UNIVERSITY OF BIRMINGHAM

ATLAS EXPERIMENT

Searches for rare top quark production and decay processes with the ATLAS experiment

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Introduction

TOP QUARK PHYSICS

- Heaviest known elementary particle
  - Large coupling to Higgs boson
  - Potentially large couplings to hypothetical new particles
- ATLAS Run 2 dataset (139 fb^{-1}) provides huge sample of top quark physics events
  - Measure rare SM processes + directly search for new physics

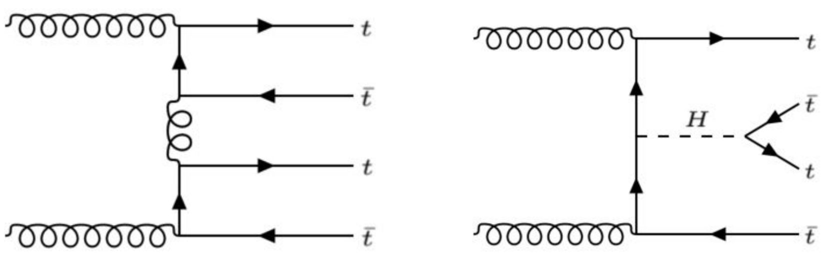
IN THIS TALK

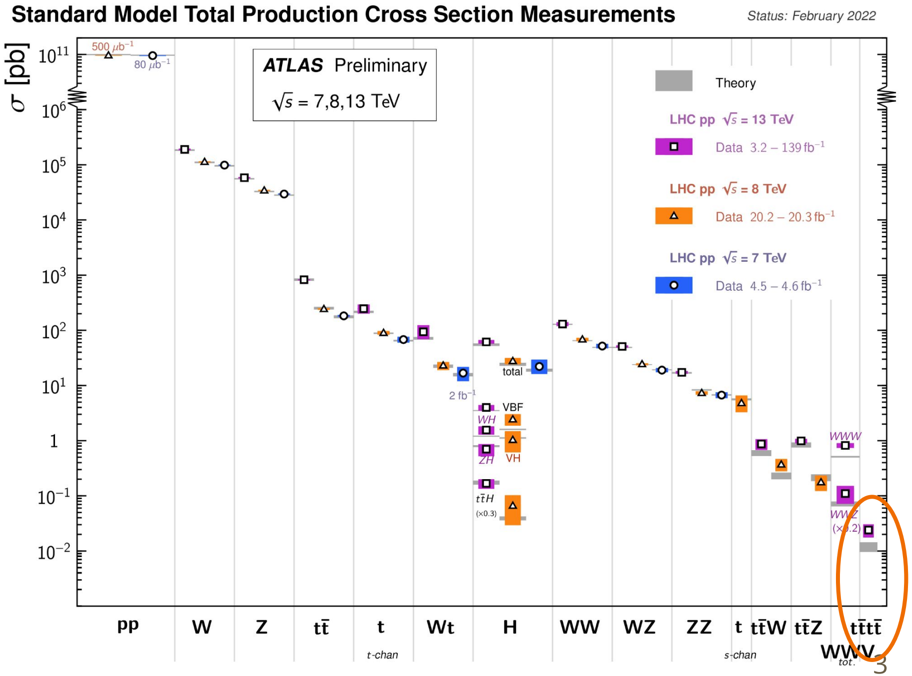
- **Observation** of 4 top quark production!
- Searches for FCNC couplings of the top quark: $tq\gamma$, tqg, tqH, tqZ
- Search for charged lepton flavour violating couplings of the top quark

Four top quark production (4t)

JHEP11(2021)118

arXiv:2303.15061



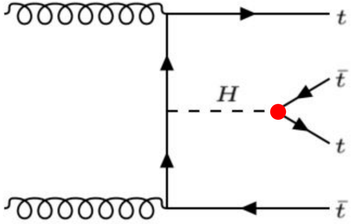


Why look for $4t$ production?

Motivation

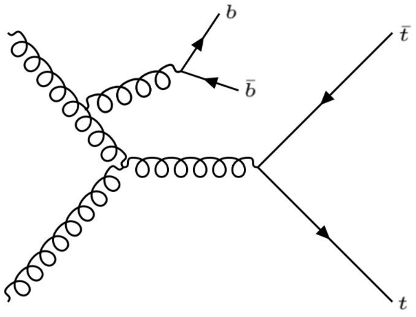
- Very rare SM process (σ^{SM}_{4t} = 12.0 ± 2.4 fb)
- Many BSM models predict enhancements to σ_{4t}
  - E.g. SUSY, 2HDM
  - Sensitivity to four-fermion EFT couplings
- σ_{4t} sensitive to CP properties of y_t

EW $4t$ production - sensitivity to y_t



Measurement channels

- 1ℓ/2ℓOS (57% BR)
  - Large irreducible $t\bar{t}$+HF(significant theoretical uncertainties)
- 2ℓSS/3ℓ (13% BR)
  - Low background (dominated by $t\bar{t}H/Z/W$ + jets)



$t\bar{t}+b\bar{b}$ production

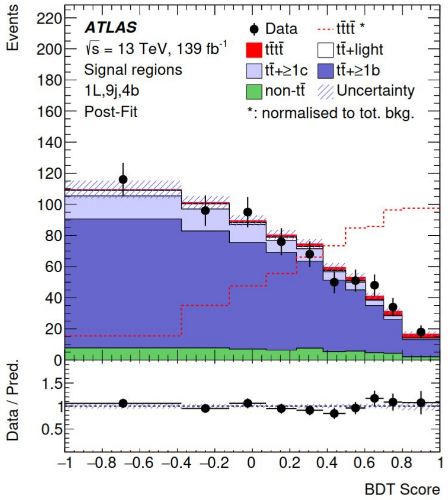
Evidence for 4t production (JHEP11(2021)118)

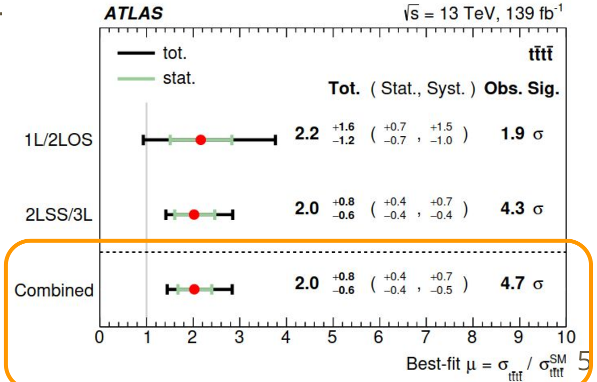
- Measurement performed in 1ℓ/2ℓOS channel
  - Events categorised by jet multiplicity and b-tagging purity
  - Resolve different flavour components of $t\bar{t}$+HF
  - Sequential kinematic reweighting to correct mis-modelling in each component
  - Profile likelihood fit to BDT discriminant
  - Limited by modelling of signal and $t\bar{t}$+HF
- Signal-like excess over background: signal strength, μ = 2.2
- Observed cross-section:

$$\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8\,(\text{stat.})\,^{+15}_{-13}\,(\text{syst.})\,\text{fb} = 26\,^{+17}_{-15}\,\text{fb}.$$

- Combination with 2ℓSS/3ℓ measurement (arXiv:2007.14858):

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.})\,\text{fb} = 24\,^{+7}_{-6}\,\text{fb}.$$





Observation of $4t$ production

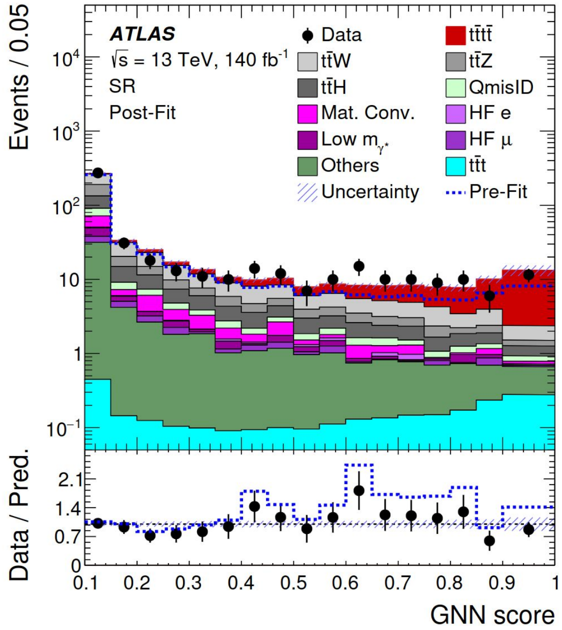
arXiv:2303.15061

- Refined measurement in 2ℓSS/3ℓ channel
- Data-driven background estimations
  - Dedicated CRs for non-prompt/fake leptons
  - Normalisation correction to $t\bar{t}W$ based on jet multiplicity
- Fully connected graph neural network for S/B discrimination
  - Reconstructed j/ℓ/E_T^{miss} as nodes
  - Angular separations encoded in edges
- Limited by modelling of signal and data-driven estimate of $t\bar{t}W$ background

$$\mu = 1.89^{+0.37}_{-0.35}(\text{stat})\ ^{+0.62}_{-0.37}(\text{syst}) = 1.89\ ^{+0.73}_{-0.51}.$$

$$\sigma_{t\bar{t}t\bar{t}} = 22.7^{+4.7}_{-4.4}(\text{stat})\ ^{+4.6}_{-3.4}(\text{syst})\ \text{fb} = 22.7\ ^{+6.6}_{-5.5}\ \text{fb}.$$

Observation of 4 tops production!



