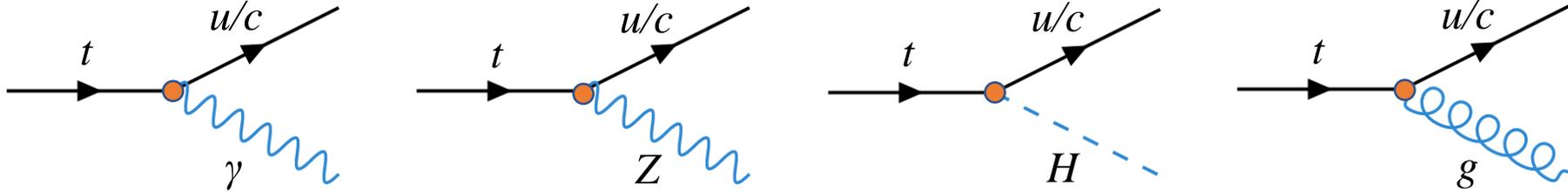# Latest FCNC results from the CMS experiment

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

can be enhanced in

BSM models

MSSM 2HDM

$$\begin{cases} \mathrm{BR}(t \to \gamma q) \sim 10^{-8} \quad 10^{-7} \\ \mathrm{BR}(t \to Zq) \sim 10^{-7} \quad 10^{-6} \\ \mathrm{BR}(t \to gq) \sim 10^{-7} \quad 10^{-5} \\ \mathrm{BR}(t \to Hq) \sim 10^{-5} \quad 10^{-6} \end{cases}$$

2209.11267

Any enhancement in the BR ⟹ Hint of BSM!

Flavor-Changing Neutral Currents involving a top quark
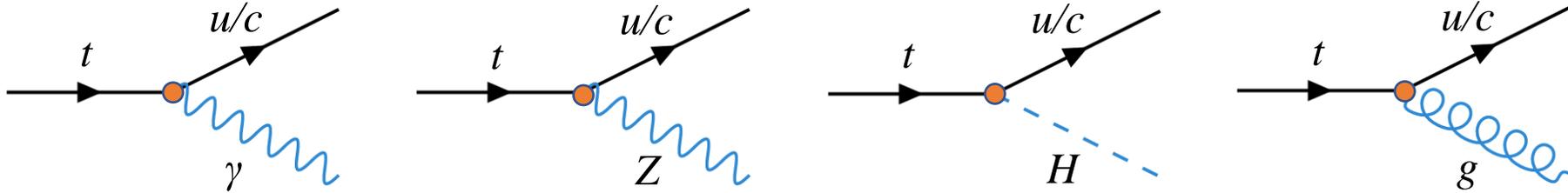
FCNC may appear in top quark **production** or **decay** at the LHC
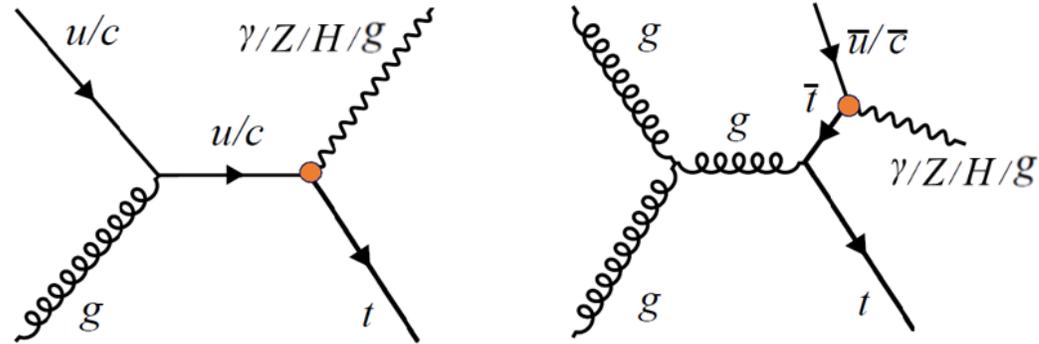
Latest CMS FCNC results

t-γ : CMS PAS TOP-21-013 *new*

t-H : PRL 129 (2022) 032001 ($H{\to}\gamma\gamma$)

JHEP 02 (2022) 169 ($H{\to} bb$)

t-g : JHEP 02 (2017) 028

t-Z : CMS-PAS-TOP-17-017

JHEP 07 (2017) 003

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FCNC t-γ

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

Signal Regions $\begin{cases} \textbf{SR1: } N_{\text{jet}} = 1, N_{b-\text{jet}} = 1 \\ \textbf{SR2: } N_{\text{jet}} \geq 2, N_{b-\text{jet}} = 1 \end{cases}$
1γ, $1e/\mu$

Backgrounds

➤ **Prompt photon**
  Simulation-based
  Data-driven corrected: $tt\gamma$ + jets, $W/Z\,\gamma$ + jets

