Single top quark production as a probe of anomalous tqγ and tqZ couplings at the FCC-ee

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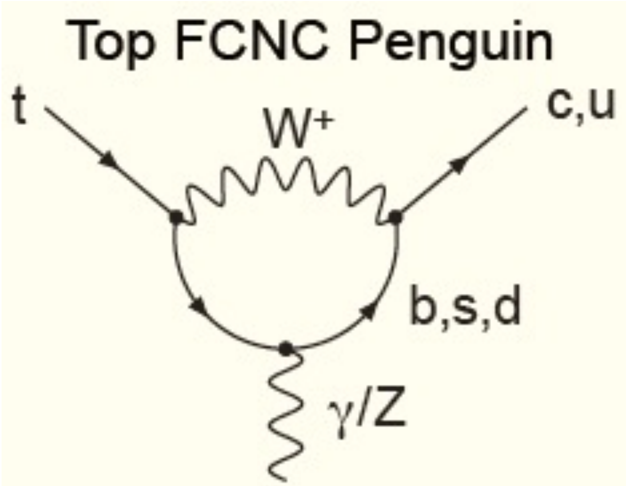
Flavor-Changing Neutral Current (FCNC)

- Flavor-changing neutral current (FCNC) interactions: Transition from a quark with flavor-X and charge-Q to another quark of flavor-Y but with the same charge-Q.
- For example: $b \rightarrow s\gamma$, $t \rightarrow u\gamma$, $t \rightarrow uZ$ …
- FCNC are forbidden at tree level and only allowed via higher order corrections such as penguin diagrams and strongly suppressed: due to GIM mechanism and smallness of the related CKM matrix elements.



SM Predictions

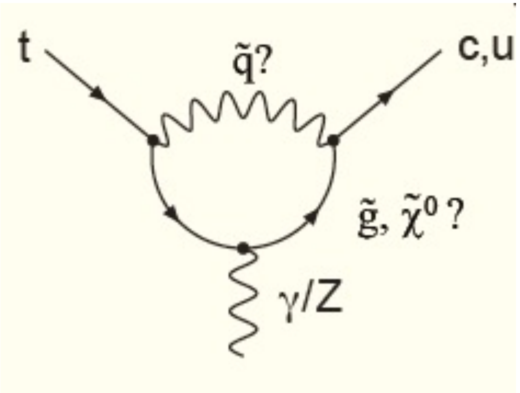
$Br(t \rightarrow cg)$	$\mathcal{O}(10^{-11})$
$Br(t \rightarrow cZ)$	$\mathcal{O}(10^{-13})$
$Br(t \rightarrow c\gamma)$	$\mathcal{O}(10^{-13})$

Phys. Rev. D 44, 1473 (1991); Phys. Lett. B 435, 401 (1998).

FCNC and new physics

- Top decays through FCNC are enhanced in many models beyond the SM. The enhancement mechanisms depends on the model. It can be done via weaker GIM cancellation by new particles in loop corrections.

- **Example:**
Supersymmetry: gluino/neutralino and squark in loop corrections.



- Experimental tests of FCNC interactions: sensitive probes of new physics.

- Any signal above SM expectations would indicate new physics.

- Measurements of FCNC branching ratios allows to constrain new physics models.

Model	BR($t \to Zq$)
Standard Model	$\mathcal{O}(10^{-14})$
$q = 2/3$ Quark Singlet	$\mathcal{O}(10^{-4})$
Two Higgs Doublets	$\mathcal{O}(10^{-7})$
MSSM	$\mathcal{O}(10^{-6})$
R-Parity violating SUSY	$\mathcal{O}(10^{-5})$