Observed (expected) significance: 6.1σ (4.3σ)

Observation of $4t$ production

arXiv:2303.15061

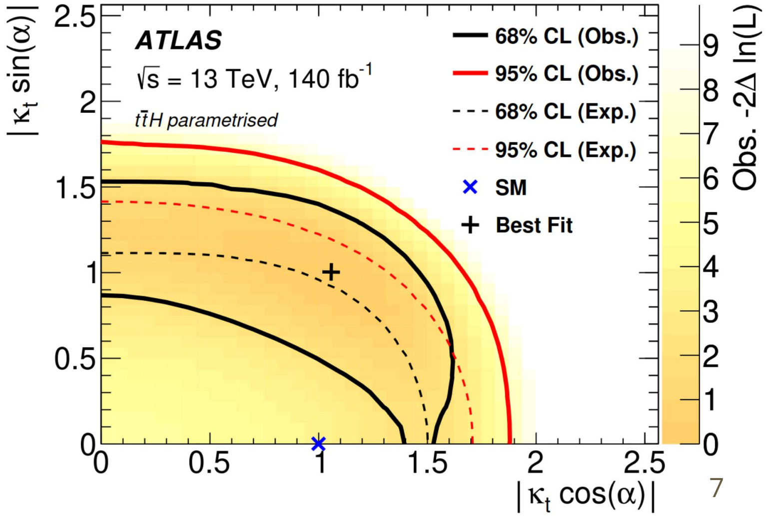
ATLAS EXPERIMENT

- Set limits on very rare (unobserved) 3 tops process (σ^{SM}_{3t} = 1.67 fb)
- Constrain the top-Higgs Yukawa coupling
- EFT operator coefficients affecting $4t$ production

$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_i C_j \sigma_{i,j}^{(2)}$$

Operators	Expected C_i/Λ^2 [TeV^{-2}]	Observed C_i/Λ^2 [TeV^{-2}]
O^1_{QQ}	[-2.4,3.0]	[-3.5,4.1]
O^1_{Qt}	[-2.5,2.0]	[-3.5,3.0]
O^1_{tt}	[-1.1,1.3]	[-1.7,1.9]
O^8_{Qt}	[-4.2,4.8]	[-6.2,6.9]

Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]



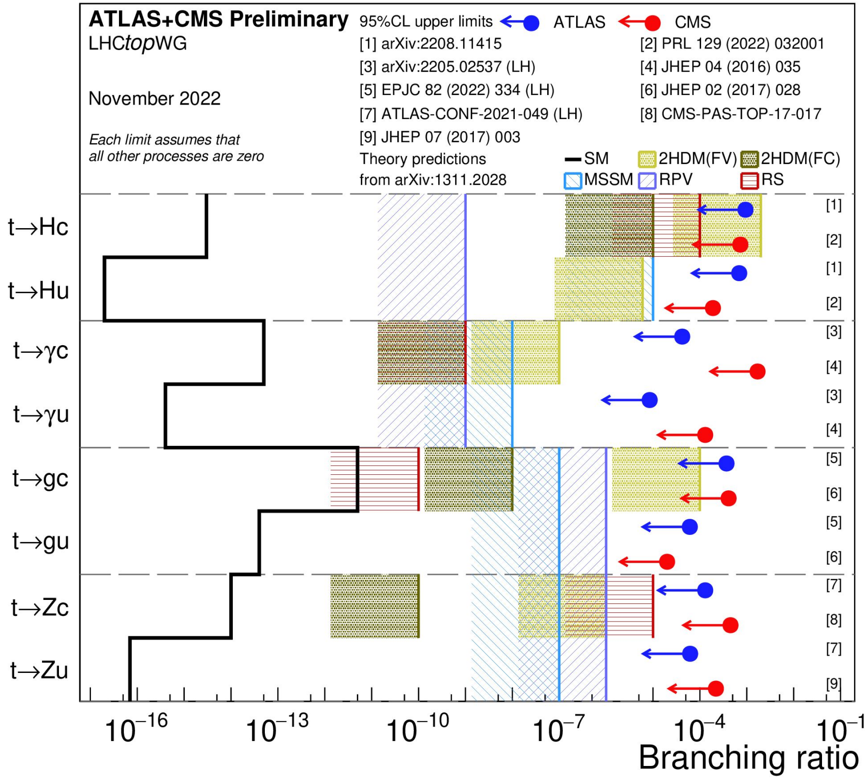
Search for flavour-changing neutral-current interactions of the top quark

tqg - Eur. Phys. J. C 82 (2022) 334

$tq\gamma$ - Phys. Lett B (2022) 137379

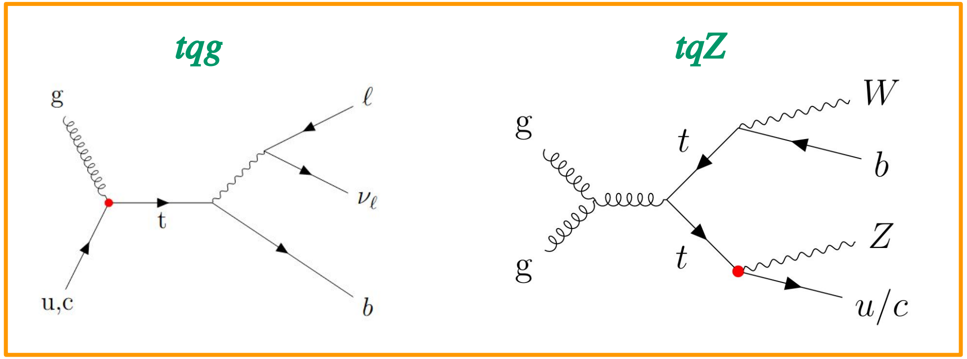
tqZ - arXiv:2301.11605

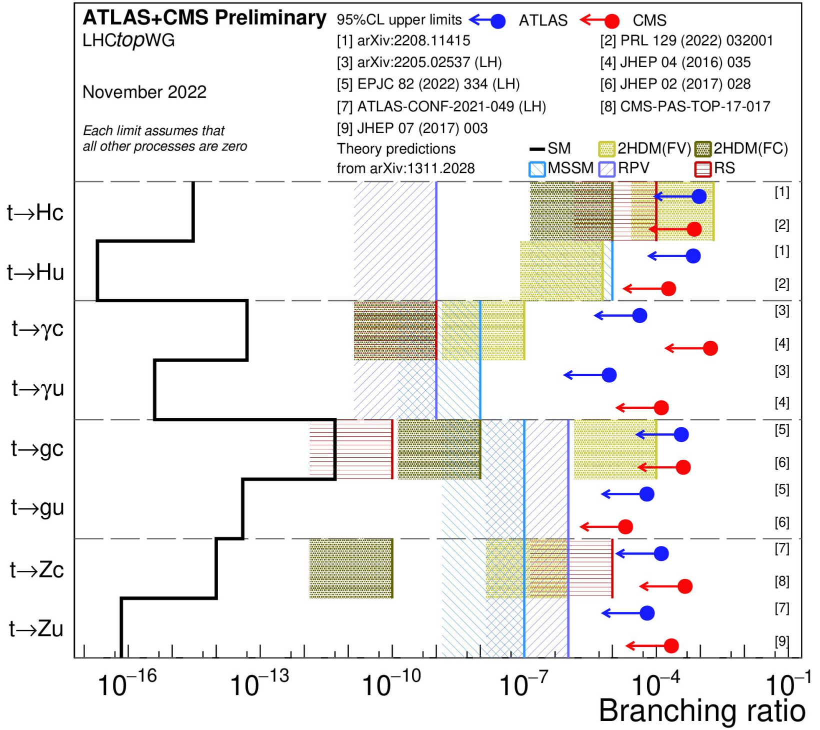
tqH - arXiv:2208.11415



Why search for FCNCs in top interactions?

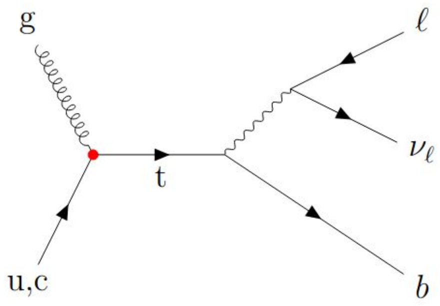
- Forbidden at tree level in the Standard Model
- Heavily suppressed at loop level through GIM mechanism
- Wide variety of BSM models predict FCNCs with rates observable at LHC
  - Describe FCNC couplings in terms of EFT framework





FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

- Search for **single top production** via FCNC *tqg* vertex ($q = u/c$)
  - Single lepton, 1 *b*-tagged jet and E^{T}_{miss}
- Data-driven estimate for events with fake leptons from multi-jet background
- Neural networks (NNs) used to discriminate between $u+g\rightarrow t$, $c+g\rightarrow t$ and background
  - Kinematic input variables including reconstructed top kinematics



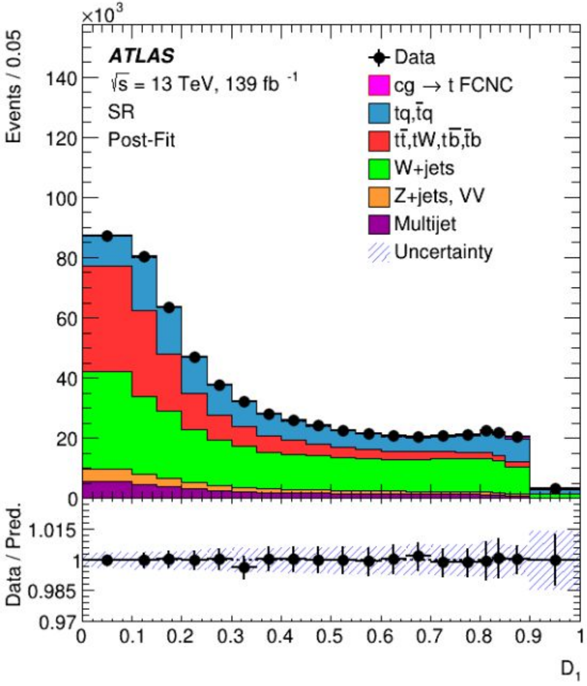
FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

- Profile likelihood fit to NN discriminants in SR
- Dominant uncertainties:
  - *ugt*: MC stat uncertainty and modelling of W+jets
  - *cgt*: parton shower modelling of FCNC *cgt* and SM *tq* processes

$$\mathcal{B}(t \to u + g) < 0.61 \times 10^{-4}$$
$$\mathcal{B}(t \to c + g) < 3.7 \times 10^{-4}$$

