Searches for Flavor Changing Neutral Currents in Top Quark Decays

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Possible FCNC Top Quark Decays

FCNC top decays to SM particles are of the form $t \rightarrow qX$

q is up or charm.

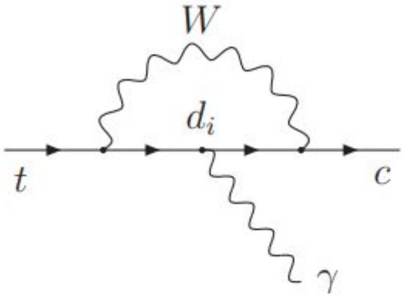
X is a neutral boson (gluon, photon, Z, Higgs)

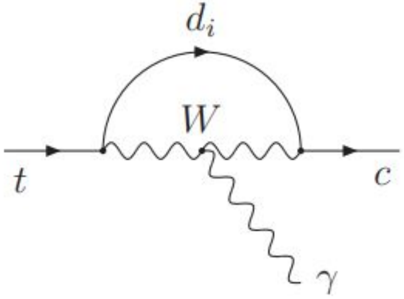
***t* Decay Modes** ▸ Expand all decays

	Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$Wq\,(q=b,s,d)$				
Γ_2	Wb				
Γ_3	$e\nu_e b$		$(11.10 \pm 0.30)\%$		
Γ_4	$\mu\nu_\mu b$		$(11.40 \pm 0.20)\%$		
Γ_5	$\tau\nu_\tau b$		$(10.7 \pm 0.5)\%$		
Γ_6	$q\bar{q}b$		$(66.5 \pm 1.4)\%$		
Γ_7	$\gamma q\,(q=u,c)$	[1]	$< 1.8 \times 10^{-4}$	CL=95%	
Γ_8	$H^+ b$, $H^+ \rightarrow \tau\nu_\tau$				
▾ **$\Delta T = 1$ weak neutral current ($T1$) modes**					
Γ_9	$Zq\,(q=u,c)$		$< 5 \times 10^{-4}$	CL=95%	
Γ_{10}	Hu		$< 1.2 \times 10^{-3}$	CL=95%	
Γ_{11}	Hc		$< 1.1 \times 10^{-3}$	CL=95%	
Γ_{12}	$\ell^+ \overline{q}\overline{q}'\,(q=d,s,b;\ q'=u,c)$		$< 1.6 \times 10^{-3}$	CL=95%	

[1] This limit is for $\Gamma(t \rightarrow \gamma q)/\Gamma(t \rightarrow Wb)$.

SM FCNC Top Decays



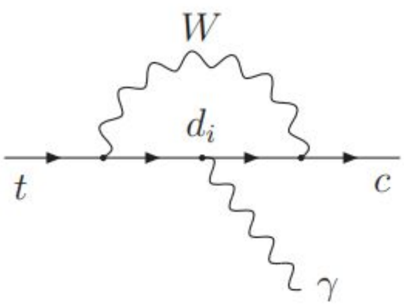


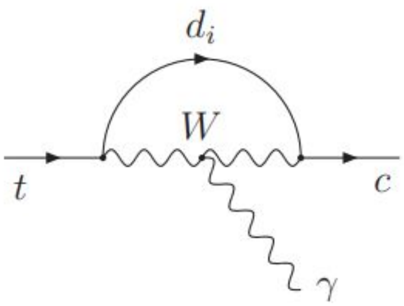
FCNC Top Decays in the SM are suppressed by a number of factors

- 1 loop processes - loop suppressed
- Involves off diagonal element of CKM matrix for the third generation - Cabibbo suppressed
- Sum over bottom type quarks in the loop - GIM suppressed

$$\sum_i V_{ti} V_{ci}^* = 0 \qquad \mathcal{M} \propto \sum_i V_{ti} V_{ci}^* f(m_i^2 / m_W^2)$$

SM FCNC Top Decays





Theoretical Branching Ratios have large uncertainties from the bottom mass and renormalization scale

