Probing the top quark FCNC anomalous couplings at FCCee

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in collaboration with

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FCC-France & Italy Workshop on Higgs, Top, EW, HF Physics, Nov 21-23, 2022, IP2I Lyon

Outline

- The top quark FCNCs in the SM and Beyond
- The effective Lagrangian approach

New PHYSICS

- Most recent ATLAS and CMS experimental results on the top FCNC interactions

  CMS: 2112.09734 [hep-ex], JHEP 02 (2022) 169 & ATLAS: ATLAS-CONF-2022-003

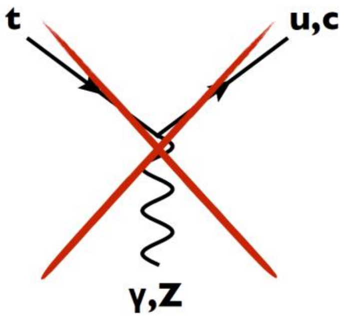
- The signal scenario and SM backgrounds
- FCNC analysis framework and object selections
- Sensitivity estimation and limit results

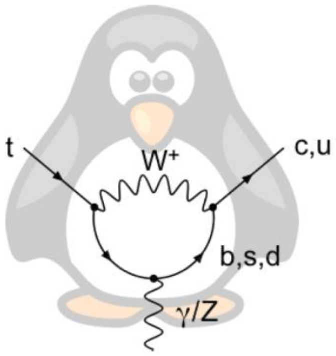
FCNC Study @ FCC-ee

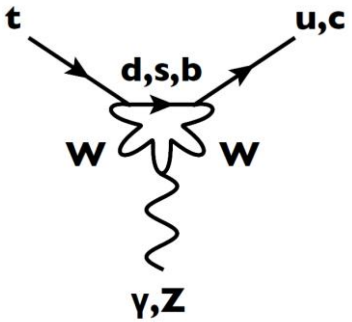
- Summary and Conclusion

The top quark FCNCs

- The Flavor-changing neutral current (FCNC) process is forbidden at tree level in the SM and is highly suppressed in one-loop corrections by the Glashow-Iliopoulos-Maiani mechanism.
- The FCNC interactions of the tqX vertex (where *q* represents up and charm quarks) are key processes to search for New Physics.







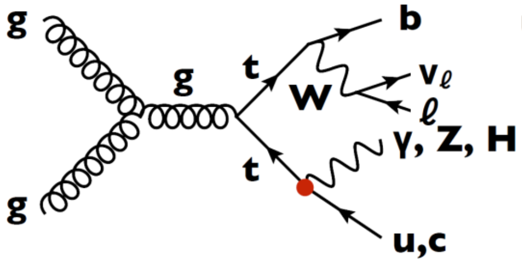
- The SM expected top quark FCNC transition is far from the sensitivity of the current experiments.
- The FCNC decay rates can be significantly enhanced in some New Physics models.
- The observation of a top quark FCNC interaction would signal the existence of New Physics.

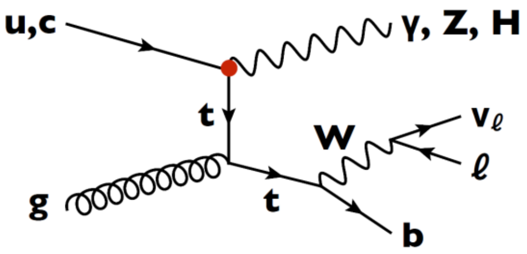
	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

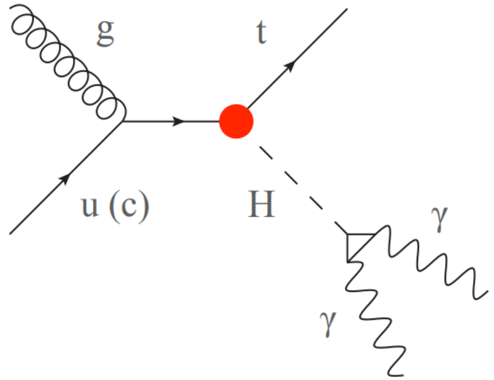
Aguilar-Saavedra J.A., Top flavor-changing neutral interactions: Theoretical expectations and experimental detection. *Acta Physica Polonica* B, 35 (2004) 2695.

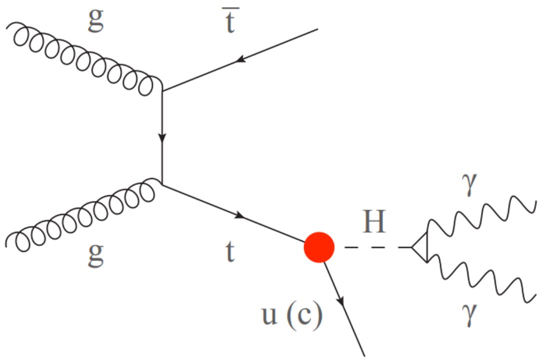
Summary of ATLAS and CMS results

- Over the years, various experiments have searched for the FCNC processes through the anomalous production or decay of top quark.
- No clear evidence for the presence of top quark FCNC interactions is observed and upper limits are set on the anomalous couplings and top quark branching ratio.







