Update of probing of anomalous $tq\gamma$ and tqZ couplings at the FCC-ee

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Analysis in FCC-ee

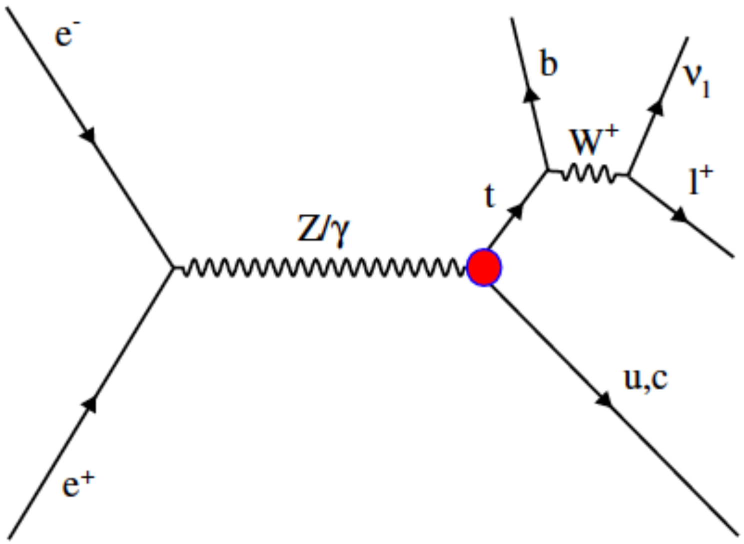
The anomalous FCNC couplings of a top quark with a photon and Z boson can be written in a model independent way using an effective Lagrangian approach.

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

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 → lvb with l = e,mu.

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



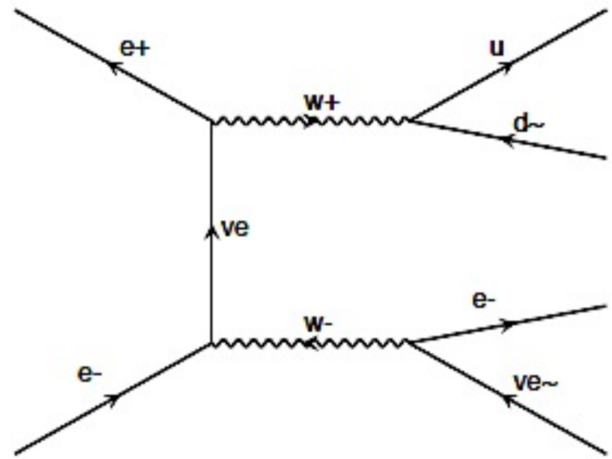
Backgrounds

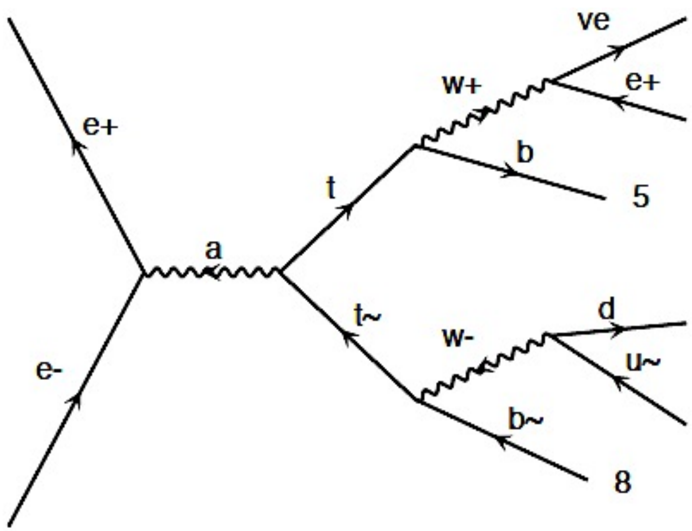
Based on the expected signature of the signal events, the main background contributions are originating from:

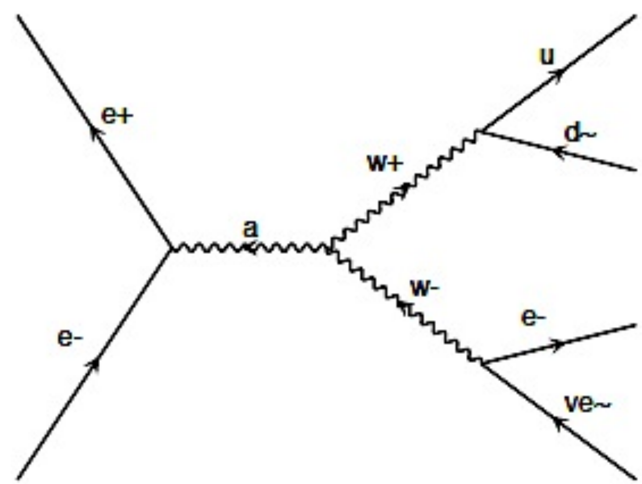
-WW production when one of the W bosons decays hadronicly and another one decays leptonically, i.e.

