Search for new interactions in the top quark sector

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Universidade do Minho
Escola de Ciências

LIP

ATLAS EXPERIMENT

MAP JOINT DOCTORAL PROGRAMMES

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COMPETE 2020

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Introduction
New interactions with the top quark

Universidade do Minho (Braga, Portugal) - 2011-2021

- Bachelor in Physics - Final project on condensed matter physics
- Master in Experimental Physics also with Laboratory of Instrumentation and Experimental Particle Physics
  - Thesis on Flavour Changing Neutral Currents with data from the ATLAS Experiment
- PhD on the search for new interactions in the top quark sector - Overview in this talk!
  - Stay at CERN in 2019 due to the ATLAS PhD Grant award

Outline
New interactions with the top quark

Useful links for more detailed information:
- PhD thesis: CERN-THESIS-2021-149
- ATLAS publication: ATLAS-CONF-2021-049

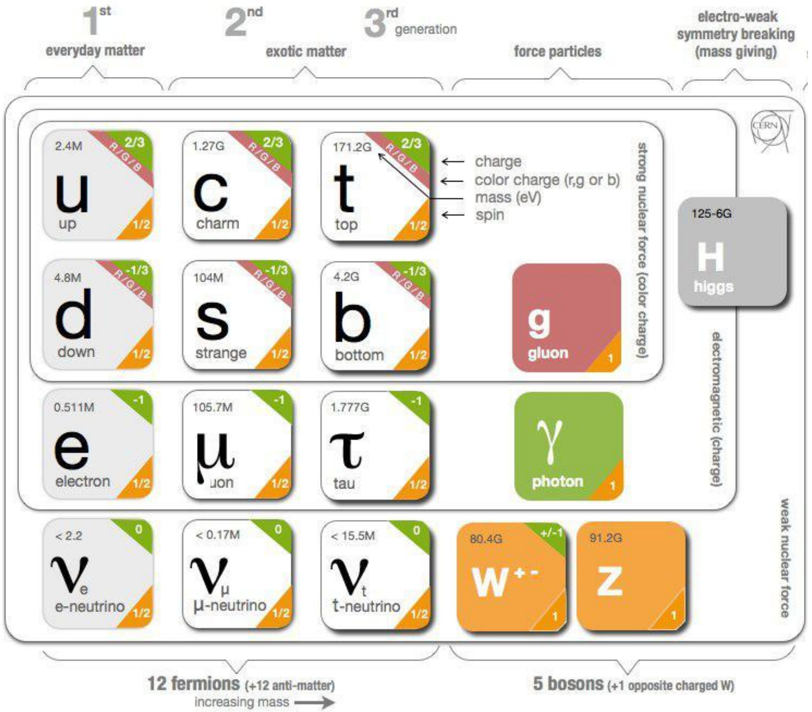
Standard Model
New interactions with the top quark

- Standard Model (SM) of Particle Physics explains the fundamental interactions except gravity

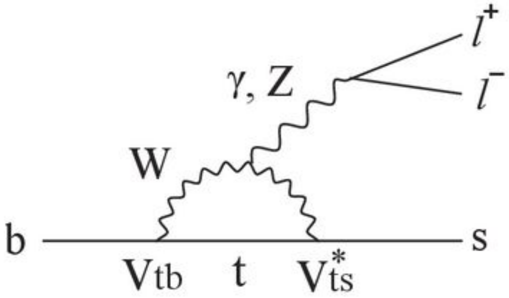
- Why studying the top quark?
- **Heaviest** fundamental particle: ~ 173 GeV
- Only quark decaying before **hadronisation**:~ $5x10^{-25}$s
- **Strongly interacting** with the electroweak sector and the **Higgs**: $y_t \sim 1$
- Inspiring to look **beyond the Standard Model:**

  Hierarchy problem: corrections to the Higgs mass

  First place to look for new particles coupling to mass



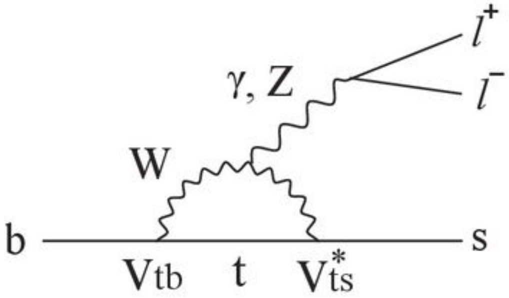
Beyond the Standard Model
New interactions with the top quark



- Flavour changing neutral currents (FCNC) processes, where a fermion changes its flavour without alternating its charge, is a great example of a rare interaction in the SM framework (with a branching ratio of ~ 10^{-14})

Beyond the Standard Model

New interactions with the top quark



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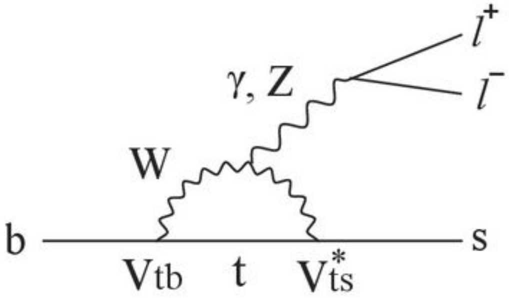
Beyond the Standard Model
New interactions with the top quark



- Flavour changing neutral currents (FCNC) processes, where a fermion changes its flavour without alternating its charge, is a great example of a rare interaction in the SM framework (with a branching ratio of ~ 10^{-14})
- Many New Physics models lead to FCNC contributions, often at tree level, by introducing new particles or interactions (with expected branching ratios between 10^{-5} and 10^{-10}):

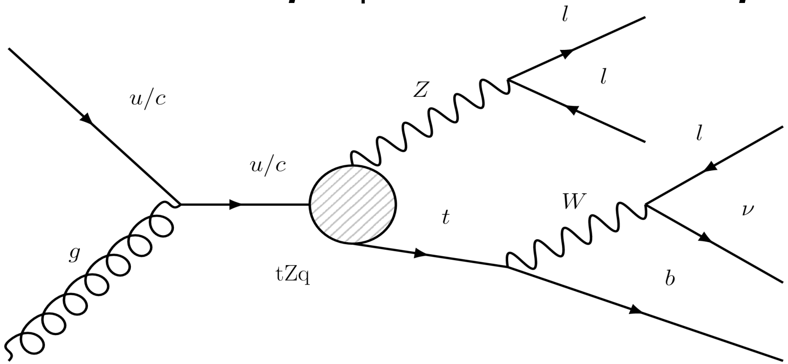
Process	SM	2HDM (FV/FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–/–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}/\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$

- Searches for FCNC processes can be performed in a model independent way using an Effective Field Theory (EFT) approach, being the SM lagrangian extended by operators in higher-dimensions:

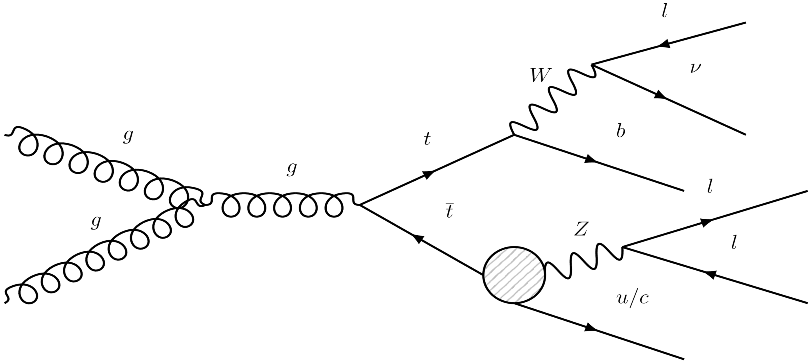
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{NP}^2} \sum_i C_i^{(6)} O_i^{(6)} + \ldots$$

Flavour Changing Neutral Currents
New interactions with top

- Top quark decay via FCNC processes present a powerful probe of new physics and it can occur in two modes:
  - In **production**: ***t+X*** production with X = *H, Z, g, γ*
  - In **decay**: ***tt*** production (with ***t*** $\rightarrow$ ***qX***) with *q* = *u, c*



Feynman diagram at Leading-Order for FCNC *tZ* production



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Flavour Changing Neutral Currents

New interactions with top

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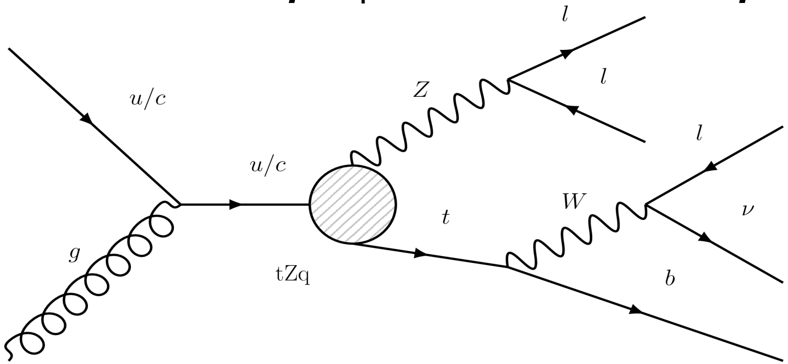
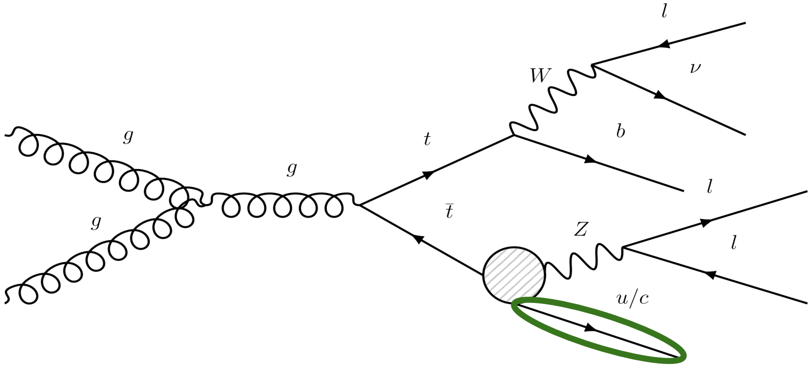


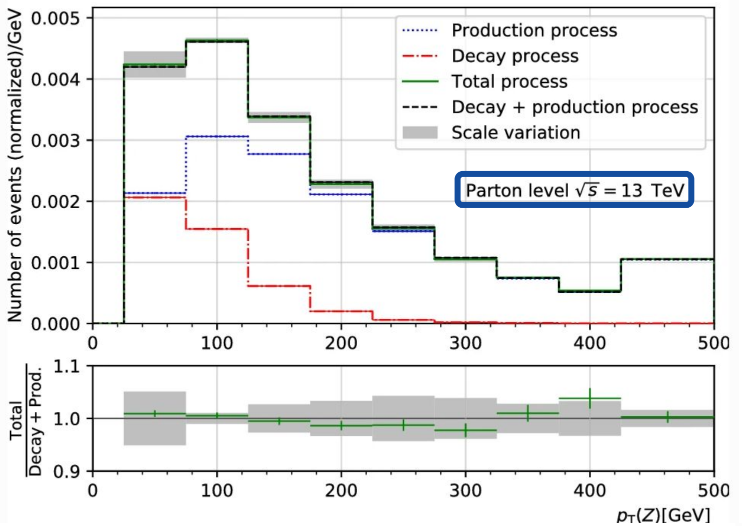
Feynman diagram at Leading-Order for FCNC *tZ* production

