



Universidade do Minho  
Escola de Ciências



LABORATÓRIO DE INSTRUMENTAÇÃO  
E FÍSICA EXPERIMENTAL DE PARTÍCULAS  
*partículas e tecnologia*

# Rare production and decay processes in the top quark sector

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10<sup>th</sup> conference on Large Hadron Collider Physics - LHCP 2022  
virtual world, May 19<sup>th</sup> 2022

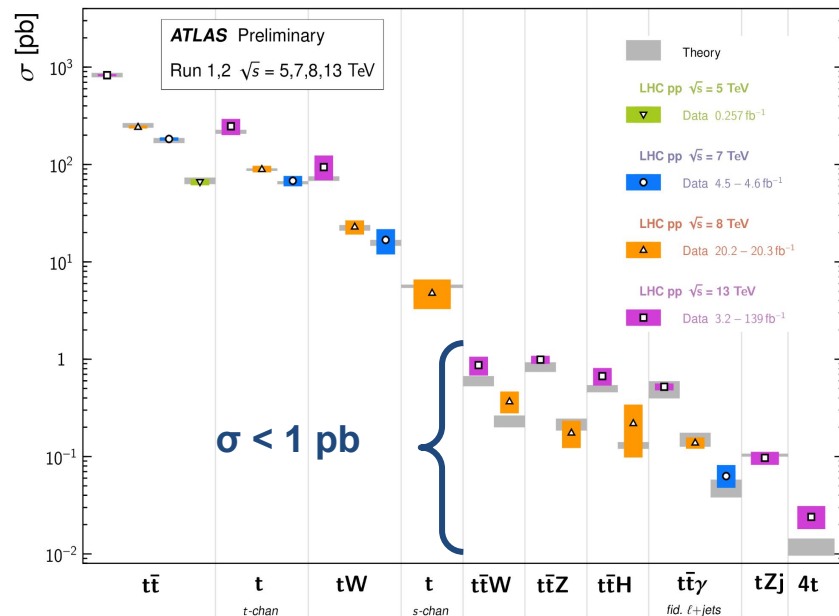
# Rare processes in the top quark sector

## Measurements: testing the SM

- Top is now in the precision era
  - approaching the fb frontier
    - important tests of the SM
  - rare processes (e.g.  $t\bar{t}+X$ ) are now important backgrounds for measurements and searches
  - precision and differential measurements
  - pushing the theory limits
    - modelling of rare top processes

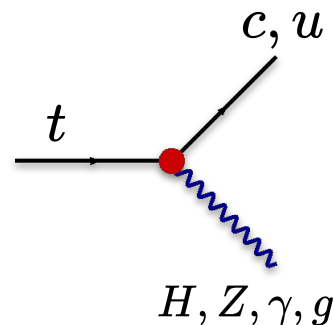
Top Quark Production Cross Section Measurements

Status: March 2022



# Rare processes in the top quark sector

## Searches: top FCNCs as a window to BSM



- FCNC interactions in the top quark are **extremely rare** in the SM
  - but can be **significantly enhanced** in BSM extensions

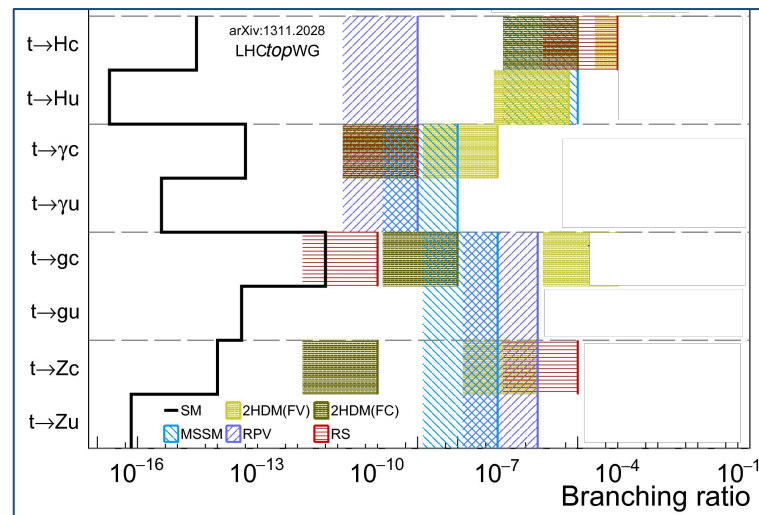
SM effective field theory:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

typically assuming  $\Lambda = 1 \text{ TeV}$

[see talks by Roman Lysak and Suman Chatterjee]

[see Xin Chen's talk]

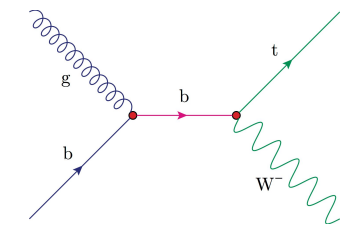
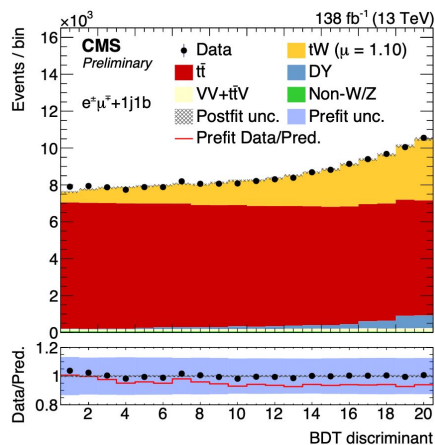
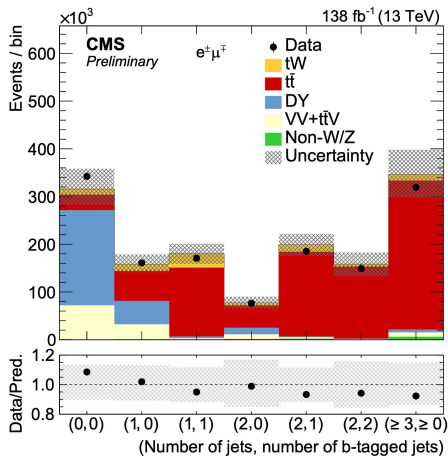


# Inclusive and differential $tW$



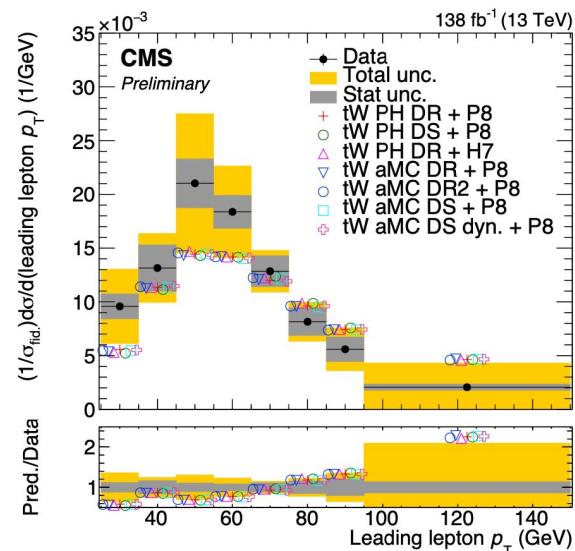
PAS TOP-21-010

- $e^\pm \mu^\mp$  events;  $n_{\text{jets}}$  and  $n_{b\text{-jets}}$  define subregions
- inclusive measurement
  - BDT for signal / bkg discrimination



$$\mu = 1.10 \pm 0.01(\text{stat}) \pm 0.11(\text{syst}) \pm 0.02(\text{lumi})$$

$$79.2 \pm 0.8(\text{stat})_{-7.2}^{+7.0}(\text{syst}) \pm 1.1(\text{lumi}) \text{ pb}$$



# single $t$ production – s-channel

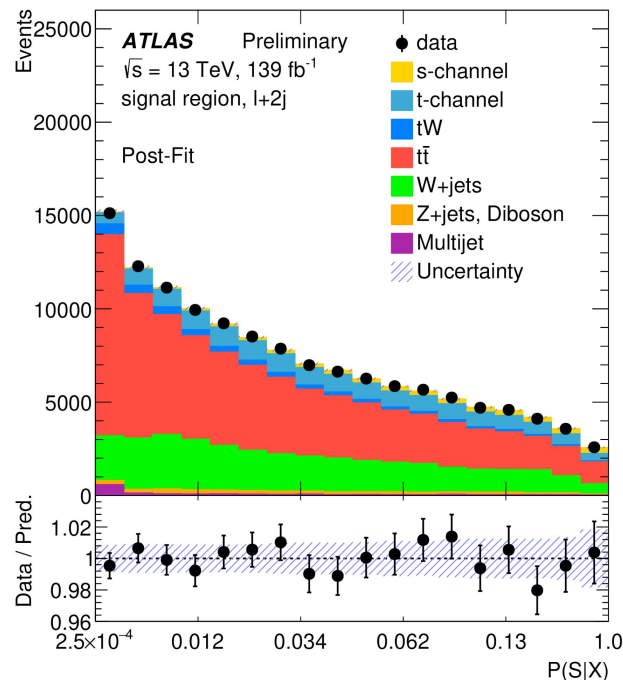
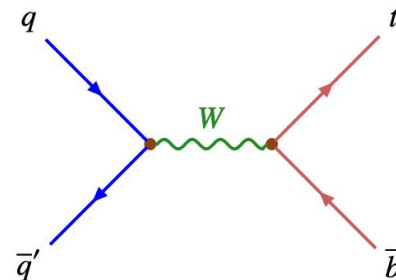


ATLAS-CONF-2022-030

- single  $\ell + 2$  b-jets events
- non-prompt lepton backgrounds from MC+data
- discriminant based on matrix-element

$$\mathcal{P}(X | H_{\text{proc}}) = \int d\Phi \frac{1}{\sigma_{H_{\text{proc}}}} \frac{d\sigma_{H_{\text{proc}}}}{d\Phi} T_{H_{\text{proc}}}(X | \Phi)$$

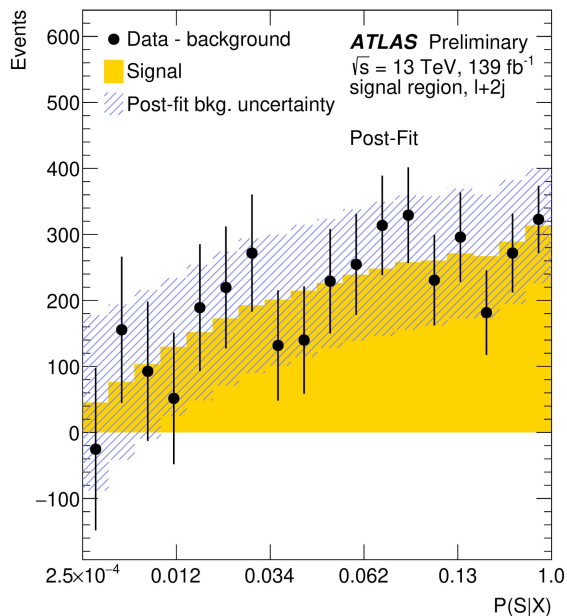
$$P(S | X) = \frac{\sum_i P(S_i) \mathcal{P}(X | S_i)}{\sum_i P(S_i) \mathcal{P}(X | S_i) + \sum_j P(B_j) \mathcal{P}(X | B_j)}$$



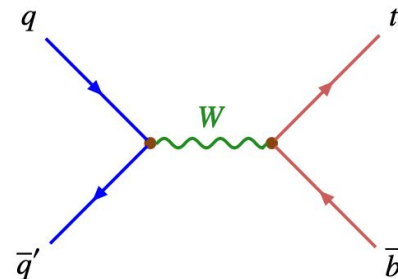
# single $t$ production – s-channel



ATLAS-CONF-2022-030



Source	$\Delta\sigma_s/\sigma_s$ [%]
$t\bar{t}$ and $W$ + jets normalisation	+24/-17
Jet energy resolution	+18/-12
Jet energy scale	+18/-13
Other s-channel modelling sources	+18/-8
Top-quark processes ISR/FSR	+13/-11
MC statistics	+13/-11
Other $t\bar{t}$ shape modelling sources	+12/-10
Flavour tagging	+12/-10
Top-quark processes PDFs	+10/-9
$W$ + jets ME scales	+6/-5
Other processes normalisation	+6/-5
Pileup	+5/-3
Other t-channel modelling sources	$\pm 5$
Luminosity	+4/-3
Other $tW$ modelling sources	+1/-2
Missing transverse energy	$\pm 1$
Multijet shape modelling	$\pm 1$
Other sources	< 1
<b>Systematics</b>	<b>+42/-34</b>
Data statistics	$\pm 8$
<b>Total</b>	<b>+42/-35</b>



$$\sigma_s = 8.2^{+3.5}_{-2.9} \text{ pb}$$

$$\sigma_s^{\text{SM}} = 10.3 \pm 0.4 \text{ pb}$$

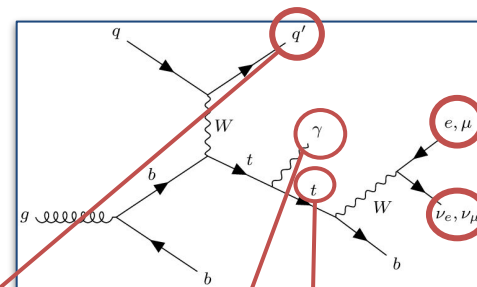
3.3  $\sigma$  significance  
[3.7  $\sigma$  expected]