-e+e- → W+W- → lv+jj.

-e-e+ → ttbar→lv+jets







Signal and background generation and simulation

- We use **MadGraph5** to generate the signal & background events. The signal and background events are generated in the 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.

-We use Delphes for detector simulation with the following parameterizations:

- Magnetic field: 5 T

Thanks to Patrizia and Barbara for their recommendations for preparing the card.

Signal and background simulations

- Resolution formula for electrons with E > 20 GeV and $|\eta|<2.5$ (CMS-like):

$$\frac{\Delta E}{E} = \frac{0.07}{\sqrt{E}} \oplus \frac{0.35}{E} \oplus 0.007$$

- Resolution formula for muons: much dependent on p_T and η of the muon (CMS-like).

- Jet energy resolution (ILD-like):

$$\frac{\Delta E_j}{E_j} = \frac{0.30}{\sqrt{E_j}}$$

Signal and background simulations

- b-tagging efficiency: we present the results with 80% and 60% for jets with $p_T > 10$ GeV and $|\eta| < 2.5$.
- A misidentification rate of 1% is taken for light jets.
- 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.
$tq\gamma$	$2154(\lambda_{tq})^2$	4879.2	$3832(\lambda_{tq})^2$	3283.7	$4302(\lambda_{tq})^2$	2197.3
$tqZ\ (\sigma_{\mu\nu})$	$1434(\kappa_{tq})^2$	4879.2	$2160(\kappa_{tq})^2$	3283.7	$2282(\kappa_{tq})^2$	2197.3
$tqZ\ (\gamma_\mu)$	$916(X_{tq})^2$	4879.2	$786(X_{tq})^2$	3283.7	$464(X_{tq})^2$	2197.3

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

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

Simulation and event selection

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

$$p_T^{l=e,\mu} \geq 10GeV - |\eta_{e,\mu}| \leq 2.5, p_T^{jets} \geq 10GeV - |\eta_j| \leq 2.5$$

-In addition to these cuts, to have well separated objects, we require $\Delta R > 0.4$.

- One isolated charged lepton is required.

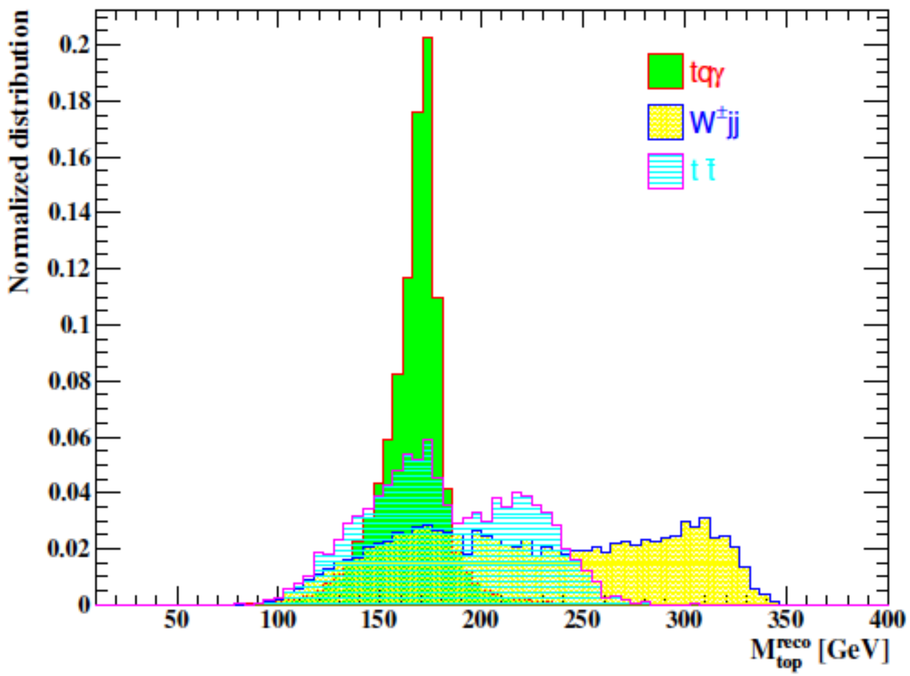
-To suppress ttbar background events, number of jet is required to be exactly two.