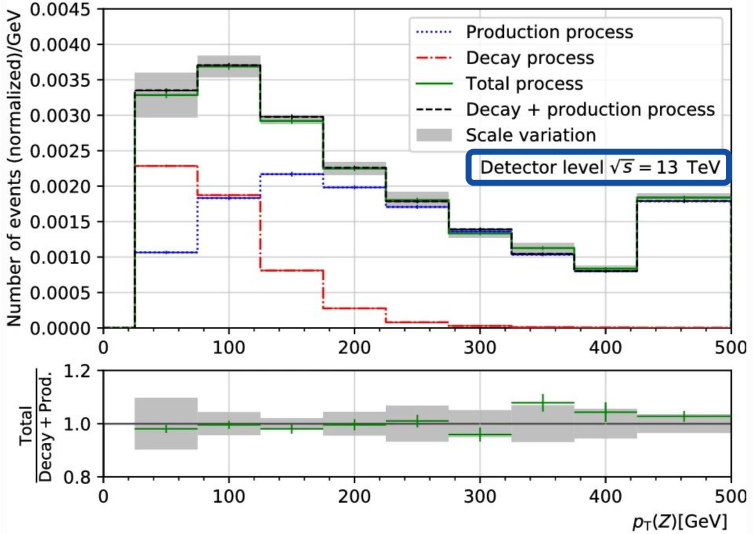


Feynman diagram at Leading-Order for FCNC *tt* decay

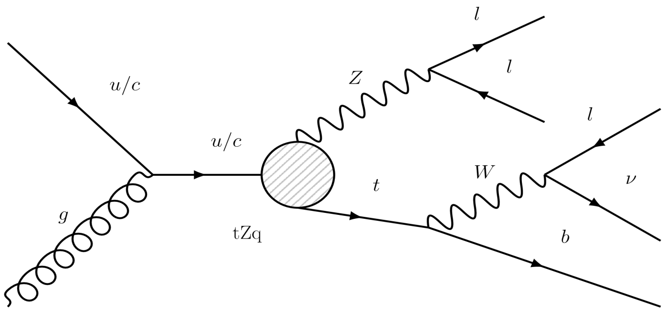
Interference studies
New interactions with top

- **Evaluation of the interference effects** between production and decay modes for **FCNC *tZq* and *tγq* anomalous couplings** performed in collaboration with the University of Dortmund (Germany)
- **Transverse momentum of Z and γ bosons** were the most sensible variables
- Interference effects found to be **smaller** than variations of the **renormalisation and factorisation scales**
- Study published in The European Physical Journal Plus



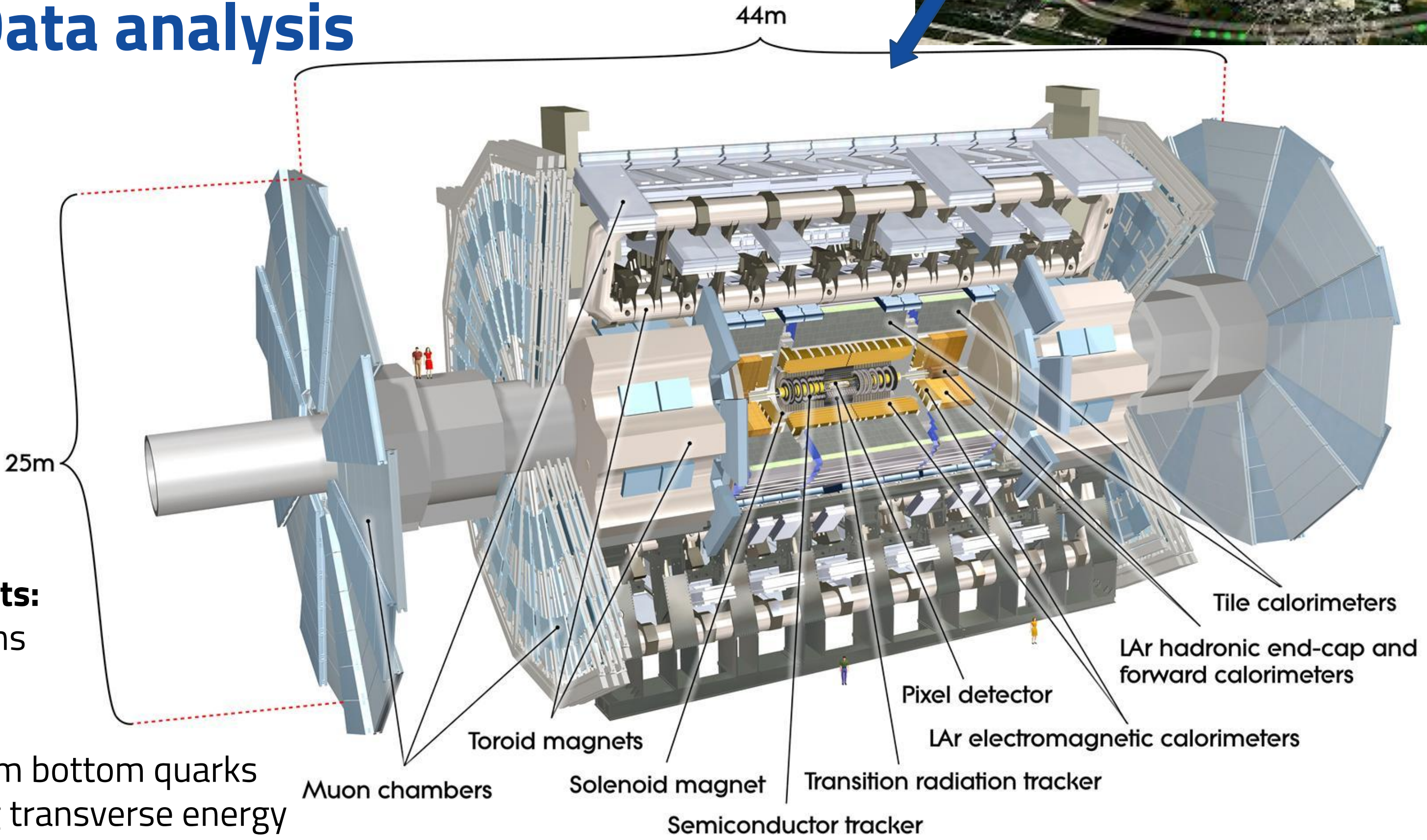


Analysis strategy
Data analysis



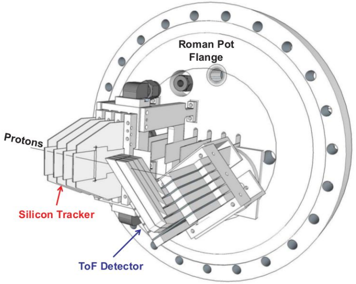
- Data analysis searching for FCNC processes with couplings between the *Z* boson, the top quark and a light-quark (up- or charm-quark):
  - Combining **production and decay** modes
  - Split into two dedicated analyses with only ***tZu*** or ***tZc*** anomalous coupling
  - **Trileptonic** topology: three leptons + *b*-tagged jet + Missing Transverse Energy (MET)
    ⇒ Leptonic decays of the *Z* boson and top quark provides a clear signature in the detector with a low jet multiplicity
  - **Main backgrounds:** *ttZ*, diboson (mainly *WZ* and *ZZ*) and SM *tZ* production
  - Collaboration with other ATLAS institutes: Roma Tor Vergata (Italy), Milano (Italy), Tbilisi (Georgia) and Berlin (Germany)

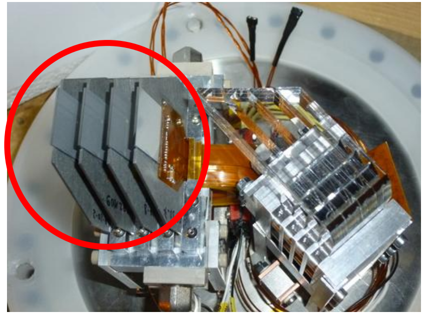
ATLAS detector
Data analysis



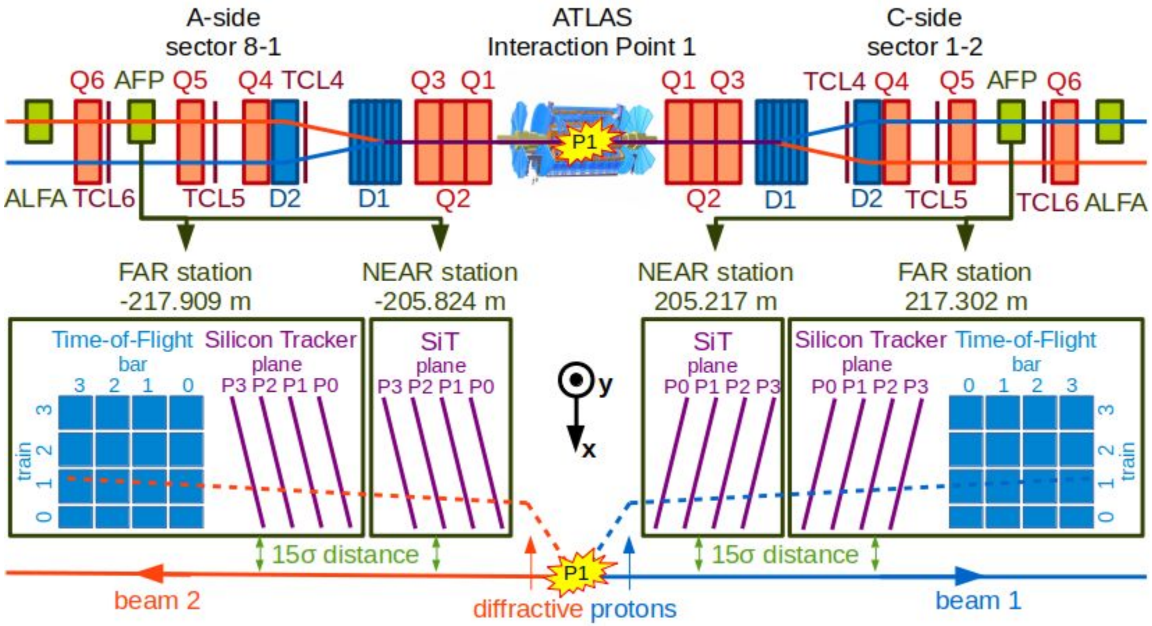
Physics objects:
- Electrons
- Muons
- Jets
- Jets from bottom quarks
- Missing transverse energy

Technical work with AFP
Qualification task





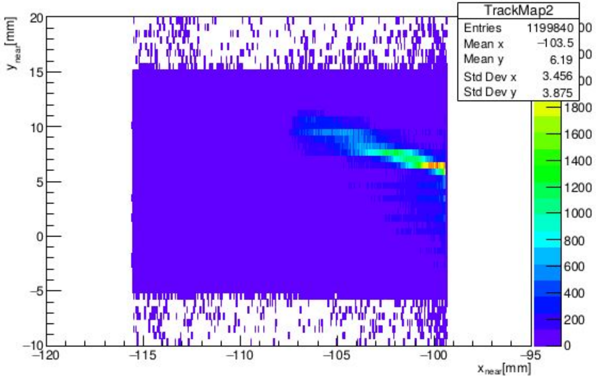
- Qualification task performed in the ATLAS Forward Proton (AFP) sub-detector
- Evaluation of the hardware trigger efficiencies of the silicon tracker



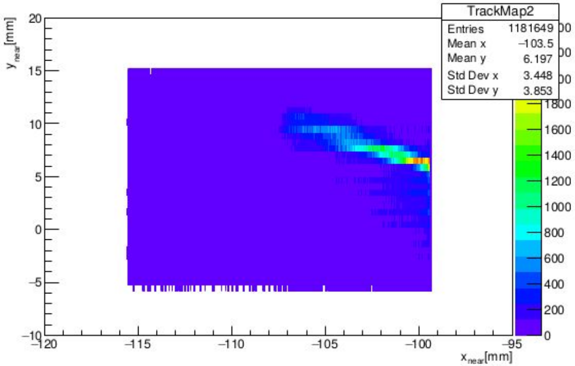
Technical work with AFP
Qualification task

- Using data recorded in 2016, when only one arm was installed, studies on the interplane and global alignment of the four pixel layers were done, followed by the definition of acceptance of the interesting hits and tracks

- Depending on the selection implemented (with requirements on the number of tracks and hits in each layer), efficiencies on the hardware trigger are between 86% and 99%



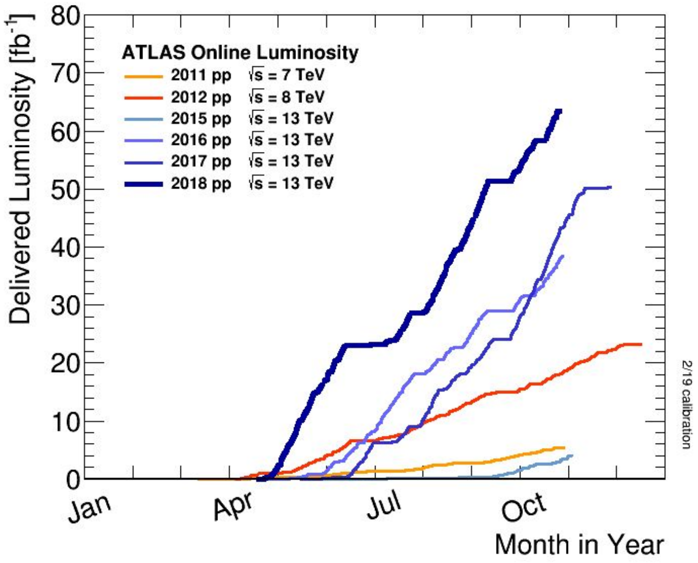
Track map of AFP C-side - With *x* slope cuts

