Contributions from dimension five and six effective operators to flavour changing top physics

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Flavour in the era of the LHC, 10/10/06

P.M. Ferreira, R. Santos , **Physical Review D74, 014006 (2006)**

P.M. Ferreira, R. Santos , **Physical Review D73, 054025 (2006)**

P.M. Ferreira, O. Oliveira , R. Santos , **Physical Review D73, 034011 (2006)**

Outline

- Effective operator formalism.
- Operator set chosen.
- Processes of single top production at LHC via FCNC's.
- Cross section expressions.
- Consequences for other processes of top production at LHC.
- Implementation at TopRex.

- 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 top quark 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; Λ 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,

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

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

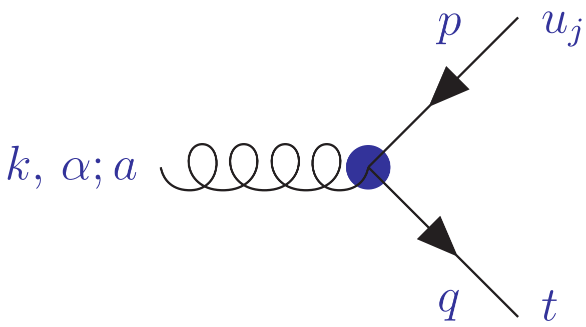
and after spontaneous symmetry breaking, we are left with a lagrangean for new physics given by

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

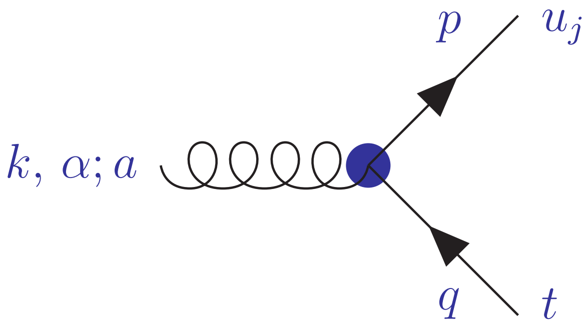
↑ ↑

CHROMOMAGNETIC MOMENTUM OPERATORS

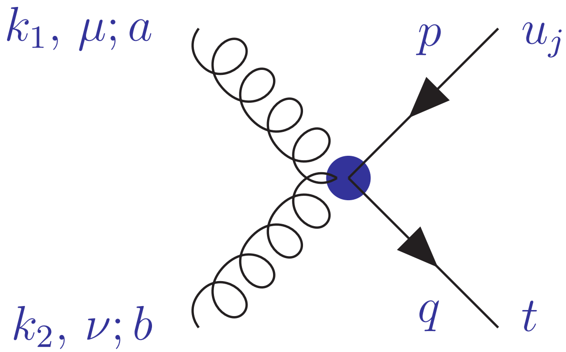
This lagrangean generates new vertices, namely



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



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



$$\frac{i\,g_s}{\Lambda^2}\left[\lambda^c\,f_{abc}\left\{\gamma_\mu\gamma_R(-\alpha_{tj}p_\nu+\alpha^*_{jt}q_\nu)+\gamma_\nu\gamma_R(\alpha_{tj}p_\mu-\alpha^*_{jt}q_\mu)\right.\right.$$
$$\left.\left.+2v\,\sigma_{\mu\nu}\,(\beta_{jt}\gamma_R+\beta^*_{tj}\gamma_L)\right\}\right]+$$
$$\frac{g_s}{2\Lambda^2}\left[(\not{k}_1 g_{\mu\nu}-k_{1\nu}\gamma_\mu)\,\gamma_R\,\left(\lambda_a\lambda_b\alpha_{tj}+\lambda_b\lambda_a\alpha^*_{jt}\right)+\right.$$
$$\left.(\not{k}_2 g_{\mu\nu}-k_{2\nu}\gamma_\mu)\,\gamma_R\,\left(\lambda_b\lambda_a\alpha_{tj}+\lambda_a\lambda_b\alpha^*_{jt}\right)\right]$$

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 :

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

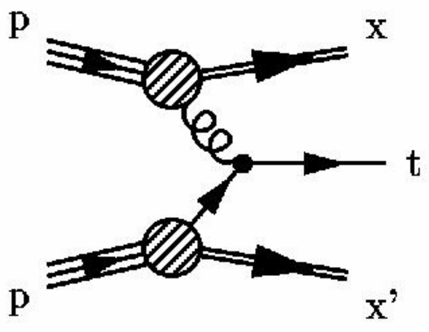
We also considered identical terms for the second generation (with couplings α_{ct}, β_{tc}, etc.)

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

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

(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:

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

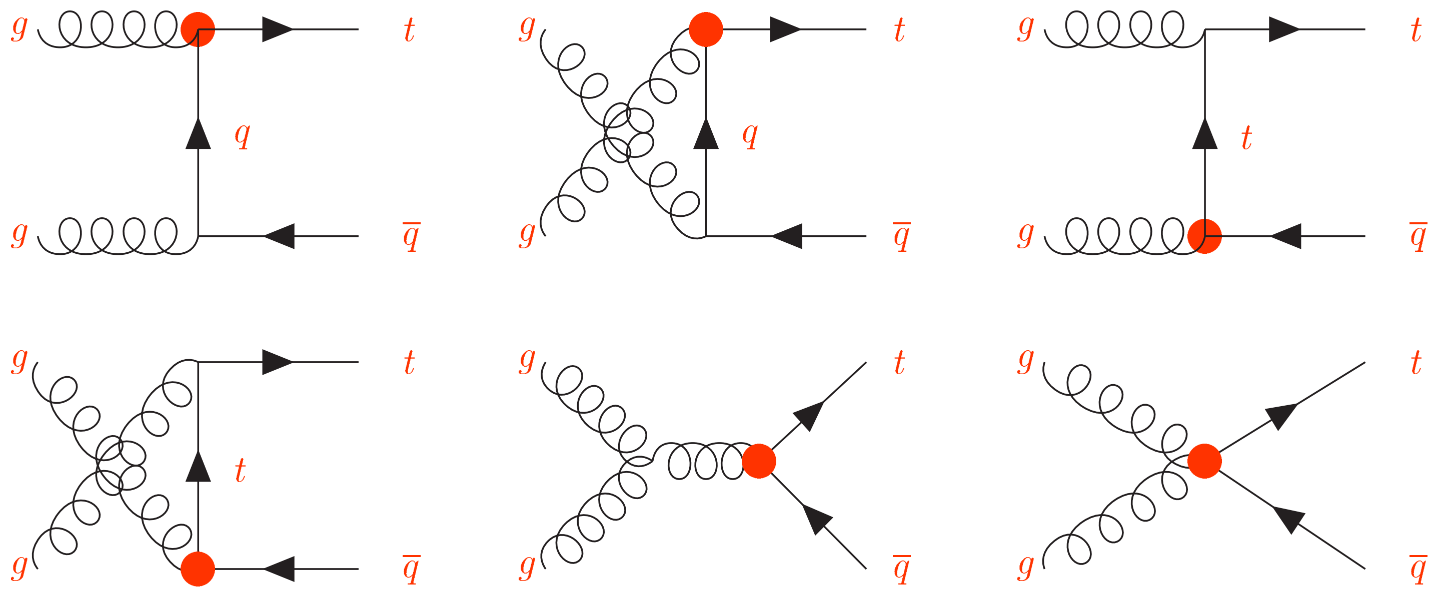
IT IS PROPORTIONAL TO THE PARTIAL WIDTHS OF THE RARE DECAYS OF THE TOP QUARK.