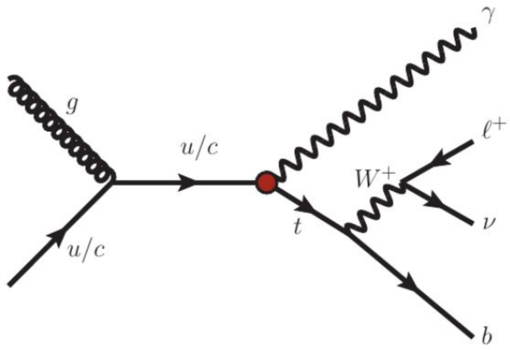
$$\frac{|C_{uG}^{ut}|}{\Lambda^2} < 0.057\ \text{TeV}^{-2} \qquad \frac{|C_{uG}^{ct}|}{\Lambda^2} < 0.14\ \text{TeV}^{-2}$$

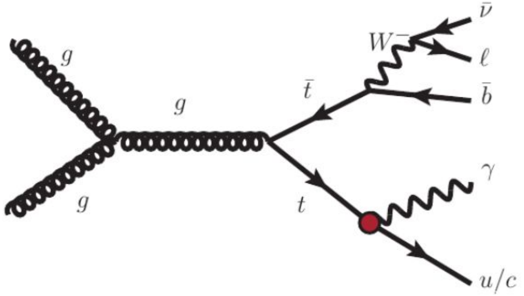
(95% CL)



FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)

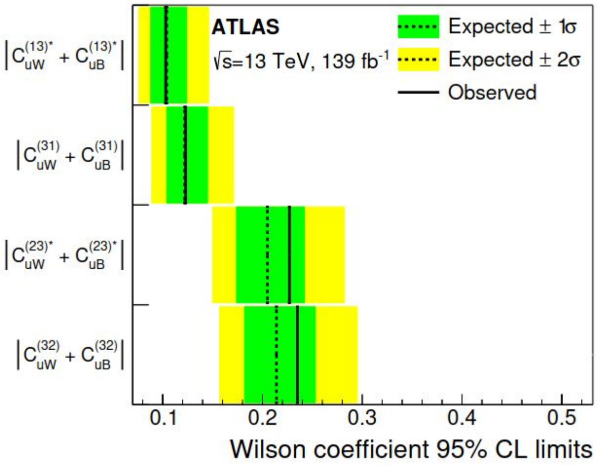
- Search for FCNC $tq\gamma$ in **top production and decay**
    - Single lepton, high p_T γ, E^T_{miss}
- CRs for main backgrounds with prompt photons ($t\bar{t}\gamma$, $W\gamma$+jets)
- Data-driven corrections to rate of electron/hadron→γ fakes

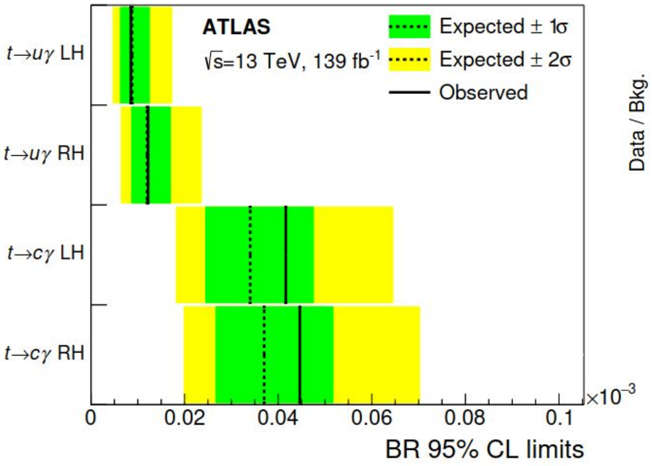


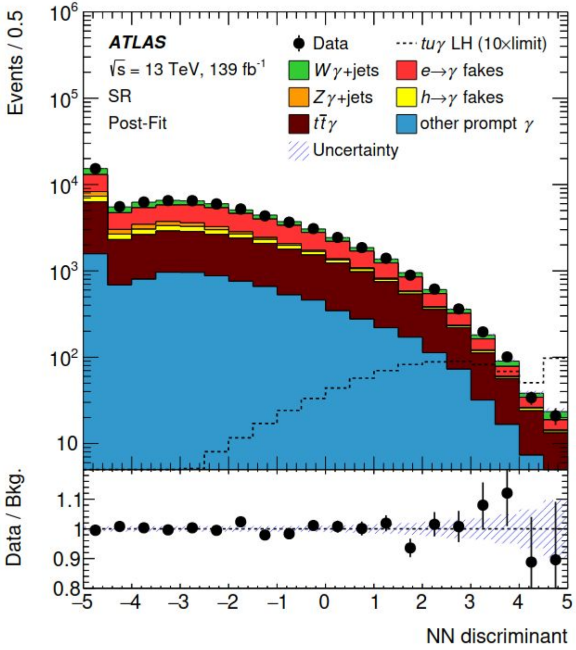


FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)

- Multiclass deep neural networks to split events into two signal modes and background
  - Combined output nodes into single discriminant to bin SR
- Dominant uncertainties: limited statistics ($tu\gamma$), $tq\gamma$ theory cross-section, $h \to \gamma$ estimate ($tc\gamma$)



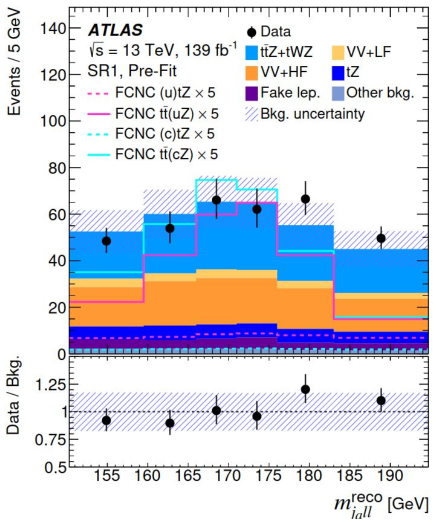




$$\mathcal{D} = \ln \frac{a \cdot y_{\text{prod}} + (1-a) \cdot y_{\text{dec}}}{y_{\text{bkg}}}$$

FCNC tqZ (arXiv:2301.11605)

- Search for FCNC tqZ in **top production and decay**
  - Trilepton event selection (*low background channel*)
- Two SRs targeting production and decay processes
  - Split by mass of reconstructed top(s)
- Additional CRs for dominant (diboson, $t\bar{t}Z$) and fake lepton ($t\bar{t}$) backgrounds

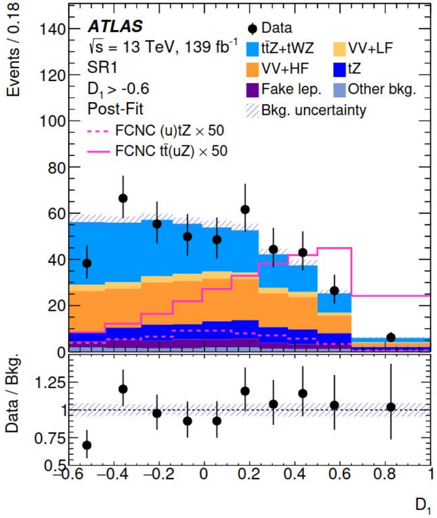


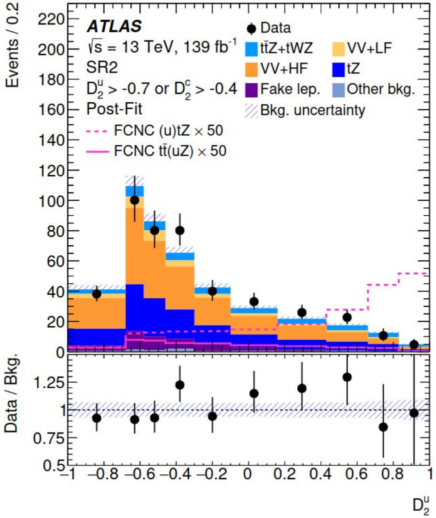
Reconstructed top mass assuming $t \to qZ$ decay

Common selections		
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV ≥ 1 OSSF pair, with $\|m_{\ell\ell} - m_Z\| < 15$ GeV		
SR1	SR2	
≥ 2 jets 1 b-jet	1 jet 1 b-jet	2 jets 1 b-jet
–	$m_T(\ell_W, \nu) > 40$ GeV	$m_T(\ell_W, \nu) > 40$ GeV
$\|m_{j_a\ell\ell}^{reco} - m_t\| < 2\sigma_{t_{FCNC}}$	–	$\|m_{j_a\ell\ell}^{reco} - m_t\| > 2\sigma_{t_{FCNC}}$
–	$\|m_{j_b\ell_W\nu}^{reco} - m_t\| < 2\sigma_{t_{SM}}$	$\|m_{j_b\ell_W\nu}^{reco} - m_t\| < 2\sigma_{t_{SM}}$

FCNC tqZ (arXiv:2301.11605)

- GBDTs used for S/B discrimination
  - Reconstructed top kinematics provide key inputs
- Dominant uncertainty: limited statistics





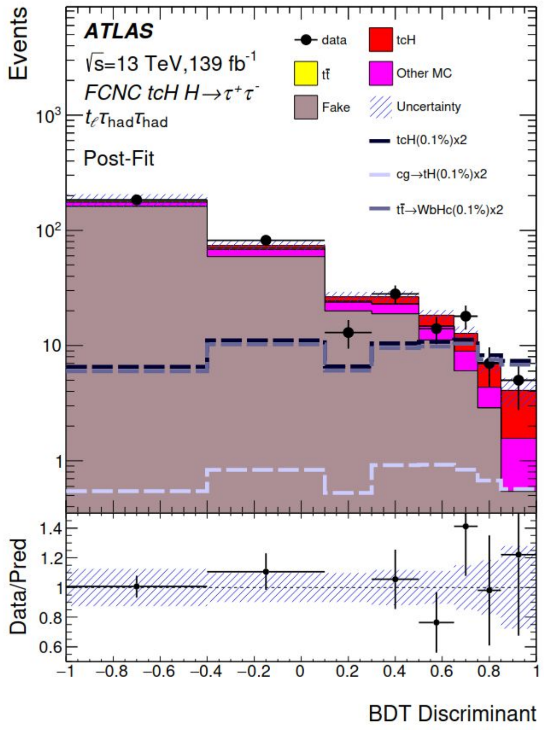
Observable	Vertex	Coupling	Observed	Expected
		SRs+CRs		
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10^{+4}_{-3}\times10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$
		SR1+CRs		
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6^{+2.9}_{-1.8}\times10^{-5}$