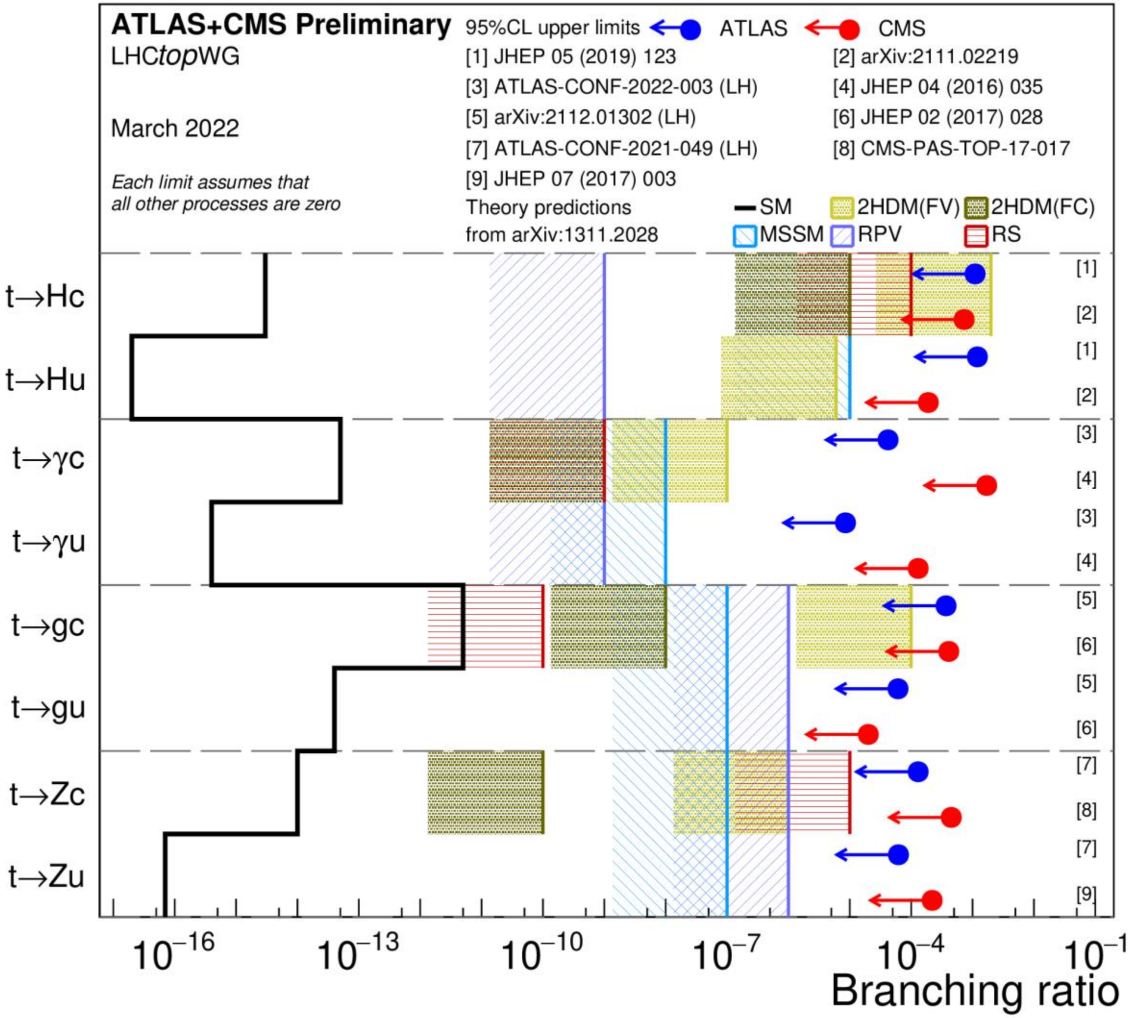


Boson	Best Limit on the BR (95% CL)		
γ	ATLAS 81 fb^{-1}, focus on $\sigma_{t+boson}$	~0.3 x 10^{-4} (up)	~2 x 10^{-4} (charm)
Z	ATLAS 36 fb^{-1}, focus on BR	~2 x 10^{-4} (up)	~2 x 10^{-4} (charm)
Higgs	CMS 137 fb^{-1}, $H \to \gamma\gamma$	~2 x 10^{-4} (up)	~7 x 10^{-4} (charm)
gluon	CMS Run-1, top+jet production	~0.2 x 10^{-4} (up)	~4 x 10^{-4} (charm)

ATLAS Collaboration, Phys. Lett. B 800 (2020) 135082, 1908.08461 [hep-ex].
ATLAS Collaboration, ATLAS-CONF-2022-003 & ATLAS-CONF-2022-013.
ATLAS Collaboration, CMS-TOP-20-007, 2111.02219 [hep-ex].
ATLAS Collaboration, JHEP02 (2022) 169, 2112.09734 [hep-ex].

The SM & beyond the SM & Experimental results

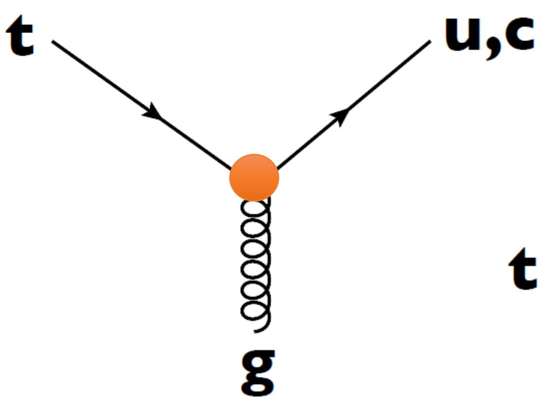
- Several extensions of the SM predict much higher branching ratios up to 10^8 - 10^9 order of magnitude larger than SM predictions
- Any observation of these rare FCNC transitions would be a clear signal of new physics beyond the SM.