arXiv:hep-ph/0409351; Acta Phys. Polor B35 (2004) 2695

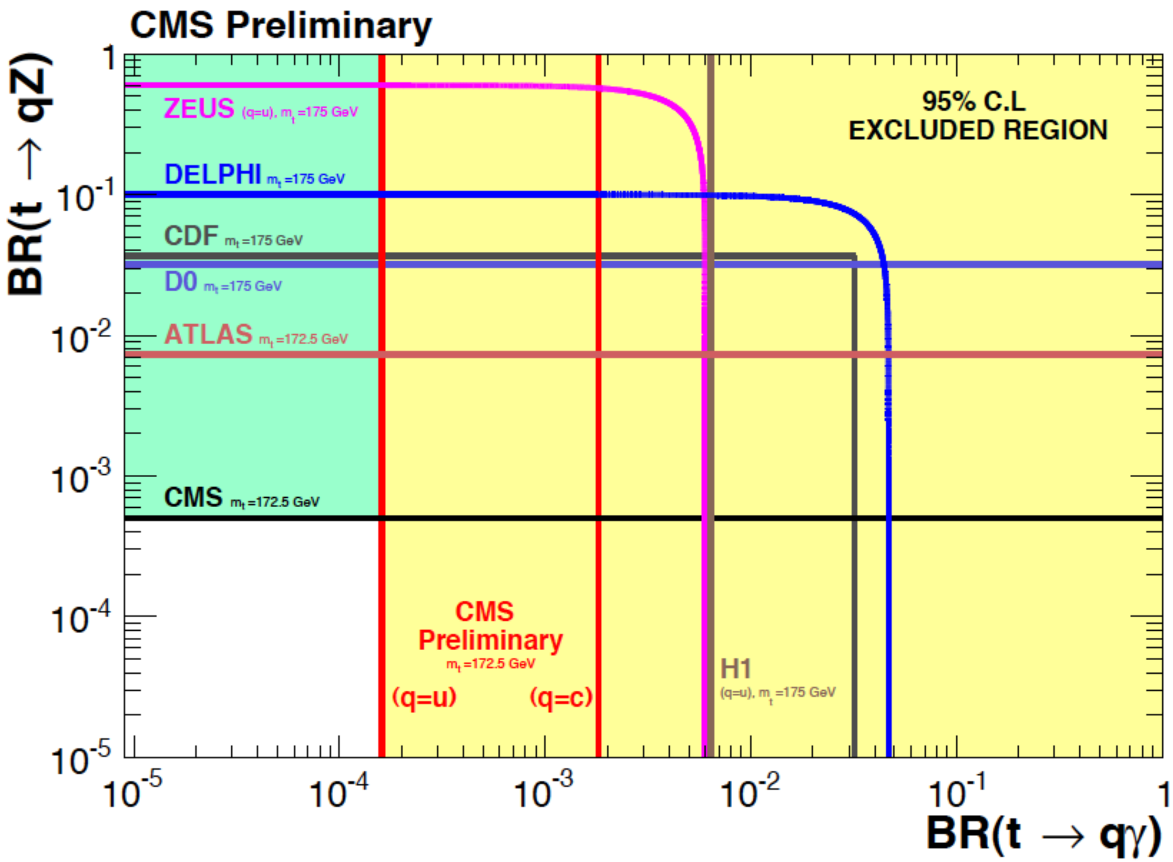
Current observed limits

The most stringent bounds are:

$$BR(t \to Zq) < 0.05\% \ , \ BR(t \to u\gamma) < 0.0161\% \ , \ BR(t \to c\gamma) < 0.182\%.$$

CMS-PAS-TOP-14-003

There are also ATLAS Results.

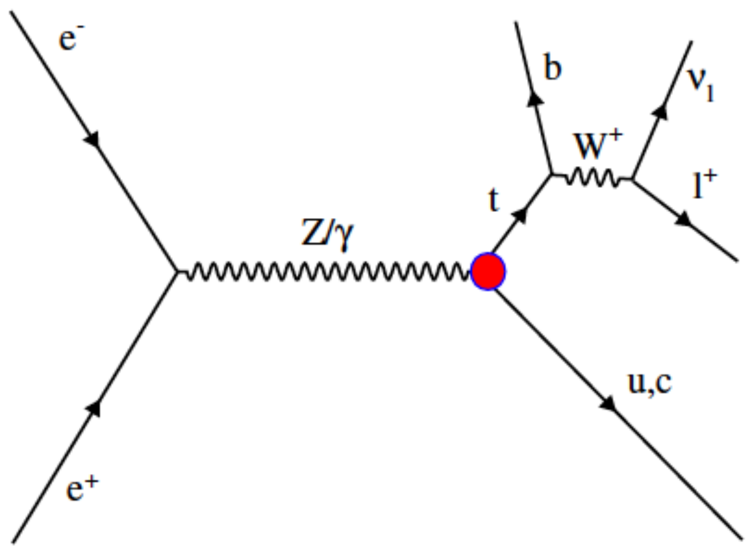


Analysis in FCC-ee

The anomalous FCNC couplings of a top quark with a photon and Z boson can be written in a model independent way using an effective Lagrangian approach.