Sensitive to same EFT operators as $tq\gamma$

FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

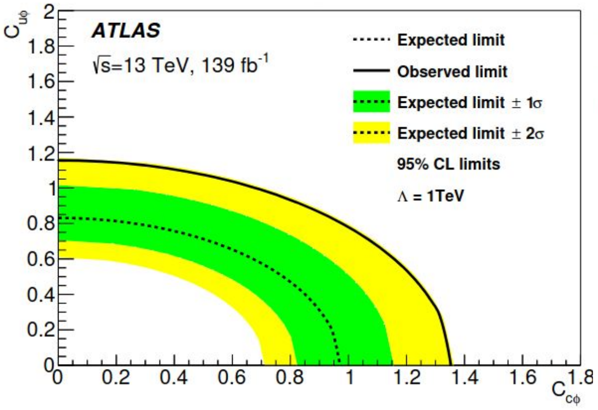
- Search for FCNC tqH in **top production and decay**
  - **Require $H\to\tau\tau$ decay**
- Many SRs targeting different top and τ-lepton decays channels
- Data-driven background estimates for fake τ_{had} and fake/non-prompt light leptons
- BDTs used for S/B discrimination
  - Rely on event kinematics for training (including kinematic reconstruction where possible)

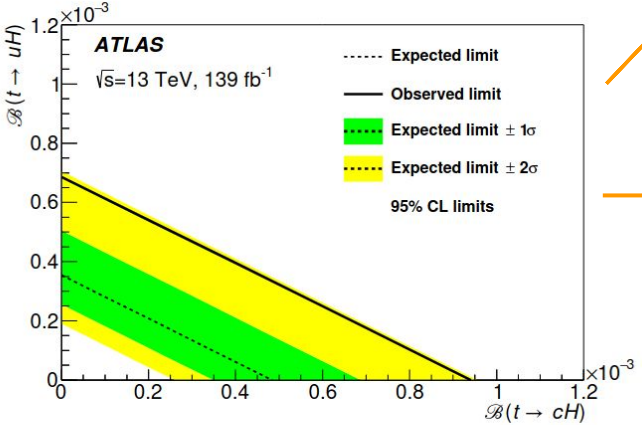
BDT discriminant in most sensitive SR

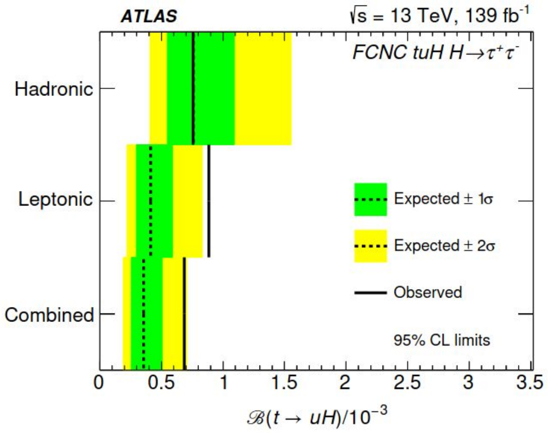


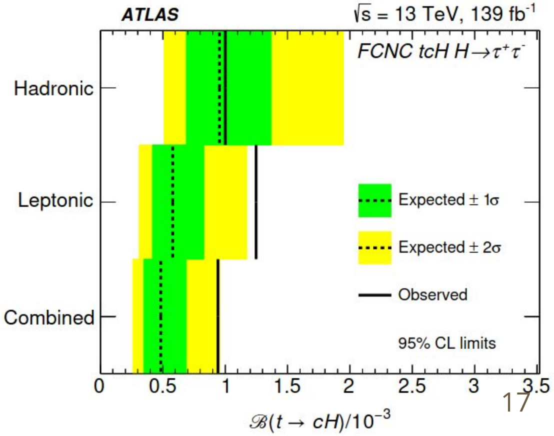
FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

- Profile likelihood fit to 7 SRs and 6 CRs
- Observe slight excess (2.3σ) above expected background
- Dominant uncertainties: statistics, MC statistics, fake estimation



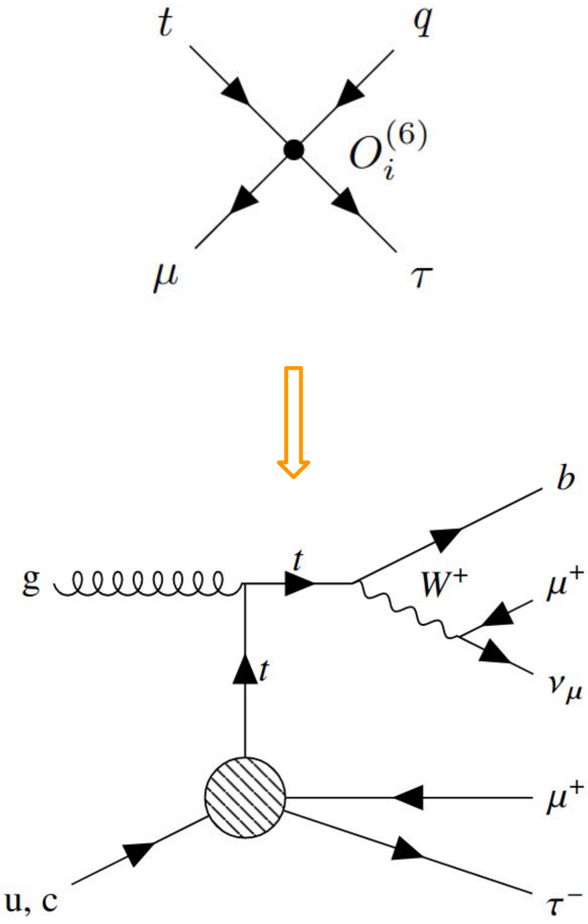






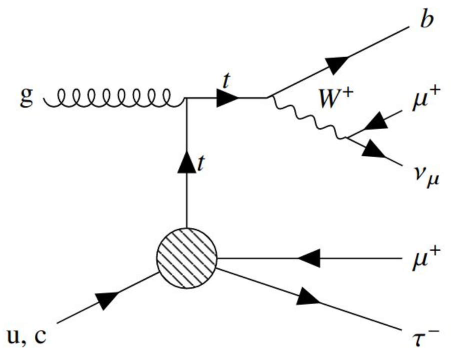
Search for charged lepton flavour violating interactions of the top quark

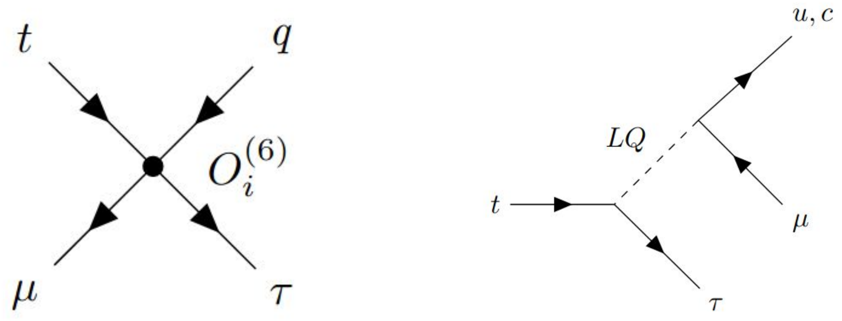
ATLAS-CONF-2023-001



cLFV in top quark interactions (ATLAS-CONF-2023-001)

- Lepton flavour conservation arises due to an accidental symmetry of the SM
- cLFV features in several BSM models (leptoquarks, SUSY, 2HDM)
- Model-independent search using EFT approach
  - Sensitive to a number of four-fermion EFT operators





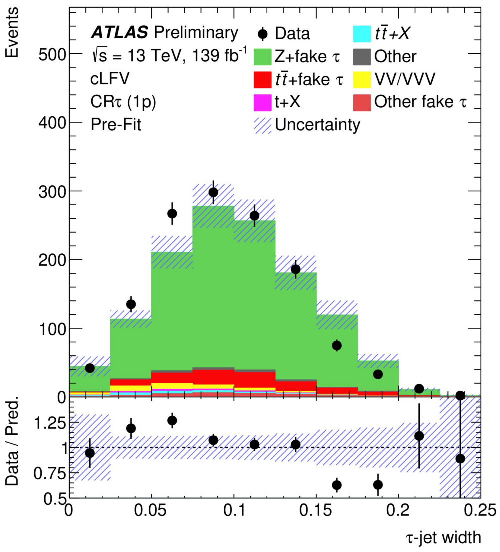
First direct search for $t\mu\tau q$ coupling!

Previous searches for $te\mu q$ coupling by ATLAS (arXiv:1809.09048) and CMS (JHEP 06 (2022) 082, CMS PAS TOP-22-005)

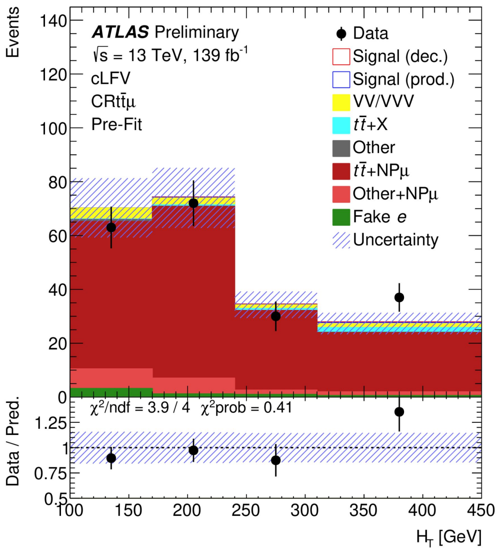
cLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

- Signal includes single top production and top quark pair decay
- Trilepton selection including *hadronic taus*
- Data-driven background estimations for fake background processes
  - Scale factors to correct rate of fake τ_{had} background
  - Correct normalisation of non-prompt background in fit



Fake τ_{had} control region



Non-prompt μ control region

cLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

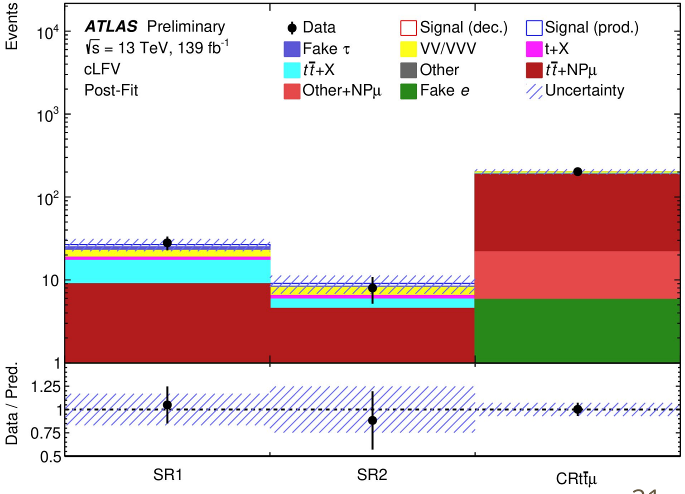
Statistically limited!

