Searches for FCNC interactions of the top quark with the ATLAS experiment at the LHC

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On behalf of ATLAS collaboration

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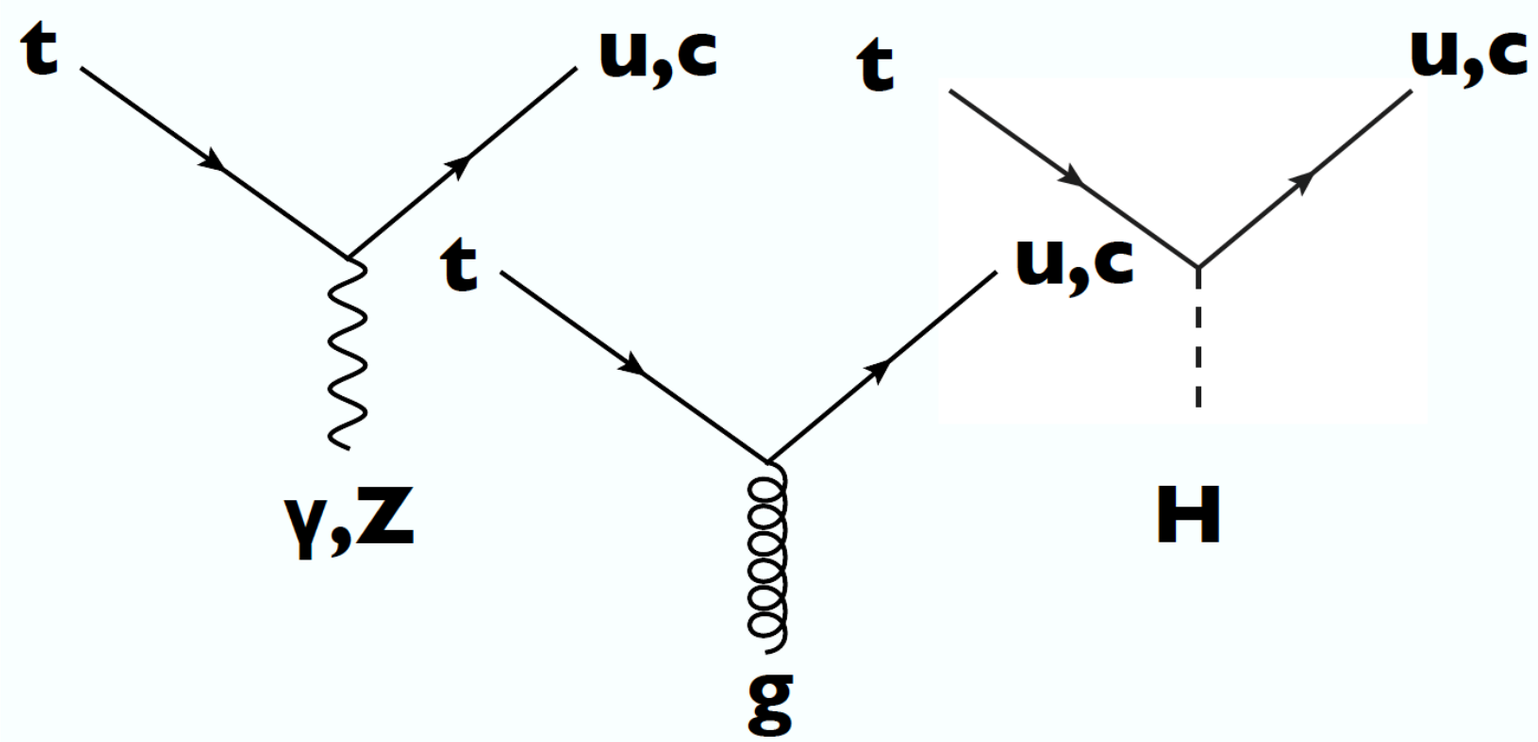
Outline

- Motivation of Top FCNC interaction
- Latest full run-2 analysis at ATLAS
  - tqy tqZ tqg tqH
- Summary

particlezoo



Why FCNC?

Flavor-changing neutral currents (FCNC) decays

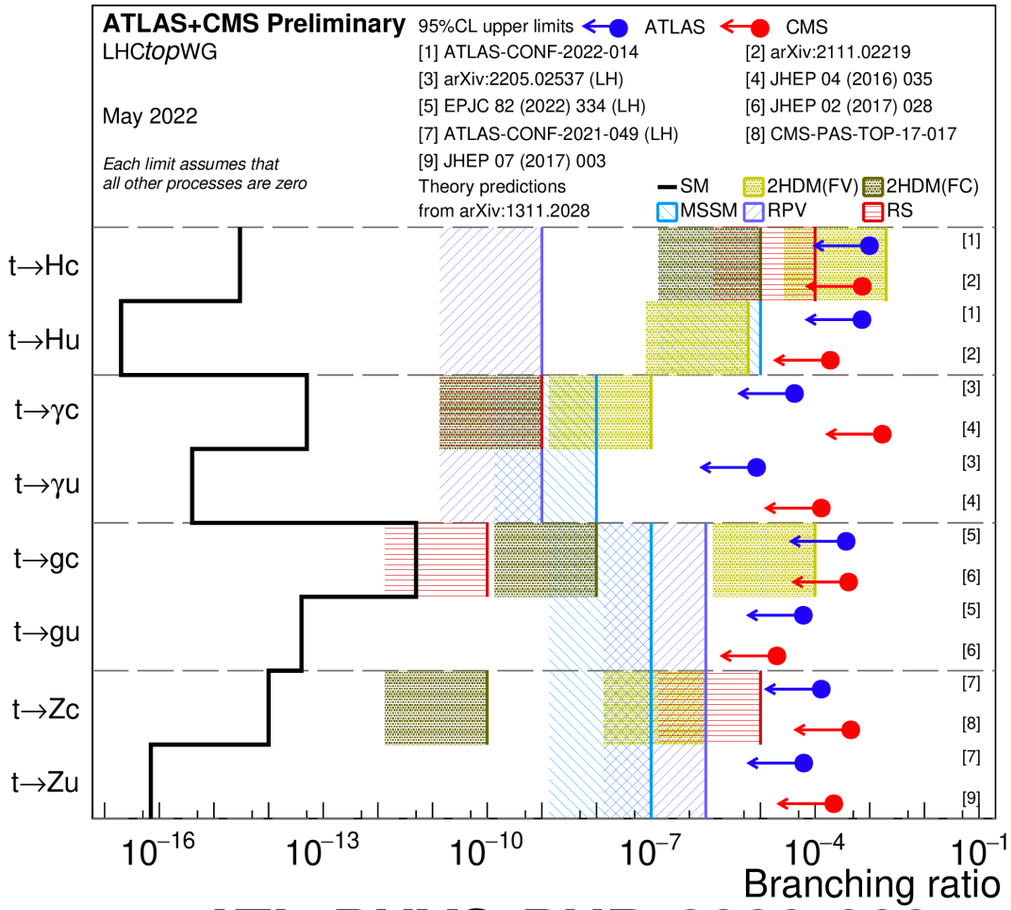
- are forbidden at tree level
- occur at one-loop level but are strongly suppressed by the **GIM mechanism**
- significantly enhanced in BSM extensions (maximum up to ~10^{-3})
- Any observation of top FCNC = BSM physics

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}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

1311.2028

Why Top?

