Latest FCNC results from the CMS experiment

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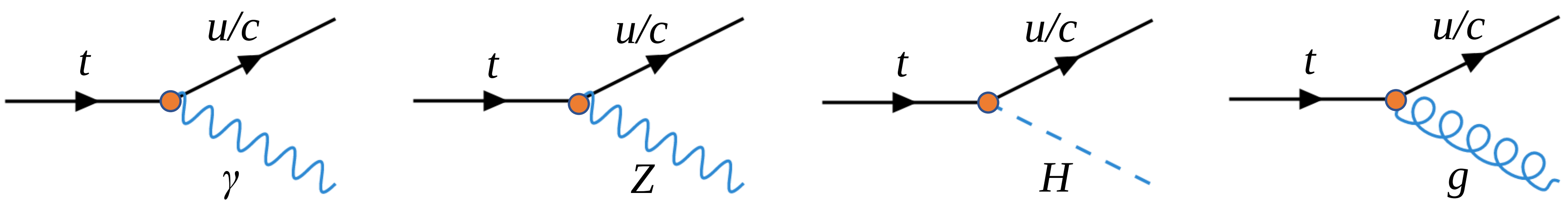
on behalf of the CMS collaboration

Conference on High Energy Physics
A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia

11-14 Sep 2023

Flavor-Changing Neutral Currents involving a top quark



FCNC forbidden at tree level in SM,
highly suppressed by the GIM mechanism beyond the tree level

Very low decay branching ratio in SM

$$\begin{cases} BR(t \to \gamma q) < 10^{-13} \\ BR(t \to Zq) < 10^{-14} \\ BR(t \to gq) < 10^{-11} \\ BR(t \to Hq) < 10^{-14} \end{cases}$$

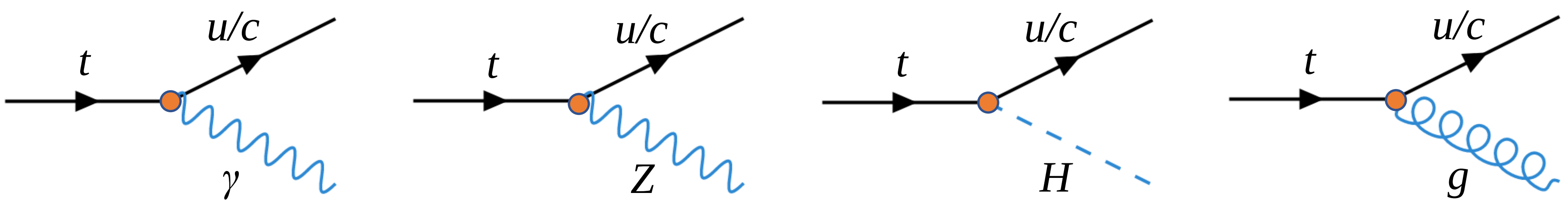
can be enhanced in BSM models →

		MSSM	2HDM
$BR(t \to \gamma q)$	~	10^{-8}	10^{-7}
$BR(t \to Zq)$	~	10^{-7}	10^{-6}
$BR(t \to gq)$	~	10^{-7}	10^{-5}
$BR(t \to Hq)$	~	10^{-5}	10^{-6}

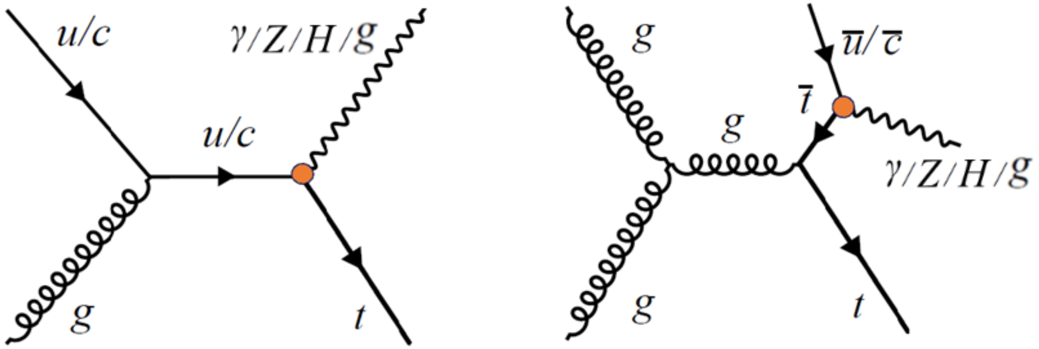
2209.11267

Any enhancement in the BR ⇒ Hint of BSM!

Flavor-Changing Neutral Currents involving a top quark



FCNC may appear in top quark **production** or **decay** at the LHC



Latest CMS FCNC results

***t-γ* :** **CMS PAS TOP-21-013** **new**

***t-g* :** **JHEP 02 (2017) 028**

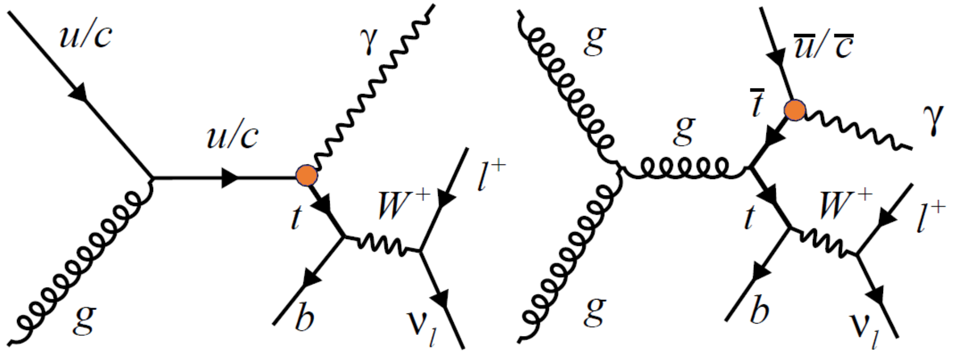
***t-H* :** **PRL 129 (2022) 032001 (*H*→*γγ*)**
JHEP 02 (2022) 169 (*H*→ *bb*)

***t-Z* :** **CMS-PAS-TOP-17-017**
JHEP 07 (2017) 003

FCNC t-γ

- **$tu\gamma/tc\gamma$ couplings** studied in **leptonic** final states
- **Full Run II data** (138 fb^{-1})

Signal Regions (1γ, $1e/\mu$)
- **SR1:** $N_{\text{jet}} = 1$, $N_{b-\text{jet}} = 1$
- **SR2:** $N_{\text{jet}} \geq 2$, $N_{b-\text{jet}} = 1$



Production mode *Decay mode*

Backgrounds

➤ **Prompt photon**

Simulation-based

Data-driven corrected: $tt\gamma$ + jets, $W/Z\,\gamma$ + jets

➤ **jet $\to \gamma$ misid**

*Data-driven method based on **ABCD** technique*

Photon-Like Jet (PLJ) region enriched in fake photons

Extrapolation Factor to transfer from PLJ region to SR

➤ **jet $\to e/\mu$ misid**

***Fake Rate** method*

FR computed in a dijet enriched region with $j \to l$ misid

Suitably defined CR reweighted by *FR*

➤ **$e \to \gamma$ misid**

Data-driven corrected simulation

CRs
- 2 tight e, $|m_{ee} - m_Z| < 10$ GeV
- 1 tight e, 1 medium γ, $|m_{e\gamma} - m_Z| < 10$ GeV

Jet/b-jet requirements same as SRs

$$SF = \frac{N_{e\gamma}(Data)/N_{ee}(Data)}{N_{e\gamma}(MC)/N_{ee}(MC)}$$

FCNC *t*-γ

CMS PAS TOP-21-013

Strategy ⇨ Multivariate classification based on BDT

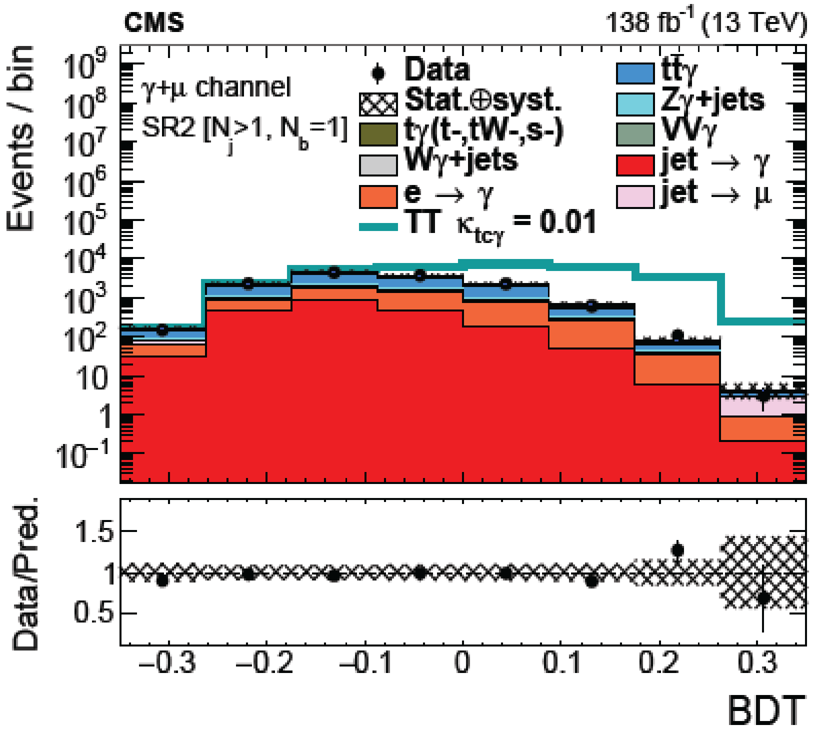
- 13 input variables
  Most important ones
  - **SR1:** p_T^{γ}, $\Delta R(\ell, b\text{-jet})$, m_{top}, $\Delta R(top, \gamma)$
  - **SR2:** $m_{jet+\gamma}$, p_T^{γ}, m_{top}, $\Delta R(\ell, b\text{-jet})$, $\Delta R(\ell, \gamma)$
- Separate BDTs for $tu\gamma$/$tc\gamma$ channels