➤ **jet → γ misid**
  Data-driven method based on **ABCD** *technique*
  Photon-Like Jet (PLJ) region enriched in fake photons
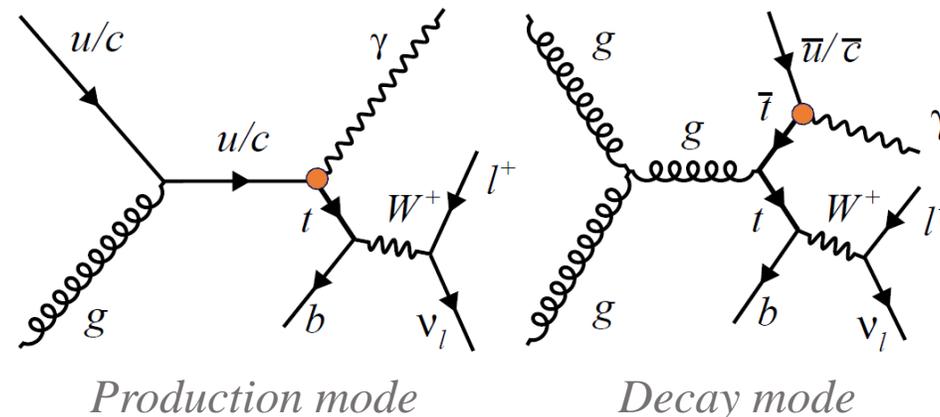 **Extrapolation Factor** to transfer from PLJ region to SR

➤ **jet → e/μ misid**
  Fake Rate *method*
  FR computed in a dijet enriched region with $j \to l$ misid
  Suitably defined CR reweighted by *FR*

Production mode   *Decay mode*

➤ **$e \to \gamma$ misid**
  Data-driven corrected simulation

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

Strategy ⟹ **Multivariate classification based on BDT**

➢ 13 input variables

Most important ones $\begin{cases} \textbf{SR1: } p_T^\gamma, \Delta R(\ell, b\text{-jet}), m_{top}, \Delta R(top, \gamma) \\ \textbf{SR2: } m_{jet+\gamma}, p_T^\gamma, m_{top}, \Delta R(\ell, b\text{-jet}), \Delta R(\ell, \gamma) \end{cases}$

➢ Separate BDTs for $tu\gamma/tc\gamma$ channels
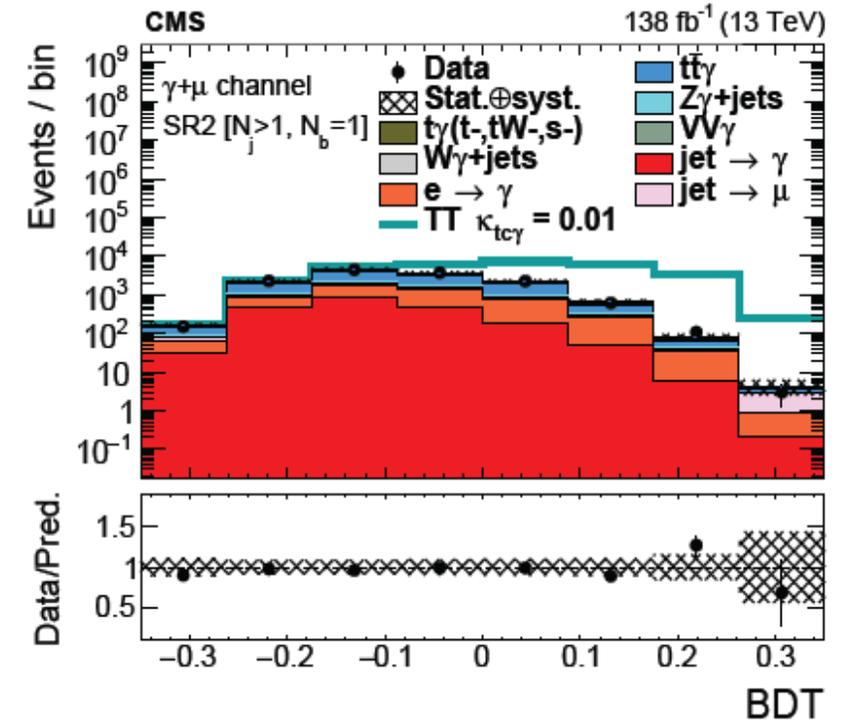
Most important uncertainty sources

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* ($H \to b\bar{b}$)