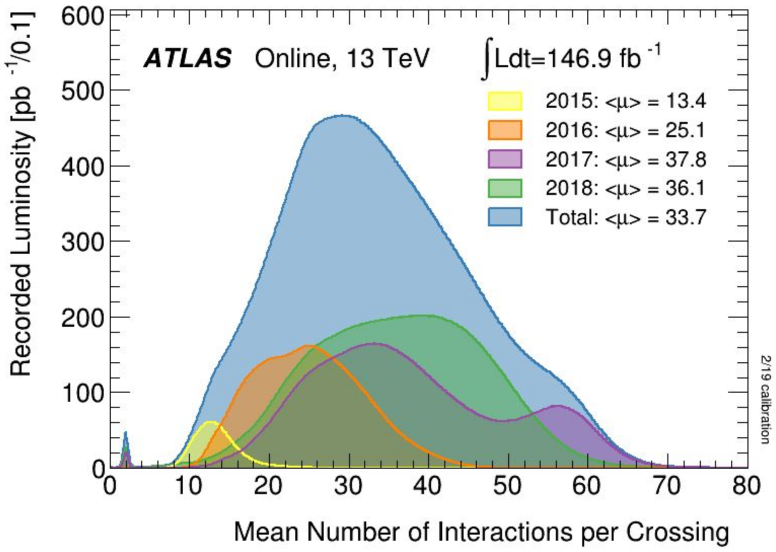


Track map of AFP C-side - With *x* and *y* slope cuts

Data and Monte Carlo samples
Data analysis

- Search for FCNC *tZq* couplings analysed the full Run-2 dataset collected between 2015 and 2018 by the ATLAS detector (139 fb^{-1}±1.7%)





Data and Monte Carlo samples
Data analysis

- Signal and background processes are modelled by Monte Carlo simulation samples

Signal:

- Top quark FCNC interactions considered at NLO in QCD using the TopFCNC UFO model with MadGraph
- Most relevant EFT operators contributing for FCNC *tZq* processes evaluated with dimension-six operator coefficients C_{uB} and C_{uW}
- Four signal scenarios: left-handed and right-handed couplings for *tZu* and *tZc* processes

Background:

- With three prompt leptons: Diboson, *ttZ*, *ttW*, *tWZ* and SM *tZ*, among other minor samples
- With non-prompt/fake leptons: *tt*, *Wt* and *Z*+jets production

Reconstruction of top quarks
Data analysis

- Two top quark candidates (SM: $t \rightarrow bW$, FCNC: $t \rightarrow qZ \rightarrow qll$) reconstructed under the FCNC *tt* decay signal hypothesis
- Decay objects to reconstruct: *b*-quark, *W* boson, *q*-quark and *Z* boson
  - *Z* boson reconstructed using the opposite-sign and same-flavour (OSSF) lepton pair with the closest invariant mass to 91.19 GeV
  - Lepton not used in *Z* boson reconstruction assumed to come from the *W* boson decay
  - MET assumed to be the transverse momentum of the neutrino
  - Minimisation of the χ^2 expression choose the jet to assign to the *q*-quark and it also determines the most probable value for the longitudinal momentum of the neutrino from the *W* boson decay:

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

Analysis strategy
Data analysis

- Two orthogonal signal regions focusing on:
  FCNC *tt* decay (SR1): >= 2 jets
  FCNC *tZ* production (SR2): = 1, 2 jets

- Suppression of *Z*+jets contribution by cutting on the transverse mass of the *W* boson ($m_T(\ell_W,\upsilon)$):

$$m_T(\ell_W,\nu) = \sqrt{2E_T^{miss}p_T(\ell)\left(1-\cos\left(\Delta\varphi(E_T^{miss},p_T(\ell))\right)\right)}$$

- Kinematic variables as **pT(*Z*)** or **$m_T(\ell_W,\upsilon)$** more important for FCNC *tZ* signal, while angular variables as **ΔR(ℓ,*Z*)** are better discriminants for the FCNC *tt* decay signal

Exactly 3 leptons with $\lvert\eta\rvert < 2.5$ and $p_T(\ell_1) > 27$ GeV, $p_T(\ell_2) > 15$ GeV, $p_T(\ell_3) > 15$ GeV; ≥ 1 OSSF pair, with $\lvert m_{\ell\ell} - 91.19\text{ GeV}\rvert < 15$ GeV		
Decay channel - Full SR1	Production channel - Full SR2	
≥ 2 jets with $\lvert\eta\rvert < 2.5$	= 1 jet with $\lvert\eta\rvert < 2.5$	= 2 jets with $\lvert\eta\rvert < 2.5$
= 1 *b*-jet	= 1 *b*-jet	= 1 *b*-jet
–	$m_T(\ell_W,\nu) > 40$ GeV	$m_T(\ell_W,\nu) > 40$ GeV
$\lvert m_t^{FCNC} - 172.5\text{ GeV}\rvert < 2\sigma^{FCNC}$	–	$\lvert m_t^{FCNC} - 172.5\text{ GeV}\rvert > 2\sigma^{FCNC}$
–	–	$\lvert m_t^{SM} - 172.5\text{ GeV}\rvert < 2\sigma^{SM}$

Process	Decay signal region (SR1)	Production signal region (SR2)
$t\bar{t}Z$	169 ±22	25 ±5
tWZ	35 ±13	10 ±4
$t\bar{t}W$	6.7 ±3.4	3.6 ±1.8
$t\bar{t}H$	7.7 ±1.2	0.95 ±0.18
VV+LF	29 ±13	33 ±12
VV+HF	150 ±70	160 ±70
tZq	50 ±8	113 ±19
$t\bar{t}$	21.2 ±3.1	33 ±11
Wt	0.50 ±0.27	0.4 ±1.2
Z+jets	11 ±11	9 ±9
VH	1.2 ±0.9	2.4 ±2.9
$t\bar{t}WW$	0.46 ±0.25	0.03 ±0.05
VVV	0.8 ±0.4	0.58 ±0.30
$t\bar{t}t\bar{t}$	0.22 ±0.11	0.0021 ±0.0022
$t\bar{t}t$	0.030 ±0.016	0.0019 ±0.0015
$t\bar{t}Z$ (2ℓ)	0.05 ±0.06	0.021 ±0.026
VV (2ℓ)	0.5 ±0.5	0.13 ±0.19
FCNC $(u)tZ$	13.2 ±2.1	52.5 ±2.8
FCNC $t\bar{t}$ (uZ)	63 ±5	10.6 ±1.5
FCNC $(c)tZ$	3.6 ±0.6	12.2 ±0.9
FCNC $t\bar{t}$ (cZ)	76 ±6	18.5 ±1.9
Total background	480 ±80	390 ±70

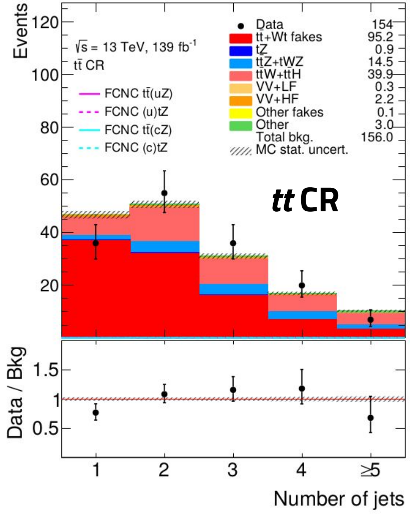
Data and Monte Carlo comparison

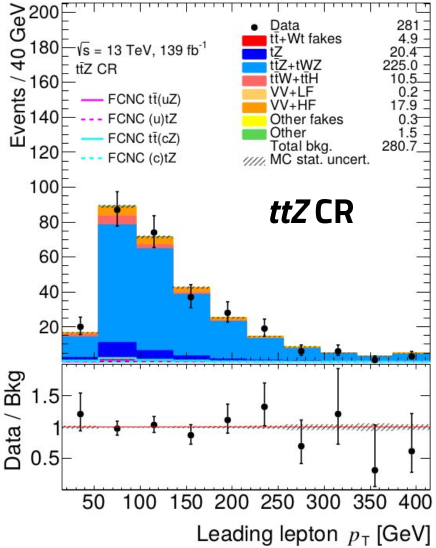
Data analysis

- Modelling of the dominant background processes tested through four dedicated control regions (CRs):

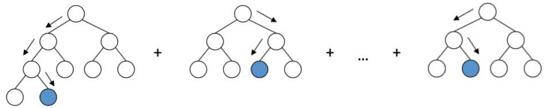
Exactly 3 leptons with $\lvert\eta\rvert < 2.5$ and $p_T(\ell_1) > 27$ GeV, $p_T(\ell_2) > 15$ GeV, $p_T(\ell_3) > 15$ GeV			
$t\bar{t}$ CR	$t\bar{t}Z$ CR	Side-band CR1	Side-band CR2
≥ 1 OS pair, no OSSF	≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSSF pair
	$\lvert m_{\ell\ell} - 91.2\,\mathrm{GeV}\rvert < 15\,\mathrm{GeV}$	$\lvert m_{\ell\ell} - 91.2\,\mathrm{GeV}\rvert < 15\,\mathrm{GeV}$	$\lvert m_{\ell\ell} - 91.2\,\mathrm{GeV}\rvert < 15\,\mathrm{GeV}$
–	–	–	$m_T(\ell_W, \nu) > 40\,\mathrm{GeV}$
≥ 1 jet with $\lvert\eta\rvert < 2.5$	≥ 4 jets with $\lvert\eta\rvert < 2.5$	≥ 2 jets with $\lvert\eta\rvert < 2.5$	$= 1$ jet with $\lvert\eta\rvert < 2.5$
$= 1$ *b*-jet	$= 2$ *b*-jets	$= 1$ *b*-jet	$= 1$ *b*-jet
–	–	$\lvert m_t^{\mathrm{FCNC}} - 172.5\,\mathrm{GeV}\rvert > 2\sigma^{FCNC}$	–
–	–	$\lvert m_t^{\mathrm{SM}} - 172.5\,\mathrm{GeV}\rvert > 2\sigma^{SM}$	$\lvert m_t^{\mathrm{SM}} - 172.5\,\mathrm{GeV}\rvert > 2\sigma^{SM}$

- While *ttZ* and side-band CRs target the main backgrounds of both signal regions, the *tt* CR allows an estimate of the non-prompt/fake leptons contribution using a semi-data driven method





Signal to background discrimination
Data analysis



- **Three multivariate discriminants** defined using **Gradient Boosted Decision Trees** (GBDT): FCNC *tZu* and *tZc* in decay, FCNC *tZu* in production and FCNC *tZc* in decay and production

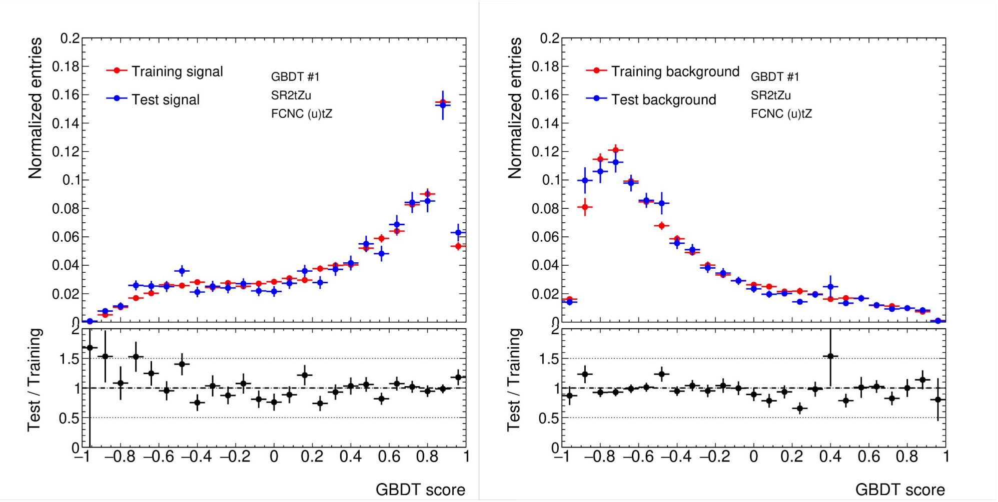
GBDT discriminant	Training Region	Training signal	Search coupling
D_1	Full SR1	FCNC tZu and tZc in $t\bar{t}$ decays	tZu, tZc
D_2^U	Full SR2	FCNC tZu in tZ production	tZu
D_2^C	Full SR2	FCNC tZc in $t\bar{t}$ decays and tZ production	tZc

