Search for flavour-changing *tZ* interactions in proton-proton collisions at 13 TeV with the ATLAS detector

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Universidade do Minho
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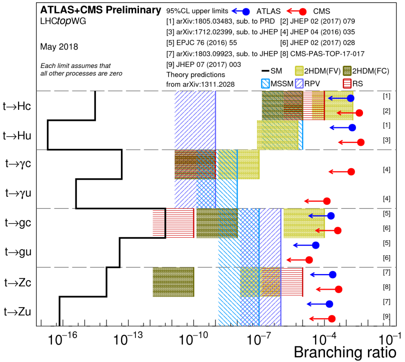
Motivation

FCNC limits overview

- Flavour Changing Neutral Currents (FCNC): change of the fermion flavour through the emission of a neutral boson
- Many types of New Physics (NP) lead to FCNC, often at tree level

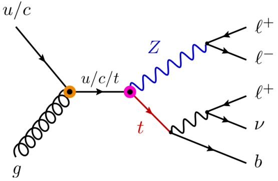


- More than 10 orders of magnitude left for FCNC $\mathcal{BR}(t \rightarrow u|cZ)$ before Standard Model (SM) suppression

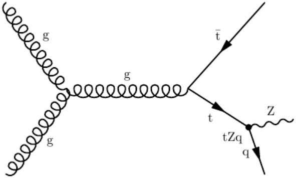
Motivation

tZq anomalous coupling

FCNC u|c+g → tZ:



tZ **production via FCNC**



$t\bar{t}$ **decay via FCNC**

- Clean 3ℓ signature: $e^+e^-\,|\,\mu^+\mu^-$ + $e\,|\,\mu$ + b-jet + $\not{E}_t$
- *tZu* and *tZc* anomalous couplings considered
- Main backgrounds: $t\bar{t}$, Z+jets and diboson processes

Signal Simulation

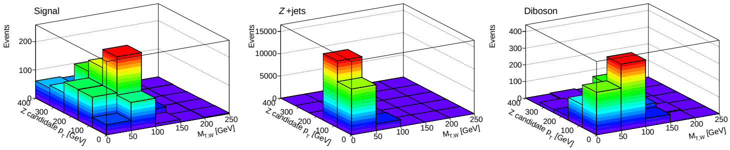
- MC production via left-handed *tZu* and *tZc* tensor couplings ($K^{\mathrm{L}}_{\mathrm{ut}}$, $K^{\mathrm{L}}_{\mathrm{ct}}$) at LO QCD using TopFCNC UFO model within MadGraph 5
- General Lagrangian for the top FCNCs

$$\begin{aligned}\mathcal{L}_{\mathrm{LO}} &= \mathcal{L}_{\mathrm{SM}} + \textstyle\sum_{q\in\{u,c\}} \Bigg[\frac{g_s}{2m_t}\bar{q}T^a\sigma^{\mu\nu}\left(\zeta^{\mathrm{L}}_{qt}P_{\mathrm{L}} + \zeta^{\mathrm{R}}_{qt}P_{\mathrm{R}}\right)tG^a_{\mu\nu} + \frac{e}{2m_t}\bar{q}\sigma^{\mu\nu}\left(\lambda^{\mathrm{L}}_{qt}P_{\mathrm{L}} + \lambda^{\mathrm{R}}_{qt}P_{\mathrm{R}}\right)tA_{\mu\nu} \\ &\quad + \frac{g_{\mathrm{w}}}{2c_{\mathrm{w}}}\bar{q}\gamma^{\mu}\left(X^{\mathrm{L}}_{qt}P_{\mathrm{L}} + X^{\mathrm{R}}_{qt}P_{\mathrm{R}}\right)tZ_{\mu} + \frac{g_{\mathrm{w}}}{4c_{\mathrm{w}}M_Z}\bar{q}\sigma^{\mu\nu}\left(K^{\mathrm{L}}_{qt}P_{\mathrm{L}} + K^{\mathrm{R}}_{qt}P_{\mathrm{R}}\right)tZ_{\mu\nu} \\ &\quad + \frac{1}{\sqrt{2}}\bar{q}\left(\eta^{\mathrm{L}}_{qt}P_{\mathrm{L}} + \eta^{\mathrm{R}}_{qt}P_{\mathrm{R}}\right)tH \Bigg] + h.c.\end{aligned}$$

Analysis with production mode

Choice of discriminant variable

- *tZ* production particularly sensitive to *tZu* coupling
- Harder distribution of the transverse momentum of the *Z* boson compared to the background processes



- For a low value of $m_T(\ell,\nu)$, the Z+jets background can be isolated
- Two complementary regions separated by low and high $m_T(\ell,\nu)$ regions defined

