Most recent FCNC searches at ATLAS and CMS

(*tZq, tγq, tgq, tHq*)

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Flavour Changing Neutral Currents

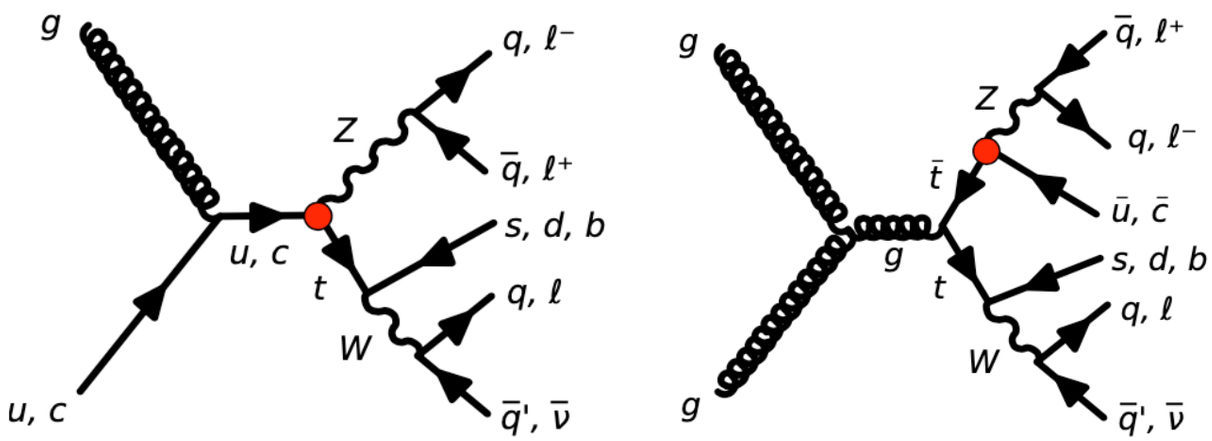
- FCNC processes are forbidden at tree level and highly suppressed at higher order in the Standard Model (SM)
  - Branching ratios of top quark decay ~ 10^{-12} to 10^{-17}
- Observation of enhanced rates would be a clear evidence for new physics
  - Several extensions to the SM include additional sources of FCNCs
  - Difference between *u* and *c* quarks arises from $|V_{ub}/V_{cb}|^2$

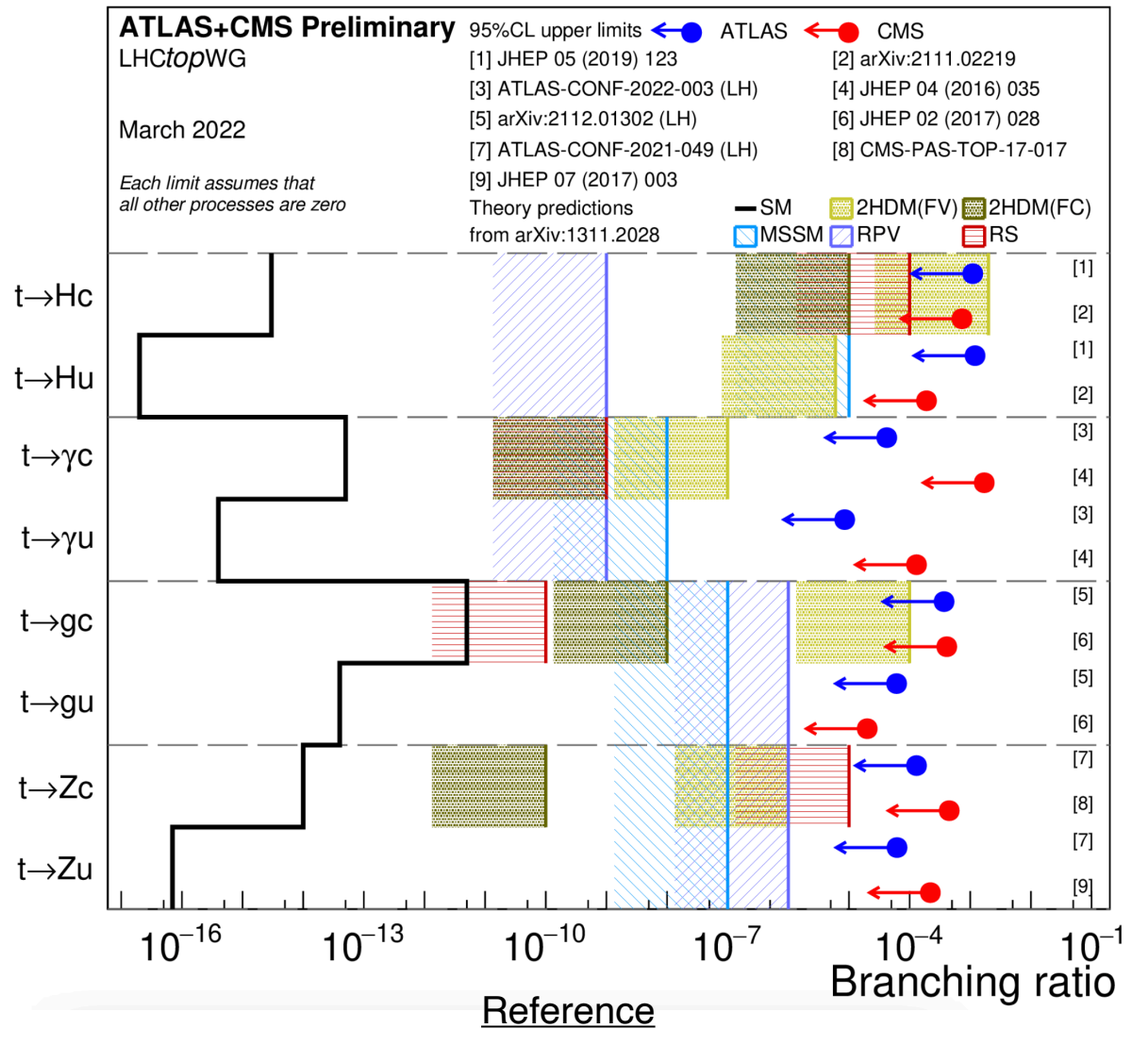
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	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}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

arXiv: 1311.2028

FCNC @ ATLAS and CMS

- Experimental searches focus on the following channels
  - *tgq, tγq, tZq, tHq*
- Production vs decay mode





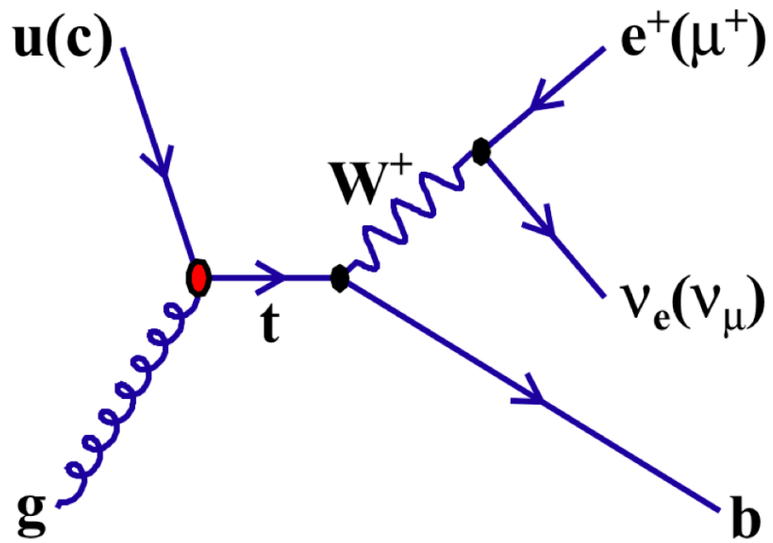
- Model independent approach

  → effective field theory

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \ldots$$

- Λ new physics energy scale (usually set to 1 TeV)
- $\mathcal{O}_i$ dimension 6 operators

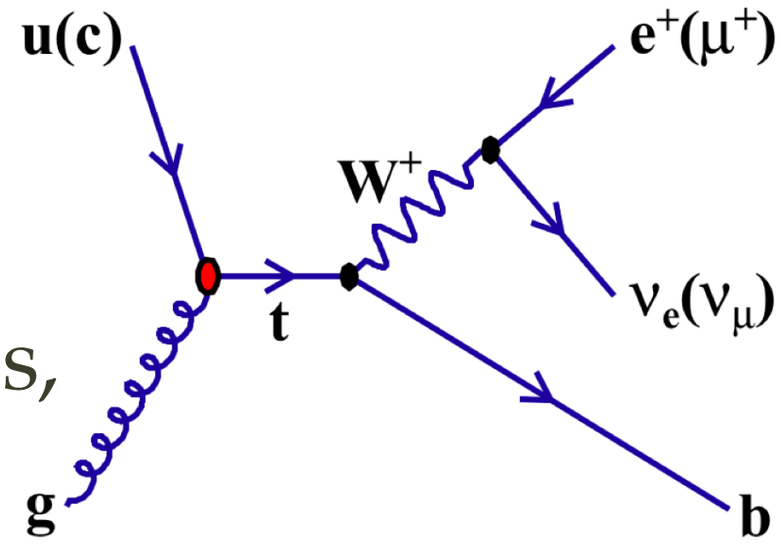
tgq



Top-gluon channel

ATLAS arXiv:2112.01302

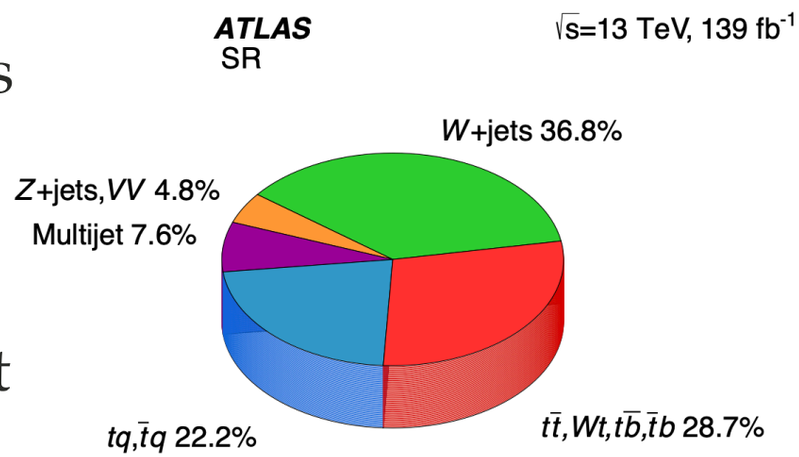
- Probes single top quark **production** via FCNC
- Reconstruct top in $t \to e/\mu\, \nu b$ final states, where $t \to \tau \nu b$ may also contribute
  - =1 lepton, ≥1 *b*-jet, $E_T^{miss} > 30$ GeV, $m_T(W) > 50$ GeV
  - Nr. of *b*-jet to define validation region, in signal region =1 *b*-jet



$$m_T(W) = \sqrt{2 p_T(\ell) E_T^{miss} \left(1 - \cos\Delta\phi\left(\ell, \vec{p}_T^{\,miss}\right)\right)}$$

- The analysis targets separate contributions from *tgu* and *tgc*
  - *Separate contributions from valence quark vs sea quark*
  - Two neural networks trained to target different signals from background
    - Target *tgc* (sea quark) signal ⇒ D_1 discriminant
    - Target *tgu* (valence quark) signal ⇒ D_2 discriminant

Discriminant distributions in backup



Results in *tqg*

ATLAS arXiv:2112.01302

- Upper limits on the production

$$\sigma(ugt) \times \mathcal{B}(t \to Wb) \times \mathcal{B}(W \to \ell\nu) < 3.0\,\text{pb} \quad \text{2.4 pb expected}$$

$$\sigma(cgt) \times \mathcal{B}(t \to Wb) \times \mathcal{B}(W \to \ell\nu) < 4.7\,\text{pb} \quad \text{2.5 pb expected}$$

$$\mathcal{B}(W \to \ell\nu) = 0.325$$

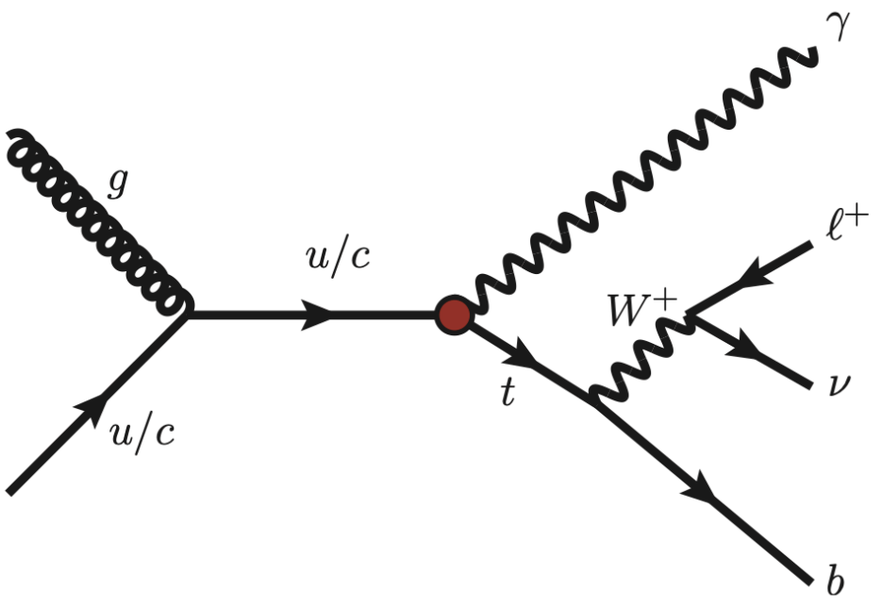
- The cross-section limits are interpreted in an EFT and converted to limits on EFT coefficients and branching ratios