# Observation of $t \gamma q$ production



ATLAS-CONF-2022-013

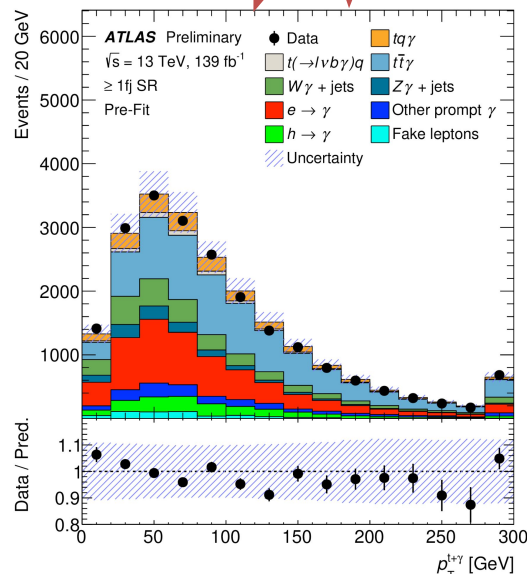
- The measurement of the production xsec is both:
  - an important test of the SM
  - a window to BSM physics affecting the top/photon EW coupling
- Previous evidence from CMS with  $4.4\sigma$  [  $36\text{fb}^{-1}$ , [PRL \(2018\)](#) ]
- analysis exploiting the presence of a fwd jet (t-channel)



$\gamma$  from top

$\gamma$  from top decays

	$\geq 1\text{fj SR}$	$0\text{fj SR}$	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	$2390 \pm 260$	$2480 \pm 320$	$890 \pm 120$	$1280 \pm 150$
$t(\rightarrow \ell\nu b\gamma)q$	$360 \pm 150$	$460 \pm 240$	$120 \pm 50$	$230 \pm 110$
$t\bar{t}\gamma$ (production)	$3100 \pm 400$	$4800 \pm 700$	$4300 \pm 600$	$2720 \pm 350$
$t\bar{t}\gamma$ (radiative decay)	$3800 \pm 600$	$9300 \pm 1400$	$5700 \pm 600$	$4300 \pm 900$
$W\gamma$ +jets	$2500 \pm 400$	$9300 \pm 1300$	$1050 \pm 190$	$31\,900 \pm 3000$
$Z\gamma$ +jets	$990 \pm 310$	$2800 \pm 800$	$440 \pm 150$	$7900 \pm 2400$
$e \rightarrow \gamma$ fake photons	$5200 \pm 500$	$10\,300 \pm 800$	$4800 \pm 400$	$5400 \pm 500$
$h \rightarrow \gamma$ fake photons	$1100 \pm 400$	$2700 \pm 800$	$1300 \pm 500$	$2500 \pm 800$
Other prompt $\gamma$	$1360 \pm 350$	$2600 \pm 900$	$1400 \pm 400$	$4100 \pm 500$
Fake leptons	$350 \pm 170$	$900 \pm 400$	$100 \pm 50$	$3300 \pm 1600$
Total	$21\,250 \pm 150$	$45\,720 \pm 240$	$20\,180 \pm 140$	$63\,590 \pm 310$
Data	21 227	45 723	20 194	63 592



# Observation of $t \gamma q$ production



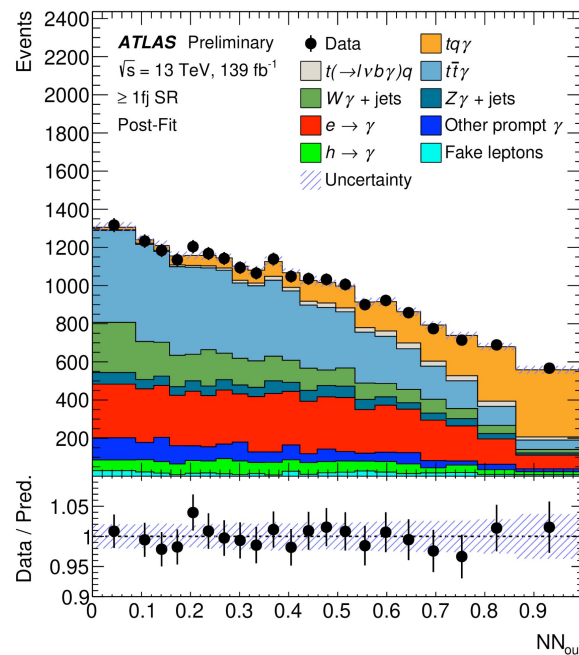
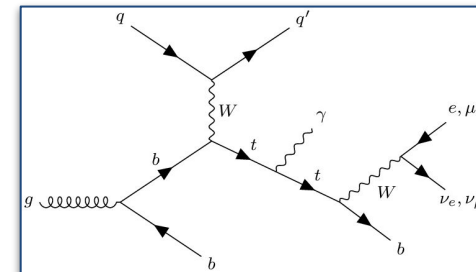
ATLAS-CONF-2022-013

- DNN used to further separate signal from bkg
- Fiducial measurements:

parton level:  $\sigma_{tq\gamma} \times B(t \rightarrow l\nu b) = 580 \pm 19 \text{ (stat.)} \pm 63 \text{ (syst.) fb}$

particle level:  $\sigma_{tq\gamma} \times B(t \rightarrow l\nu b) + \sigma_{t(\rightarrow l\nu b\gamma)q} = 287 \pm 8 \text{ (stat.)} \pm 31 \text{ (syst.) fb}$

- major systematic uncertainties:
  - background modelling:  $t\bar{t}\gamma \sim 6\%$ ;  $t\bar{t} \sim 3\%$
  - MC statistics:  $tq\gamma \sim 3\%$ ; all other  $\sim 3\%$
- measured xsec  $\sim 40\%$  higher than SM prediction
  - $2.5\sigma$  and  $1.9\sigma$  in the parton and particle level
  - consistent with the CMS result



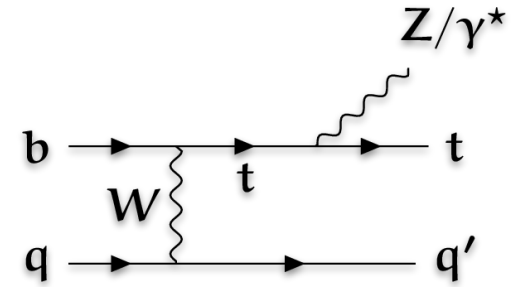


# Inclusive and differential $tZq$

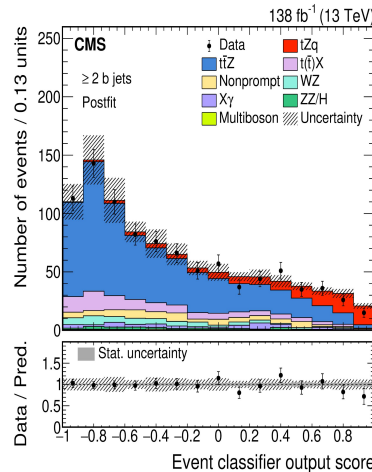
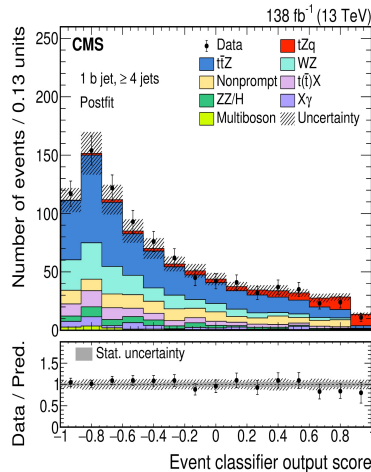
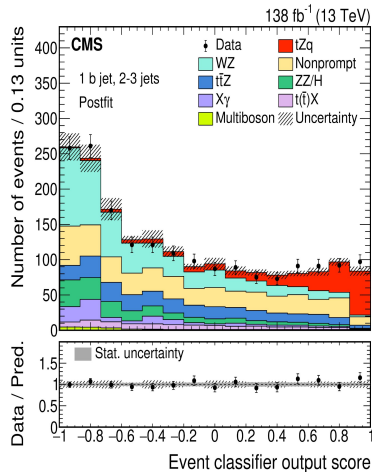


*JHEP* 02 (2022) 107

- $3\ell$  events;  $n_{\text{jets}}$  and  $n_{\text{b-jets}}$  define subregions
- inclusive measurement
  - BDT for signal / bkg discrimination



$$\mu = \frac{\sigma_{tZq}}{\sigma_{tZq}^{\text{SM}}} = 0.933_{-0.077}^{+0.080} (\text{stat})_{-0.064}^{+0.078} (\text{syst}).$$



$$\sigma_{tZq} = 87.9_{-7.3}^{+7.5} (\text{stat})_{-6.0}^{+7.3} (\text{syst}) \text{ fb}$$

- main syst:  $tZq$  modelling, non-prompt  $\ell$  and  $WZ$  norm.
- compatible with the SM and with the previous ATLAS observation ([JHEP 2018](#))

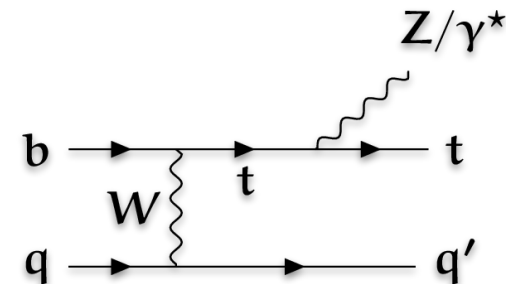
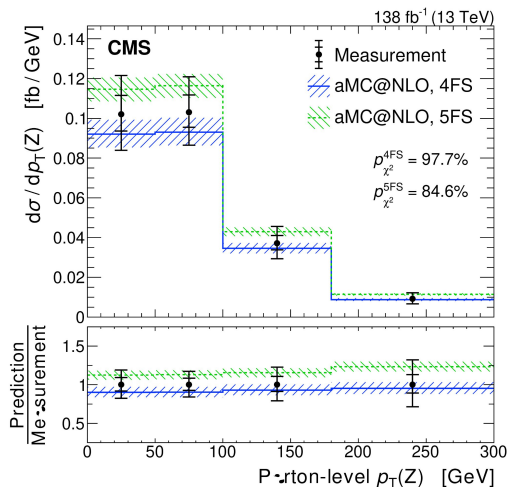
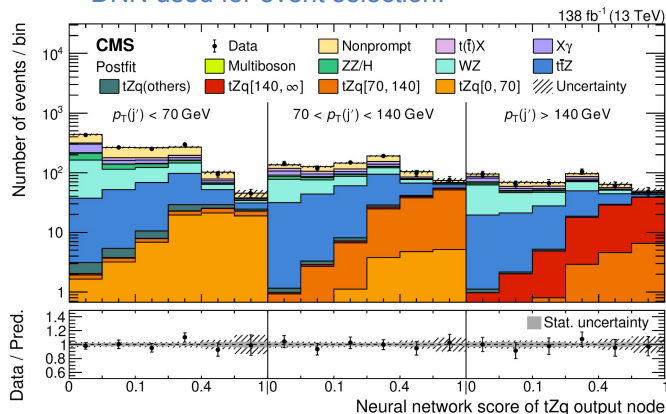
# Inclusive and differential $tZq$



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- Parton & particle level, 9 variables:  
 $p_T(t)$ ,  $p_T(Z)$ ,  $p_T(\ell_t)$ ,  $m(3\ell)$ ,  $\Delta\Phi(\ell, \ell')$ ,  
 $\cos(\theta_{\text{pol}}^*)$ ,  $m(t, Z)$ ,  $p_T(j')$ ,  $|n|(j')$

DNN used for event selection:



- Similar goodness-of-fit for 4FS and 5FS in all variables
- spin asymmetries:  
 $A_t = 0.54 \pm 0.16$  (stat)  $\pm 0.06$  (syst)  
 (SM = 0.44 / 0.45 for 4FS/5FS)

$$\frac{d\sigma}{d\cos(\theta_{\text{pol}}^*)} = \sigma_{tZq} \left( \frac{1}{2} + A_\ell \cos(\theta_{\text{pol}}^*) \right)$$

$$\cos(\theta_{\text{pol}}^*) = \frac{\vec{p}(q'^*) \cdot \vec{p}(\ell_t^*)}{|\vec{p}(q'^*)| |\vec{p}(\ell_t^*)|}, \quad A_\ell = \frac{1}{2} P a_\ell$$