After integration on the CTEQ6M parton density functions, we obtain

$$\begin{aligned}
\sigma(p\,p \to g\,q \to t) &= \; [10.5\, BR(t \to u\,g) \,+\, 1.6\, BR(t \to c\,g)]\; |V_{tb}|^2\; 10^4 \\
\sigma(p\,p \to g\,\bar{q} \to \bar{t}) &= \; [2.7\, BR(t \to u\,g) \,+\, 1.6\, BR(t \to c\,g)]\; |V_{tb}|^2\; 10^4
\end{aligned}$$

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

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

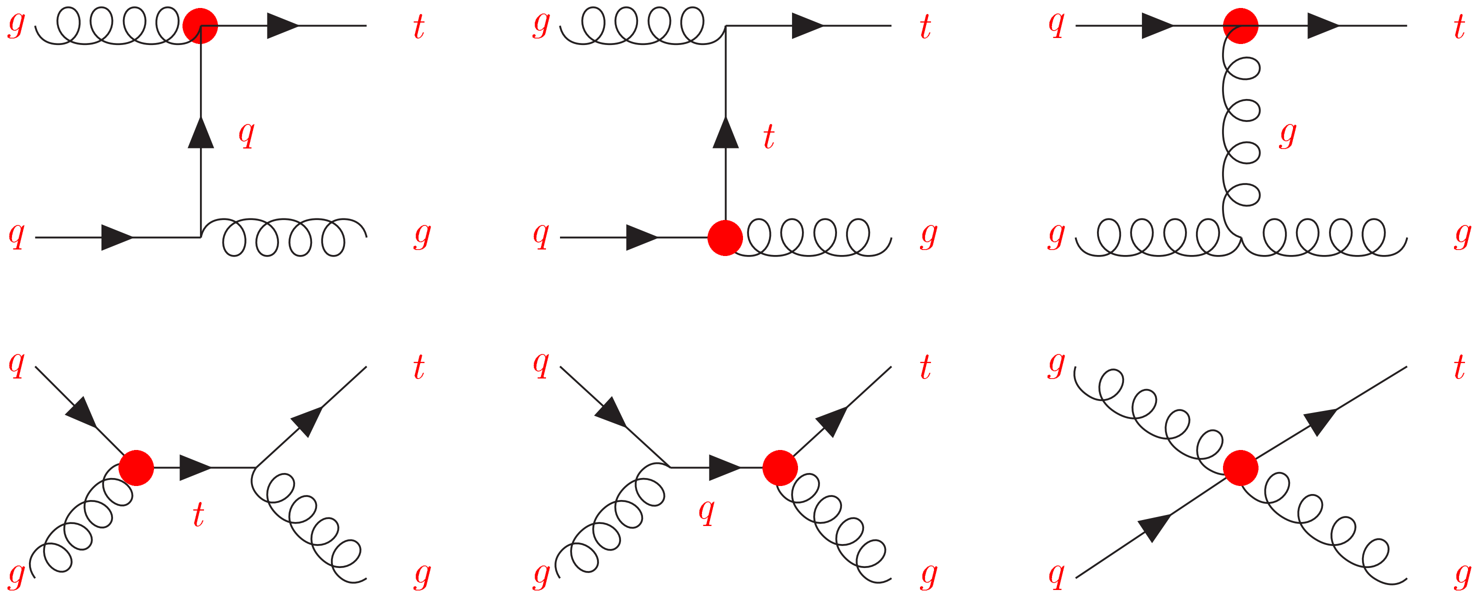
After PDF integration, we obtain

$$\sigma(pp \to gg \to t\bar{q}) = [0.5\mathrm{BR}(t \to ug) + 0.5\mathrm{BR}(t \to cg)]|V_{tb}|^2 10^4 \quad \textbf{pb}$$

$$\sigma(pp \to gg \to \bar{t}q) = \sigma(pp \to gg \to t\bar{q})$$

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

Gluon-quark fusion



We obtain, with a cut in P_T of the final particles of 15 GeV,

$$\sigma(pp \to gq \to gt) = [8.2\mathrm{BR}(t \to ug) + 0.8\mathrm{BR}(t \to cg)]|V_{tb}|^2 10^4$$

$$\sigma(pp \to g\bar{q} \to g\bar{t}) = [1.5\mathrm{BR}(t \to ug) + 0.8\mathrm{BR}(t \to cg)]|V_{tb}|^2 10^4$$

pb

DIRECT:

$$\sigma(pp \to g\,q \to t) = [10.5\,BR(t \to u\,g) + 1.6\,BR(t \to c\,g)]\,|V_{tb}|^2\,10^4$$
$$\sigma(pp \to g\,\bar{q} \to \bar{t}) = [2.7\,BR(t \to u\,g) + 1.6\,BR(t \to c\,g)]\,|V_{tb}|^2\,10^4$$