Signal and Control Regions

Event selection

- Three signal regions
- Two control regions: $t\bar{t}$ and WZ diboson backgrounds

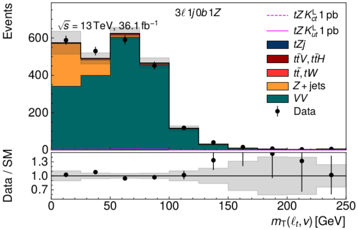
Selection	SR			CR	
	m_T^W-low	m_T^W-high	2-jet	$t\bar{t}$ 2	WZ
No. leptons	$= 3$	$= 3$	$= 3$	$= 3$	$= 3$
No. jets	$= 1$	$= 1$	$= 2$	≥ 2	$= 1$
No. b-jets	$= 1$	$= 1$	$= 1$	≥ 1	$= 0$
Z candidate	≥ 1	≥ 1	≥ 1	< 1	≥ 1
m_T^W	< 50 GeV	> 50 GeV	–	–	–

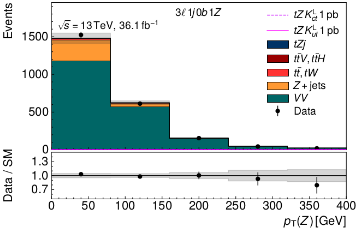
- Definition of the transverse mass of the W boson:

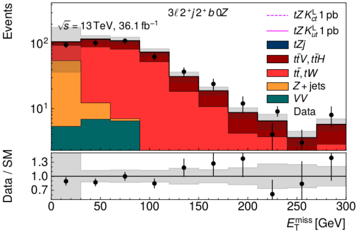
$$m_T^W = \sqrt{2 \not{E}_t p_t^\ell \left(1 - \cos\left(\Delta\varphi(\not{E}_t,\, p_t^\ell)\right)\right)}$$

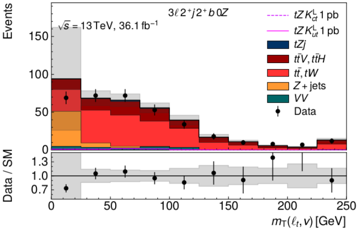
Control Regions

Post-fit plots

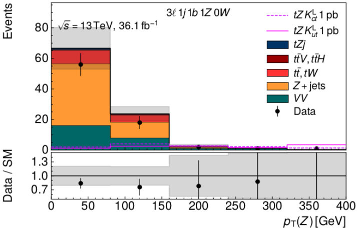


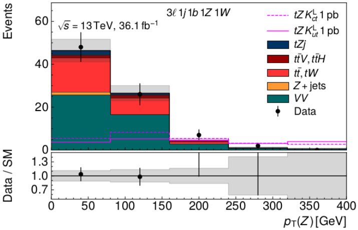


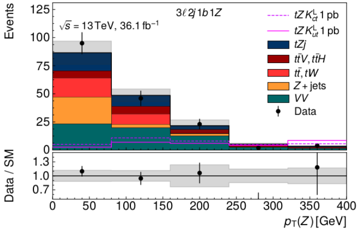




Signal Regions
Post-fit plots



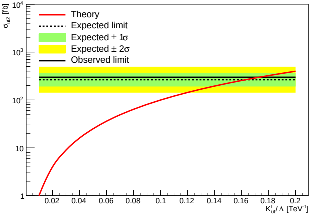




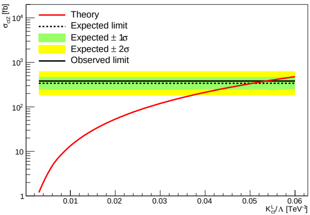
Results

95% expected upper limits on cross-sections, couplings and BRs

Limit for K^{L}_{ut}



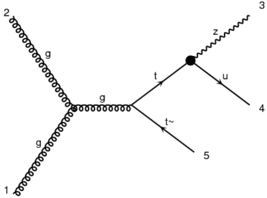
Limit for K^{L}_{ct}



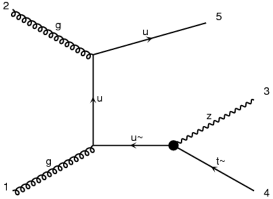
Coupling	$\sigma_{\text{FCNC tZ}}$ [pb]	K/Λ_{NP} [TeV^{-1}]	$\mathcal{BR}(t \to qZ)$ ATLAS	$\mathcal{BR}(t \to qZ)$ CMS
	***tZu* anomalous coupling**			
Expected	0.284	0.0171	2.25×10^{-4}	1.50×10^{-4}
Observed	0.318	0.0183	2.52×10^{-4}	2.40×10^{-4}
	***tZc* anomalous coupling**			
Expected	0.369	0.0547	2.34×10^{-3}	3.70×10^{-4}
Observed	0.401	0.0581	2.54×10^{-3}	4.50×10^{-4}