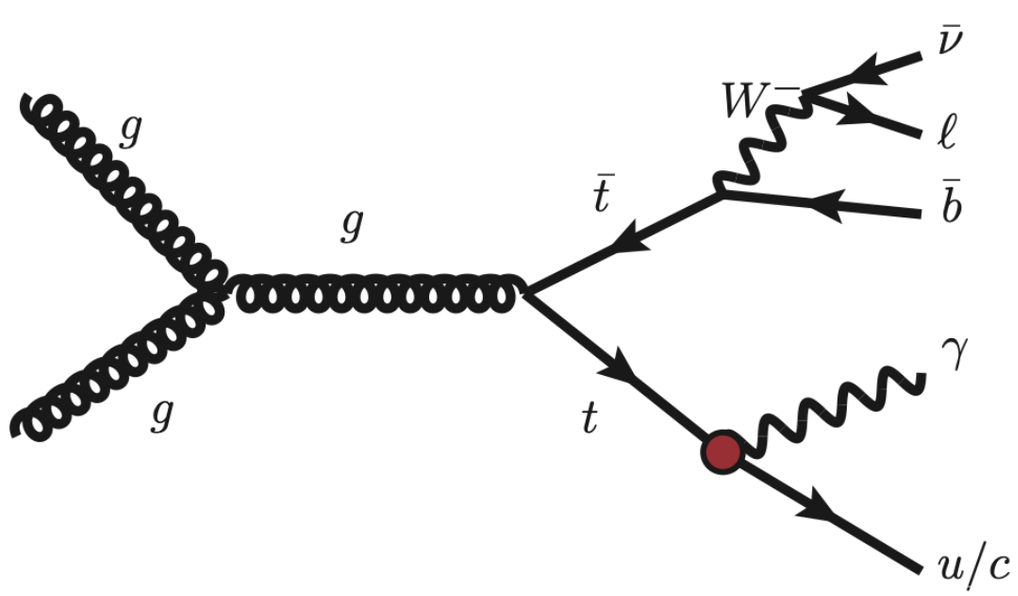
$$\frac{|C_{uG}^{ut}|}{\Lambda^2} < 0.057\,\text{TeV}^{-2} \quad \text{and} \quad \frac{|C_{uG}^{ct}|}{\Lambda^2} < 0.14\,\text{TeV}^{-2}$$

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

- **A factor of 2 improvement wrt the ATLAS 8 TeV results**

tγq

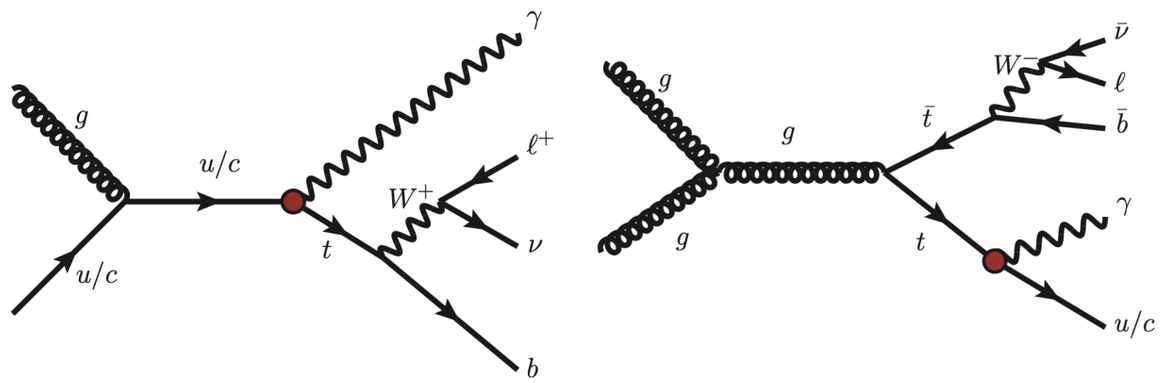


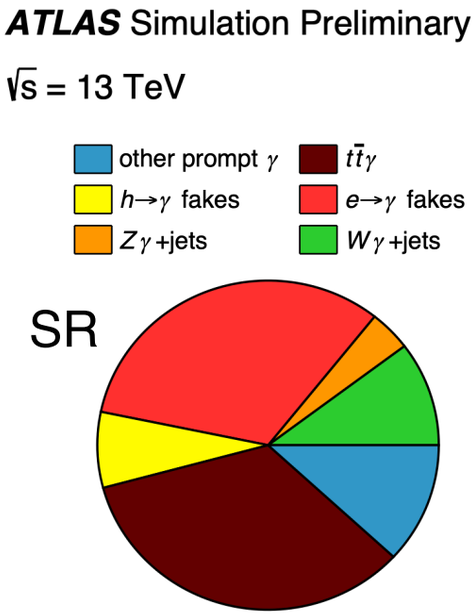


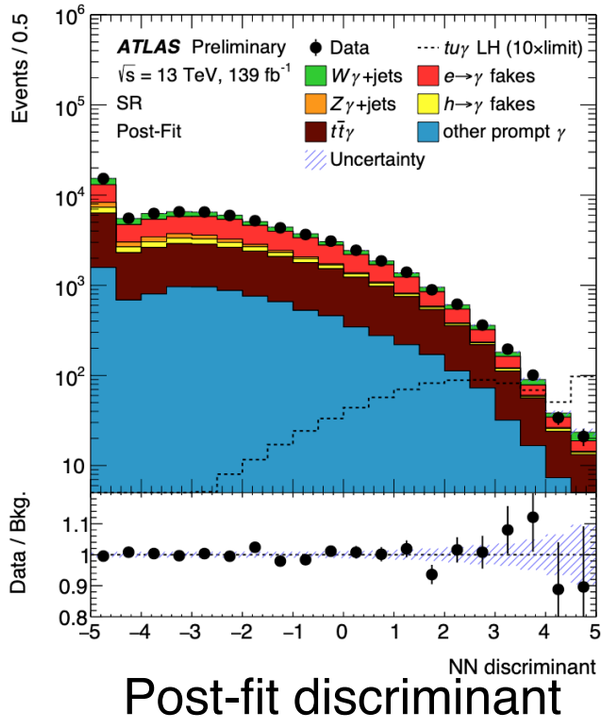
Top-photon channel

ATLAS-CONF-2022-003

- Target both **production** and **decay** of FCNC $t\gamma q$ vertices
- Background estimation
  - $e\to\gamma$: estimate a fake factor to correct simulation
  - $h\to\gamma$: transfer factor from control region
  - Others: Monte-Carlo simulation
- Two neural network targeting $tu\gamma$ and $tc\gamma$ signal separately
  - Multi-class NN to separate production mode, decay mode and background
  - Up to 30% better sensitivity than binary classifier







Post-fit discriminant

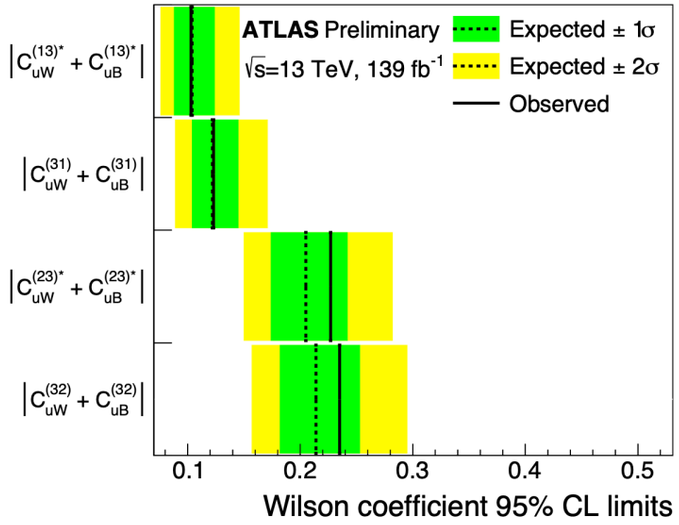
Results in *tγq*

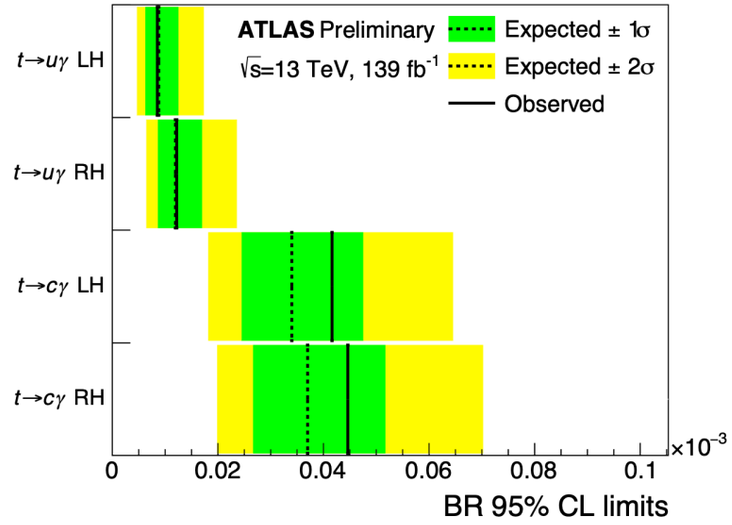
ATLAS-CONF-2022-003

- Upper limits

Effective coupling	Coefficient limits Expected	Coefficient limits Observed	Coupling	BRs $[10^{-5}]$ Expected	BRs $[10^{-5}]$ 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

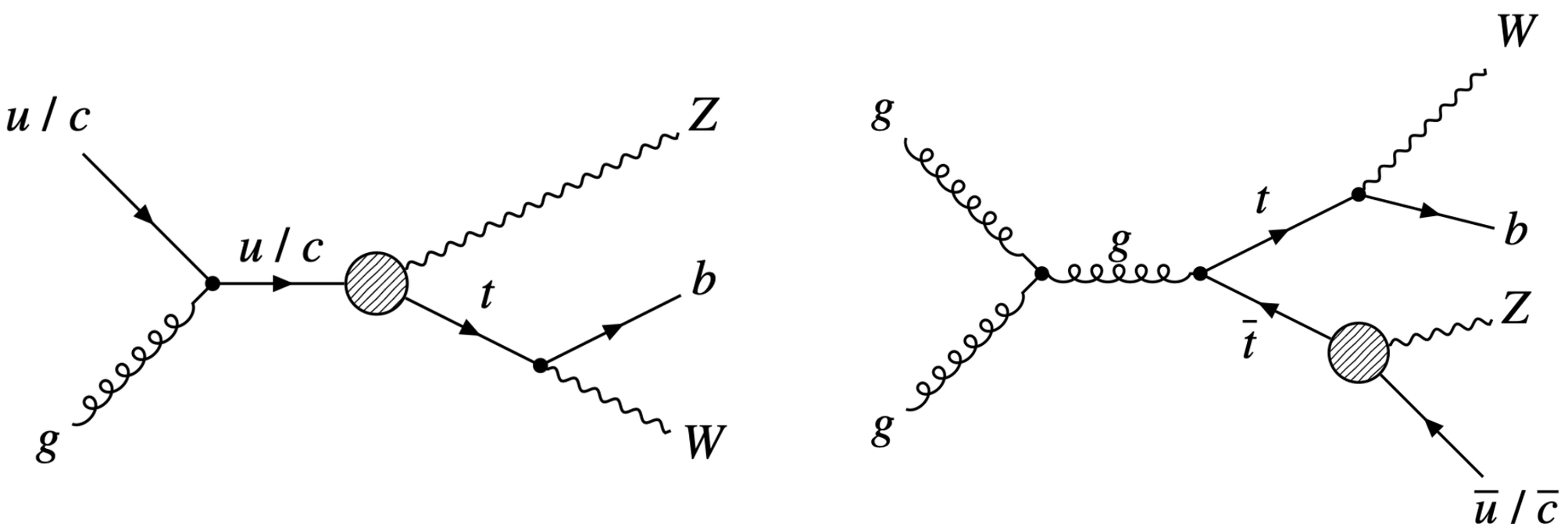
- Translated to limits on Wilson coefficients





- **3.3–5.4 times improvement wrt ATLAS 13 TeV 81 fb^{-1} results**
  - More signal region, more optimised analysis and higher luminosity

