Recent Results on FCNC from ATLAS and CMS

Wei-Ming Yao (LBNL), Jiwon Park(Hanyang)

On behalf of the ATLAS and CMS Collaborations

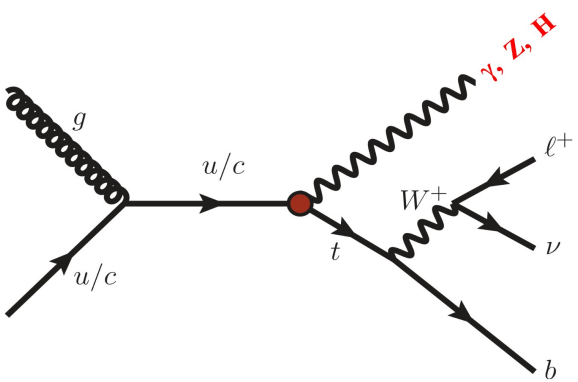
LHCtopWG 2022 meeting, CERN, Jun 15-17, 2022

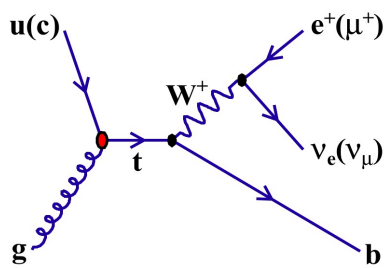
Outline

- Introduction
- Review recent FCNC results with full Run2 data involving all bosons:
  - $t \to q\gamma$ [ATLAS arXiv:2205.02537]
  - $t \to qZ$ [ATLAS-CONF-2021-049]
  - $t \to qg$ [ATLAS arXiv:2112.01302]
  - $t \to qH$, q=u, c
    - $H \to \gamma\gamma$ [CMS arXiv:2111.02219]
    - $H \to \tau\tau$ [ATLAS-CONF-2022-014]
    - $H \to bb$ [CMS JHEP02(2022)169; ATLAS-CONF-2022-027]
- Conclusions

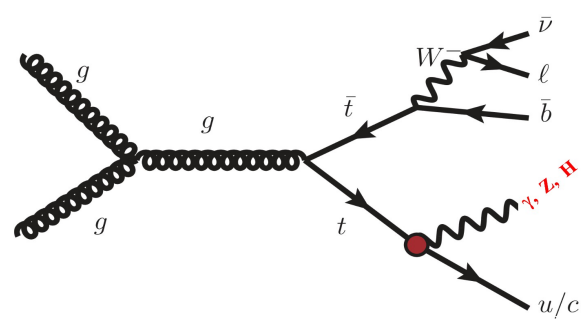
Introduction

- LHC measurements so far are consistent with SM predictions
- While looking for new physics, searches for top FCNC are well motivated
- Top FCNC is forbidden at tree level and highly suppressed due to GIM
- $B(t \to qV^0) < 10^{-12}$ in SM, but can be enhanced to 10^{-5} in some BSM models
- Any observation of top FCNC is evidence for new physics
  - FCNC single-top production (ST): enhancement of $\sigma(tV^0)$
  - FCNC top decay (TT): enhancement of $B(t \to qV^0)$, $V^0 = \gamma/Z/H/g$
  - EFT Wilson coefficients link two processes together [arXiv:1412.5594]





ST production



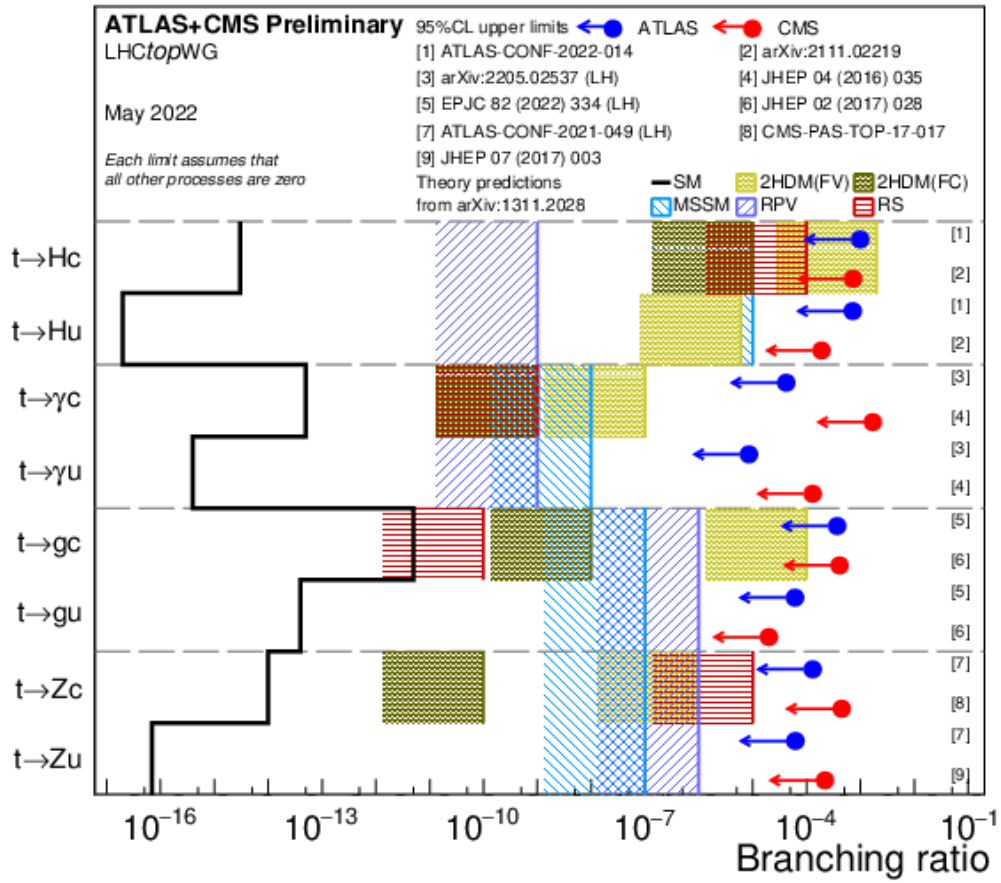
SM $t = t_\ell, t_h$

FCNC $t \to qV^0$

TT decay

Top FCNC Experimental Limits

- Top FCNC have been actively searched for by ATLAS and CMS
- Best limits that are getting closer to constraining some BSM models



Overview Analysis Strategies

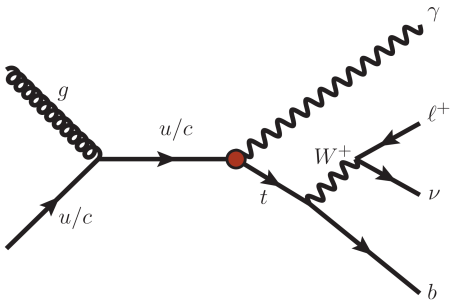
- Most analysis includes signals from both production (ST) and decays (TT)
- Mostly focus on the t_ℓ decay that the lepton provides a trigger
- The t_h decay is also used if trigged by other objects in the event
- Kinematic fit and TMVA are essential to suppress the background
- Common object selection is used: ℓ(e,μ) , τ, γ, jets, b-tagging, met...