❖ **Top production/decay modes** with **13TeV (137 fb^{-1})** data

❖ $1e/\mu$, $N_{jet} \geq 3$, $2 \leq N_{b-jet} \leq 4$
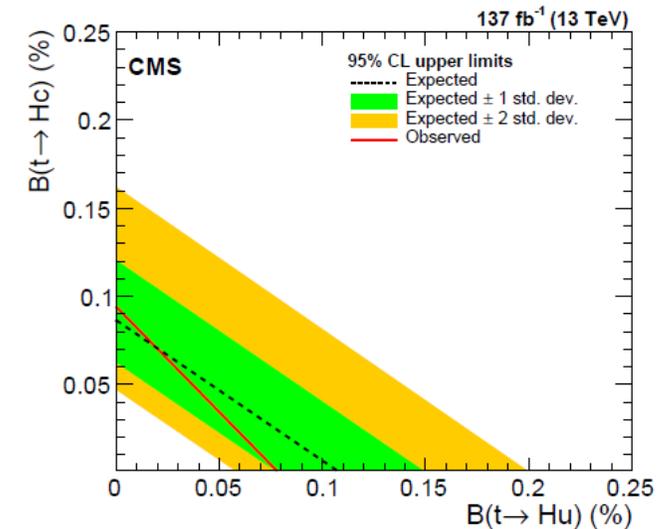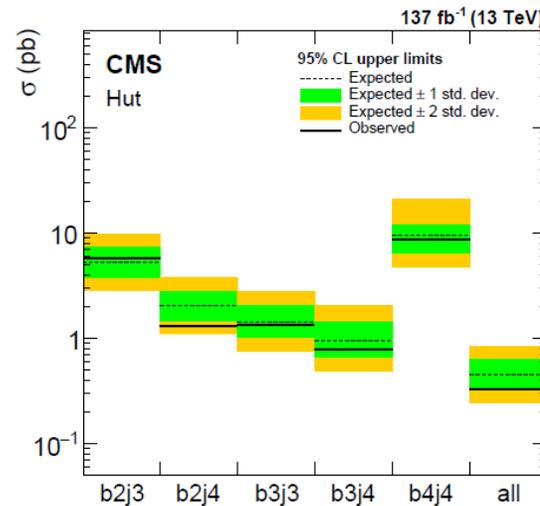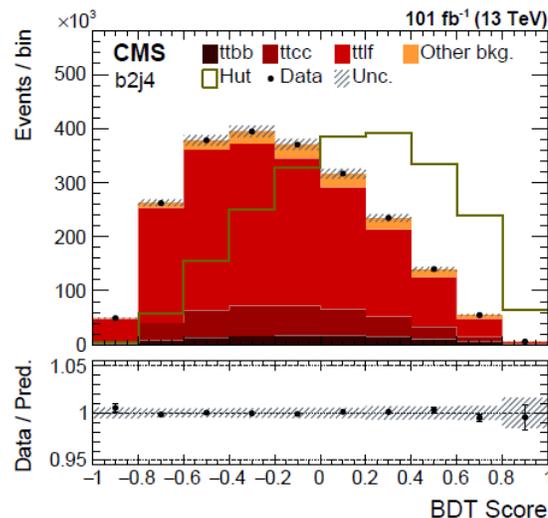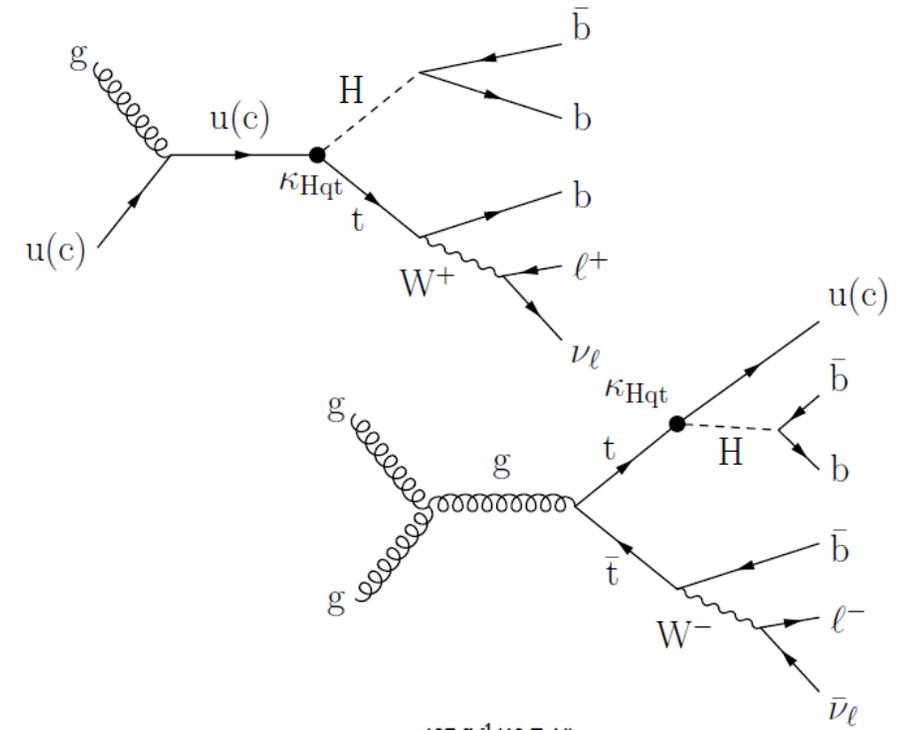 **5 SRs** based on jet/*b*-jet multiplicity