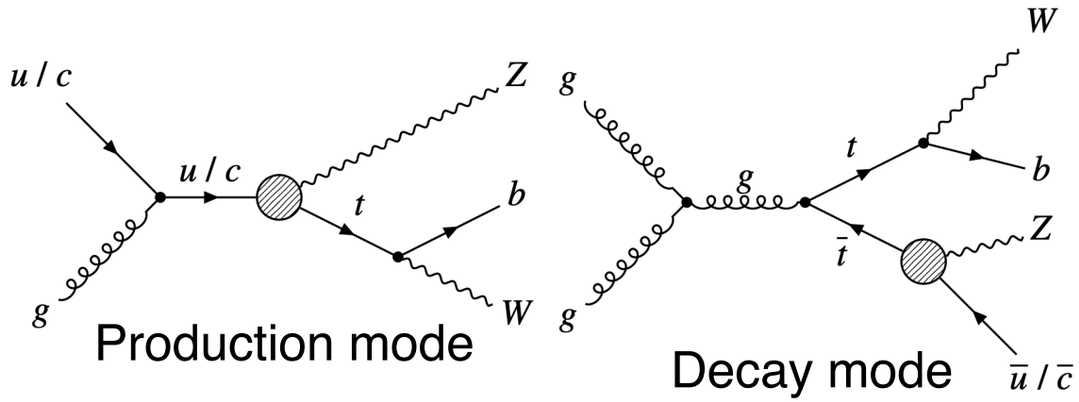
tZq



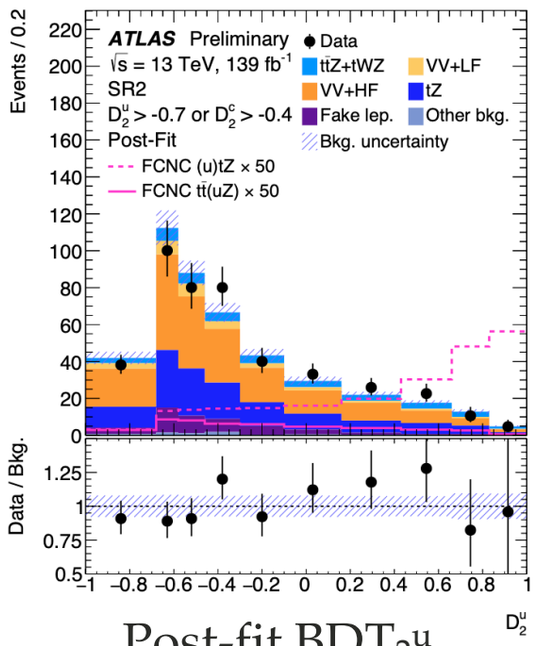
Top-Z channel

ATLAS-CONF-2021-049

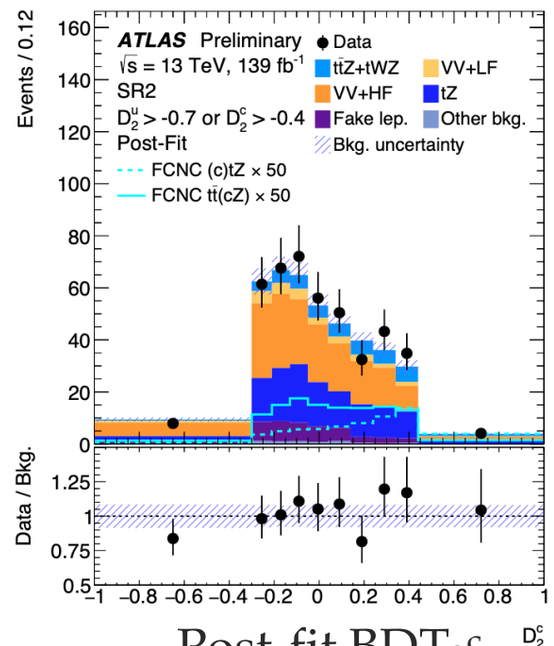
- Target both production and decay of FCNC tZq vertices
  - $Z \to \ell\ell$, semi-leptonic top decay ⇒ tri-leptons
- Analysis regions
  - ≥2 jet 1 b-jet (SR1) targeting decay mode or ≥1 jet 1 b-jet (SR2) targeting production mode
  - Orthogonality cut applied on reconstructed top mass when njet > 1
- Background estimation
  - $t\bar{t}$, $t\bar{t}Z$ yields estimated in control regions
  - VV+heavy flavour estimated in sideband regions
  - Others from MC simulation



- Separate signal against all bkg
  - BDT_1: SR1 tZu and tZc decay mode
  - BDT_2^u: SR2 tZu in production mode
  - BDT_2^c: SR2 tZc in both modes



Post-fit BDT_2^u



Post-fit BDT_2^c

Results in *tqZ*

ATLAS-CONF-2021-049

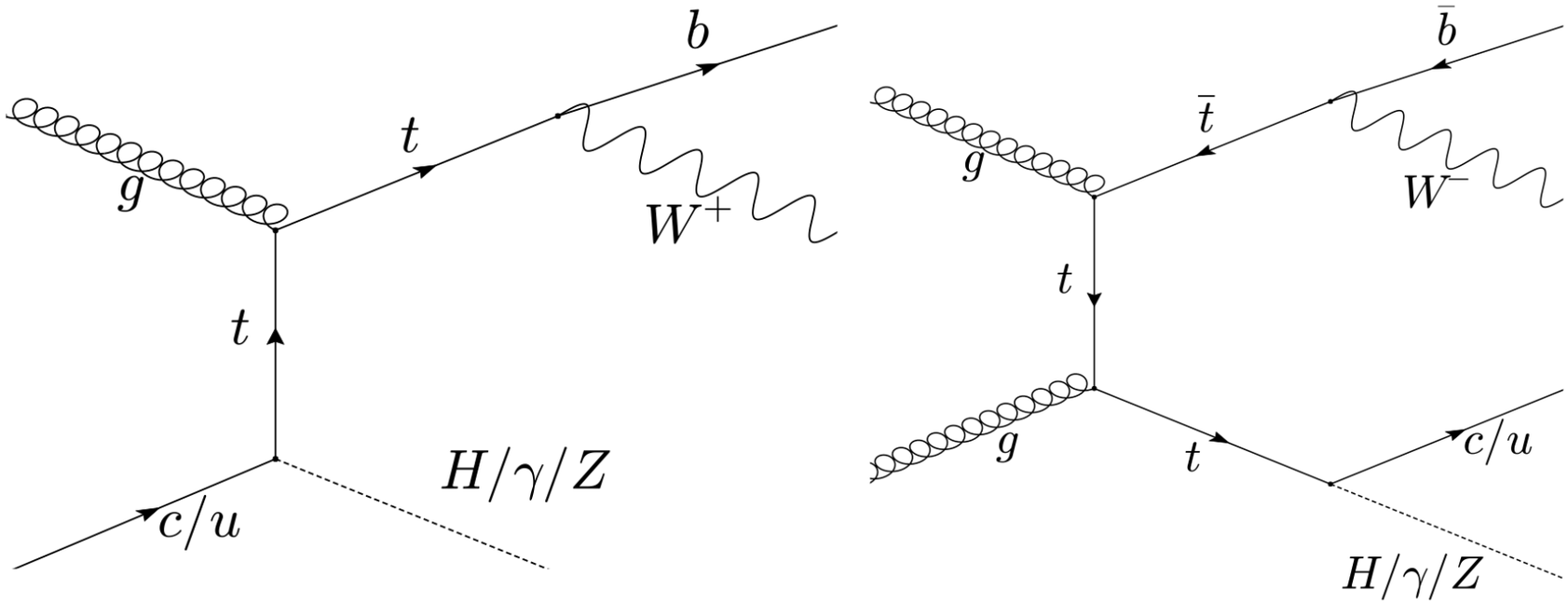
Observable	Vertex	Coupling	Observed	Expected
	SR1+CRs			
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	9.7	$8.6^{+3.6}_{-2.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.5	$8.2^{+3.4}_{-2.3}$
	SR2+CRs			
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	7.8	$6.1^{+2.7}_{-1.7}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.0	$6.6^{+2.9}_{-1.8}$
	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	$0.19^{+0.04}_{-0.03}$

LH: left hand
RH: right hand

←Higher sensitivity from SR2

- **5 (3) factors improvement on the BR of t → Zu (t → Zc)**
  - Inclusion of production mode, MVA technique, and higher luminosity

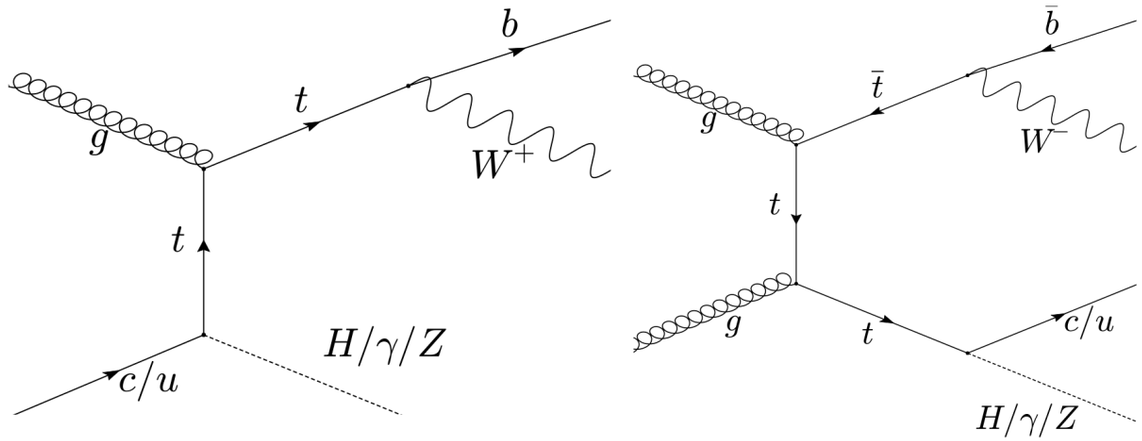
tHq



Top-Higgs channel

ATLAS-CONF-2022-014

- Explored both **production** and **decay** of FCNC *tHq* vertices
  - Top quark: leptonic or hadronic decay
  - H→ττ: $\tau_{had}\tau_{had}$ or $\tau_{lep}\tau_{had}$
- Analysis regions
  - Employ seven signal regions in a combination of top and di-tau decay, and additional jets
  - BDT is trained in each of the SR to separate signal from SM background
- Background estimation
  - Fake τ: estimate a transfer factor in control region
  - Others: Monte-Carlo simulation



Regions		b-jet	light flavour jets	lepton	hadronic taus
SR	$t_\ell\tau_{had}\tau_{had}$	1	≥ 0	1	2
	$t_\ell\tau_{had}$-1j	1	1	1	1
	$t_\ell\tau_{had}$-2j	1	2	1	1
	$t_h\tau_{lep}\tau_{had}$-2j	1	2	1	1
	$t_h\tau_{lep}\tau_{had}$-3j	1	≥ 3	1	1
	$t_h\tau_{had}\tau_{had}$-2j	1	2	0	2
	$t_h\tau_{had}\tau_{had}$-3j	1	≥ 3	0	2

Discriminant distributions in backup

Results in *tqH (ττ)*

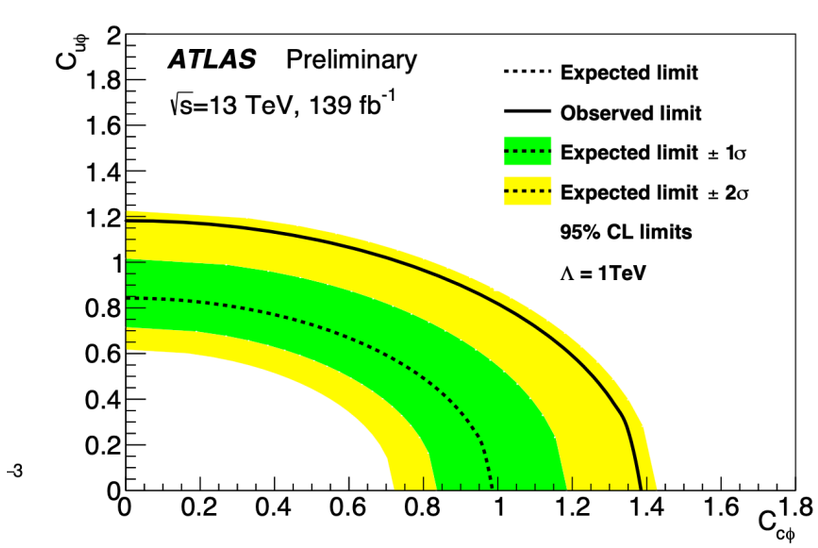
ATLAS-CONF-2022-014

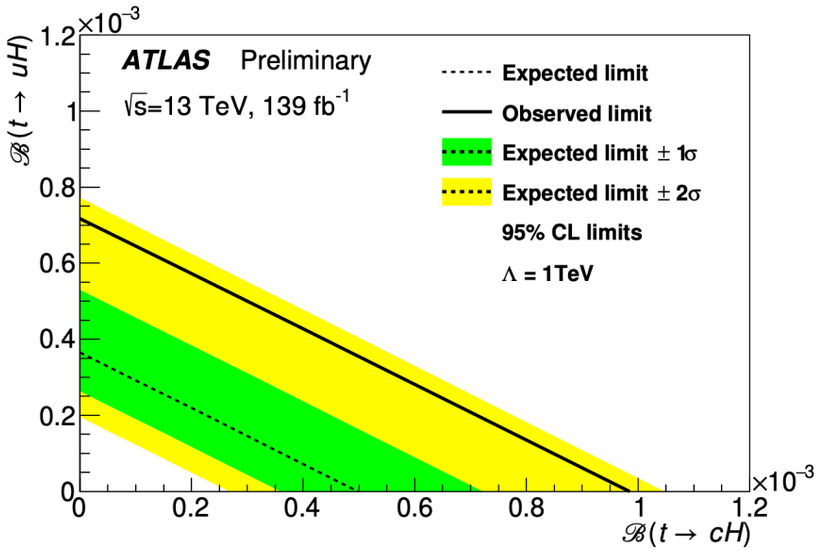
- Upper limits

$$\mathscr{B}(t \to uH) < 7.2 \times 10^{-4}\,(3.6^{+1.7}_{-1.0} \times 10^{-4}),\ \text{assuming}\ \mathscr{B}(t \to cH) = 0$$

$$\mathscr{B}(t \to cH) < 9.9 \times 10^{-4}\,(5.0^{+2.2}_{-1.4} \times 10^{-4}),\ \text{assuming}\ \mathscr{B}(t \to uH) = 0$$

  - 2D contours





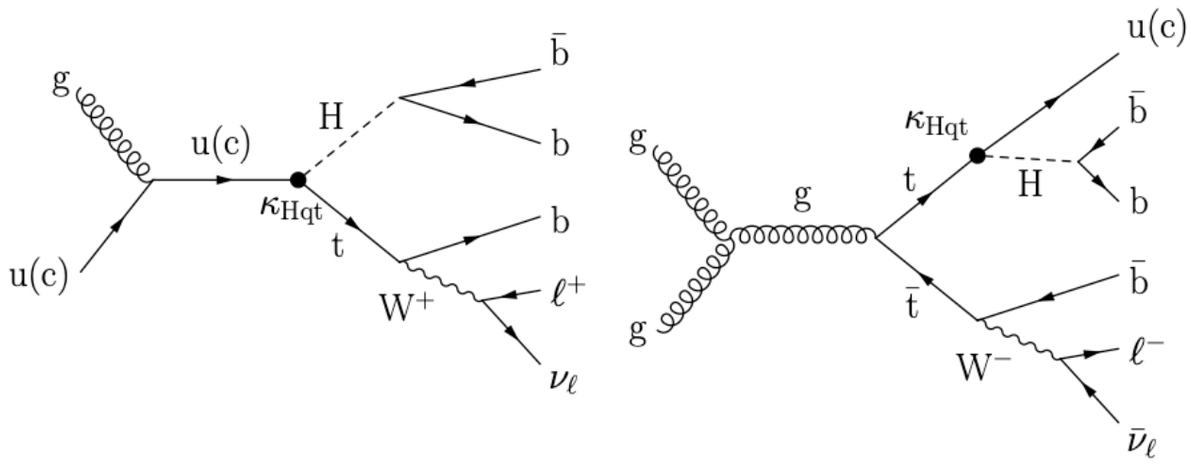
  - A slight excess of data is observed above background with a significance of 2.3 σ
  - Limits translate to *tHq* Wilson coefficients $C_{u\phi} < 1.18\,(0.83)$ $C_{c\phi} < 1.38\,(0.97)$