Most important uncertainty sources

Non-prompt γ, normalizations of $Z\gamma$ + jets and $W\gamma$ + jets, misidentified γ

Limits obtained by combining SR1 and SR2

Combined	Obs. limit	Exp. limit	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9 - 8.4) \times 10^{-3}$	$(5.1 - 10.1) \times 10^{-3}$
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7 - 9.7) \times 10^{-3}$	$(5.7 - 11.5) \times 10^{-3}$
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89 - 1.78) \times 10^{-5}$	$(0.64 - 2.57) \times 10^{-5}$
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$



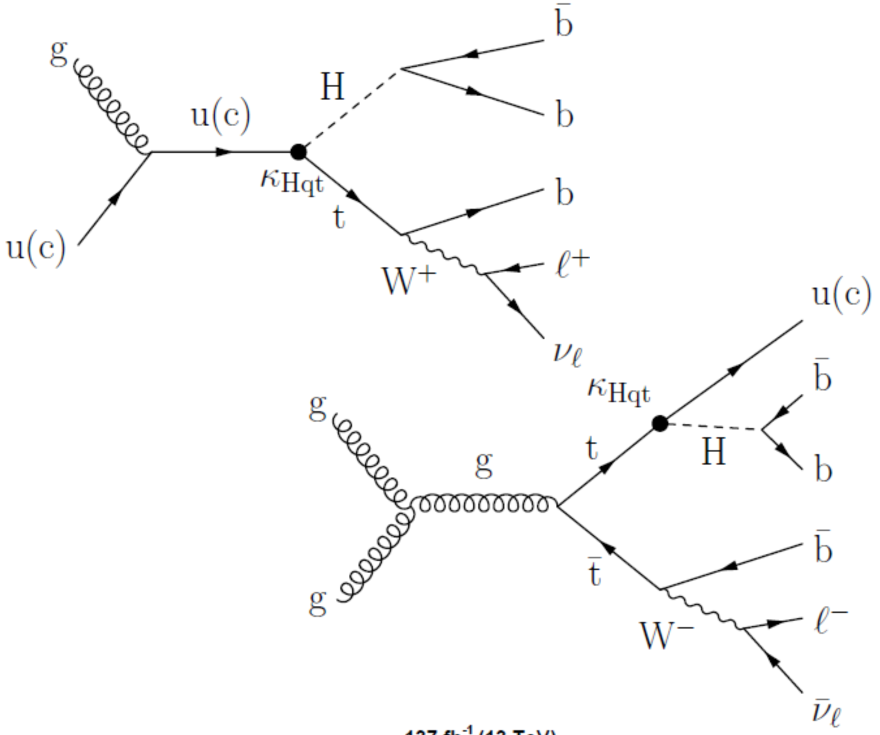
Improvement w.r.t. 8 TeV (19.8 fb^{-1}) CMS result 1511.03951

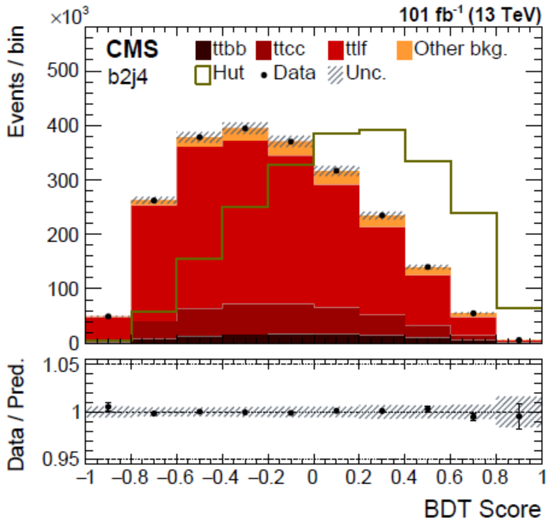
- ✓ FCNC top decay mode, *e* channel, int. luminosity
- ✓ Factor **10/100** improvement in limits on **BR($t \to u\gamma$)/BR($t \to c\gamma$)**

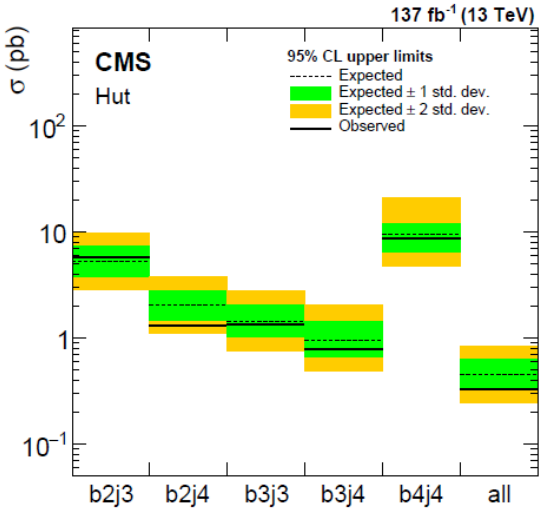
FCNC *t-H* ($H \to b\bar{b}$)

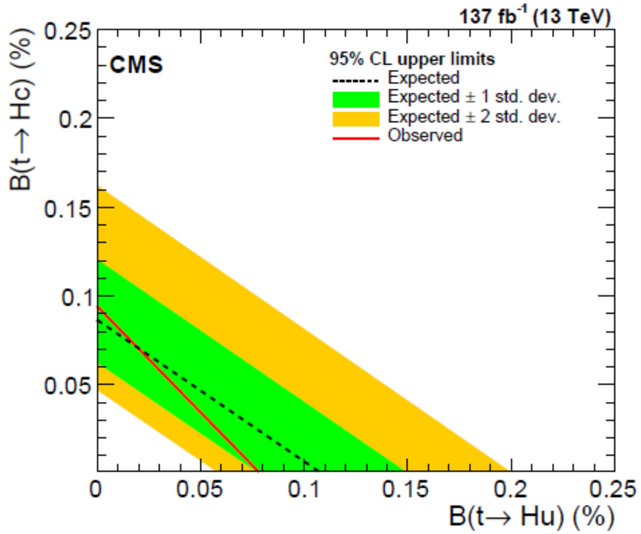
JHEP 02 (2022) 169

- **Top production/decay modes** with **13TeV (137 fb^{-1})** data
- $1e/\mu$, $N_{jet} \geq 3, 2 \leq N_{b-jet} \leq 4$
  5 SRs based on jet/*b*-jet multiplicity
- **2-step MVA**
  - Event rec: DNN selects the best jet assignment combination
  - Signal-bkg separation: BDT
- **Backgrounds**
  $t\bar{t}$ + jets, $t\bar{t}Z$, $t\bar{t}W$, …
- **Uncertainties**
  b-tagging, jet energy scale/resolution, bkg cross section, …









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JHEP 02 (2022) 169

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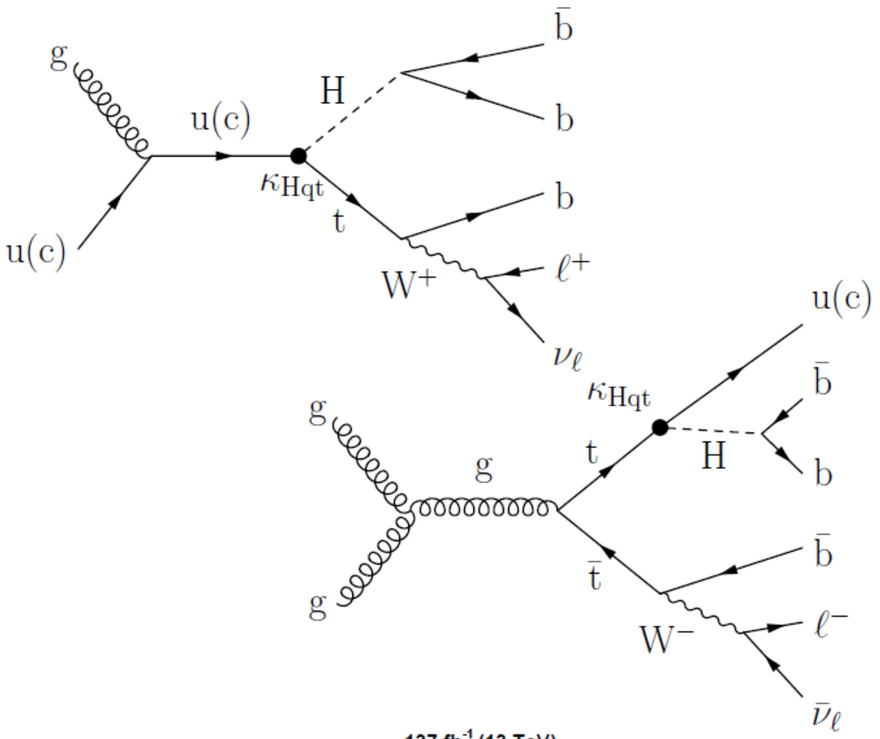
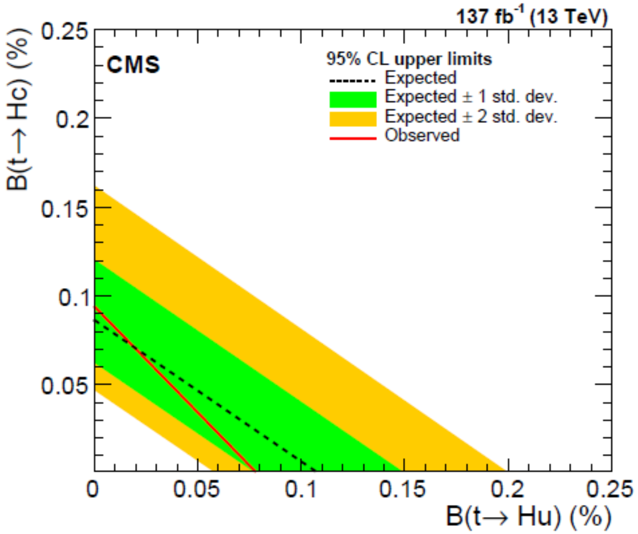
  $t\bar{t}$ + jets, $t\bar{t}Z$, $t\bar{t}W$, ...
- **Uncertainties**
  b-tagging, jet energy scale/resolution, bkg cross section, …
- **Limits**