-To reconstruct top quark, the highest p_T b-tagged jets is chosen in case of more than one b-tag.

-In case of no b-tag jet, the one which gives closest mass to top quark mass is selected.

Event reconstruction

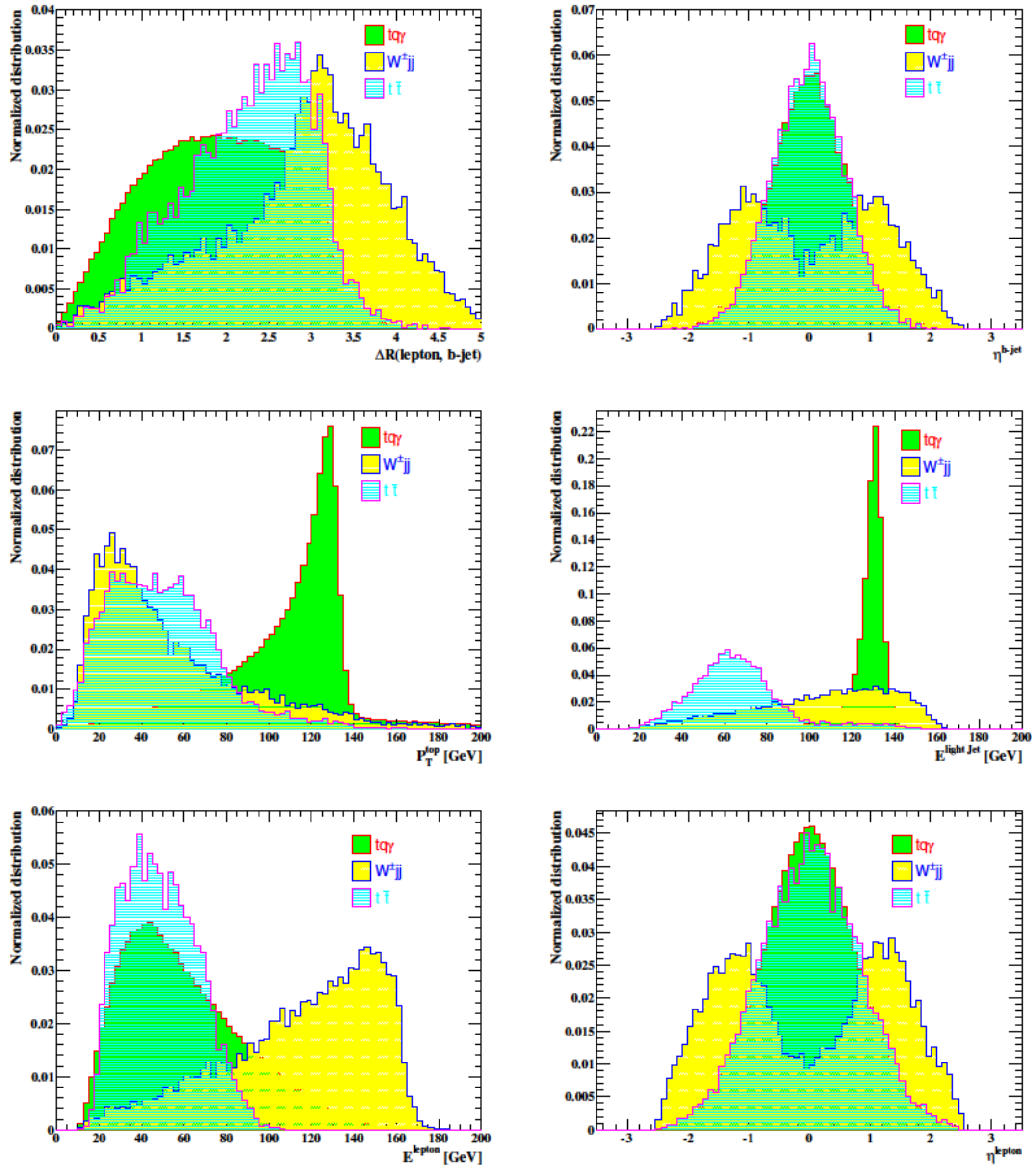
$\sqrt{s}$	240 GeV		350 GeV		500 GeV	
FCNC couplings	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.	σ(fb) Signal	σ(fb) Bkg.
$tq\gamma$	$1040.4(\lambda_{tq})^2$	60.94	$1892.5(\lambda_{tq})^2$	62.04	$2099.8(\lambda_{tq})^2$	36.02
$tqZ\ (\sigma_{\mu\nu})$	$691.4(\kappa_{tq})^2$	60.94	$1064.6(\kappa_{tq})^2$	62.04	$1107.5(\kappa_{tq})^2$	36.02
$tqZ\ (\gamma_{\mu})$	$439.9(X_{tq})^2$	60.94	$383.1(X_{tq})^2$	62.04	$219.5(X_{tq})^2$	36.02