- A factor of 5 improvement wrt ATLAS 13 TeV 36 fb^{-1} results
  - **2.5 comes from additional SR and improved techniques**

Top-Higgs ($b\bar{b}$) channel

CMS JHEP 02 (2022) 169

- Explored FCNC tHq vertices via both production and decay
  - Top quark: leptonic or hadronic decay
  - $H \to b\bar{b}$



- Event selection
  - =1 lepton (e / μ), ≥ 3 jets, ≥ 2 b-jets
  - 5 categories

	N jets = 3	N jets ≥ 4
N b-jets = 2	✓	✓
N b-jets = 3	✓	✓
N b-jets = 4	—	✓

- 2017–2018 dataset is analysed and combined with 2016 from previous publication

- b-jet pairing
  - A neural network is trained to separate the correct and incorrect pairings
  - 82–86% efficiency in production mode and 77–79% decay mode
- A BDT is trained to separate signal from bkg

Discriminant distributions in backup

Results in *tqH(bb)*

CMS JHEP 02 (2022) 169

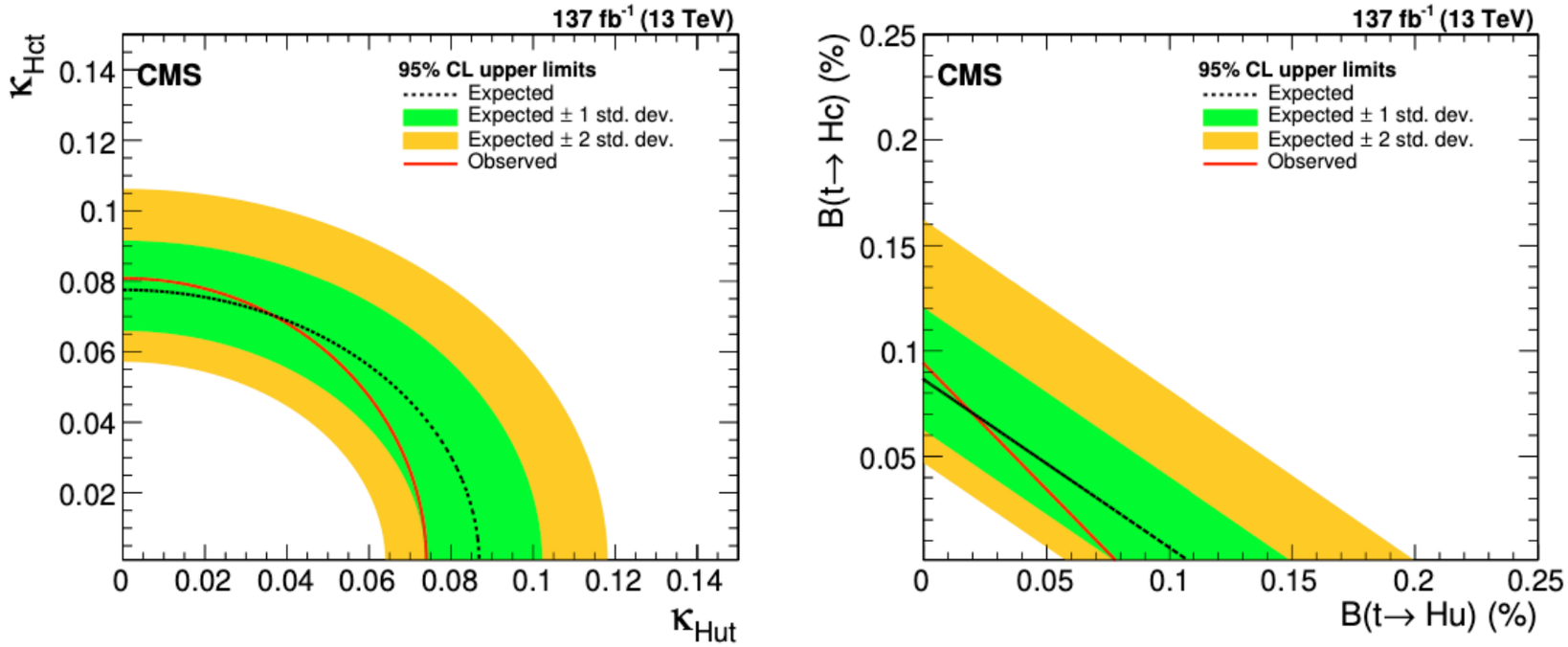
- Upper limit

$$\mathcal{B}(\mathrm{t} \to \mathrm{Hu}) < 0.079\,(0.11)\%$$

$$\mathcal{B}(\mathrm{t} \to \mathrm{Hc}) < 0.094\,(0.086)\%$$

Assuming the other branching ratio at zero

  - 2D contours

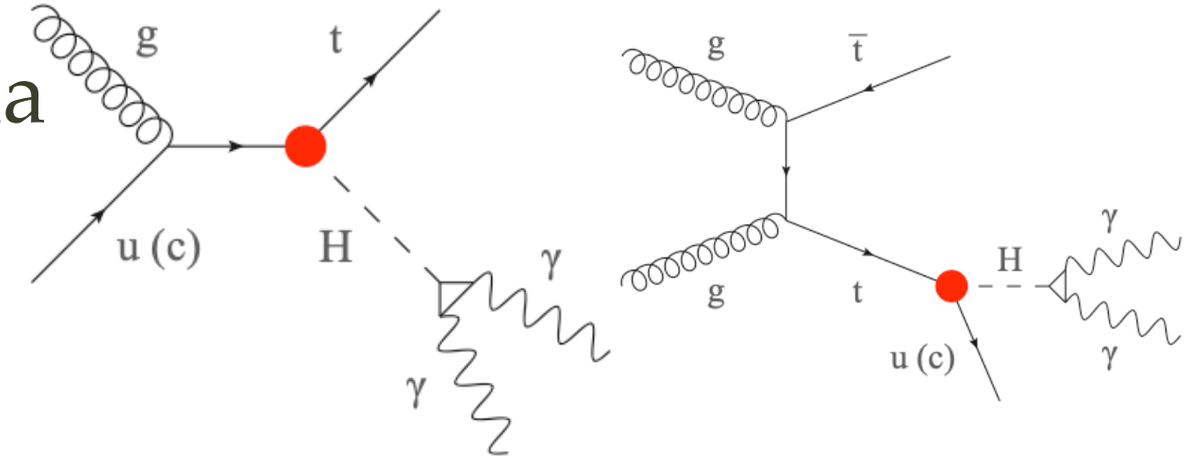


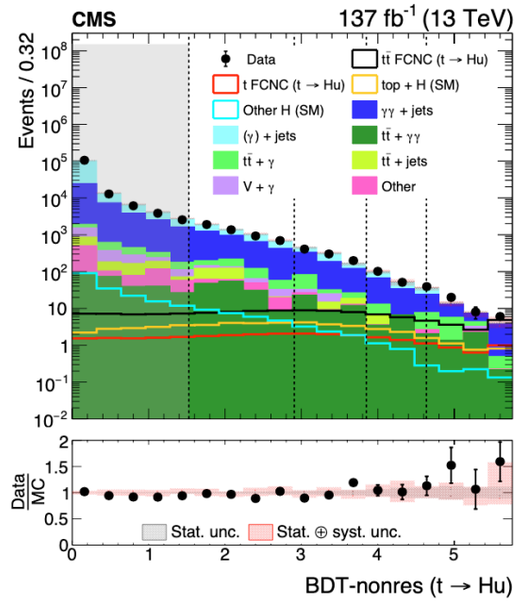
- Most sensitivity comes from b3j4 category due to suppression of SM $t\bar{t}$.

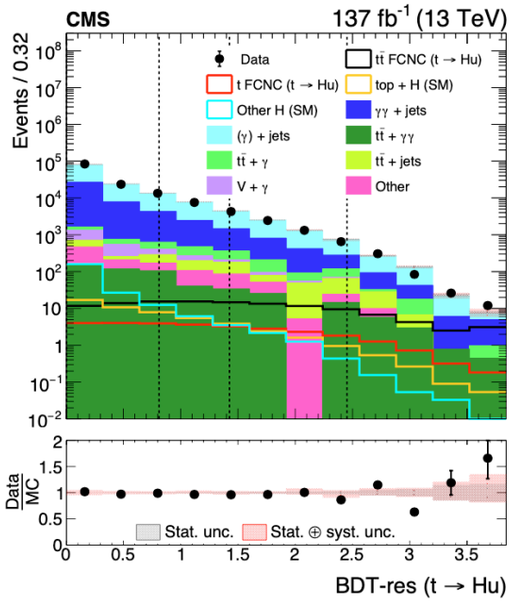
Top-Higgs ($\gamma\gamma$) channel

CMS arXiv: 2111.02219

- Explored FCNC tHq vertices via both production and decay
  - Top quark: leptonic or hadronic decay
  - $H \to \gamma\gamma$
- Event selection
  - Leptonic channel: =1 lepton, ≥ 1 jet
  - Hadronic channel: =0 lepton, ≥ 3 jets, ≥ 1 *b*-jet
- Signal and bkg separation
  - 8 BDTs: *tHu* vs *tHc*, leptonic vs hadronic channels, resonant vs non-resonant $\gamma\gamma$ bkg
  - BDT scores used to categorise events