		Observed	*Expected*
$\mathrm{BR}(t\rightarrow uH)$	<	7.9×10^{-4}	(1.1×10^{-3})
$\mathrm{BR}(t\rightarrow cH)$	<	9.4×10^{-4}	(8.6×10^{-4})

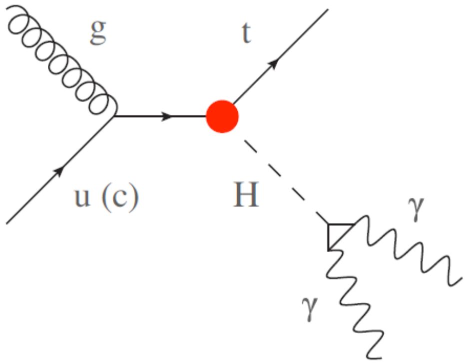


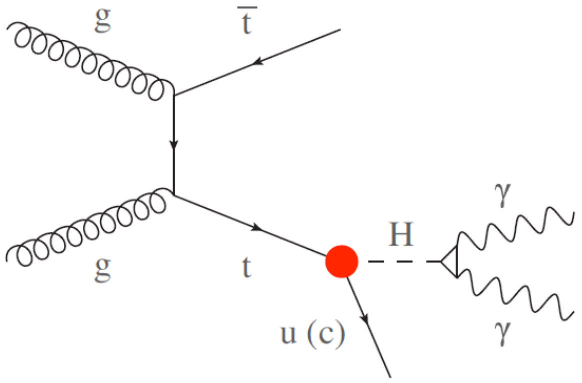


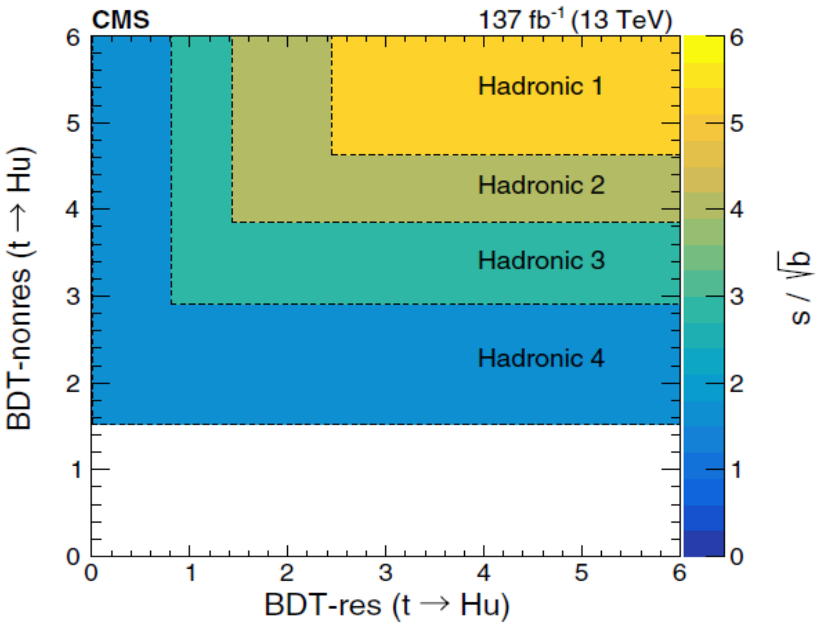
FCNC *t-H* ($H \to \gamma\gamma$)

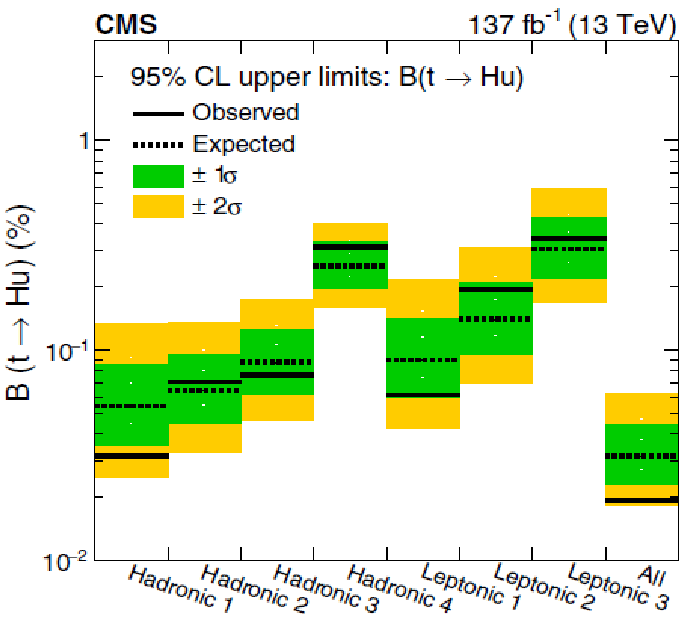
PRL 129 (2022) 032001

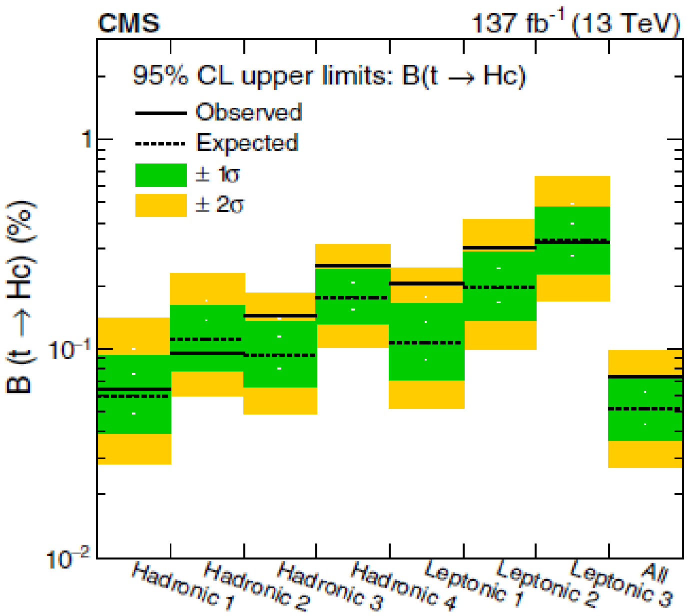
- ***tqH* coupling** studied in $\gamma\gamma$ final state with **top leptonic / hadronic** decay modes **(13 TeV / 137 fb^{-1})**
- **Multijet, γ+jets with $j \to \gamma$ misid bkg** estimated from data
- **NNs trained** to best identify top decay products
- **Separate BDTs** for resonant & nonresonant bkgs **used for SR definition**
- **Mass constraint variables / Quadratic equation method**
- **$m_{\gamma\gamma}$ distributions** fitted simultaneously











FCNC t-H ($H\to\gamma\gamma$)

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- ***tqH* coupling** studied in $\gamma\gamma$ final state with **top leptonic / hadronic** decay modes **(13 TeV / 137 fb^{-1})**
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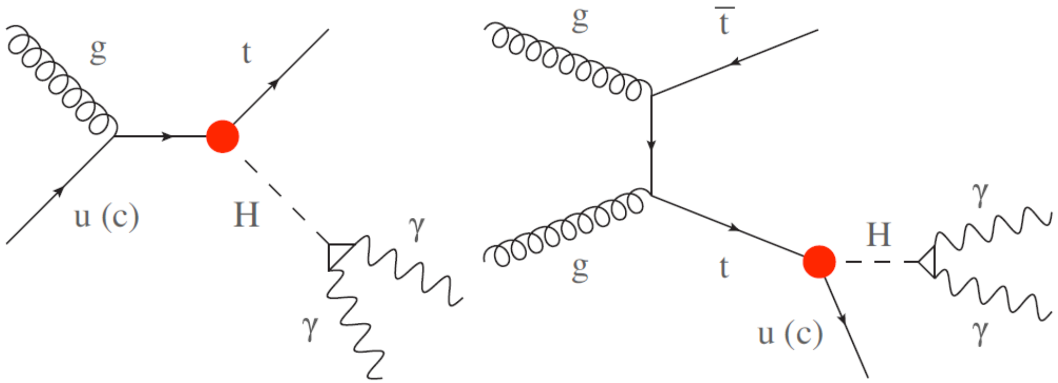


Limits *Observed (Expected)*

$\mathrm{BR}(t\to uH) < 1.9\times10^{-4}$ (3.1×10^{-4}) $\mathrm{BR}(t\to cH) < 7.3\times10^{-4}$ (5.1×10^{-4})

Limits from $H\to b\bar{b}$ search JHEP 02 (2022) 169

$\mathrm{BR}(t\to uH) < 7.9\times10^{-4}$ (1.1×10^{-3}) $\mathrm{BR}(t\to cH) < 9.4\times10^{-4}$ (8.6×10^{-4})

FCNC *t-Z*

JHEP 07 (2017) 003

- ***tZq* coupling** studied using data produced at $\sqrt{s} = 8$ TeV $(19.7\ \text{fb}^{-1})$
- **Single top / top pair production** in 3-lepton final states : $3e$, $2e1\mu$, $1e2\mu$, 3μ
- **Selection:**

  3 leptons (2 OSSF leptons in Z mass window) + { 1 jet, 1 *b*-tagged jet (ST) ; ≥ 2 jets, ≥ 1 *b*-tagged jet (TT) }