$$\mathcal{L}_{eff} = \sum_{q=u,c}\Big[e\lambda_{tq}\bar{t}(\lambda^v - \lambda^a\gamma^5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}qA^\mu + \frac{g_W}{2c_W}\kappa_{tq}\bar{t}(\kappa^v - \kappa^a\gamma^5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}q\ Z^{\mu\nu} + \frac{g_W}{2c_W}X_{tq}\ \bar{t}\gamma_\mu(x^L P_L + x^R P_R)q\ Z^\mu\Big] + \text{h.c.}\,,$$

The anomalous FCNC interaction tqA and tqZ lead to production of a top quark in association with a light quark in electron-positron collisions.

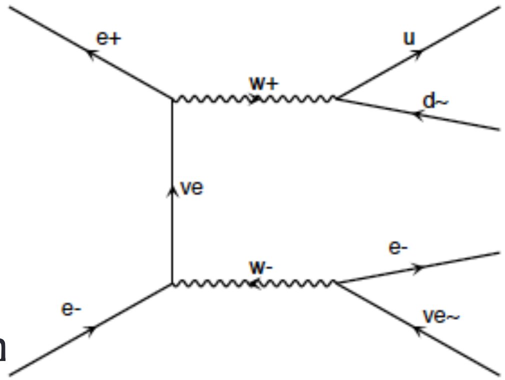


In this work, we only concentrate on the leptonic decay of the W boson in top quark, i.e. t → Wb → lνb with l = e,mu.

Final state: charged lepton, a b-jet, a light-jet and missing energy

Backgrounds

Based on the expected signature of the signal events, the main background contribution is originating from WW production when one of the W bosons decays hadronicly and another one decays leptonically, i.e. e+e- → W+W → lv+jj.

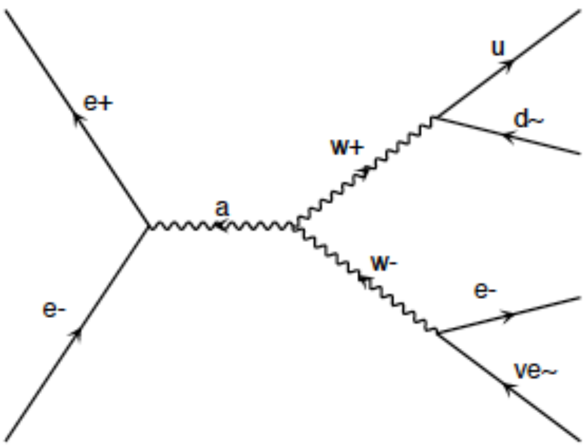


Signal and background generation

-We use MadGraph5 to generate the signal & background events. The signal and background events are generated in th center-of-mass energies of 240, 350 and 500 GeV.

-We employ Pythia 8.1 package for parton showering, hadronization and decay of unstable particles.

-To reconstruct jets the FastJet package with an anti-**k**t algorithm with a cone size of **R** = 0.4 is used.



Cross sections of signal & backgrounds

Cross-sections×BR(t→lvb) (l = e,mu) for three signal scenarios, tqA , tqZ (vector-tensor) before applying cuts:

$\sqrt{s}$	240 GeV		350 GeV		500 GeV	
FCNC couplings	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.
$tq\gamma$	$1077(\lambda_{tq})^2$	4879	$1916(\lambda_{tq})^2$	3221.2	$2151(\lambda_{tq})^2$	2048.6
$tqZ\ (\sigma_{\mu\nu})$	$717(\kappa_{tq})^2$	4879	$1080(\kappa_{tq})^2$	3221.2	$1141(\kappa_{tq})^2$	2048.6
$tqZ\ (\gamma_{\mu})$	$458(X_{tq})^2$	4879	$393(X_{tq})^2$	3221.2	$232(X_{tq})^2$	2048.6

All cross sections have been calculated with **MadGraph5**.