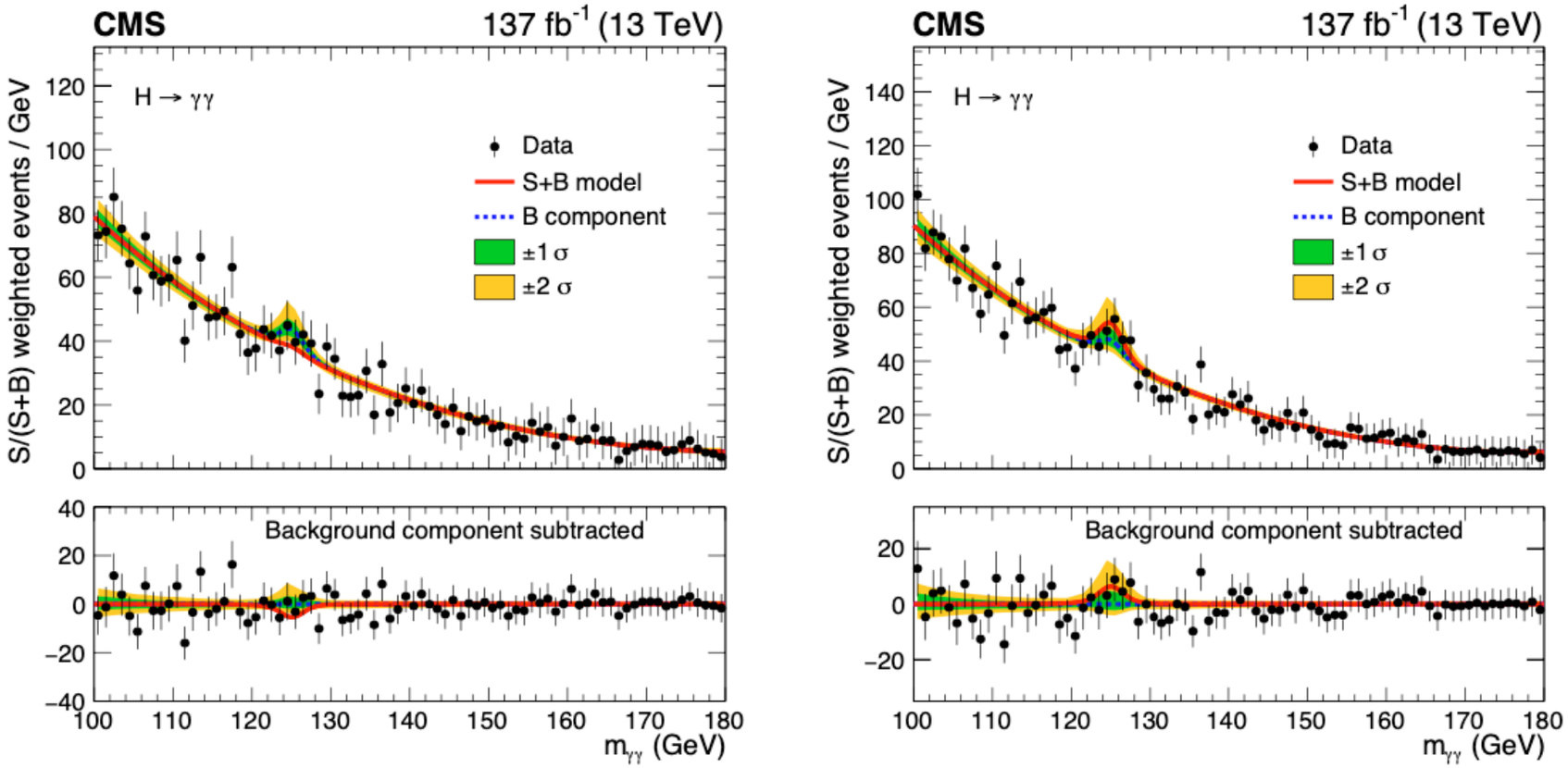




Results in *tqH(γγ)*

CMS arXiv: 2111.02219

- Discriminant: $m_{\gamma\gamma}$
  - Combined over all categories



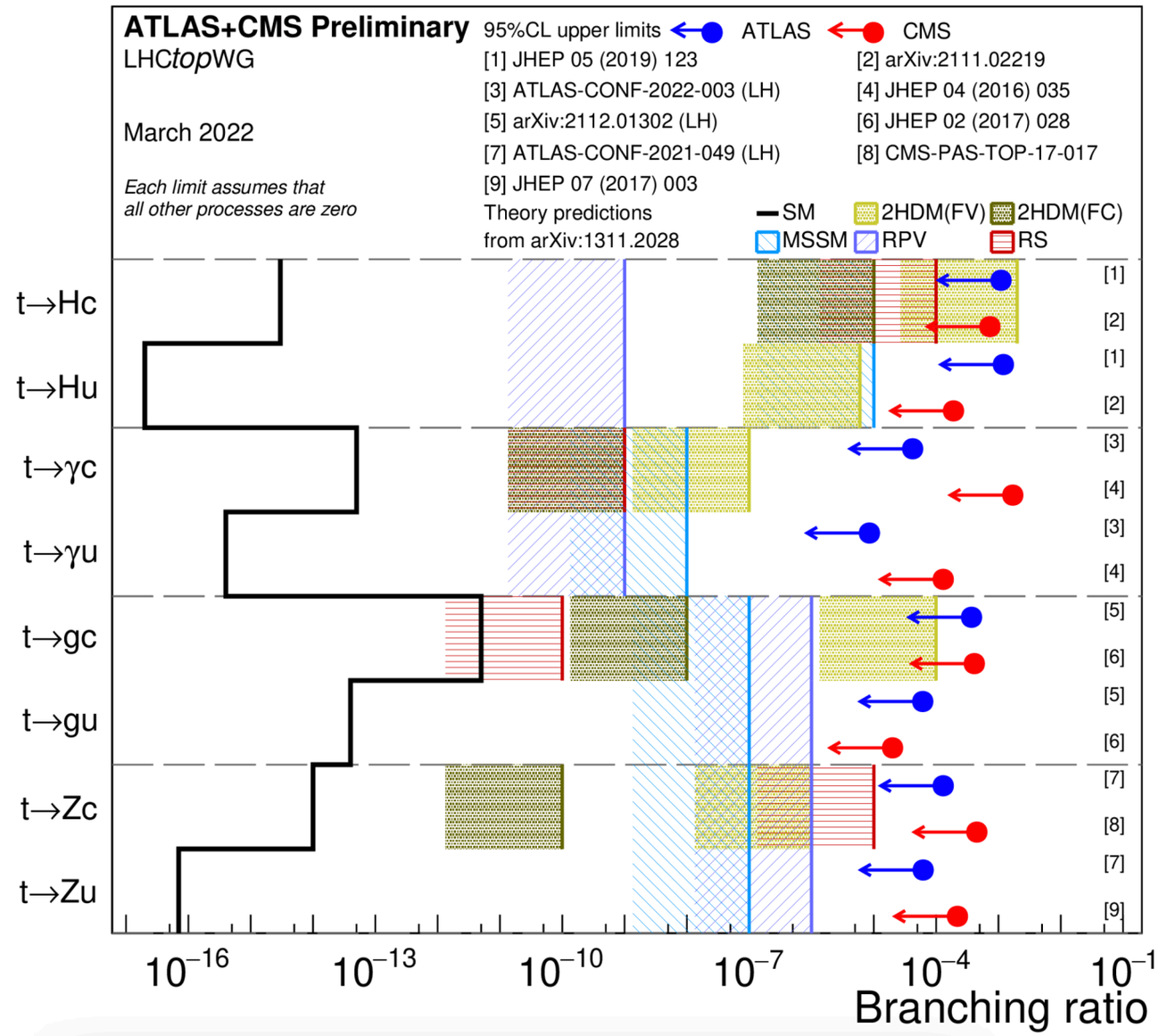
- Upper limit

$$0.019\,(0.031)\%\ \text{for}\ \mathcal{B}(\mathrm{t} \to \mathrm{Hu})$$

$$0.073\,(0.051)\%\ \text{for}\ \mathcal{B}(\mathrm{t} \to \mathrm{Hc})$$

Summary

- A lot of activities on ATLAS and CMS probing FCNC vertices with top quark — tZq, $t\gamma q$, tgq, tHq signatures
  - Including EFT interpretations



	ATLAS	CMS	
		(bb)	$(\gamma\gamma)$
$(\tau\tau)$	9.9×10^{-4}	9.4×10^{-4}	7.3×10^{-4}
	7.2×10^{-4}	7.9×10^{-4}	1.9×10^{-4}
LH	4.16×10^{-4}		
LH	0.85×10^{-4}		
LH	3.7×10^{-4}		
LH	0.61×10^{-4}		
LH	1.3×10^{-4}		
LH	0.62×10^{-4}		

Stay tuned

Backup

Top-gluon channel

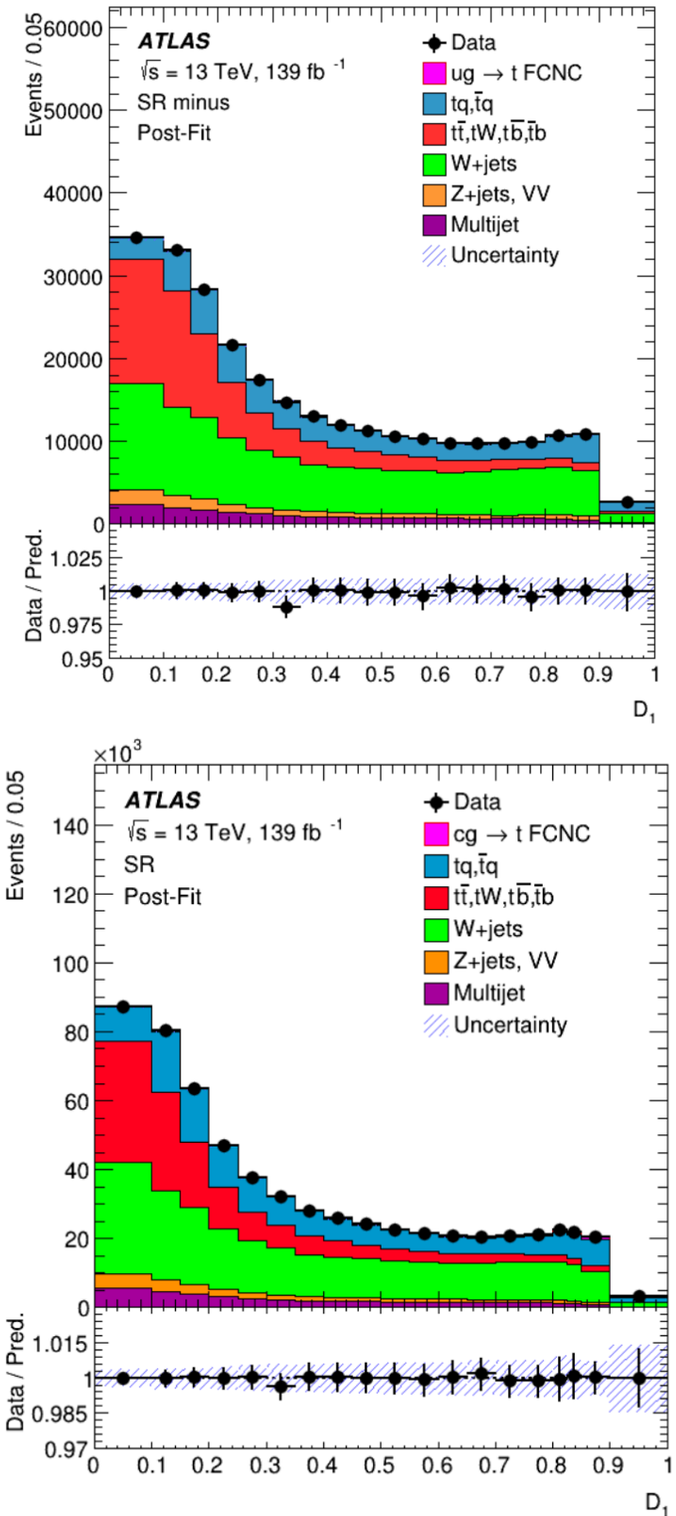
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2018-06/

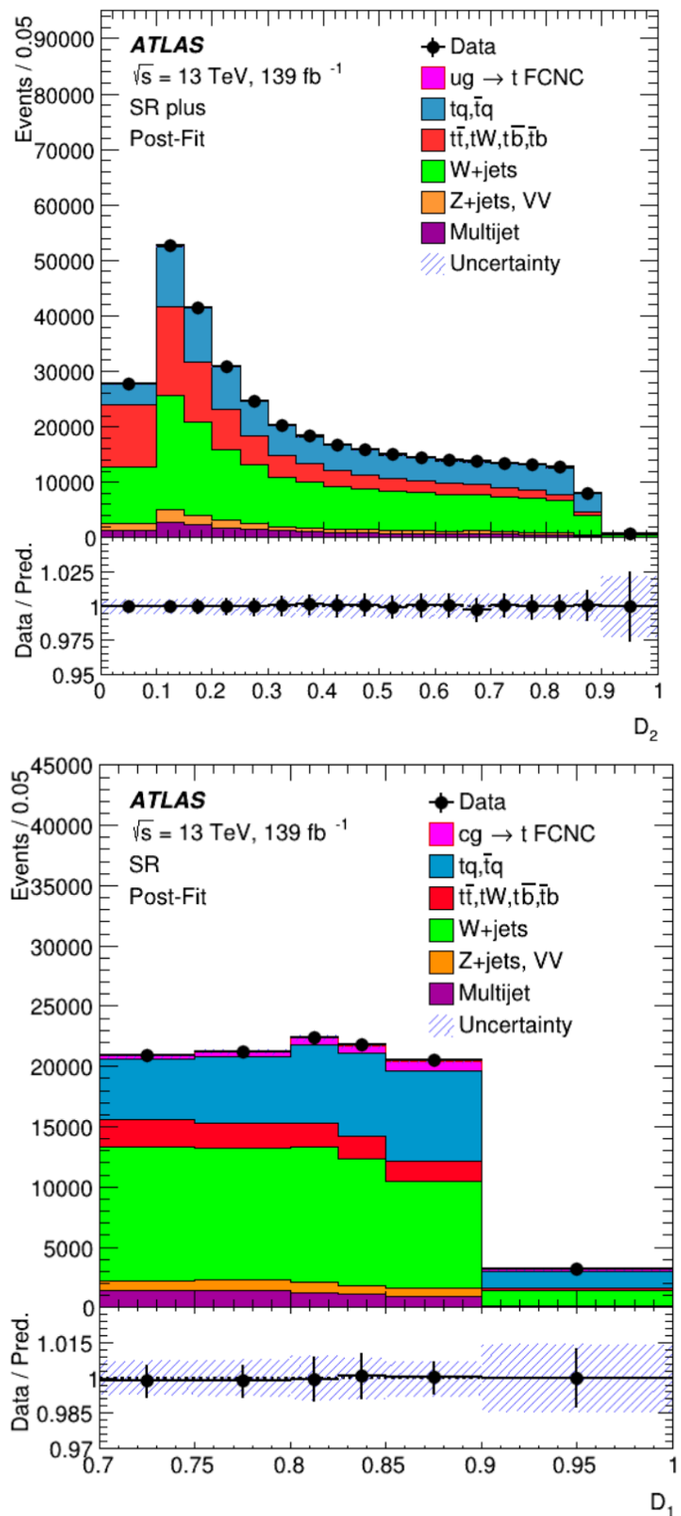
Observable	Common requirements
$n_{\text{Tight}}(e) + n_{\text{Medium}}(\mu)$	$= 1$
$n_{\text{Loose}}(e) + n_{\text{Loose}}(\mu)$	$= 1$
$E_{\text{T}}^{\text{miss}}$	$> 30\,\text{GeV}$
$m_{\text{T}}\,(W)$	$> 50\,\text{GeV}$
$n(j)$	≥ 1
$p_{\text{T}}\,(\ell)$	$> 50\,\text{GeV} \cdot \left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$

	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	$= 1$
$D_{1(2)}$	–	$0.3 < D_{1(2)} < 0.6$	–	$0.2 < D_{1(2)} < 0.4$

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}

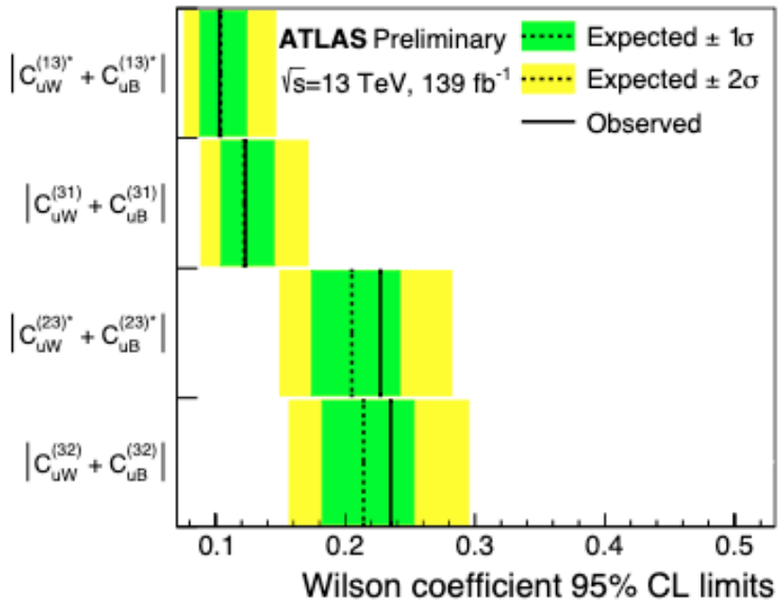
Top-gluon channel — postfit discriminant





tyq

Top-photon channel — yields



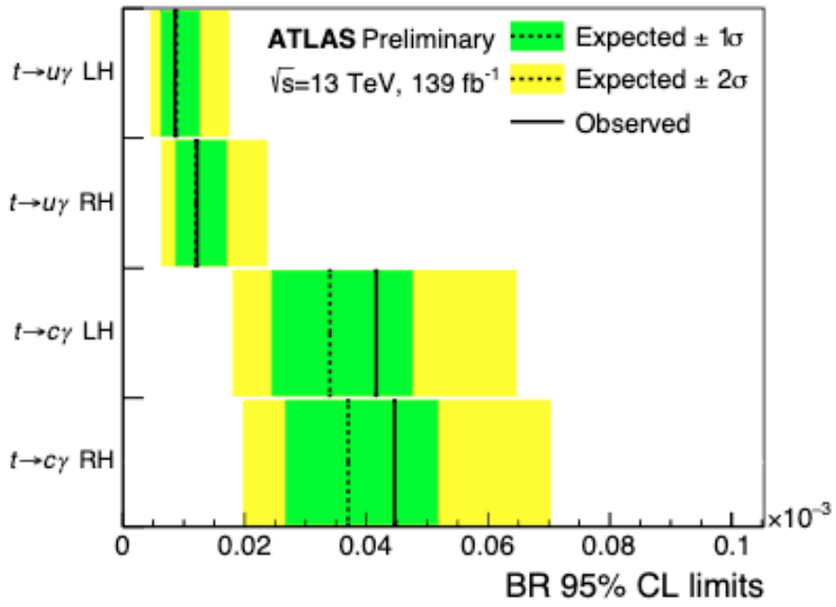


Figure 5: The 95% CL limits on the effective coupling constants (left) and BRs (right). The expected (observed) limits are shown with the dotted (solid) lines. The green (yellow) bands represent one (two) standard deviations for the limits. The scale of new physics is set to $\Lambda = 1$ TeV.