# Search for charged lepton flavor violation

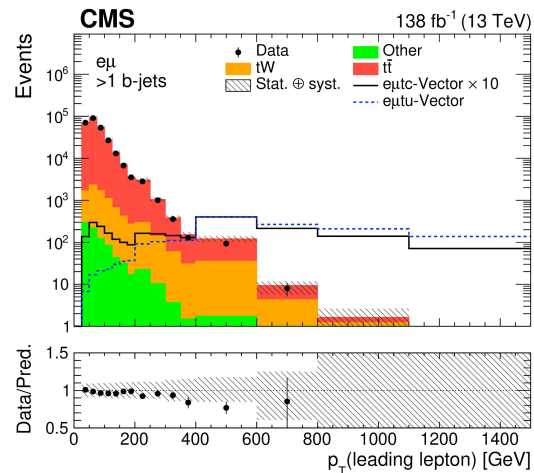
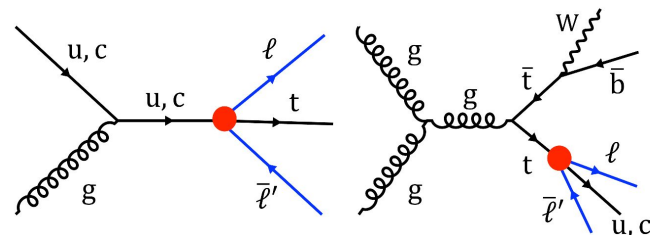


CMS-TOP-19-006

- CLFV suppressed in SM with massive neutrinos.
- BSM LFV underlying mechanism unknown
- $t\ell\ell'$  interaction described by EFT operators such as

$$O_{lq}^{(1)ijkl} = (\bar{l}_i \gamma^\mu l_j) (\bar{q}_k \gamma^\mu q_l)$$

- no SM interference assumed
- $q = u, c$  considered separately
- EFT vertex in both single top production and  $t\bar{t}$  decay
- Always one hadronic top decay
- 2ℓOS (1e, 1μ), 1 b-jet
  - Dominant uncertainty: b-tagging



Backgrounds:  
 $t\bar{t}$  (90%),  $tW$  (modelled with MC events)

$$O_{\text{vector}} = O_{lq} + O_{lu} + O_{eq} + O_{eu}$$

$$O_{\text{scalar}} = O_{\text{lequ}}^{(1)}$$

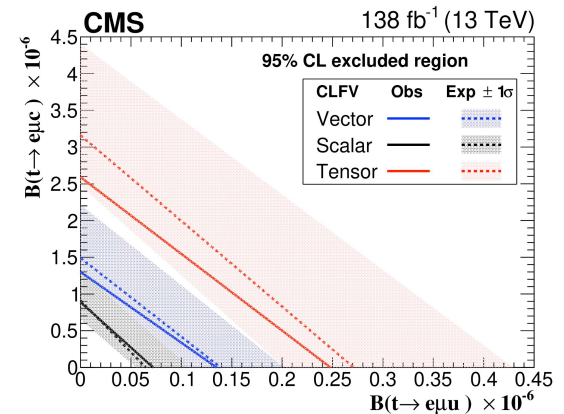
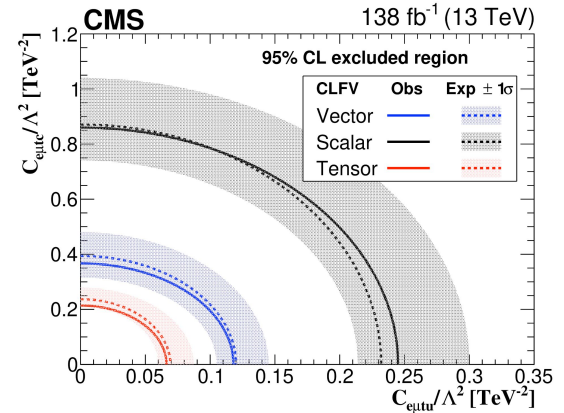
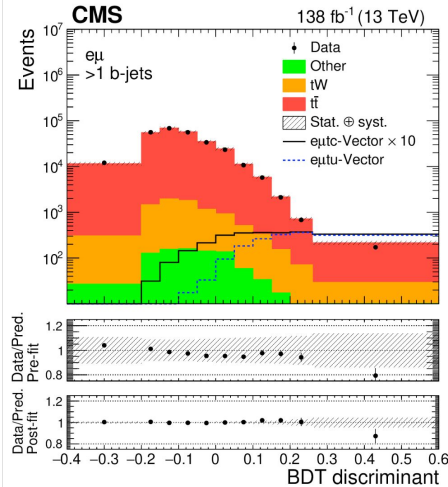
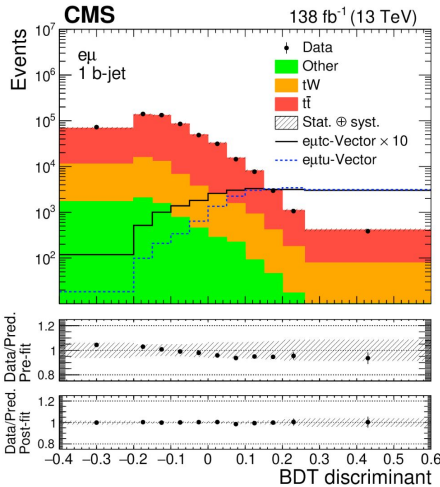
$$O_{\text{tensor}} = O_{\text{lequ}}^{(3)}$$

# Search for charged lepton flavor violation



CMS-TOP-19-006

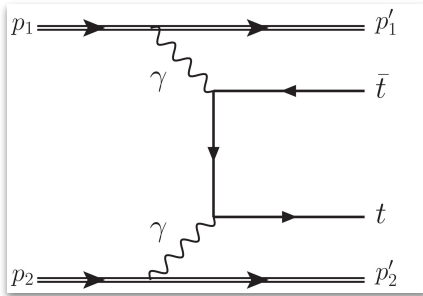
- One BDT trained in SR for all categories
- BDT applied also in CR (2 b-jets)
- SR+CR BDT shape fit for one operator at a time



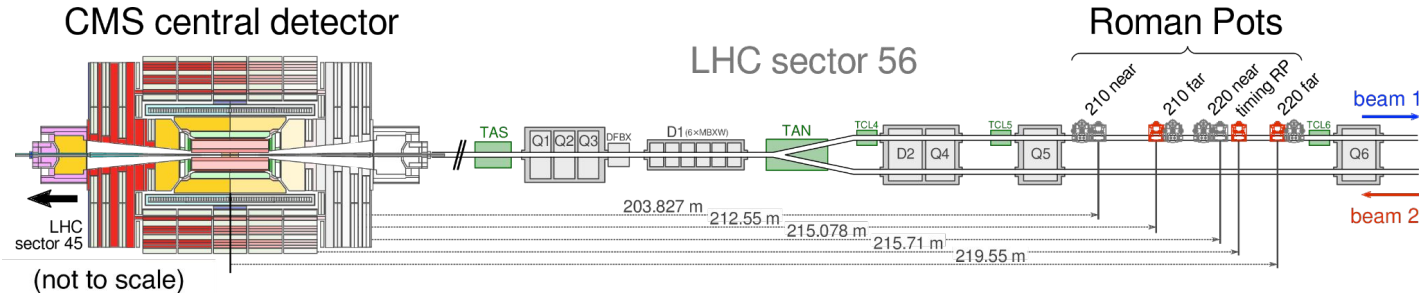
# Central exclusive production of $t\bar{t}$ production



[CMS-PAS-TOP-21-007](#)



- Production of  $t\bar{t}$  pairs in  $pp$  scattering via the exchange of colourless particles, such as photons or pomerons
- Predicted to occur at LHC with  $O(0.1 \text{ fb})$  cross-section (and large uncertainties on it)
- Can provide information on the top-photon EW coupling



# Central exclusive production of $t\bar{t}$ production

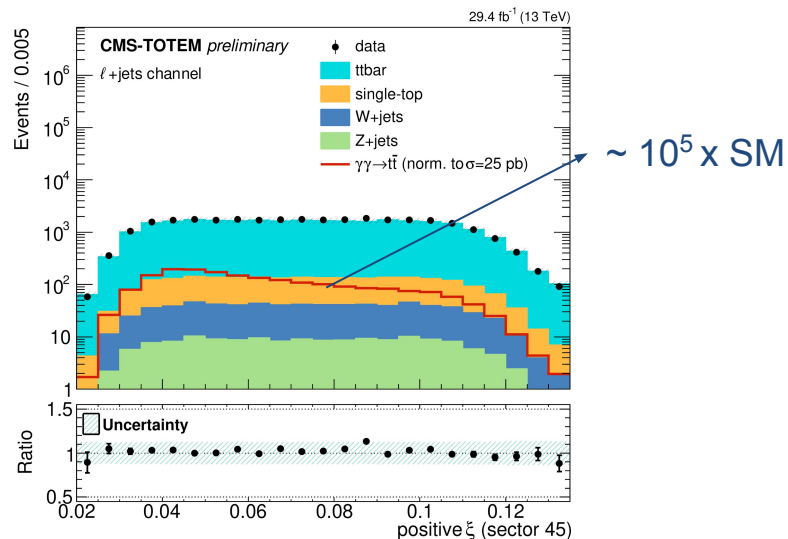


[CMS-PAS-TOP-21-007](#)

- 2017 data, 29.4 fb<sup>-1</sup>
- single and dilepton analyses, jet and b-tagged jet multiplicity
- 1 **proton tagged** on each side of CT-PPS
- In CEP the invariant mass and the rapidity of the **central system X** are related to the fractional momentum loss of the proton ( $\xi$ ):

$$M_X = \sqrt{s\tilde{\xi}_1\tilde{\xi}_2},$$

$$y_X = \frac{1}{2} \ln \frac{\tilde{\xi}_1}{\tilde{\xi}_2},$$



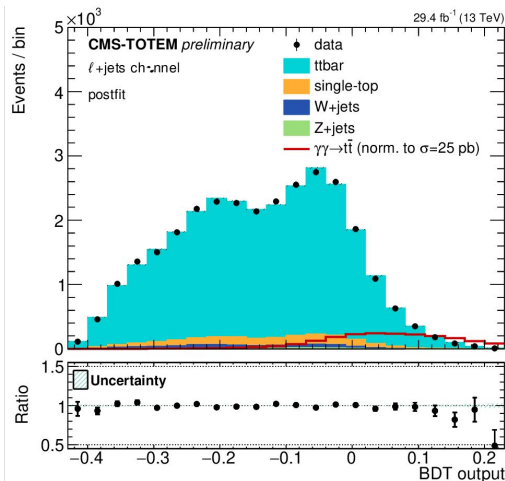
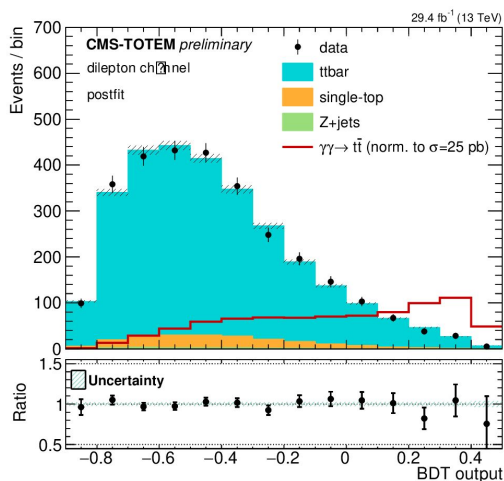
- Main **background** from QCD production of  $t\bar{t}$ , overlapping with unrelated pileup protons
  - estimated by embedding MC samples with pileup protons taken from data
- Main **systematics**: background normalisation, FSR modelling, jet energy corrections and resolution, and proton reconstruction

# Central exclusive production of $t\bar{t}$ production

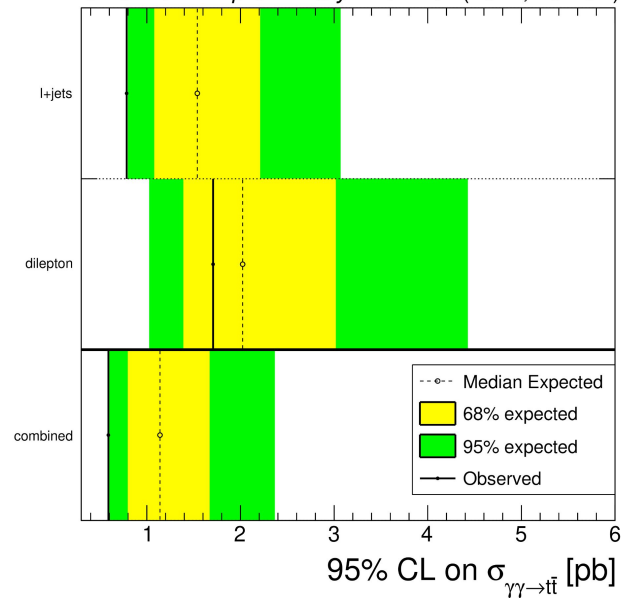


CMS-PAS-TOP-21-007

- 15 kinematic variables used to train a BDT



CMS-TOTEM preliminary 29.4 fb<sup>-1</sup> (2017, 13 TeV)