Simulation and event selection

-To account for the detector resolution, the nal state particles (leptons and jets) are smeared according to a Gaussian distribution with the following parameterization:

$$\frac{\Delta E_j}{E_j} = \frac{40\%}{\sqrt{E_j\ (GeV)}} \oplus 2.5\%\ ,\ \frac{\Delta E_\ell}{E_\ell} = \frac{15\%}{\sqrt{E_\ell\ (GeV)}} \oplus 1\%\ ,$$

-In our analysis, b-tagging plays an important role to reject the contribution of WW background.

-We present the results with 70%; 80%; 90% for the eciencies of b-tagging and a 10% mis-tagging rates.

-Now, we apply the following detector acceptance cuts on the final state objects:

$$p_T^{jet,\ell,b_{jet}} \geq 25\ \text{GeV},\ \not{E}_T^{miss} \geq 25\ \text{GeV},\ |\eta^{jet,\ell,b_{jet}}| < 2.5,$$

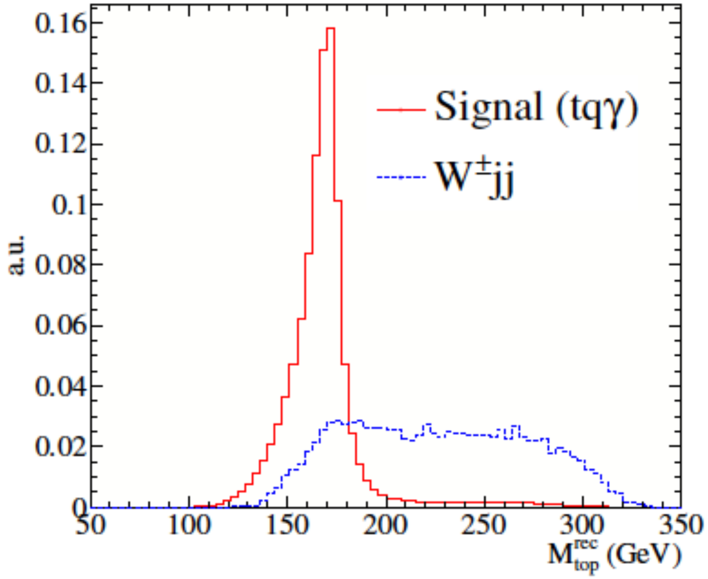
-In addition to these cuts, to have well separated objects, we require DR > 0.4.

Event reconstruction

$\sqrt{s}$	240 GeV		350 GeV		500 GeV	
FCNC couplings	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.
$tq\gamma$	$317.7(\lambda_{tq})^2$	1361.2	$595.8(\lambda_{tq})^2$	901.9	$720.5(\lambda_{tq})^2$	577.7
$tqZ\ (\sigma_{\mu\nu})$	$210.8(\kappa_{tq})^2$	1361.2	$332.6(\kappa_{tq})^2$	901.9	$381.1(\kappa_{tq})^2$	577.7
$tqZ\ (\gamma_{\mu})$	$135.1(X_{tq})^2$	1361.2	$122.2(X_{tq})^2$	901.9	$76.1(X_{tq})^2$	577.7

In order to reconstruct the top quark, all components of the neutrino momentum is needed.

