Top quark flavor changing neutral currents and dipole moments through three and four-top quark productions at the LHC

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Outline

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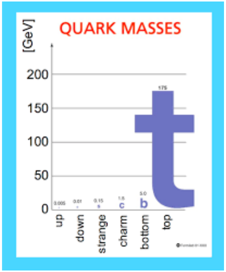
- Top quark
- Rare top quark interactions
- Top quark Flavor changing neutral currents
- Top quark chromo electric and magnetic dipole moments

Why top quark is important?

- Top quark is the heaviest elementary particle known.
- Due to its short lifetime, the top quark decays before hadronization so it offers the unique opportunity to study the properties of a bare quark.
- Top quark is a very clean laboratory for strong and electroweak interactions.
- Its mass is close to the scale of electroweak symmetry breaking (EWSB) and Yukawa coupling.

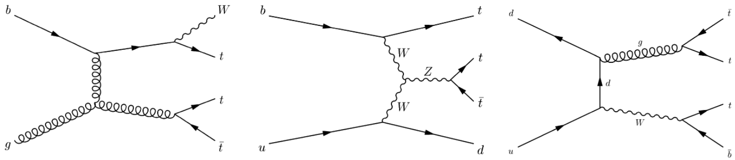
So top quark with its unique features, provides a great opportunity to test the standard model (SM) of particle physics as well as probe beyond the SM.



Three top quark production

- In the SM at leading order, three-top quark events are produced in 3 ways.
- The sum of cross section of all processes amounts to around 2 fb at the LHC with the center of-mass energy of 14 TeV [1].

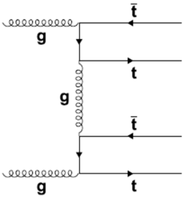
$$pp \to 3t + W^{\pm}, pp \to 3t + b, pp \to 3t + jets.$$



[1] V. Barger, W. Y. Keung and B. Yencho, "Triple-Top Signal of New Physics at the LHC," Phys. Lett. B 687, 70 (2010).

Four top quark production

- In the SM, four-top quarks are mainly produced via gluon fusion.
- The cross section of the four-top quark production at the LHC with the center-of-mass energy of 13 TeV is around 9 fb [2].



Although three and four-top rates are extremely small with respect to the pair or single top quark production by around five order of magnitudes, these processes are particularly sensitive to New Physics (NP) beyond the SM.

[2] A. M. Sirunyan et al. [CMS Collaboration], Phys. Lett. B 772, 336 (2017)

Rare top quark interactions

- Top quark Flavor changing neutral currents

Rare top quark interactions

- Top quark Flavor changing neutral currents
- Top quark chromoelectric and chromomagnetic dipole moments

Top quark FCNC interactions

- ⋆ In the SM, the top quark is expected to decay to a W boson and a bottom quark.
- ⋆ The top quark flavor-changing neutral current (FCNC) are the interactions that the top decays to a neutral boson and an up or charm quark.
- ⋆ FCNC is highly suppressed because of the GIM mechanism in the Standard Model.
- ⋆ Flavor-changing neutral top decays can still occur very rarely through loops (at a level $\leq 10^{-14}$). The SM branching ratio is so far below the current experimental sensitivity.
- ⋆ Many theoretical models beyond SM like SUSY, extra dimensions and two Higgs doublet model predict higher branching fractions up to 10^{-3} 10^{-5}.
- ⋆ Observation of the FCNC in top decay modes would be a sign of new physics beyond the SM.