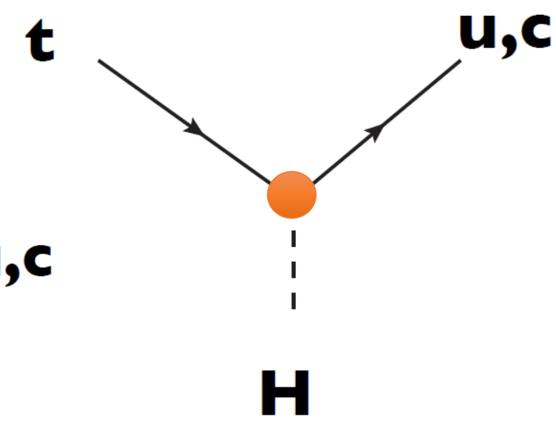


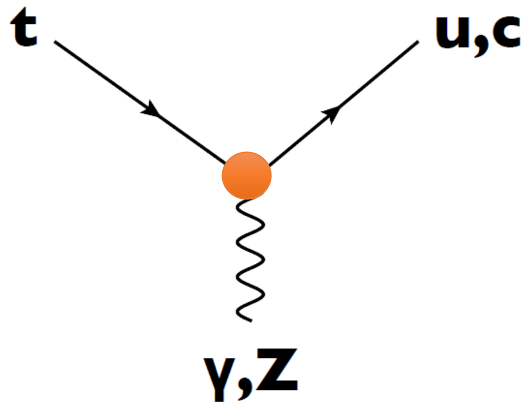
The Effective Lagrangian Approach

- The most general effective Lagrangian describing the FCNC interactions can be parametrized as

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



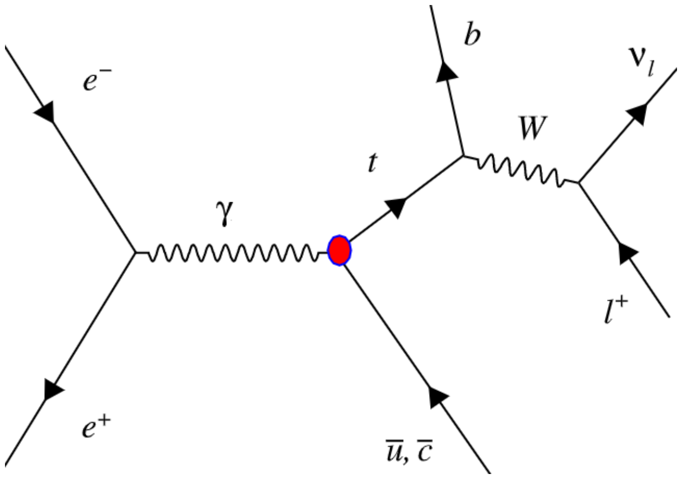


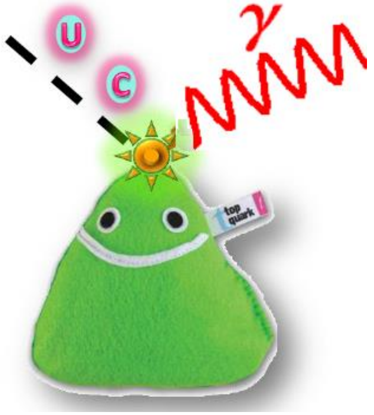


- Focusing on the $tq\gamma$ interactions, deviation from the SM predictions due to FCNC transitions involving the top quark can be parameterized in terms of anomalous couplings and described by an effective Lagrangian of the form:

$$\frac{e}{2m_t}\bar{q}\sigma^{\mu\nu}(\lambda_{qt}^{L}P_L + \lambda_{qt}^{R}P_R)tA_{\mu\nu}$$

- The λ_{ut} and λ_{ct} are the dimensionless real parameters which determine the strength of FCNC interactions with photon.





- The top quark decay width at leading order in SM is:

$$\Gamma(t \to bW^+) = \frac{\alpha}{16\, s_W^2} |V_{tb}|^2 \frac{m_t^3}{M_W^2} \left[1 - 3\frac{M_W^4}{m_t^4} + 2\frac{M_W^6}{m_t^6}\right]$$

- The top quark anomalous decay width at leading order is:

$$\Gamma(t \to q\gamma) \ = \ \frac{\alpha}{2} \left|\lambda_{qt}\right|^2 m_t$$

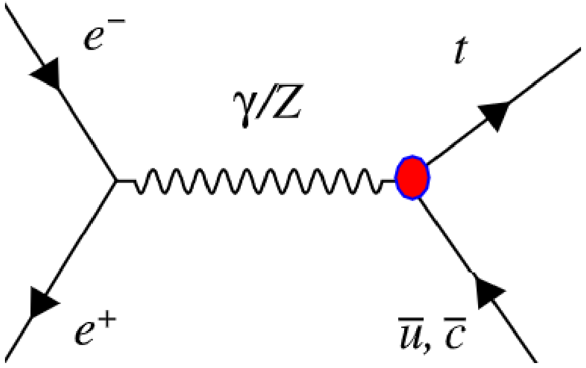
- The anomalous branching ratio of top quark decay is a function of anomalous coupling and can be written at leading order as:

$$\mathrm{BR}(t \to q\gamma) = 0.428\ \lambda_{qt}^2$$

FCNC@FCC-ee: the signal scenario

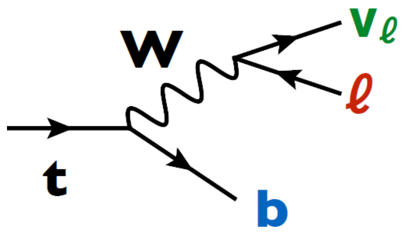
- The anomalous FCNC interaction $tq\gamma$ and tqZ lead to production of a top quark in association with a light quark (q=u, c) in electron- positron collisions.

- Planned phase of FCC-ee @ $\sqrt{s}$ = 240 GeV.