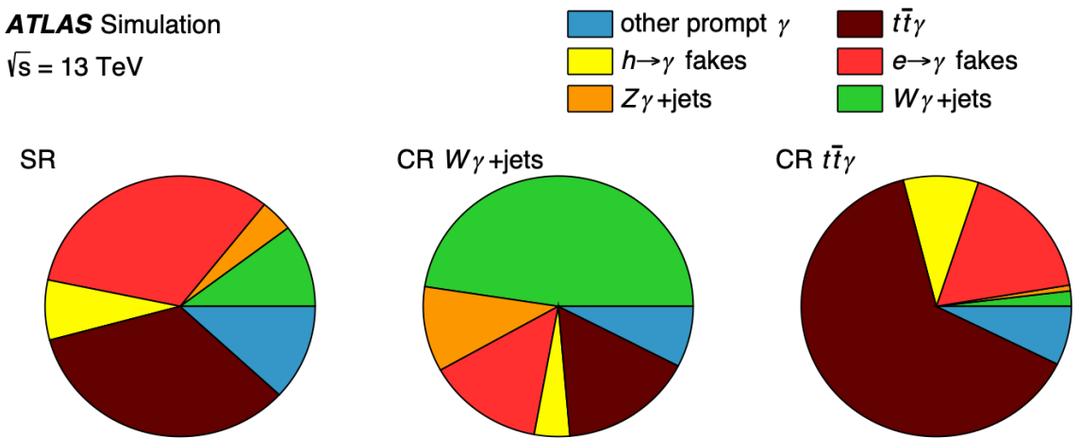
- is the heaviest (short lifetime) known fundamental particle
  - it is the only quark that decays before hadronising
  - spin information passes to decay products
- dominant decay mode: $t \rightarrow Wb$
  - all other couplings can be considered **rare => FCNC decay**
- many SM extensions predict the new particles that couple to top quarks
- LHC is a Top quark factory
  - Large top production allows many precision measurements/searches for many SM and BSM analyses
  - FCNC involving lighter quark covered by B and Charm factories (1204.0735 ATL-PHYS-PROC-2016-136)



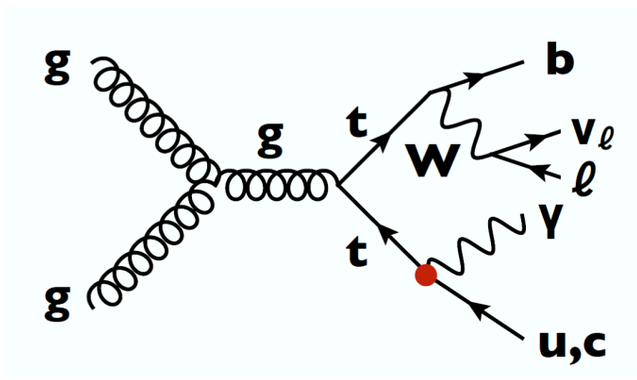
ATL-PHYS-PUB-2022-030

FCNC $t \to q\gamma$ 2205.02537

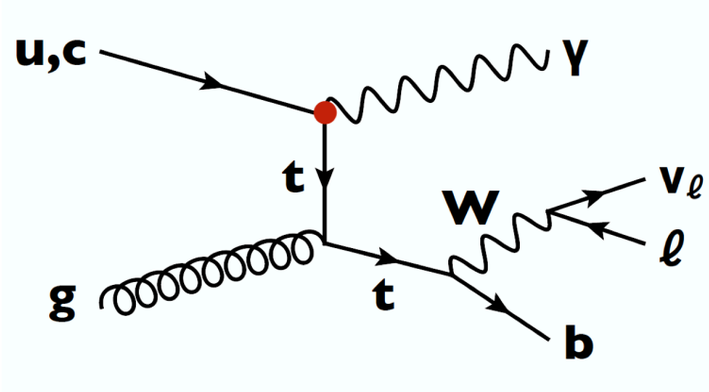
- Analysis Strategy:
  - optimize for FCNC production & decay
  - One SR: 1γ + 1lep + missing Et >30GeV + 1 b-jet + >= 1jet
  - Control regions for main background processes with prompt photons
    - CR $t\bar{t} + \gamma$
    - CR $W + \gamma +$ jets
  - Normalization of $t\bar{t} + \gamma$ and $W + \gamma +$ jets free-floating in the fit
- Other main background: photon fakes (data-driven estimate of $e \to \gamma$ and $h \to \gamma$ fakes)