- Profile likelihood fit across two SRs and non-prompt muon CR
- Stringent limits on Wilson coefficients corresponding to 2Q2L operators
  - Improve upon the previous results by up to a factor of 51

	Exclusion limit $B(t \to \mu\tau q)$	
	Stat. only	All systematics
Expected	7.57×10^{-7}	9.82×10^{-7}
Observed	9.43×10^{-7}	10.8×10^{-7}

	95% CL upper limits on Wilson coefficients c/Λ^2 [TeV^{-2}]							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Previous (u)	12	12	12	12	26	26	3.4	3.4
ATLAS expected (u)	0.47	0.44	0.43	0.46	0.49	0.49	0.11	0.11
ATLAS observed (u)	0.49	0.47	0.46	0.48	0.51	0.51	0.11	0.11
Previous (c)	14	14	14	14	29	29	3.7	3.7
ATLAS expected (c)	1.6	1.6	1.5	1.6	1.8	1.8	0.35	0.35
ATLAS observed (c)	1.7	1.6	1.6	1.6	1.9	1.9	0.37	0.37

Previous limits from JHEP04 (2019) 014 (reinterpretation of JHEP07 (2018) 176)

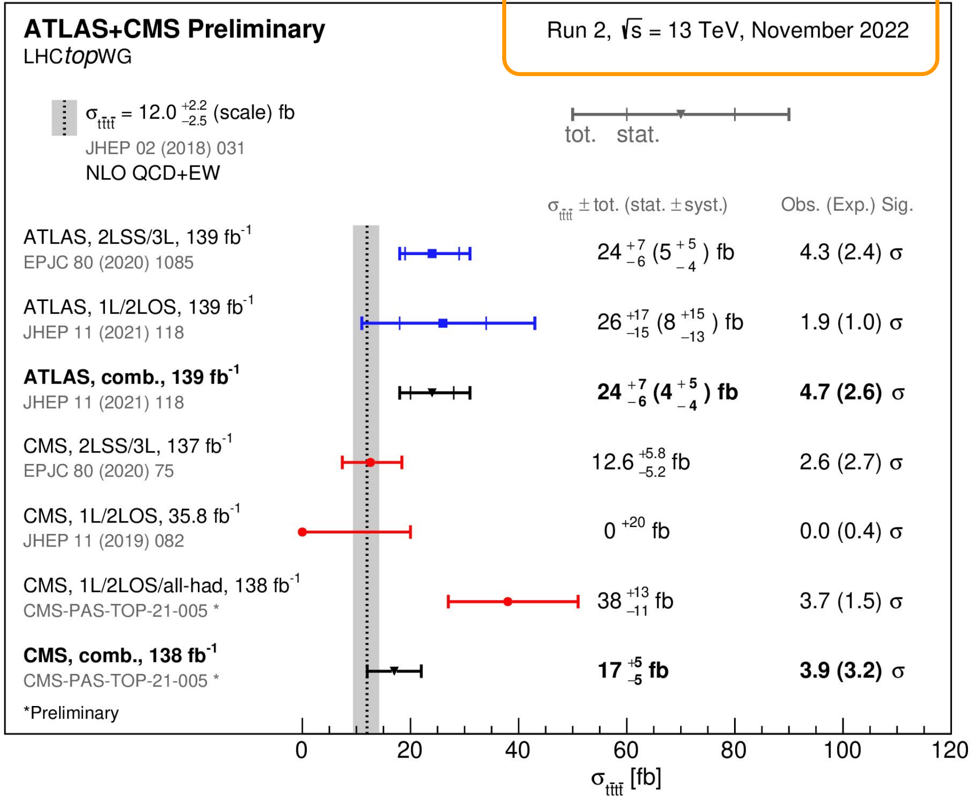


Conclusions

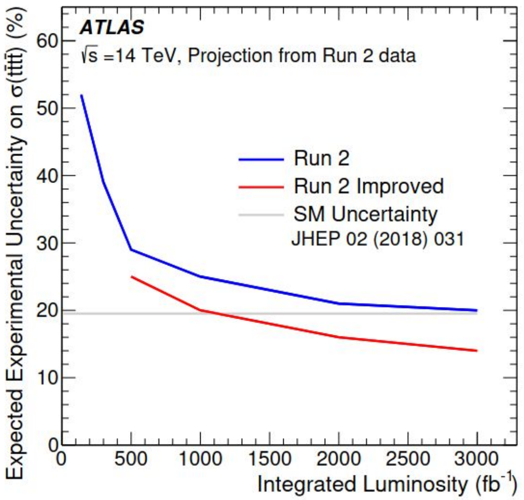
- Many exciting Run 2 rare top results!
  - **First observation of 4t production!**
  - Several measurements, particularly multilepton, are statistical limited $\rightarrow$ expect further improvements from Run 3 and HL-LHC
- Diverse FCNC top couplings programme
  - $tq\gamma$, tqg, tqH, tqZ
  - Most stringent limits on these branching ratios observed by ATLAS to date
- First search for cLFV $t\mu\tau q$ coupling
  - Complements existing $te\mu q$ searches
- Full programme of ATLAS top physics results

BACKUP

4t production measurements at the LHC



HL-LHC 4t prospects (ATL-PHYS-PUB-2022-004)



Study into HL-LHC sensitivity - ATL-PHYS-PUB-2022-004

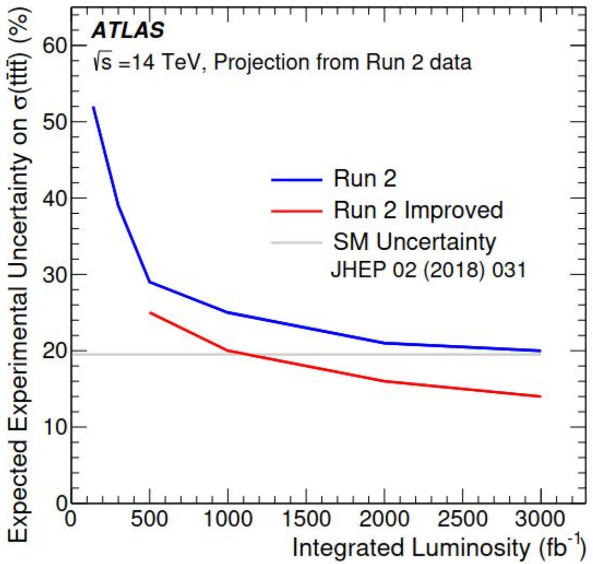
Consider conservative/optimistic systematic reductions with 3000 ifb at 14 TeV in 2ℓSS/3ℓ channel

Expected significance (wrt B-only hypothesis): 4.2-6.4σ

Expected uncertainty on cross section: 14%-20%

HL-LHC 4t prospects

(ATL-PHYS-PUB-2022-004)



Integrated luminosity (fb^{-1})	"Run 2"	"Run 2 Improved"
500	3.5	4.1
1000	3.9	4.9
2000	4.0	5.9
3000	4.2	6.4

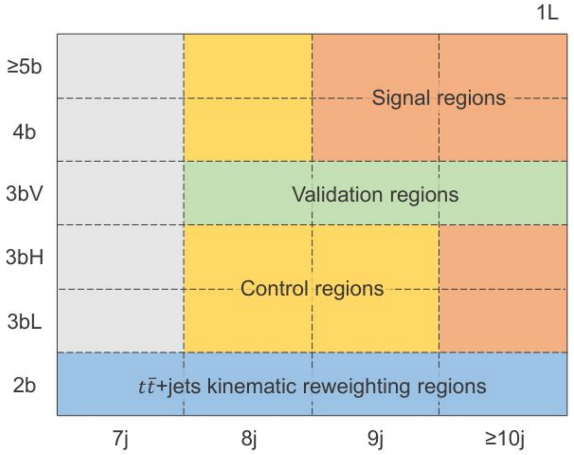
Uncertainty source	Treatment in the "Run 2 Improved" model
Signal modelling	
$t\bar{t}t\bar{t}$ cross section	Half of Run 2
$t\bar{t}t\bar{t}$ modelling	Half of Run 2
Background modelling	
$t\bar{t}W$+jets modelling	
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
Jets multiplicity modelling	Scaled by Run 2 pulls
Additional heavy flavour jets	Scaled by luminosity
$t\bar{t}$ modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Non-prompt leptons modelling	Scaled by luminosity
$t\bar{t}H$+jets and $t\bar{t}Z$+jets modelling	
Cross section	Half of Run 2
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
PDF	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Other background modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Charge misassignment	Same as Run 2
Template fit shape uncertainties	
Mat. Conv., γ^*, and HF non-prompt leptons	Scaled by luminosity
Other fake leptons	Half of Run 2
Additional heavy flavour jets	Half of Run 2
Instrumental	
Jet uncertainties	Same as Run 2
Jet flavour tagging (light-flavour jets)	Half of Run 2
Luminosity	Same as Run 2
Jet flavour tagging (b-jets)	Half of Run 2
Jet flavour tagging (c-jets)	Half of Run 2
Other experimental uncertainties	Same as Run 2