- All the signal and background events selected by the signal regions divided into five equal parts and used for the training (80%) or for the testing (20%)
- Choice of the input variables taking into account the separation power, the correlation with other variables and the performance loss

GBDT performance
Data analysis

- Detailed study of the variables separation power and its importance to the final discriminants provided a great performance for the three cases: 80% for D_1, 85% for D_2^U and 69% for D_2^C
- Optimisation of the GBDT hyper-parameters varying the number of threes and shrinkage, among others, with a total of 144 combinations
  ⇒ Reference parameters produce a stable and optimal GBDT performance

SR1		SR2 tZu		SR2 tZc	
Variable	$\langle s^2 \rangle$	Variable	$\langle s^2 \rangle$	Variable	$\langle s^2 \rangle$
$m_{b\ell\nu}$	0.1364	p_T^Z	0.3104	p_T^Z	0.07408
p_T^q	0.07345	p_T^b	0.175	p_T^b	0.05261
N_{jets}	0.05747	$\Delta R(b,Z)$	0.08017	$m_{b\ell\nu}$	0.02282
$m_{q\ell\ell}$	0.04173	$m_{b\ell\nu}$	0.04636	$\Delta R(b,Z)$	0.02143
$\Delta R(t_{SM}, t_{FCNC})$	0.0410	χ^2_{tZ}	0.03171	χ^2_{tZ}	0.01561
$\Delta R(\ell,Z)$	0.02441	$\Delta R(\ell,Z)$	0.024	$\Delta R(\ell,Z)$	0.008783



Training and test comparison for signal and background for the discriminant with *tZu* coupling on production

GBDT performance
Data analysis

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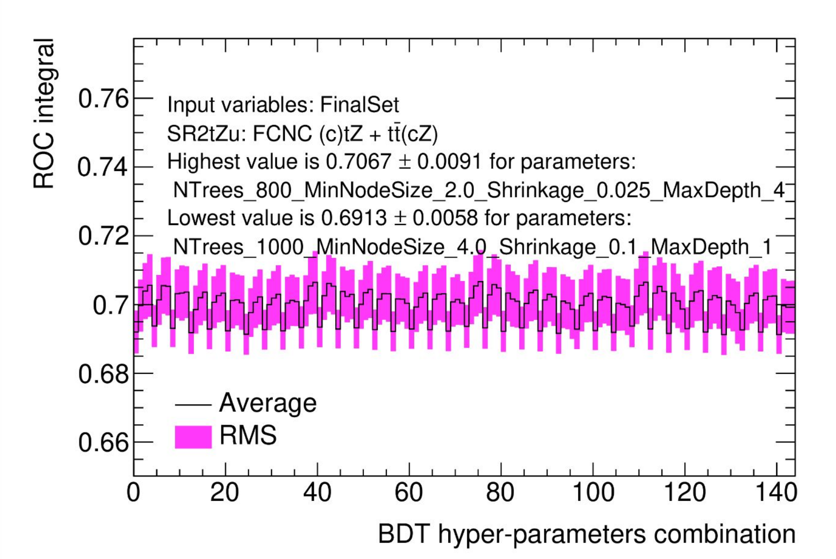
- Optimisation of the GBDT hyper-parameters varying the number of threes and shrinkage, among others, with a total of 144 combinations
  ⇒ Reference parameters produce a stable and optimal GBDT performance

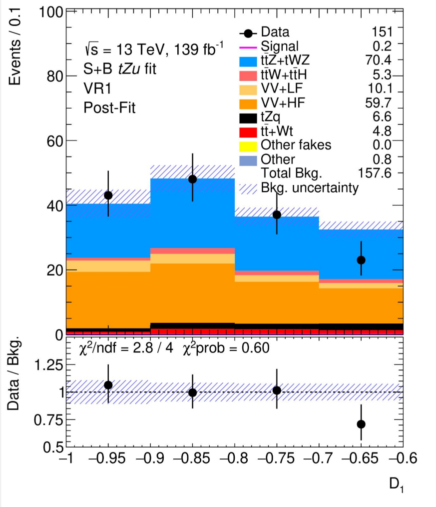
Option	Value for D_1	Value for D_2^u	Value for D_2^c
NTrees	800	800	1000
MinNodeSize		2%	
BoostType		Grad	
Shrinkage	0.05	0.05	0.025
UseBaggedBoost		True	
BaggedSampleFraction		0.6	
nCuts		200	
MaxDepth	2	2	1
NegWeightTreatment		IgnoreNegWeightsInTraining	

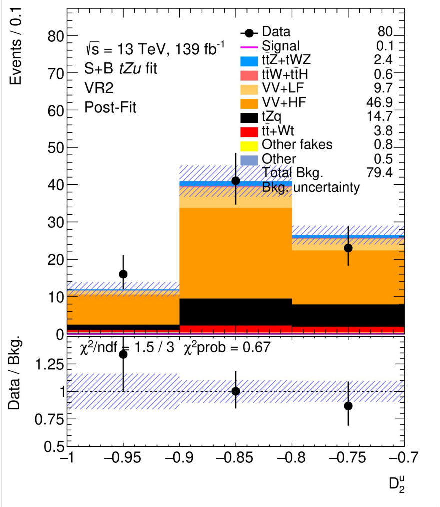


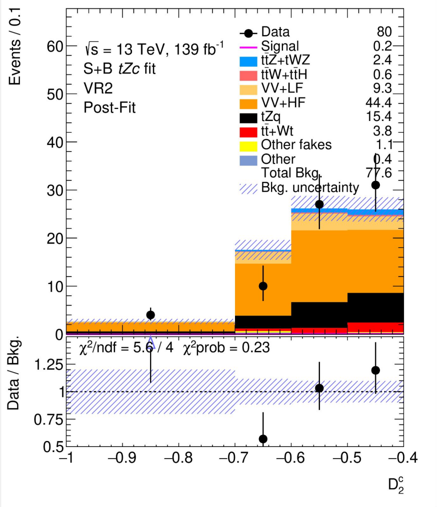
Validation regions
Data analysis

Validation Region	Defined from	Applied cut
VR1	Full SR1	$D_1 <$ -0.6
VR2	Full SR2	$D_2^u <$ -0.7 and $D_2^c <$ -0.4

- **Validation regions** used to assess the background estimation defined by the same cuts of the signal regions but **inverting cuts on GBDT score**, while:
  - Minimising the effect on the expected limits (< 1%)
  - Keeping the contribution from signal as low as possible (~ 2%)





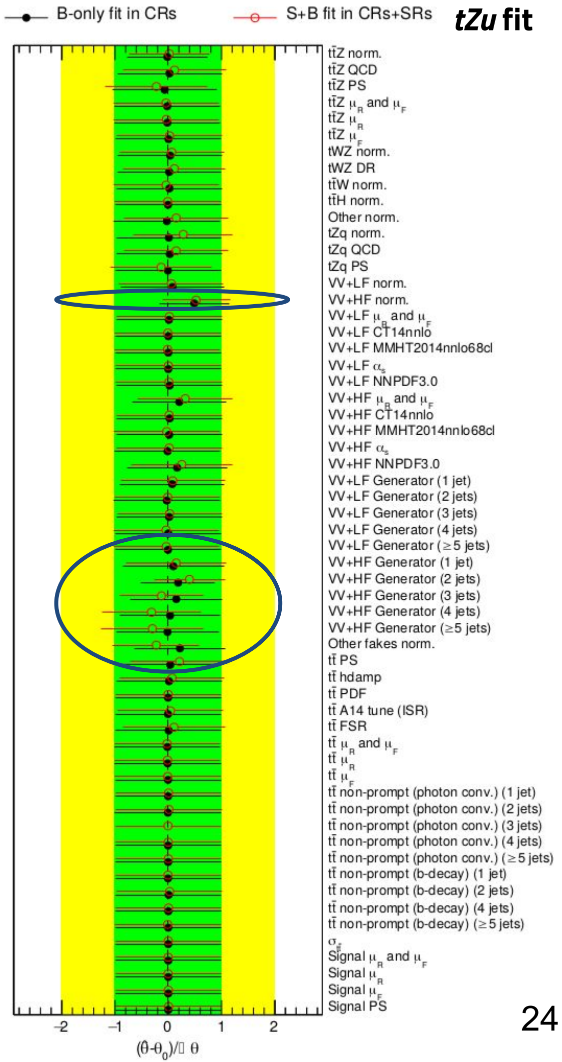


Likelihood fit
Data analysis

- Profile likelihood fit performed under the signal-plus-background hypothesis using real data in all regions

- Several systematic uncertainties considered: background normalisation and modelling, objects resolution and efficiency, signal parton shower variations, among others

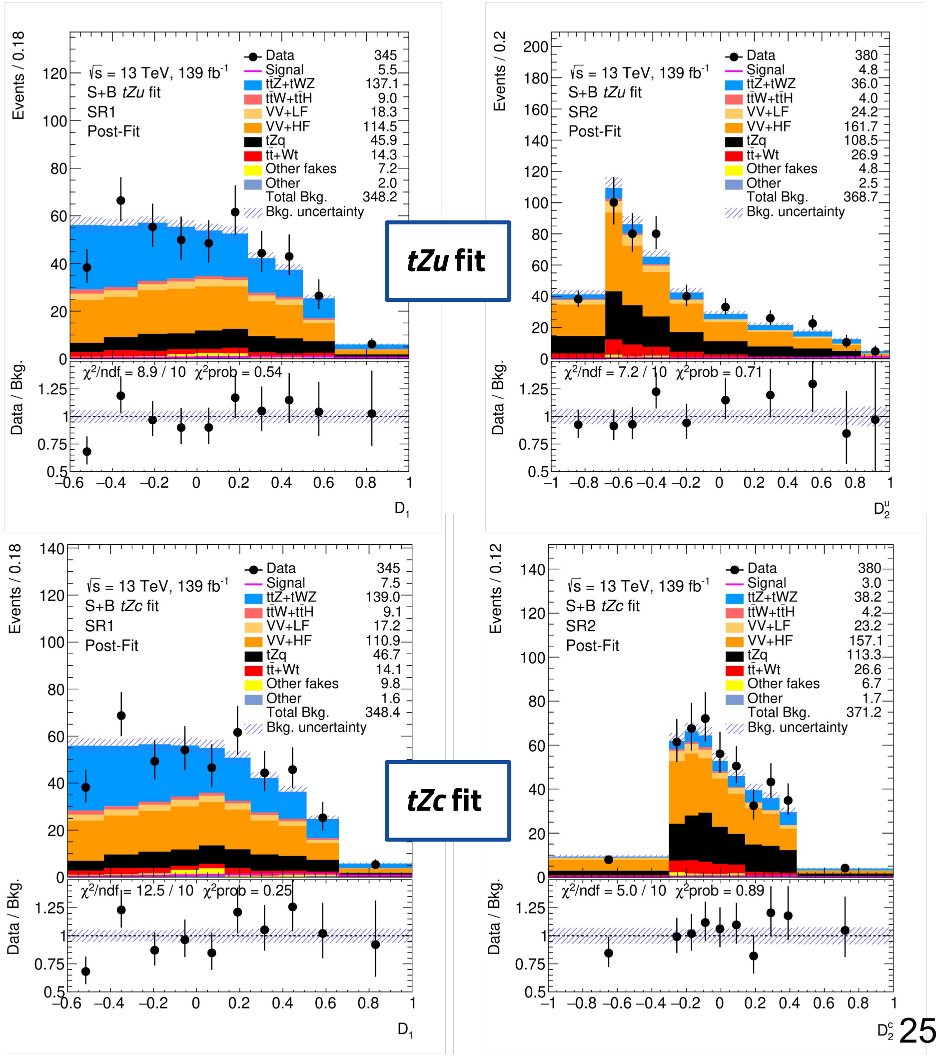
- Fitted nuisance parameters within their prior uncertainties
  ⇒ Data well modelled with the Monte Carlo expectation



