Search for FCNC Interactions at the FCC-ee

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Outline of the talk

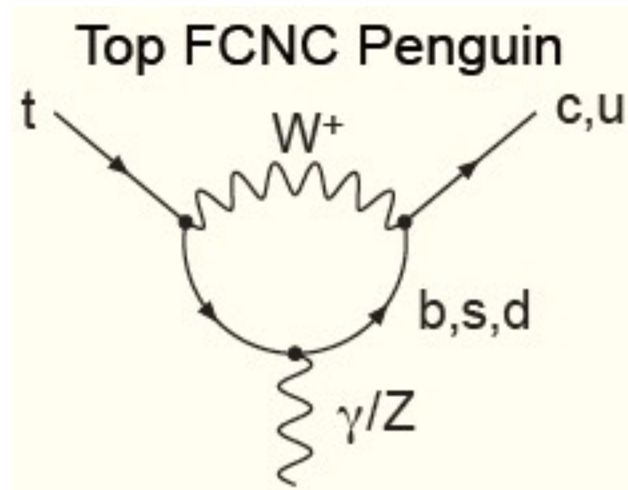
- Introduction: Flavor-Changing Neutral Current
- FCNC and New Physics
- Experimental Searches for FCNC
- Comparison with the LHC
- Summary and Plans

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: $t \to cH$, $t \to u\gamma$, $t \to uZ$ …**
- **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

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

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.**

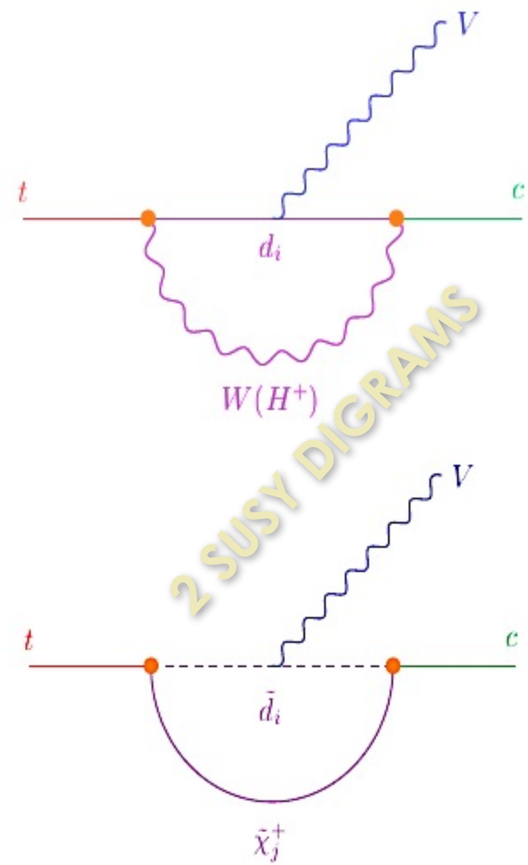
Example:

➢ **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.**



Analysis in FCC-ee

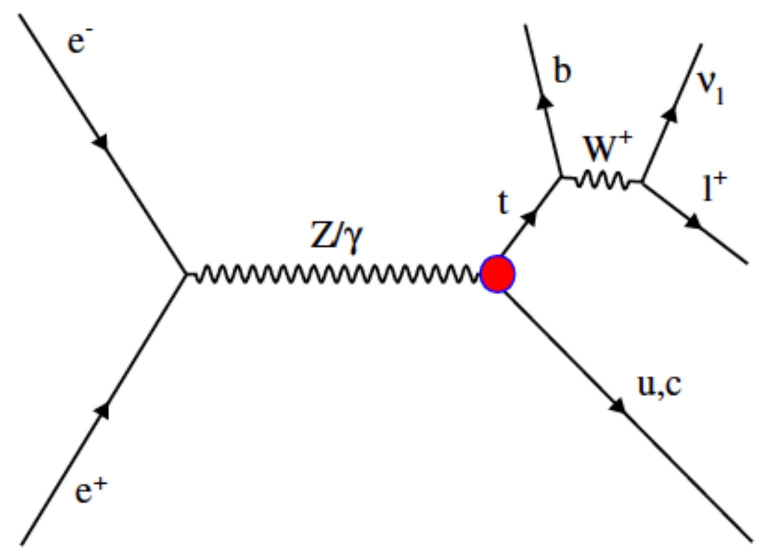
The anomalous FCNC couplings of a top quark with a photon and Z boson can be written in a model independent way using an effective Lagrangian approach.