Background composition



FCNC decay

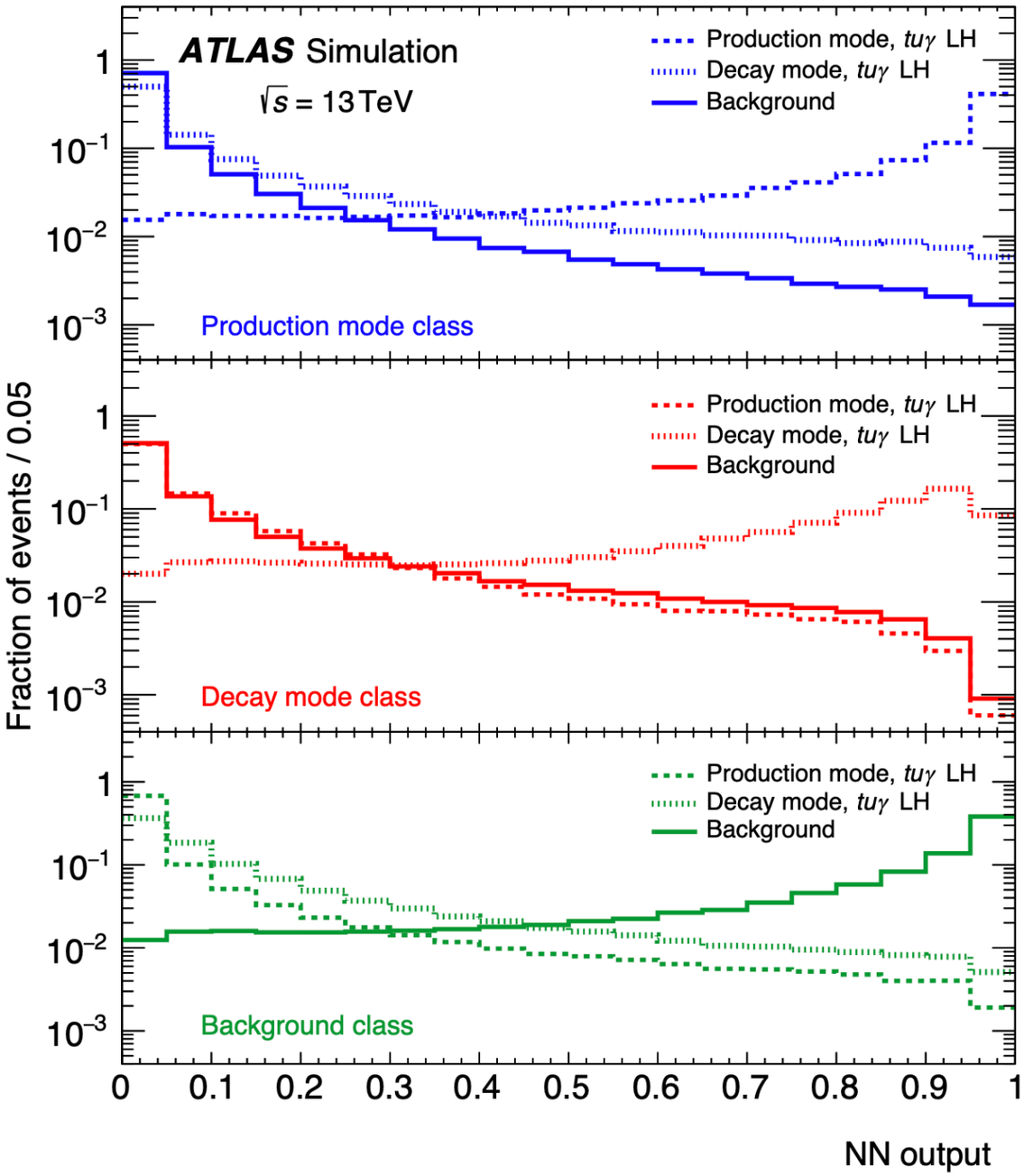


FCNC production

FCNC $t \to q\gamma$ 2205.02537

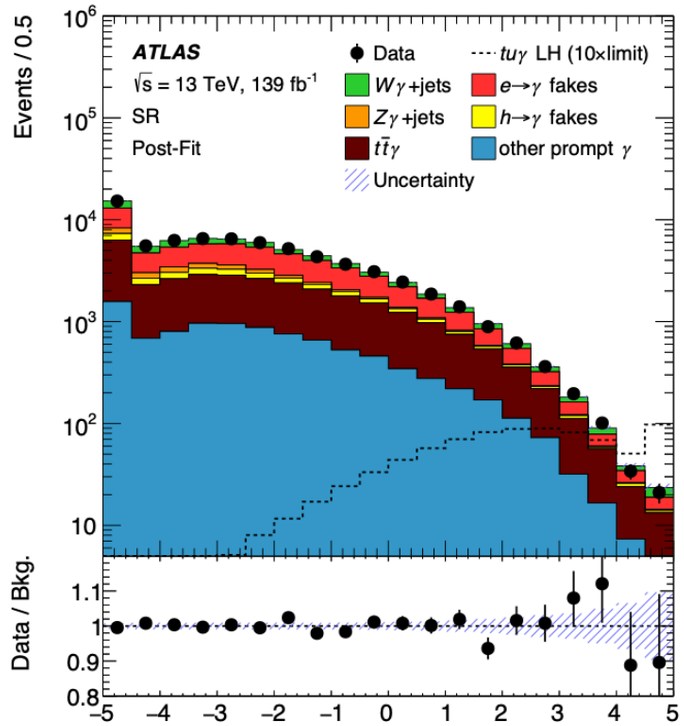
- Multi-class neural network (NN): for separation of both signal modes from background
  - ~ 30% better than binary classification
  - separate network for up & charm (2 NNs)
  - for classification of prod, decay, bkg (three output class, multinomial classifier)
    - $\overrightarrow{y} = (y_{prod}, y_{de}, y_{bkg})$
- NN architecture:
  - Input: 37 variables
  - fully-connected, feed-forward NNs, six hidden layers
  - Adam optimiser, ReLU activation, L2 regularization
  - Categorical cross-entropy loss with 3D softmax output
- Signal outputs combined in **likelihood ratio**:

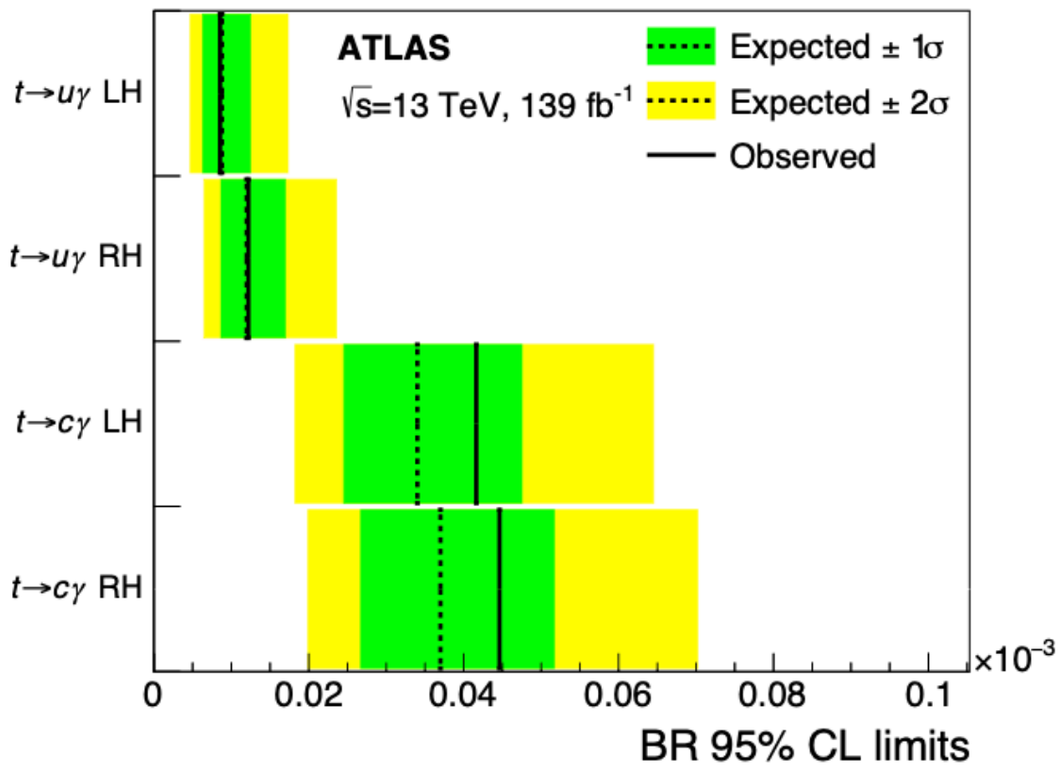
$$\mathrm{D} = \ln \frac{a * y_{prod} + (1-a) * y_{dec}}{y_{bkg}}$$

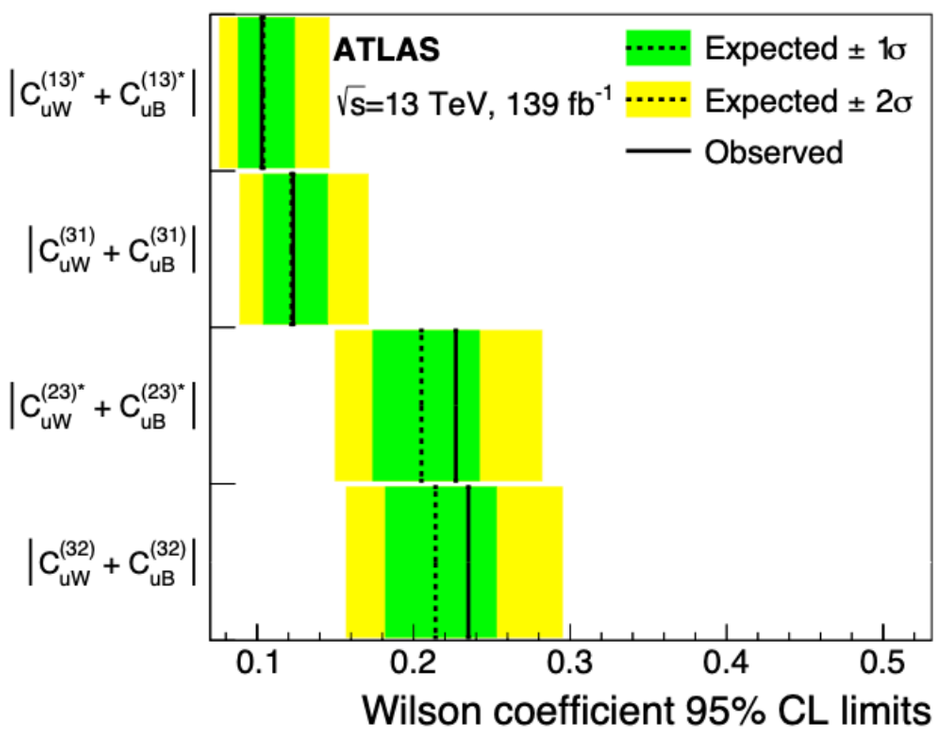


FCNC $t \to q\gamma$ 2205.02537

- background model in agreement with data
- NN output score distribution used for a profile-likelihood fit to data
  - Factors 3.3 - 5.4 better than 81fb^{-1} analysis (1908.08461)
    - adding events with more than one jet
  - Statistical uncertainties dominate
    - All systematics together worsen limits by ~20% ($tu\gamma$) or ~40% ($tc\gamma$)