❖ **2-step MVA** $\begin{cases} \text{Event rec: DNN selects the best jet assignment combination} \\ \text{Signal-bkg separation: BDT} \end{cases}$

❖ **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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FCNC t-H ($H \to b\bar{b}$)

❖ **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** $\begin{cases} \text{Event rec: DNN selects the best jet assignment combination} \\ \text{Signal-bkg separation: BDT} \end{cases}$
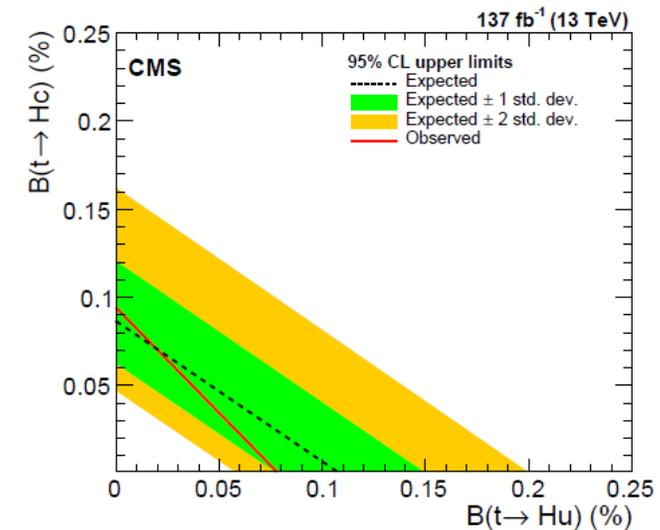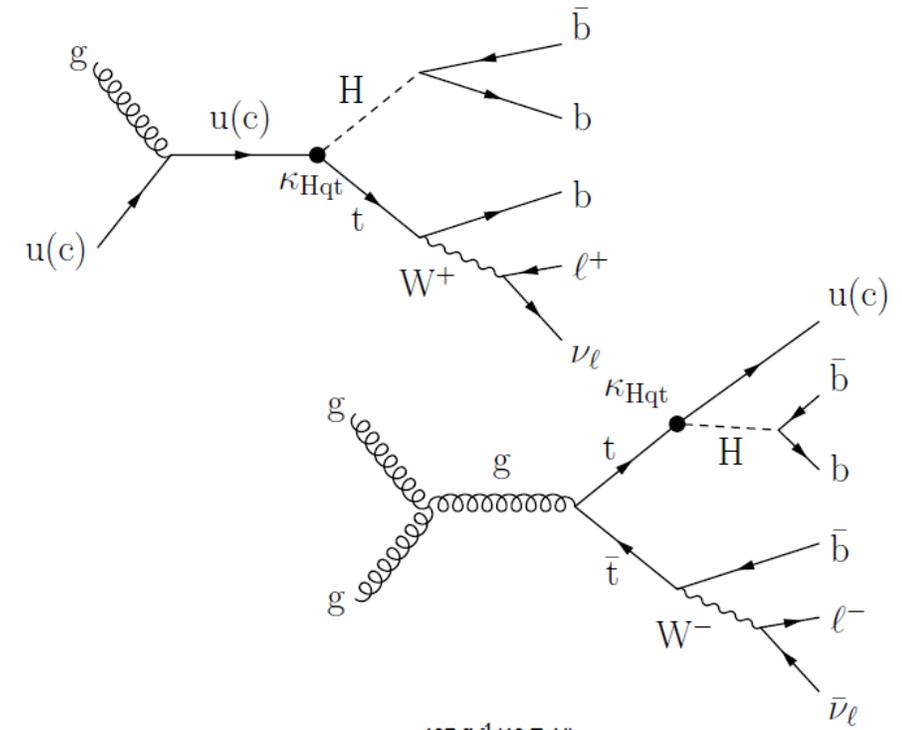
❖ **Backgrounds**
  $t\bar{t}$ + jets, $t\bar{t}Z$, $t\bar{t}W$, ...