- We concentrate on the leptonic decay channel of the W boson in top quark.

$$e^-e^+ \to Z/\gamma \to t\bar{q}\ \ (\bar{t}q) \qquad t \to Wb \to \ell\nu_\ell b$$



The signal Monte Carlo samples and the main backgrounds

- In order to simulate and generate the signal events, the effective Lagrangian describing the FCNC couplings is implemented with the FeynRules package, then the model has been imported to a UFO module and inserted in MadGraph 5 package.
- The signal samples are generated for all top-quark FCNC scenarios at the center-of-mass energies of 240 GeV.
- All final signal Monte Carlo samples are generated in the FCCSW framework with DelphesPythia8_EDM4HEP and IDEA Delphes Card.
- Based on the expected signature of the signal events, the main backgrounds contributions are originating from:

Process	$\sqrt{s}$ (GeV)	Cross Section (pb)
ZH	240	0.201868
WW	240	16.4385
ZZ	240	1.35899
Single top	240	0.000010753
eeZ [eebb]	240	0.4557
eeZ [eeqq (q=u, d, s)]	240	1.6369

Official samples, spring 2021

HEP-FCC/
FCCAnalyses

FCNC analysis framework

- FCCAnalyses Framework (https://github.com/HEP-FCC/FCCAnalyses).

- Different recombination schemes are studied in this work: We focus on the E-scheme.

- Different jet algorithms available on FCCAnalyses framework are studied in this analysis: We focus on the ee-kt-Durham.

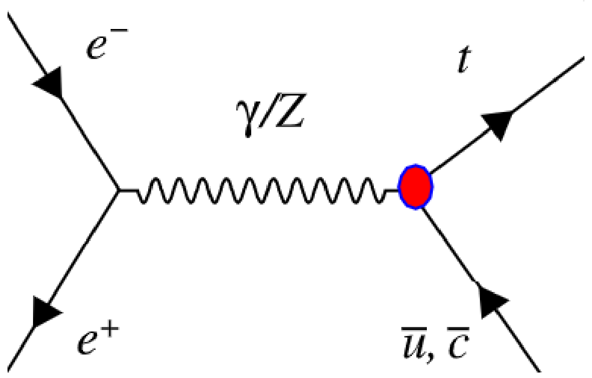
- The study is performed for the different light quark flavors (q= u and c) separately, and for the electron and muon channel as well.

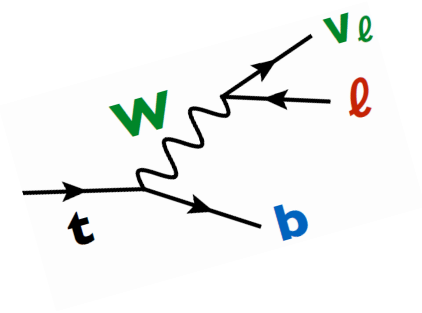
FCC

Software for Future Circular Colliders (hh, ee, he)

The object selection

- The top-FCNC signal signature: 1 lepton + 1 neutrino + jets ($n^{jets} = 2$) + 1 *b*-tag .