$t \to qX$	ST	TT	t_ℓ	t_h	Triggers.	KinFit	TMVA
γ(ATL)	x	x	x		1ℓ		NN
$Z \to \ell\ell$(ATL)	x	x	x		$1,2\ell$	x	BDT
g (ATL)	x		x		1ℓ	x	NN
$H \to \gamma\gamma$(CMS)	x	x	x	x	di-γ	x	BDT
$H \to \tau\tau$(ATL)	x	x	x	x	1ℓ/di-τ	x	BDT
$H \to bb$(CMS)	x	x	x		1ℓ	x	BDT
$H \to bb$(ATL)		x	x		1ℓ		NN

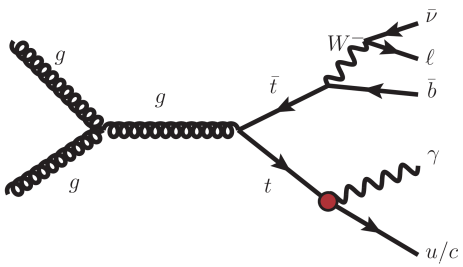
FCNC t→qγ, q=u,c

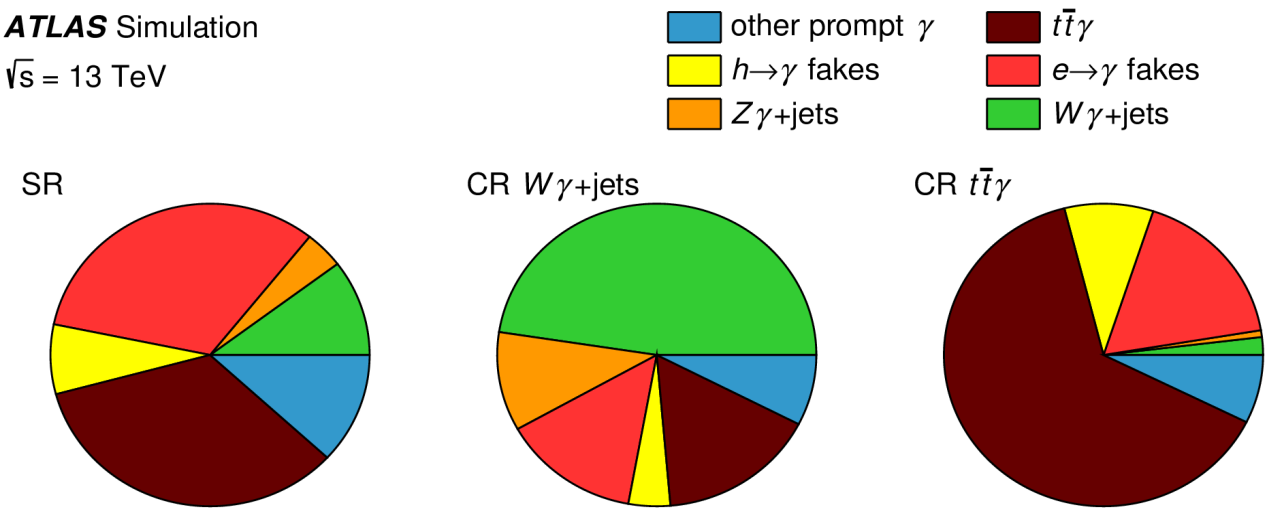
[arXiv:2205.02537]

- Analysis Strategy
  - Optimize for production(tγ) & t(qγ)t decays in t→ℓvb
  - Triggered by single lepton trigger (pT>27 GeV)
  - Select:1γ pT>20 GeV + 1 lep + met + 1-btag jet



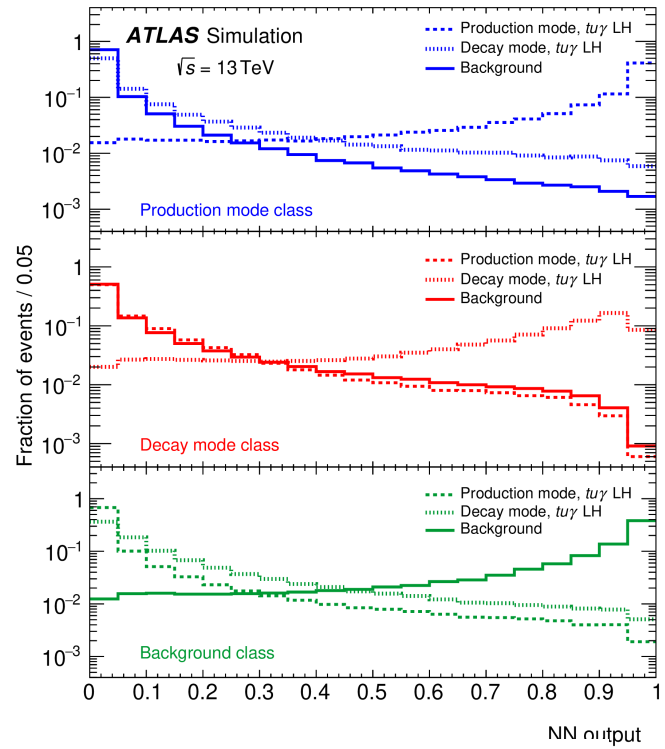
- Background: dominated by ttγ and tt+e→γ fakes
  - Normalized by control regions (CR) of ttγ & Wγ+jets
  - Fake estimates are data-driven

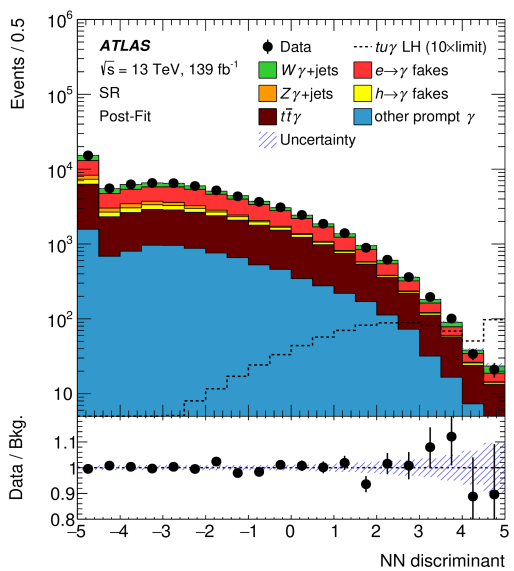


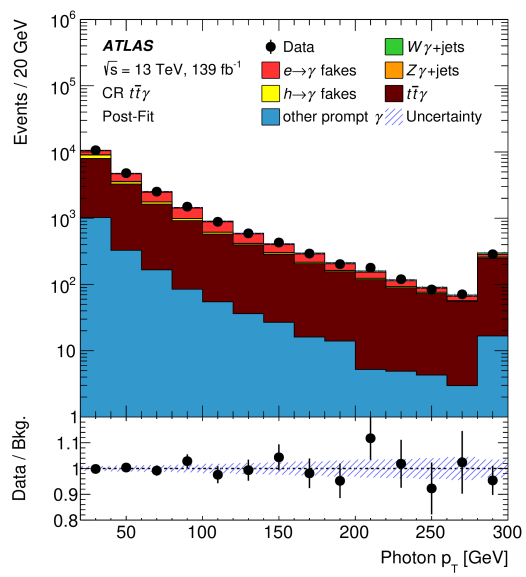


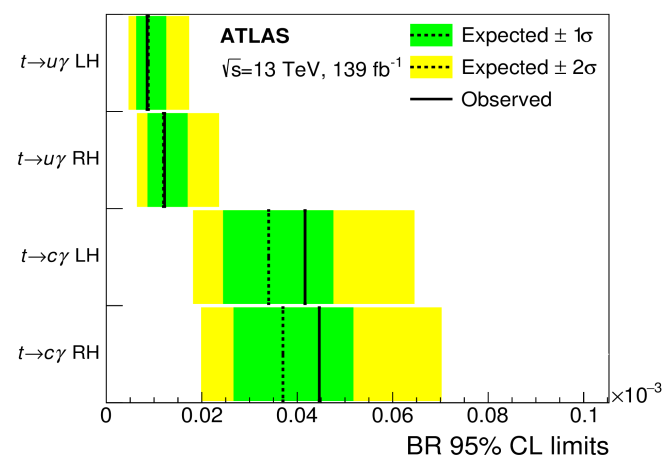
FCNC t→qγ Results

- Multi-class Neural Nets(NN) are trained:
  - Deep NN with 6 hidden layers and 37 inputs
  - 3 output nodes targeting: y_{prod}, y_{dec}, y_{bkg}
  - Outputs are combined in likelihood ratio
  - Separate NN for t→uγ and t→cγ signals
- Background model in agreement with the data
- $B(t\to u\gamma)<0.85/1.2\cdot10^{-5}$, $B(t\to c\gamma)<4.2/4.5\cdot10^{-5}$ for L/RH





