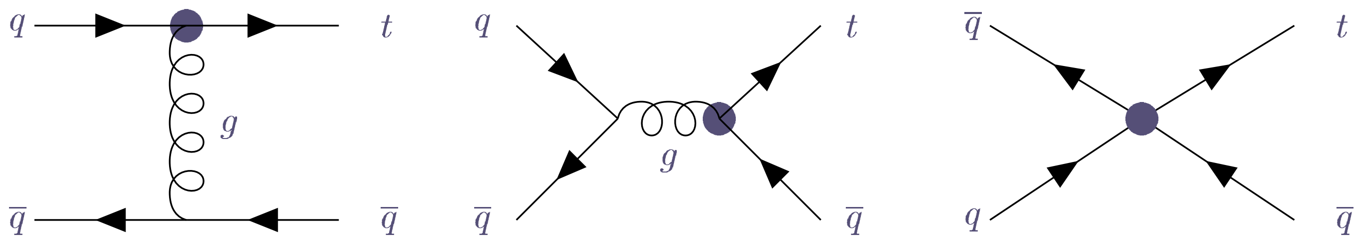
- **Single top production therefore seems a very good channel to search for new physics, because it is very sensitive to it.**

- **Even a small excess of single top production over the SM expected value might be interesting.**

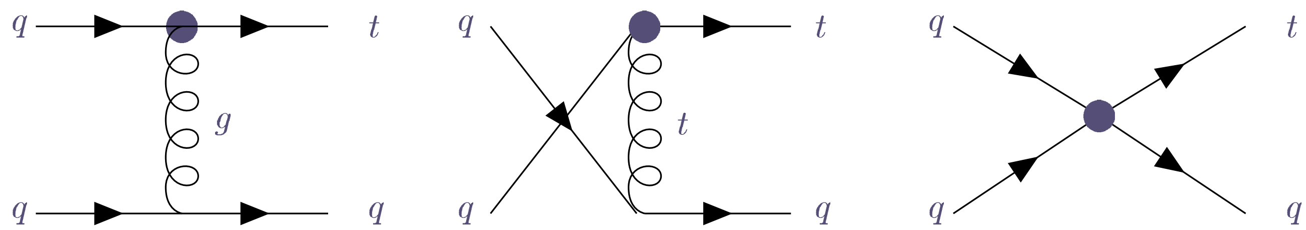
Four fermion channels

There are EIGHT possible channels of single top production, and interference terms between the gluonic operators and the four fermion channels. The resulting expressions are extremely complicated. The nice proportionality to the branching ratios is destroyed.

$$q\,\bar{q} \rightarrow t\,\bar{q}$$



$$q\,q \rightarrow t\,q$$



The result of the pdf integration for the u and c-quark four-fermion channels is given by:

$$\sigma_{4F}^{(u)} = \Big[190\,|\alpha_{ut}|^2 + 199\,|\alpha_{tu}|^2 - 153\,\mathrm{Re}(\alpha_{ut}\,\alpha_{tu}) + 429\,\mathrm{Im}(\alpha_{ut}\,\beta_{tu}) - 487\,\mathrm{Im}(\alpha_{tu}\,\beta_{tu}^*)$$
$$+ 846\,\left(|\beta_{tu}|^2 + |\beta_{ut}|^2\right) + 176\,\mathrm{Re}(\alpha_{ut}\,\gamma_{u_1}) - 184\,\mathrm{Re}(\alpha_{tu}\,\gamma_{u_1}^*) - 17\,\mathrm{Im}(\beta_{tu}\,\gamma_{u_1}^*)$$
$$- 6\,\mathrm{Re}(\alpha_{ut}\,\gamma_{u_2}) + 17\,\mathrm{Re}(\alpha_{tu}\,\gamma_{u_2}^*) + 0.7\,\mathrm{Im}(\beta_{tu}\,\gamma_{u_2}^*)$$
$$+ 524\,|\gamma_{u_1}|^2 + 94\,|\gamma_{u_2}|^2 + 88\,|\gamma_{u_3}|^2 \Big] \frac{1}{\Lambda^4}\ \mathrm{pb}$$