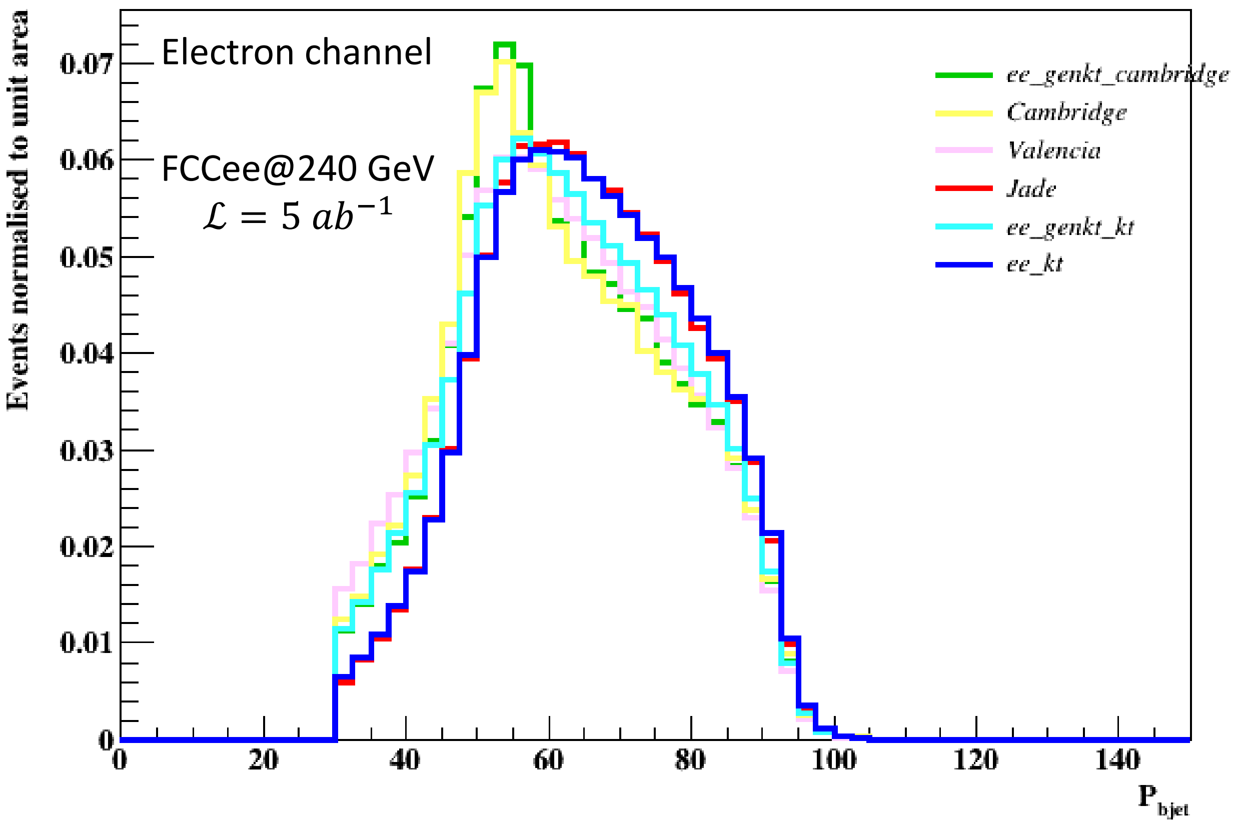


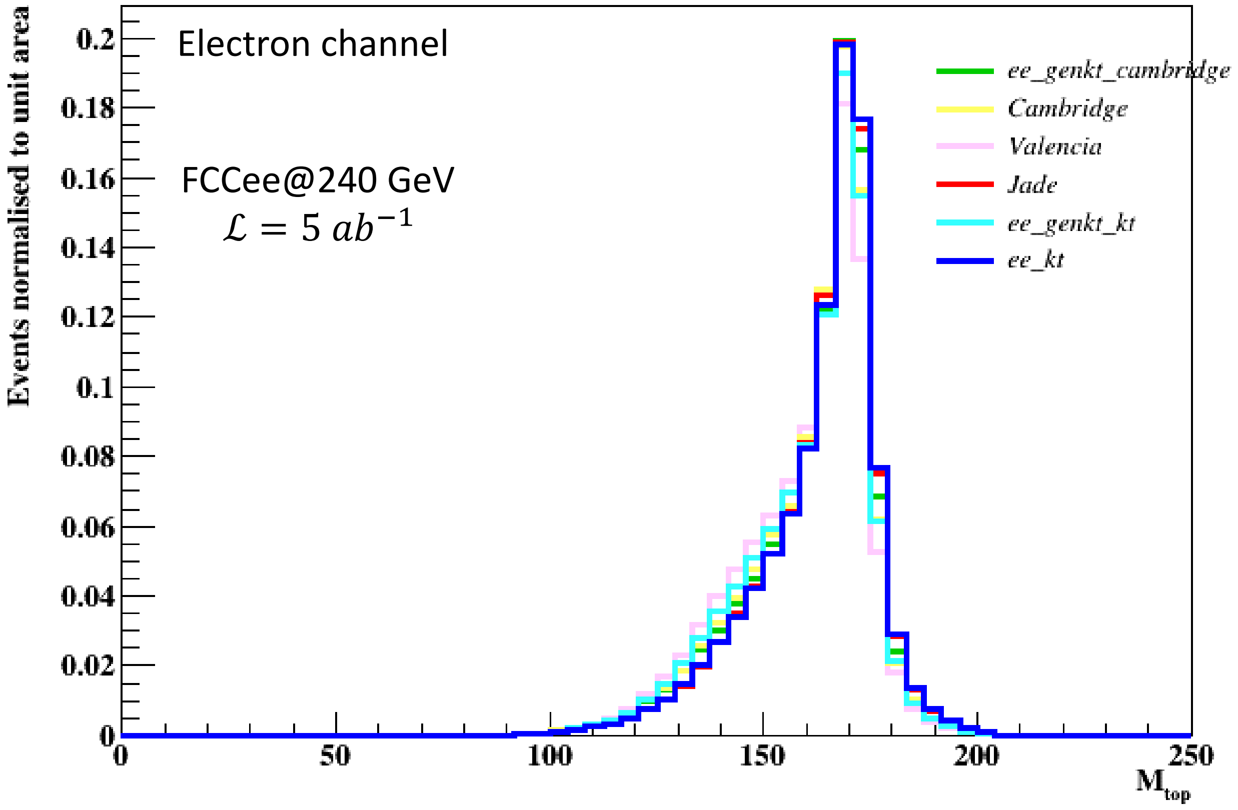


- The momentum of the lepton and jets: $p^l > 10$ & $p^{jets} > 10$.
- The polar angle of the lepton and jets: $\theta^l > 13$ & $\theta^{jets} > 13$.
- The angular separation between the lepton and jets $\Delta R(l,\ jets) < 0.3$.
- The angular separation between the lepton and jets $\Delta R(l,\ jets) > 0.5$.