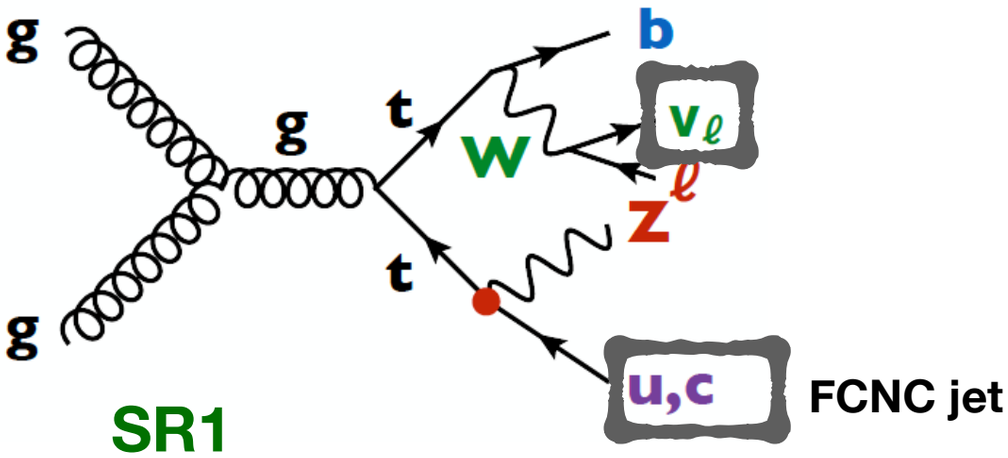
Wilson coefficients for dim-6 operators

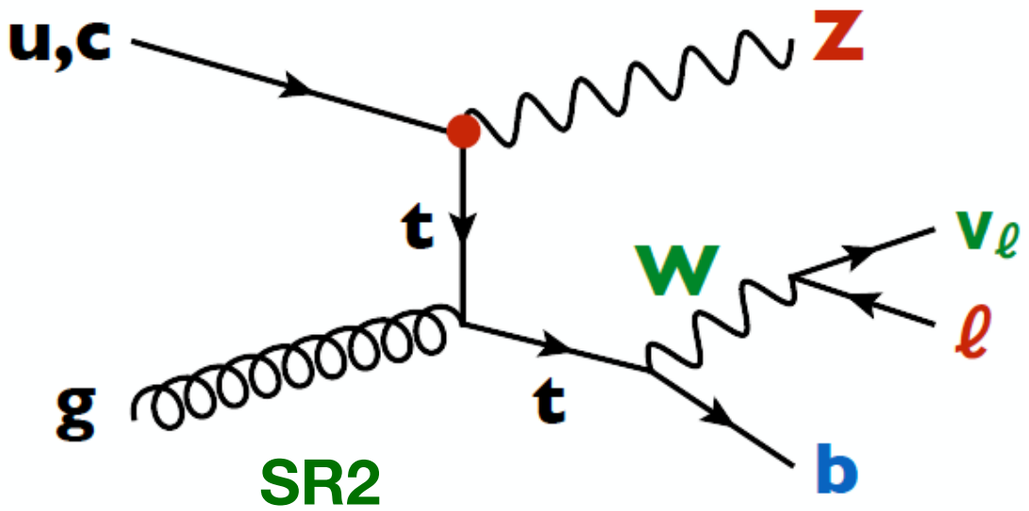
FCNC $t \to qZ$ ATLAS-CONF-2021-049

- Analysis Strategy
  - $Z \to \ell\ell$ with $\ell = e, \mu$ isolated leptons and $m_{\ell\ell} \sim m_Z$, 1b-jet, W decay leptonically
  - **2 SRs**: SR1 (FCNC decay) SR2 (FCNC production)
  - 4 CRs: ttbar CR, ttbarZ CR, Side-band CRs (mass of SM top and FCNC top)
  - χ^2 minimization to

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

  - Central value of masses and widths are taken from fit to reconstructed FCNC decay signal events.
  - Select FCNC jet (for FCNC decay only, for FCNC production, χ^2_{tZ} is constructed.)
  - Fit $P_z(\nu)$

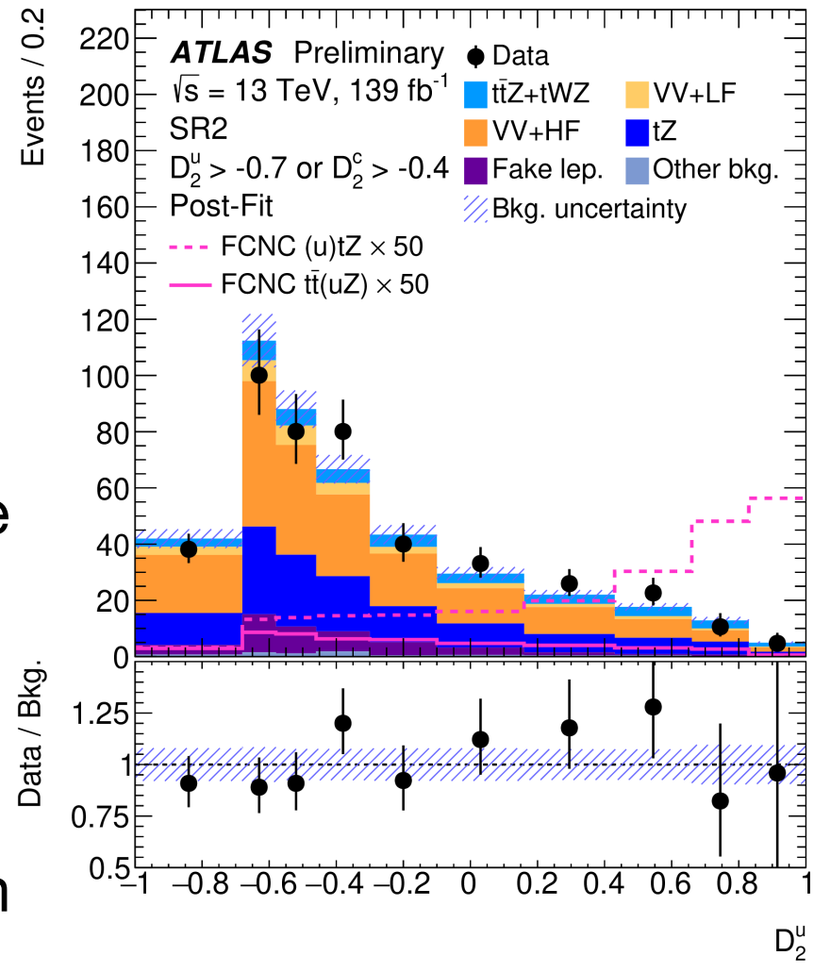




FCNC $t \to qZ$ ATLAS-CONF-2021-049

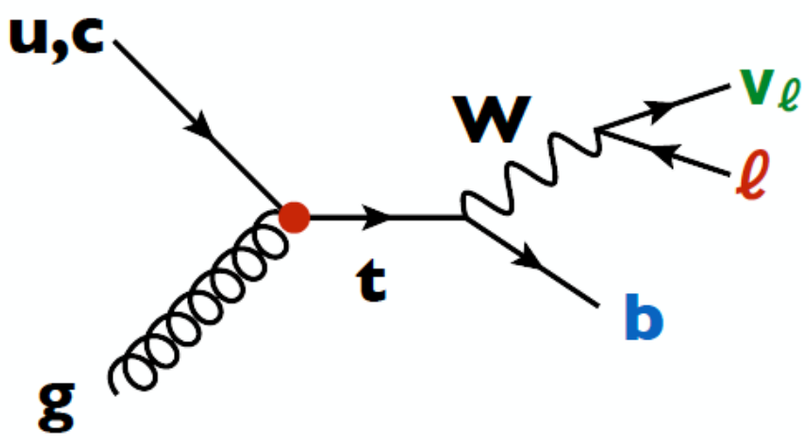
- Signal separation:
  - GBDTs were built in each SR
  - Applying 5-fold Cross-Validation
  - Training BDTs for:
    - FCNC decay
    - FCNC production via up quark
    - FCNC production/decay with charm
- Upper limits on Branching ratio and Wilson coefficient are extracted from profile-likelihood fit to BDT scores.
- Comparison between previous (36fb^{-1}) and current observed limits show a significant improvement using the full Run-2 dataset with:
  - a factor of ~3 for tZu ~2 for tZc coupling
  - 36 fb^{-1} result: decay mode only
  - The statistical uncertainty is the dominant contribution