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

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

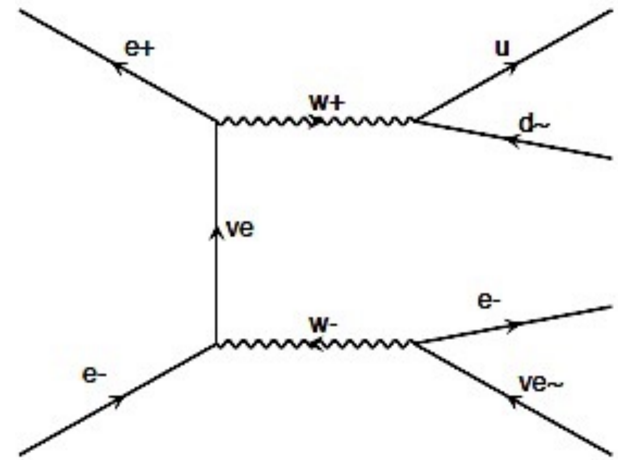
Based on the expected signature of the signal events, the main background contributions are originating from:

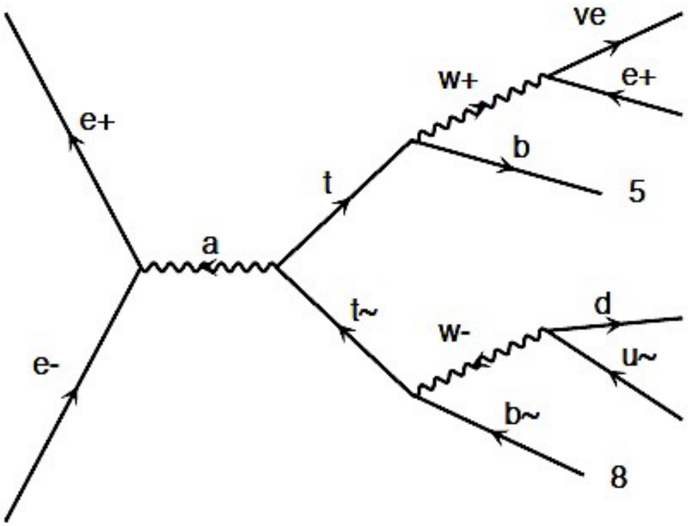
-WW production when one of the W bosons decays hadronically and another one decays leptonically, i.e.

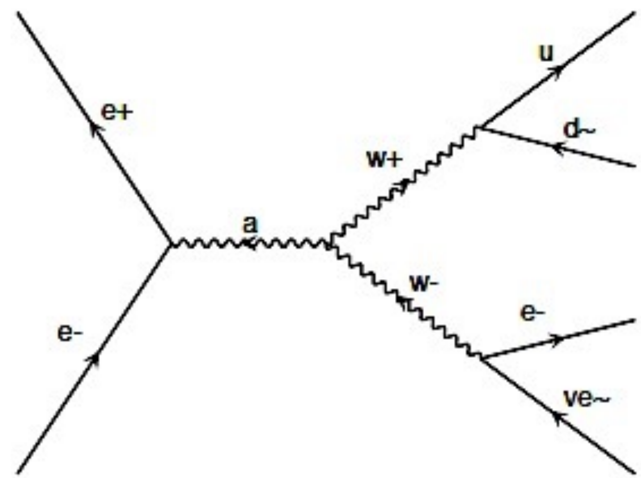
$-e^+e^- \rightarrow W^+W^- \rightarrow l\nu_l + jj.$

Depending on the center of mass energy there is also a significant contribution from top pair production:

$-e^-e^+ \rightarrow ttbar \rightarrow l\nu_l + jets$







$Z+l^+l^-$ will be added to the backgrounds

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.