- $BR(t \to c\gamma) = (4.6^{+1.2}_{-1.0} \pm 0.2 \pm 0.4^{+1.6}_{-0.5}) \times 10^{-14}$
- $BR(t \to cg) = 4.6 \times 10^{-12}$
- $BR(t \to cZ) = 10^{-14}$
- $BR(t \to cH) = 3 \times 10^{-15}$
- $BR(t \to uX) = 7.9 \times 10^{-3}$ $(BR(t \to cX))$

Experimental limits are at 10^{-4} at best.

$$\sum_i V_{ti} V_{ci}^* = 0 \qquad \mathcal{M} \propto \sum_i V_{ti} V_{ci}^* f(m_i^2 / m_W^2)$$

BSM FCNC Top Decays

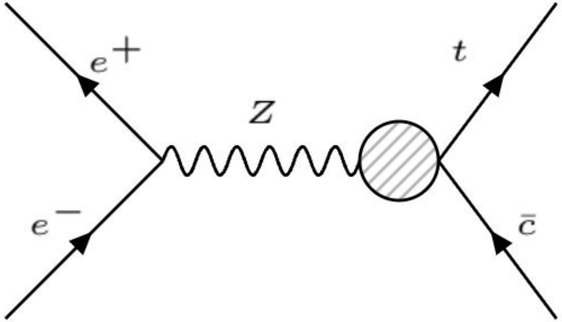
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

BSM models - particularly extensions to the Higgs sector - often feature enhanced FCNC couplings

FCNC interactions are an important constraint, and measurements of top quark can FCNC can be complementary to FCNC limits from light hadron decays.

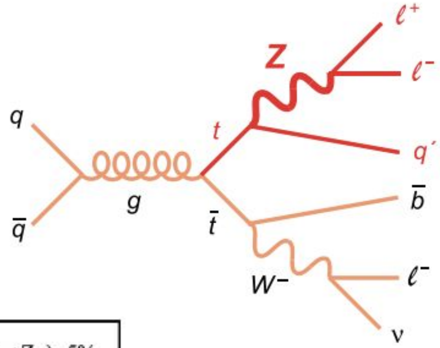
https://arxiv.org/pdf/1311.2028.pdf

Searching for t→qZ before the LHC



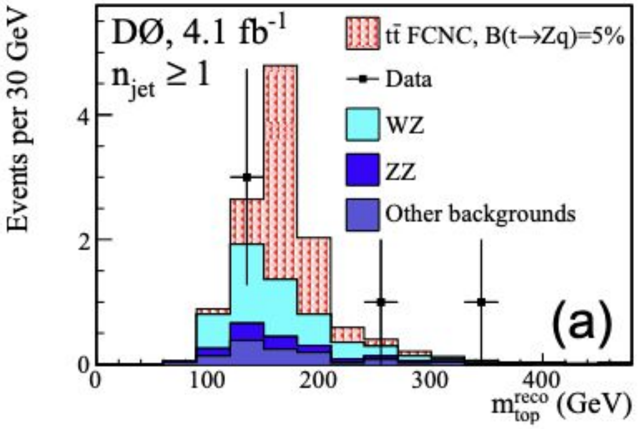
tqZ vertex can be searched for via single top production

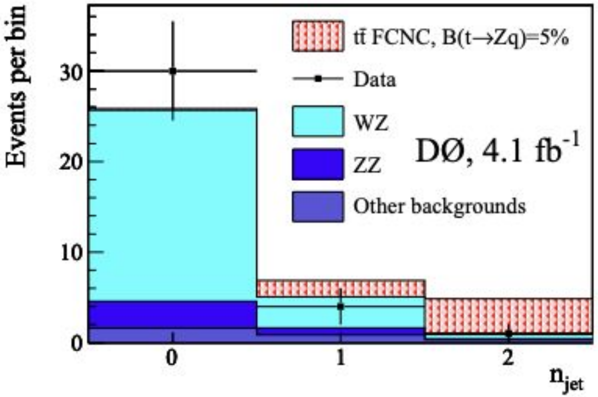
- Results from LEP searching for $e^+e^- \to tq$
- Would have constituted discovery of the top quark