Signature objects:
- 1 lepton
- 1 neutrino
- =2 jets
- 1 *b*-tag

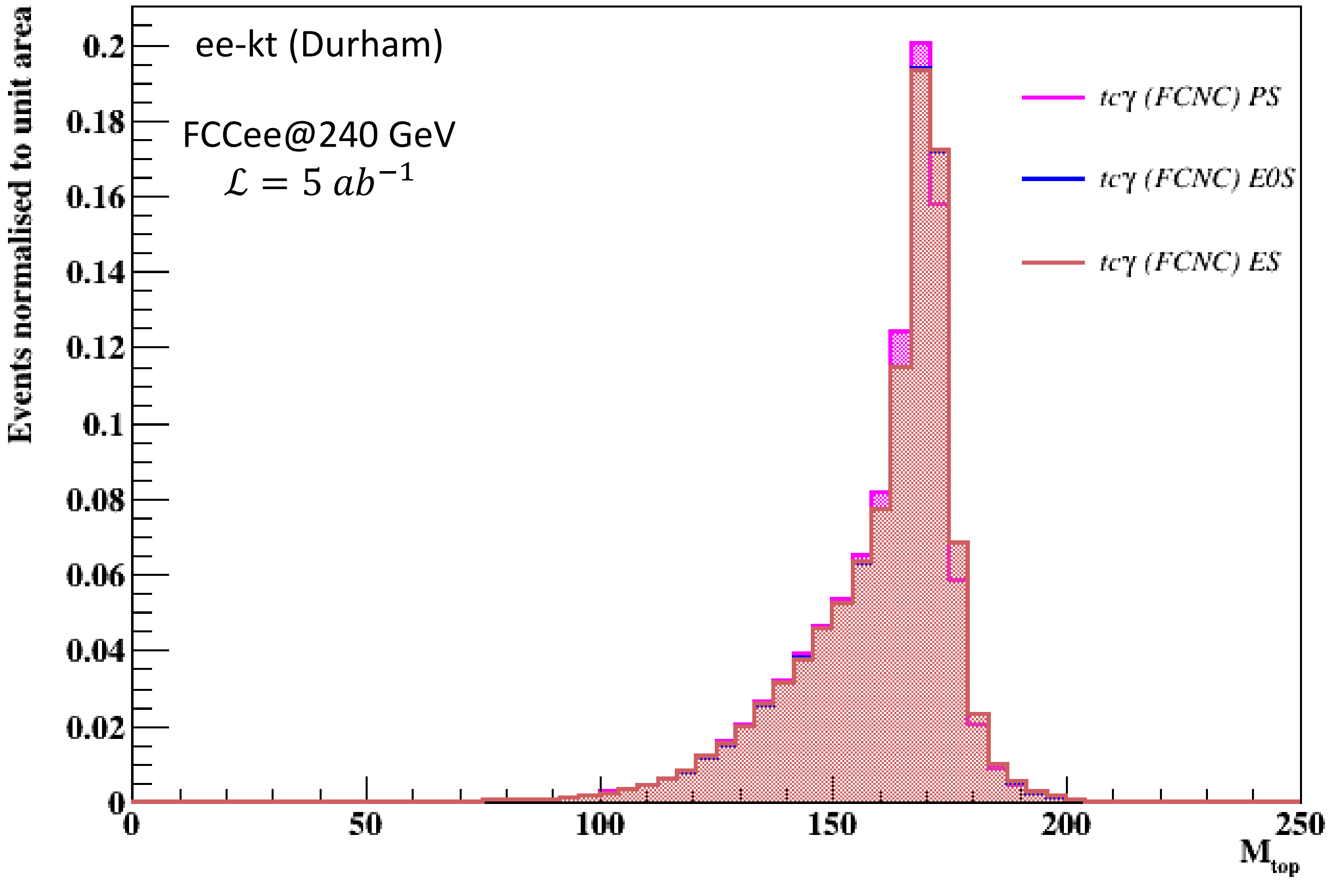
Jet clustering algorithms study: Comparison of different algorithms





The reconstructed top quark mass distributions and the momentum of b-jets candidate for $\boldsymbol{tc\gamma}$ signal.

Jet recombination schemes: Comparison of different scheme



Reconstructed op-quark mass distribution for three different schemes and for the $tc\gamma$ signal.

Jet definition & Signature objects

- Jet Definition = ee-kt (Durham) & E-scheme

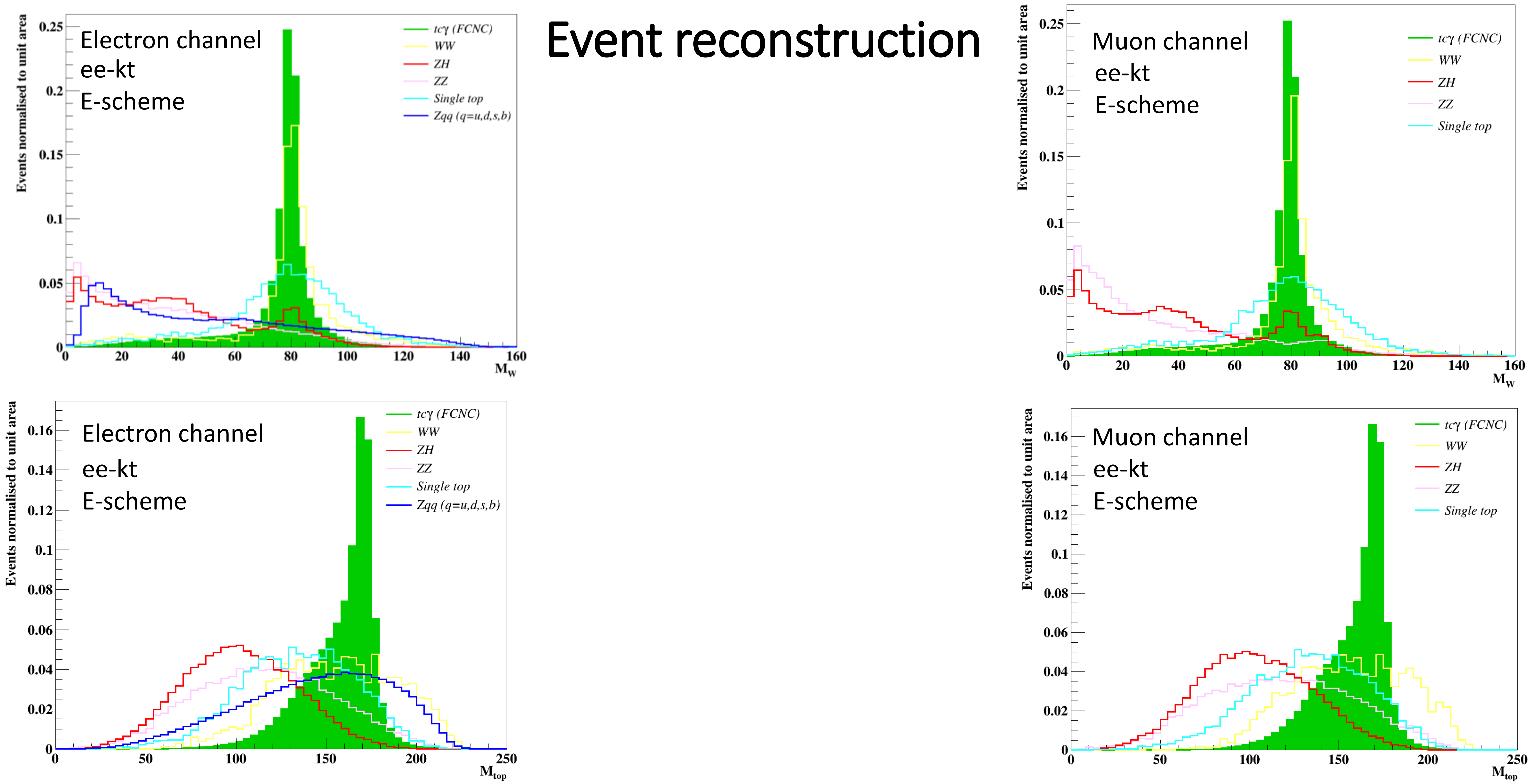
- Exclusive processes & exactly two jets