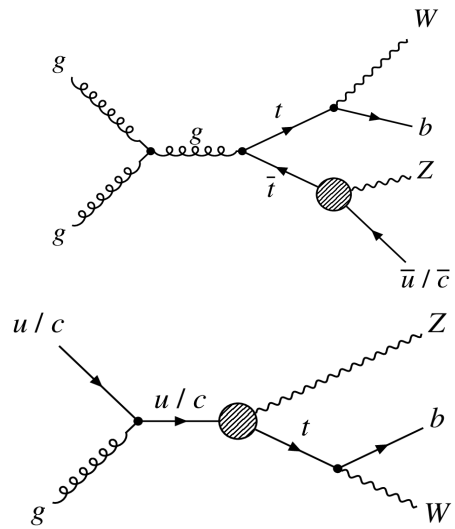


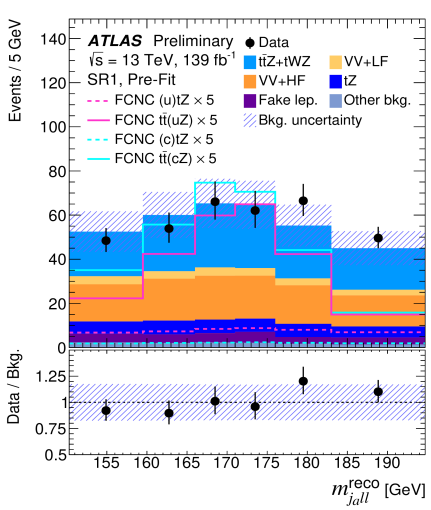


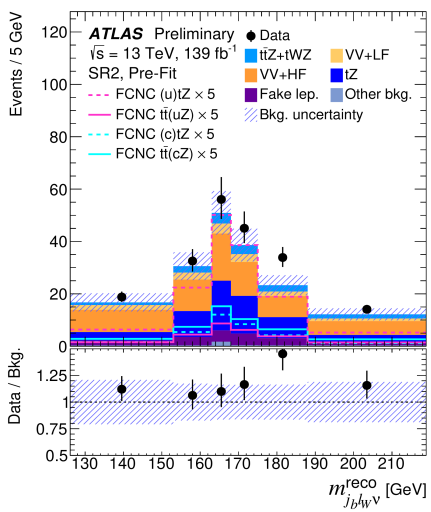
FCNC t→qZ(→ℓℓ), q=u,c

[ATLAS-CONF-2021-049]

- Analysis strategy:
  - Optimize 2 signal region(SR) for production & decay
  - Select trilepton final states with Z→ℓℓ and t→ℓvb
- Background dominated by ttV and diboson
  - Four CR: tt, ttZ, and 2 top mass-sideband of SR
- Kinematic reconstruction SM/FCNC top by minimizing χ^2
  - Selecting any light jet as q-jet for top FCNC decay
- Train BDT for each SR to separate signal from bkg





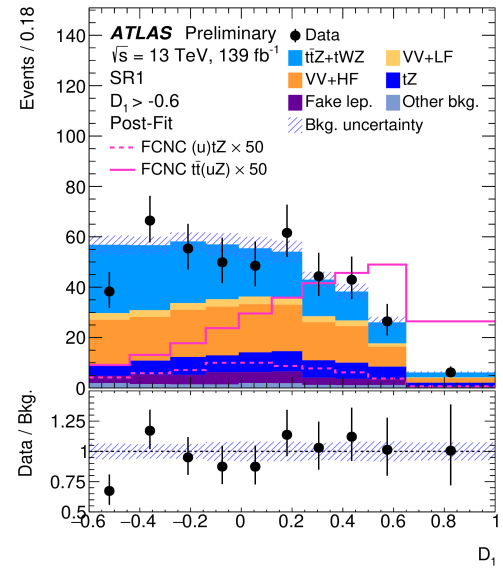


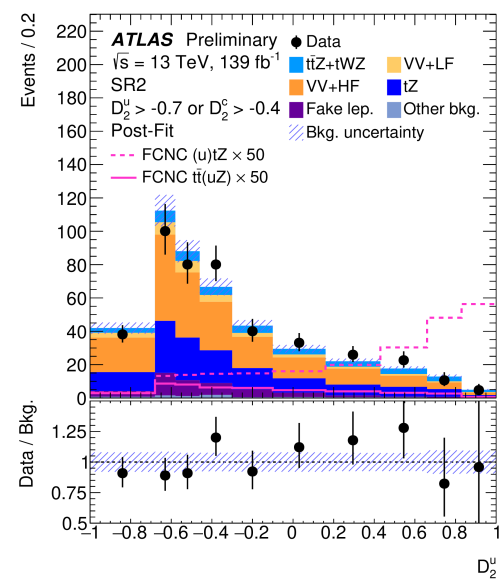
	SR1 ($D_1 > -0.6$)	SR2 ($D_2^u > -0.7$ or $D_2^c > -0.4$)
$t\bar{t}Z + tWZ$	137 ± 12	36 ± 6
$VV + \mathrm{LF}$	18 ± 7	24 ± 8
$VV + \mathrm{HF}$	114 ± 19	162 ± 26
tZ	46 ± 7	108 ± 18
$t\bar{t} + tW$ fakes	14 ± 4	27 ± 8
Other fakes	7 ± 8	5 ± 6
$t\bar{t}W$	4.2 ± 2.1	3.1 ± 1.6
$t\bar{t}H$	4.8 ± 0.7	0.89 ± 0.17
Other bkg.	2.0 ± 1.0	2.5 ± 2.9
FCNC $(u)tZ$	0.9 ± 1.7	4 ± 8
FCNC $t\bar{t}(uZ)$	5 ± 9	0.8 ± 1.5
Total background	348 ± 15	369 ± 21
Data	345	380

FCNC t→qZ Results

- Data are consistent with background expectations
- Set limits on B(t→uZ) and B(t→cZ), dim-6 coefficients
- Results are still statistics limited
- Sensitivity improved by factor of 3-5 of previous limits

Observable	Vertex	Coupling	Observed	Expected
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	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}
$\lvert C_{uW}^{(13)*}\rvert, \lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert, \lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert, \lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert, \lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$

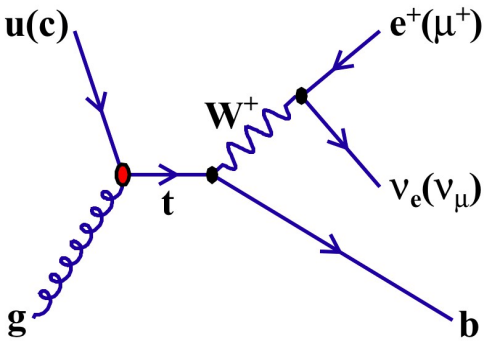


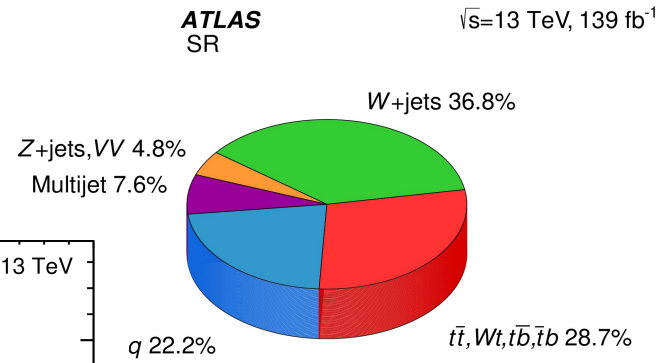


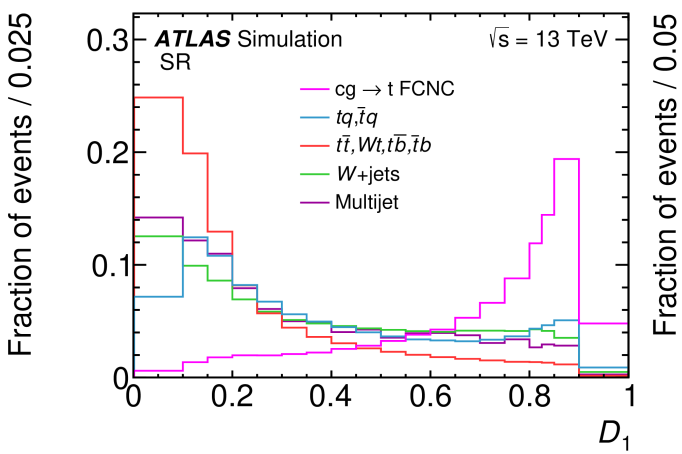
FCNC t→qg, q=u,c

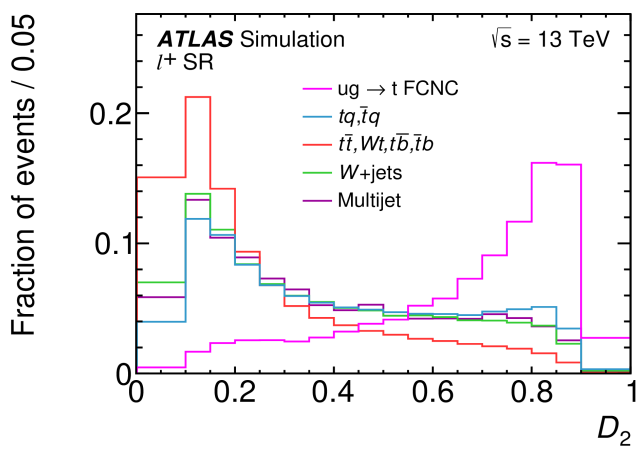
[arXiv:2112.01302]