Limits on $\mathcal{BR}(t \to uZ)$ comparable to CMS results

- FCNC at production and decay can have the same final state
- Interferences effects between both modes should be studied



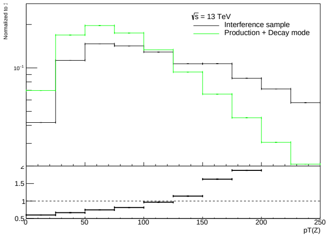
Decay

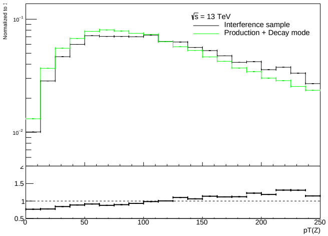


Production

Interference Studies
Production and Decay

- Phenomenological study being currently done using Monte Carlo generation with MadGraph5 importing the TopFCNC UFO model
- Only *tZq* anomalous coupling considered at this stage



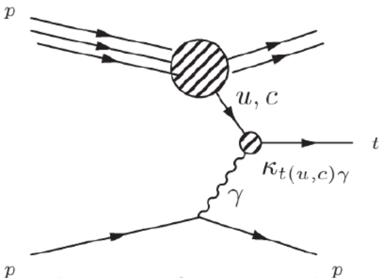


Transverse momentum of the Z boson

Photoproduction via FCNC

Prospects

- Probing $t\gamma u$ and $t\gamma c$ couplings
- Final state composed by proton remnants, a top quark and a proton
- An interesting possibility is using the data collected by the ATLAS Forward Proton (AFP) detector in the forward region



Proton goes through the beam pipe

Summary

- Analysis of tZ production implemented with expected upper limits in agreement with similar searches

Expected upper limits			
$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Mode	$\mathcal{BR}(t \to qZ)$
13	35.9 - CMS	Decay and production	$1.5{\cdot}10^{-4}$ ($q = u$)
13	35.9 - CMS	Decay and production	$3.7{\cdot}10^{-4}$ ($q = c$)
13	36.1 - ATLAS	Decay	$2.4{\cdot}10^{-4}$ ($q = u$)
13	36.1 - ATLAS	Decay	$3.2{\cdot}10^{-4}$ ($q = c$)
13	36.1 - This analysis	Production	$2.2{\cdot}10^{-4}$ ($q = u$)
13	36.1 - This analysis	Production	$2.3{\cdot}10^{-3}$ ($q = c$)

- Possibility of having an analysis with both production and decay profiting from the full 13 TeV dataset
- Study of the interferences between both channels is under way
- Photoproduction via FCNC processes are being considered for a future analysis

Appendix

Motivation
FCNC suppression in the SM

- Predictions for the branching ratios of FCNC top decays by the SM and some NP models

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to gu$	$3.7 \cdot 10^{-14}$	$1.5 \cdot 10^{-7}$	—	—	$8 \cdot 10^{-5}$	$2 \cdot 10^{-4}$
$t \to Zu$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$	$3 \cdot 10^{-5}$
$t \to \gamma u$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
$t \to Hu$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	$\approx 10^{-5}$	$\approx 10^{-6}$
$t \to gc$	$4.6 \cdot 10^{-12}$	$1.5 \cdot 10^{-7}$	$\approx 10^{-4}$	$\approx 10^{-8}$	$8 \cdot 10^{-5}$	$2 \cdot 10^{-4}$
$t \to Zc$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\approx 10^{-7}$	$\approx 10^{-10}$	$2 \cdot 10^{-6}$	$3 \cdot 10^{-5}$
$t \to \gamma c$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\approx 10^{-6}$	$\approx 10^{-9}$	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
$t \to Hc$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\approx 10^{-5}$	$\approx 10^{-5}$	$\approx 10^{-6}$

Common Selection

Event selection

- Common cuts for the objects:
  - $p_t(\ell_1) > 27$ GeV
  - $p_t(\ell_2) > 25$ GeV
  - $p_t(\ell_3) > 15$ GeV
  - $p_t(j) > 30$ GeV
  - 1 b-jet (77% WP, $|\eta| < 2.5$)
  - no other jet (77% WP, $|\eta| < 4.5$)
  - $|m(\ell\ell)$ - $m(Z)| < 10$ GeV
- Definition of the transverse mass of the W boson:

$$m_T^W = \sqrt{2 \not{E}_t p_t^\ell \left(1 - \cos\left(\Delta\varphi(\not{E}_t,\, p_t^\ell)\right)\right)}$$