Fit results
Data analysis

- Signal strength compatible with zero for both cases:
  tZu: μ = **0.08 ± 0.12 (stat) ± 0.08 (syst)**
  tZc: μ = **0.10 ± 0.17 (stat) ± 0.14 (syst)**
  ⇒ Data and SM prediction are in agreement within uncertainties and no evidence of new physics is found

- Post-fit impact on the signal strength parameter of ~ 3% for *tZu* (from SM *tZ* normalisation) and ~ 6% for *tZc* case (from *VV*+Heavy-Flavour generator with 3 jets)



Limits
Data analysis

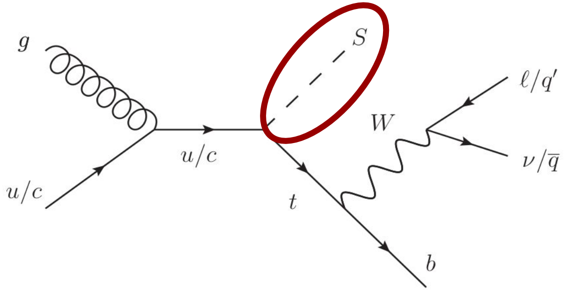
Signal coupling	tZu, left-handed	tZu, right-handed	tZc, left-handed	tZc, right-handed
$\mathcal{BR}(t \rightarrow qZ)[10^{-5}]$	$6.16\ (4.88^{+2.1}_{-1.4})$	$6.56\ (5.05^{+2.1}_{-1.4})$	$13.02\ (10.76^{+4.7}_{-3.0})$	$11.73\ (10.06^{+4.3}_{-2.8})$
$\sigma(pp \rightarrow tZ)$[fb]	$37\ (29^{+14}_{-12})$	$33\ (27^{+15}_{-11})$	$118\ (96^{+12}_{-8})$	$119\ (99^{+12}_{-7})$

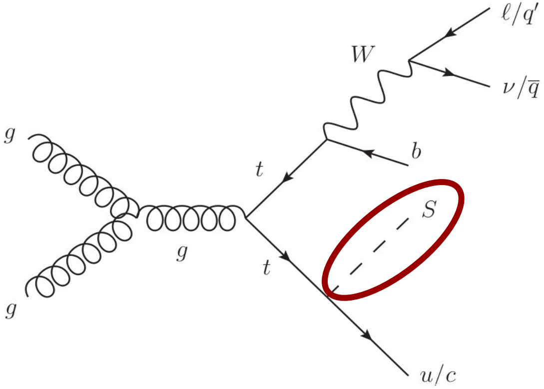
- **95% Confidence Level (CL) upper limits on the BR(*t* → *qZ*)** are extracted using the CL_s method with profile likelihood ratio as test statistics, being later converted to **limits on the Wilson coefficients and on the production cross-section**
- Systematic uncertainties have an **impact on the limits** of 25 % for *tZu* and 35% for *tZc*
- **Most stringent limits** for the FCNC *tZq* anomalous couplings with an improvement by a factor of 3 (2) for the *tZu* (*tZc*) couplings compared with the limits from the previous analysis

Signal coupling	Wilson coefficients	95 % CL upper limit
tZu, left-handed	$\lvert C_{uW}^{(13)*}\rvert, \lvert C_{uB}^{(13)*}\rvert$	$0.151\ (0.134^{+0.026}_{-0.019})$
tZu, right-handed	$\lvert C_{uW}^{(31)}\rvert, \lvert C_{uB}^{(31)}\rvert$	$0.156\ (0.136^{+0.026}_{-0.021})$
tZc, left-handed	$\lvert C_{uW}^{(23)*}\rvert, \lvert C_{uB}^{(23)*}\rvert$	$0.22\ (0.20^{+0.04}_{-0.03})$
tZc, right-handed	$\lvert C_{uW}^{(32)}\rvert, \lvert C_{uB}^{(32)}\rvert$	$0.208\ (0.194^{+0.038}_{-0.029})$

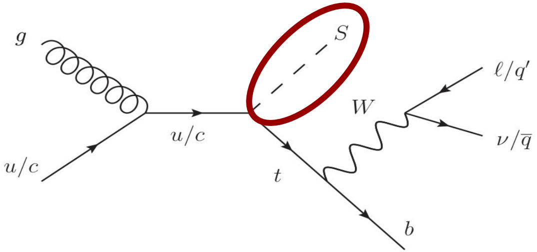
Scalar *S* particle
Phenomenology

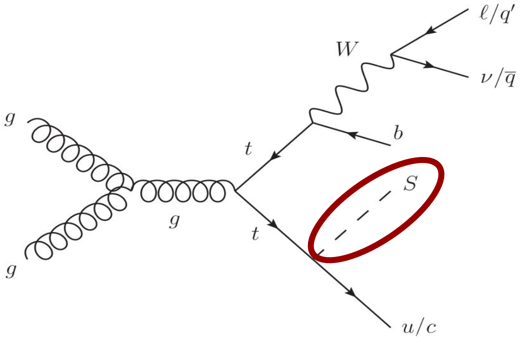
- **Sensitivity study** with FCNC in the top sector mediated by **a new scalar particle at the electroweak scale** performed in collaboration with theorists from LIP-Minho and from University of Granada (Spain)
- Such processes can easily arise in **scenarios of new physics** (in particular in composite Higgs models) and are poorly constrained by current experiments
- Study published in Journal of High Energy Physics





Scalar *S* particle
Phenomenology

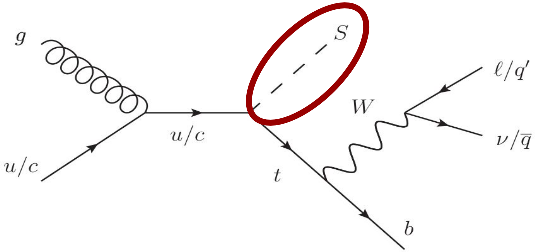


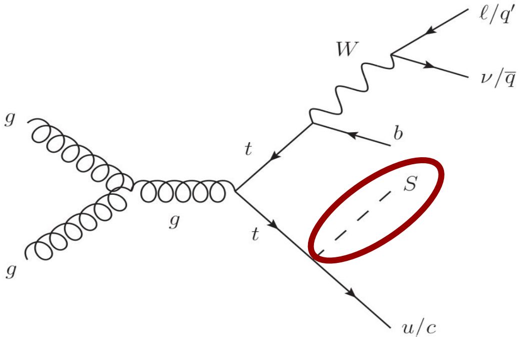


- **Three independent channels** (with **leptonic or hadronic** decays of the top quark considered for different cases):
  1) $pp \to tS + j$ with $S \to \mu^+\mu^-$: a scalar *S* decaying into a pair of muons
  2) $pp \to tS + j$ with $S \to \tau^+\tau^-$: a scalar *S* decaying into a pair of taus
  3) $pp \to tSS + j$ with $S \to \mu^+\mu^-$: two scalars *S* both decaying into a pair of muons

- Useful variables for the signal selection:
  - Jet multiplicity
  - Lepton multiplicity
  - Invariant masses requirement
  - Total mass of the system

Scalar *S* particle
Phenomenology





- **Three independent channels** (with **leptonic or hadronic** decays of the top quark considered for different cases):
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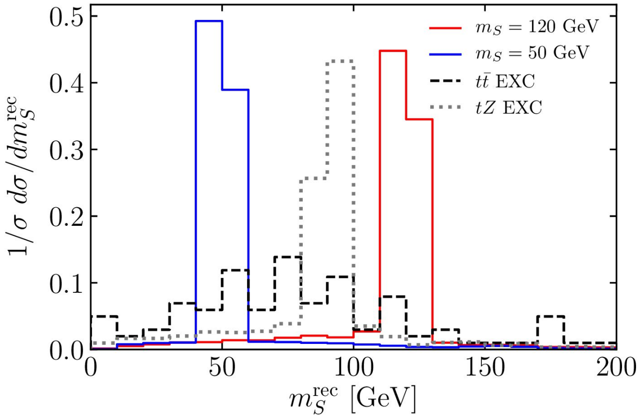
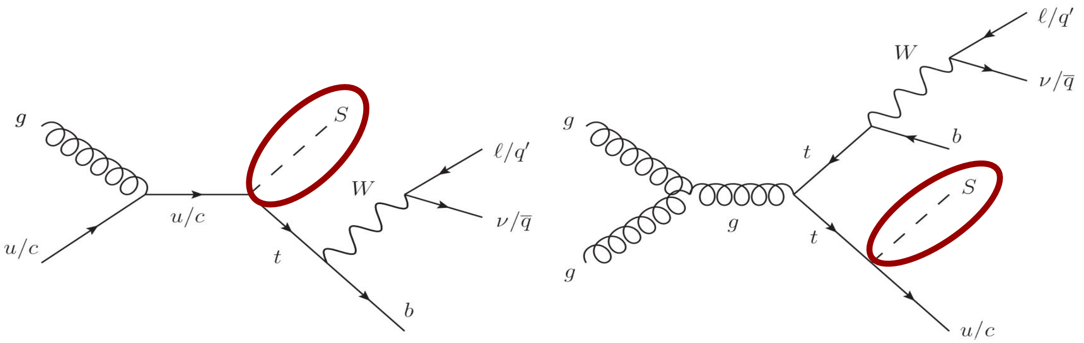
  3) *pp* → *tSS* + *j* with $S \to \mu^+\mu^-$: two scalars *S* both decaying into a pair of muons

- Useful variables for the signal selection:
  - Jet multiplicity: **≥ 1 jet, = 1 *b*-jet**
  - Lepton multiplicity: **= 3 ℓ**
  - Invariant masses requirement: **$|m_t^{rec} - m_t| < 50$ GeV and $|m_S^{rec} - m_S| < 30$ GeV**
  - Total mass of the system: **m(total) < 1 TeV**



Scalar *S* particle
Phenomenology



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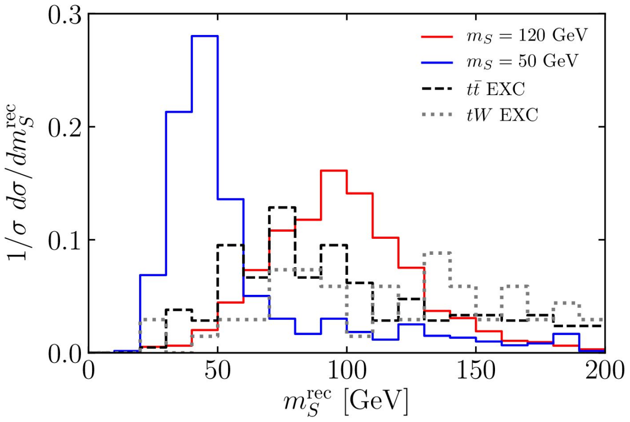
- Useful variables for the signal selection:
  - Jet multiplicity: **≥ 3 jets, = 1 *b*-jet**
  - Lepton multiplicity: **= 1 ℓ**
  - Invariant masses requirement: **$|m_S^{rec} - m_S| < 30$ GeV**
  - Total transverse mass of the system: **m_T(total) < 500 GeV**