Table 2: The 95% CL limits on the effective coupling constants and BRs. The expected limits with their uncertainties, representing one standard deviation, as well as observed limits are shown. The scale of new physics is set to $\Lambda = 1$ TeV.

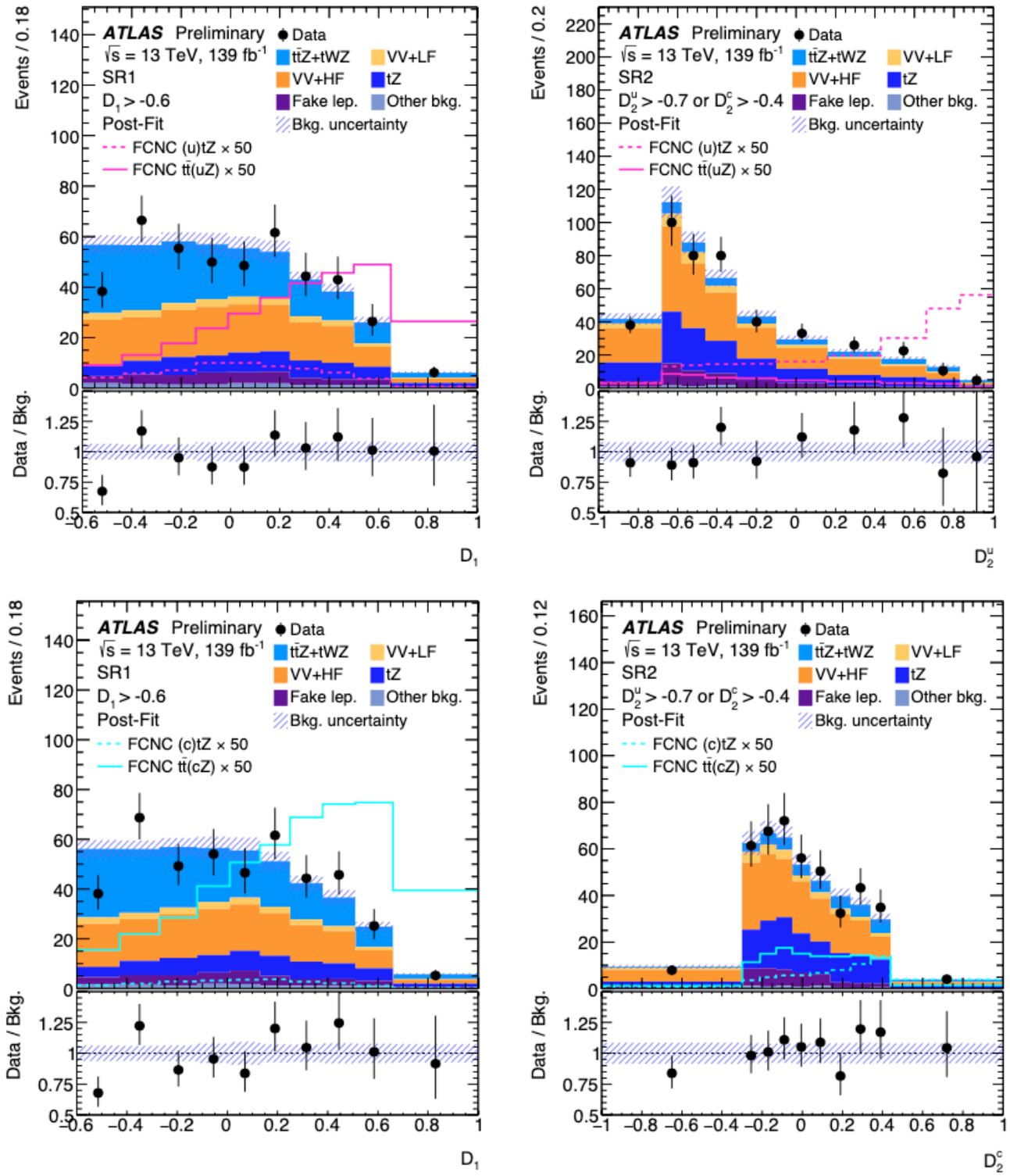
Effective coupling	Coefficient limits		Coupling	BRs $[10^{-5}]$	
	Expected	Observed		Expected	Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ 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

Top-Z channel — yields

Table 5: Predicted and observed yields in the two SRs considered in the fit. The signal and background predictions are shown after the fit to data for the FCNC tZu LH coupling extraction. The quoted uncertainties include the statistical and systematic uncertainties of the yields, computed taking into account correlations among nuisance parameters and among processes. For the backgrounds with a non-prompt or fake lepton, the contribution from $t\bar{t} + tW$ is shown separately from 'Other fakes'. For the minor backgrounds, the contribution from $t\bar{t}W$ and $t\bar{t}H$ are shown separately from 'Other 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 + LF	18 ± 7	24 ± 8
VV + 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

Top-Z channel — discriminant



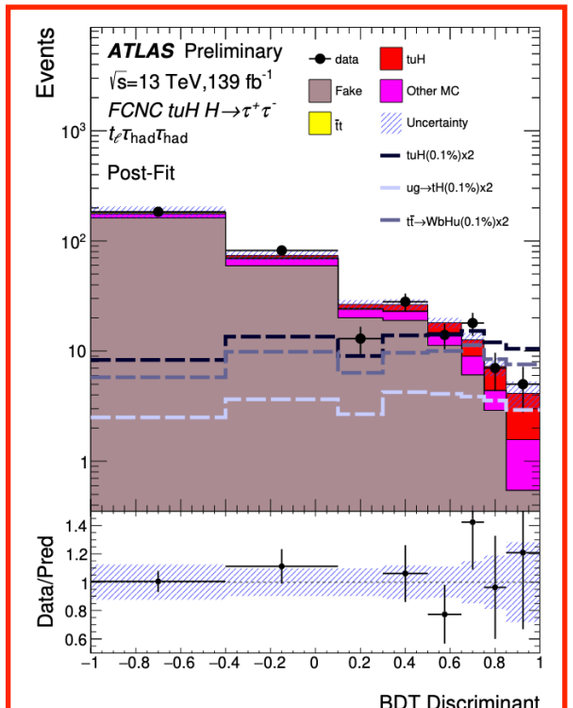
tHq

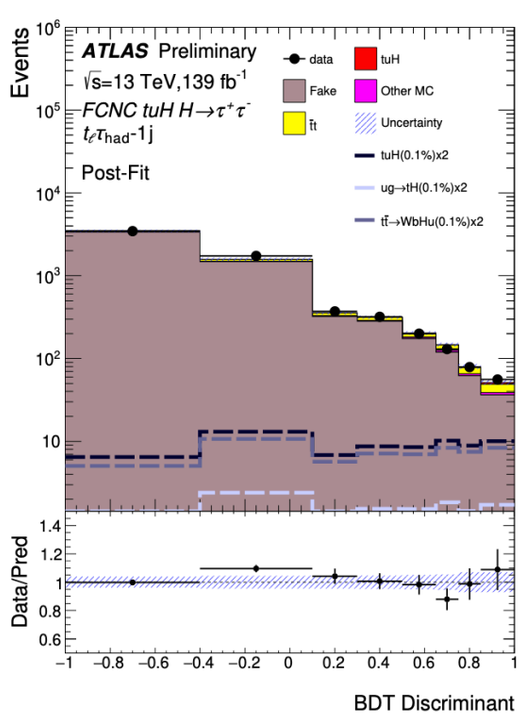
Top-Higgs channel — region definition

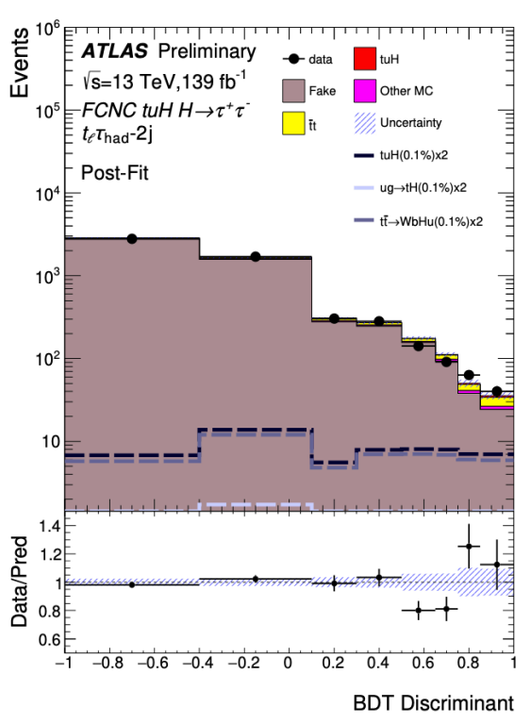
Regions		b-jet	light flavour jets	lepton	hadronic taus	charge
SR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_\ell\tau_{\text{had}}$-1j	1	1	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell\tau_{\text{had}}$-2j	1	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	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
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