❖ **Uncertainties**
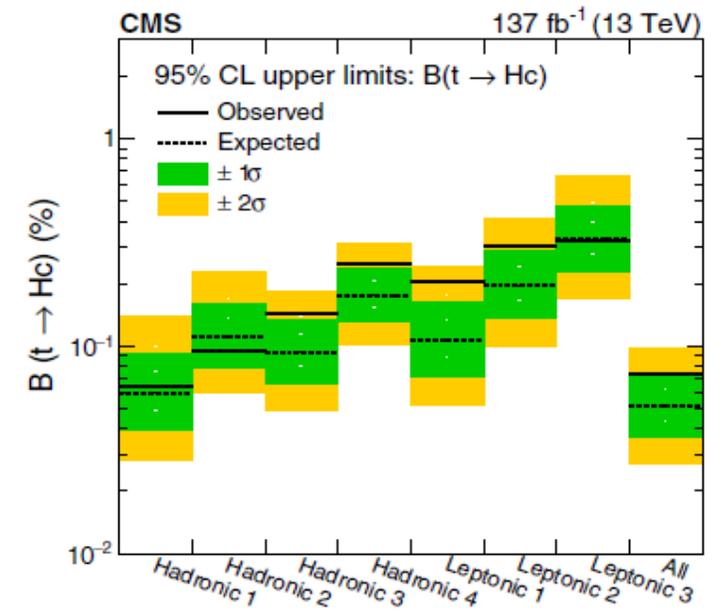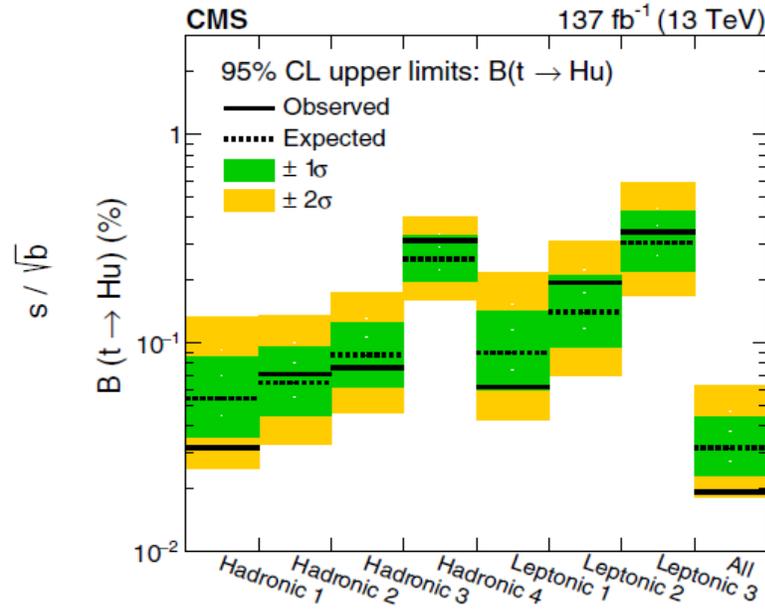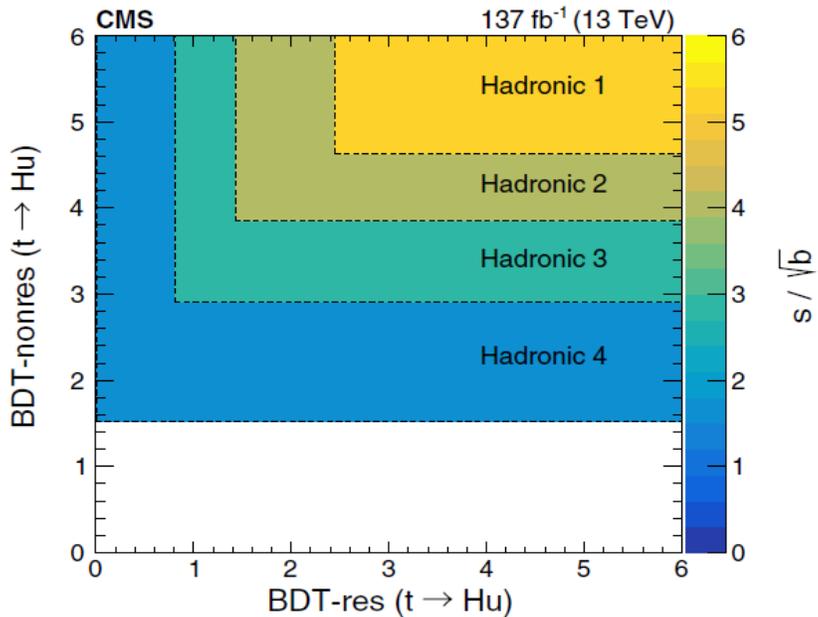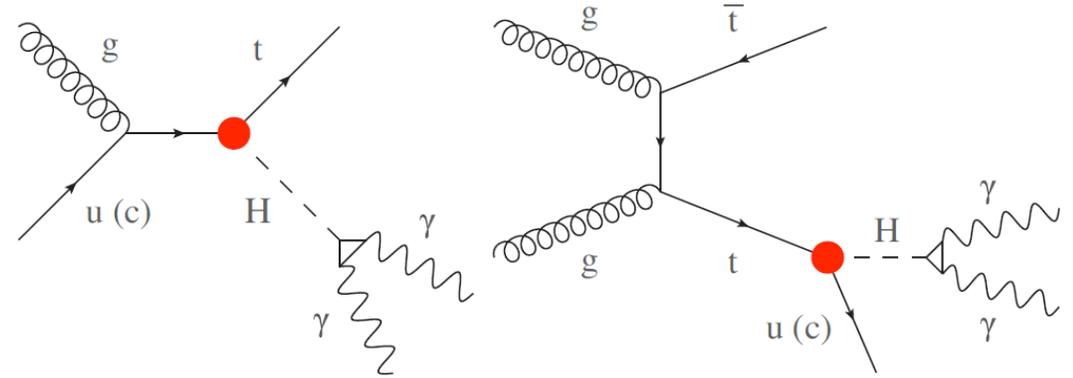 b-tagging, jet energy scale/resolution, bkg cross section, …