pb

GLUON-GLUON

$$\sigma(pp \to gg \to t\bar{q}) = [0.5\mathrm{BR}(t \to ug) + 0.5\mathrm{BR}(t \to cg)]|V_{tb}|^2 10^4$$
$$\sigma(pp \to gg \to \bar{t}q) = \sigma(pp \to gg \to t\bar{q})$$

pb

GLUON-QUARK

$$\sigma(pp \to gq \to gt) = [8.2\mathrm{BR}(t \to ug) + 0.8\mathrm{BR}(t \to cg)]|V_{tb}|^2 10^4$$
$$\sigma(pp \to g\bar{q} \to g\bar{t}) = [1.5\mathrm{BR}(t \to ug) + 0.8\mathrm{BR}(t \to cg)]|V_{tb}|^2 10^4$$

pb

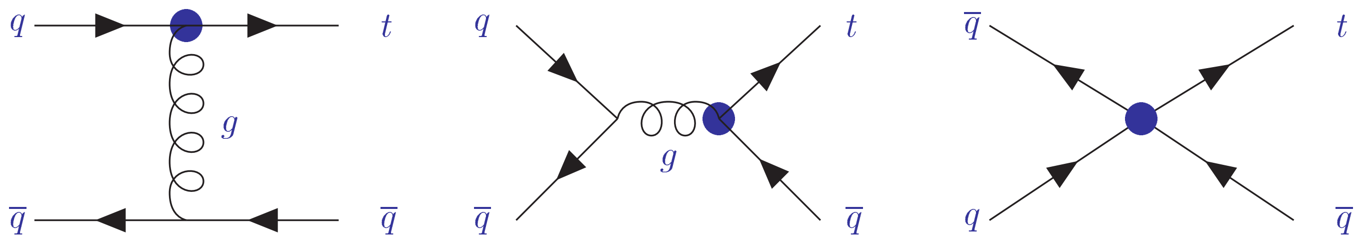
- **In the SM, the branching ratio of $t \to c\,g$ is expected to be of the order of 10^{-12}, but in other models (2HDM, SUSY), that value may increase by as much as 8 orders of magnitude!**

- **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.**

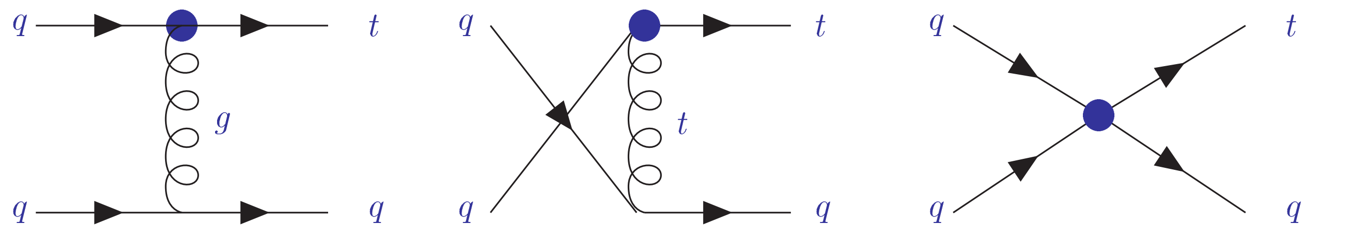
Four fermion channels

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:

$$\sigma_{4F}^{(u)} = [171|\alpha_{ut}|^2 + 179|\alpha_{tu}|^2 - 176\,\mathrm{Re}(\alpha_{ut}\alpha_{tu}) + 331\,\mathrm{Im}(\alpha_{ut}\beta_{tu}) - 362\,\mathrm{Im}(\alpha_{tu}\beta^*_{tu}) + 689(|\beta_{tu}|^2 + |\beta_{ut}|^2)$$
$$+ 177\,\mathrm{Re}(\alpha_{ut}\gamma_{u_1}) - 185\,\mathrm{Re}(\alpha_{tu}\gamma^*_{u_1}) - 16\,\mathrm{Im}(\beta_{tu}\gamma^*_{u_1}) - 17\,\mathrm{Re}(\alpha_{ut}\gamma_{u_2}) + 17\,\mathrm{Re}(\alpha_{tu}\gamma^*_{u_2}) + 0.1\,\mathrm{Im}(\beta_{tu}\gamma^*_{u_2})$$
$$+ 525|\gamma_{u_1}|^2 + 94|\gamma_{u_2}|^2 + 88|\gamma_{u_3}|^2]\frac{1}{\Lambda^4}\ \mathrm{pb}.$$

$$\sigma_{4F}^{(c)} = [20|\alpha_{ct}|^2 + 20|\alpha_{tc}|^2 - 12\,\mathrm{Re}(\alpha_{ct}\alpha_{tc}) + 55\,\mathrm{Im}(\alpha_{ct}\beta_{tc}) - 53\,\mathrm{Im}(\alpha_{tc}\beta^*_{tc}) + 107(|\beta_{tc}|^2 + |\beta_{ct}|^2)$$
$$+ 41\,\mathrm{Re}(\alpha_{ct}\gamma_{c_1}) - 41\,\mathrm{Re}(\alpha_{tc}\gamma^*_{c_1}) + 0.2\,\mathrm{Im}(\beta_{tc}\gamma^*_{c_1}) - 3\,\mathrm{Re}(\alpha_{ct}\gamma_{c_2}) + 3\,\mathrm{Re}(\alpha_{tc}\gamma^*_{c_2}) - 0.5\,\mathrm{Im}(\beta_{tc}\gamma^*_{c_2})$$
$$+ 95|\gamma_{c_1}|^2 + 24|\gamma_{c_2}|^2 + 27|\gamma_{c_3}|^2]\frac{1}{\Lambda^4}\ \mathrm{pb}.$$