Scalar *S* particle
Phenomenology

- **Three independent channels** (with **leptonic or hadronic** decays of the top quark considered for different cases):
  1) $pp \to tS + j$ with $S \to \mu^+\mu^-$: a scalar *S* decaying into a pair of muons
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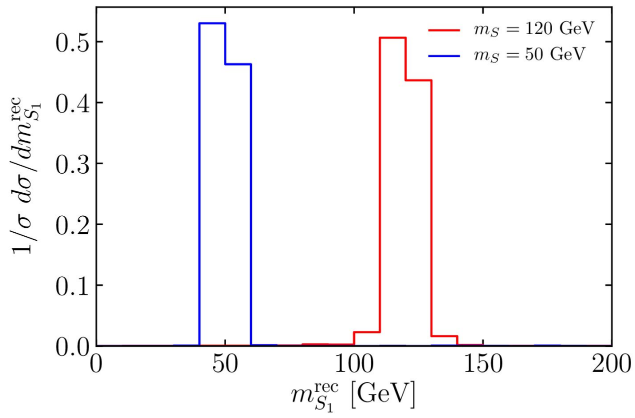
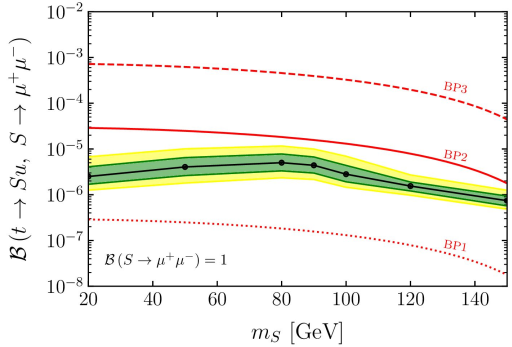
  3) **$pp \to tSS + j$ with $S \to \mu^+\mu^-$: two scalars *S* both decaying into a pair of muons**

- Useful variables for the signal selection:
  - Jet multiplicity: **≥ 3 jets, = 1 *b*-jet**
  - Lepton multiplicity: **= 4 ℓ**
  - Invariant masses requirement:
    $|m_t^{rec} - m_t| < 50$ GeV and
    $|m_S^{rec} - m_S| < 30$ GeV
  - Total mass of the system:
    m(total) < 1 TeV

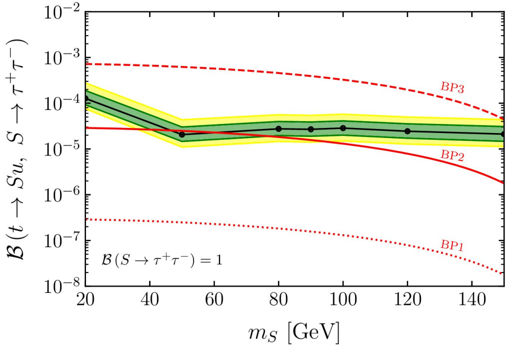


Scalar S particle - Expected limits
Phenomenology

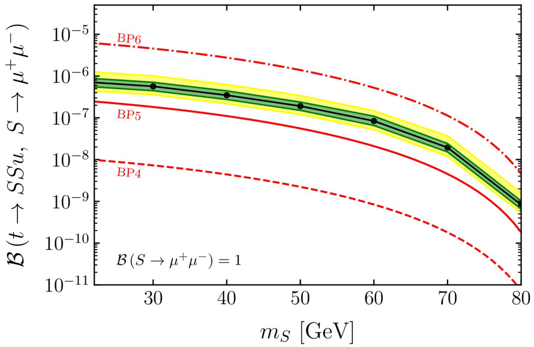
1) $pp \rightarrow tS,\ S \rightarrow \mu^+ \mu^-$



2) $pp \rightarrow tS,\ S \rightarrow \tau^+ \tau^-$



3) $pp \rightarrow tSS,\ S \rightarrow \mu^+ \mu^-$



Excluding at 95% CL:

- $\sigma\ (pp \rightarrow tS,\ S \rightarrow \mu^+ \mu^-) > 10^{-3}$ pb
- BR ($t \rightarrow Sq$) > 5 (15) x 10^{-7} with $q = u\ (c)$ for a m_S of 150 GeV

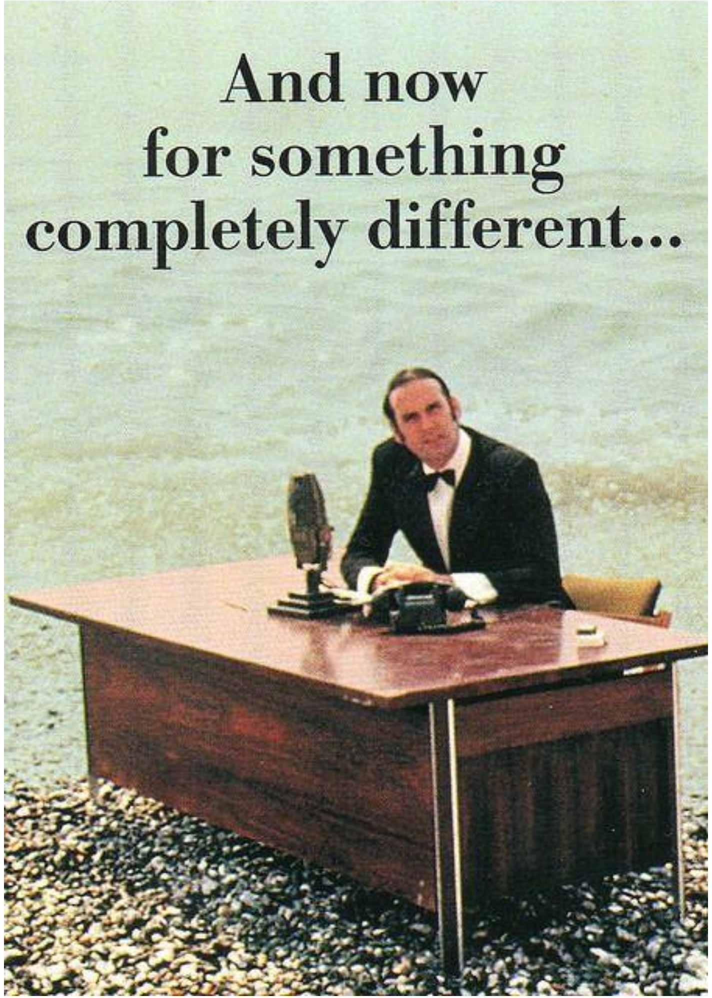
- $\sigma\ (pp \rightarrow tS,\ S \rightarrow \tau^+ \tau^-) > 10^{-2}$ pb
- BR ($t \rightarrow Sq$) > 11 (12) x 10^{-6} with $q = u\ (c)$ for a m_S of 50 GeV

- $\sigma\ (pp \rightarrow tSS,\ S \rightarrow \mu^+ \mu^-) > 10^{-3}$ pb
- BR ($t \rightarrow Sq$) > 5 (25) x 10^{-10} with $q = u\ (c)$ for a m_S of 80 GeV

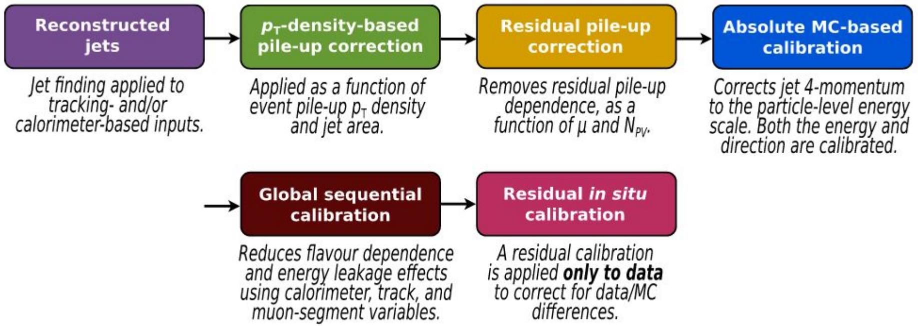
Conclusions

New interactions with the top quark

- Phenomenological studies of **interference effects** between production and decay modes with ***tZq*** **and** ***tγq*** **anomalous couplings**
- **Data analysis** searching for *tZq* anomalous coupling with **both production and decay modes** with full Run-2 dataset collected by the ATLAS detector
  - Most stringent limits set for the $t \to qZ$ processes with significant improvement with respect to previous analysis
- Sensitivity study on the search for a **new particle with top quark decays via FCNC** processes targeting distinct production modes and final states
- Estimate of the **hardware trigger efficiencies** with the AFP silicon tracker
- **Strong engagement with the ATLAS and university communities** through the CERN ATLAS team, expert on-call shifts, Early Career Scientist Board appointment, CERN guide to exhibitions and ATLAS cavern and International Masterclasses on Particle Physics

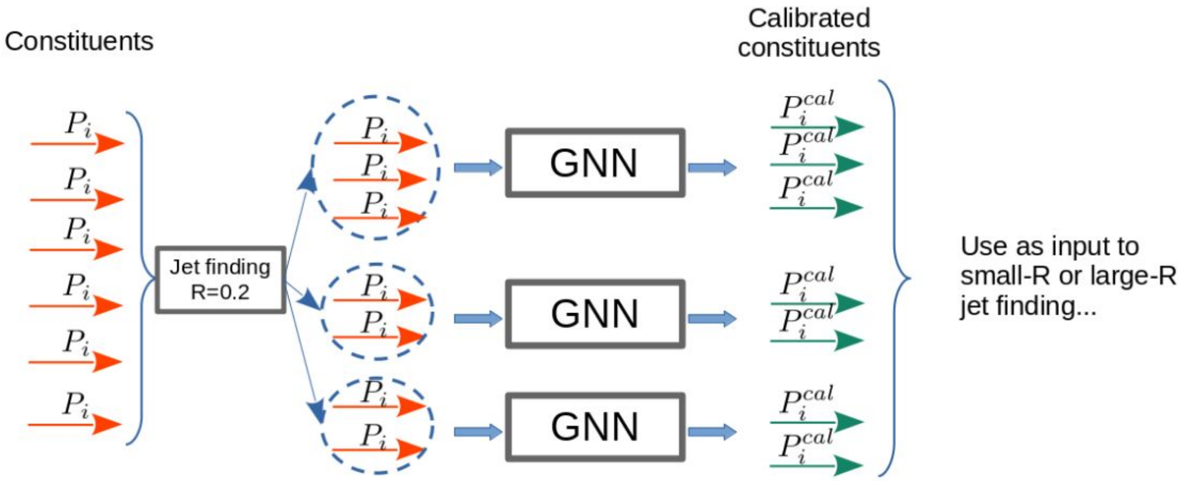

And now
for something
completely different...

Next steps
New challenges



Focusing now on jets:

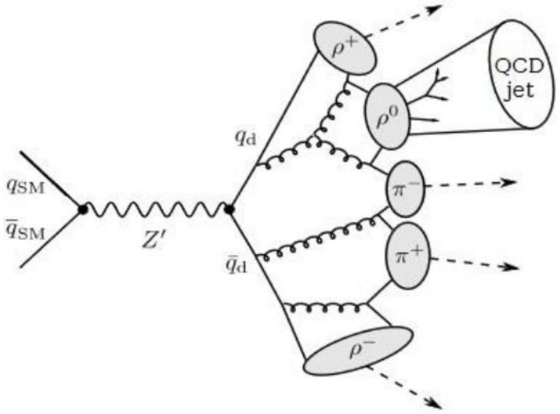
- Calibration of the constituents of very small radius jets (with ΔR=0.2) by using Graph Neural Networks

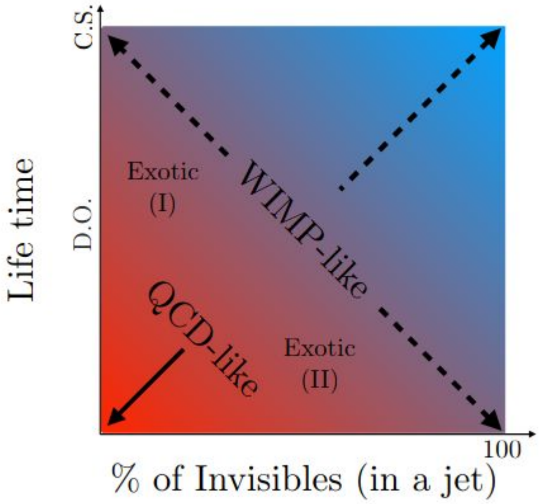


Next steps
New challenges

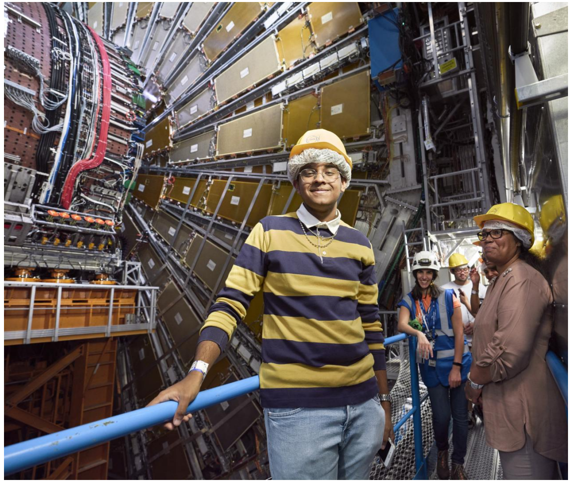
Focusing now on jets:

- Calibration of the constituents of very small radius jets (with ΔR=0.2) by using Graph Neural Networks
- Search for New Physics contributions in the dark QCD sector
  - Analysis targeting emerging jets with data recorded by the ATLAS detector during Run-3 (2022-2024)
  - Validation of new Pythia 8 Hidden Valley module within the Dark Showers Snowmass project





Thanks!