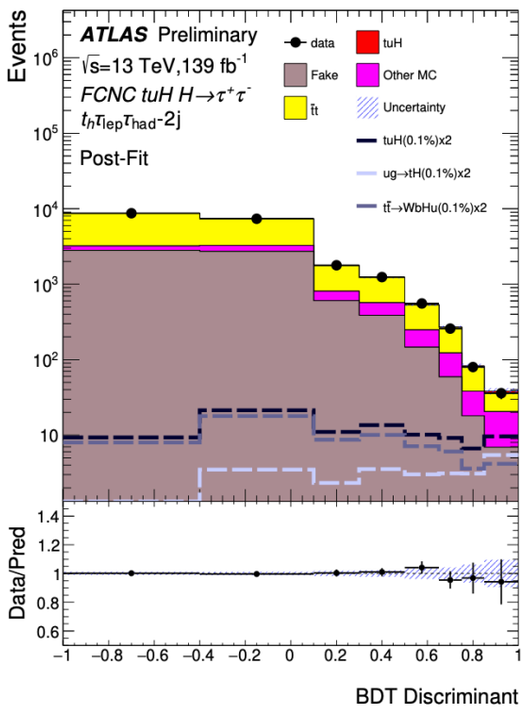
Top-Higgs channel — *tuH* postfit

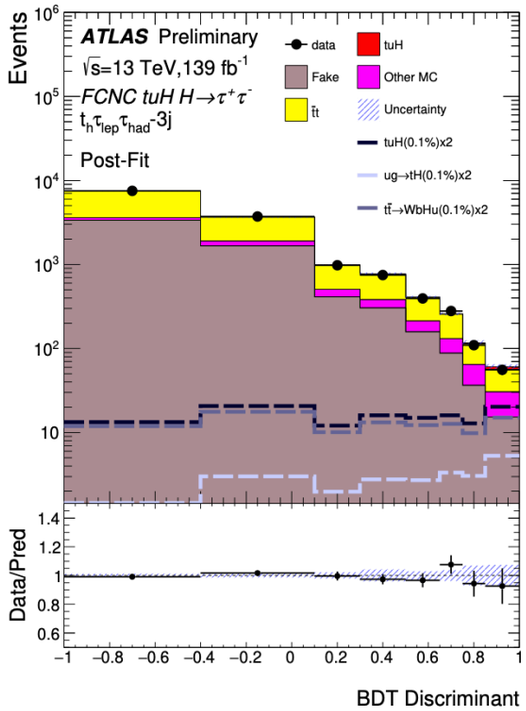
Contribute most to the slight excess

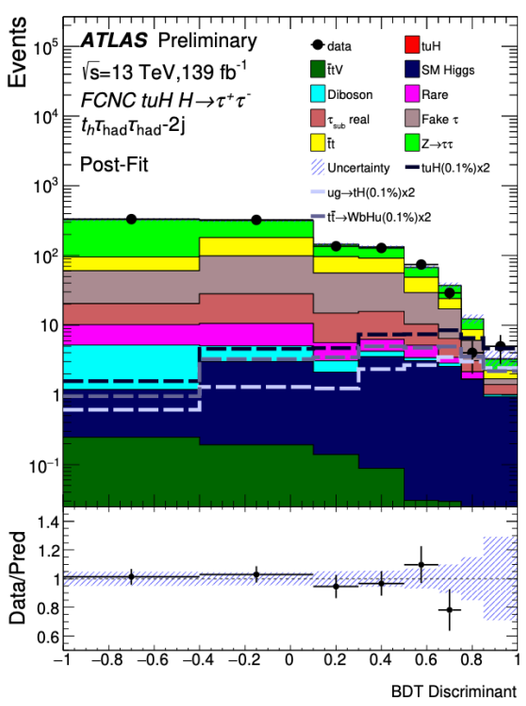


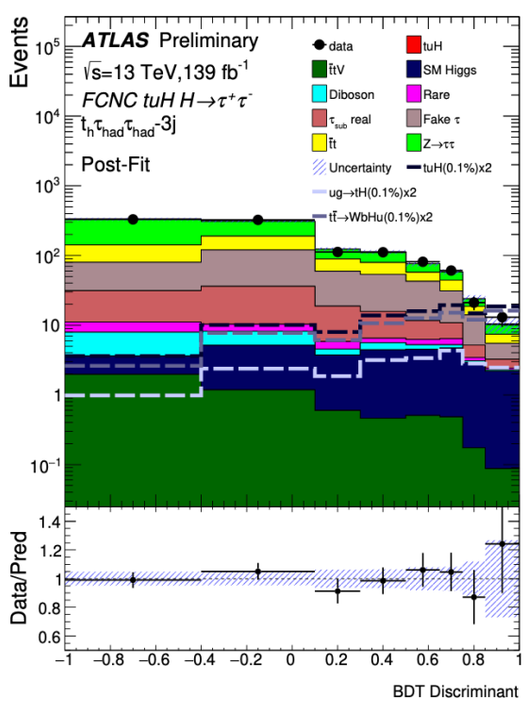






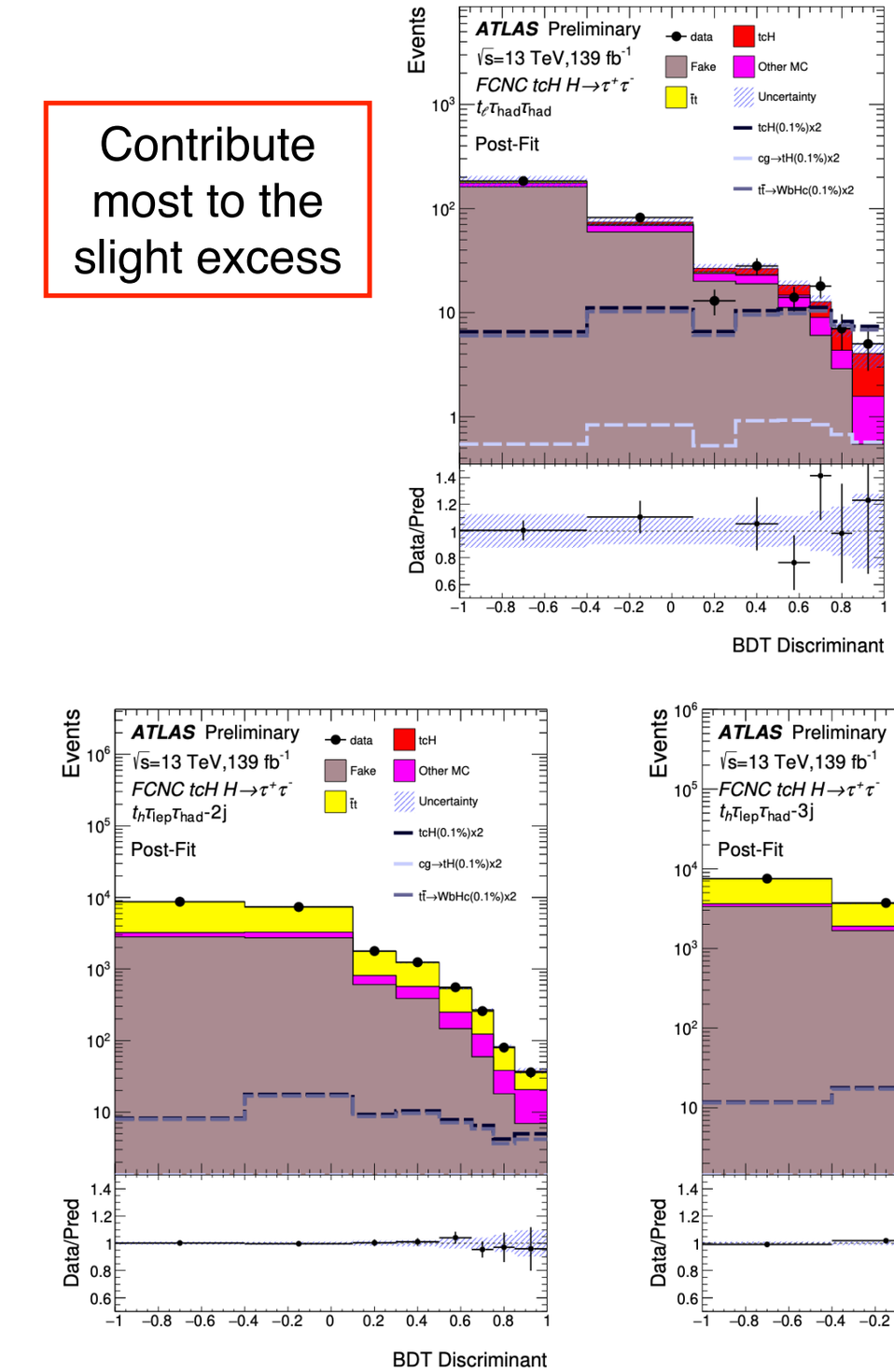




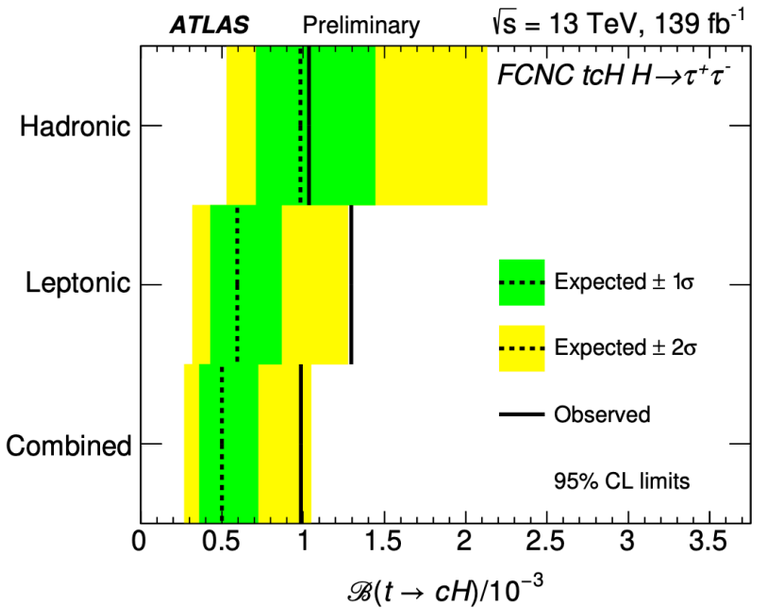


Top-Higgs channel — *tcH* postfit

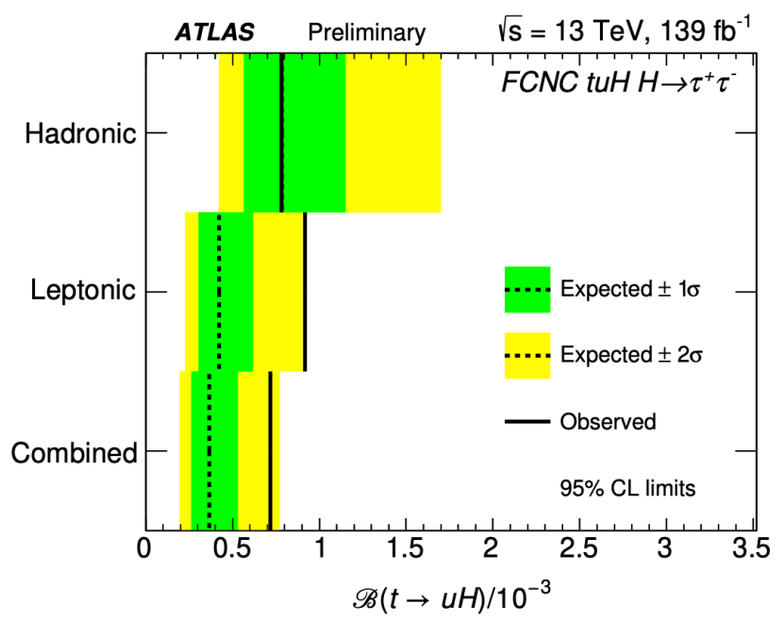
Contribute most to the slight excess



Top-Higgs channel — sensitivity



Assuming Br($t \to uH$) = 0



Assuming Br($t \to cH$) = 0

Table 8: Summary of 95% CL upper limits on $\mathscr{B}(t \to cH)$ and $\mathscr{B}(t \to uH)$, significance and best-fit branching ratio in signal regions with a benchmark branching ratio of $\mathscr{B}(t \to qH) = 0.1\%$. Expected significance is obtained from Asimov fit with a signal injection corresponding to a branching ratio of 0.1%.

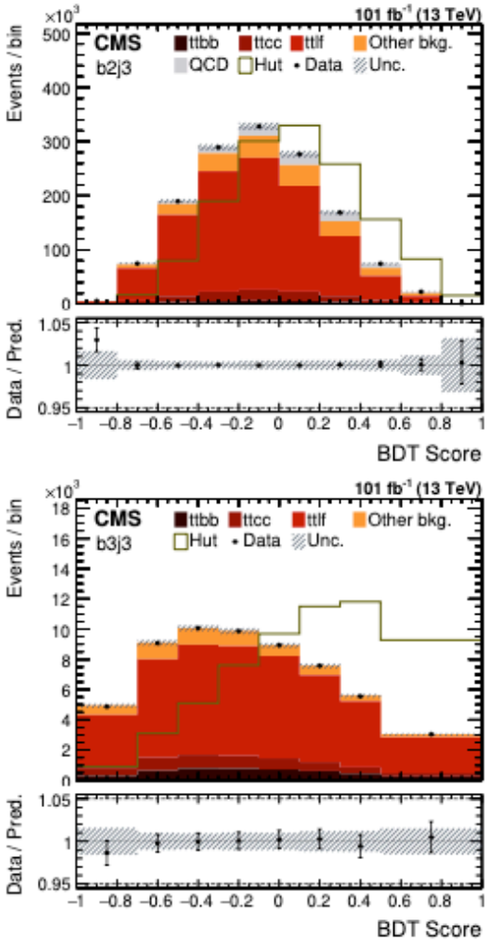
Signal Regions	$t \to cH$ 95% CL upper limits[10^{-3}] Observed (Expected)	$t \to cH$ Significance	$t \to cH$ $\mathscr{B}$[10^{-3}]	$t \to uH$ 95% CL upper limits[10^{-3}] Observed (Expected)	$t \to uH$ Significance	$t \to uH$ $\mathscr{B}$[10^{-3}]
$t_h\tau_{had}\tau_{had}$-2j	$1.85(2.80^{+1.30}_{-0.78})$	$-0.96(0.78)$	$-1.03^{+1.04}_{-1.04}$	$1.10(1.65^{+0.79}_{-0.46})$	$-0.90(1.25)$	$-0.55^{+0.59}_{-0.59}$
$t_h\tau_{had}\tau_{had}$-3j	$1.18(1.06^{+0.50}_{-0.30})$	$0.34(1.87)$	$0.16^{+0.47}_{-0.47}$	$1.00(0.89^{+0.42}_{-0.25})$	$0.36(2.13)$	$0.14^{+0.40}_{-0.40}$
Hadronic Combination	$1.04(0.98^{+0.46}_{-0.28})$	$0.26\ (1.99)$	$0.11^{+0.43}_{-0.43}$	$0.78(0.78^{+0.37}_{-0.22})$	$0.11(2.33)$	$0.04^{+0.34}_{-0.34}$
$t_l\tau_{had}$-2j	$4.86(4.32^{+1.89}_{-1.21})$	$0.40(0.48)$	$0.81^{+2.04}_{-2.04}$	$3.93(3.55^{+1.56}_{-0.99})$	$0.34(0.58)$	$0.57^{+1.66}_{-1.66}$
$t_l\tau_{had}$-1j	$3.94(3.67^{+1.66}_{-1.03})$	$0.24(0.57)$	$0.40^{+1.70}_{-1.70}$	$3.10(2.87^{+1.29}_{-0.80})$	$0.24(0.73)$	$0.31^{+1.33}_{-1.33}$
$t_h\tau_{lep}\tau_{had}$-2j	$4.81(5.85^{+2.90}_{-1.63})$	$-0.52(0.39)$	$-1.36^{+2.56}_{-2.56}$	$2.56(3.05^{+1.38}_{-0.85})$	$-0.48(0.69)$	$-0.66^{+1.38}_{-1.38}$
$t_h\tau_{lep}\tau_{had}$-3j	$2.78(2.79^{+1.36}_{-0.78})$	$-0.04(0.76)$	$-0.04^{+1.26}_{-1.26}$	$2.07(2.09^{+0.94}_{-0.58})$	$-0.05(0.98)$	$-0.04^{+0.98}_{-0.98}$
$t_l\tau_{had}\tau_{had}$	$1.41(0.63^{+0.29}_{-0.18})$	$2.64(3.24)$	$0.74^{+0.34}_{-0.34}$	$1.01(0.45^{+0.21}_{-0.13})$	$2.64(4.08)$	$0.53^{+0.25}_{-0.25}$
Leptonic Combination	$1.29(0.59^{+0.27}_{-0.17})$	$2.59(3.34)$	$0.68^{+0.32}_{-0.32}$	$0.92(0.42^{+0.19}_{-0.12})$	$2.59(4.23)$	$0.48^{+0.23}_{-0.23}$
Combination	$0.99\ (0.50^{+0.22}_{-0.14})$	$2.34(3.69)$	$0.51^{+0.25}_{-0.25}$	$0.72\ (0.36^{+0.17}_{-0.10})$	$2.31(4.49)$	$0.37^{+0.18}_{-0.18}$

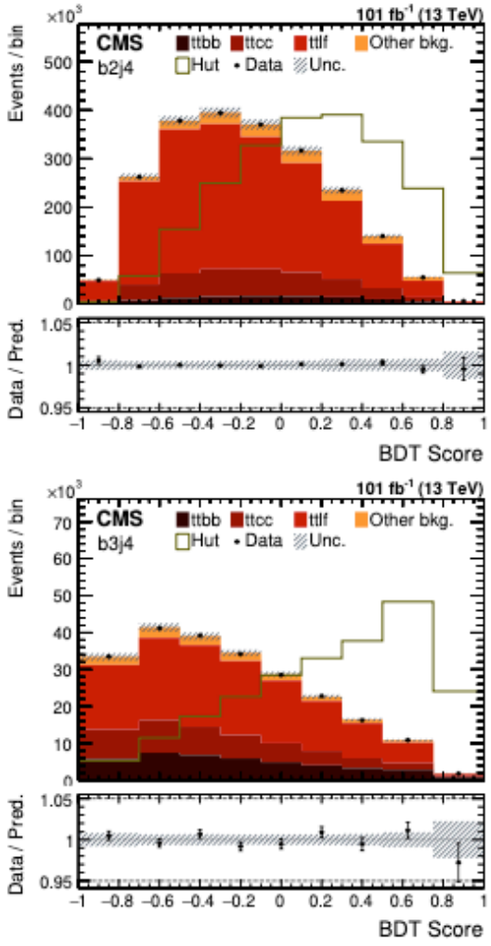
Top-Higgs channel — postfit unc.