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:

$$\sigma^{(u)}_{\text{single } t} = [756|\alpha_{ut}|^2 + 764|\alpha_{tu}|^2 + 994\,\mathrm{Re}(\alpha_{ut}\alpha_{tu}) + 9942|\beta_{ut}|^2 - 17\,\mathrm{Re}(\alpha_{ut}\gamma_{u_2}) + 17\,\mathrm{Re}(\alpha_{tu}\gamma^*_{u_2}) + 94|\gamma_{u_2}|^2 + 88|\gamma_{u_3}|^2]\frac{1}{\Lambda^4}\ \text{pb}$$

$$\sigma^{(c)}_{\text{single } t} = [109|\alpha_{ct}|^2 + 109|\alpha_{tc}|^2 + 166\,\mathrm{Re}(\alpha_{ct}\alpha_{tc}) + 1514|\beta_{ct}|^2 - 3\,\mathrm{Re}(\alpha_{ct}\gamma_{c_2}) + 3\,\mathrm{Re}(\alpha_{tc}\gamma^*_{c_2}) + 24|\gamma_{c_2}|^2 + 27|\gamma_{c_3}|^2]\frac{1}{\Lambda^4}\ \text{pb}$$

For anti top production, the results are:

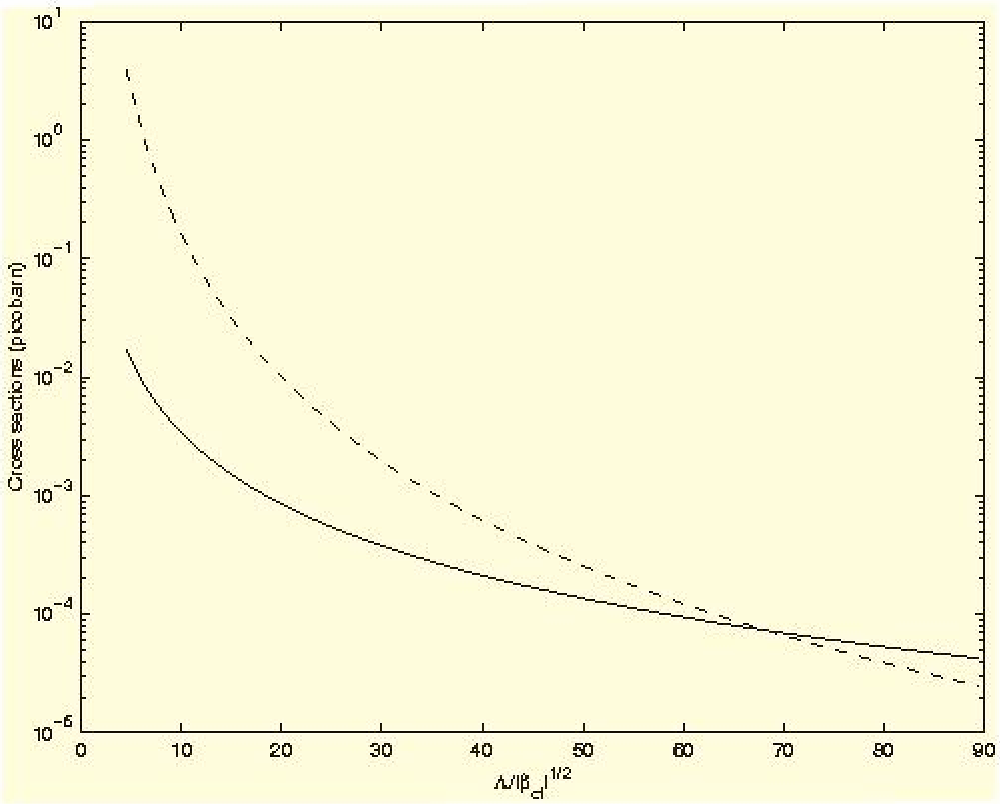
$$\sigma^{(u)}_{\text{single } \bar{t}} = [174|\alpha_{ut}|^2 + 174|\alpha_{tu}|^2 + 265\,\mathrm{Re}(\alpha_{ut}\alpha_{tu}) + 2422|\beta_{ut}|^2 + 3\,\mathrm{Re}(\alpha_{ut}\gamma_{u_2}) - \mathrm{Re}(\alpha_{tu}\gamma^*_{u_2}) + 26|\gamma_{u_2}|^2 + 35|\gamma_{u_3}|^2]\frac{1}{\Lambda^4}\ \text{pb},$$

$$\sigma^{(c)}_{\text{single } \bar{t}} = [109|\alpha_{ct}|^2 + 109|\alpha_{tc}|^2 + 166\,\mathrm{Re}(\alpha_{ct}\alpha_{tc}) + 1514|\beta_{ct}|^2 + 7\,\mathrm{Re}(\alpha_{ct}\gamma_{c_2}) - 7\,\mathrm{Re}(\alpha_{tc}\gamma^*_{c_2}) + 29|\gamma_{c_2}|^2 + 29|\gamma_{c_3}|^2]\frac{1}{\Lambda^4}\ \text{pb}.$$

There is also interference between the electroweak (SM) single top production processes and our gluonic terms, but the resulting cross sections are extremely small.

Interference cross section:

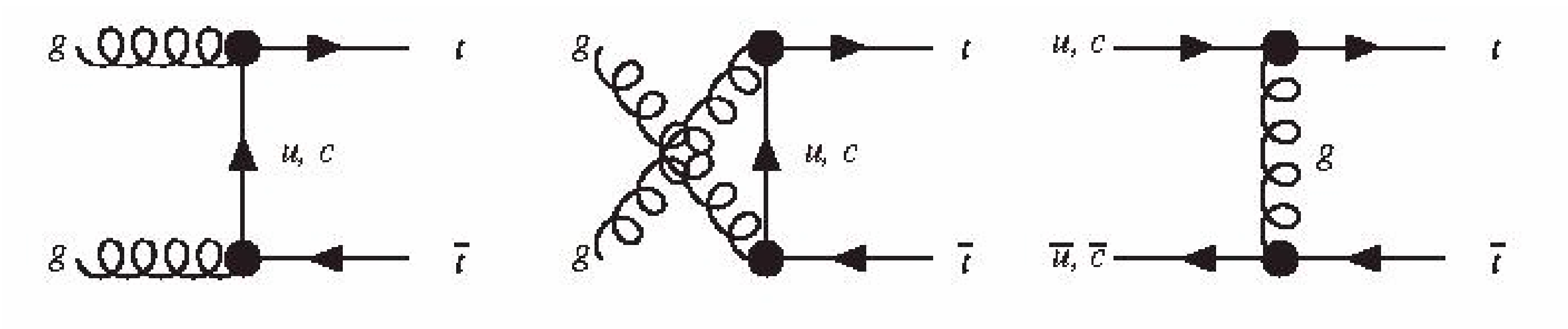
$$\sigma^{\mathrm{int}}_{\mathrm{single}\ t} = 0.81\,\frac{|\mathrm{Re}(\beta_{ut})|}{\Lambda^2} + 0.27\,\frac{|\mathrm{Re}(\beta_{ct})|}{\Lambda^2}\ \mathrm{pb}$$



Interference (solid line) versus total cross section, in terms of $\Lambda/|\beta_{ct}|^{1/2}$

These same gluonic efective operators have consequences in other channels of top quark production.