Objects definition
Data analysis

- Electrons, muons, jets (that can be tagged as coming from a bottom-quark) are used in the analysis, as well as the missing transverse momentum
- Following a few optimisation studies, the criteria applied to these physics objects was defined as:

Objects	p_T	$\|\eta\|$	ID	Isolation	Additional cuts
Electrons	> 15 GeV	< 2.47	`MediumLH`	`PLVTight`	$\|d_0^{BL}$ significance$\| < 5$ $\|\Delta z_0^{BL} \sin\theta\| < 0.5$ mm
Muons	> 15 GeV	< 2.5	`Medium`	`PLVTight`	$\|d_0^{BL}$ significance$\| < 3$ $\|\Delta z_0^{BL} \sin\theta\| < 0.5$ mm
Jets	> 25 GeV	< 2.5	PFlow	–	JVT
b-jets	> 25 GeV	< 2.5	`DL1r` @77%	–	–

FCNC *tZq*

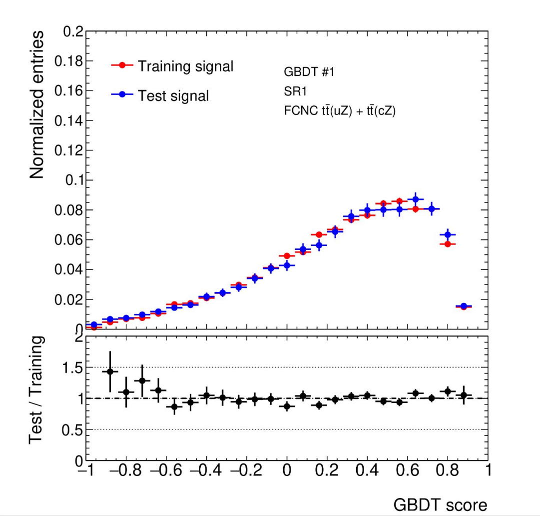
Multivariate discriminant - D_1

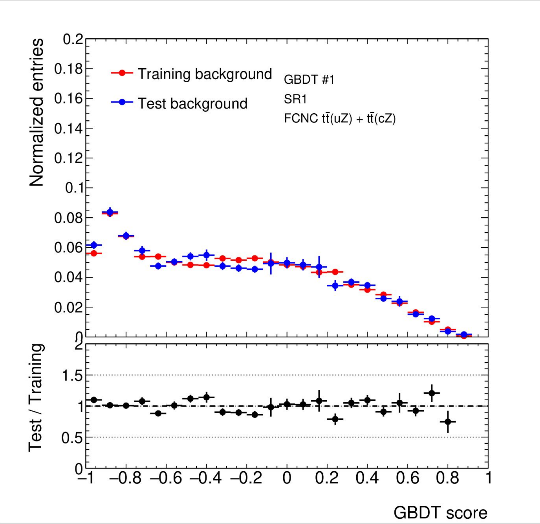
Variable separation

Variable	$\langle s^2 \rangle$	Definition
$m_{b\ell\nu}$	0.1364	SM top-quark candidate mass
p_T^q	0.07345	u/c-quark candidate transverse momentum
N_{jets}	0.05747	Jet multiplicity
$m_{q\ell\ell}$	0.04173	FCNC top-quark candidate mass
$\Delta R(t_{SM}, t_{FCNC})$	0.04109	ΔR between SM and FCNC top-quark candidates
$\Delta R(\ell, Z)$	0.02441	ΔR between W boson lepton and Z boson candidates

Variable importance

Variable	GBDT #1	GBDT #2	GBDT #3	GBDT #4	GBDT #5
$m_{q\ell\ell}$	0.1886	0.1899	0.1929	0.1821	0.1825
$\Delta R(t_{SM}, t_{FCNC})$	0.179	0.1728	0.17	0.1768	0.1723
$m_{b\ell\nu}$	0.1755	0.1687	0.1571	0.1729	0.1646
$\Delta R(\ell, Z)$	0.1656	0.18	0.1775	0.173	0.1891
p_T^q	0.1637	0.1626	0.1678	0.1614	0.1592
N_{jets}	0.1277	0.126	0.1346	0.1338	0.1322





FCNC *tZq*

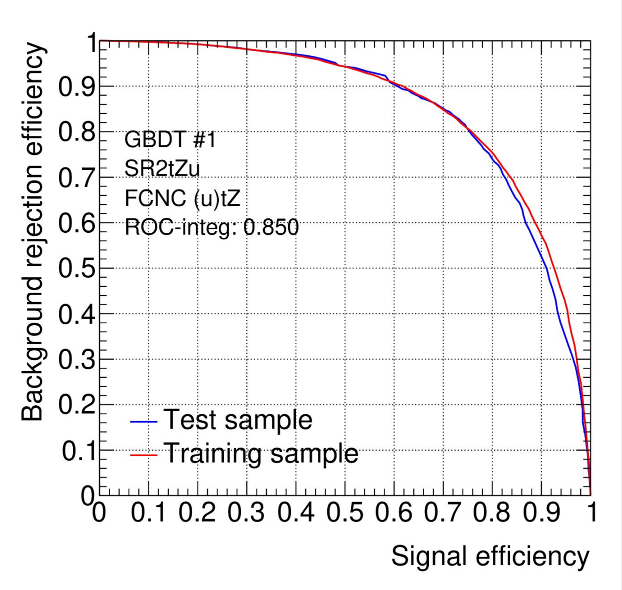
Multivariate discriminant - D_2^u input variables

Variable separation

Variable	$\langle s^2 \rangle$	Definition
p_T^Z	0.3104	Z boson candidate transverse momentum
p_T^b	0.175	b-quark candidate transverse momentum
$\Delta R(b,Z)$	0.08017	ΔR between b-quark and Z boson candidates
$m_{b\ell\nu}$	0.04636	SM top-quark candidate mass
χ^2_{tZ}	0.03171	χ^2 from the kinematic fit under the tZ production signal hypothesis
$\Delta R(\ell,Z)$	0.024	ΔR between W boson lepton and Z boson candidates

Variable importance

Variable	GBDT #1	GBDT #2	GBDT #3	GBDT #4	GBDT #5
$\Delta R(b,Z)$	0.1793	0.1761	0.1791	0.1809	0.1778
p_T^Z	0.1784	0.1717	0.1736	0.1785	0.181
$m_{b\ell\nu}$	0.1755	0.1819	0.1743	0.173	0.1776
$\Delta R(\ell,Z)$	0.1748	0.1739	0.1776	0.1762	0.166
p_T^b	0.1741	0.1778	0.1658	0.1715	0.1766
χ^2_{tZ}	0.1178	0.1186	0.1296	0.1199	0.121



FCNC *tZq*

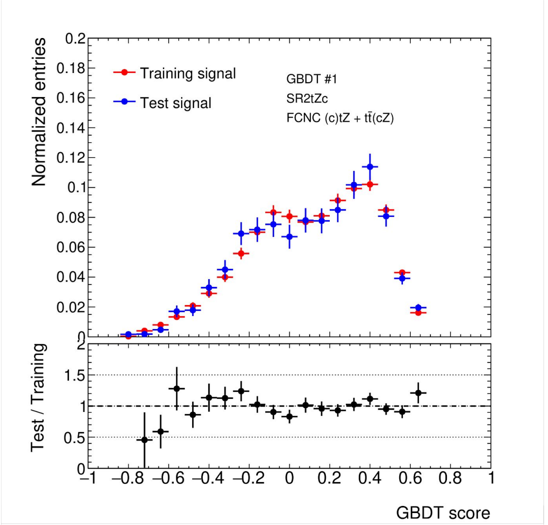
Multivariate discriminant - D_2^c

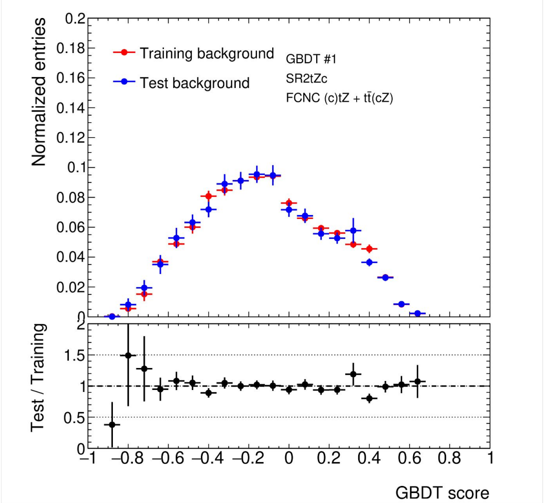
Variable separation

Variable	$\langle s^2 \rangle$	Definition
p_T^Z	0.07408	Z boson candidate transverse momentum
p_T^b	0.05261	b-quark candidate transverse momentum
$m_{b\ell\nu}$	0.02282	SM top-quark candidate mass
$\Delta R(b,Z)$	0.02143	ΔR between b-quark and Z boson candidates
χ^2_{tZ}	0.01561	χ^2 from the kinematic fit under the FCNC tZ production signal hypothesis
$\Delta R(\ell,Z)$	0.008783	ΔR between W boson lepton and Z boson candidates

Variable importance

Variable	GBDT #1	GBDT #2	GBDT #3	GBDT #4	GBDT #5
$\Delta R(b,Z)$	0.1938	0.1932	0.1962	0.188	0.1889
p_T^Z	0.1889	0.1869	0.19	0.1774	0.1857
$m_{b\ell\nu}$	0.1787	0.1805	0.1737	0.1826	0.183
$\Delta R(\ell,Z)$	0.1596	0.159	0.1496	0.1584	0.1639
p_T^b	0.152	0.1508	0.1557	0.1508	0.157
χ^2_{tZ}	0.127	0.1296	0.1347	0.1427	0.1216

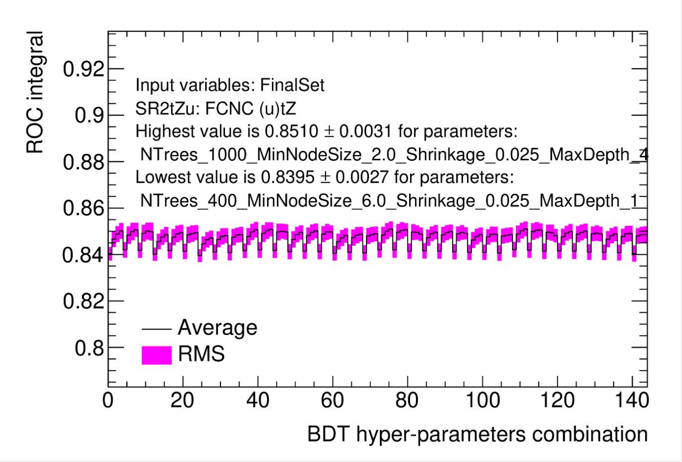


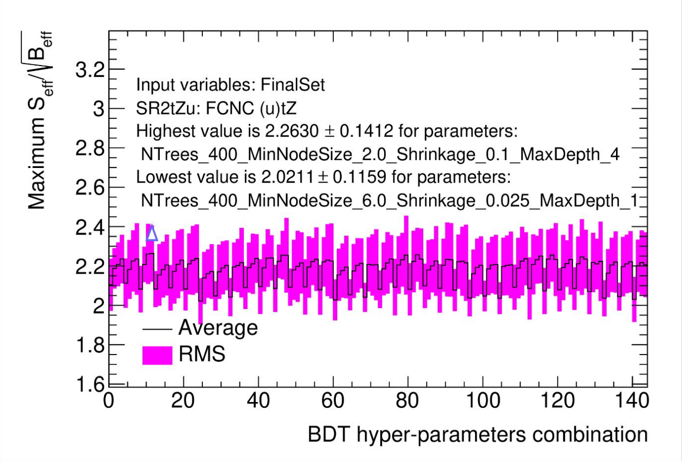


FCNC *tZq*
Multivariate discriminants

- **BDT hyper-parameters optimisation** is performed with 144 combinations of GBDT parameters: NTrees=[400,600,800,1000]; minNodSize=[2.0,4.0,6.0]; shrinkage=[0.025,0.05,0.1]; maxDepth=[1,2,3,4]
- **Small difference** between highest and lowest S/√B ⇒ **Stable BDT performance**