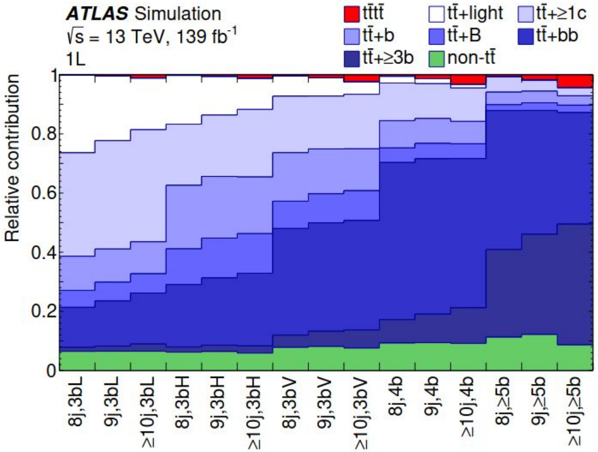
Evidence for 4t production

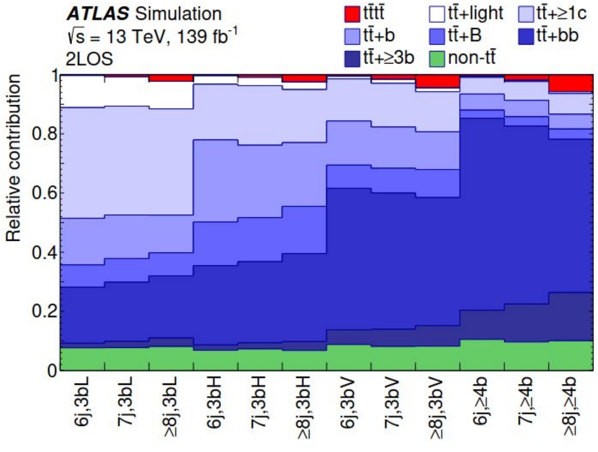
(JHEP11(2021)118)

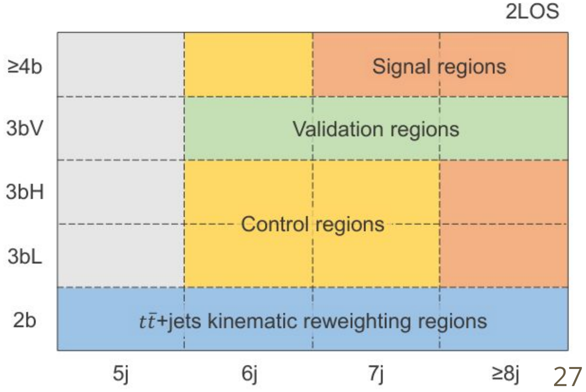
Pseudo-continuous b-tagging used to separate the different flavour components of the associated jets in the $t\bar{t}$+jets background.

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	$= 2$	-
3bL	≤ 2	$= 3$	-
3bH	$= 3$	$= 3$	$= 3$
3bV	$= 3$	$= 3$	≥ 4
$\geq$4b (2LOS)	-	≥ 4	-
4b (1L)	-	$= 4$	-
$\geq$5b (1L)	-	≥ 5	-

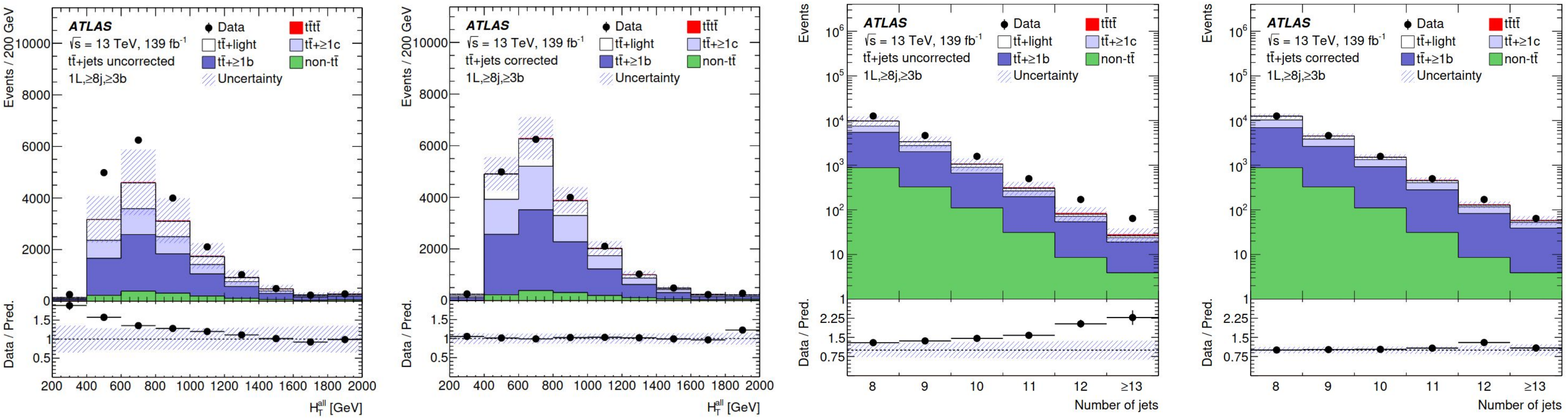








Evidence for 4t production (JHEP11(2021)118)



Effect of data-driven corrections to $t\bar{t}$+HF background:

- Separate scaling for each flavour component
- Sequential kinematic reweighting to correct modelling (incl. jet multiplicity, total event energy)

Observation of 4*t* production

arXiv:2303.15061

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_0 or ℓ_1 is from virtual photon (γ^*) decay ℓ_0 and ℓ_1 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_0 or ℓ_1 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge is ± 1	$p_T^{\ell_2}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge is ± 1	$p_T^{\ell_2}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\|\eta(e)\| < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\|\eta(e)\| < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_0 and ℓ_1 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_0 and ℓ_1 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$	GNN score

Observation of 4t production

arXiv:2303.15061

Fake/non-prompt background	$\mathrm{NF}_{\text{Mat. Conv.}}$	$\mathrm{NF}_{\text{Low } m_{\gamma^*}}$	$\mathrm{NF}_{\text{HF } e}$	$\mathrm{NF}_{\text{HF } \mu}$
Value	$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$	$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

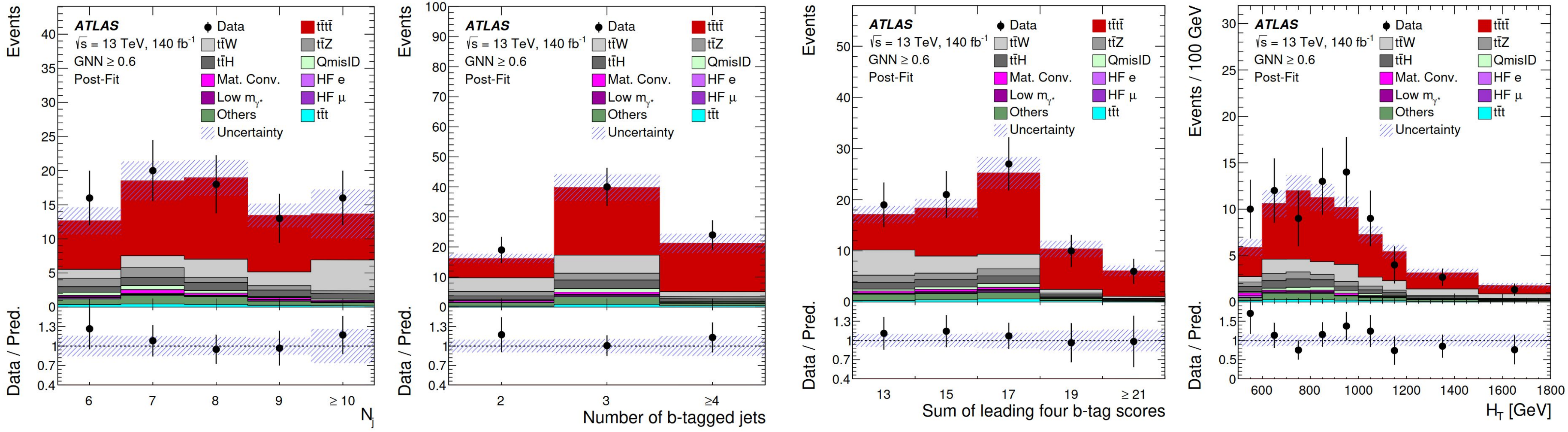
$$\mathrm{NF}_{t\bar{t}W(j)} = \mathrm{NF}_{t\bar{t}W^+(4\text{jet})} \times \Pi_{j'=4}^{j'=j-1} \left[a_0 + \frac{a_1}{1+(j'-4)} \right] + \mathrm{NF}_{t\bar{t}W^-(4\text{jet})} \times \Pi_{j'=4}^{j'=j-1} \left[a_0 + \frac{a_1}{1+(j'-4)} \right]$$

$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^+(4\text{jet})}$	$\mathrm{NF}_{t\bar{t}W^-(4\text{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$

Observation of 4t production

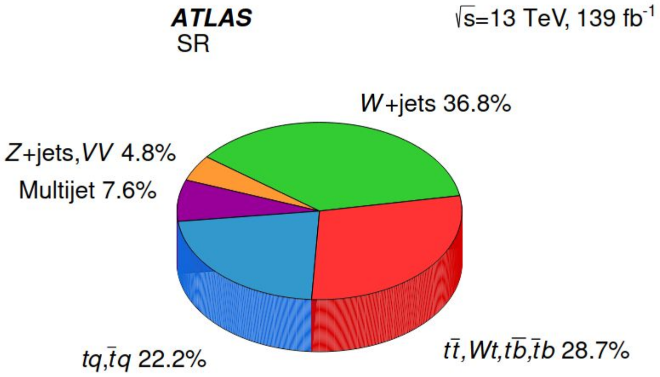
arXiv:2303.15061

- Signal+background model in high GNN score region shows good agreement with observed data



FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

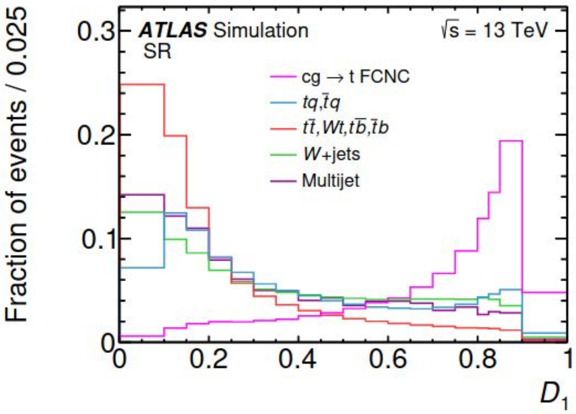
Observable	Common requirements			
$n_{\text{Tight}}(e) + n_{\text{Medium}}(\mu)$	$= 1$			
$n_{\text{Loose}}(e) + n_{\text{Loose}}(\mu)$	$= 1$			
$E_{\text{T}}^{\text{miss}}$	$> 30\,\text{GeV}$			
$m_{\text{T}}(W)$	$> 50\,\text{GeV}$			
$n(j)$	≥ 1			
$p_{\text{T}}(\ell)$	$> 50\,\text{GeV} \cdot \left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$			
	Analysis regions			
	SR	W+jets VR	$t\bar{t}$ VR	tq VR
$n(\lvert\eta(j)\rvert < 2.5)$	$= 1$	$= 1$	$= 2$	$= 1$
$n(b)$	$= 1$	$= 1$	$= 2$	$= 1$
ϵ_b	30%	60% (veto 30%)	30%	30%
$n(\lvert\eta(j)\rvert > 2.5)$	≥ 0	≥ 0	≥ 0	$= 1$
$D_{1(2)}$	–	$0.3 < D_{1(2)} < 0.6$	–	$0.2 < D_{1(2)} < 0.4$

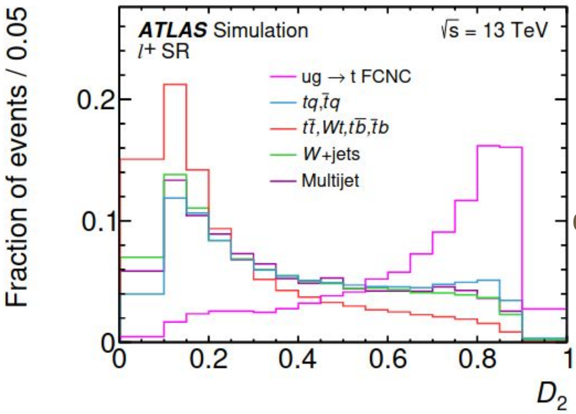


FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

- Two NNs to discriminate S/B
  - D_1 trained only on $c+g\to t$ (incl. $\bar{c}+g\to\bar{t}$) - optimised for sea quark production
  - D_2 trained only on $u+g\to t$ (excl. $\bar{u}+g\to\bar{t}$) - optimised for valence quark production
  - Multijet background excluded from NN training
- Use D_1 in *cgt* analysis and ℓ^- channel of *ugt* analysis
- Use D_2 in ℓ^+ channel of *ugt* analysis

NN output discriminant distribution for *cgt* analysis

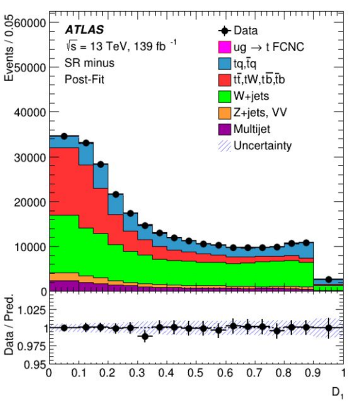


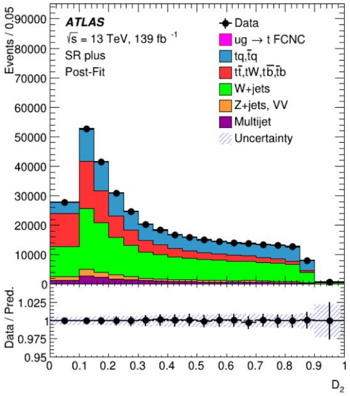


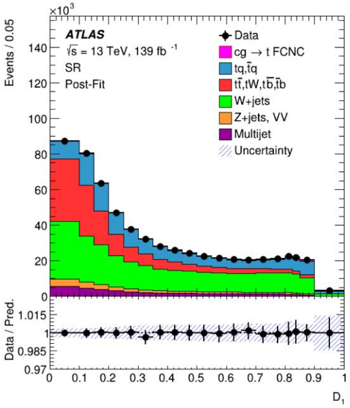
NN output discriminant distribution for *ugt* analysis

FCNC *tqg* ([Eur. Phys. J. C 82 (2022) 334])

NN discriminant distributions in SRs



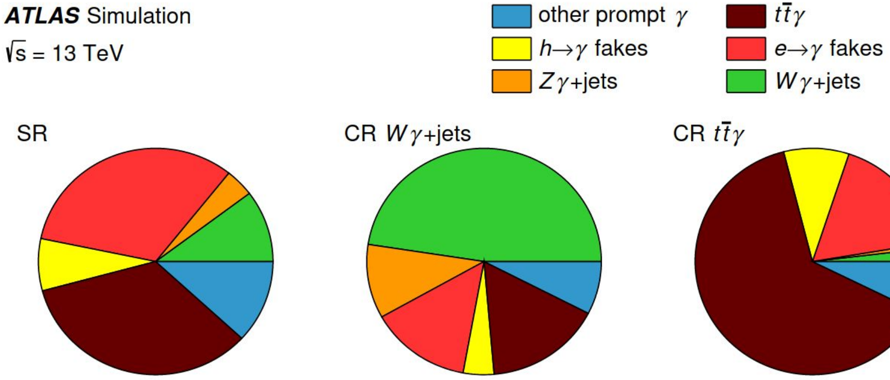


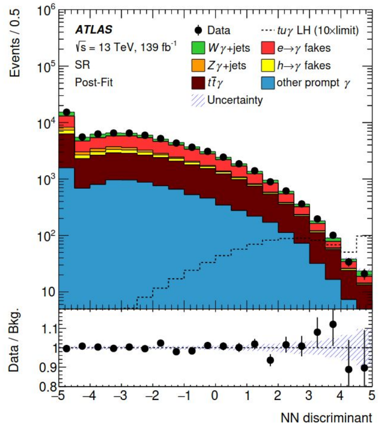


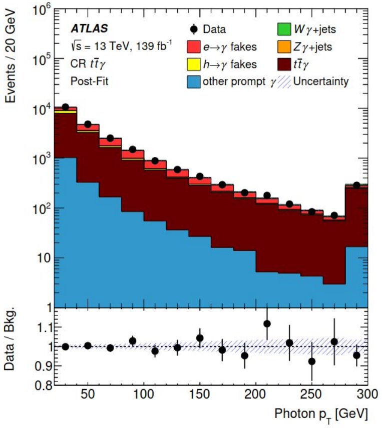
Scenario	Description	$\mathcal{B}_{95}^{\text{exp}}(t \to u + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \to c + g)$
(1)	Data statistical only	1.1×10^{-5}	2.4×10^{-5}
(2)	Experimental uncertainties also	3.1×10^{-5}	12×10^{-5}
(3)	All uncertainties except MC statistical	3.9×10^{-5}	18×10^{-5}
(4)	All uncertainties	4.9×10^{-5}	20×10^{-5}

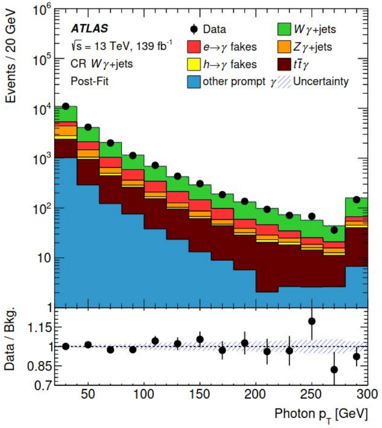
FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)

Object	SR	CR $t\bar{t}\gamma$	CR $W\gamma$+jets
Photon ($p_{\mathrm{T}} > 20$ GeV)	$= 1$		
Lepton ($p_{\mathrm{T}} > 27$ GeV)	$= 1$		
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV		
Jets ($p_{\mathrm{T}} > 25$ GeV)	≥ 1	≥ 4	≥ 1
b-tagged jets (60% WP)	$= 1$	–	$= 0$
b-tagged jets (70% WP)	$= 1$	≥ 1	$= 0$
b-tagged jets (77% WP)	$= 1$	≥ 2	$= 1$
$m(e,\gamma)$	–	–	$\notin [80, 100]$ GeV

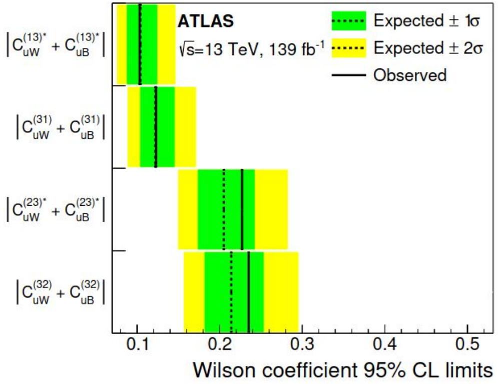


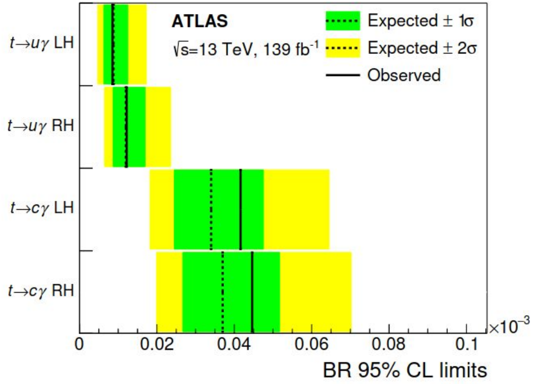


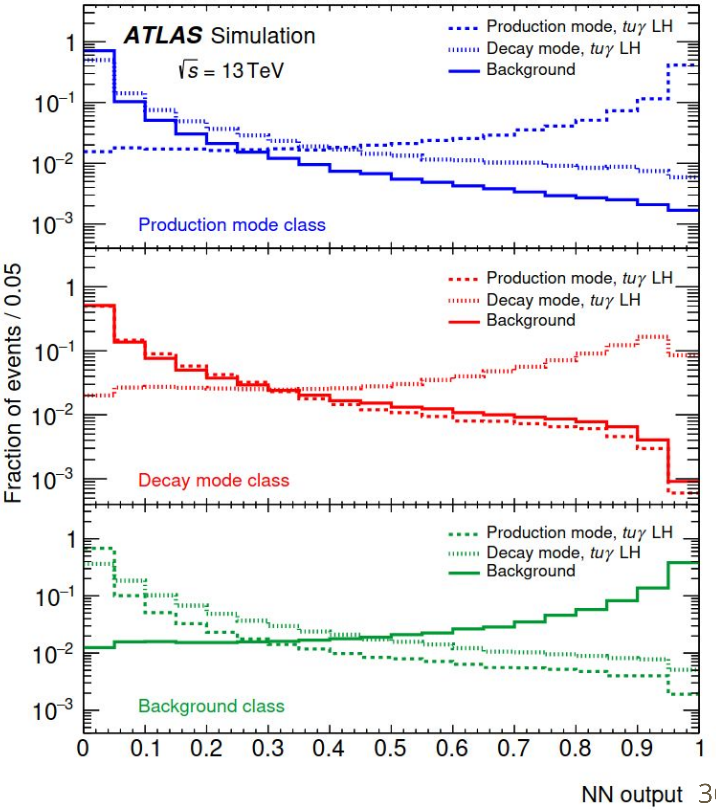




FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)