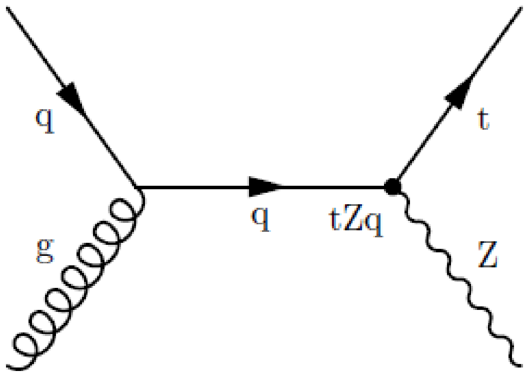
- **Backgrounds:**

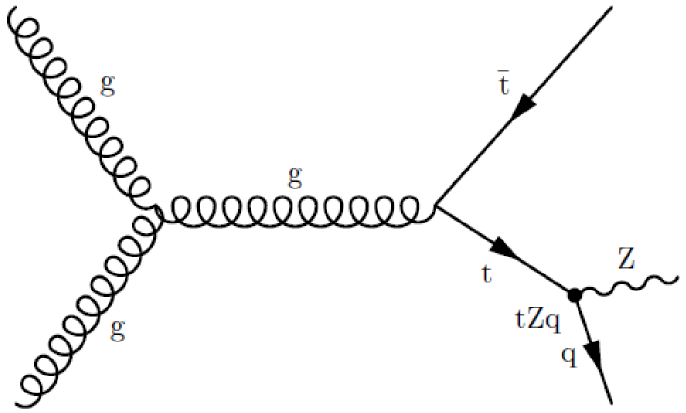
  Single top, *ttV*, diboson (*WZ* dominated), $t\bar{t}$, DY+jets

  $t\bar{t}$, DY+jets → **nonprompt-lepton bkg**

  diboson, nonprompt-lepton bkg → **data-driven estimation**

  inverted isolation criteria on 3rd lepton for nonprompt bkg est.





- **BDT** trained using top/*Z* kinematic variables, charge (asymmetry) of the lepton from *W* decay, jet/*b*-tagging properties
- **Uncertainties:** JES, JER, *b*-tagging, background normalization, …

FCNC *t-Z*

JHEP 07 (2017) 003

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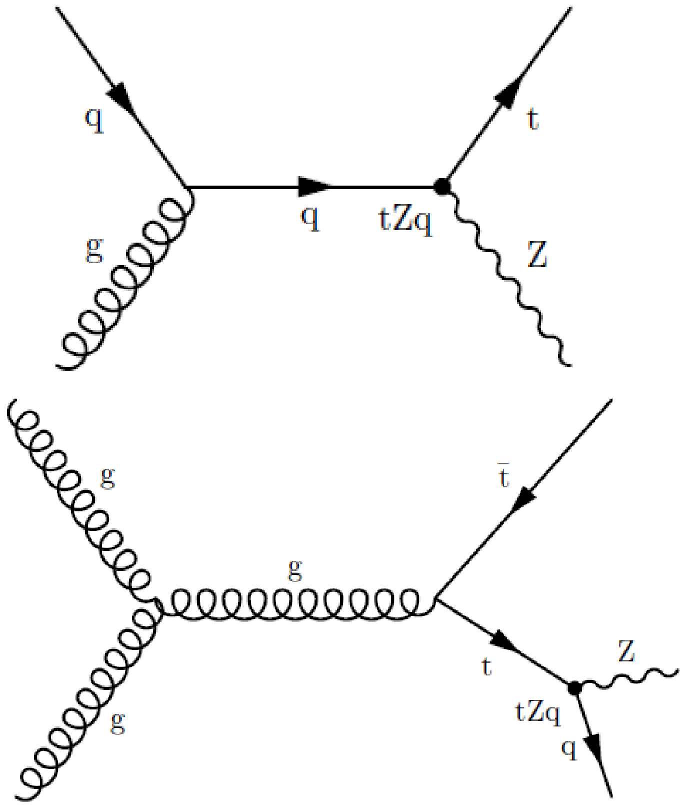
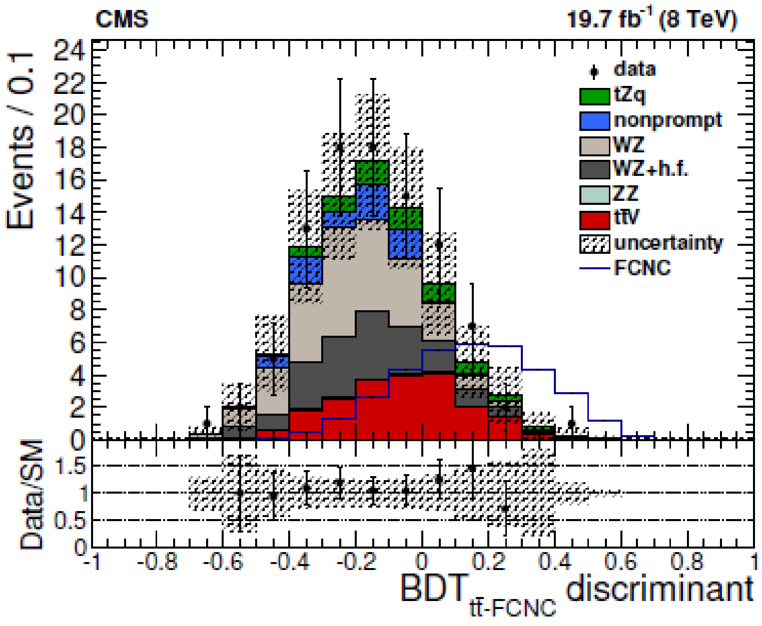
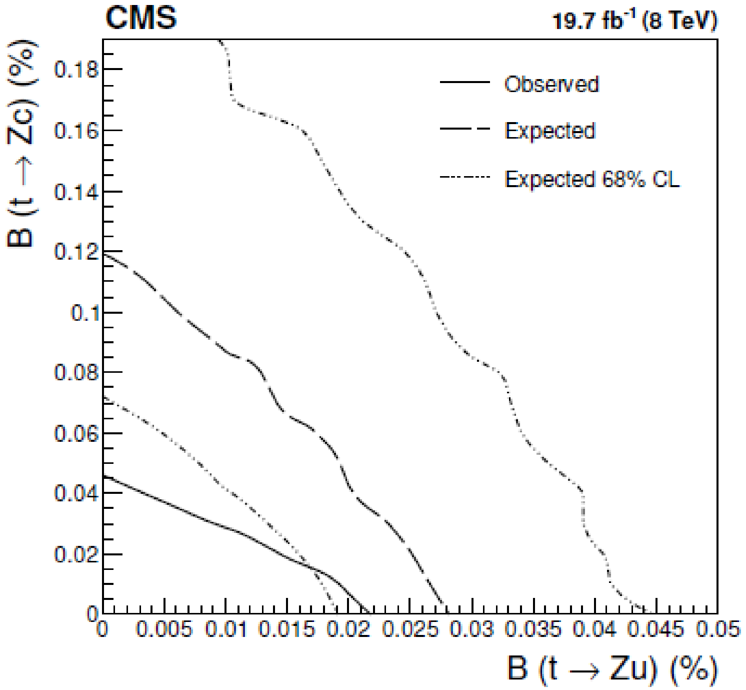




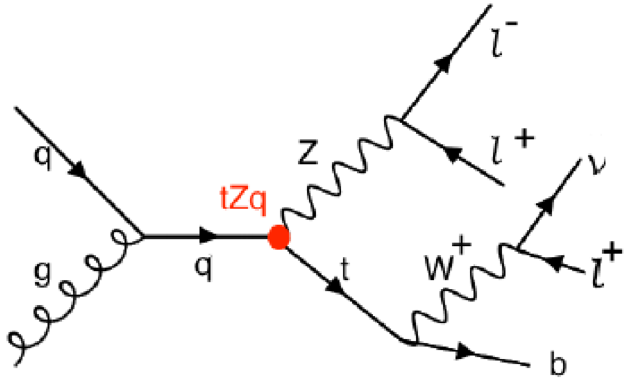


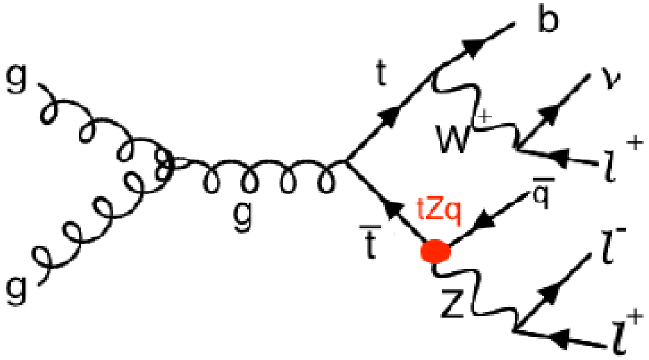
Limits	*Observed*	*Expected*
BR($t\to uZ$)	$< 2.2\times10^{-4}$	(2.7×10^{-4})
BR($t\to cZ$)	$< 4.9\times10^{-4}$	(1.18×10^{-3})

FCNC *t-Z*

CMS-PAS-TOP-17-017

- ***tuZ* and *tcZ* couplings** studied using 2016 data (13 TeV / 35.9 fb^{-1})
- **ST, TT** production modes
- **Both *Z*,*W* decay leptonically** → 3-lepton final states
- **Important bkgs:** *WZ*+jets, $t\bar{t}Z$, *SM tZq* (3-lepton topology identical to signal)
- **Not prompt-lepton bkg** coming from DY+jets, $t\bar{t}$





5 statistically independent regions

	STSR	TTSR	WZCR	STCR	TTCR
N_{jet}	1	$\geq 2, \leq 3$	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$
N_{b-jet}	1	≥ 1	0	1	≥ 1
Z window	✓	✓	✓	✗	✗

WZCR: *WZ*+jets, NPLs from DY+jets

STCR, TTCR: NPLs from $t\bar{t}$ +jets

- **BDT** trained using kinematic observables and *b*-tagging information separately in each SR and lepton channel