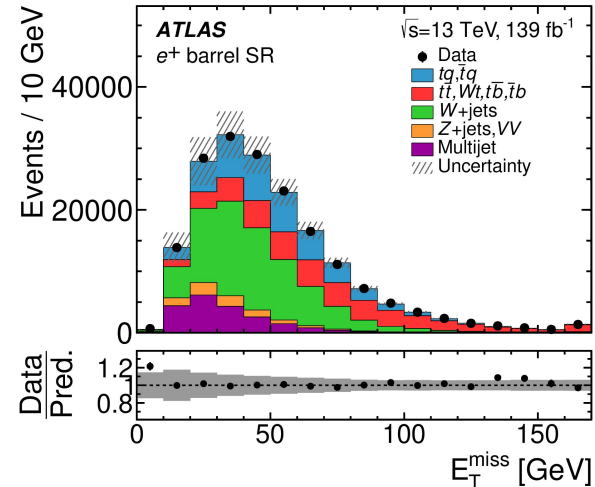
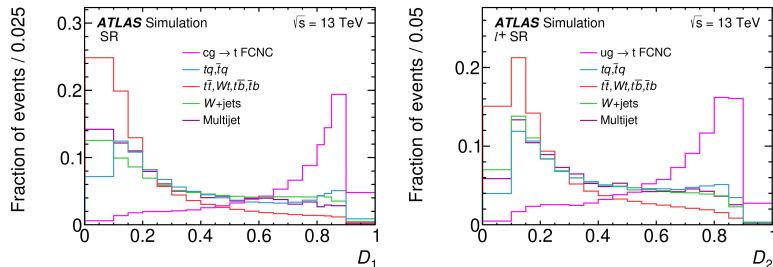
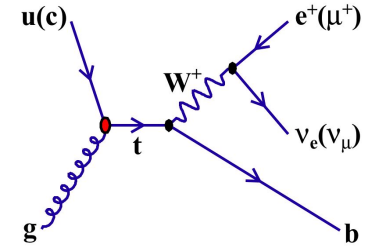
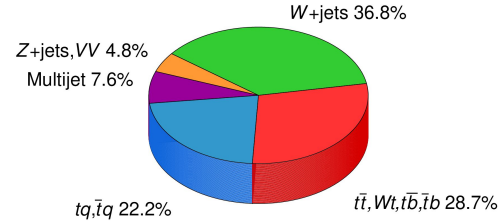
obs. upper limit: 0.59 pb

# FCNC: $tqg$



EPJC 82 (2022) 334

- Probing the  $tqg$  vertex in direct top production
- Reconstruct top in  $t \rightarrow e\mu vb$  final states ( $t \rightarrow \tau\nu b$  may also contribute)
  - =1 lepton,  $\geq 1$  b-jet,  $E_T^{\text{miss}} > 30$  GeV,  $m_T(W) > 50$  GeV
  - different regions based on b-tag multiplicity
- separate contributions from  $tgu$  and  $tgc$ 
  - $tgc$  (sea quark) signal  $\Rightarrow$  D1 discriminant
  - $tgu$  (valence quark) signal  $\Rightarrow$  D2 discriminant

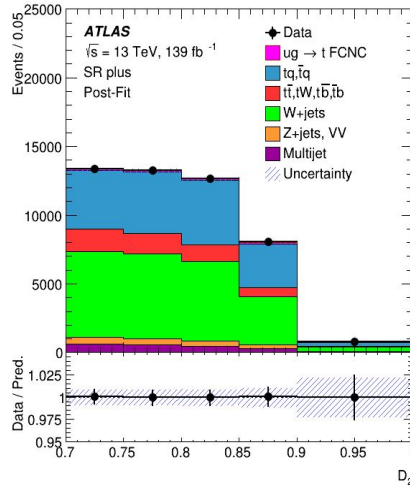
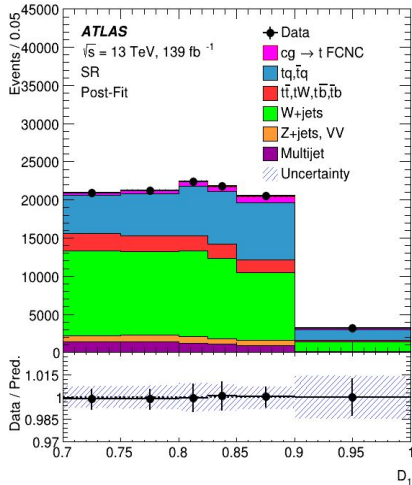
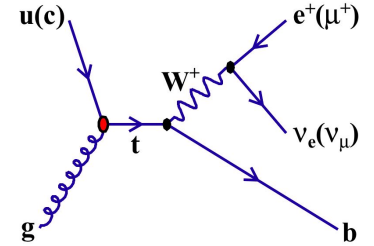




# FCNC: $tqg$



EPJC 82 (2022) 334



$$\sigma(ugt) \times \mathcal{B}(t \rightarrow Wb) \times \mathcal{B}(W \rightarrow \ell\nu) < 3.0 \text{ pb}$$

$$\sigma(cgt) \times \mathcal{B}(t \rightarrow Wb) \times \mathcal{B}(W \rightarrow \ell\nu) < 4.7 \text{ pb}$$

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

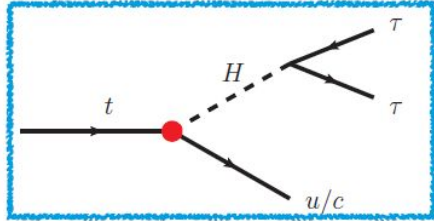
$$\mathcal{B}(t \rightarrow u + g) < 0.61 \times 10^{-4} \quad \text{and} \quad \mathcal{B}(t \rightarrow c + g) < 3.7 \times 10^{-4}$$

👉 ~ 2 improvement over previous 8 TeV measurement

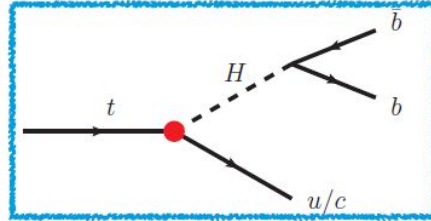
Main uncertainties: MC stat, back./signal modelling and MET

# probing the $tqH$ vertex

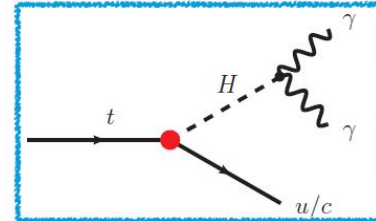
- many possible signatures, depending on the Higgs decay



$H \rightarrow \tau\tau$



$H \rightarrow b\bar{b}$



$H \rightarrow \gamma\gamma$

- dedicated analyses for each signature
  - both single top production -  $tH$  production via FCNC - and pair production of top quarks with  $t \rightarrow qH$  FCNC decay considered

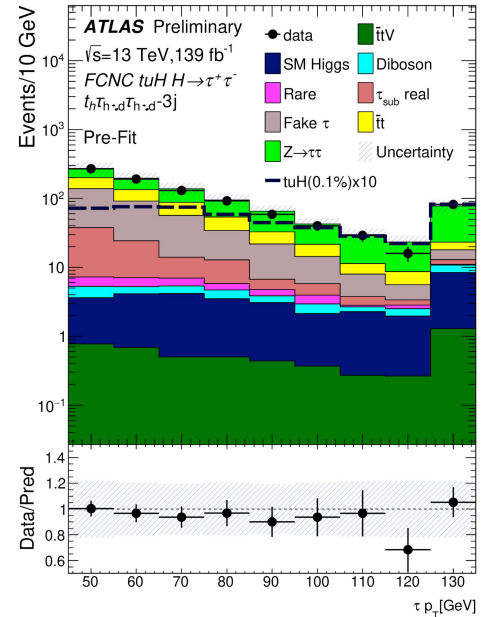
# FCNC: $tqH, H \rightarrow \tau\tau$



ATLAS-CONF-2022-014

- $T_{\text{had}} T_{\text{had}}$  Or  $T_{\text{lep}} T_{\text{had}}$

	Regions	$b$ -jet	light flavour jets	lepton	hadronic taus	charge
SR	$t_{\ell}\tau_{\text{had}}\tau_{\text{had}}$	1	$\geq 0$	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	$\geq 3$	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	$\geq 3$	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
VR	$t_{\ell}\tau_{\text{had}}\tau_{\text{had}}-SS$	1	$\geq 0$	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
CRtt	$t_{\ell}t_{\ell}1b\tau_{\text{had}}$	1	$\geq 0$	2	1	$t_{\ell}t_{\ell}$ OS
	$t_{\ell}t_{\ell}2b\tau_{\text{had}}$	2	$\geq 0$	2	1	$t_{\ell}t_{\ell}$ OS
	$t_{\ell}t_h2b\tau_{\text{had}}-2jSS$	2	2	1	1	$t_{\ell}\tau_{\text{had}}$ SS
	$t_{\ell}t_h2b\tau_{\text{had}}-2jOS$	2	2	1	1	$t_{\ell}\tau_{\text{had}}$ OS
	$t_{\ell}t_h2b\tau_{\text{had}}-3jSS$	2	$\geq 3$	1	1	$t_{\ell}\tau_{\text{had}}$ SS
	$t_{\ell}t_h2b\tau_{\text{had}}-3jOS$	2	$\geq 3$	1	1	$t_{\ell}\tau_{\text{had}}$ OS



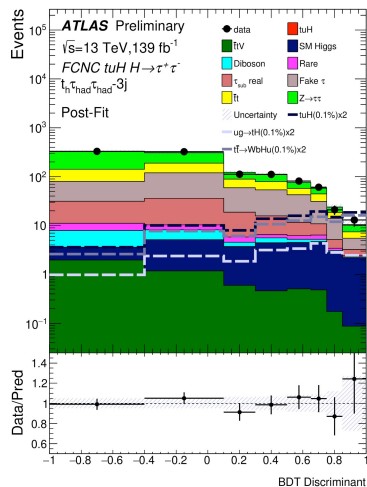
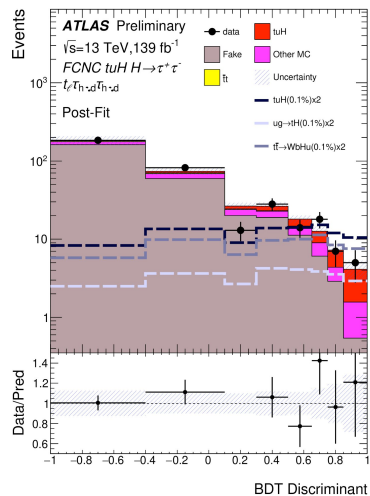
divide and conquer!

# FCNC: $tqH, H \rightarrow \tau\tau$

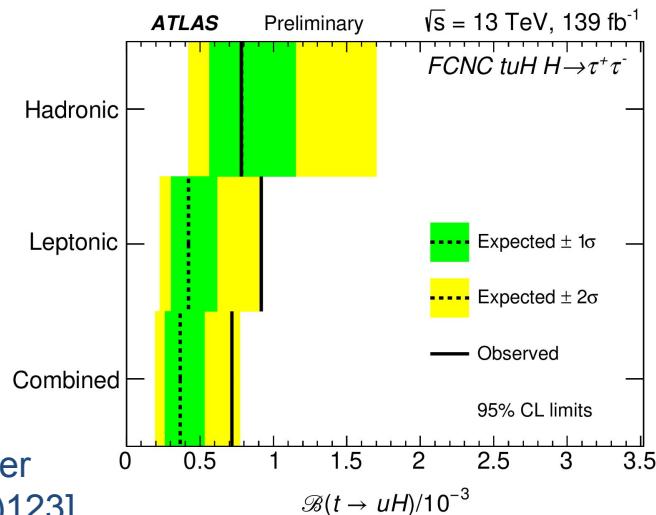
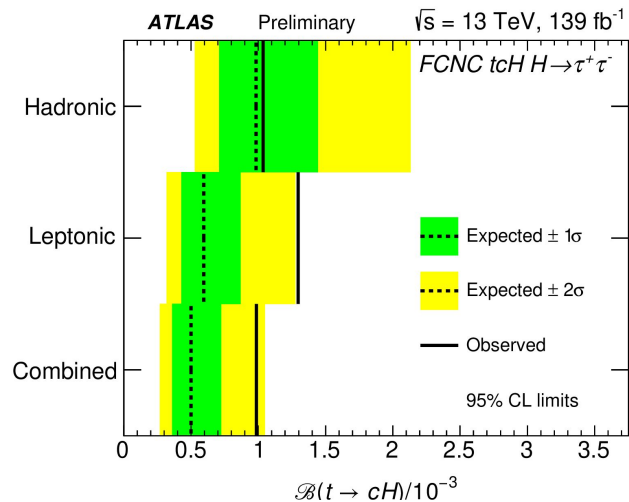