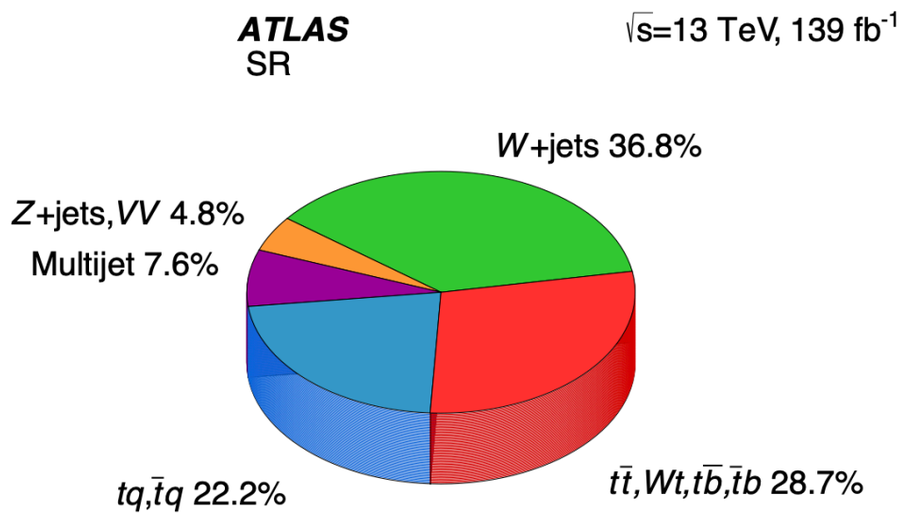
SRs+CRs				
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	RH	12	10^{+4}_{-3}
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	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	$0.19^{+0.04}_{-0.03}$



FCNC $t \to qg$ Eur.Phys.J.C82(2022)334

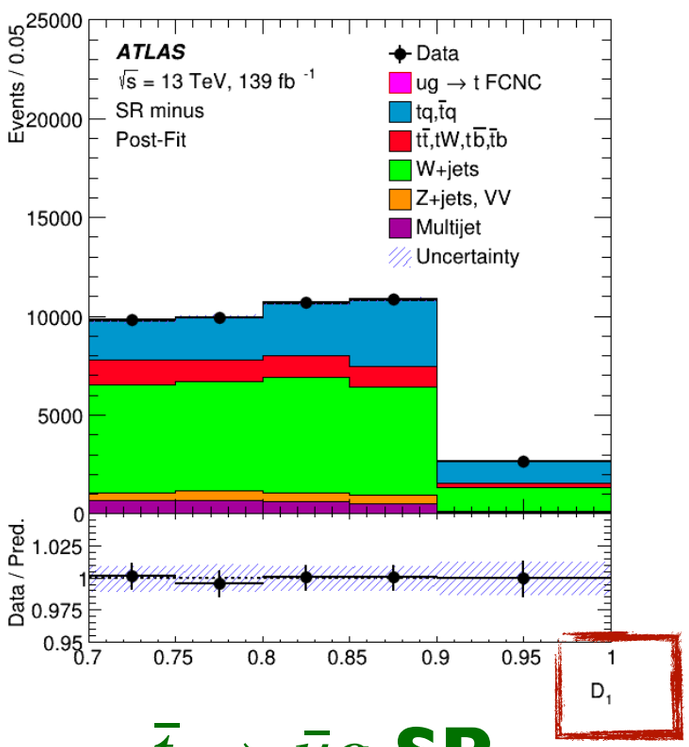
- Analysis Strategy:
  - 1 b-jet + high-P_T leptons (e or μ) + large missing Et
  - Consider **production ONLY**
    - decay mode contains a jet initiating gluon, indistinguishable with QCD bkg.
  - Top quark can be constructed using 4-momentum conservation (W on-shell)
  - Fake rate determined in a data-driven way for multi-jet estimation (jets fake leptons)
  - Custom very tight b-tag to suppress light-jets



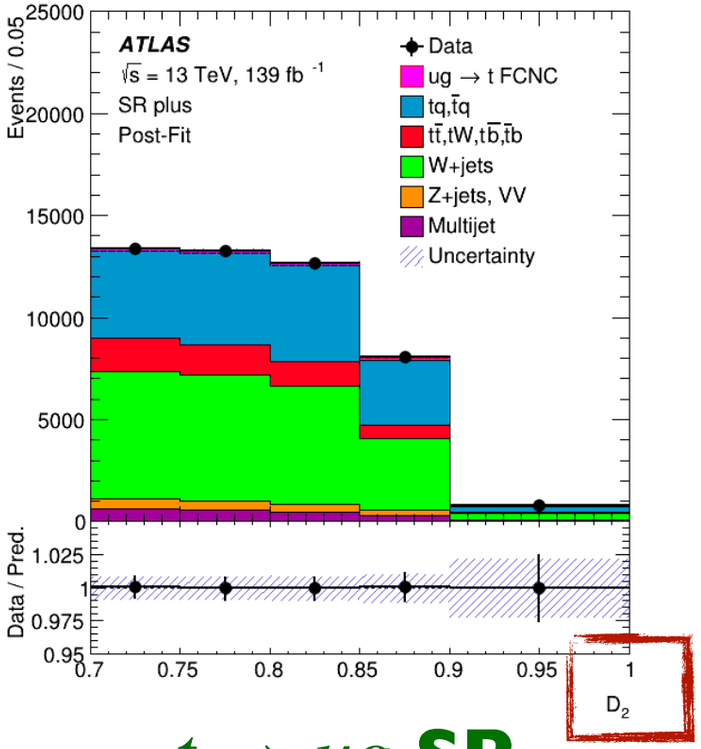


FCNC $t \to qg$ Eur.Phys.J.C82(2022)334

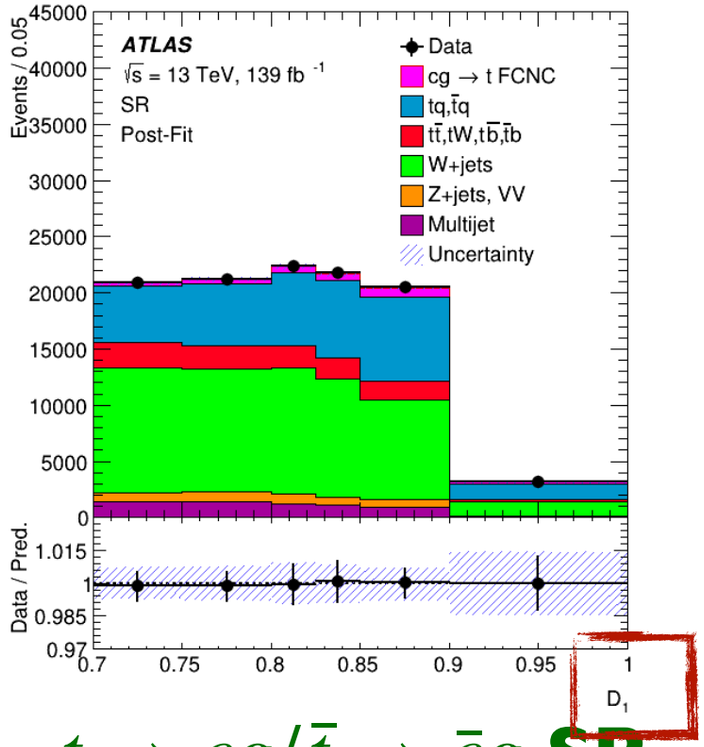
- Train artificial neural networks to obtain discriminants separating signal and background
  - 2 NNs: **D1 for** $\bar{u}g\bar{t}, cgt, \bar{c}g\bar{t}$ **D2 for** ugt
  - three-layer feed forward NN with transformation of 12/9 input variables
- Profile maximum-likelihood fit to the NN discriminant
- Factors of 1.5 - 2 better than run-1 analysis, main systematics: bkg modelling, jet/MET-related
  - BR($t \to ug$) < 0.61 x 10^{-4} (expected: BR($t \to ug$)< 0.49 x 10^{-4})
  - BR($t \to cg$) < 3.7 x 10^{-4} (expected: BR($t \to cg$)< 2.0 x 10^{-4})