FCNC *t-Z*

CMS-PAS-TOP-17-017

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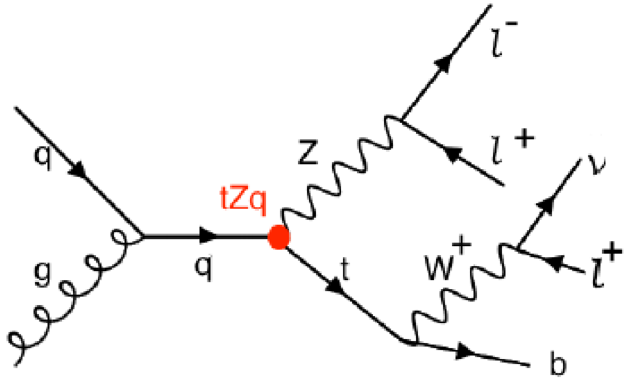
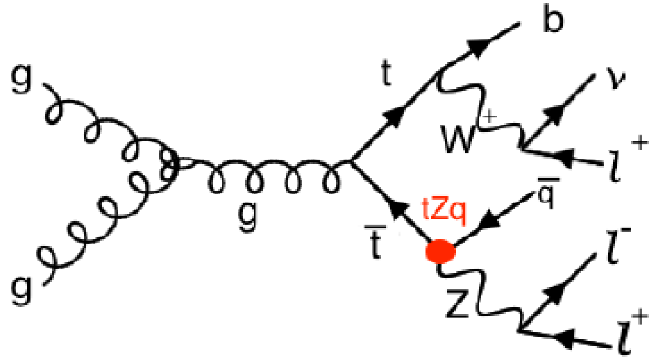
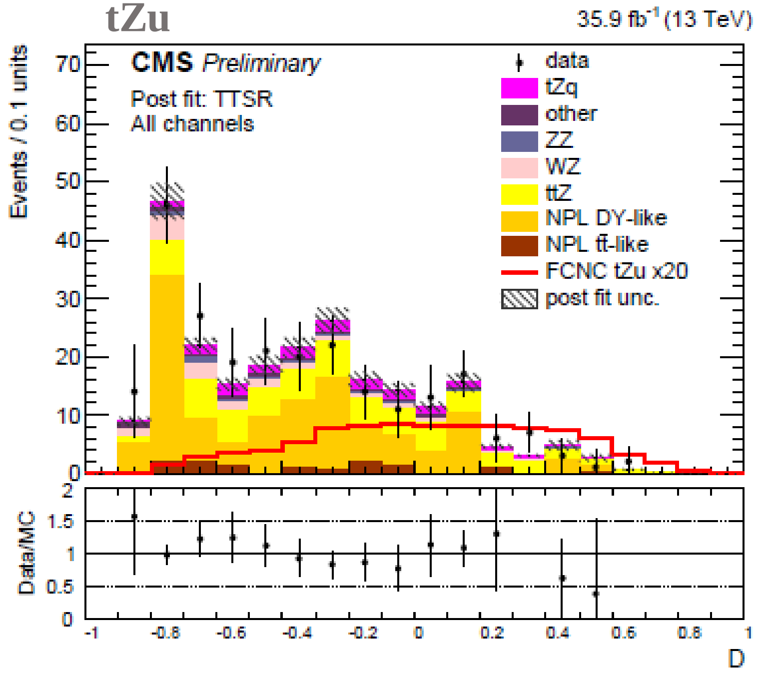
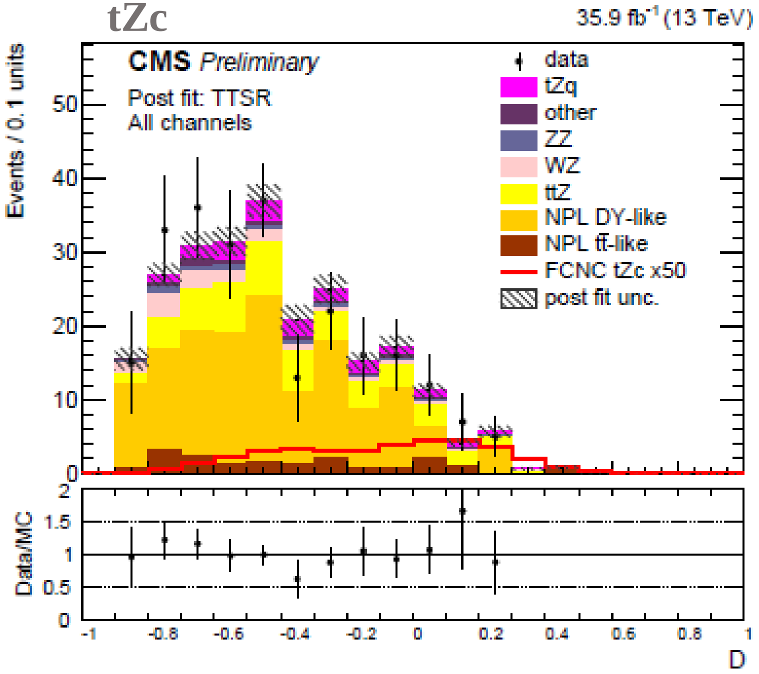




tZu



tZc



- **Uncertainties:** NPL yield normalization, backgrounds cross sections, scale factors, jet energy scale, …

FCNC *t-Z*

CMS-PAS-TOP-17-017

- ***tuZ* and *tcZ* couplings** studied using 2016 data (13 TeV / 35.9 fb^{-1})
- **ST, TT** production modes
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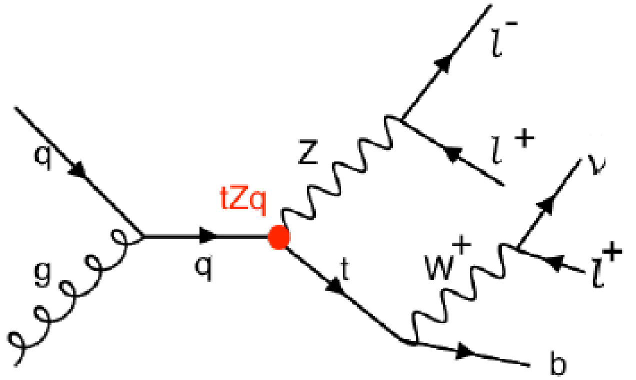
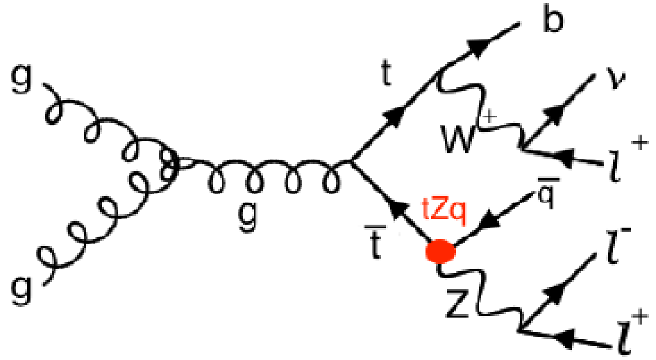
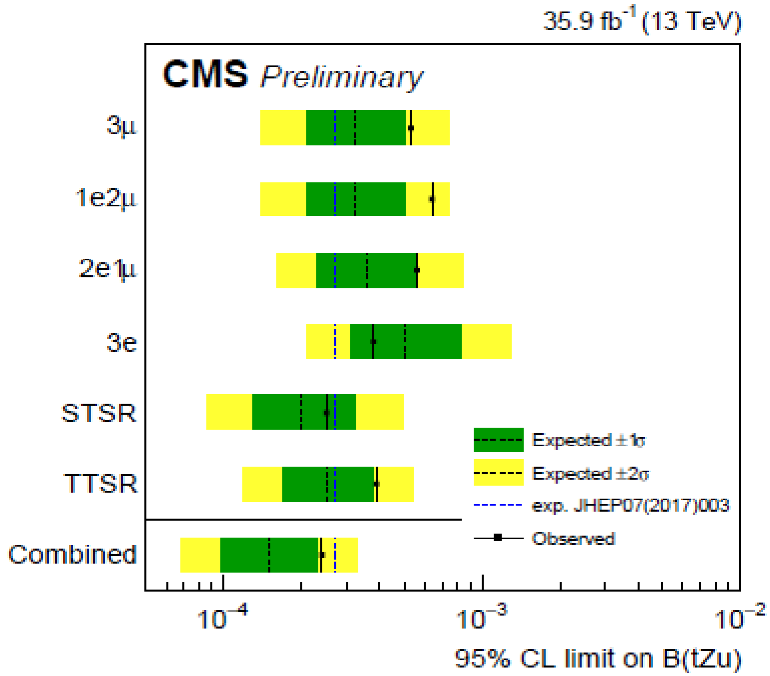
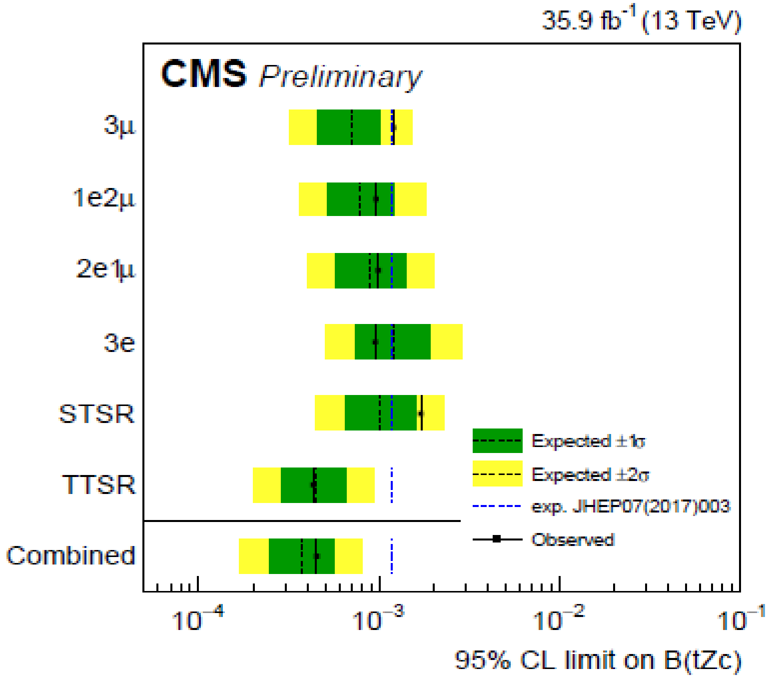