- Analysis strategy:
  - Consider single top only, difficult for t(qg)t decays
  - Select 1ℓ+1b+met for t→ℓvb
  - Kinematic reconstruction for top by minimizing χ^2
- Background dominated by W+HF and SM top
  - Fake estimates are data-driven
  - Custom very tight b-tag to suppress light-jets
- Train 2NN to separate signals from background
  - D1 for $\bar{u}g\bar{t}$, cgt and $\bar{c}g\bar{t}$; D2 for ugt



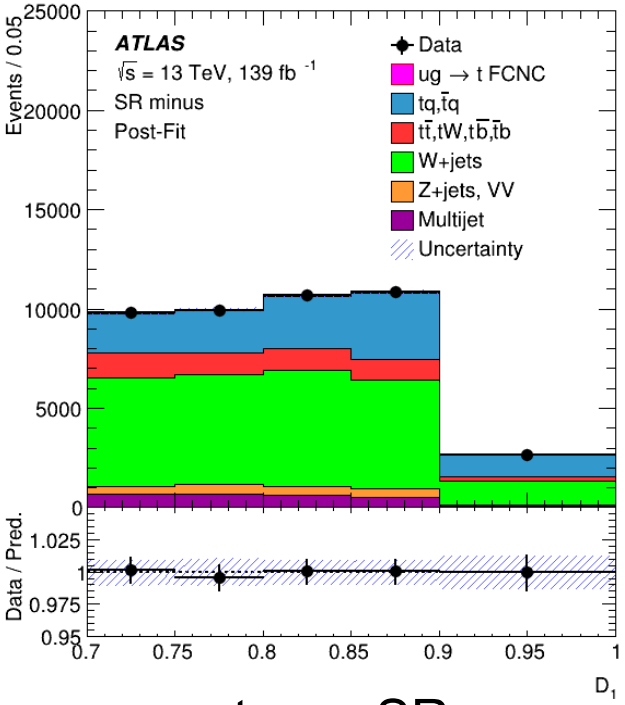




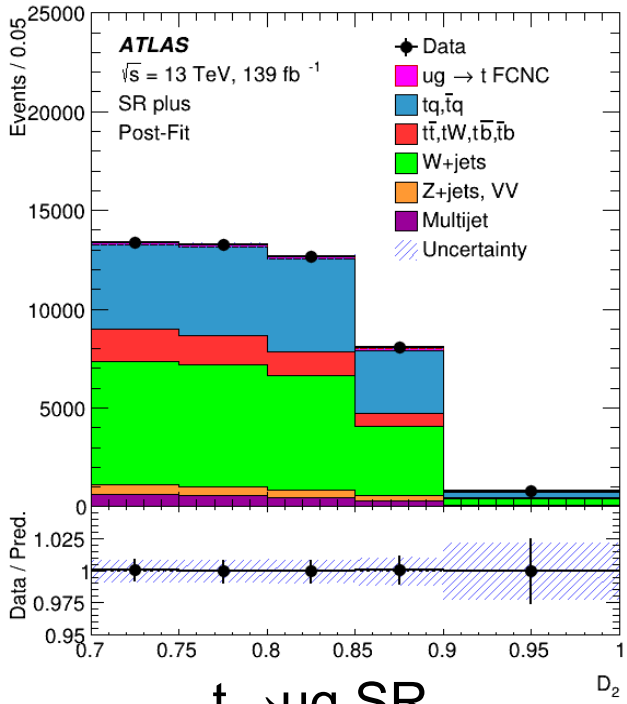


FCNC t→qg Results

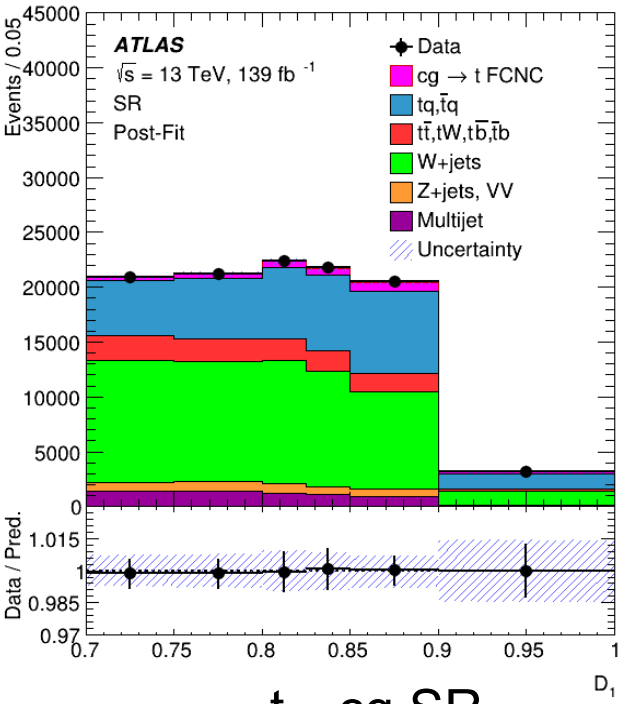
- Data are consistent with background expectations
- Set limits (exp) on $B(t\rightarrow ug)<0.61(0.49)\cdot 10^{-4}$ and $B(t\rightarrow cg)<3.7(2.0)\cdot 10^{-4}$
  - Analysis is systematic dominated
  - Sensitivity improved by factor of 1.5-2 better than run1 analysis



t→ug SR



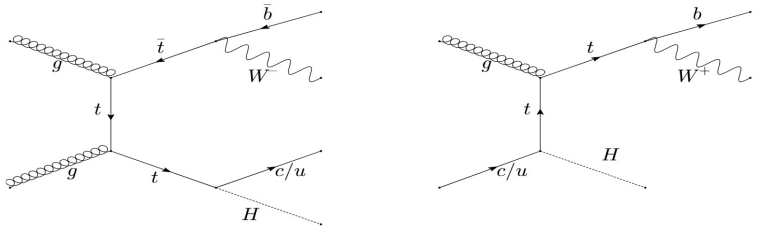
t→ug SR



t→cg SR

FCNC t→qH, q=u,c

- Searches for the tqH vertex in production (tH) and t(qH)t decays
  - H→γγ,
  - H→ττ,
  - H→ bb
  - SM top decays leptonically (t_ℓ) or hadronically (t_h)



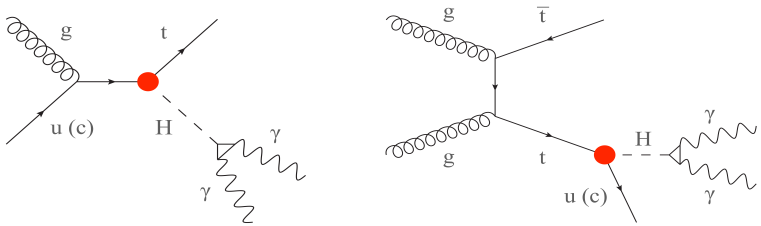
- Highly suppressed in the SM due to GIM
- Sensitive to BSM and Yukawa coupling of Higgs boson (SM σ(tH)=92 fb)
- Assume B(t→qH)=0.1%: σ(qHt)=1.7pb; σ(ug→tH)=0.71pb; σ(cg→tH)=0.10pb