-The detector simulation is obtained using a preliminary Delphes card (now available in the FCCsoftware for further validation and testing).The parameters used are:

- Magnetic field: 5 T (currently redoing the analysis with 3 Tesla)
- ECAL CMS inspired
- HCAL ILD inspired
- B-tagging efficiency of 80% and 60% (pt>10 and |eta|<2.5)
- Mis-tagging efficiency of 1% for light quarks. It is important also to see the effect of a 5% charm mis-tagging efficiency (in progress)
- Also, this channel is a benchmark for the study of the charm-tagging efficiency (in progress).
- Jets are reconstructed with FastJet with anti-kt with a cone of R=0.4

Cross sections of signal & backgrounds

Total 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**.

Event selection

-Now, we apply the following detector acceptance cuts on the final state objects: one lepton and only two jets

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

-In addition to these cuts, to have well separated objects, we require $\Delta R > 0.4$ (distance among all objects)

- Only one isolated charged lepton is required. Veto extra leptons.

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

- since only one FCNC vertex is allowed in the event, the top quark is reconstructed with its SM decay t->Wb

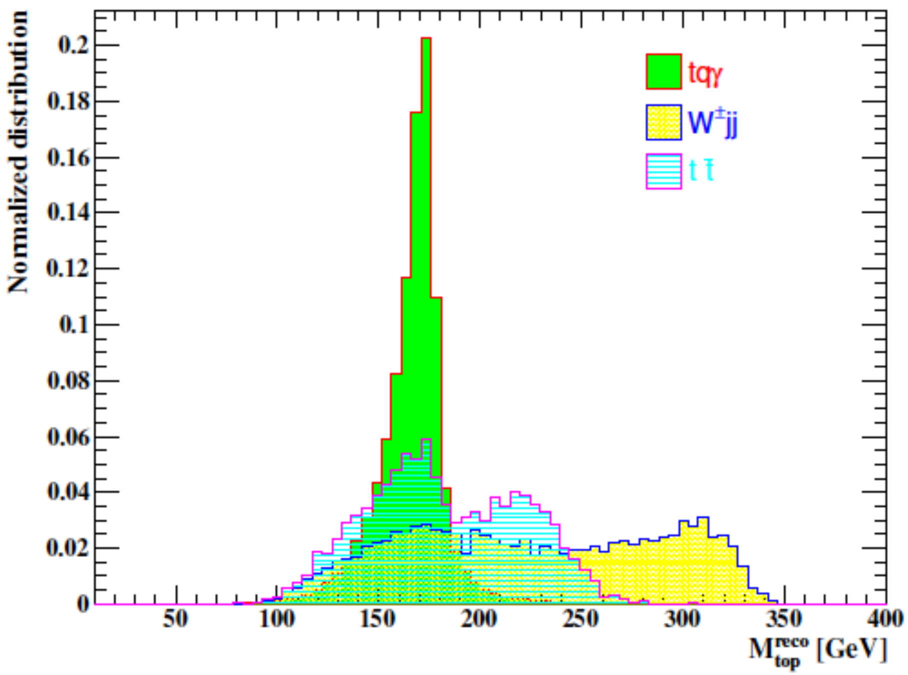
  -To reconstruct top quark, the highest p_T b-tagged jets is chosen in case of more than one b-tag.