Experimental evidence

The most stringent limits on the top FCNC branching fractions by the LHC experiments [3][4][5][6][7]:

$$\mathscr{B}(t \to u\gamma) < 1.3 \times 10^{-4}\,,\ \mathscr{B}(t \to c\gamma) < 1.70 \times 10^{-3}\,,$$

$$\mathscr{B}(t \to uZ) < 2.2 \times 10^{-4}\,,\ \mathscr{B}(t \to cZ) < 4.9 \times 10^{-4}\,,$$

$$\mathscr{B}(t \to uH) < 4.7 \times 10^{-3}\,,\ \mathscr{B}(t \to cH) < 4.7 \times 10^{-3}\,,$$

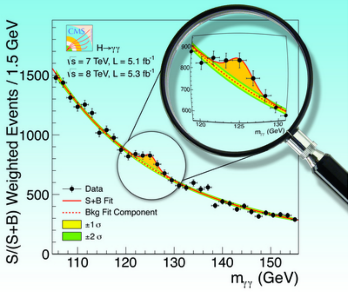
$$\mathscr{B}(t \to ug) < 4.0 \times 10^{-5}\,,\ \mathscr{B}(t \to cg) < 2.0 \times 10^{-5}\,,$$

$$\mathscr{B}(t \to ug) < 2.0 \times 10^{-5}\,,\ \mathscr{B}(t \to cg) < 4.1 \times 10^{-4}\,.$$

[3] V. Khachatryan et al. [CMS Collaboration], JHEP 1604, 035 (2016),
[4] A. M. Sirunyan et al. [CMS Collaboration], JHEP 1707, 003 (2017),
[5] CMS Collaboration [CMS Collaboration], CMS-PAS-TOP-17-003,
[6] G. Aad et al. [ATLAS Collaboration], Eur. Phys. J. C 76, no. 2, 55 (2016),
[7] V. Khachatryan et al. [CMS Collaboration], JHEP 1702, 028 (2017).

How to look for new physics?

Model Dependent
SUSY, 2HDM,
New Particles
resonances in spectra



Model Independent [a]
New Interactions
among SM particles

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i O_i^{d=6} + h.c.,$$

$O_i^{d=6}$ dimension-6 gauge invariant operators
c_i Wilson coefficients
Λ Energy scale of NP

[a] J. A. Aguilar-Saavedra, Nucl. Phys. B 812, 181 (2009).

Effective Lagrangian

The most general effective Lagrangian describing the FCNC interactions can be parameterized as:

$$\begin{aligned}\mathscr{L}_{\text{FCNC}} &= \sum_{q=u,c}\Bigg[\frac{g_s}{2m_t}\bar{q}\lambda^a\sigma^{\mu\nu}(\zeta^L_{qt}P^L+\zeta^R_{qt}P^R)tG^a_{\mu\nu}-\frac{1}{\sqrt{2}}\bar{q}(\eta^L_{qt}P^L+\eta^R_{qt}P^R)tH \\ &- \frac{g_W}{2c_W}\bar{q}\gamma^\mu(X^L_{qt}P_L+X^R_{qt}P_R)tZ_\mu+\frac{g_W}{4c_Wm_Z}\bar{q}\sigma^{\mu\nu}(\kappa^L_{qt}P_L+\kappa^R_{qt}P_R)tZ_{\mu\nu} \\ &+ \frac{e}{2m_t}\bar{q}\sigma^{\mu\nu}(\lambda^L_{qt}P_L+\lambda^R_{qt}P_R)tA_{\mu\nu}\Bigg]+\text{h.c.},\end{aligned}$$

ζ_{qt}, η_{qt}, X_{qt}, κ_{qt} and λ_{qt} are the real parameters which determine the strength of FCNC interactions with gluon, Higgs, Z and photon, respectively.

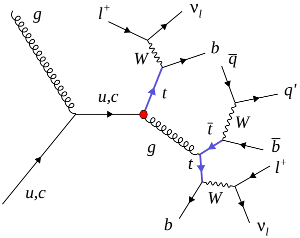
Sensitivity of three-top quark production to fcnc couplings

Signal process:

- ✓ two isolated same-sign charged leptons,
- ✓ large missing transverse energy,
- ✓ several jets (three of them come from b-quarks).