Signature objects:

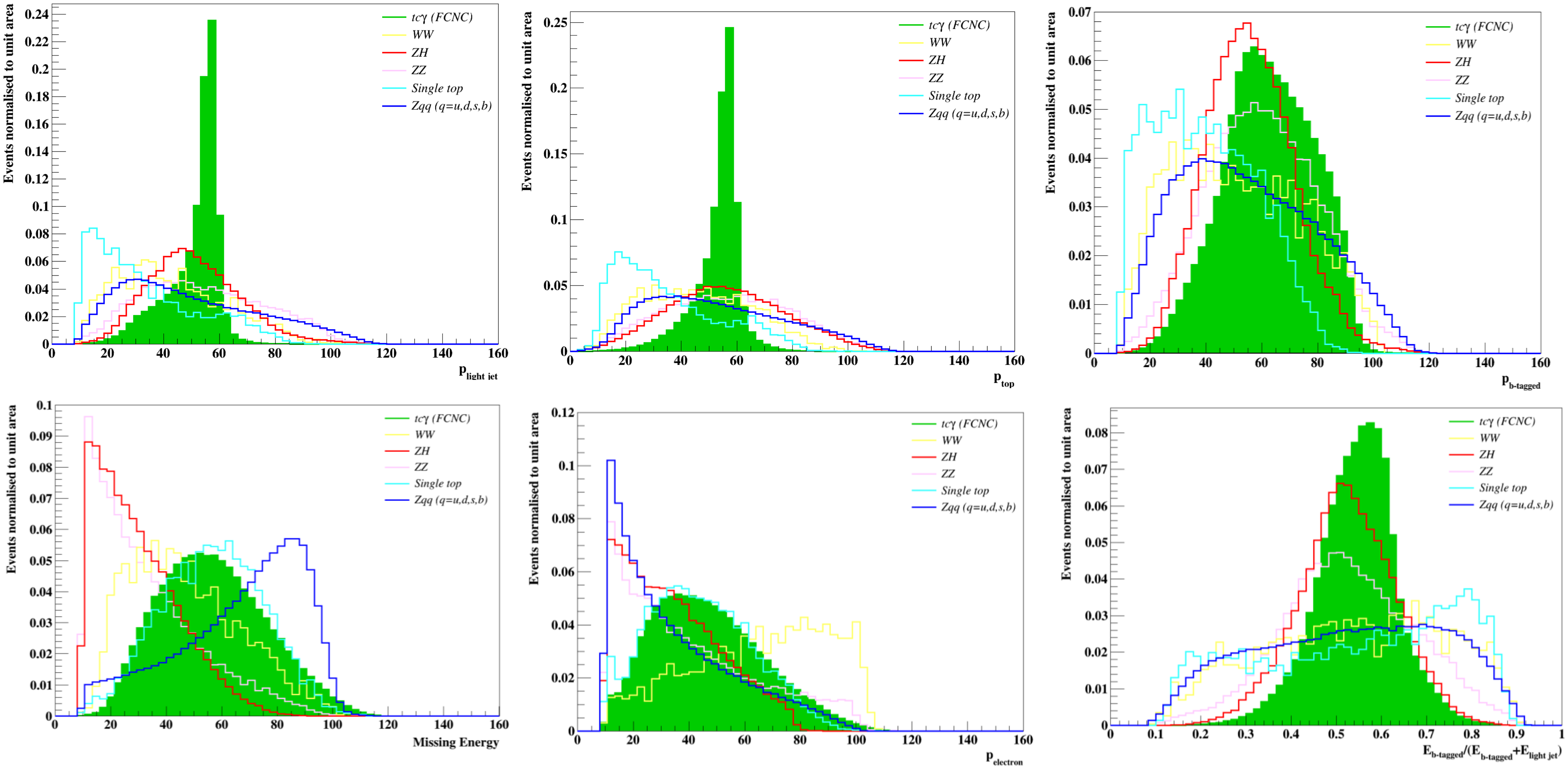
- 1 lepton (electron or muon)
- 1 neutrino
- $=$ 2 jets
- 1 *b*-tagged

The ‘exclusive’ Durham kt algorithm: Physics Performance meeting, June 2022, https://indico.cern.ch/event/1173562/

Event reconstruction



Reconstructed W and top boson mass distributions for signal and SM backgrounds for electron and muon channel.



The momentum of light jet, the momentum top quark, the momentum of b-jet candidate, the Missing Energy, the momentum of electron, and the energy ratio of *b*-jet to light jet for signal and the SM backgrounds.