	Published only	$\mathcal{L}$ [fb^{-1}]	95% CL observed upper limits on $B(t \to cH)$	on $B(t \to uH)$
ATLAS	$H \to b\bar{b}$ [32]	36.1	4.2×10^{-3}	5.2×10^{-3}
	$H \to \gamma\gamma$ [33]	36.1	2.2×10^{-3}	2.4×10^{-3}
	$H \to \tau\tau$ ($\tau_{\rm lep}\tau_{\rm had}$, $\tau_{\rm had}\tau_{\rm had}$) [32]	36.1	1.9×10^{-3}	1.7×10^{-3}
	$H \to WW^*, \tau\tau, ZZ^*$ (2ℓSS, 3ℓ) [34]	36.1	1.6×10^{-3}	1.9×10^{-3}
	Combination [32]	36.1	1.1×10^{-3}	1.2×10^{-3}
CMS	$H \to b\bar{b}$ [35]	35.9	4.7×10^{-3}	4.7×10^{-3}
	$H \to b\bar{b}$ [36]	137	9.4×10^{-4}	7.9×10^{-4}

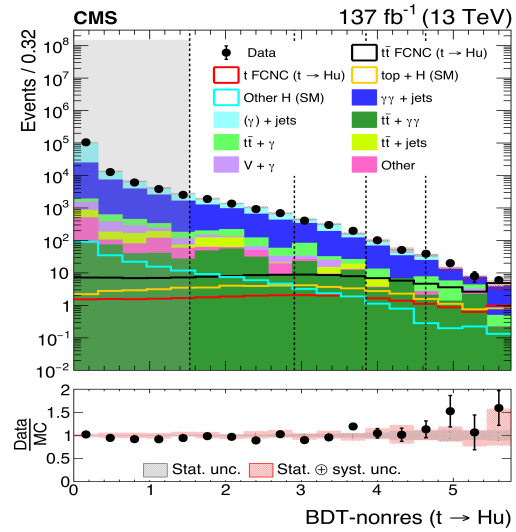
FCNC t→qH(→γγ), q=u,c

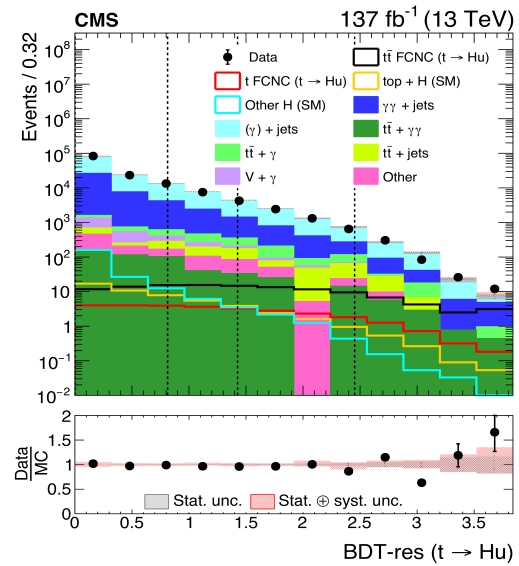
[arXiv:2111.02219]

- Optimize prod- and decay- FCNC process
  - Triggered by di-photon triggers
  - Leptonic channel: 1ℓ, >=1j, 2γ
  - Hadronic channel: >=3j, >=1b, 2γ



- Select pair of photons in 100<mγγ<160 GeV
- Kinematic reconstruction for SM/FCNC top with NN
- Train BDT to separate signal from background using kinematics, excluding mγγ
  - 8 BDT: tuH or tcH, 1ℓ or 0ℓ, H→γγ(res) or nonres
- Events are categorized using BDT scores:
  - 3 leptonic and 4 hadronic categories

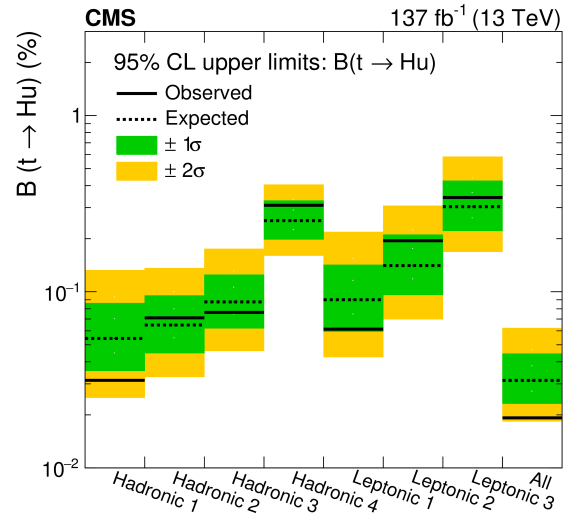


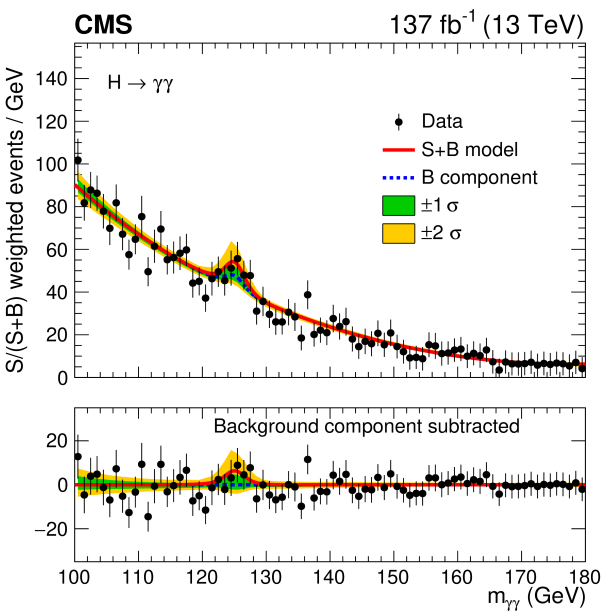


Hadronic channel

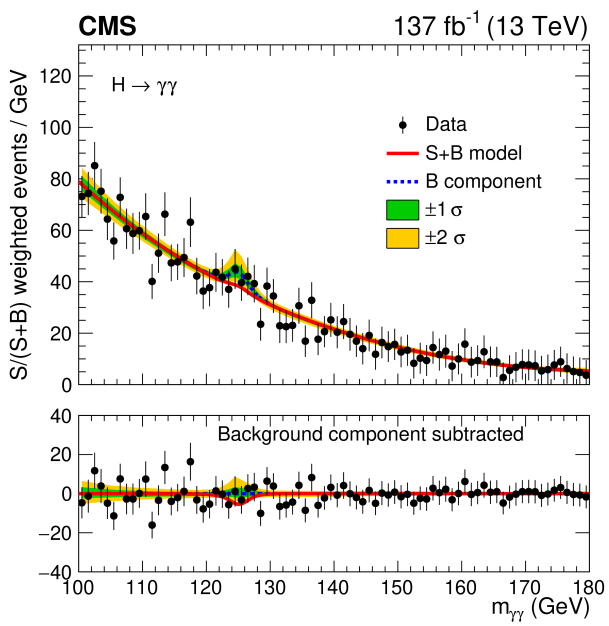
FCNC t→qH(γγ) Results

- Simultaneous fit to mγγ in all BDT categories
- Data are consistent with background expectation
- Set upper limits (exp) in categories & combination:
  - $B(t \to uH) < 1.9\ (3.1) \cdot 10^{-4}$
  - $B(t \to cH) < 7.3\ (5.1) \cdot 10^{-4}$

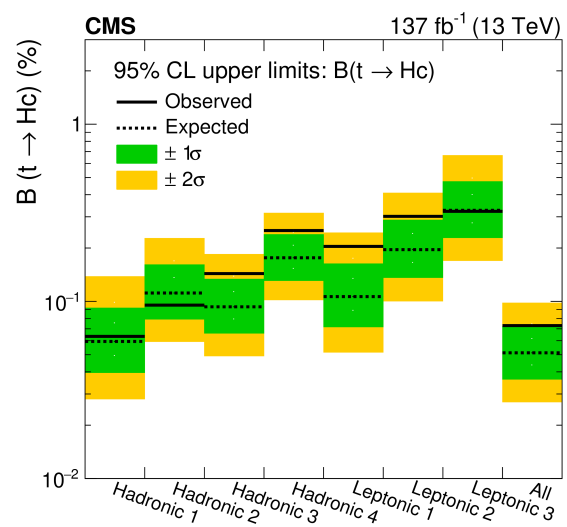




t→uH



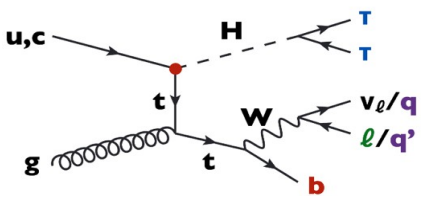
t→cH



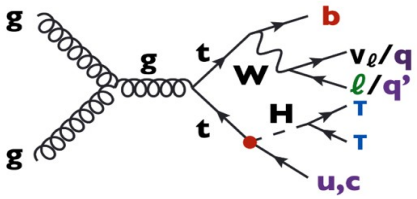
FCNC t→qH(→ττ), q=u,c

[ATLAS-CONF-2022-014]

- Optimize prod- decay-FCNC process, taking into account leptonic & hadronic top (t_ℓ, t_h) and τ(τ_ℓ, τ_{had}) decays
  - Triggered by single lepton (leptonic);di-tau (hadronic) trig.
  - Divided into 5 SR in leptonic- & 2 SR hadronic- channels



- Background: data-driven using CR tt, anti-τ; tested with SS
- Kinematic reconstruction H→ττ in Ht_h using collinear approx.