D0 and CDF produced the direct constraints on FCNC Branching Ratios

- Best limit is 3% for tqZ





https://arxiv.org/pdf/1103.4574.pdf

Searching for t→qZ at the LHC

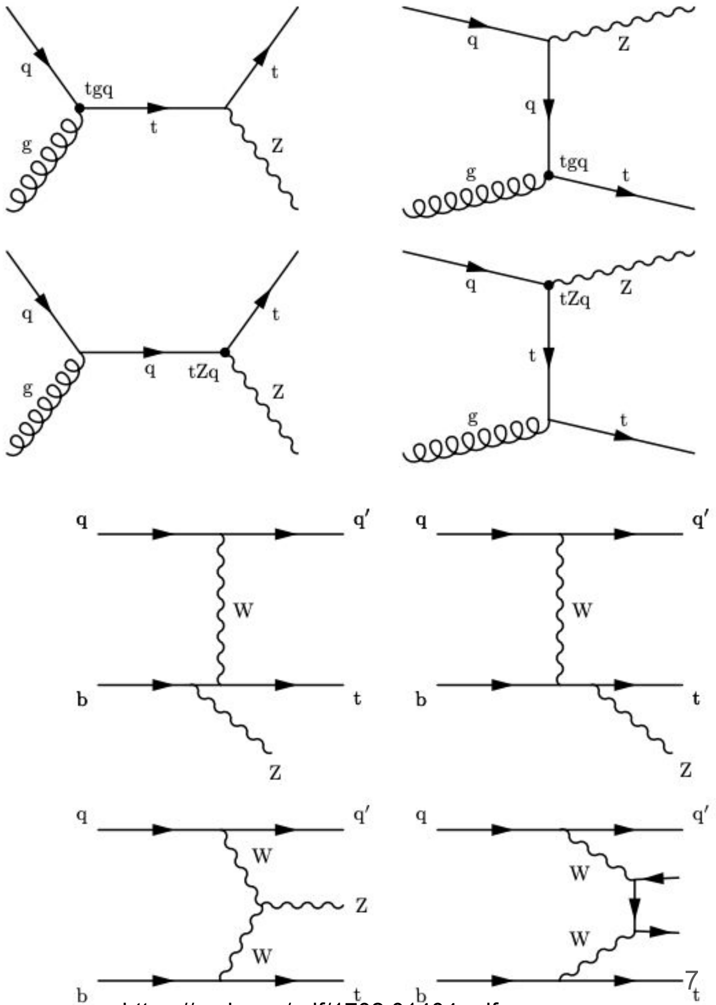
ATLAS and CMS both have results at √s = 7 and 8 TeV

Search channel is the same as at the Tevatron

- tt → bW qZ → blv ql^+l^-
- Final state has 3 leptons (1 pair OSSF), 2 jets (1 b-jet), and MET

CMS has additional constraints on the tqZ vertex from single top production at √s = 8 TeV

Strongest constraints come from ATLAS result on partial run 2 data at √s = 13 TeV



https://arxiv.org/pdf/1702.01404.pdf

ATLAS Run 2 t→qZ Search Signal Region Event Selection

Events are selected from single electron (muon) triggers with p_T thresholds of 24 (20) GeV in 2015 data and 26 (26) GeV in 2016 data as well as triggers with higher p_T thresholds and looser isolation requirements

Trilepton Cuts

- Leading lepton p_T > 25 (27) GeV in 2015 (2016)
- 3 isolated leptons with $|\eta| < 2.5$ and p_T > 15 GeV

Signal Region Cuts

- OSSF lepton pair with $|m_{ll} - m_Z| < 15$ GeV
- MET > 20 GeV
- ≥ 2 jets with p_T > 25 GeV and $|\eta| < 2.5$
- Exactly 1 b-tagged jet

ATLAS Run 2 t→qZ Search Event Reconstruction

The top two top quarks and the W boson are reconstructed by minimizing a □^{2} score for the mass peaks, where the masses are minimized over the assignments of objects as well as p_z of the neutrino.

The means and widths of the peaks are taken from correctly matched simulated data with truth information.