ATLAS-CONF-2022-014

- BDT is trained in each of the SR to separate signal from SM background



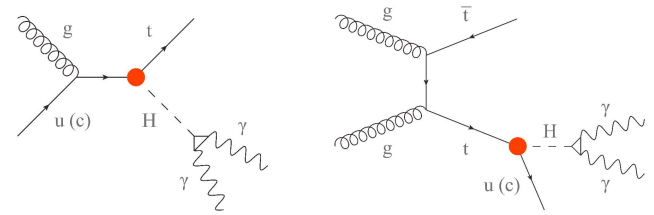
→ Significant improvement over previous limits [JHEP05(2019)123]



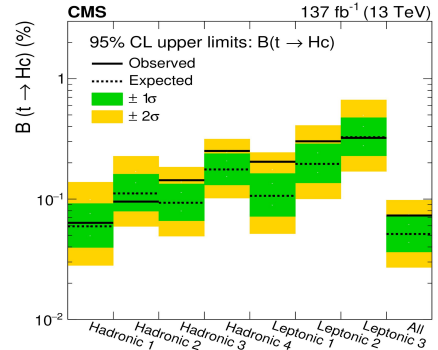
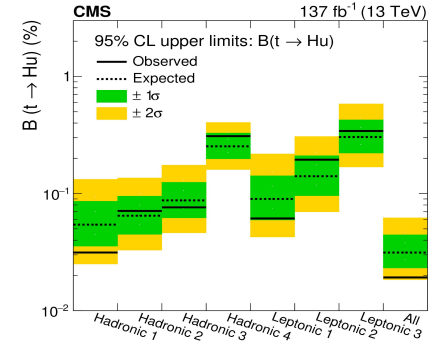
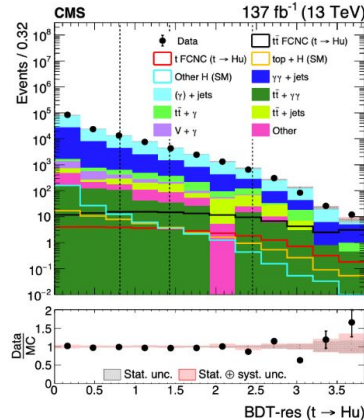
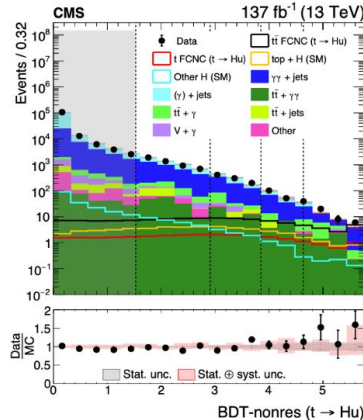
# FCNC: $tqH, H \rightarrow \gamma\gamma$



[arXiv:2111.02219](https://arxiv.org/abs/2111.02219)



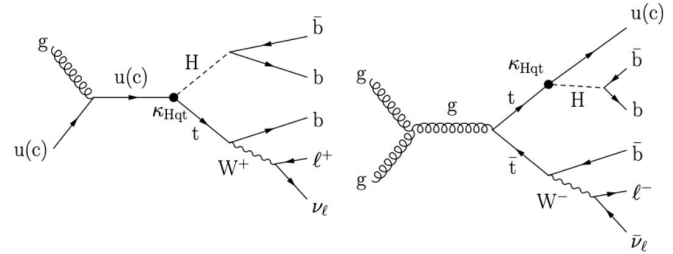
- Event selection
  - Leptonic channel: =1 lepton,  $\geq 1$  jet
  - Hadronic channel: =0 lepton,  $\geq 3$  jets,  $\geq 1$   $b$ -jet
- 8 BDTs:  $tHu$  vs  $tHc$ , leptonic vs hadronic channels, resonant vs non-resonant  $\gamma\gamma$  bkg



# FCNC: $tqH, H \rightarrow b\bar{b}$



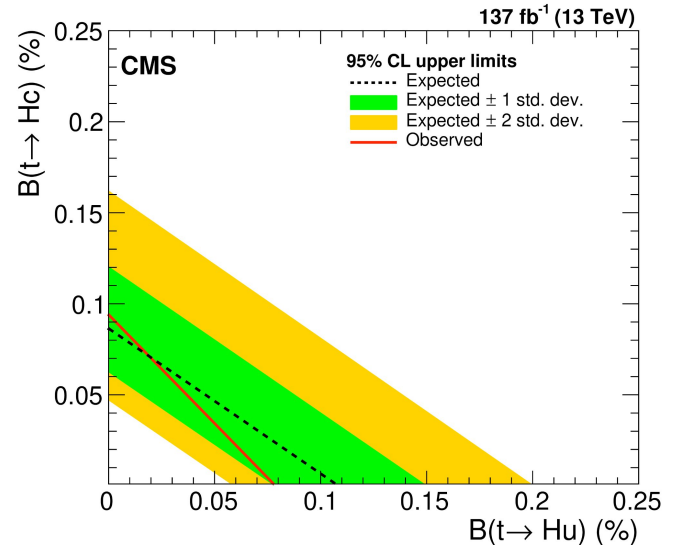
[JHEP 02 \(2022\) 169](#)



- Event selection
 

{	• =1 lepton ( $e/\mu$ ), $\geq 3$ jets, $\geq 2$ $b$ -jets		
	• 5 categories		
		<b>N jets = 3</b>	<b>N jets <math>\geq 4</math></b>
	<b>N b-jets = 2</b>	✓	✓
<b>N b-jets = 3</b>	✓	✓	
<b>N b-jets = 4</b>	–	✓	
- NN for  $b$ -jet pairing
- BDT for signal / background discrimination
- 2017–2018 dataset is analysed and combined with 2016 from previous publication

→ significant sensitivity from the  $b3j4$  category due to suppression of SM  $t\bar{t}$

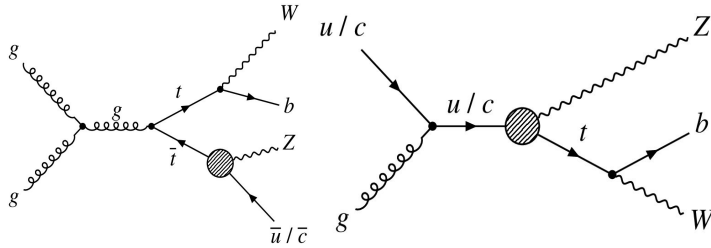


→ factor of 3–6 improvement over previous result in the same channel [[JHEP06\(2018\)102](#)]

# FCNC: $tqZ$

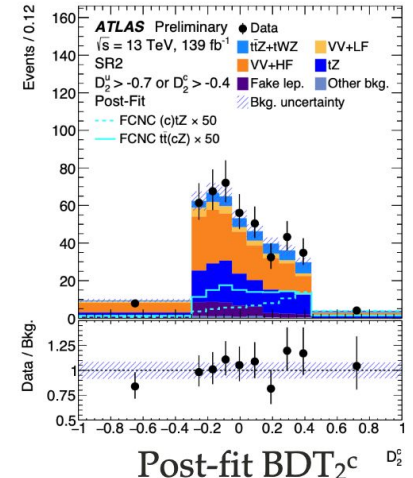
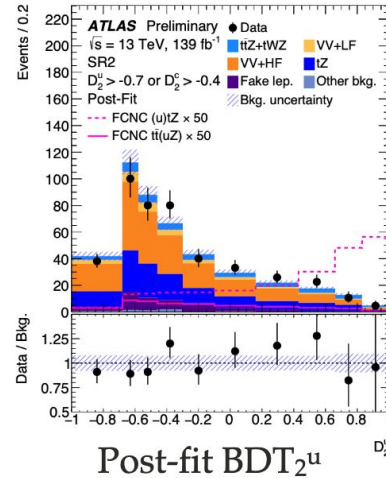


ATLAS-CONF-2021-049



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

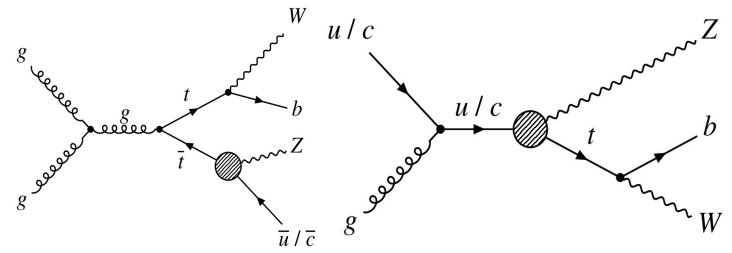
- Discriminate signal from background
  - BDT1 : SR1  $tZu$  and  $tZc$  decay mode
  - BDT2u : SR2  $tZu$  in production mode
  - BDT2c: SR2  $tZc$  in both modes



# FCNC: $tqZ$



ATLAS-CONF-2021-049



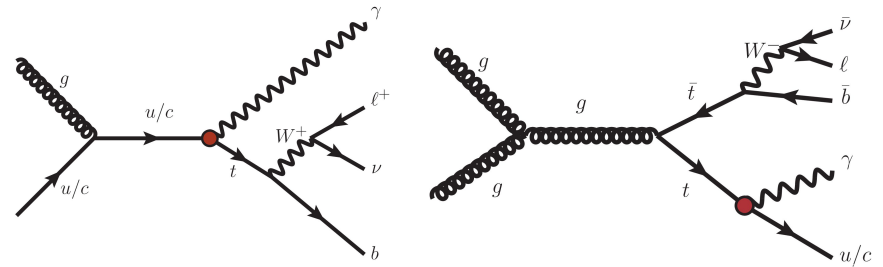
Observable	Vertex	Coupling	Observed	Expected
SR1+CRs				
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZu$	LH	9.7	$8.6^{+3.6}_{-2.4}$
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZu$	RH	9.5	$8.2^{+3.4}_{-2.3}$
SR2+CRs				
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZu$	LH	7.8	$6.1^{+2.7}_{-1.7}$
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZu$	RH	9.0	$6.6^{+2.9}_{-1.8}$
SRs+CRs				
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZu$	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZu$	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZc$	LH	13	$11^{+5}_{-3}$
$\mathcal{B}(t \rightarrow Zq) [10^{-5}]$	$tZc$	RH	12	$10^{+4}_{-3}$
$ C_{uW}^{(13)*} $ and $ C_{uB}^{(13)*} $	$tZu$	LH	0.15	$0.13^{+0.03}_{-0.02}$
$ C_{uW}^{(31)} $ and $ C_{uB}^{(31)} $	$tZu$	RH	0.16	$0.14^{+0.03}_{-0.02}$
$ C_{uW}^{(23)*} $ and $ C_{uB}^{(23)*} $	$tZc$	LH	0.22	$0.20^{+0.04}_{-0.03}$
$ C_{uW}^{(32)} $ and $ C_{uB}^{(32)} $	$tZc$	RH	0.21	$0.19^{+0.04}_{-0.03}$



# FCNC: $tq\gamma$



arXiv:2205.02537

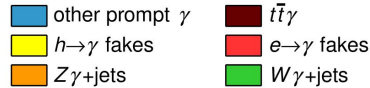


## Background estimation

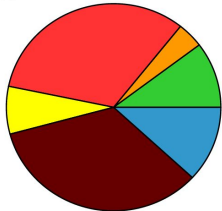
- $e \rightarrow \gamma$ : estimate a fake factor to correct simulation
- $h \rightarrow \gamma$ : transfer factor from control region
- others: Monte-Carlo simulation

ATLAS Simulation

$\sqrt{s} = 13$  TeV



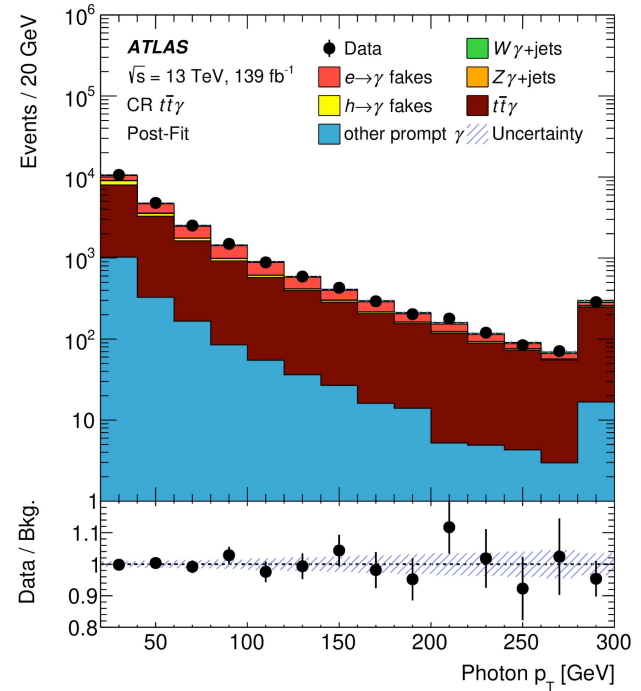
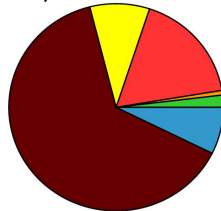
SR