  -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

Reconstructed top mass distribution for signal and backgrounds at 350 GeV

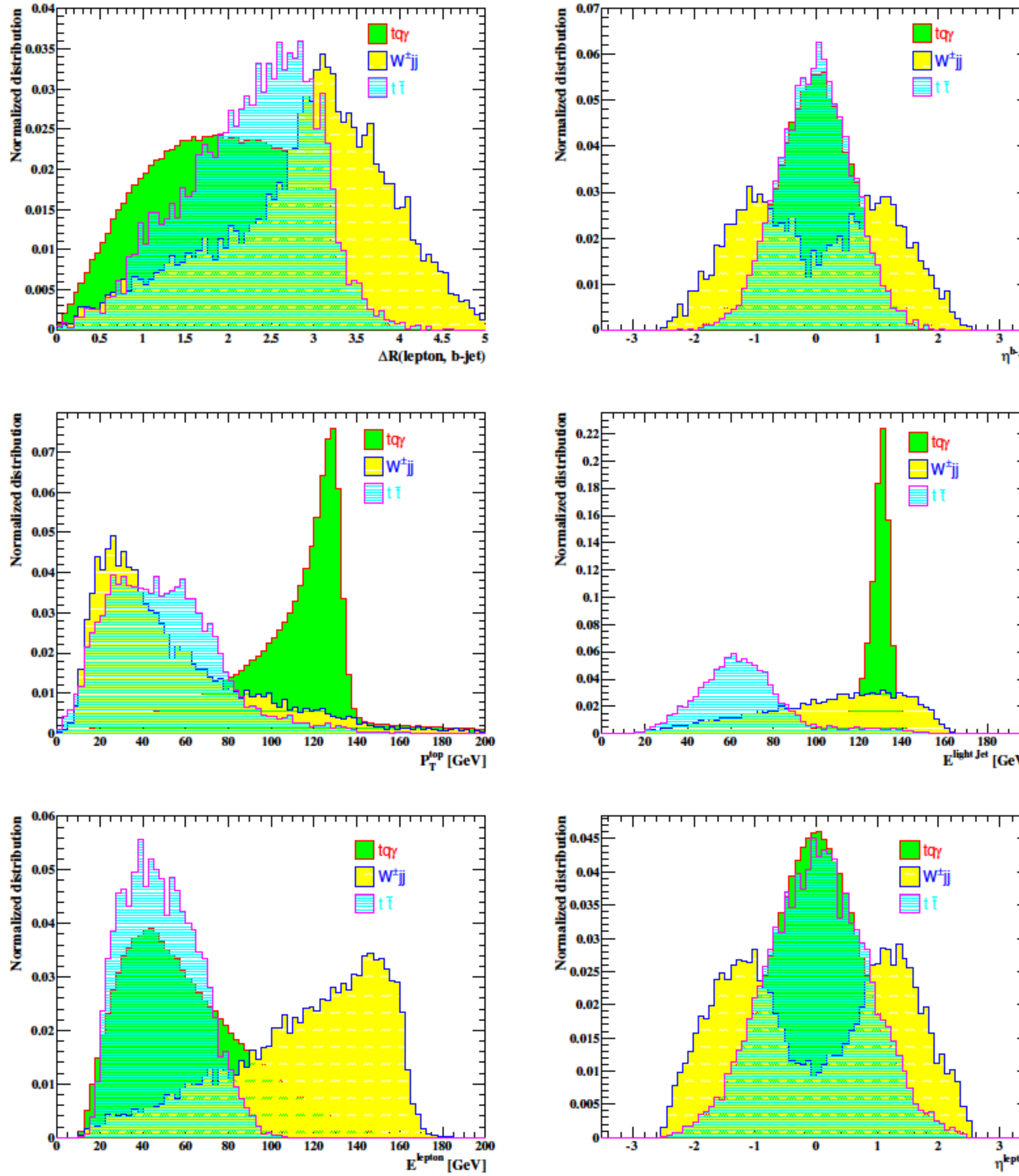


Signal Optimization

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

<u>Personal note:</u> this analysis is still very much « hadron collider » style. possibly the use of different strategy profiting of the lepton collider environment would provide a simpler and even more effective result.



Signal and background rates after optimization

After the MVA analysis, a signal efficiency of around **90%** and a background efficiency of **1-3%** are achieved, depending on the signal scenario and the center-of-mass energy of the electron-positron machine. 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**:

$\sqrt{s}$ (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}

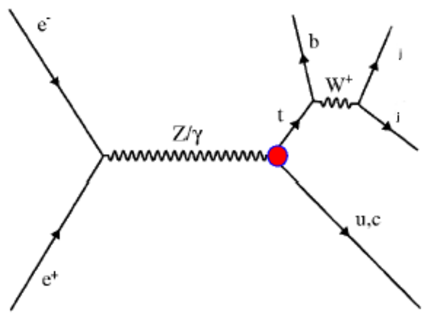
Upper limits on the branching ratios under the assumption of 60% b-tag efficiency for only the center-of-mass energy of 350 GeV:

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

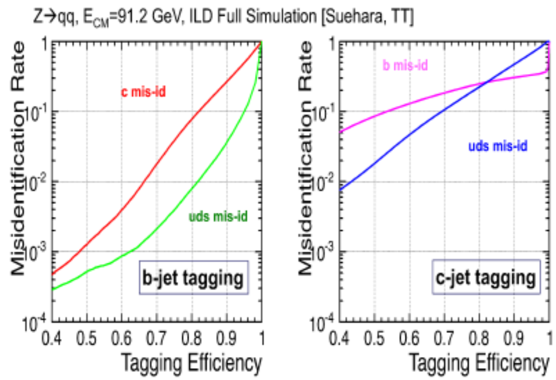
Decreasing the b-tagging efficiency from 80% to 60% leads to slightly looser limits.

Top FCNC in hadronic final state: a first look (Biswas, Margaroli, Mele - Roma 1)

Signal $e^+e^- \to tj \to jjjj$.



Higgs Hadronic Decays: Flavor Tagging



ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

Background $e^+e^- \to Wjj \to jjjj$ cross-section = 686.77 fb

For this channel the b-tagging and c-tagging are clearly more crucial.
A 80% b-tagging and 10% c-tagging mistag have been used (taken from ILD studies)
Work in progress…results soon….

Comparison with the LHC Results

CMS PAS FTR-13-016

95% CL upper limits on the branching ratios from LHC and FCC-ee:

	LHC8,19.7/fb	LHC14,300/fb	LHC14,3/ab	FCC-ee, 350GeV, 100/fb	FCC-ee, 350GeV,3/ab
Br(t→Zq)	10^{-3}	2.7×10^{-4}	1×10^{-4}	3.69×10^{-5}	4.42×10^{-6}
Br(t→γq)	1.6×10^{-4} (q=u)	---	---	2.15×10^{-5}	3.3×10^{-6}

Summary and Plans

- At the FCC-ee, 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.
  - Analysis can be further optimized and combined with the hadronic channel. These limits can still be improved significantly.

- This analysis can be used as a benchmark for detector studies and simulation validation:
  - 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.
  - Need to study the effect of different charm quark efficiency and mis-id.
  - Need to study the effect of a different magnetic field and detector resolutions

Backup

Effective Lagrangian

[Acta Phys.Polon.B35(2004)2695]

The most general effective Lagrangian to describe the top FCNC interactions can be modeled as (keeping up to dim 5 operators)

$$-\mathcal{L}^{\text{eff}} = \frac{g}{2c_W}\mathcal{X}_{qt}\,\bar{q}\gamma_\mu(x^L_{qt}P_L + x^R_{qt}P_R)tZ^\mu + \frac{g}{2c_W}\kappa_{qt}\,\bar{q}(\kappa^v_{qt} + \kappa^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}tZ^\mu$$
$$+e\lambda_{qt}\,\bar{q}(\lambda^v_{qt} + \lambda^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}tA^\mu + g_s\zeta_{qt}\,\bar{q}(\zeta^v_{tq} + \zeta^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}T^a qG^{a\mu}$$
$$+\frac{g}{2\sqrt{2}}g_{qt}\,\bar{q}(g^v_{qt} + g^a_{qt}\gamma_5)tH + \text{H.c.}$$

The corressponding branching ratios are related to the couplings as

$$\text{Br}(t \to qZ)_\gamma = 0.472\ \mathcal{X}^2_{qt}$$
$$\text{Br}(t \to qZ)_\sigma = 0.367\ \kappa^2_{qt}$$
$$\text{Br}(t \to q\gamma) = 0.428\ \lambda^2_{qt}$$
$$\text{Br}(t \to qg) = 7.93\ \zeta^2_{qt}$$
$$\text{Br}(t \to qH) = 3.88 \times 10^{-2}\ g^2_{qt}$$

(assuming $\Gamma^t_{tot} = \Gamma(t \to bW^+) = 1.61$ GeV)