The reconstruction efficiency is 80% for the FCNC top and 58% for the SM top.

The final signal region selection requires $|m_t^{reco} - 172.5\ \text{GeV}| < 40$ GeV and $|m_W^{reco} - 80.4\ \text{GeV}| < 30$ GeV

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a \ell_a \ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b \ell_c \nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c \nu} - m_W\right)^2}{\sigma^2_W},$$

ATLAS Run 2 t→qZ Search Backgrounds

Prompt Leptons

- Diboson (WZ + jets → lllv + jets)
- ttZ (ttZ → blv bqq' ll)
- tZ
- Controlled through a combination of simulation and control regions

Non-Prompt Leptons

- Leptons are either fakes or come from heavy flavor decays
- Z+jets
- Ttbar
- Controlled through a semi data-driven approach

ATLAS Run 2 t→qZ Search Non-Prompt Scale Factors

Prior to the final fit, they define regions to control the contribution from various sources of non-prompt leptons and derive scale factors which are then applied to the relevant MC simulated background samples

	Targeting Z+jets		Targeting ttbar	
	"Light" region – e	"Light" region – μ	"Heavy" region – e	"Heavy" region – μ
	eee or $e\mu\mu$, OSSF $\lvert m_{\ell\ell} - 91.2$ GeV$\rvert < 15$ GeV ≥ 1 jet $E_{T}^{miss} < 40$ GeV $m_{T} \leq 50$ GeV	$\mu\mu\mu$ or μee, OSSF $\lvert m_{\ell\ell} - 91.2$ GeV$\rvert < 15$ GeV ≥ 1 jet $E_{T}^{miss} < 40$ GeV $m_{T} \leq 50$ GeV	$e\mu\mu$, OS no OSSF ≥ 2 jet	μee, OS no OSSF ≥ 2 jet
Scale Factors	2.2 ± 0.8	1.9 ± 0.9	1.1 ± 0.3	1.1 ± 0.7

ATLAS Run 2 t→qZ Search Control Regions

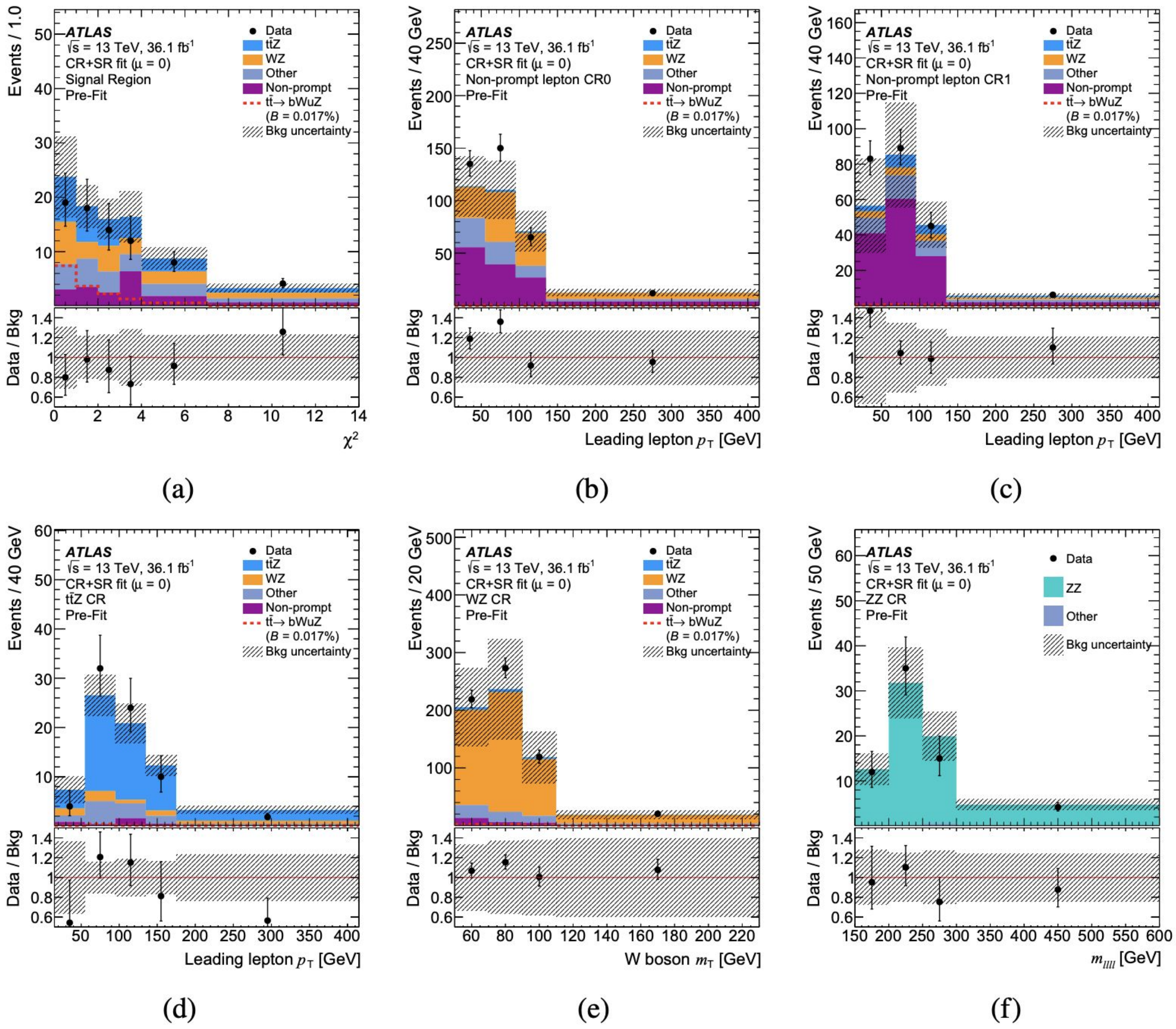
In addition to the signal region, 5 control regions are defined and included in the final fit to constrain the backgrounds.