For instance, the interference terms between the effective operators and the SM for the production of top-antitop pairs if of the same order, Λ^{-4}, as the previous processes.

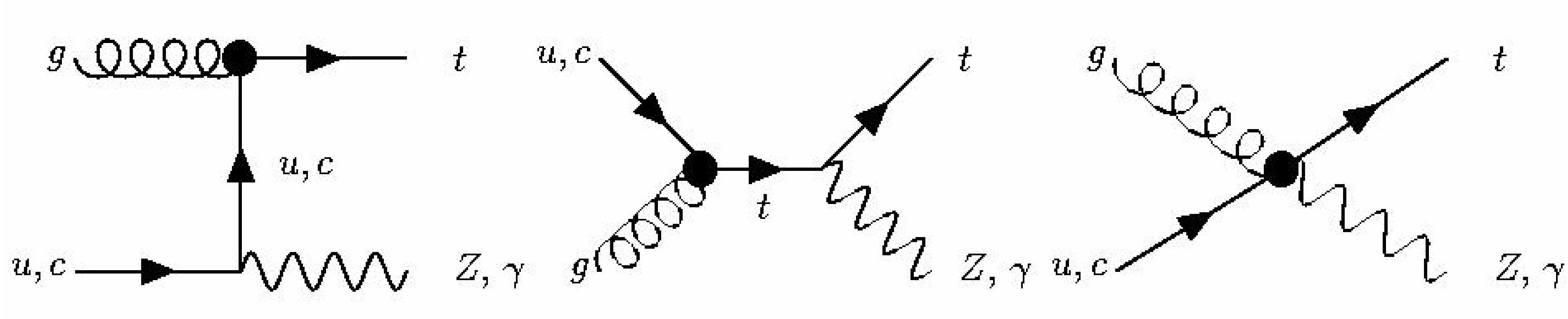


The resulting cross sections, though, are very small. After integration on the pdfs,

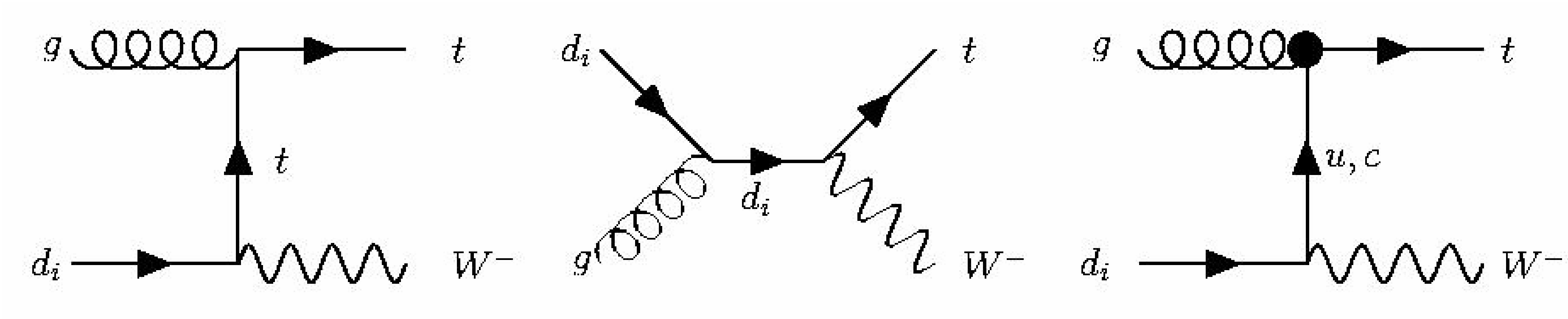
$$\sigma^{(u)}_{p\,p\to t\,\bar{t}} = \Big\{ -0.6\,|\alpha_{tu}|^2 - 0.8\,|\alpha_{ut}|^2 - 0.3\,Re[\alpha_{ut}\,\alpha_{tu}] + 7.1\,(|\beta_{ut}|^2 + |\beta_{tu}|^2) + 8.5\,Im[\alpha_{ut}\,\beta_{tu}] + 9.0\,Im[\alpha_{tu}\,\beta^*_{tu}]\Big\}\,\frac{1}{\Lambda^4}\,\mathrm{pb}$$

$$\sigma^{(c)}_{p\,p\to t\bar{t}} = \Big\{ -0.4\,|\alpha_{ct} + \alpha_{tc}|^2 + 7.6\,(|\beta_{ct}|^2 + |\beta_{tc}|^2) + 9.1\,Im[\alpha_{ct}\,\beta_{tc} - \alpha_{tc}\,\beta^*_{tc}]\Big\}\,\frac{1}{\Lambda^4}\,\mathrm{pb}$$

Likewise, there are contributions from these operators to the associated production of a top quark alongside a gauge or higgs boson – those channels might be of great interest due to the distinct final signature – through the following Feynman diagrams:



There identical diagrams for top + higgs production. For top + W, we have



t + γ cross section

$$\frac{d\,\sigma(g\,q \to t\,\gamma)}{dt} = \frac{e^2}{18\,m_t^2\,s^2\,t\,(t+u)^2}\,(m_t^6 - t\,m_t^4 + s^2\,m_t^2 + 3\,s\,t\,m_t^2 - 2\,s^2\,t)\,u\,\Gamma(t \to q\,g)$$

t + Z⁰ cross section

$$\frac{d\,\sigma(g\,u \to t\,Z)}{dt} = \frac{e^2\,m_t^2}{1728\,\pi\,\Lambda^4\,S_{2w}^2}\;\frac{F_{tZ}^1\,|\alpha_{ut} + \alpha_{tu}^*|^2 \;+\; F_{tZ}^2\,Im[(\alpha_{ut} + \alpha_{tu}^*)\,\beta_{tu}] \;+\; F_{tZ}^3\,|\beta_{tu}|^2 + F_{tZ}^4|\beta_{ut}|^2}{m_z^2\,s^2\,t\,(t+u)^2}$$

t + W cross section

$$\frac{d\,\sigma^{NEW}(g\,d \to t\,W^-)}{dt} = \frac{e^2\,|V_{qd}|^2\,(m_t^2 - t)\;\;(s\,t + 2\,m_w^2\,u)\;\;v^2}{24\,m_w^2\,\pi\,s^2\,S_w^2\,t}\;\frac{|\beta_{qt}|^2}{\Lambda^4}$$

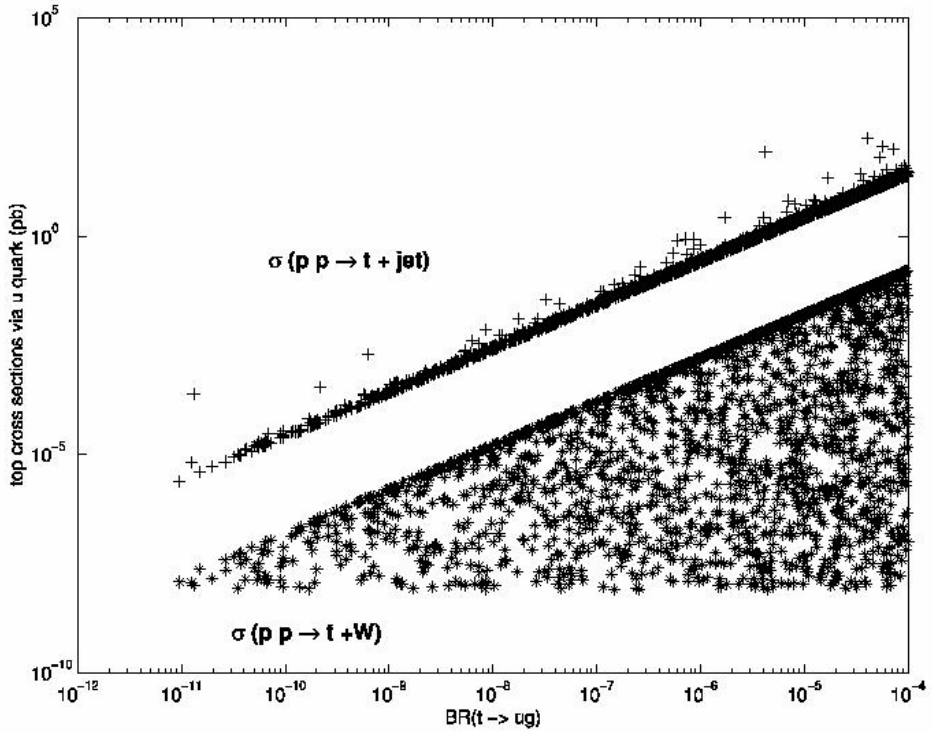
t + h cross section

$$\frac{d\,\sigma(g\,u \to t\,h)}{dt} = \{F_{th}^1\,|\alpha_{ut} + \alpha_{tu}^*|^2 \;+\; F_{th}^2\,Im[(\alpha_{ut} + \alpha_{tu}^*)\,\beta_{tu}] \;+\; F_{th}^3\,(|\beta_{tu}|^2 + |\beta_{ut}|^2)\}\;\frac{1}{\Lambda^4}$$

• Of the resulting cross sections, the one for the process t + γ is, once again, proportional to the width of the rare flavour changing decays of the top. The cross section for t + Z^0 and t + h production is *approximately* proportional to the same quantity. Notice also that the cross section for t + W depends on a single coupling.

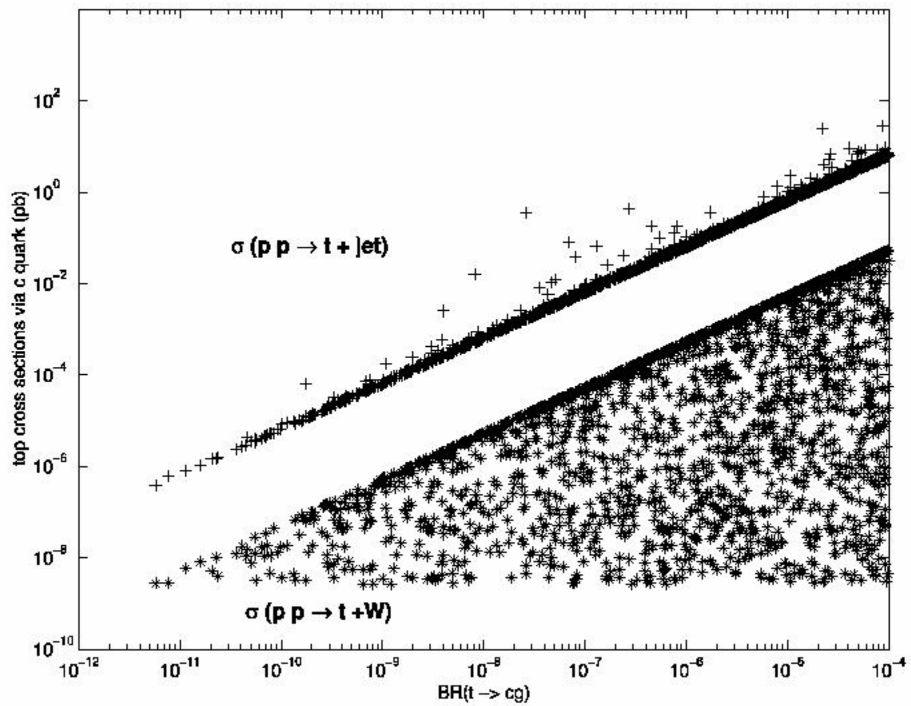
• This proportionality, already observed in the gluonic processes, is hitherto unexplained. We believe it is related to gauge invariance (it only occurs when two *massless* spin-1 particles are involved in the process) but it also might have something to do with chiral symmetry – in all results presented so far, the only quark to have mass different from zero is the top. The proportionality to the width vanishes if the other quark masses are allowed to be different from zero.