❖ **Limits**

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

FCNC *t-H* (*H*→γγ)

- ❖ **tqH coupling** studied in γγ final state with **top leptonic / hadronic** decay modes (**13 TeV / 137 fb^{-1}**)
- ❖ **Multijet, γ+jets with j→γ 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

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

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

❖ **Multijet, γ+jets with $j \rightarrow \gamma$ 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
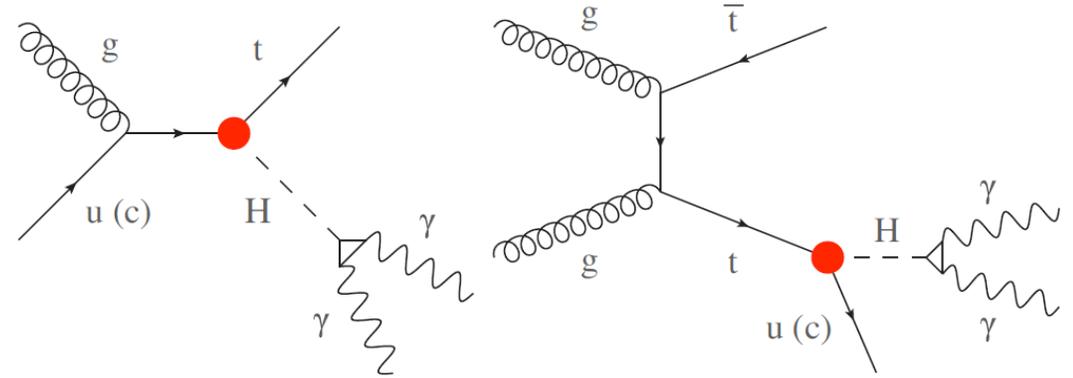
Limits   *Observed (Expected)*

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

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

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

FCNC *t-Z*

❖ ***tZq* coupling** studied using data produced at $\sqrt{s} = 8$ TeV (19.7 fb^{-1})

❖ **Single top / top pair production** in 3-lepton final states : *3e, 2e1μ, 1e2μ, 3μ*

❖ **Selection:**

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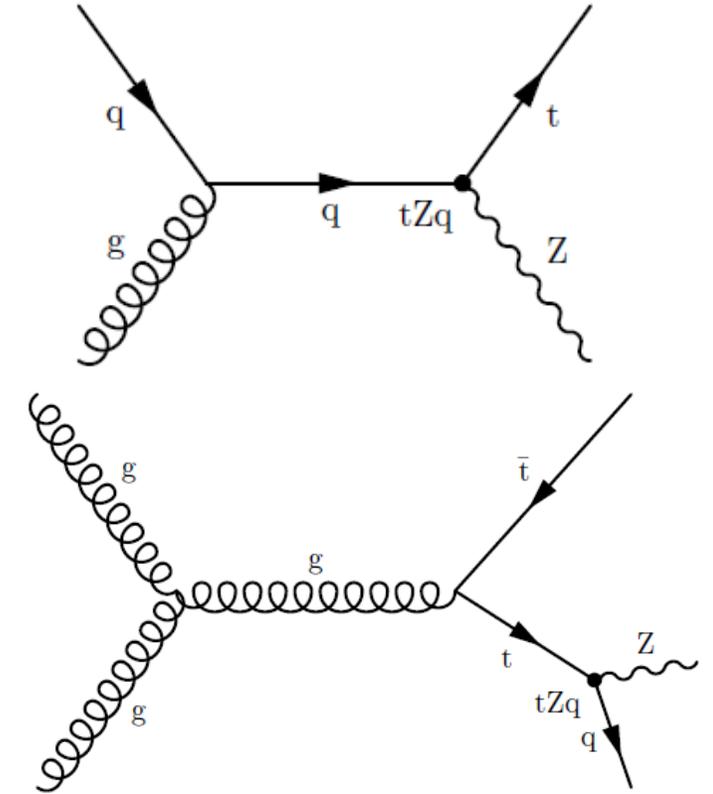 - ≥ 2 jets
  - ≥ 1 *b*-tagged jet (TT)