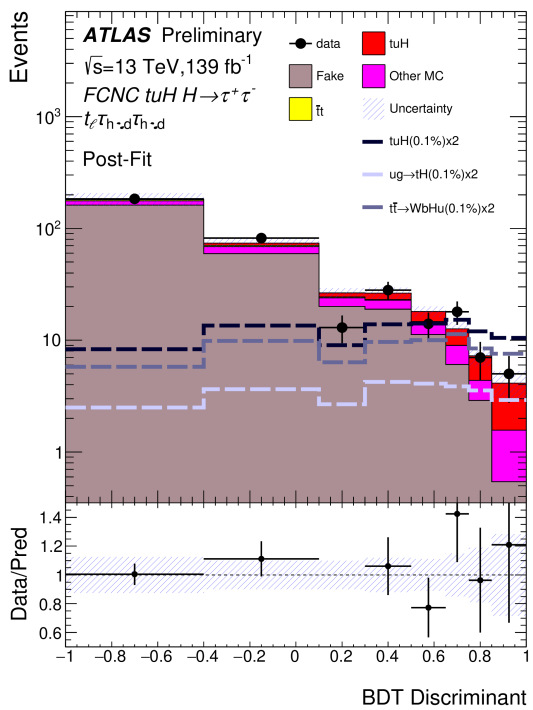


- Train BDT per SR to separate signal from background.

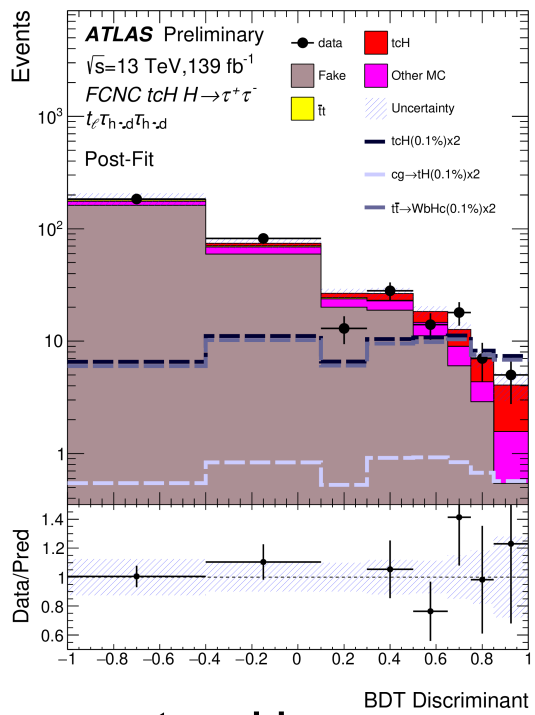
Requirement	leptonic channel $t_h\tau_{lep}\tau_{had}$	leptonic channel $t_\ell\tau_{had}\tau_{had}$	leptonic channel $t_\ell\tau_{had}$	hadronic channel $t_h\tau_{had}\tau_{had}$
Trigger	single-lepton trigger			di-τ trigger
Leptons	=1 isolated e or μ			=0 isolated e or μ
τ_{had}	=1 τ_{had}	≥2 τ_{had}	=1 τ_{had}	≥2 τ_{had}
Electric charge (Q)	$Q_\ell \times Q_{\tau_{had,1}} < 0$	$Q_{\tau_{had,1}} \times Q_{\tau_{had,2}} < 0$	$Q_\ell \times Q_{\tau_{had,1}} > 0$	$Q_{\tau_{had,1}} \times Q_{\tau_{had,2}} < 0$
Jets	3, ≥4 jets	≥1 jets	2, ≥3 jets	3, ≥4 jets
b-tagging		=1 b-jets		=1 b-jets

FCNC t→qH(ττ) Results

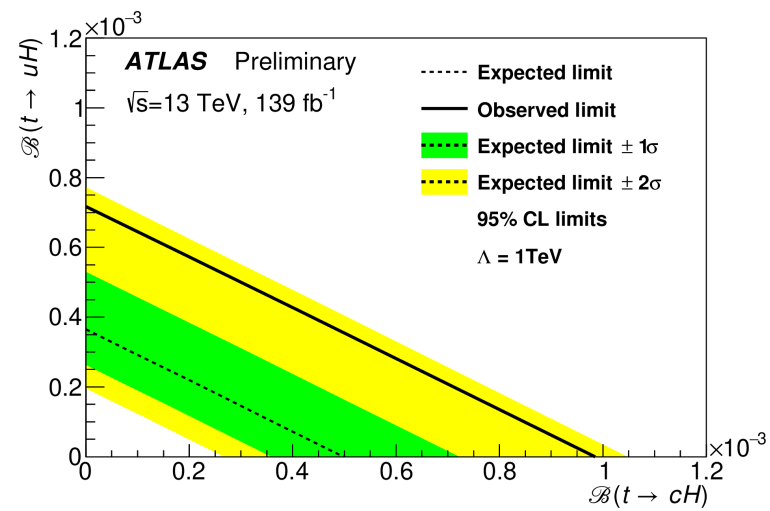
- BDTs are fitted to extract B(t→uH) and B(t→cH) signals
- Small excess of data are observed with significance of 2.3σ, mainly in t_ℓ+2τ_{had}
- Set 2-D upper limits(exp): B(t→uH) < 6.9(3.5) ·10^{-4}; B(t→cH) < 9.4 (4.8)· 10^{-4}
- Results significantly improved than previous one by including more channels