$$\sigma_{4F}^{(c)} = \Big[23\,|\alpha_{ct}|^2 + 22\,|\alpha_{tc}|^2 - 6\,\mathrm{Re}(\alpha_{ct}\,\alpha_{tc}) + 79\,\mathrm{Im}(\alpha_{ct}\,\beta_{tc}) - 79\,\mathrm{Im}(\alpha_{tc}\,\beta_{tc}^*)$$
$$+ 156\,\left(|\beta_{tc}|^2 + |\beta_{ct}|^2\right) + 41\,\mathrm{Re}(\alpha_{ct}\,\gamma_{c_1}) - 41\,\mathrm{Re}(\alpha_{tc}\,\gamma_{c_1}^*) - 0.3\,\mathrm{Im}(\beta_{tc}\,\gamma_{c_1}^*)$$
$$+ 3\,\mathrm{Re}(\alpha_{ct}\,\gamma_{c_2}) + 2\,\mathrm{Re}(\alpha_{tc}\,\gamma_{c_2}^*) - 0.5\,\mathrm{Im}(\beta_{tc}\,\gamma_{c_2}^*)$$
$$+ 95\,|\gamma_{c_1}|^2 + 24\,|\gamma_{c_2}|^2 + 27\,|\gamma_{c_3}|^2 \Big] \frac{1}{\Lambda^4}\ \mathrm{pb}$$

We can now use the equations of motion to simplify the results; we choose to set β_{ut} and γ_{c1} to zero. Summing all contributions for single top production, we obtain:

$$\sigma^{(u)}_{single\ t} = \Big[1884\,|\alpha_{ut}|^2 + 1893\,|\alpha_{tu}|^2 + 3235\,\mathrm{Re}(\alpha_{ut}\,\alpha_{tu}) + 27658\,|\beta_{ut}|^2$$
$$- 6\,\mathrm{Re}(\alpha_{ut}\,\gamma_{u_2}) + 17\,\mathrm{Re}(\alpha_{tu}\,\gamma^*_{u_2}) + 121\,|\gamma_{u_2}|^2 + 88\,|\gamma_{u_3}|^2 \Big] \frac{1}{\Lambda^4}\,\mathrm{pb}$$

$$\sigma^{(c)}_{single\ t} = \Big[310\,|\alpha_{ct}|^2 + 309\,|\alpha_{tc}|^2 + 568\,\mathrm{Re}(\alpha_{ct}\,\alpha_{tc}) + 4703\,|\beta_{ct}|^2$$
$$+ 3\,\mathrm{Re}(\alpha_{ct}\,\gamma_{c_2}) + 2\,\mathrm{Re}(\alpha_{tc}\,\gamma^*_{c_2}) + 24\,|\gamma_{c_2}|^2 + 27\,|\gamma_{c_3}|^2 \Big] \frac{1}{\Lambda^4}\,\mathrm{pb}$$

For anti top production, the results are:

$$\sigma^{(u)}_{single\ \bar{t}} = \Big[498\,|\alpha_{ut}|^2 + 498,|\alpha_{tu}|^2 + 912\,\mathrm{Re}(\alpha_{ut}\,\alpha_{tu}) + 7539\,|\beta_{ut}|^2$$
$$- 1.4\,\mathrm{Re}(\alpha_{ut}\,\gamma_{u_2}) + 2.9\,\mathrm{Re}(\alpha_{tu}\,\gamma^*_{u_2}) + 26\,|\gamma_{u_2}|^2 + 35\,|\gamma_{u_3}|^2 \Big] \frac{1}{\Lambda^4}\,\mathrm{pb}$$

$$\sigma^{(c)}_{single\ \bar{t}} = \Big[310\,|\alpha_{ct}|^2 + 309\,|\alpha_{tc}|^2 + 568\,\mathrm{Re}(\alpha_{ct}\,\alpha_{tc}) + 4703\,|\beta_{ct}|^2$$
$$+ 3\,\mathrm{Re}(\alpha_{ct}\,\gamma_{c_2}) + 2\,\mathrm{Re}(\alpha_{tc}\,\gamma^*_{c_2}) + 24\,|\gamma_{c_2}|^2 + 27\,|\gamma_{c_3}|^2 \Big] \frac{1}{\Lambda^4}\,\mathrm{pb}$$

Conclusions

- We used a very general dimension six operator set to compute anomalous ocntributions for single top production cross sections at the LHC.

- The fact that we worked in a fully gauge-invariant manner allowed us to simplify the results by eliminating two of the new couplings.

- The cross sections for the purely gluonic channels are proportional to the branching ratios of the rare FCNC decays of the top. These are allowed even in the SM, but are expected to be much more favoured in more general models.

- The four-fermion contributions spoil the nice proportionality to the branching ratio – but also liberate us from its bounds. Even if the top rare decays are according to the SM, the terms in γ_2 and γ_3 might give sizeable contributions to the cross sections.

- Full detector simulations are needed to study the possibility of observing these processes in a realistic manner…