Final selection cuts

We select those variables which have the best possible discrimination power between the signal and background processes. The following variables are used in the analysis:

- The reconstructed top-quark mass distribution $140 < M_{top}^{rec} < 190$
- The reconstructed W boson mass distribution $70 < M_{W}^{rec} < 90$
- The momentum of *b* jet candidate $p^{b-jet} > 40$
- The momentum of highest energy light jet in each event $p^{light-jet} > 40$
- The momentum of electron (or muon) $p^{electron} > 20$
- The Missing Energy $ME > 30$
- The angular separation between the lepton and *b*-jet $\Delta R(l,\ b-jet) < 3.5$

○ The energy ration of b-jet to light jet $0.35 < \frac{E_{b-jet}}{E_{b-jet}+E_{ligh\ jet}} < 0.70$

○ The scalar sum of momentum $H_T > 190$

The signal and SM backgrounds after final selection cuts

- Cross-sections (in fb) for the signal scenarios (electron channel) and the corresponding SM backgrounds passing sequential cuts.

Cuts	$tc\gamma$	tcZ	ZH	WW	ZZ	eebb	eeqq (q=uds)	Single top
$\sigma(fb)$	14.327	34.132	201.868	16438.5	1358.99	455.7	1636.9	0.010753
Preselection	3.1542	7.5154	1.1953	3.75948	2.76677	19.251	0.155146	0.0003208
Final selection	1.3686	3.2622	0.00847	0.254797	0.01127	0.1807	0.001439	3.2259×10^{-7}

Sensitivity estimation

- To estimate the sensitivities, the upper limits on the branching ratios at 95% C.L is calculated.

- In order to set 95% CL upper limits on the anomalous FCNC couplings and consequently on the branching ratios, the CLs technique is used.

- For the limits calculations the RooStats package is used.

- $\epsilon_{signal}, N_{bkgs}, \ldots$

A.L. Read, J. Phys. G 28 (2002) 2693.
B. Mistlberger, F. Dulat, arXiv:1204.3851 [hep-ph].
L. Moneta, et al., PoS ACAT 2010 (2010) 057, arXiv:1009.1003 [physics.data-an].

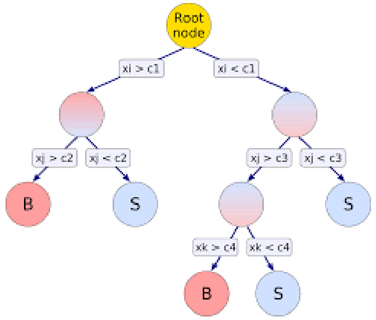
Limit results

- Results for the leptonic channel $[e^+e^- \rightarrow tq \rightarrow (bw)q \rightarrow (bl\nu_l)q]$ at $\sqrt{s} = 240$ GeV and for an integrated luminosity of $5\ ab^{-1}$.

FCC-ee (240 GeV)	$\boldsymbol{Br(t \rightarrow c\gamma)}$	$\boldsymbol{Br(t \rightarrow cZ)}$
Electron Channel	6.19×10^{-5}	2.27×10^{-5}
Muon Channel	4.45×10^{-5}	1.63×10^{-5}

- The limits for the $t \rightarrow u\gamma$ and $t \rightarrow uZ$ are the same order.
- The muon channel does not include the *eebb and eeqq (q=u, d, s)* backgrounds.
- We expect much better limits after the combination of these two channels.
- The limits would be improved using advanced technique, such as TMA analysis.

TMVA



Comparison with LHC & HE-LHC & FCC-hh

FCC-ee@240 GeV	$Br(t \to c\gamma)$	$Br(t \to cZ)$
Electron (e) Channel	6.19×10^{-5}	2.27×10^{-5}
Muon (μ) Channel	4.45×10^{-5}	1.63×10^{-5}

LHC results	$Br(t \to uZ)$	$Br(t \to cZ)$
ATLAS [ATLAS-CONF-2021-049]	6.20×10^{-5}	13×10^{-5}
LHC results	$Br(t \to uZ)$	$Br(t \to cZ)$
CMS [JHEP 07 (2017) 003]	2.20×10^{-4}	4.90×10^{-4}
	$Br(t \to u\gamma)$	$Br(t \to c\gamma)$
ATLAS [ATLAS-CONF-2022-003]	1.20×10^{-5}	4.5×10^{-5}

FCC-ee@240 GeV [3 ab^{-1}]	$Br(t \to q\gamma)$	$Br(t \to qZ)$
Physics Letter B 775 (2017) 25	3.70×10^{-5}	4.5×10^{-5}

HL-LHC [3 ab^{-1}] **@ 14 TeV**	$Br(t \to uZ)$	$Br(t \to cZ)$
Eur. Phys. J. C 77 (2017) 769	4.10×10^{-5}	1.60×10^{-3}
FCC-hh [10 ab^{-1}] **@ 100 TeV**	$Br(t \to uZ)$	$Br(t \to cZ)$
Eur. Phys. J. C 77 (2017) 769	2.70×10^{-6}	5.0×10^{-5}
HE-LHC [15 ab^{-1}] **@ 27 TeV**	$Br(t \to uZ)$	$Br(t \to cZ)$
Nucl. Phys. B 958 (2020) 115141	2.40×10^{-4}	1.56×10^{-3}
FCC-hh [10 ab^{-1}] **@ 100 TeV**	$Br(t \to u\gamma)$	$Br(t \to c\gamma)$
Nucl. Phys. B 958 (2020) 115141	6.26×10^{-4}	1.74×10^{-3}

Summary and Conclusion

- We presented the results for the leptonic (electron & muon) channel of single-top quark production via FCNC at FCC-ee.
- This study has been done in the official FCCAnalysis framework.
- At the FCC-ee, one can achieve upper limits on the branching ratios ($tc\gamma$ and tcZ) up to 10^{-5} with $5\ ab^{-1}$ at the center-of-mass energy of 240 GeV.
- We expect that the limits presented in this talk would be improved by considering the TMVA analysis.
- In terms of future work: FCNC@365 GeV and combination with the 240 GeV results & Uncertainty Estimations.

Thank you