Effective coupling	Coefficient limits Expected	Coefficient limits Observed	Coupling	BR limits $[10^{-5}]$ Expected	BR limits $[10^{-5}]$ Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$0.205^{+0.037}_{-0.031}$	0.227	$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$0.214^{+0.039}_{-0.032}$	0.235	$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

FCNC tqZ (arXiv:2301.11605)

Common selections		
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV ≥ 1 OSSF pair, with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV		
SR1	SR2	
≥ 2 jets	1 jet	2 jets
1 b-jet	1 b-jet	1 b-jet
–	$m_T(\ell_W, \nu) > 40$ GeV	$m_T(\ell_W, \nu) > 40$ GeV
$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t\rvert < 2\sigma_{t_{\text{FCNC}}}$	–	$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{\text{FCNC}}}$
–	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{\text{SM}}}$	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{\text{SM}}}$

Common selections			
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV			
$t\bar{t}$ CR	$t\bar{t}Z$ CR	Side-band CR1	Side-band CR2
≥ 1 OS pair, no OSSF	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV
–	–	–	$m_T(\ell_W, \nu) > 40$ GeV
≥ 1 jet	≥ 4 jets	≥ 2 jets	1 jet
1 b-jet	2 b-jets	1 b-jet	1 b-jet
–	–	$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{\text{FCNC}}}$	–
–	–	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert > 2\sigma_{t_{\text{SM}}}$	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert > 2\sigma_{t_{\text{SM}}}$

FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

Requirement	Leptonic channels			Hadronic channel
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	$t_\ell\tau_{\text{had}}$	$t_h\tau_{\text{had}}\tau_{\text{had}}$
Trigger	single-lepton trigger			di-τ trigger
Leptons	=1 isolated e or μ			=0 isolated e or μ
τ_{had}	=1 τ_{had}	=2 τ_{had}	=1 τ_{had}	=2 τ_{had}
Electric charge (Q)	$Q_\ell \times Q_{\tau_{\text{had1}}} = -1$	$Q_{\tau_{\text{had1}}} \times Q_{\tau_{\text{had2}}} = -1$	$Q_\ell \times Q_{\tau_{\text{had1}}} = 1$	$Q_{\tau_{\text{had1}}} \times Q_{\tau_{\text{had2}}} = -1$
Jets	$\geq$3 jets	$\geq$1 jets	$\geq$2 jets	$\geq$3 jets
b-tagging	=1 b-jets			=1 b-jets

Regions		b-jets	Light-flavour jets	Leptons	Hadronic τ decays	Charge
SR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_\ell\tau_{\text{had}}$-1j	1	1	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell\tau_{\text{had}}$-2j	1	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	1	2	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	1	≥ 3	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	1	2	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
VR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$-SS	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j SS	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
CRtt	$t_\ell t_\ell 1b\tau_{\text{had}}$	1	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_\ell 2b\tau_{\text{had}}$	2	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jSS	2	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jOS	2	2	1	1	$t_\ell\tau_{\text{had}}$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jSS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jOS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ OS

FCNC $tqH(\tau\tau)$

(arXiv:2208.11415)

Signal Region	$t \to cH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to cH$ Significance	$t \to cH$ $\mathcal{B}$ [10^{-3}]	$t \to uH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to uH$ Significance	$t \to uH$ $\mathcal{B}$ [10^{-3}]
$t_h\tau_{\rm had}\tau_{\rm had}$-2j	$1.80\,(2.72^{+1.18}_{-0.76})$	−0.96 (0.78)	$-1.03^{+1.03}_{-1.03}$	$1.07\,(1.60^{+0.71}_{-0.45})$	−0.90 (1.31)	$-0.55^{+0.58}_{-0.58}$
$t_h\tau_{\rm had}\tau_{\rm had}$-3j	$1.14\,(1.02^{+0.45}_{-0.29})$	0.34 (1.87)	$0.16^{+0.47}_{-0.47}$	$0.97\,(0.86^{+0.38}_{-0.24})$	0.36 (2.25)	$0.14^{+0.40}_{-0.40}$
Hadronic combination	$1.00\,(0.95^{+0.42}_{-0.27})$	0.26 (1.99)	$0.11^{+0.43}_{-0.43}$	$0.76\,(0.76^{+0.33}_{-0.21})$	0.12 (2.52)	$0.04^{+0.34}_{-0.34}$
$t_\ell\tau_{\rm had}$-2j	$4.77\,(4.23^{+1.72}_{-1.18})$	0.41 (0.47)	$0.85^{+2.06}_{-2.06}$	$3.84\,(3.48^{+1.42}_{-0.97})$	0.36 (0.58)	$0.61^{+1.68}_{-1.68}$
$t_\ell\tau_{\rm had}$-1j	$3.80\,(3.56^{+1.51}_{-0.99})$	0.22 (0.58)	$0.36^{+1.70}_{-1.70}$	$2.98\,(2.78^{+1.17}_{-0.78})$	0.22 (0.73)	$0.29^{+1.33}_{-1.33}$
$t_h\tau_{\rm lep}\tau_{\rm had}$-2j	$4.71\,(5.71^{+2.68}_{-1.60})$	−0.52 (0.38)	$-1.36^{+2.56}_{-2.56}$	$2.50\,(2.97^{+1.25}_{-0.83})$	−0.47 (0.70)	$-0.66^{+1.38}_{-1.38}$
$t_h\tau_{\rm lep}\tau_{\rm had}$-3j	$2.71\,(2.71^{+1.25}_{-0.76})$	−0.03 (0.77)	$-0.03^{+1.26}_{-1.26}$	$2.02\,(2.03^{+0.86}_{-0.57})$	−0.05 (0.99)	$-0.03^{+0.98}_{-0.98}$
$t_\ell\tau_{\rm had}\tau_{\rm had}$	$1.35\,(0.61^{+0.27}_{-0.17})$	2.64 (3.31)	$0.74^{+0.33}_{-0.33}$	$0.97\,(0.44^{+0.19}_{-0.12})$	2.64 (4.38)	$0.53^{+0.24}_{-0.24}$
Leptonic combination	$1.25\,(0.58^{+0.25}_{-0.16})$	2.61 (3.46)	$0.69^{+0.31}_{-0.31}$	$0.88\,(0.41^{+0.18}_{-0.11})$	2.60 (4.62)	$0.49^{+0.22}_{-0.22}$
Combination	$0.94\,(0.48^{+0.20}_{-0.14})$	2.34 (4.02)	$0.51^{+0.24}_{-0.24}$	$0.69\,(0.35^{+0.15}_{-0.10})$	2.31 (5.18)	$0.37^{+0.18}_{-0.18}$

cLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

Preselection:	
Number of leptons	$N_\ell = 3,\ p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$
Leading muon / electron p_T	$p_T > 27$ GeV
Trigger matching	≥ 1 trigger-matched muon / electron
Sum of lepton charges	$\sum q_i = \pm 1$

	SR1	**SR2**	**CRτ**	**CR$tt\mu$**
Lepton flavour	$2\mu 1\tau_{\text{had-vis}}$			$2\mu 1e$ ($\ell_3 = \mu$)
N_{jets}	≥ 2	1	≥ 2	≥ 2
$N_{b-\text{tags}}$	1	1	1	≤ 2
Muon p_T cut	> 15 GeV	> 15 GeV	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Tight*	*Tight*	*Loose*
Muon charges	SS	SS	OS	-
$\lvert m_{\mu\mu}^{OS} - M_Z\rvert$	-	-	<10 GeV	>10 GeV

cLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

Operator	Lorentz Structure	
$O_{lq}^{1(ijkl)}$	$(\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma_\mu q_l)$	Vector
$O_{lq}^{3(ijkl)}$	$(\bar{l}_i \gamma^\mu \sigma^I l_j)(\bar{q}_k \gamma_\mu \sigma^I q_l)$	Vector
$O_{eq}^{(ijkl)}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma_\mu q_l)$	Vector
$O_{lu}^{(ijkl)}$	$(\bar{l}_i \gamma^\mu l_j)(\bar{u}_k \gamma_\mu u_l)$	Vector
$O_{eu}^{(ijkl)}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma_\mu u_l)$	Vector
$^\ddagger O_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$	Scalar
$^\ddagger O_{lequ}^{3(ijkl)}$	$(\bar{l}_i \sigma^{\mu\nu} e_j)\varepsilon(\bar{q}_k \sigma_{\mu\nu} u_l)$	Tensor

$$\Gamma(t \to \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{lq}^{-(ijk3)}|^2 + 4|c_{eq}^{(ijk3)}|^2 + 4|c_{lu}^{(ijk3)}|^2 + 4|c_{eu}^{(ijk3)}|^2 + |c_{lequ}^{1(jik3)}|^2 + |c_{lequ}^{1(ij3k)}|^2 + 48|c_{lequ}^{3(jik3)}|^2 + 48|c_{lequ}^{3(ij3k)}|^2\Big\}$$