• What values are predicted for these cross sections? We varied the parameters $\{\alpha , \beta\}$ randomly and obtained the values for the cross sections (t + jet, t + γ, t + Z^0, t + W, t + h and top-antitop pair production) in terms of the branching ratios BR(t $\rightarrow$ u g) and BR(t $\rightarrow$ c g). The top-antitop values are not shown, as they are too small – less than one picobarn, at best.

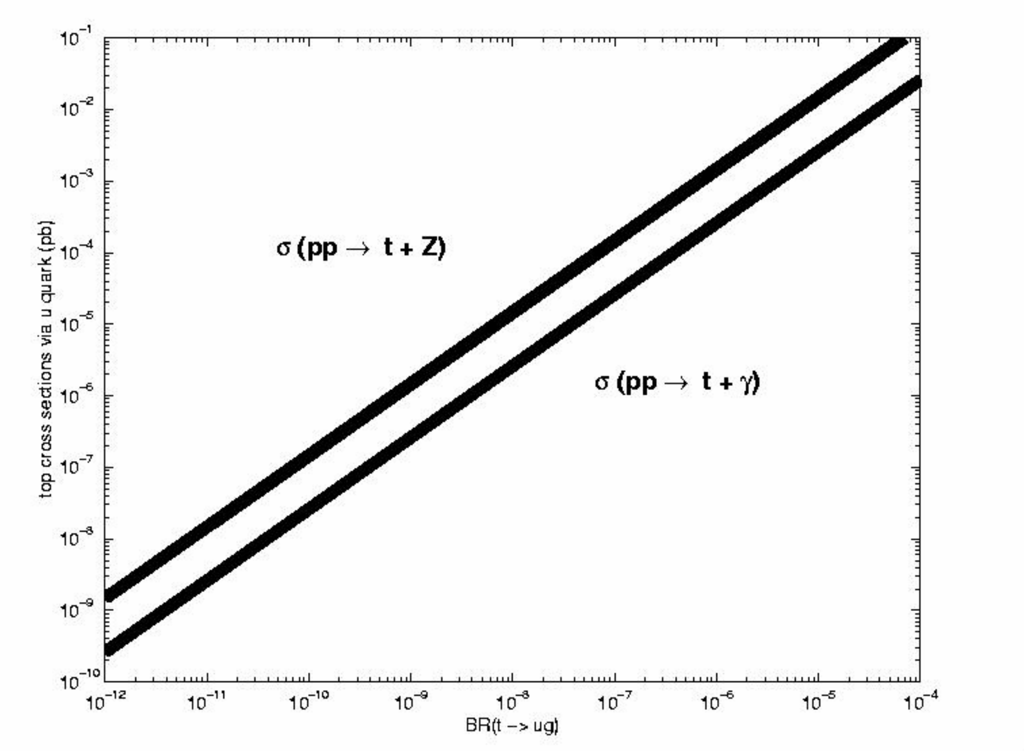


top + jet and top + W production cross sections via a *u* quark versus BR(t → u g) .

top + jet and top + W production cross sections via a *c* quark versus BR(t → c g) .

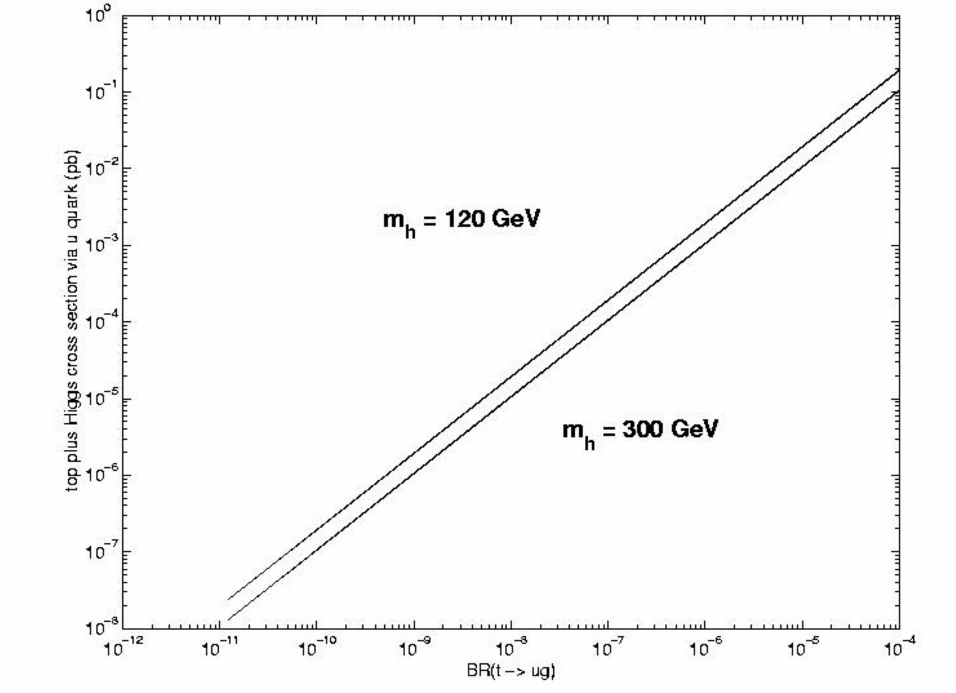


Unless extremely high values for BR(t → u g) and BR(t → c g) occur (currently not possible even in exotic SM extensions), the only process for which one might observe flavour-changing top contributions is top + jet.



top + γ and top + Z production cross sections via a *u* quark versus BR(t $\rightarrow$ u g) .

top + higgs production cross section via a *u* quark versus BR(t $\rightarrow$ u g), for two values of the higgs mass.



Notice the very low values predicted for the cross sections. Again, t + jet seems the only channel where these operators might have a sizeable contribution.

TopRex Implementation

• In collaboration with Sergey Slabospitsky, several of the processes described here have been included in TopRex, version 4.20.