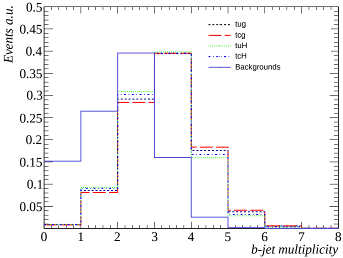
background processes:

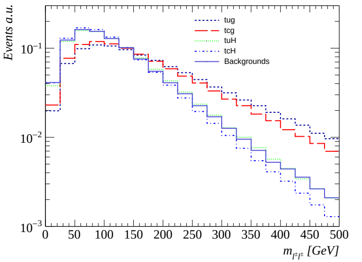
- ✓ *ttZ*,
- ✓ *ttW*,
- ✓ SM four-top,
- ✓ *ttWW*,
- ✓ *ttZZ*,
- ✓ *WWZ*



We perform the analysis for L=300 and 3000 fb $^{-1}$ of the LHC at the center-of-mass energy of 14 TeV

Cut
(I) $2\ell^{\pm\pm}, \lvert\eta_\ell\rvert < 2.5, p_T > 10$ GeV, $m_{\ell\ell} > 10$ GeV
(II) MET> 30 GeV
(III) $n_j \geq 5, \lvert\eta_j\rvert < 2.5, p_T > 20, \Delta R(\ell,j) > 0.4, \Delta R(j_1,j_2) > 0.4$
(IV) Number of b-jet≥ 3





The obtained upper limits in terms of $\mathscr{B}(t \to qX)$

The upper limits on the tqX FCNC at 95% C.L obtained at the $\sqrt{s}$ = 14 TeV based on the integrated luminosities of 300 and 3000 fb^{-1} in comparison with a recent ATLAS experiment analysis [8] and the CMS analysis [9].

Branching fraction	three-top, 300 fb^{-1}	three-top, 3 ab^{-1}	other-channels, HL-LHC, 3 ab^{-1}
$\mathscr{B}(t \to uH)$	1.03×10^{-3}	3.09×10^{-4}	2.4×10^{-4}
$\mathscr{B}(t \to cH)$	8.52×10^{-3}	2.54×10^{-3}	2.0×10^{-4}
$\mathscr{B}(t \to ug)$	4.00×10^{-4}	1.19×10^{-4}	-
$\mathscr{B}(t \to cg)$	4.51×10^{-3}	1.35×10^{-3}	-
$\mathscr{B}(t \to uZ) - \sigma_{\mu\nu}$	2.73×10^{-3}	8.18×10^{-4}	4.3×10^{-5}
$\mathscr{B}(t \to cZ) - \sigma_{\mu\nu}$	2.67×10^{-2}	7.98×10^{-3}	5.8×10^{-5}
$\mathscr{B}(t \to uZ) - \gamma_{\mu}$	5.73×10^{-3}	1.71×10^{-3}	4.3×10^{-5}
$\mathscr{B}(t \to cZ) - \gamma_{\mu}$	4.52×10^{-2}	1.35×10^{-2}	5.6×10^{-5}
$\mathscr{B}(t \to u\gamma)$	2.18×10^{-2}	6.53×10^{-3}	2.7×10^{-5}
$\mathscr{B}(t \to c\gamma)$	2.14×10^{-1}	6.40×10^{-2}	2.0×10^{-4}

[8] ATLAS Collaboration [ATLAS Collaboration], ATL-PHYS-PUB-2016-019,
[9] CMS Collaboration [CMS Collaboration], CMS-PAS-FTR-16-006.

The sensitivity of the four-top quark production to the weak and strong top quark dipole moments

Top quark dipole moments

- In the SM, at leading order, dipole interactions do not exist.
- The size of top quark dipole moments are so small that the LHC would not be able to observe them.
- There are several beyond the SM theories which predict sizable enhancements which make the dipoles accessible by the LHC detectors.
- Any observation of considerable deviations from zero would be an indication to beyond the SM physics.
- We have studied the top dipole moments in ttg and ttZ vertices.