Signal and Control Regions

Event selection

- Three signal regions
- Two control regions: $t\bar{t}$ and WZ diboson backgrounds

Selection	**SR**			**VR**			**CR**	
	m_T^W**-low**	m_T^W**-high**	**2-jet**	**Z+jets 1**	**Z+jets 2**	$\mathbf{t\bar{t}}$ **1**	$\mathbf{t\bar{t}}$ **2**	WZ
No. leptons	$=3$	$=3$	$=3$	$=2$	$=2$	$=2$	$=3$	$=3$
No. jets	$=1$	$=1$	$=2$	$=1$	$=2$	$=2$	≥ 2	$=1$
No. b-jets	$=1$	$=1$	$=1$	$=1$	$=2$	$=2$	≥ 1	$=0$
Z candidate	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	< 1	< 1	≥ 1
m_T^W	< 50 GeV	> 50 GeV	–	–	–	–	–	–

Signal Regions

Event yields

SR1 m_T^W-low			
	Pre-fit	Post-fit	Ratio
$tZ\ \kappa_L^{ut}$	11.5 ± 1.2	11.5 ± 1.2	1.00 ± 0.10
$tZ\ \kappa_L^{ct}$	12.7 ± 1.3	12.7 ± 1.3	1.00 ± 0.10
tZj	1.5 ± 0.5	1.5 ± 0.5	1.00 ± 0.32
$t\bar{t}V, t\bar{t}H$	1.3 ± 0.4	1.3 ± 0.4	1.04 ± 0.32
$t\bar{t}, tW$	8 ± 8	13.5 ± 3.2	1.74 ± 0.41
$Z+$jets	35 ± 38	52 ± 14	1.46 ± 0.40
VV	23 ± 7	26 ± 5	1.12 ± 0.20
Total	69 ± 40	94 ± 15	1.36 ± 0.22
Data	78		

SR2 m_T^W-high			
	Pre-fit	Post-fit	Ratio
$tZ\ \kappa_L^{ut}$	20.5 ± 1.5	20.5 ± 1.3	1.00 ± 0.07
$tZ\ \kappa_L^{ct}$	25.2 ± 2.1	24.9 ± 1.9	0.99 ± 0.07
tZj	3.3 ± 1.1	3.4 ± 1.0	1.04 ± 0.31
$t\bar{t}V, t\bar{t}H$	3.2 ± 1.1	3.4 ± 1.0	1.04 ± 0.30
$t\bar{t}, tW$	13 ± 13	25 ± 5	1.85 ± 0.41
$Z+$jets	0.9 ± 1.0	1.0 ± 0.7	1.20 ± 0.75
VV	39 ± 13	46 ± 7	1.19 ± 0.19
Total	60 ± 19	78 ± 8	1.32 ± 0.13
Data	83		

SR3 2-jets			
	Pre-fit	Post-fit	Ratio
$tZ\ \kappa_L^{ut}$	28.8 ± 2.0	28.4 ± 1.8	0.99 ± 0.06
$tZ\ \kappa_L^{ct}$	34.3 ± 2.1	34.3 ± 2.0	1.00 ± 0.06
tZj	30 ± 9	31 ± 9	1.04 ± 0.30
$t\bar{t}V, t\bar{t}H$	18 ± 6	19 ± 5	1.04 ± 0.29
$t\bar{t}, tW$	15 ± 15	27 ± 6	1.80 ± 0.39
$Z+$jets	19 ± 20	30 ± 11	1.59 ± 0.57
VV	48 ± 35	59 ± 17	1.23 ± 0.36
Total	130 ± 45	166 ± 15	1.28 ± 0.12
Data	170		

Signal Extraction Fit
Strategy

Use a binned likelihood function with a signal strength, $\mu = \sigma_{\text{FCNC}}/1\,\text{pb}$ (not multiplied by $\mathcal{B}(tZ \to 3\ell\nu b)$), and nuisance parameters (NPs) for systematic uncertainties. The $p_{\text{t}}(Z)$ distributions in the 3 signal and 2 control regions with 5 bins each used as discriminant variable

- Find μ such that p-value on B-only Asimov dataset is 0.05
  ► expected upper limit
- Fit B-only model to B-only Asimov dataset
  ► expected estimates of NPs
- Fit S+B model to S+B Asimov dataset
  ► expected approximate impact of uncertainties
- Fit B-only model to parts of observed data
  ► Estimates of NPs for post-fit plots, modelling checks

Signal Extraction Fit

Nuisance Parameters

B, Asimov

B, observed