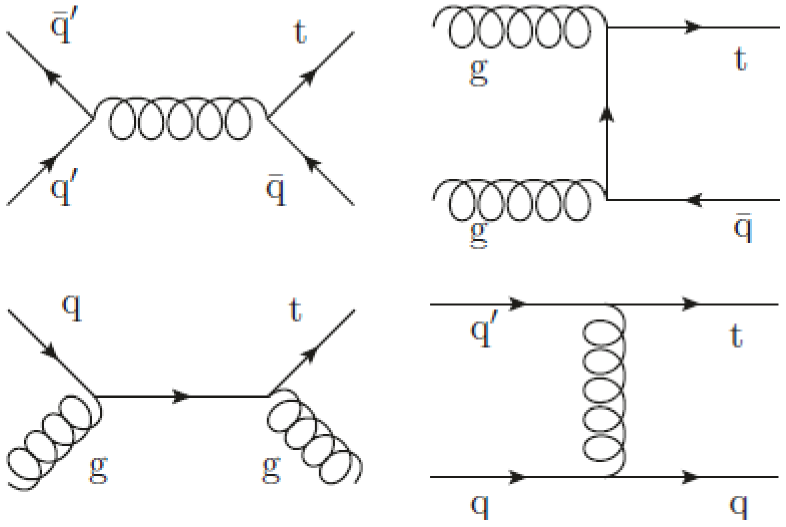
Limits		*Observed*	*Expected*
$BR(t\to uZ)$	<	2.4×10^{-4}	(1.5×10^{-4})
$BR(t\to cZ)$	<	4.5×10^{-4}	(3.7×10^{-4})

Limits from JHEP 07 (2017) 003			
$BR(t\to uZ)$	<	2.2×10^{-4}	(2.7×10^{-4})
$BR(t\to cZ)$	<	4.9×10^{-4}	(1.18×10^{-3})

FCNC *t-g*

JHEP 02 (2017) 028

- ***tqg*** studied using **5 fb^{-1} (7 TeV)** and **19.7 fb^{-1} (8 TeV)** of data
- **SR:** 1μ, $N_{jet} = 2$ or 3, $N_{b-jet} \geq 1$, $N_{non\ b-tagged} \geq 1$



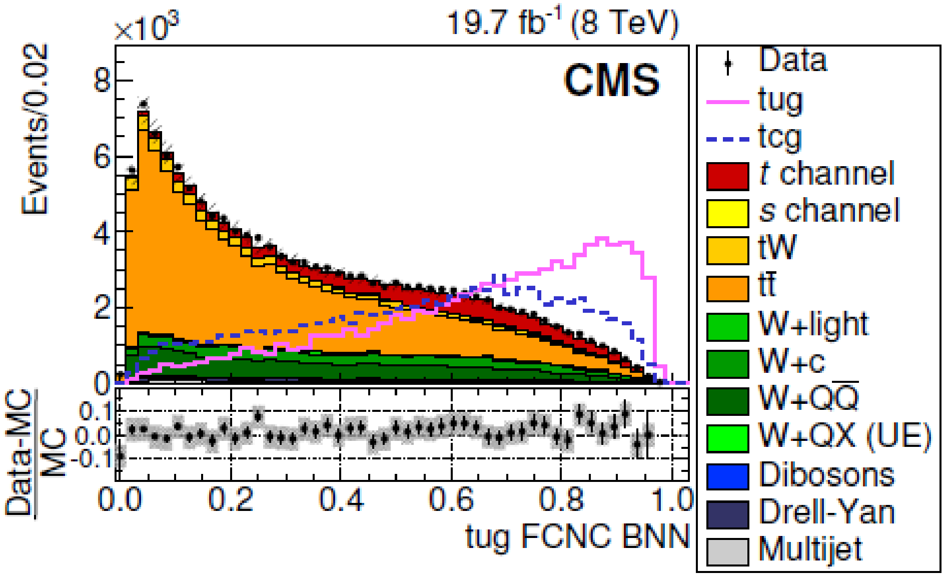
Main backgrounds

- ***W*+jets, $t\bar{t}$**

Constrained using dedicated CRs

- **non-prompt *μ***

Mostly from multijet production
Estimated using CR defined by inverted isolation criteria
Suppressed by imposing the cut BNN > 0.7
BNN trained with $M_T(W)$, $\Delta\phi(\mu, \vec{p}_T^{miss})$, …



Signal extraction

Separate BNNs for ***FCNC tug/tcg*** signals
p_z^{ν} obtained by *W* mass constraint

FCNC *t-g*

JHEP 02 (2017) 028

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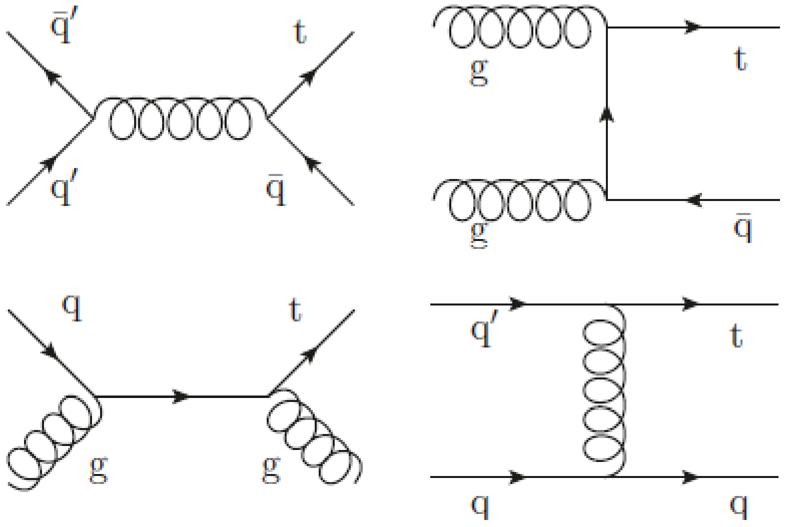