Option	Value for D_1	Value for D_2^u	Value for D_2^c
NTrees	800	800	1000
MinNodeSize		2%	
BoostType		Grad	
Shrinkage	0.05	0.05	0.025
UseBaggedBoost		True	
BaggedSampleFraction		0.6	
nCuts		200	
MaxDepth	2	2	1
NegWeightTreatment		IgnoreNegWeightsInTraining	





Systematic uncertainties
Data analysis

- **Object energy scale/resolution and efficiencies:** leptons, jets, b-tagged jets and missing transverse momentum
- Luminosity and pile-up reweighting
- **Parton shower variations** for signal, *ttZ*, SM *tZ* and *tt*
- Normalisation uncertainty applied for all **backgrounds**
- **Diboson systematic** uncertainties split into light- and heavy-flavour contribution
- **Diboson generator** and ***tt*** **non-prompt background** (photon conversion and *B*-meson decay) split into **jet multiplicities**
- **Normalisation of the *tt*+*Wt*** background as a free-floating parameter
- Symmetrisation, smoothing and pruning (1% on the normalisation and 0.5% on the shape) are applied to all systematic uncertainties

Process	Rate uncertainty
$t\bar{t}+Wt$	–
$t\bar{t}Z$	12 %
$t\bar{t}W$	50 %
tWZ	30 %
tZq	15 %
VV+LF	20 %
VV+HF	30 %
Z+jets	100 %
$t\bar{t}H$	15 %
Other	50 %

FCNC *tZq*

Systematic uncertainties

Source	Naming of NPs
Lepton reconstruction	EL_SF_Trig EL_SF_Reco EL_SF_ID EL_SF_Isol MU_SF_Trigger_STAT MU_SF_Trigger_SYST MU_SF_ID_STAT MU_SF_ID_SYST MU_SF_ID_STAT_LOWPT MU_SF_ID_SYST_LOWPT MU_SF_Isol_STAT MU_SF_Isol_SYST MU_SF_TTVA_STAT MU_SF_TTVA_SYST
Lepton momentum scale and resolution	EG_SCALE_ALL EG_RESOLUTION_ALL MUON_ID MUON_MS MUON_SCALE MUON_SAGITTA_RHO MUON_SAGITTA_RESBIAS

Jet energy scale	GlobalReduction_JET_BJES_Response GlobalReduction_JET_EffectiveNP_1-8restTerm GlobalReduction_JET_EtaIntercalibration_Modelling GlobalReduction_JET_EtaIntercalibration_NonClosure_2018data GlobalReduction_JET_EtaIntercalibration_NonClosure_highE GlobalReduction_JET_EtaIntercalibration_NonClosure_negEta GlobalReduction_JET_EtaIntercalibration_NonClosure_posEta GlobalReduction_JET_EtaIntercalibration_TotalStat GlobalReduction_JET_Flavor_Composition GlobalReduction_JET_Flavor_Response GlobalReduction_JET_PunchThrough_MC16
Jet energy resolution	GlobalReduction_JET_JER_DataVsMC_MC16 GlobalReduction_JET_JER_EffectiveNP_1-7restTerm GlobalReduction_JET_Pileup_OffsetMu GlobalReduction_JET_Pileup_OffsetNPV GlobalReduction_JET_Pileup_PtTerm GlobalReduction_JET_Pileup_RhoTopology GlobalReduction_JET_SingleParticle_HighPt
Jet vertex tagger	jvt
Missing transverse momentum	MET_SoftTrk_Scale MET_SoftTrk_ResoPerp MET_SoftTrk_ResoPara
b-tagging efficiency	bTagSF_eigenvars_B_0-8 bTagSF_eigenvars_C_0-3 bTagSF_eigenvars_Light_0-3

Event yields
Data analysis

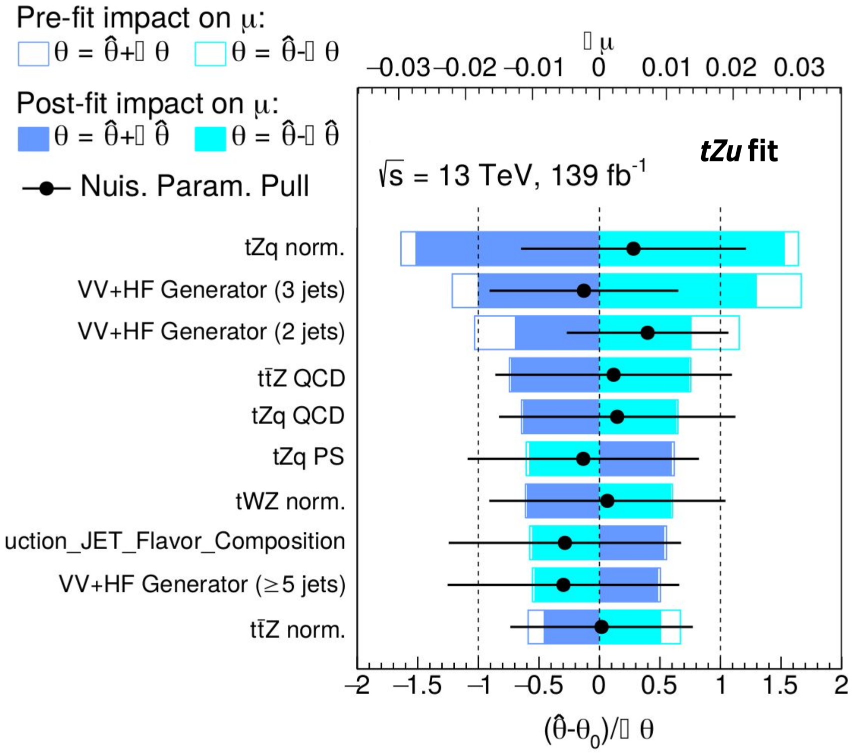
- Data and post-fit background prediction in all control and validation regions within the uncertainty ⇒ No evidence of instability in the fit

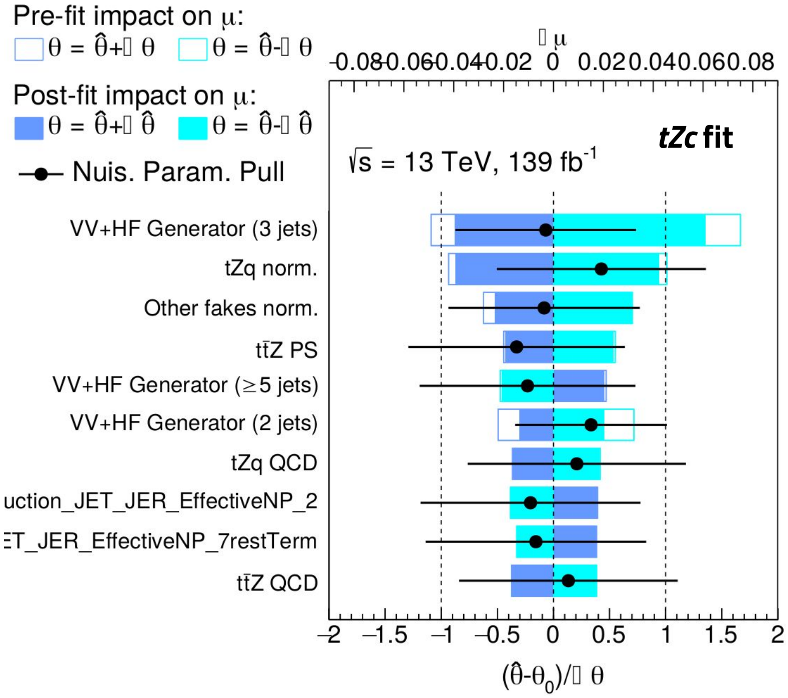
Post-fit	SR1	SR2	Side-band CR1	Side-band CR2	$t\bar{t}Z$ CR	$t\bar{t}$ CR
$t\bar{t}Z + tWZ$	137 ±12	36 ±6	102 ±14	8.2 ±1.4	230 ±18	15.4 ±1.5
$t\bar{t}W$	4.2 ±2.1	3.1 ±1.6	4.5 ±2.3	2.3 ±1.2	3.0 ±1.5	27 ±13
$t\bar{t}H$	4.8 ±0.7	0.89 ±0.17	2.6 ±0.4	0.33 ±0.07	7.5 ±1.2	14.1 ±2.2
VV + LF	18 ±7	24 ±8	27 ±11	12 ±4	0.23 ±0.19	0.38 ±0.25
VV + HF	114 ±19	162 ±26	166 ±25	64 ±9	17 ±8	2.9 ±0.5
tZq	46 ±7	108 ±18	22 ±4	6.8 ±1.4	21 ±5	0.96 ±0.19
$t\bar{t}$ +Wt	14 ±4	27 ±8	9.3 ±2.6	7.2 ±2.1	4.0 ±1.3	93 ±19
Other fakes	7 ±8	5 ±6	2 ±4	2.0 ±2.8	0.15 ±0.18	0.08 ±0.09
Other	2.0 ±1.0	2.5 ±2.9	3.3 ±2.5	0.8 ±0.4	1.9 ±0.9	3.2 ±1.5
FCNC (u)tZ	0.9 ±1.7	4 ±8	0.4 ±0.7	0.17 ±0.33	0.09 ±0.18	0.05 ±0.10
FCNC $t\bar{t}$ (uZ)	5 ±9	0.8 ±1.5	0.14 ±0.27	0.04 ±0.07	0.11 ±0.20	0.018 ±0.035
Total background	348 ±15	369 ±21	338 ±18	104 ±8	284 ±16	157 ±13
Data	345	380	343	104	286	157
Data / Bkg.	0.99 ±0.04	1.03 ±0.06	1.01 ±0.05	1.00 ±0.08	1.01 ±0.06	1.00 ±0.08
S / $\sqrt{B}$	0.016	0.013	0.002	0.002	0.001	0.000

Post-fit	VR1	VR2
$t\bar{t}Z + tWZ$	70 ±7	2.4 ±0.6
$t\bar{t}W$	2.3 ±1.2	0.48 ±0.25
$t\bar{t}H$	3.0 ±0.5	0.108 ±0.033
VV + LF	10 ±5	9.7 ±3.0
VV + HF	60 ±14	47 ±8
tZq	6.6 ±1.5	14.7 ±2.6
$t\bar{t}$ +Wt	4.8 ±2.1	3.8 ±1.4
Other fakes	0.03 ±0.24	0.8 ±1.1
Other	0.8 ±0.4	0.5 ±0.6
FCNC (u)tZ	0.08 ±0.16	0.07 ±0.14
FCNC $t\bar{t}$ (uZ)	0.14 ±0.27	0.05 ±0.10
Total background	158 ±13	79 ±7
Data	151	80
Data / Bkg.	0.96 ±0.08	1.01 ±0.09
S / $\sqrt{B}$	0.001	0.002

FCNC *tZq*

Ranking plots





Scalar *S* particle
Phenomenology

Generation of signal and background events considering a center-of-mass energy of 13 TeV with full simulation through MadGraph, Pythia and Delphes:

- Signal events: UFO model implemented with Feynrules assuming seven benchmark masses of the scalar S - 20, 50, 80, 90, 100, 120 and 150 GeV
- Background processes: tW, ttV, VV, ZVV, tt, V + jets and tZ, with $V = W,Z$

Reconstruction of the top quark:

- Reconstruction of the top quark through a jet coming from a bottom quark and the W boson decayed into one lepton and missing transverse momentum. The hadronic decay of the W boson is considered for the $pp \rightarrow tSS$ scenario.

Limits on the branching ratios $t \rightarrow Sq$ at 95% CL were obtained through a tool using the CL_s method and assuming an integrated luminosity of 150 fb^{-1}