❖ **Backgrounds:**
  Single top, *ttV*, diboson (*WZ* dominated), $t\bar{t}$, DY+jets
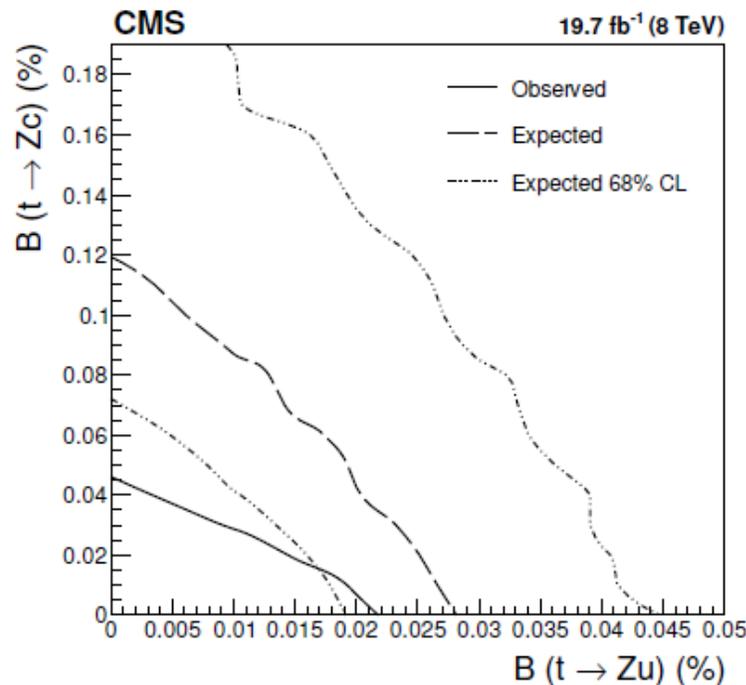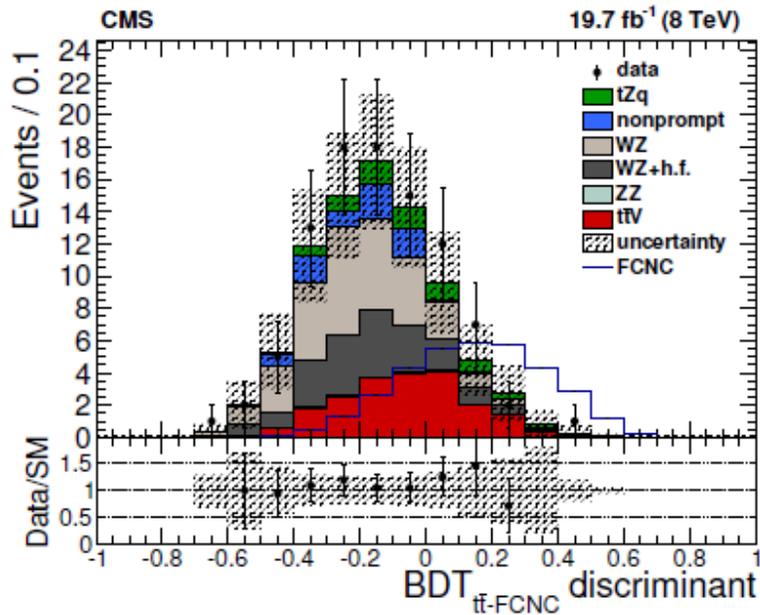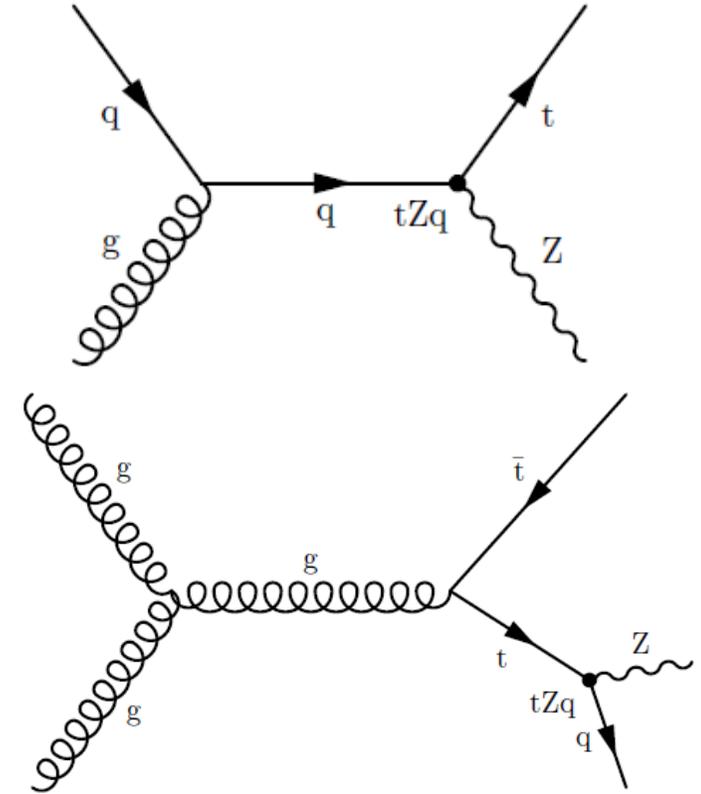
  nonprompt-lepton bkg