CR  $W\gamma$ +jets



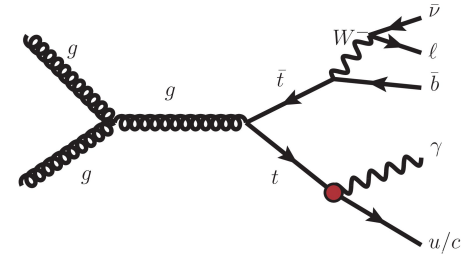
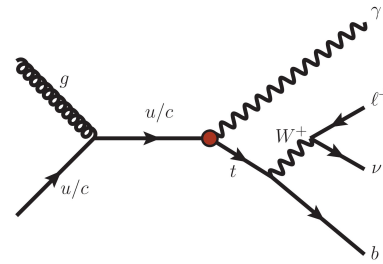
CR  $t\bar{t}\gamma$



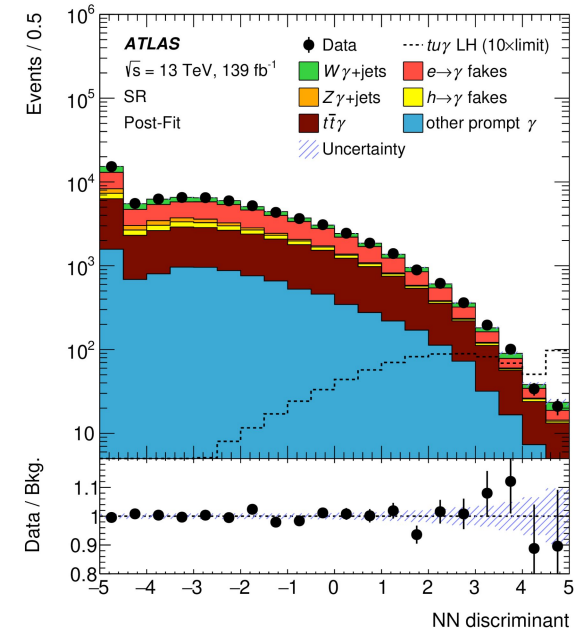
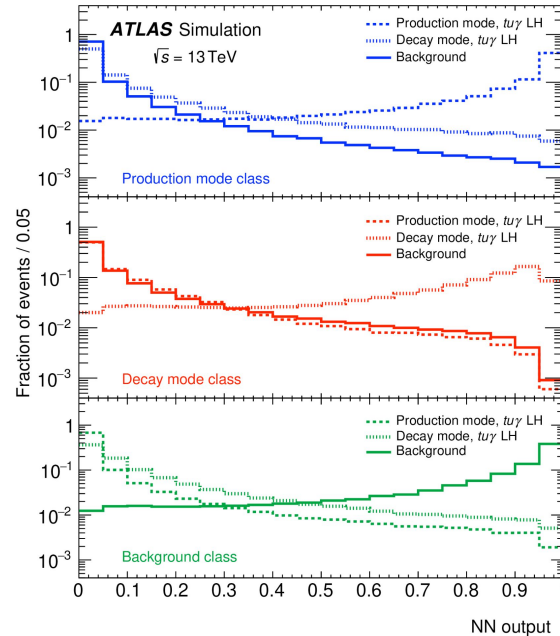
# FCNC: $tq\gamma$



[arXiv:2205.02537](https://arxiv.org/abs/2205.02537)



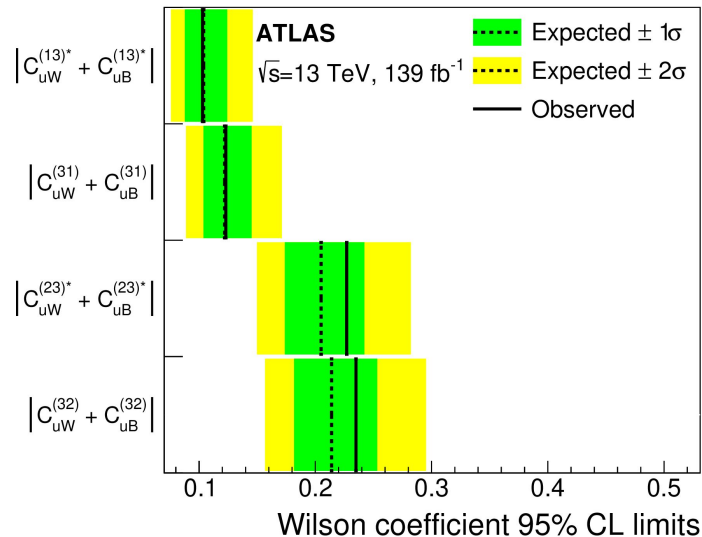
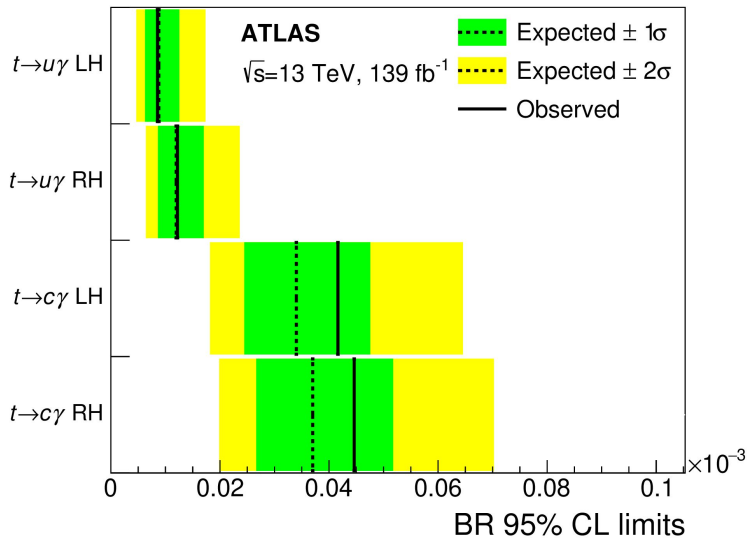
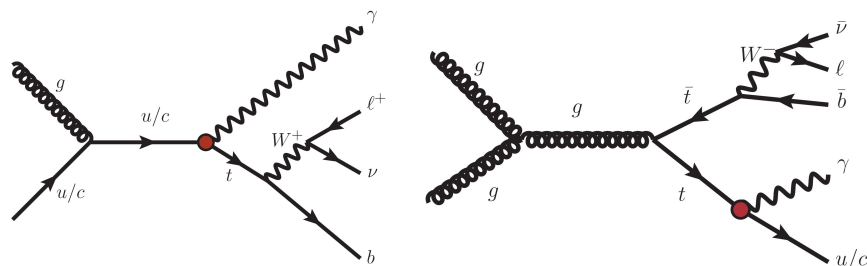
- Two neural network targeting  $tq\gamma$  and  $t\bar{c}\gamma$  signal separately
  - Multi-class NN to separate production mode, decay mode and background
  - Up to 30% better sensitivity than binary classifier



# FCNC: $tq\gamma$

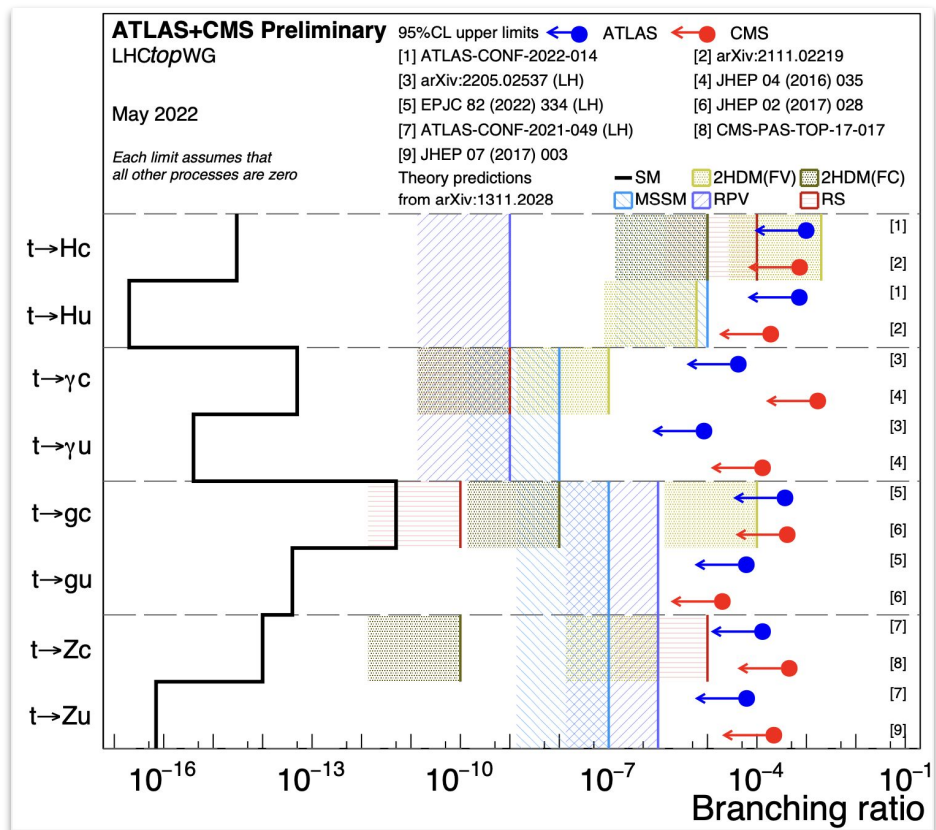


arXiv:2205.02537



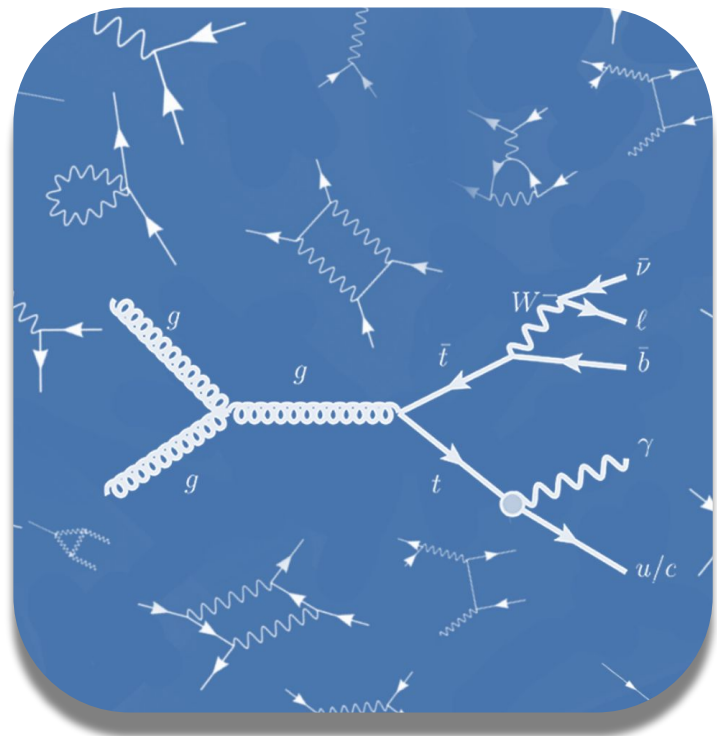
→ factor of 3–5 improvement over previous result [[PLB 800 \(2020\) 135082](#)]

# FCNC in the top sector summary



# summary

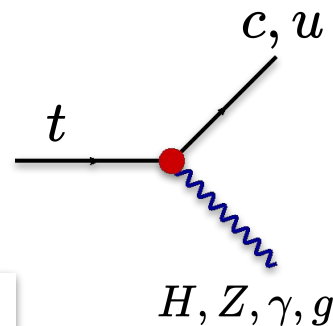
- LHC is a top factory, which allows to probe extremely rare processes in the top quark sector
  - approaching the fb barrier
  - precision measurements and searches
    - tests of the SM
    - window to new physics
- run-3 is starting... stay tuned!