Signal Optimization

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

- Top Mass
- $\Delta R(W,b)$
- η_b
- p_T^{top}
- E_{lepton}
- E_{jet}
- η_l



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.
$tq\gamma$	$964.4(\lambda_{tq})^2$	10.69	$1820.4(\lambda_{tq})^2$	4.33	$1932.6(\lambda_{tq})^2$	2.09
$tqZ\ (\sigma_{\mu\nu})$	$632.4(\kappa_{tq})^2$	9.76	$1020.9(\kappa_{tq})^2$	4.39	$1022.5(\kappa_{tq})^2$	2.20
$tqZ\ (\gamma_\mu)$	$398.1(X_{tq})^2$	9.44	$361.4(X_{tq})^2$	5.33	$200.8(X_{tq})^2$	2.28

Upper limits

In order to set upper limit on the branching ratios, we use the CL_S method 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**:

NEW

$\sqrt{s}$ (GeV)	240	350	500
$Br(t \to q\gamma)$	2.23×10^{-4}	2.15×10^{-5}	1.04×10^{-5}
$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	2.72×10^{-4}	3.69×10^{-5}	1.86×10^{-5}
$Br(t \to qZ)$ (γ_{μ})	4.73×10^{-4}	1.58×10^{-4}	1.21×10^{-4}

OLD

$\sqrt{s}$ (GeV)	240	350	500
$Br(t \to q\gamma)$	5.9×10^{-4}	2.3×10^{-5}	8.9×10^{-6}
$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	8.8×10^{-4}	6.7×10^{-5}	1.4×10^{-5}
$Br(t \to qZ)$ (γ_{μ})	1.4×10^{-3}	1.9×10^{-4}	8.4×10^{-5}

b-tag eff = 70%, mistag=5%

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

Limits versus b-tagging efficiency

Upper limits on the branching ratios under the assumption of 60% b-tag efficiency:

$\sqrt{s}$	$Br(t \to q\gamma)$	$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	$Br(t \to qZ)$ (γ_μ)
350 GeV	6.64×10^{-5}	1.40×10^{-4}	1.67×10^{-4}

B-tagging efficiency of 80%:

$\sqrt{s}$ (GeV)	240	350	500
$Br(t \to q\gamma)$	2.23×10^{-4}	2.15×10^{-5}	1.04×10^{-5}
$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	2.72×10^{-4}	3.69×10^{-5}	1.86×10^{-5}
$Br(t \to qZ)$ (γ_μ)	4.73×10^{-4}	1.58×10^{-4}	1.21×10^{-4}

Decreasing the b-tagging efficiency from 80% to 60% have a considerable effect on the results.

CMS PAS FTR-13-016

Comparison with LHC Future results

$\mathcal{B}(t \to Zq)$	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	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$

LHC tqγ limits: $BR(t \to u\gamma) < 0.0161\%$, $BR(t \to c\gamma) < 0.182\%$.

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

With 3 ab^{-1} at 350 GeV: BR(t→qγ) < 3.3×10^{-6} and BR(t→qγ) < 4.42×10^{-6}

Summary

- We repeated the analysis including a raw detector simulation with Delphes.
- We can achieve upper limits on the branching ratios down to 10^{-6} with 3 ab^{-1} at the center-of-mass energy of 350 GeV.
- The results are sensitive to b-tagging efficiency so that decreasing b-tag efficiency leads to make the bounds looser by a factor 3-5.
- Including charm tagging to the Delphes card to be able to probe tuV and tcV separately→

To be done