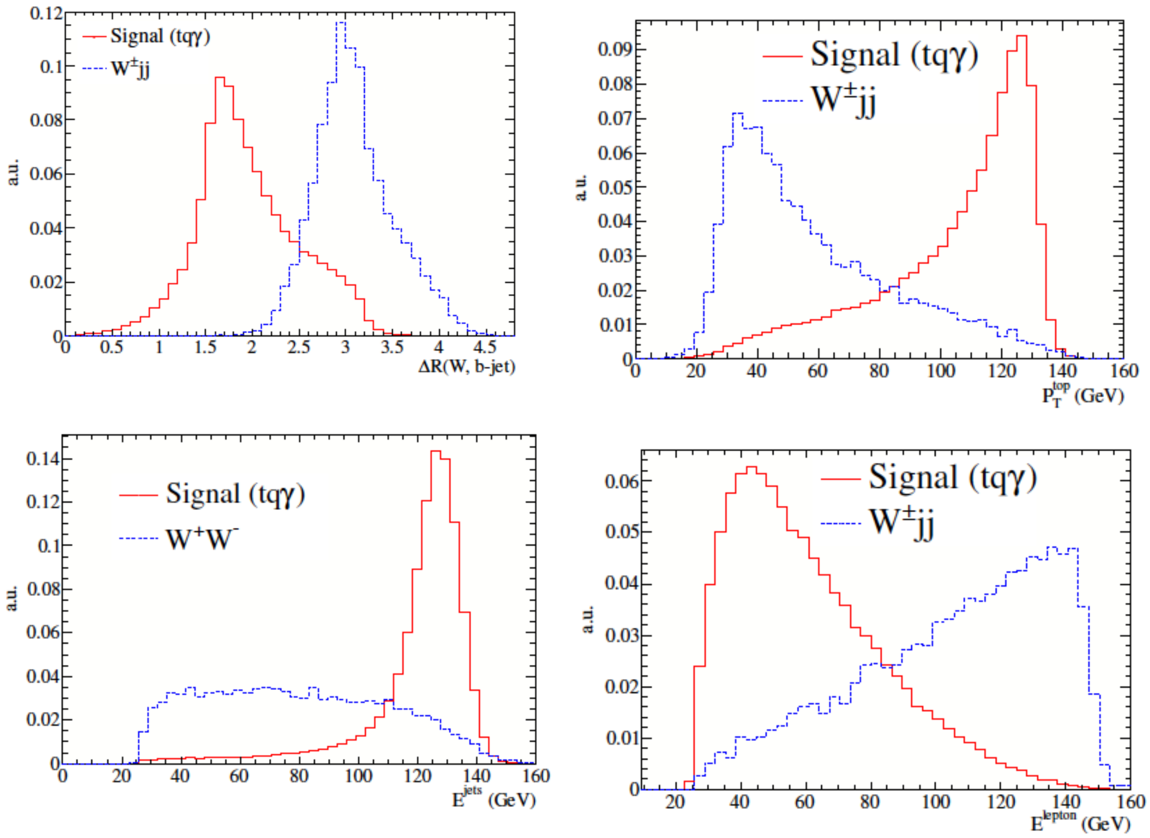
We obtain the z-component of the neutrino momentum by using the W boson mass constraint.



Signal Optimization

To separate signal from background events, we use a MVA analysis with the following input variables:

Variables	Variable ranking
$\Delta R(W, b_{jet})$	1
$\eta^{b_{jet}}$	2
$M^{rec}_{W,b_{jet}}$	3
$P_T^{b_{jet}}$	4
E^{ℓ}	5
P_T^{top}	6
E^{jets}	7



Signal Optimization

After the MVA analysis, a signal efficiency of around 90% and a background efficiency of 1-3% are achieved, depends on the signal scenario and the center-of-mass energy of the electron-positron. The cross sections after the MVA analysis are presented in the table:

$\sqrt{s}$	240 GeV		350 GeV		500 GeV	
FCNC couplings	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.
$tq\gamma$	$288.6(\lambda_{tq})^2$	180	$571(\lambda_{tq})^2$	23.7	$215.2(\lambda_{tq})^2$	2.3
$tqZ\ (\sigma_{\mu\nu})$	$190.7(\kappa_{tq})^2$	160	$317.5(\kappa_{tq})^2$	18.3	$377.7(\kappa_{tq})^2$	1.7
$tqZ\ (\gamma_\mu)$	$122.2(X_{tq})^2$	168.3	$116.7(X_{tq})^2$	26.7	$74.9(X_{tq})^2$	2.6

Upper limits

In order to set upper limit on the branching ratios, we use the CL_S method used by ATLAS and CMS to set exclusion limits.