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$\lvert m_{\ell\ell}^{\mathrm{reco}} - 91.2\ \mathrm{GeV}\rvert$	< 15 GeV	< 15 GeV	< 15 GeV	> 15 GeV	< 15 GeV
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b-tagged jets	2	0	0	0 (1)	1
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 20 GeV	> 40 GeV	> 20 GeV	> 20 GeV	> 20 GeV
$m_{\mathrm{T}}^{\ell\nu}$	-	> 50 GeV	-	-	-
$\lvert m_{\ell\nu}^{\mathrm{reco}} - 80.4\ \mathrm{GeV}\rvert$	-	-	-	-	< 30 GeV
$\lvert m_{j\ell\nu}^{\mathrm{reco}} - 172.5\ \mathrm{GeV}\rvert$	-	-	-	-	< 40 GeV
$\lvert m_{j\ell\ell}^{\mathrm{reco}} - 172.5\ \mathrm{GeV}\rvert$	-	-	-	-	< 40 GeV

ATLAS Run 2 t→qZ Search Systematics

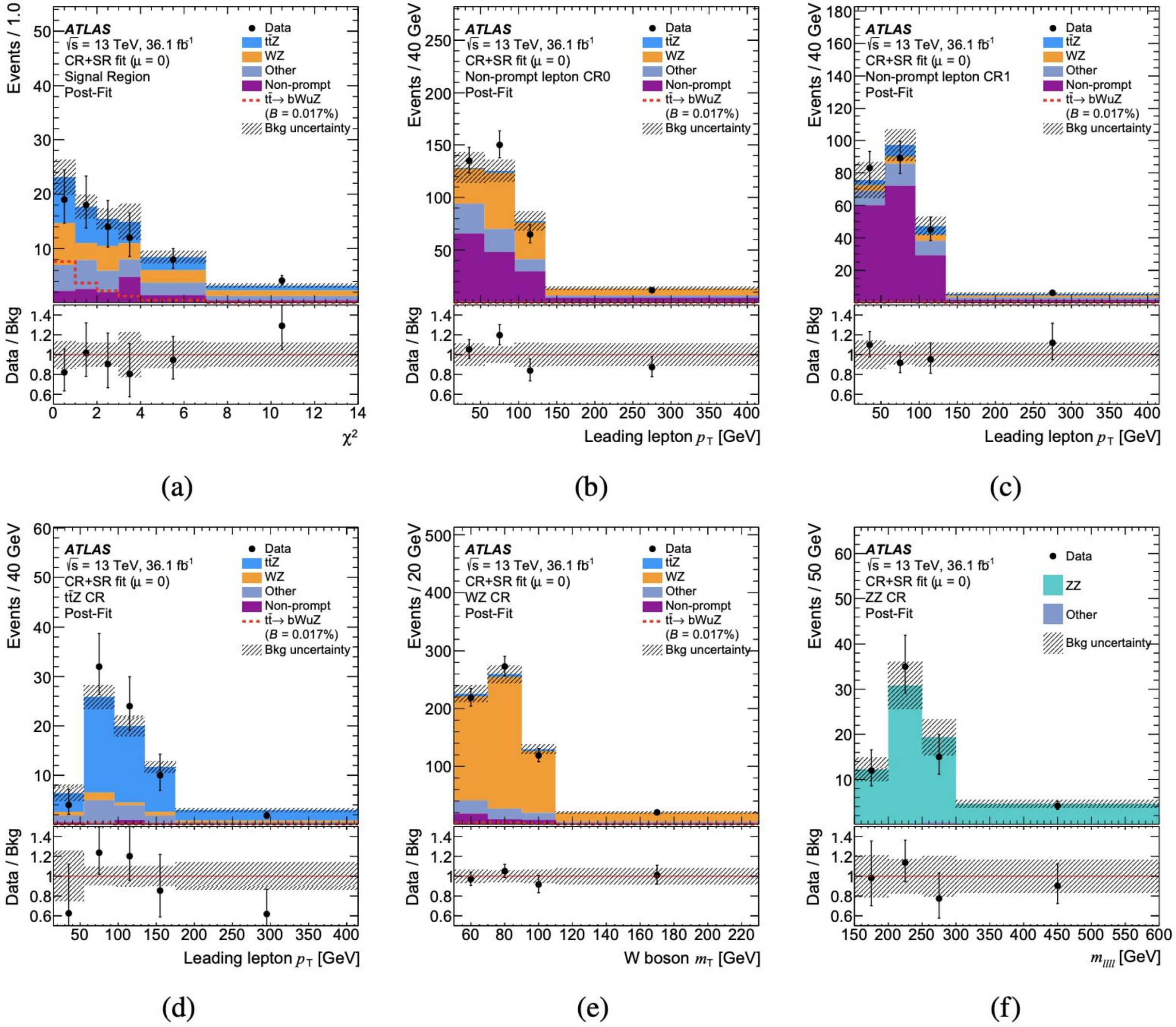
The systematic uncertainties are dominated by theory uncertainties in every region, even after profiling the theory uncertainties using the control regions

Post-fit Source	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1	SR	
	B [%]	B [%]	B [%]	B [%]	B [%]	B [%]	S [%]
Event modelling	22	10	11	9	23	18	5
Leptons	2.0	2.4	2.9	2.6	2.9	2.6	1.8
Jets	5	6	11	8	4	8	4
b-tagging	7	1.4	0.6	2.1	2.8	4	3.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.3	3.3	2.5	2.8	0.7	4	1.4
Non-prompt leptons	1.1	1.1	—	8	12	5	—
Pile-up	5	1.2	5	3.3	1.7	3.5	2.2
Luminosity	2.0	2.0	2.1	1.3	0.8	1.6	2.1