• These include the couplings $\{\alpha, \beta\}$, and the processes

Process 31: $q\,\bar{q} \to t\,\bar{u}\,(\bar{c})$

Process 33: $g\,g \to t\,\bar{u}\,(\bar{c})$

Process 33: $g\,u\,(c) \to t\,g$

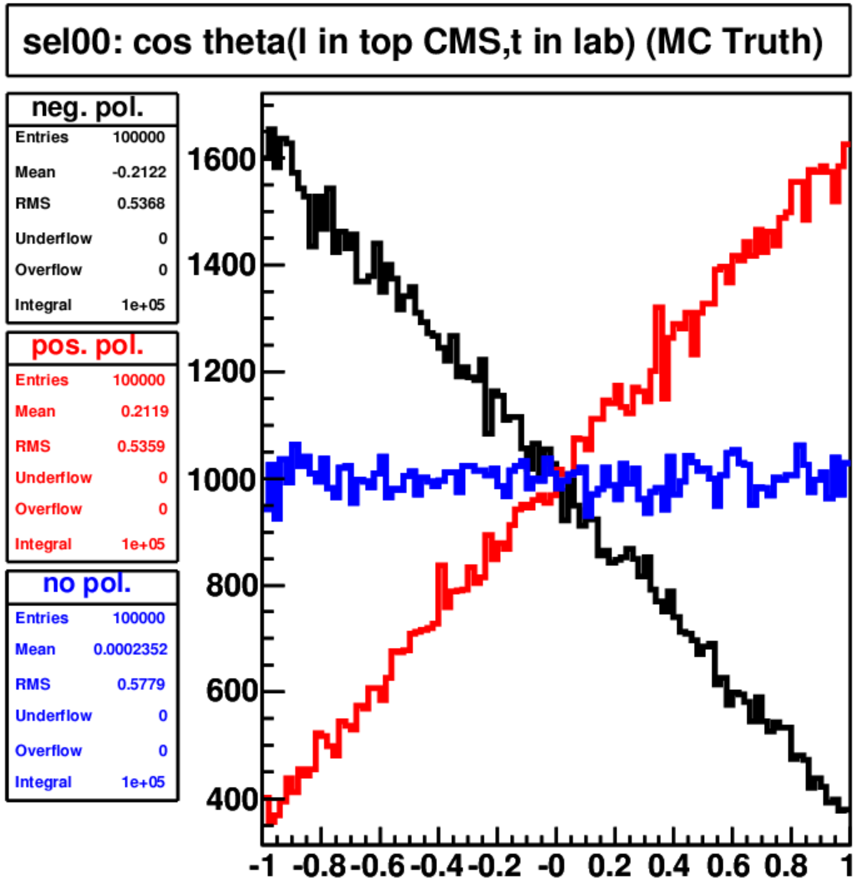
• Thus, with this new version of TopRex, it will be possible to perform a realistic analysis of the possibility of observing these rare flavour-changing decays at the LHC, including detector effects.

Preliminary results (J. Carvalho, N. Castro, F. Veloso, A. Onofre, S. Slabospitsky) of an analysis of the angular distributions of the process $t \rightarrow bW \rightarrow b\, l\, \nu$, including only the β coefficients:

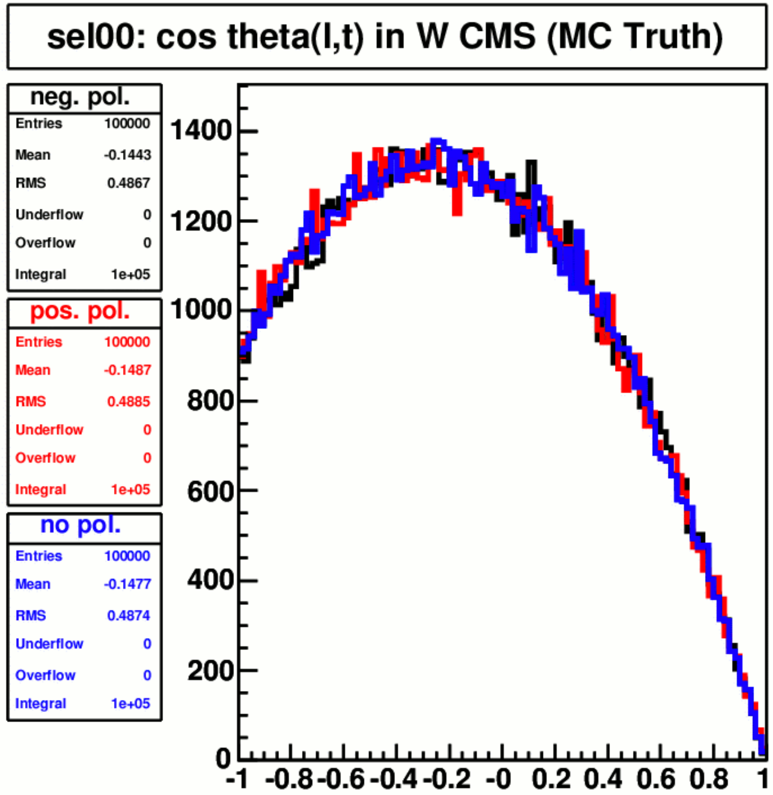
- The samples generated included all processes, with $\alpha = 0$;
- One sample corresponds to a pure V-A theory ($\beta_{tc} = 0$, $\beta_{ct} = 1$).
- Another to a pure V+A model, $\beta_{tc} = 1$, $\beta_{ct} = 0$.
- The third sample to no polarization, $\beta_{tc} = \beta_{ct} = 1$.

•Size of samples: 100000 events.

•As we may see in the following plots, the angular distributions in several frames of reference (W and top rest frames) are very distinct in each of the samples.



top-rest frame, angle between lepton and top direction of flight



W-rest frame, angle between lepton and top

Conclusions

- We used a very general dimension six operator set to compute anomalous contributions for 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.

- Expressions for associated top production (with a gauge or higgs boson) were also obtained, as well as for processes of top-antitop production via flavour changing processes.

- The numerical values found for all of these cross sections reinforce that the channel of single top + jet production is the likeliest to find new physics – as all the others have very small cross sections at the LHC, for reasonable values of the top rare decay branching ratios.

- Full detector simulations are needed to study the possibility of observing these processes in a realistic manner, which is why these calculations are being fed into TopRex.

- Future work will include the four-fermion terms in TopRex and other processes of top production as well. Also, we wish to include processes with polarized top quarks.