t→uH



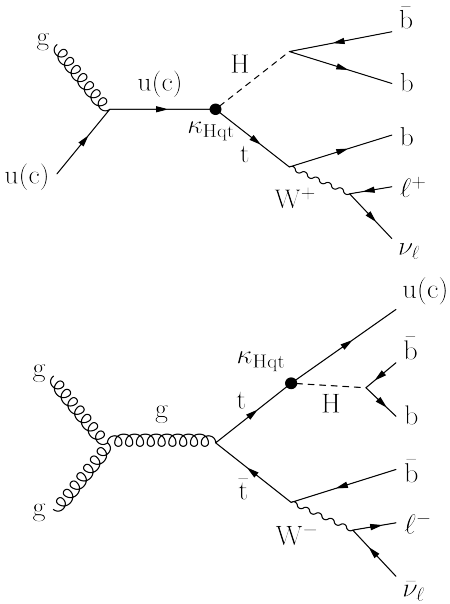
t→cH

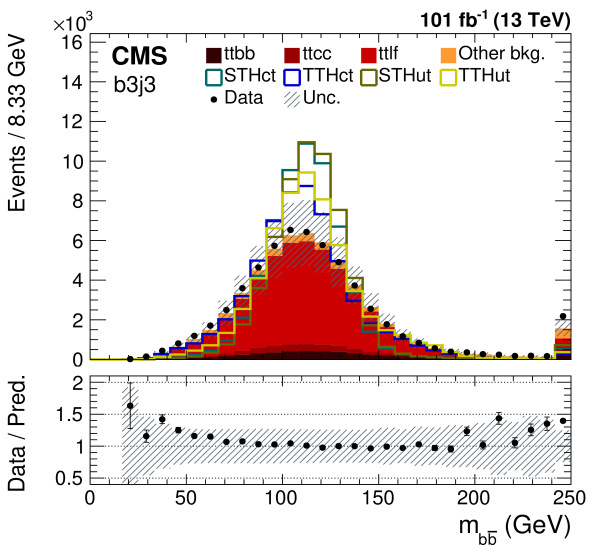


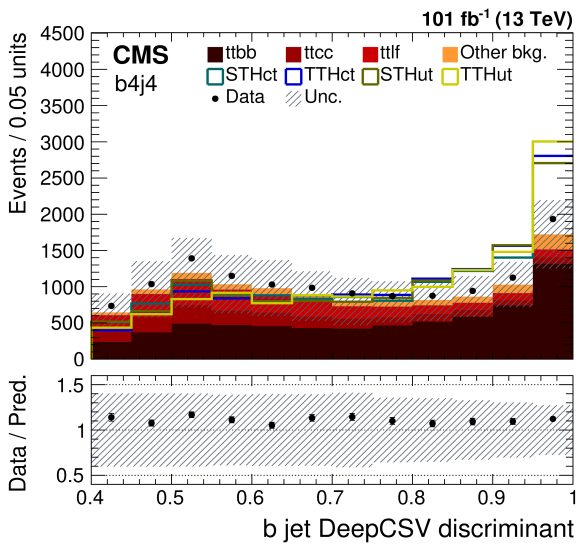
FCNC t→qH(→bb), q=u,c

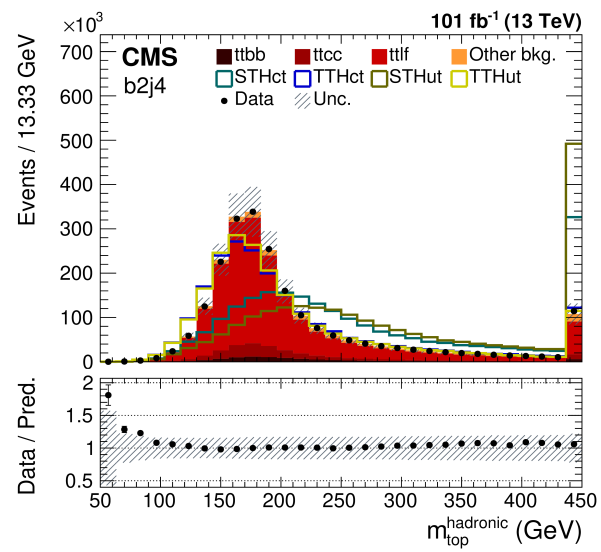
[JHEP02(2022)169]

- Optimize prod(tH) and t(qH)t decay FCNC processes with SM t→ℓvb decaying leptonically.
  - One isolated lepton, >=3j and >=2b
  - Categorization:6SR (b2j3, b3j3, b2j4, b3j4, and b4j4)
  - 2017+18 data are analyzed, combined with 2016 result
- Kinematic reco. using DNN jet assignment target: tH, qHt, tt
- Train BDTs with kinematics to separate signal from bkg



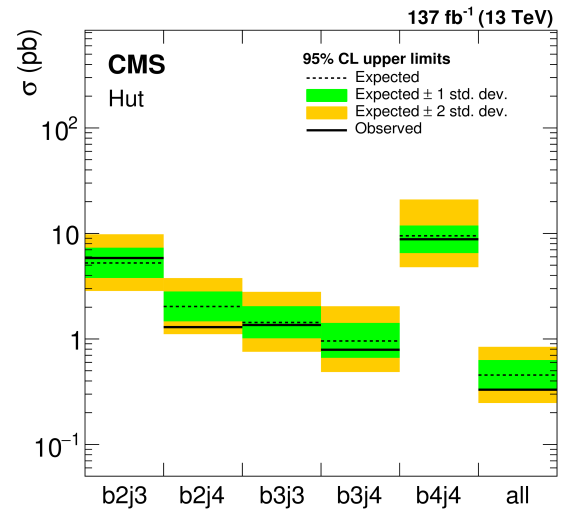


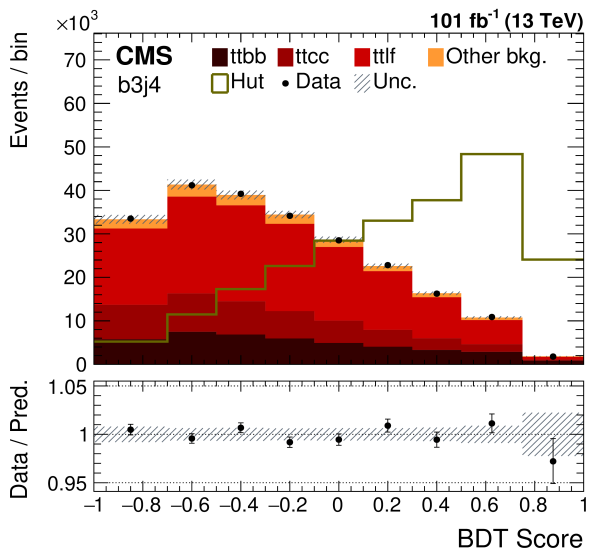




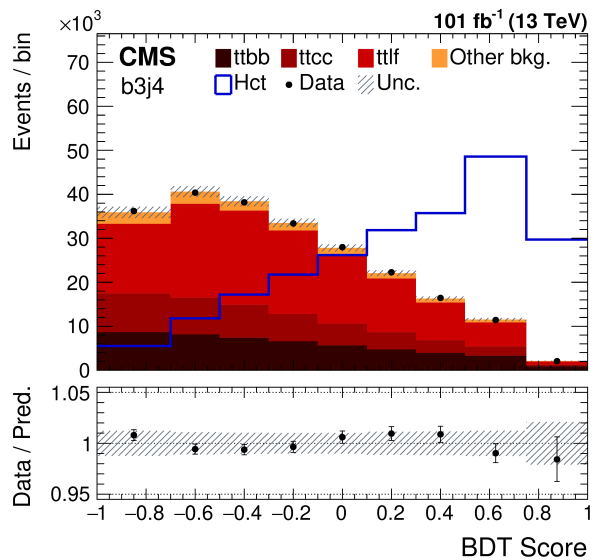
FCNC t→qH(bb) Results

- BDTs are fitted to extract B(t→uH), B(t→cH) signals
- Data are consistent with expected SM background
- Set upper limits(exp) in SRs and combination (2-D):
  - B(t→uH) <7.9 (11) $\cdot 10^{-4}$
  - B(t→cH) < 9.4 (8.6) $\cdot 10^{-4}$
- Results systematic dominated by b-tag and $t\bar{t}$ modeling