Fit Setup

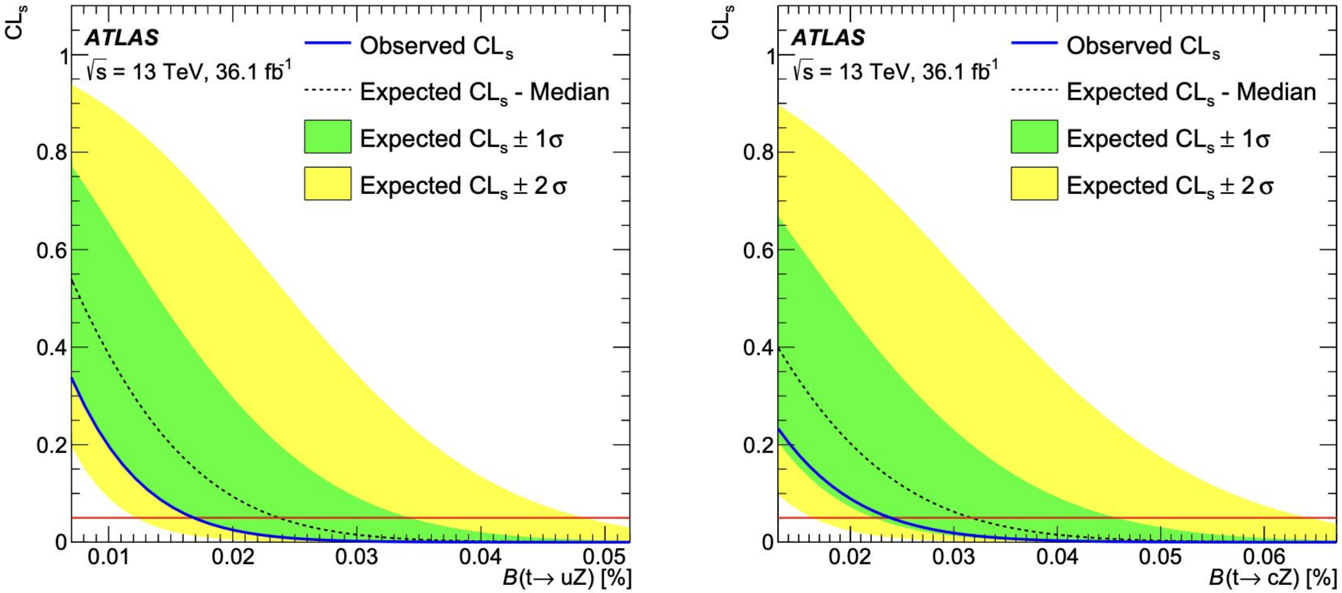
Kinematic distributions in the signal region and control regions are simultaneously fit



Post Fit Distributions

ATLAS Run 2 $t \to qZ$ Search Results

95% CL Limits: $B(t \to uZ) < 1.7 \times 10^{-4}$, $B(t \to cZ) < 2.4 \times 10^{-4}$