# Backup

# Rare processes in the top quark sector

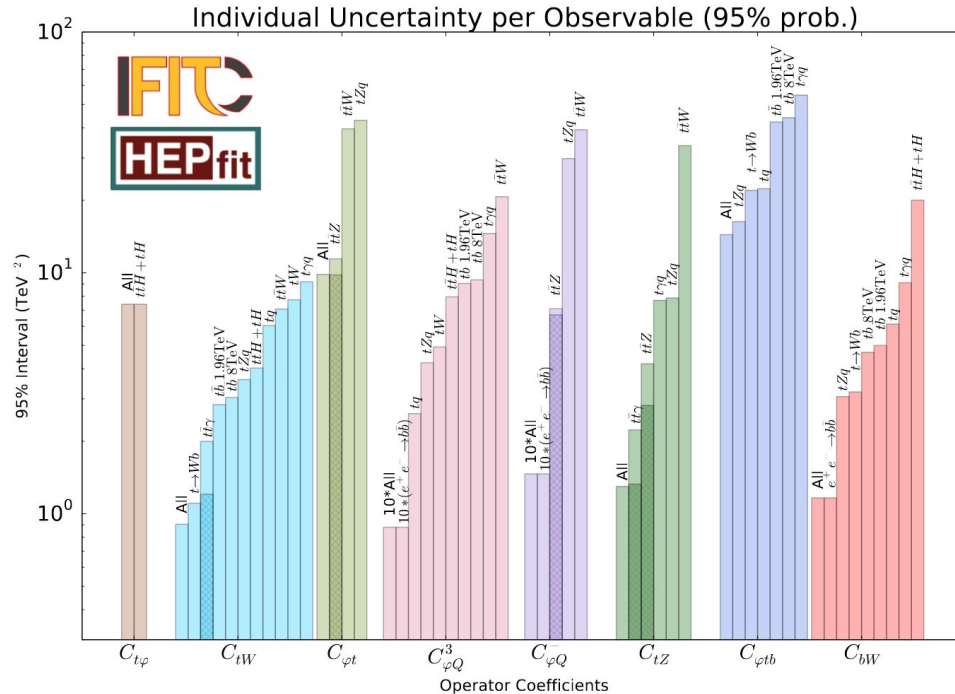
## Searches: top FCNCs as a window to BSM



Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \rightarrow Zu$	$7 \times 10^{-17}$	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \rightarrow Zc$	$1 \times 10^{-14}$	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \rightarrow gu$	$4 \times 10^{-14}$	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \rightarrow gc$	$5 \times 10^{-12}$	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \rightarrow \gamma u$	$4 \times 10^{-16}$	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \rightarrow \gamma c$	$5 \times 10^{-14}$	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \rightarrow hu$	$2 \times 10^{-17}$	$6 \times 10^{-6}$	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \rightarrow hc$	$3 \times 10^{-15}$	$2 \times 10^{-3}$	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

[ [arXiv:1311.2028](https://arxiv.org/abs/1311.2028) ]

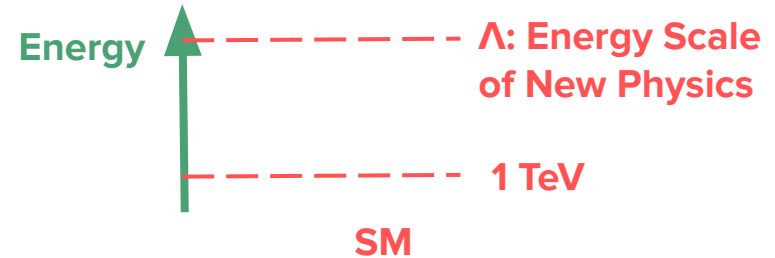
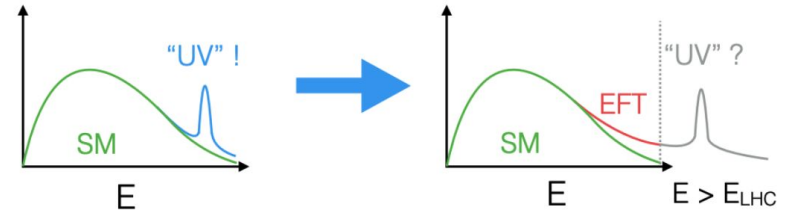
# Rare processes in the top quark sector as a window to BSM





# Effective field theory in the top-quark sector

- An **EFT approach** in top-quark sector is being pursued at the LHC since almost the beginning of data taking
  - using precision measurements and searches for rare events as a probe for physics beyond the Standard Model
  - Experience in the *LHC top WG* and, more recently, in the *LHC EFTWG*



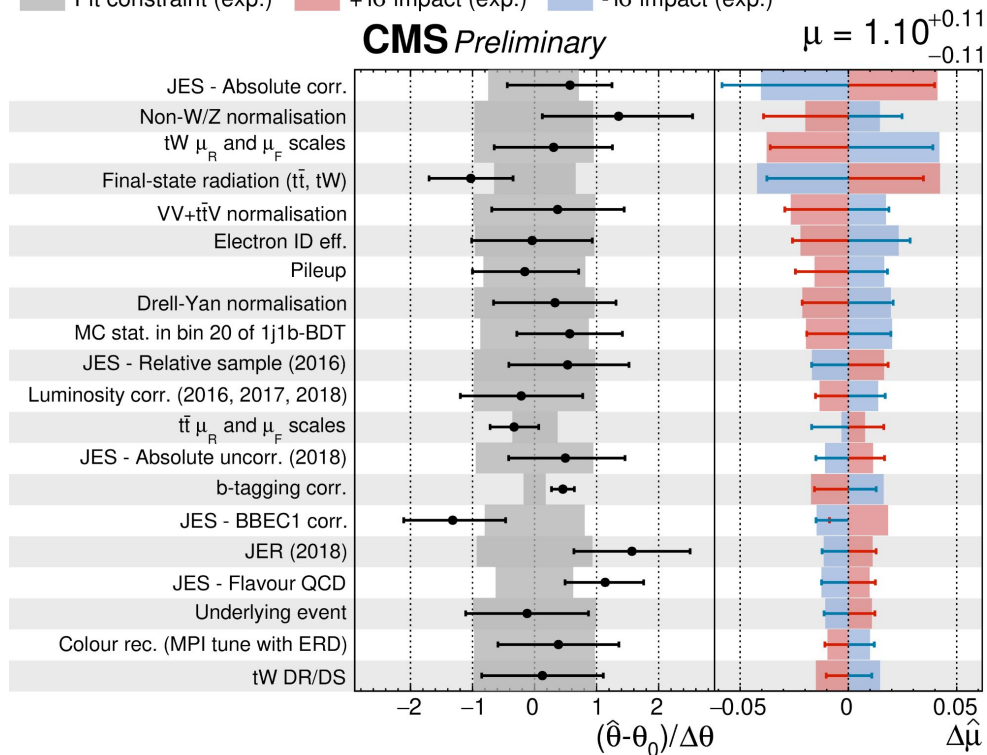
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

# Inclusive $tW$



PAS TOP-21-010

- Fit constraint (obs.)    — +1 $\sigma$  impact (obs.)    — -1 $\sigma$  impact (obs.)
- Fit constraint (exp.)    ■ +1 $\sigma$  impact (exp.)    ■ -1 $\sigma$  impact (exp.)



# Differential $tW$

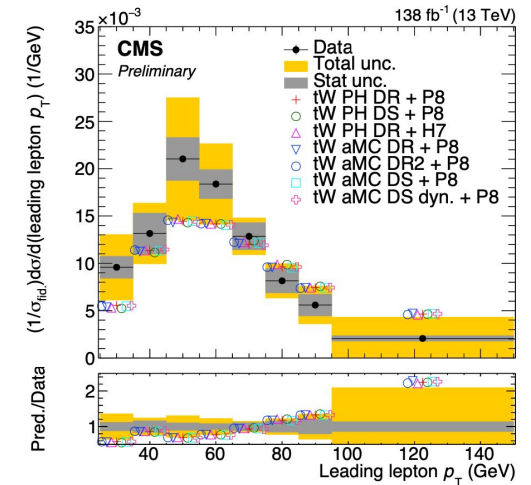
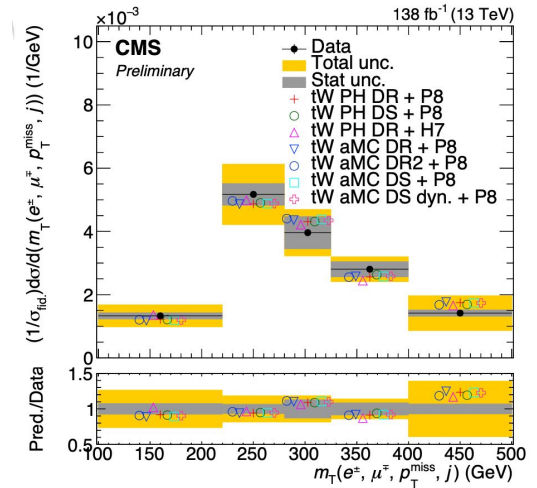


PAS TOP-21-010

- unfolding used to obtain several diff. xsec measurements
- definition of the fiducial region:

Number of leptons	$\geq 2$
Leading lepton $p_T$	$> 25$ GeV
Invariant mass of all dilepton pairs	$> 20$ GeV
Number of jets	1
Number of loose jets	0
Number of b jets	1

Muons		Electrons		Jets		Loose jets	
$p_T$ (GeV)	$ \eta $	$p_T$ (GeV)	$ \eta $	$p_T$ (GeV)	$ \eta $	$p_T$ (GeV)	$ \eta $
$> 20$	$< 2.4$	$> 20$	$< 2.4$ && ( $< 1.4442$    $> 1.5660$ )	$> 30$	$< 2.4$	$> 20, < 30$	$< 2.4$



# Observation of $t \gamma q$ production



ATLAS-CONF-2022-013

parton-level

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	$\pm 5.6\%$
Background MC statistics	$\pm 3.5\%$
$t\bar{t}$ modelling	$\pm 3.4\%$
$tq\gamma$ MC statistics	$\pm 3.4\%$
$t(\rightarrow \ell\nu b\gamma)q$ modelling	$\pm 1.9\%$
Additional background uncertainties	$\pm 1.9\%$
$tq\gamma$ modelling	$\pm 1.8\%$
$t(\rightarrow \ell\nu b\gamma)q$ MC statistics	$\pm 0.3\%$
Lepton fakes	$\pm 2.2\%$
$h \rightarrow \gamma$ photon fakes	$\pm 2.2\%$
$e \rightarrow \gamma$ photon fakes	$\pm 0.6\%$
Luminosity	$\pm 2.2\%$
Pileup	$\pm 1.2\%$
Jets and $E_T^{\text{miss}}$	$\pm 4.0\%$
Photons	$\pm 2.5\%$
Leptons	$\pm 0.9\%$
$b$ -tagging	$\pm 0.8\%$
Total systematic uncertainty	$\pm 10.9\%$

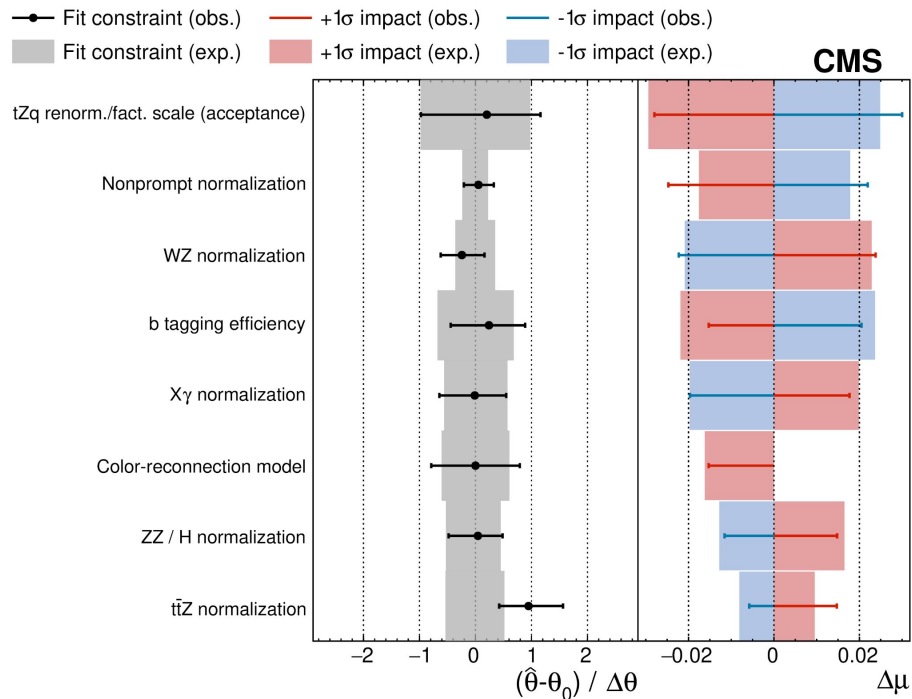
particle-level

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	$\pm 5.7\%$
Background MC statistics	$\pm 3.5\%$
$t\bar{t}$ modelling	$\pm 3.1\%$
$tq\gamma$ MC statistics	$\pm 3.1\%$
$t(\rightarrow \ell\nu b\gamma)q$ modelling	$\pm 2.2\%$
$tq\gamma$ modelling	$\pm 2.0\%$
Additional background uncertainties	$\pm 1.9\%$
$t(\rightarrow \ell\nu b\gamma)q$ MC statistics	$\pm 0.3\%$
Lepton fakes	$\pm 2.4\%$
$h \rightarrow \gamma$ photon fakes	$\pm 2.2\%$
$e \rightarrow \gamma$ photon fakes	$\pm 0.6\%$
Luminosity	$\pm 2.2\%$
Pileup	$\pm 1.3\%$
Jets and $E_T^{\text{miss}}$	$\pm 3.9\%$
Photons	$\pm 2.5\%$
Leptons	$\pm 0.9\%$
$b$ -tagging	$\pm 0.6\%$
Total systematic uncertainty	$\pm 11.0\%$

# Inclusive and differential $tZq$



[JHEP 02 \(2022\) 107](#)



# Search for charged lepton flavor violation



[CMS-TOP-19-006](#)