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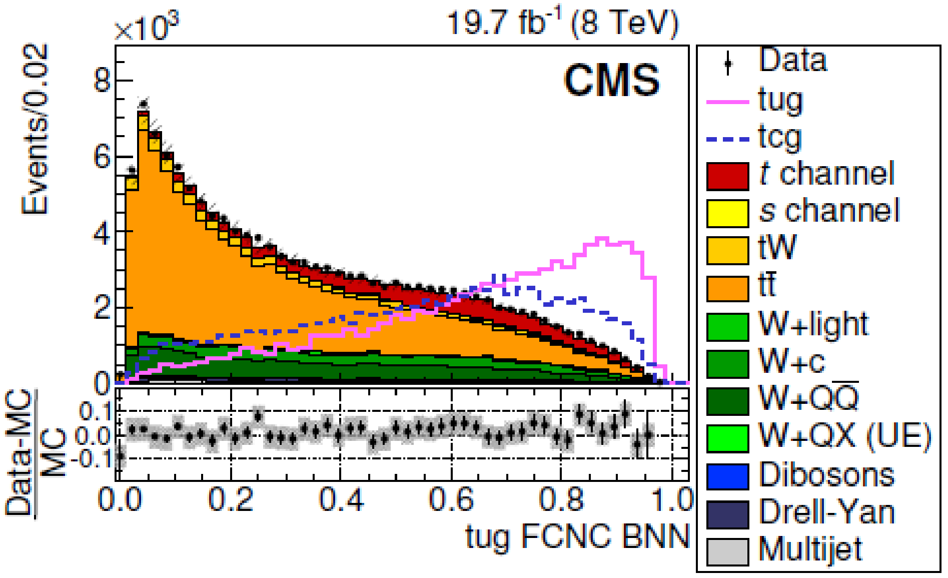
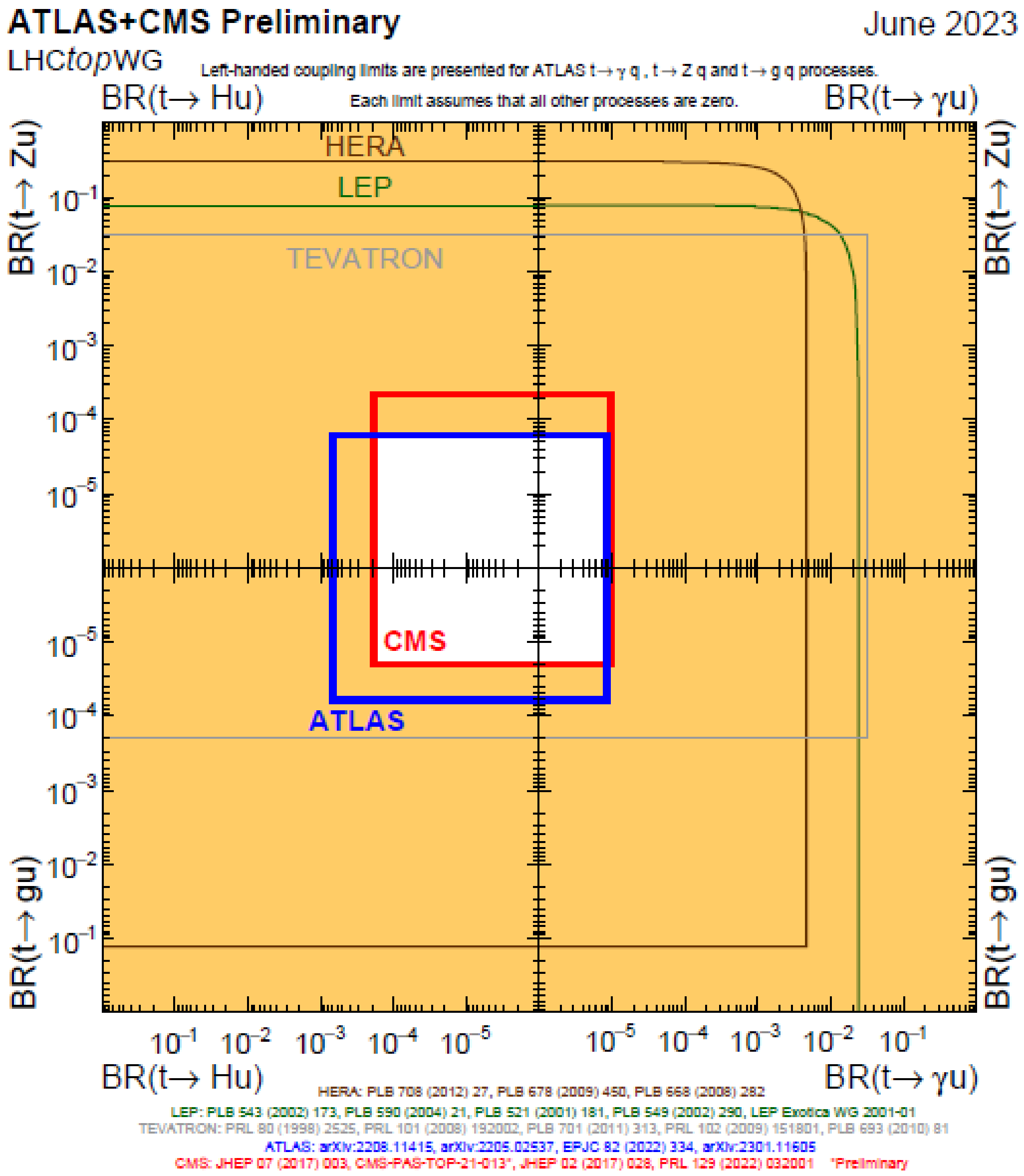
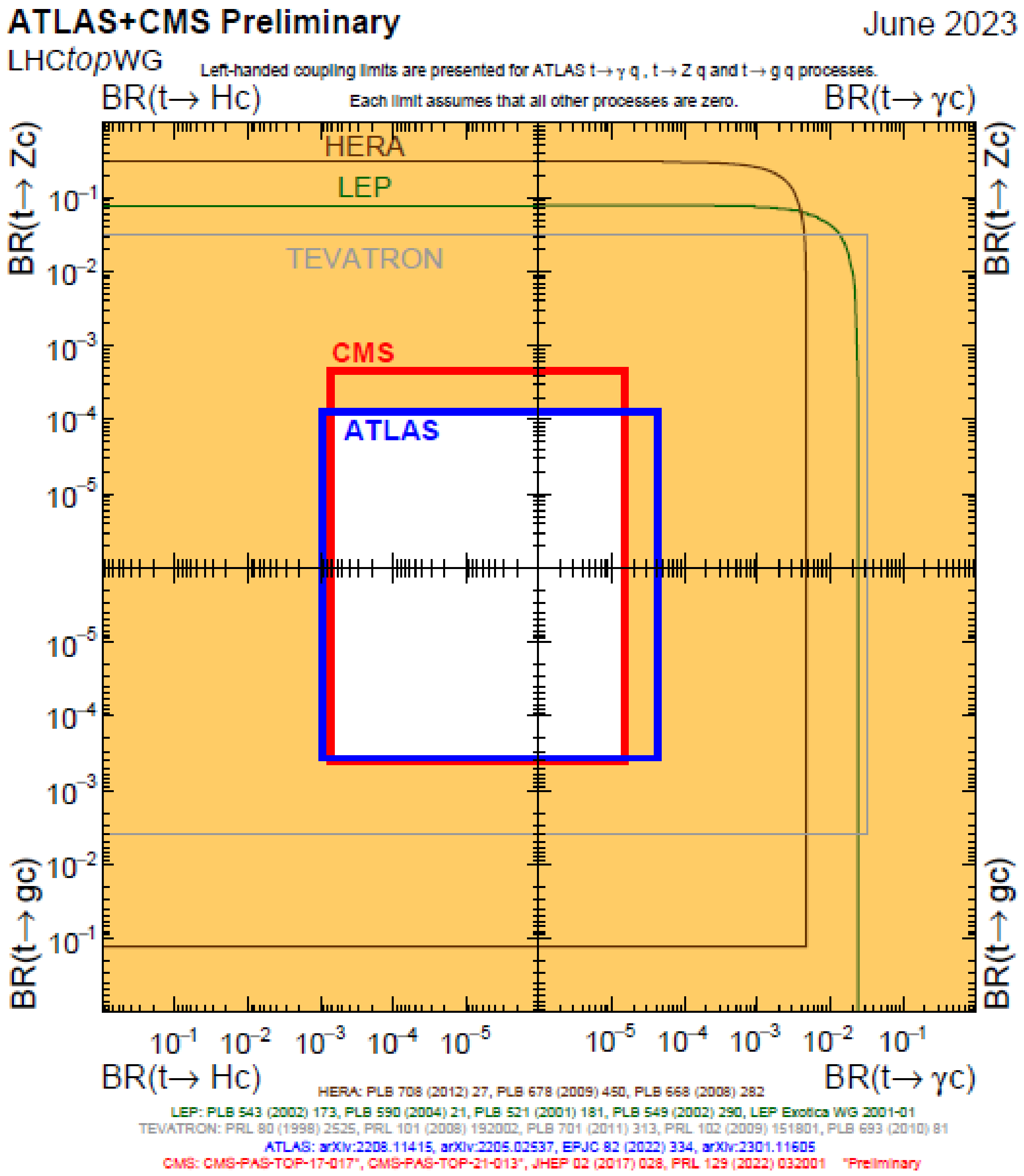


Limits:

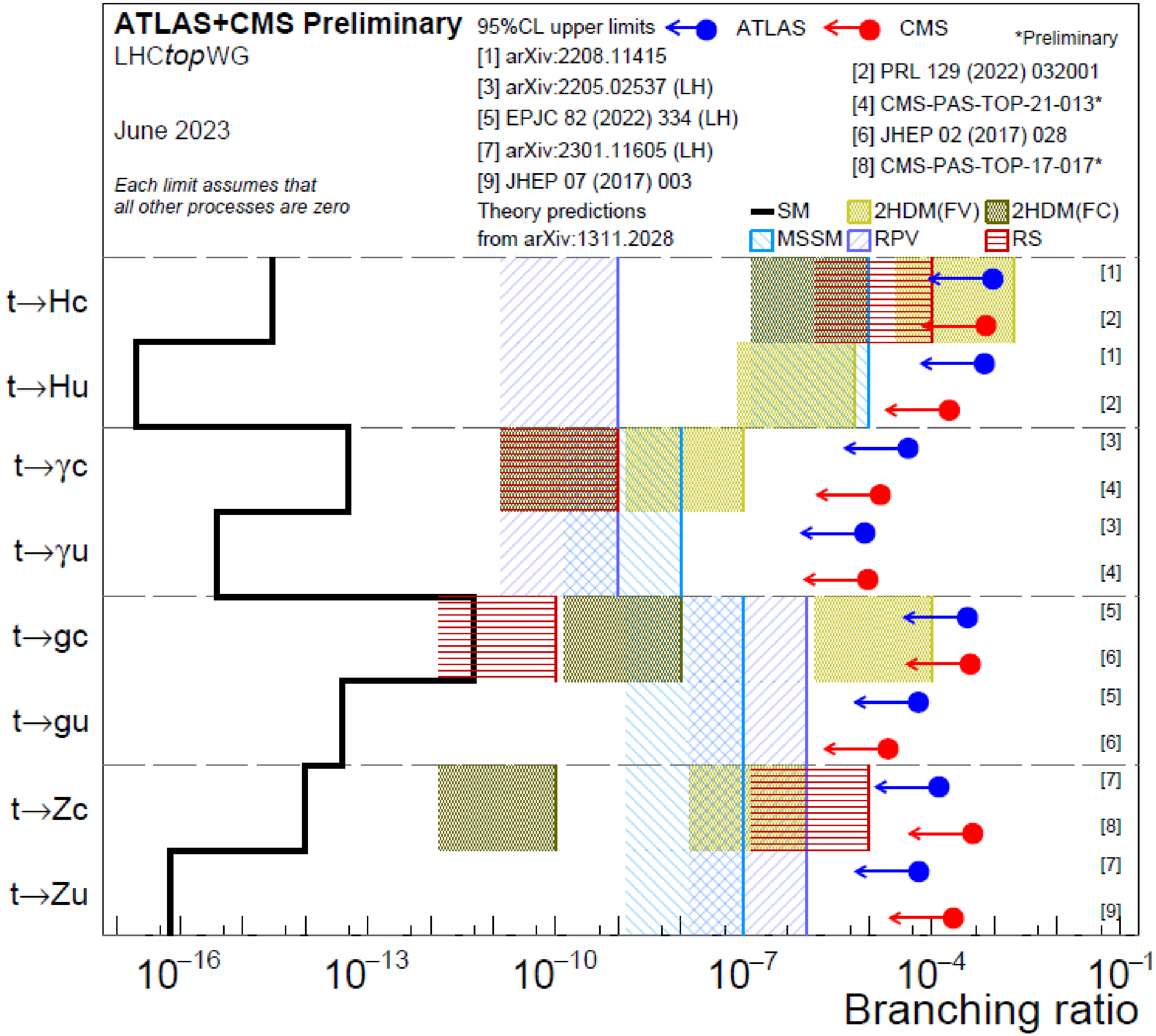
		Observed	*Expected*
BR($t\to ug$)	<	2.0×10^{-5}	(2.8×10^{-5})
BR($t\to cg$)	<	4.1×10^{-4}	(2.8×10^{-4})

Summary of the current observed limits





Summary of the current observed limits



Summary & outlook

Top quark measurements at the LHC provide a golden opportunity to test the SM and probe new physics. CMS experiment continues to analyze Top events to find deviations from the SM and shed light on unknown phenomena.