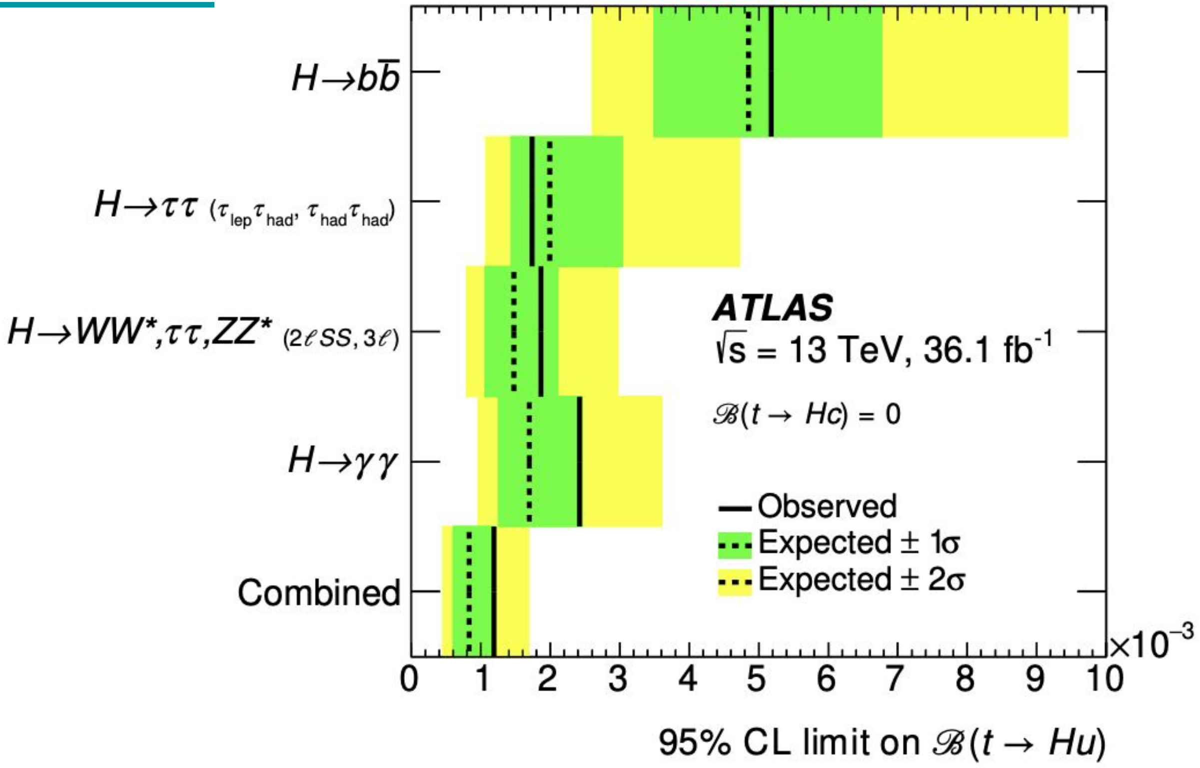


Experimental Outlook of $t \rightarrow cZ$

- Observation of this decay mode in the SM with any current or proposed collider is not feasible.
- Experimental limits are approaching a regime where they can contribute to limits on plausible models.
- Projections for HL-LHC limits reach $\approx 10^{-5}$, enough to rule out some currently allowed models.
- Goals to constrain BSM physics are not fixed!

ATLAS Run 2 t→qH Search

The best limit for top decays to Higgs come from an ATLAS analysis on partial run 2 data which uses a combination of all major Higgs decay modes



Top quark FCNC Overview

There is a chance for HL-LHC results or results from a future collider to start probing a well-motivated parameter space

Process	Br Limit	Search	Dataset
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV

Process	SM	2HDM(FV)	2HDM(FC)	MSSM		
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$		
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$		
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	[illegible]	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Caution: These numbers are not up to date. The experimental limits are lower than shown and the theoretical predictions have been pushed lower by other measurements.

References

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- CMS Collaboration *Search for associated production of a Z boson with a single top quark and for tZ flavour-changing interactions in pp collisions at \sqrt{s}=8 TeV.* JHEP 07 (2017) 003. arxiv:1702.01404
- ATLAS Collaboration. *Search for flavour-changing neutral current top-quark decays t→qZ in proton-proton collision at \sqrt{s} = 13 TeV with the ATLAS detector.* JHEP 07 (2018) 176. Arxiv:1803.09923
- Inspire searches of all results mentioned in the PDG
  - tqZ: https://inspirehep.net/literature?sort=mostrecent&size=25&page=1&q=keyword%20%22Q007%3ADESIG%3D2%22
  - tqH: https://inspirehep.net/literature?sort=mostrecent&size=25&page=1&q=keyword%20%22Q007%3ADESIG%3D13%22

Backup

ATLAS Run 2 t→qZ Search Systematics

The systematic uncertainties are dominated by theory uncertainties in every region

Pre-fit Source	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1	SR	
	B [%]	B [%]	B [%]	B [%]	B [%]	B [%]	S [%]
Event modelling	29	40	13	24	40	30	5
Leptons	2.1	2.4	3.0	2.6	2.9	2.6	1.9
Jets	6	8	15	10	4	9	4
b-tagging	7	1.5	0.6	2.3	3.0	5	3.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	4	2.6	3.0	0.8	5	1.4
Non-prompt leptons	1.1	1.3	—	12	15	6	—
Pile-up	5	1.3	5	3.5	1.8	4	2.3
Luminosity	2.0	2.0	2.1	1.3	0.8	1.7	2.1