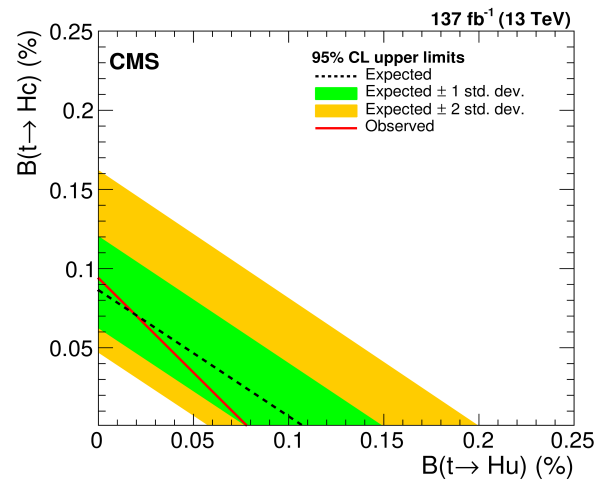




t→uH

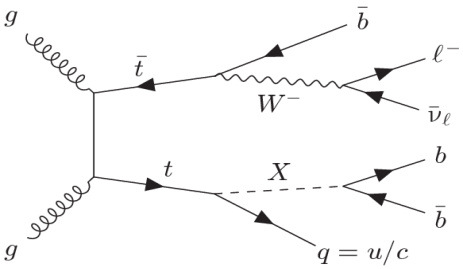


t→cH



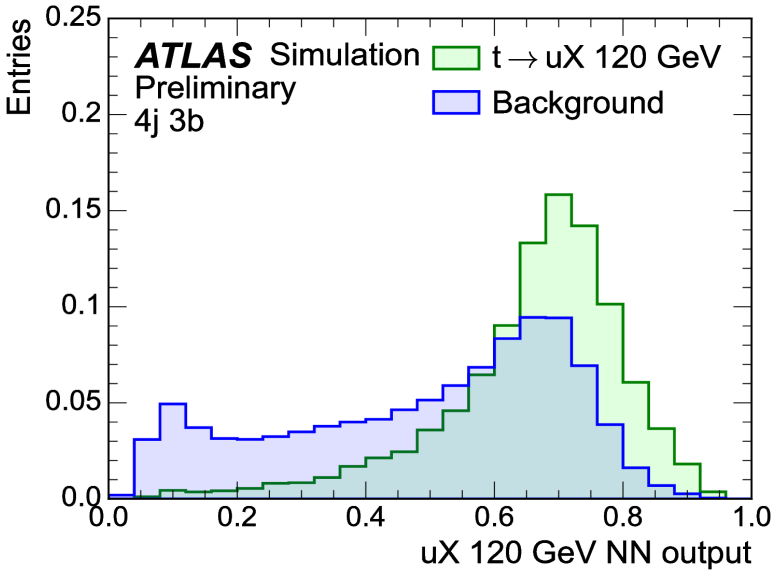
FCNC t→qX(→bb), q=u,c

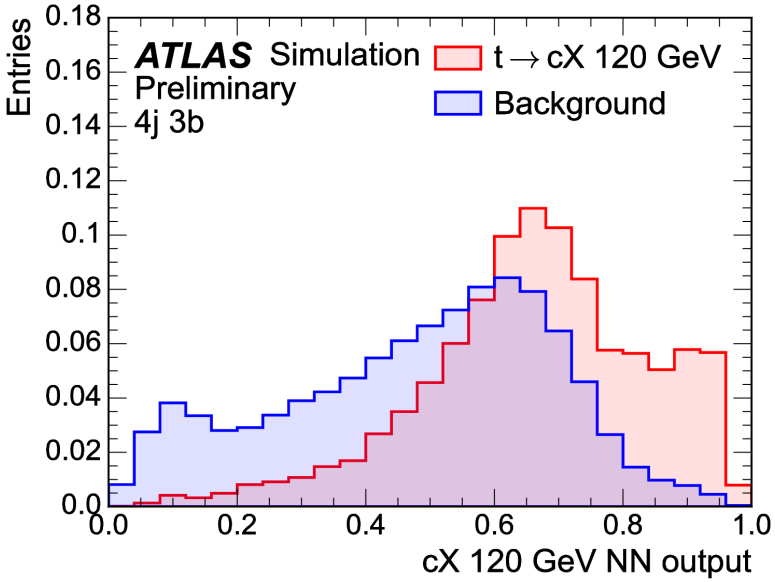
- Search for t→qX, X→bb for 20<mX<160 GeV from $t\bar{t}$ decay [ATLAS-CONF-2022-027]
  with SM t→ℓvb and similar to Hbb when mX=125 GeV
  - One isolated lepton, >=4j and >=2b(60%)+1bl(70%)
  - Categorization: 3SR(b3j4, 5, 6) + 2CR(2b+1bl, >=4b)



- Background dominated by tt+jets
  - Corrected using data-based correction from CR(2b+1bl)

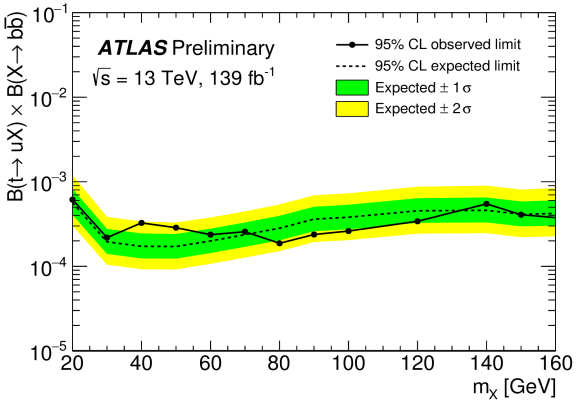
- Train NNs with kinematics to separate sig from bkg for mX

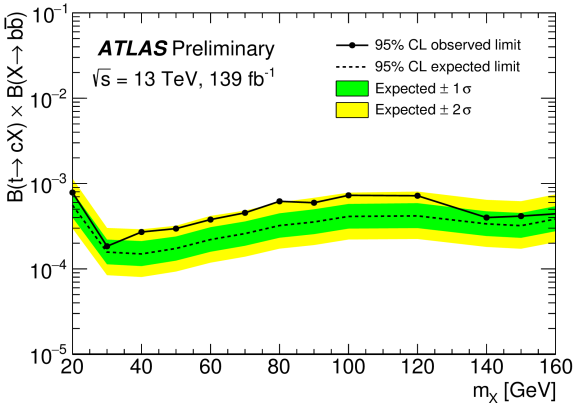


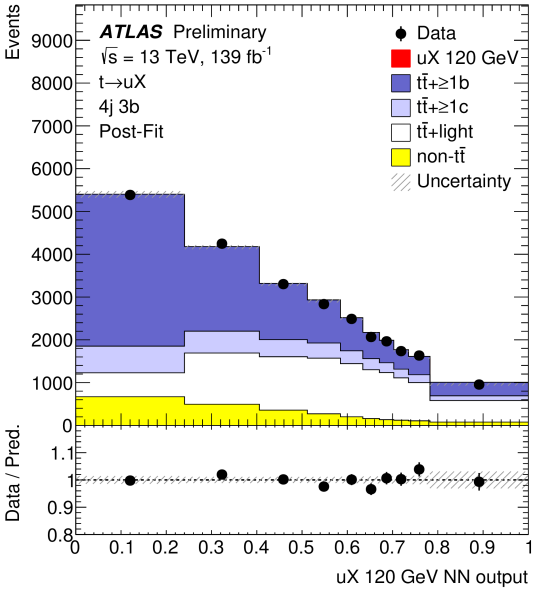


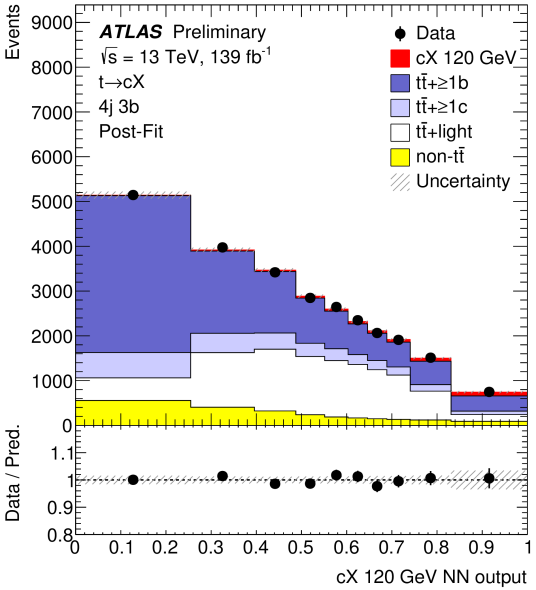
FCNC t→qH(bb) Results

- Backgrounds in SR are normalized by CR(>=4b)
- NN are fitted for each mass and decay hypothesis
- Small excess of 1.8-2σ, but incompatible with signal
- Set upper limits on B(t→qX) · B(X→bb) vs mX
- H→bb: B(t→uH) < 7(8)·10^{-4}; B(t→cH) < 10(7)·10^{-4}
- Results systematic dominated by b-tag & $t\bar{t}$ modeling









Obs(exp) H→bb	B(t→uH) x 10^{-4}	B(t→cH) x 10^{-4}
ATLAS	7(8)	10(7)
CMS	7.9(11)	9.4(8.6)

Top FCNC Summary

- New FCNC searches are updated using full run2 data
- Most searches are significantly improved beyond luminosity scaling with new techniques and including more channels

$t \to qX$	Previous	Old/New(Exp.)		Old/New(Obs.)	
New	Old	Up	Charm	Up	Charm
γ(ATL)	ATL 81fb^{-1}	3-5	5-6	3-5	4-5
$Z \to \ell\ell$(ATL)	ATL 36fb^{-1}	5	3	3	2
g (ATL)	ATL 8TeV	2	3	2	2
$H \to \gamma\gamma$(CMS)	ATL 36fb^{-1}	5.5	3	13	3
$H \to \tau\tau$(ATL)	ATL 36fb^{-1}	6	4	2	2
$H \to bb$(CMS)	CMS 36fb^{-1}	3	5	6	5
$H \to bb$(ATL)	ATL 36fb^{-1}	6	6	7	4

Conclusion

- ATLAS and CMS are updating their top FCNC searches with full run2 data
- Results are significantly improved beyond luminosity scaling by a factor of 2
- There are still more channels to be released and their combinations to follow.