$\bar{t} \to \bar{u}g$ **SR**



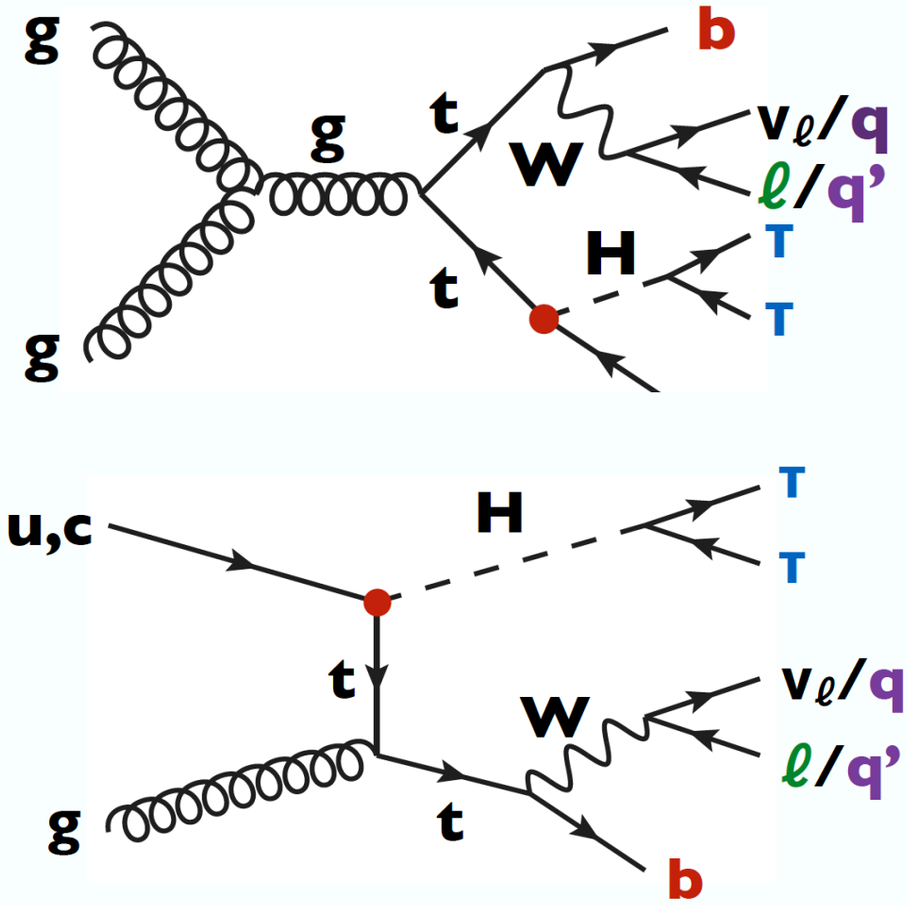
$t \to ug$ **SR**



$t \to cg/\bar{t} \to \bar{c}g$ **SR**

FCNC $t \to qH(\tau\tau)$ ATLAS-CONF-2022-014

- Analysis Strategy (7 SRs are defined based on):
  - # of leptons, (b-)jet multiplicities, tau decay mode, W decay mode
  - $t_\ell(t_h)$: W from SM top decays leptonically (hadronically)
  - $\tau_{lep}(\tau_{had})$: tau lepton decays leptonically (hadronically)

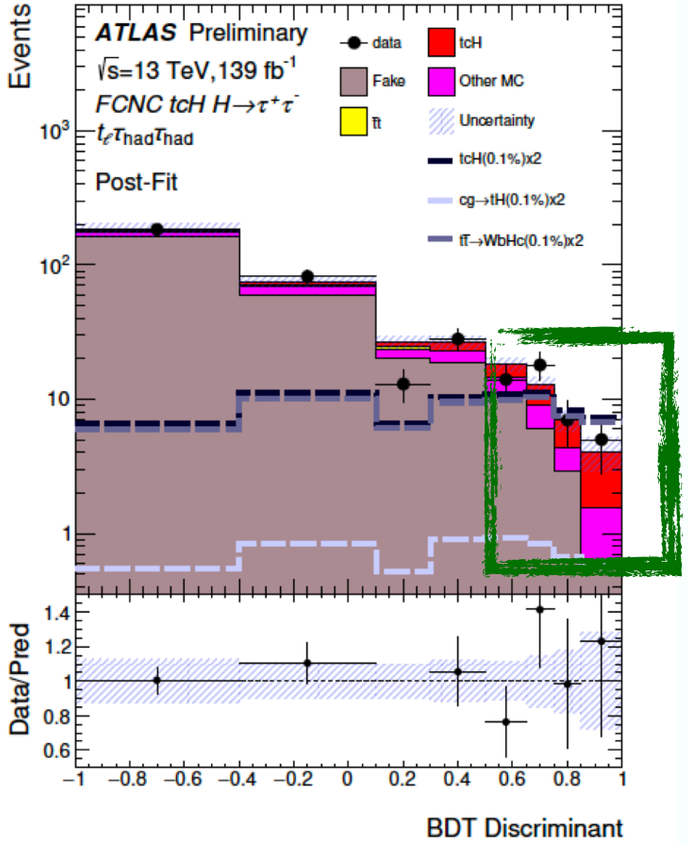


Requirement	leptonic channel $t_h\tau_{\text{lep}}\tau_{\text{had}}$	leptonic channel $t_l\tau_{\text{had}}\tau_{\text{had}}$	leptonic channel $t_l\tau_{\text{had}}$	hadronic channel $t_h\tau_{\text{had}}\tau_{\text{had}}$
Trigger	single-lepton trigger			di-τ trigger
Leptons	=1 isolated e or μ			no isolated e or μ
τ_{had}	=1 τ_{had}	2 τ_{had}	=1 τ_{had}	2 τ_{had}
Electric charge (Q)	$Q_\ell \times Q_{\tau_{\text{had},1}} < 0$	$Q_{\tau_{\text{had},1}} \times Q_{\tau_{\text{had},2}} < 0$	$Q_\ell \times Q_{\tau_{\text{had},1}} > 0$	$Q_{\tau_{\text{had},1}} \times Q_{\tau_{\text{had},2}} < 0$
Jets	3, $\geq$ 4 jets	$\geq$1 jets	2, $\geq$3 jets	3, $\geq$4 jets
b-tagging		=1 b-tagged jets		=1 b-tagged jets