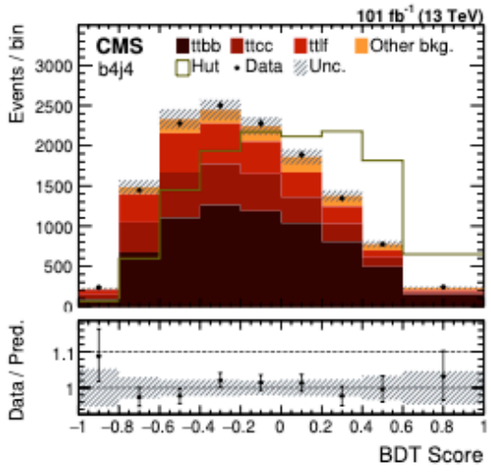
Source of uncertainty	$\Delta\mathcal{B}$ [10^{-5}]	
	$t \to uH$	$t \to cH$
Lepton ID	0.6	1.0
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.7	0.8
Fake lepton modeling	0.9	1.1
JES and JER	2.4	3.2
Flavour tagging	2.7	3.7
$t\bar{t}$ modeling	2.9	4.3
Other MC modeling	2.1	2.9
Fake τ modeling	3.2	4.6
Signal modeling including Br($H \to \tau\tau$)	5.3	7.0
τ ID	3.3	4.4
Luminosity and Pileup	0.9	1.3
MC statistics	5.1	7.0
Total systematic uncertainty	11.2	15.5
Data statistical uncertainty	14.1	19.6
Total uncertainties	18	25

Top-H(*bb*) channel — postfit BDT

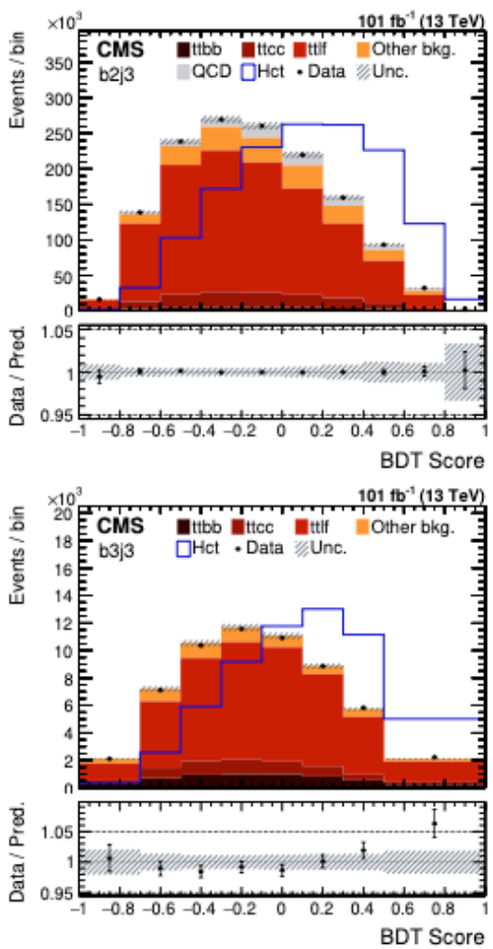
tuH

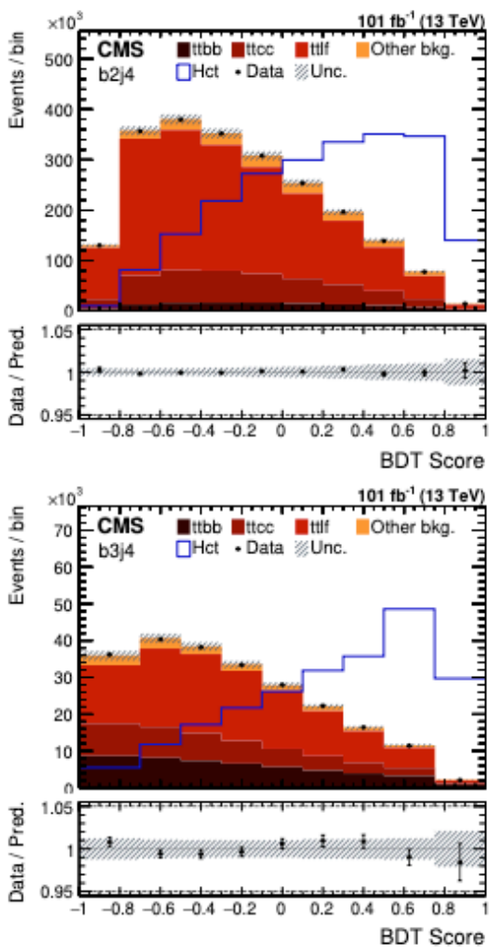


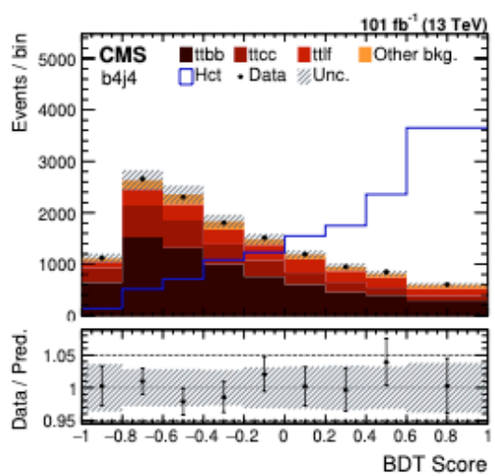




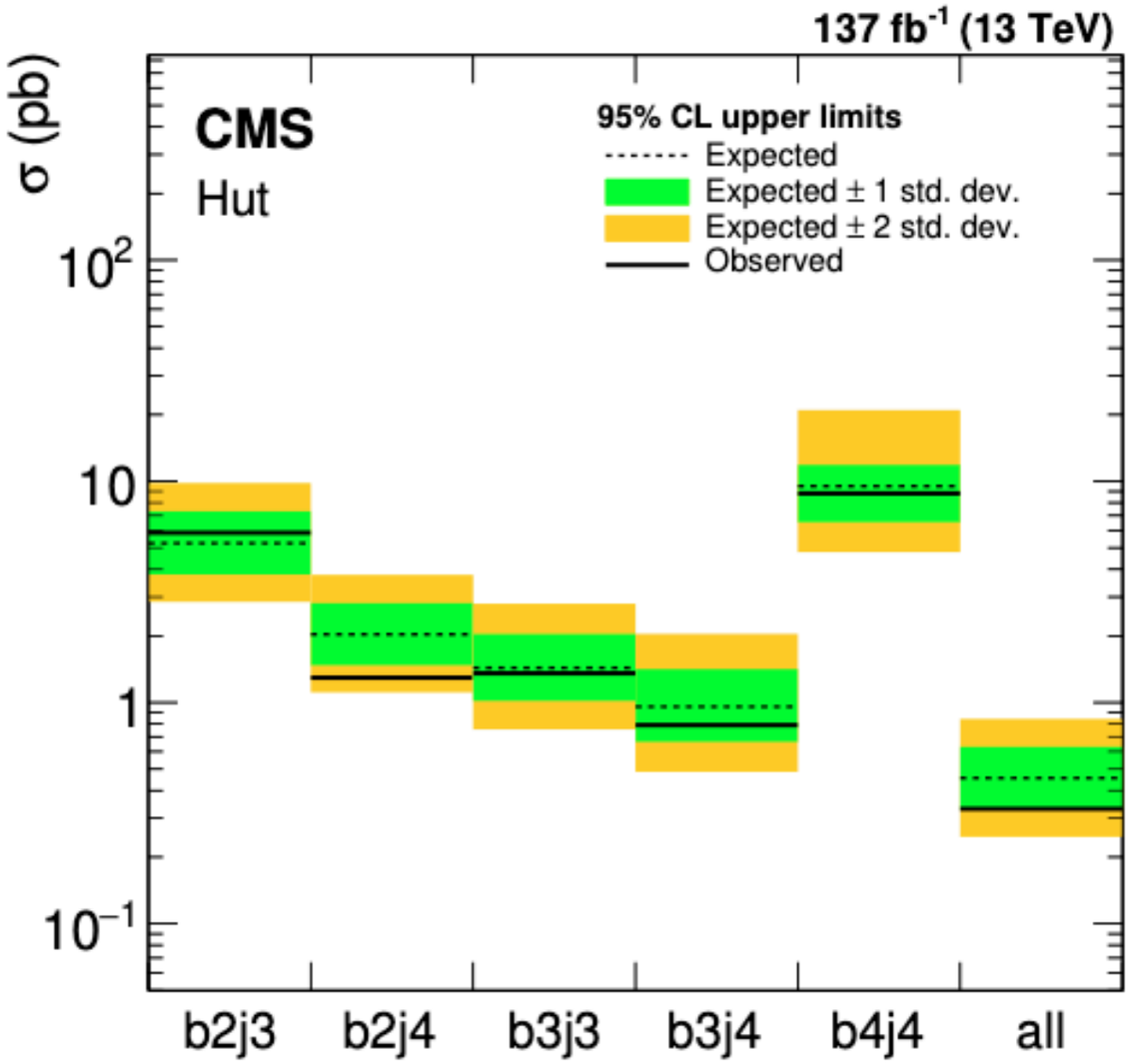
tcH

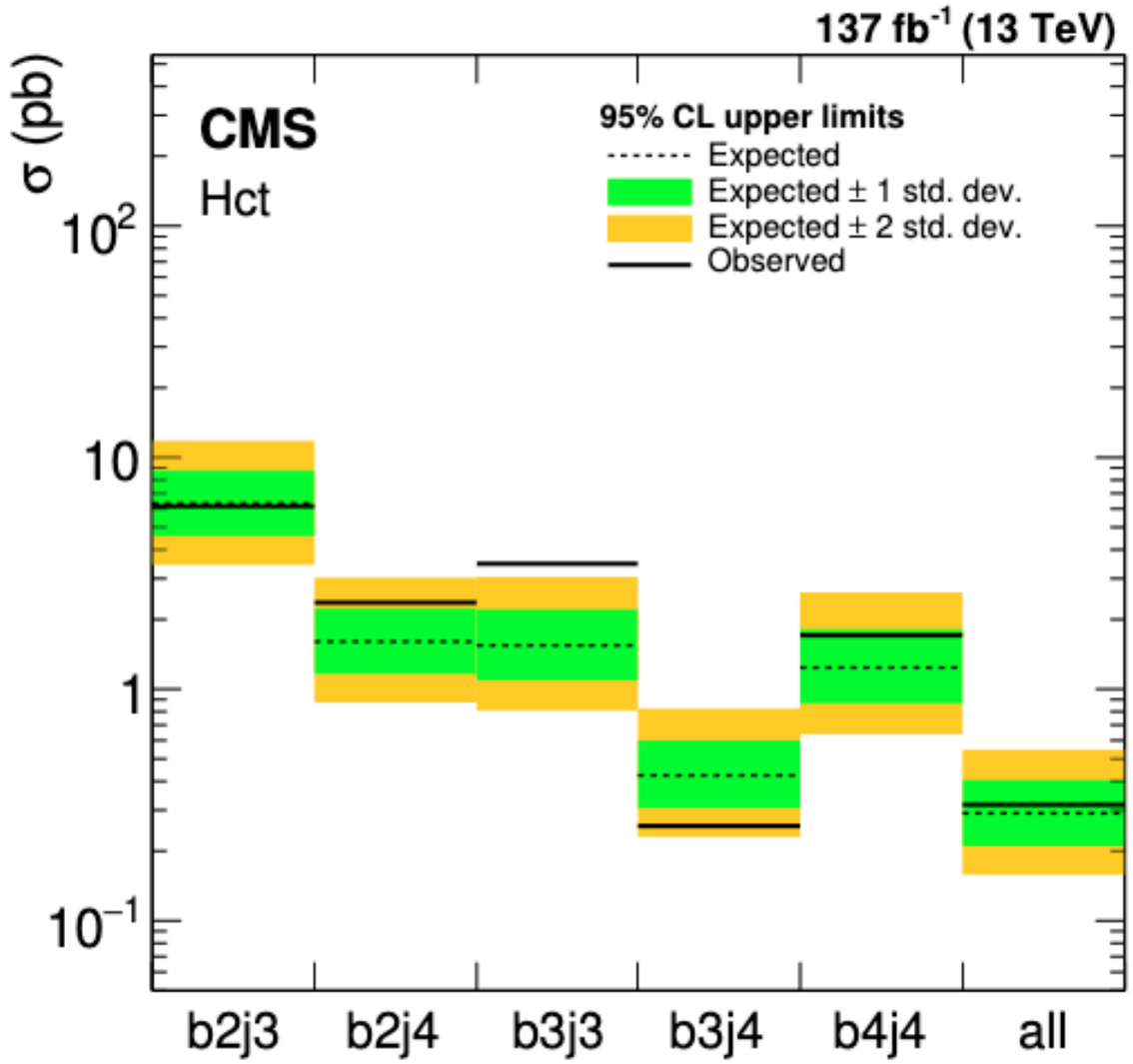






Top-H(*bb*) channel





Top-H($\gamma\gamma$) channel