First, upper limits are set on the signal cross section, then it is translated to upper Limits on the anomalous couplings→ upper limit on the branching ratios **@ 100/fb**:

$\sqrt{s}$ (GeV)	240	350	500
$\mathcal{B}r(t \to q\gamma)$	2.066×10^{-4}	3.859×10^{-5}	8.753×10^{-6}
$\mathcal{B}r(t \to qZ)$ $(\sigma_{\mu\nu})$	2.394×10^{-4}	4.700×10^{-5}	1.126×10^{-5}
$\mathcal{B}r(t \to qZ)$ (γ_{μ})	3.942×10^{-3}	1.664×10^{-3}	7.087×10^{-4}

LHC Future results

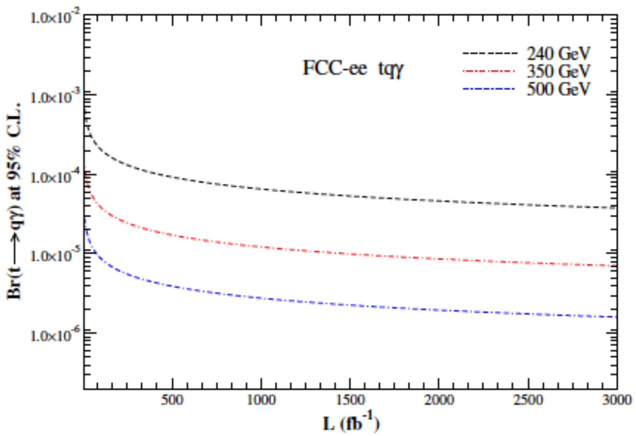
CMS PAS FTR-13-016

$\mathcal{B}(t \to Zq)$	$19.5\ fb^{-1}$ @ 8 TeV	$300\ fb^{-1}$ @ 14 TeV	$3000\ fb^{-1}$ @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$

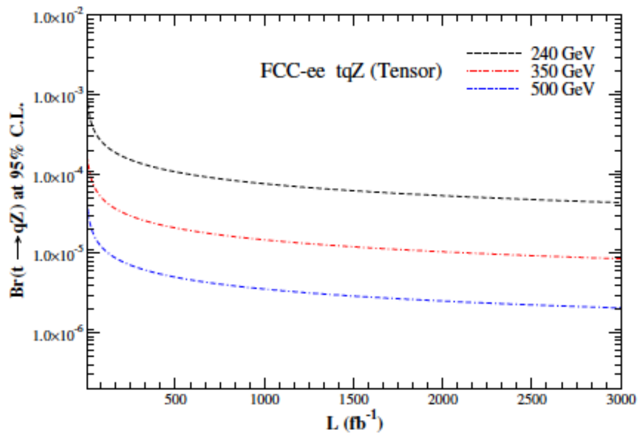
300 fb^{-1} of 14 TeV data leads to a bound around half of the present limit from 7+8 TeV.

FCC-ee with 100 fb^{-1} would be able to set upper limits at the order of 10^{-5}.

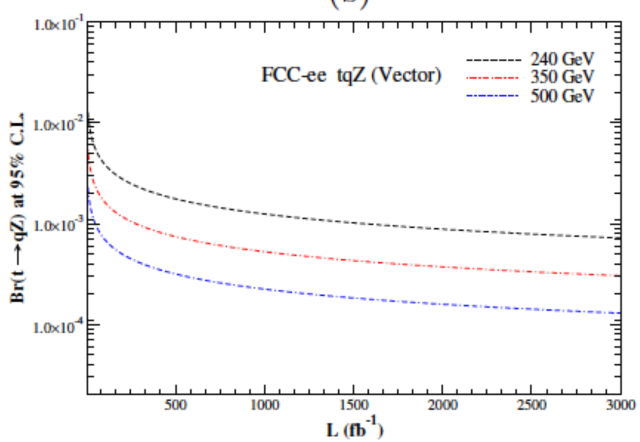
Upper limits as a function of the integrated luminosity for three signal scenarios:



(a)



(b)



(c)