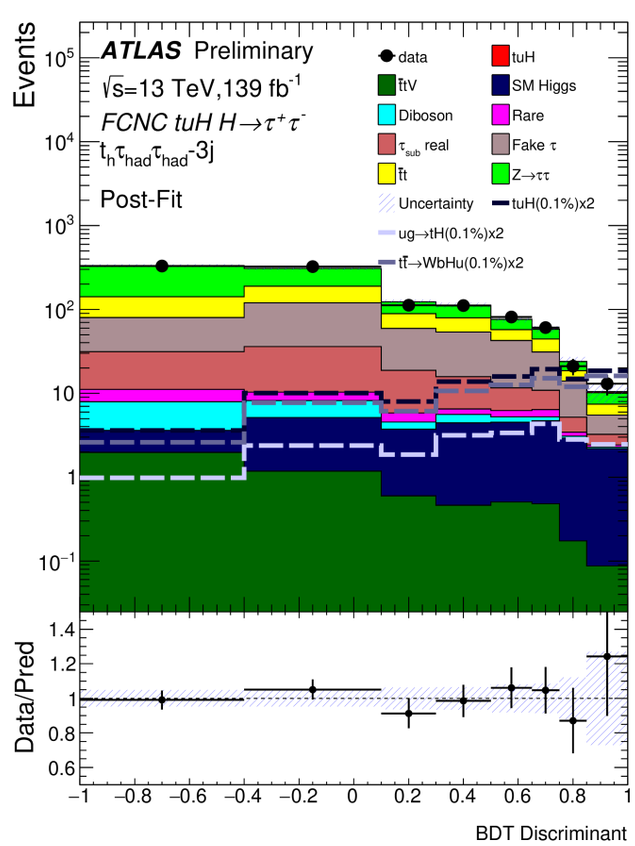
FCNC $t \to qH(\tau\tau)$ ATLAS-CONF-2022-014

- Lep channel: data-MC scale factors from tt CRs (2 b-tags or 2 leptons)
- Had channel: events with looser τ ID multiplied with fake factors (from W+jets CR)
- One BDT per signal region with 12-17 kinematic input features
- Comparison between previous (36fb^{-1} JHEP05(2019)123) and current observed limits show a significant improvement using the full Run-2 dataset with:
  - a factor of ~5 (2.5) for expected (observed) upper limit
  - The statistical uncertainty is the dominant contribution
  - Small excess of data are observed with significance of 2.3σ, mainly in tlep + 2 hadtau