Source	$t\bar{t}$ (%)	CLFV signal	
		decay (%)	production (%)
Trigger	1.2	1.2	2.9
Electron identification and isolation	1.6	1.6	3.9
Muon identification and isolation	0.6	0.6	0.7
Electron energy scale and resolution	<0.1	<0.1	<0.1
Muon momentum scale and resolution	<0.1	<0.1	<0.1
Jet energy scale and resolution	2.5	2.1	1.2
b tagging	3.1	3.9	4.5
Pileup	0.3	0.3	0.2
ME scale	0.9	0.8	0.7
ISR/FSR scale	1.5	2.9	1.9
PDF	0.8	0.8	0.9
UE tune	0.4	—	—
ME/PS matching	<0.1	—	—
Color reconnection	1.0	—	—
MC statistical	<0.1	<0.1	<0.1

# Search for charged lepton flavor violation



CMS-TOP-19-006

Vertex	Int. type	Cross section [fb]		$C_{e\mu tq}/\Lambda^2$ [TeV <sup>-2</sup> ]		$\mathcal{B}(10^{-6})$	
		Exp	Obs	Exp	Obs	Exp	Obs
$e\mu tu$	Vector	7.02	6.78	0.12	0.12	0.14	0.13
	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
$e\mu tc$	Vector	11.21	9.73	0.39	0.37	1.49	1.31
	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59

$$O_{\text{vector}} = O_{lq} + O_{lu} + O_{eq} + O_{eu}$$

$$O_{\text{scalar}} = O_{\text{lequ}}^{(1)}$$

$$O_{\text{tensor}} = O_{\text{lequ}}^{(3)}$$

$$O_{lq}^{(3)abcd} = (\bar{l}_a \gamma^\mu \tau^I l_b) (\bar{q}_c \gamma_\mu \tau^I q_d),$$

$$O_{lq}^{(1)abcd} = (\bar{l}_a \gamma^\mu l_b) (\bar{q}_c \gamma_\mu q_d),$$

$$O_{lu}^{abcd} = (\bar{l}_a \gamma^\mu l_b) (\bar{u}_c \gamma_\mu u_d),$$

$$O_{eq}^{abcd} = (\bar{e}_a \gamma^\mu e_b) (\bar{q}_c \gamma_\mu q_d),$$

$$O_{eu}^{abcd} = (\bar{e}_a \gamma^\mu e_b) (\bar{u}_c \gamma_\mu u_d),$$

$$O_{\text{lequ}}^{(1)abcd} = (\bar{l}_a e_b) \varepsilon (\bar{q}_c u_d),$$

$$O_{\text{lequ}}^{(3)abcd} = (\bar{l}_a \sigma^{\mu\nu} e_b) \varepsilon (\bar{q}_c \sigma_{\mu\nu} u_d),$$



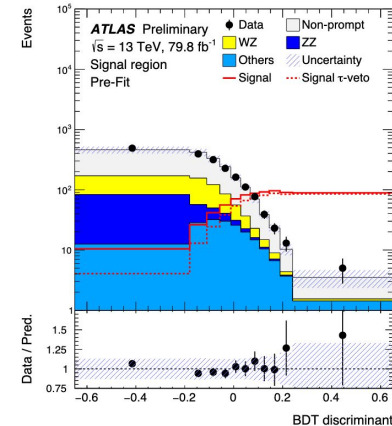
$t\ell\ell'q$  interaction  $\ell = e, \mu, q = u, c$  [79.8 fb<sup>-1</sup>]  
(ATLAS-CONF-2018-044)

## Remarks

Upper limit on inclusive process

Decay only, 3 $\ell$  final state

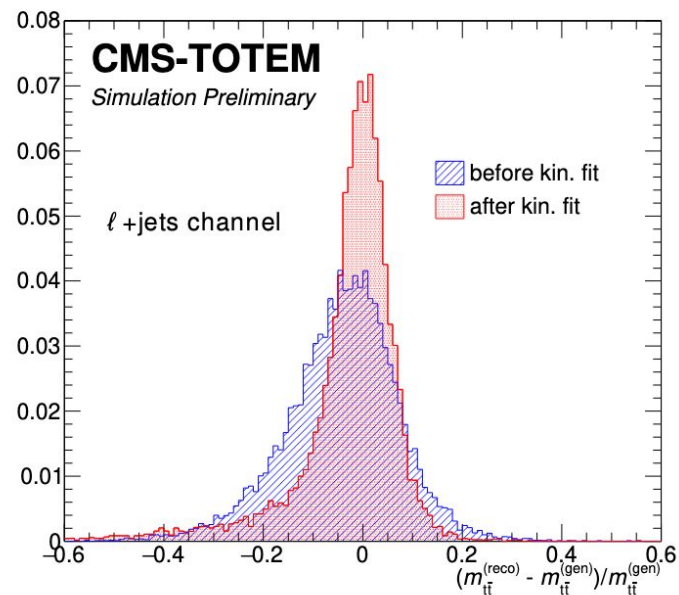
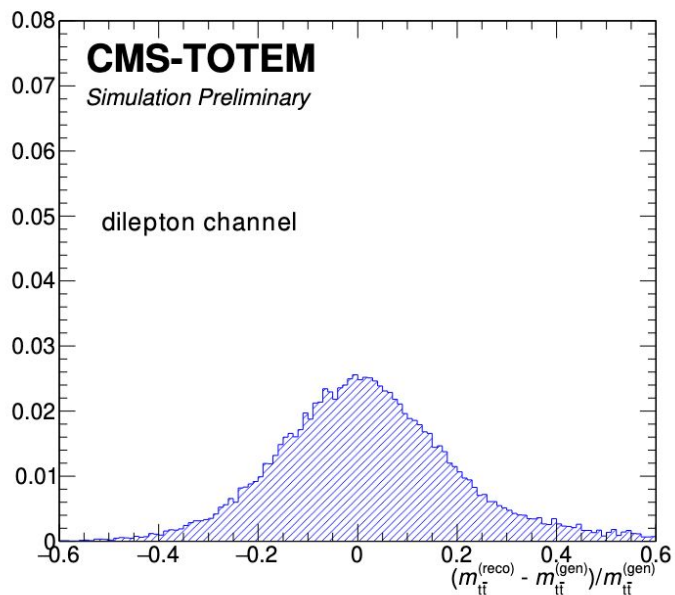
Different EFT basis, no EFT interpretation



# Central exclusive production of $t\bar{t}$ production



[CMS-PAS-TOP-21-007](#)

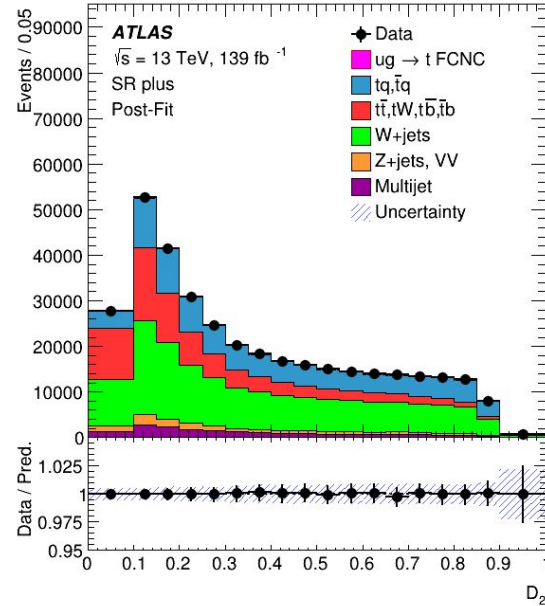
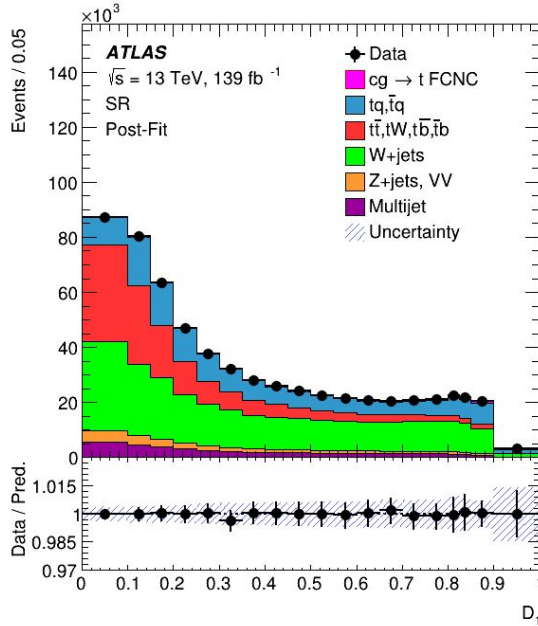
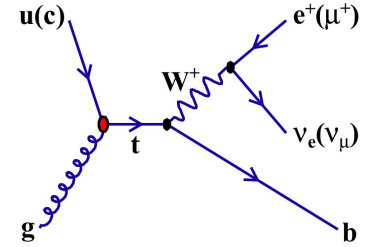




# FCNC: $tqg$



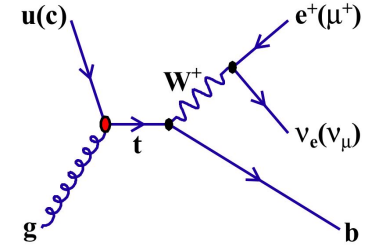
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# FCNC: $tqg$



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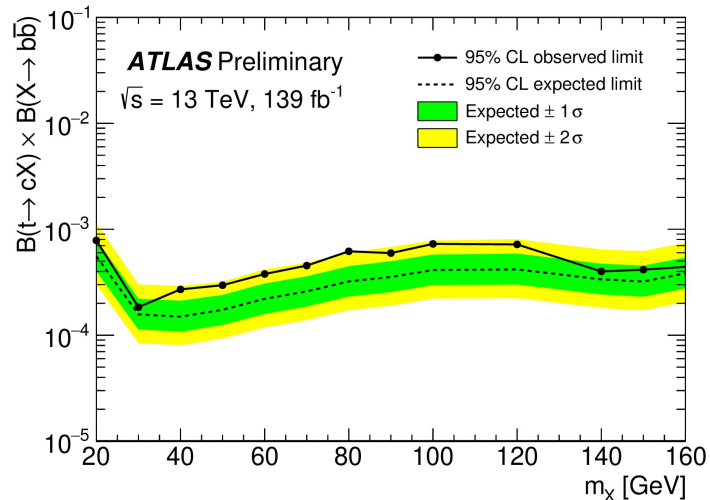
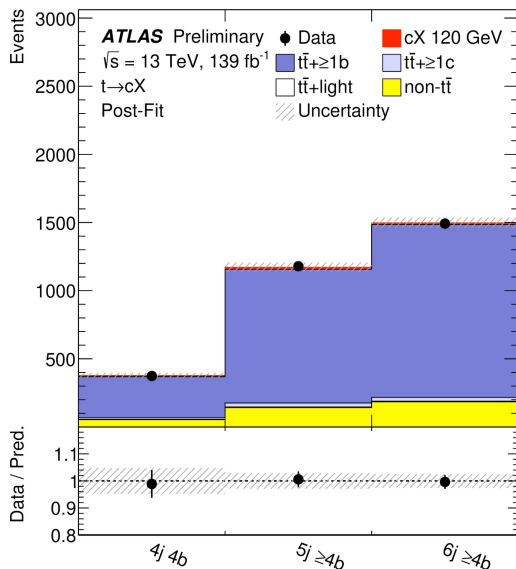
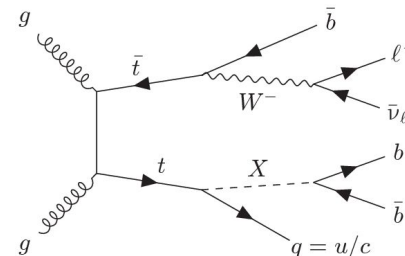
Description	$\mathcal{B}_{95}^{\text{exp}}(t \rightarrow u + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \rightarrow c + g)$
Data statistical only	$1.1 \times 10^{-5}$	$2.4 \times 10^{-5}$
Experimental uncertainties also	$3.1 \times 10^{-5}$	$12 \times 10^{-5}$
All uncertainties except MC statistical	$3.9 \times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

Analysis	$\mathcal{B}_{95}^{\text{obs}}(t \rightarrow u + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \rightarrow u + g)$	$\mathcal{B}_{95}^{\text{obs}}(t \rightarrow c + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \rightarrow c + g)$
ATLAS 13 TeV	$6.1 \times 10^{-5}$	$4.9 \times 10^{-5}$	$37 \times 10^{-5}$	$20 \times 10^{-5}$
ATLAS 8 TeV	$12 \times 10^{-5}$	$11 \times 10^{-5}$	$64 \times 10^{-5}$	$57 \times 10^{-5}$
CMS 7 TeV $\oplus$ 8 TeV	$2.0 \times 10^{-5}$	$2.8 \times 10^{-5}$	$41 \times 10^{-5}$	$28 \times 10^{-5}$

# FCNC: $tqX, X \rightarrow b\bar{b}$



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see Ken Johns' talk