Current 95% CL observed (expected) limits on top FCNC decays by the CMS experiment:

$$BR(t \to u\gamma) < 0.95 \times 10^{-5}\ (1.20 \times 10^{-5})$$
$$BR(t \to c\gamma) < 1.51 \times 10^{-5}\ (1.54 \times 10^{-5})$$

$$BR(t \to uZ) < 2.2 \times 10^{-4}\ (2.7 \times 10^{-4})$$
$$BR(t \to cZ) < 4.5 \times 10^{-4}\ (3.7 \times 10^{-4})$$

$$BR(t \to uH) < 1.9 \times 10^{-4}\ (3.1 \times 10^{-4})$$
$$BR(t \to cH) < 7.3 \times 10^{-4}\ (5.1 \times 10^{-4})$$

$$BR(t \to ug) < 2.0 \times 10^{-5}\ (2.8 \times 10^{-5})$$
$$BR(t \to cg) < 4.1 \times 10^{-4}\ (2.8 \times 10^{-4})$$

So far, there are no signs of any new physics!

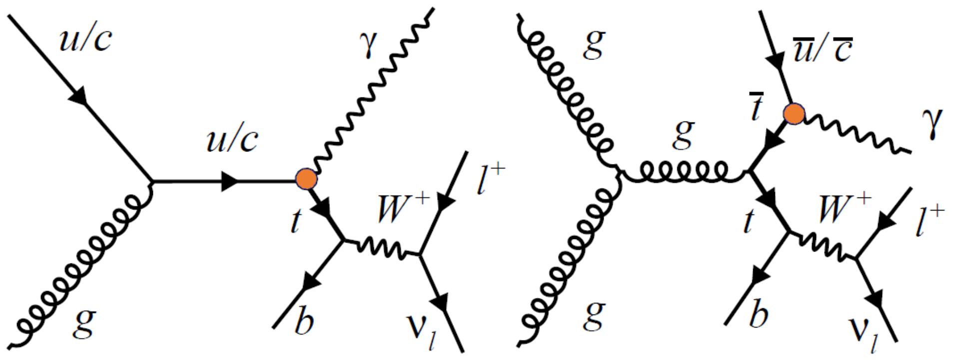
So, the upcoming searches are going to be very exciting!

Backup

FCNC t-γ Signal / Bkg

CMS PAS TOP-21-013

- **$tu\gamma$ / $tc\gamma$ couplings** studied in **leptonic (e, μ)** final states
- **Full Run II data** (138 fb^{-1})
- **Selection**
  1 photon, 1 electron / muon



Production mode *Decay mode*

Signal Regions

SR1	SR2
$N_{\text{jet}} = 1$, $N_{b-\text{jet}} = 1$	$N_{\text{jet}} \geq 2$, $N_{b-\text{jet}} = 1$
⇩	⇩
top ***production*** *mode*	top ***decay*** *mode*

Backgrounds

- **Prompt photon**
  Simulation-based using parental info of photons
  e.g. $tt\gamma$ + jets, $W\gamma$ + jets , $Z\gamma$ + jets, $tj\gamma$, $WW\gamma$, $WZ\gamma$, $ZZ\gamma$
  Data-driven corrected: $tt\gamma$ + jets, $W\gamma$ + jets, $Z\gamma$ + jets
- **Jets misidentified as photon (jet $\rightarrow \gamma$)**
- **Jets misidentified as electron/muon (jet $\rightarrow e/\mu$)**
- **Electrons misidentified as photon ($e \rightarrow \gamma$)**

FCNC *t-γ* Background estimation

CMS PAS TOP-21-013

Jets misidentified as photon (jet$\rightarrow\gamma$) ⇨ *Data-driven method based on* ***ABCD*** *technique*

Photon-Like Jet (PLJ) region:

Enriched in fake photons

Defined by inverted γ ID/Iso (Loose ID)

Misidentified normalization in SR determined using the Extrapolation Factor:

$$EF(p_T^\gamma) = \frac{N_A^{\text{Mis.Id.}}(p_T^\gamma)}{N_{PLJ}(p_T^\gamma)}$$

Sideband regions defined by **PFChIso**, $\sigma_{i\eta i\eta}$ variables ⇨ $N_A^{\text{Mis.Id.}}(p_T^\gamma) = \frac{N_B(p_T^\gamma) \times N_C(p_T^\gamma)}{N_D(p_T^\gamma)}$

Uncertainties

Non-zero correlation between PFChIso and $\sigma_{i\eta i\eta}$

Contamination of sideband and PLJ regions with prompt photons

Validity of method ensured by comparing data-driven and simulation-based estimations

Dominated by $W+$jets, $Z+$jets, top pair, single top, diboson processes

FCNC t-γ Background estimation

CMS PAS TOP-21-013

Jets misidentified as electron/muon (jet $\rightarrow e/\mu$)

Modeled using the ***Fake Rate*** method:

$$FR\,(p_T^l, \eta^l) = \frac{\text{\# of events passing tight selection}}{\text{\# of all events}}$$

- Computed in a region dominated by di-jet events with one jet $\rightarrow e/\mu$ misidentification
- Apply weight $w = \frac{FR}{1-FR}$ to CR defined by requiring one loose (not tight) lepton
- Contamination from real leptons subtracted

Validation using γ + jet simulated sample

Compare γ + jet yield from FR method with its direct contribution

Dominated by γ + jets , $W\gamma$ + jets , $Z\gamma$ + jets , $tt\gamma$ + jets, …

FCNC t-γ *Background estimation*

CMS PAS TOP-21-013

Electrons misidentified as photon ($e \longrightarrow \gamma$) *Data-driven corrected simulation*

Modeling
Simulation-based (rec. γ matched to gen. e)
Scale Factors applied to correct the simulation

Control Regions
- **DY + jets CR** ⇒ 2 tight electrons, $|m_{ee} - m_Z| < 10$ GeV
- **$e \longrightarrow \gamma$ CR** ⇒ 1 tight electron, 1 medium photon, $|m_{e\gamma} - m_Z| < 10$ GeV

Scale Factors defined as $SF(e \longrightarrow \gamma) = \dfrac{\frac{N_{e\gamma}(Data)}{N_{ee}(Data)}}{\frac{N_{e\gamma}(MC)}{N_{ee}(MC)}}$

Dominated by
- **e** channel: DY + jets, $t\bar{t}$, single top tW-channel, diboson (ee decay mode)
- **μ** channel: $t\bar{t}$, single top tW-channel, diboson ($e\mu$ decay mode)

FCNC t-γ *Limits*

CMS PAS TOP-21-013

Strategy ⇒ Multivariate classification based on BDT

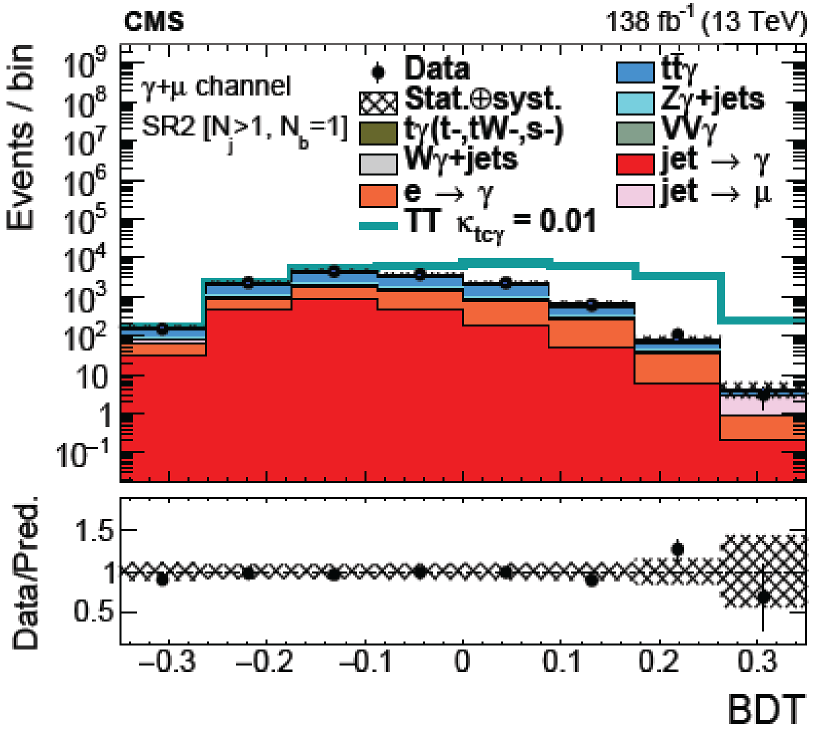
- 13 input variables
  Most important ones
  - **SR1:** p_T^{γ}, $\Delta R(\ell, b\text{-jet})$, m_{top}, $\Delta R(top, \gamma)$
  - **SR2:** $m_{jet+\gamma}$, p_T^{γ}, m_{top}, $\Delta R(\ell, b\text{-jet})$, $\Delta R(\ell, \gamma)$
- Separate BDTs for $tu\gamma$/$tc\gamma$ channels

Most important uncertainty sources

Non-prompt γ, normalizations of $Z\gamma$ + jets and $W\gamma$ + jets, misidentified γ

Limits obtained by combining SR1 and SR2

Combined	Obs. limit	Exp. limit	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9 - 8.4) \times 10^{-3}$	$(5.1 - 10.1) \times 10^{-3}$
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7 - 9.7) \times 10^{-3}$	$(5.7 - 11.5) \times 10^{-3}$
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89 - 1.78) \times 10^{-5}$	$(0.64 - 2.57) \times 10^{-5}$
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$



Improvement w.r.t. 8 TeV (19.8 fb^{-1}) CMS result 1511.03951

- ✓ FCNC top decay mode, e channel, int. luminosity
- ✓ Factor **10/100** improvement in limits on **BR($t \to u\gamma$)/BR($t \to c\gamma$)**