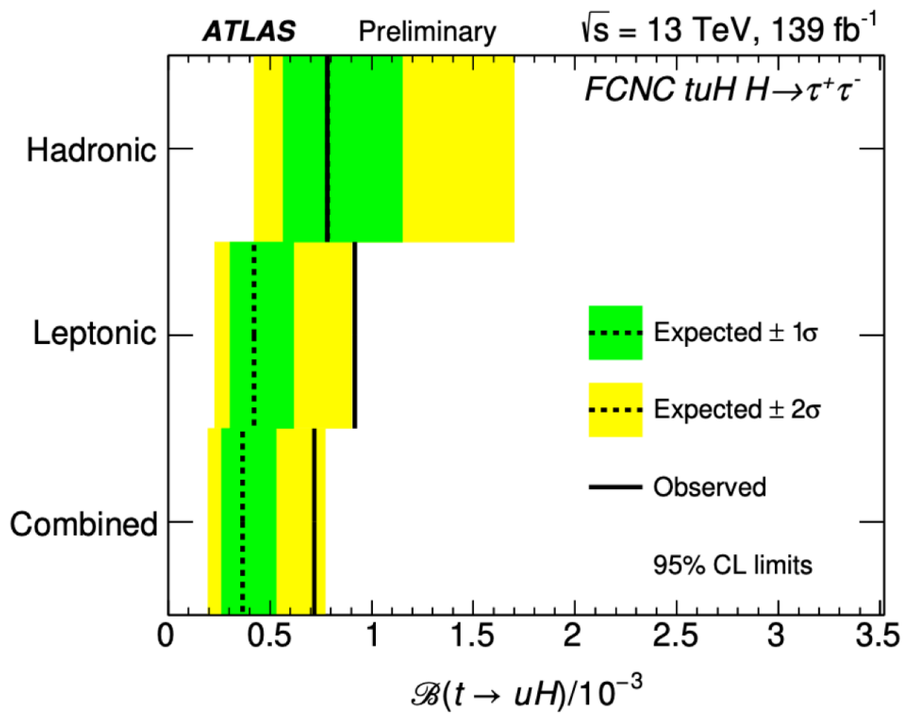
Most sensitive leptonic SR



Most sensitive hadronic SR

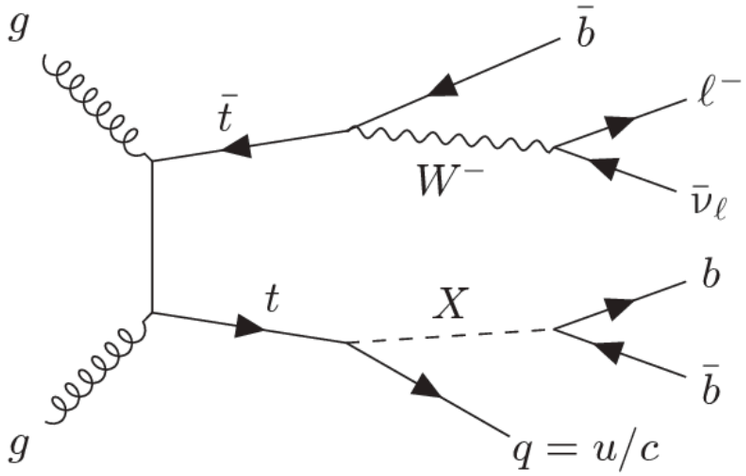


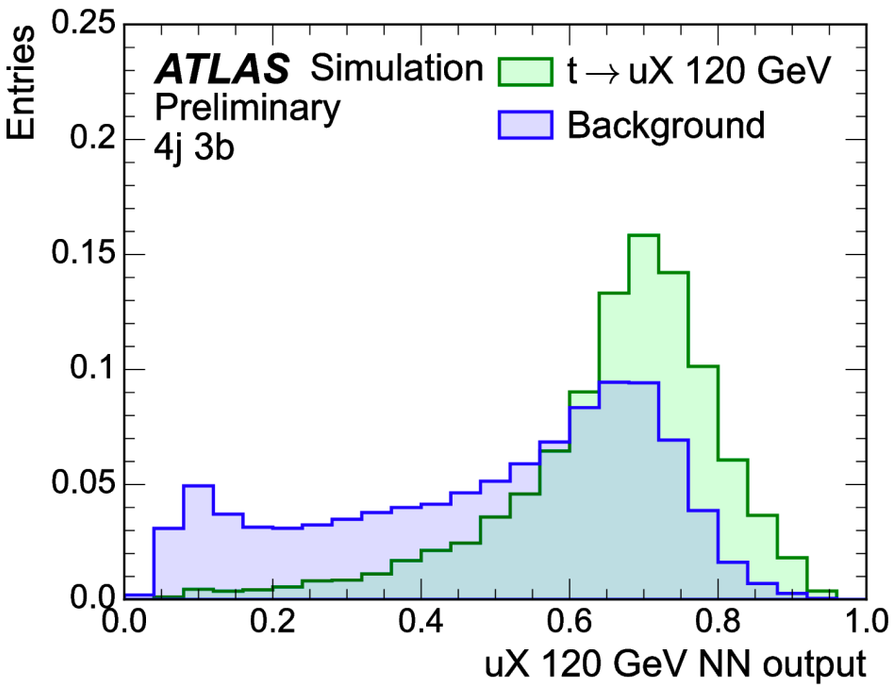
Excess 2.3σ significance

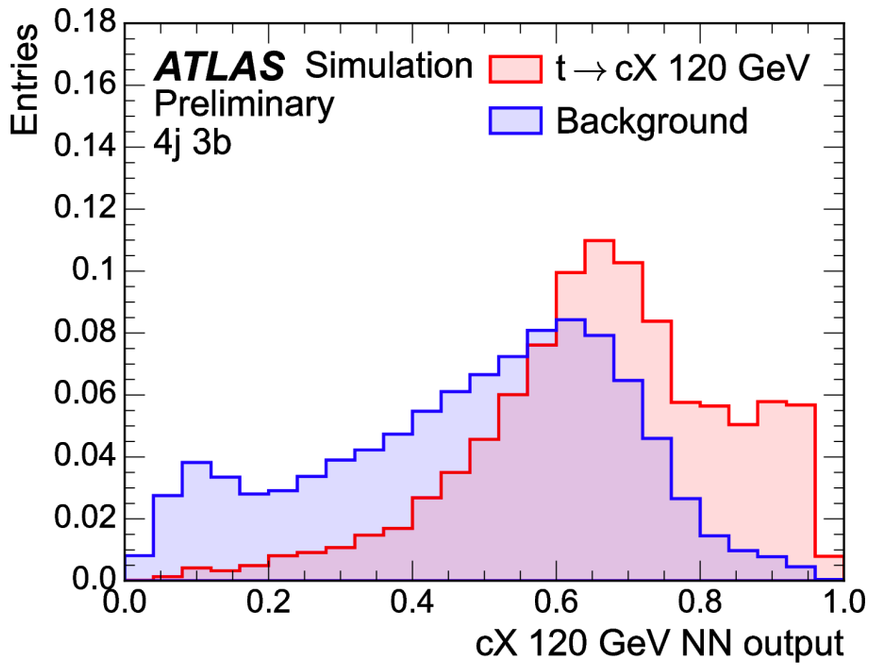


FCNC $t \to qX(bb)$ ATLAS-CONF-2022-027

- Search for t→qX (X→bb) for 20<mX<160 GeV from ttbar decay with SM t→ℓvb and similar to Hbb when mX=120 GeV
- Analysis strategy:
  - One isolated lepton, ≥4 jets, ≥3b
  - Categorization: SRs: 4j3b, 5j3b, 6j3b CRs: 4b(4,5,6)j, 2b-tag + 1b-tag loose(bl)
- Background dominated by ttbar+jets
  - ttbar reweighting from data/MC ratios in CR(2b+1bl)
- Train NNs with kinematics to separate sig from bkg for X

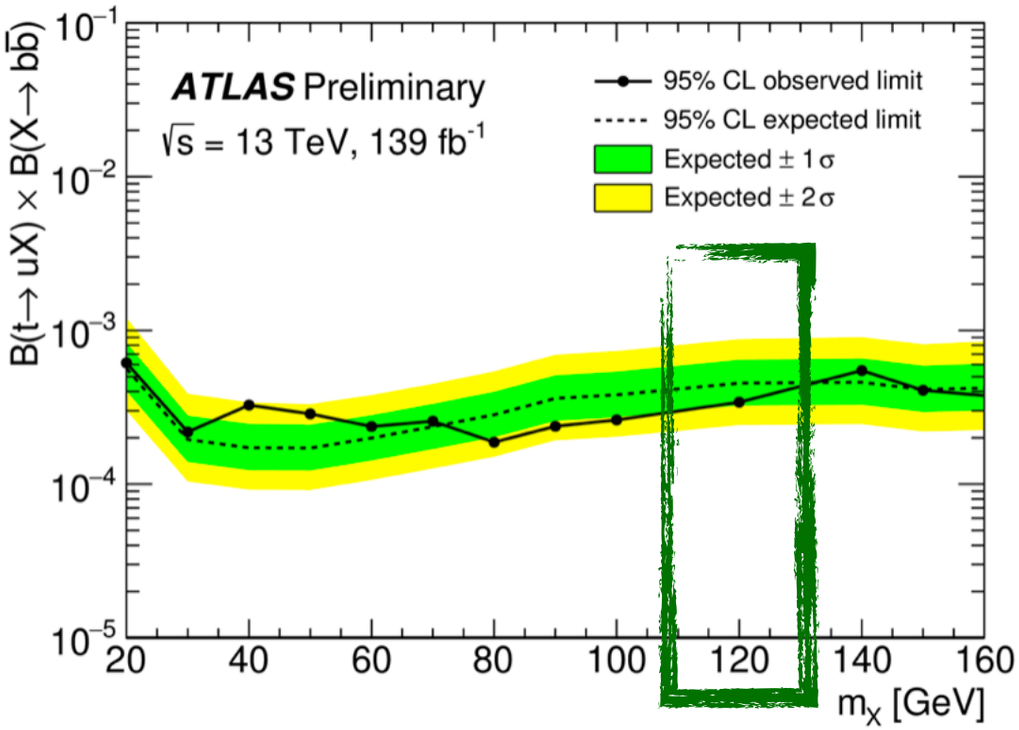


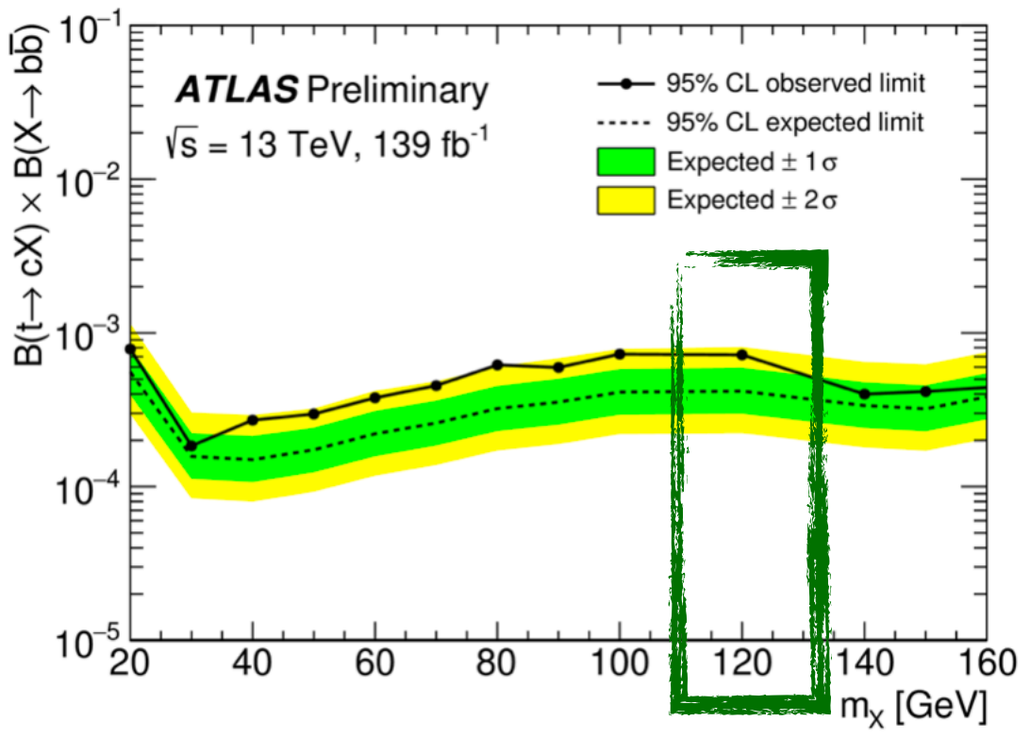




FCNC $t \to qX(bb)$ ATLAS-CONF-2022-027

- NN scores are fitted for each mass and decay hypothesis
  - When **mX=120 GeV**, similar to **tqH(bb) process**, small excess of 1-2σ
- Set upper limits on **BR(t→qX) x BR(X→bb)** vs **mX**
- **when mX = 120 GeV**
  - B(t→uX) < 8×10^{-4}
  - B(t→cX) < 7×10^{-4}
  - Improvement of ~6 in expected limits compared to tqH(bb) results (JHEP05(2019)123)
- Dominated systematics: b-tag & ttbar modeling & JER,JES





FCNC summary

- LHC is a Top factory and ideal for probing FCNC signatures with top quark for all elementary bosons— tqγ, tqZ, tqg and tqH
- New top FCNC search results improved the limits by factors up to ~6
- Run-3 expects more exciting opportunities!

Improvement factor w.r.t. previous best ATLAS search

	Expected		Observed	
	up	charm	up	charm
γ	~5	~6	~3-5	~4-5
Z	~5	~3	~3	~2
H	~2	~2	~2	~1.1
g	~2	~3	~2	~2