Theoretical framework

The effective Lagrangian including dimension-six operators for gtt and Ztt on the four-top-quark production at the LHC can be written as [10], [11]

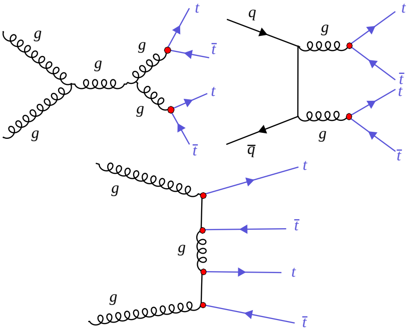
$$\mathscr{L}_{gt\bar{t}} = -g_s\bar{t}\frac{\lambda^a}{2}\gamma^\mu t G^a_\mu - g_s\bar{t}\lambda^a\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(d^g_V + i d^g_A\gamma_5)tG^a_\mu,$$

$$\mathscr{L}_{Zt\bar{t}} = -\frac{g_W}{2c_W}\bar{t}\gamma^\mu\left(X^L_{tt}P_L + X^R_{tt}P_R - 2s^2_W Q_t\right)t\, Z_\mu - \frac{g_W}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(d^Z_V + i\, d^Z_A\gamma_5\right)t\, Z_\mu .$$

[10] J. A. Aguilar-Saavedra, B. Fuks and M. L. Mangano, Phys. Rev. D 91, 094021 (2015),
[11] R. Rntsch and M. Schulze, JHEP 1508, 044 (2015).

sensitivity of four-top quark production to the top quark dipole moments

Illustrative leading order Feynman diagrams for $t\bar{t}t\bar{t}$ production representing the effect of strong dipole moments



sensitivity of four-top quark production to the top quark dipole moments

Considering at most an effective vertex in each diagram, the total four-top cross section becomes at most a quadratic function of dipole moments:

$$\begin{aligned}
\sigma(pp \to t\bar{t}t\bar{t})(fb) &= \sigma_{\rm SM} + 154.827 \times d_V^g + 3404.44 \times (d_V^g)^2, \\
\sigma(pp \to t\bar{t}t\bar{t})(fb) &= \sigma_{\rm SM} + 2731.27 \times (d_A^g)^2, \\
\sigma(pp \to t\bar{t}t\bar{t})(fb) &= \sigma_{\rm SM} - 0.689188 \times d_V^Z + 37.0581 \times (d_V^Z)^2, \\
\sigma(pp \to t\bar{t}t\bar{t})(fb) &= \sigma_{\rm SM} + 27.962 \times (d_A^Z)^2,
\end{aligned}$$

The quadratic terms in the cross section are corresponding to the power of Λ^{-4} which are the first contributing terms for the strong and weak dipole moments.

The upper limits on $d^g_{A,V}$ and $d^Z_{A,V}$

The upper limits at 95% CL on the strong ($d^g_{A,V}$) and weak ($d^Z_{A,V}$) dipole moments using the CMS experiment measurement [12] are presented

Coupling	Current four-top with 35.6 fb^{-1}	Future four-top with 300 fb^{-1}
d^g_V	[-0.20, 0.11]	[-0.07,0.03]
d^g_A	[-0.16, 0.16]	[-0.05, 0.05]
d^Z_V	[-1.42,1.45]	[-0.45, 0.47]
d^Z_A	[-1.65, 1.65]	[-0.53, 0.53]

[12] A. M. Sirunyan et al. [CMS Collaboration], Eur. Phys. J. C 78, 2, 140 (2018)

Summary

- ✓ By obtaining the upper limits on the FCNC branching fractions, we demonstrate that the three-top quark production is sensitive to the top quark FCNC couplings.
- ✓ The calculated upper limits on the strong ($d^{g}_{A,V}$) and weak ($d^{Z}_{A,V}$) dipole moments through four top quark production are compatible with the other bounds extracted from the other processes at the LHC.