  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, …

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FCNC *t-Z*

- ❖ ***tZq* coupling** studied using data produced at $\sqrt{s} = 8$ TeV (19.7 fb^{-1})

- ❖ **Single top / top pair production** in 3-lepton final states : *3e, 2e1μ, 1e2μ, 3μ*

- ❖ **Selection:**

3 leptons (2 OSSF leptons in Z mass window) +

$$\begin{cases} 1 \text{ jet} \\ 1 \text{ } b\text{-tagged jet} \end{cases} \text{(ST)}$$

$$\begin{cases} \geq 2 \text{ jets} \\ \geq 1 \text{ } b\text{-tagged jet} \end{cases} \text{(TT)}$$

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

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FCNC *t-Z*

❖ ***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	✓	✓	✓	✗	✗

WZ+jets
NPLs from DY+jets   NPLs from *t$\bar{t}$* +jets
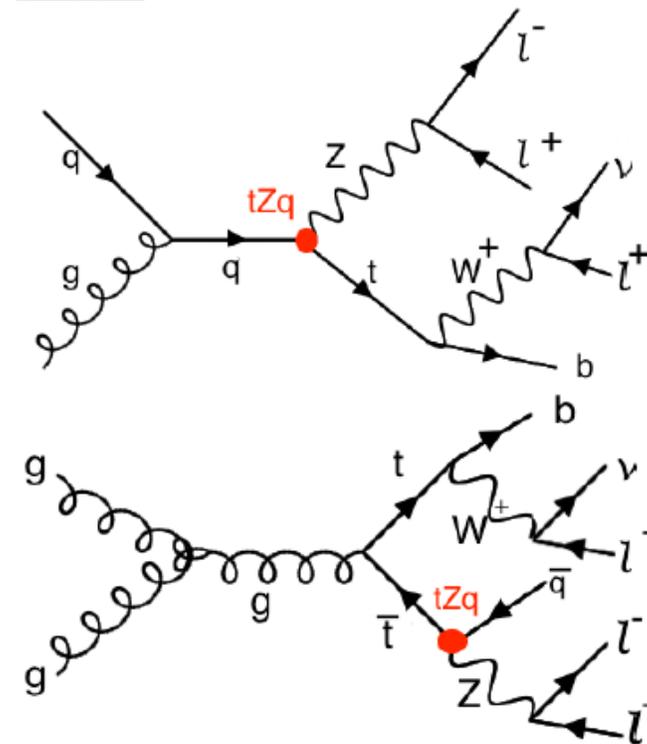
❖ **BDT** trained using kinematic observables and *b*-tagging information separately in each SR and lepton channel

FCNC *t-Z*

❖ ***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, $t\bar{t}$
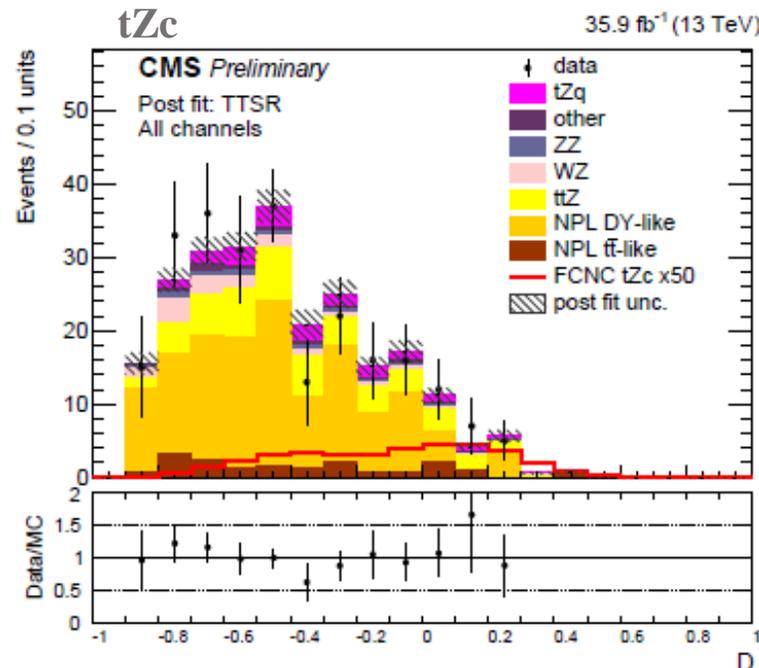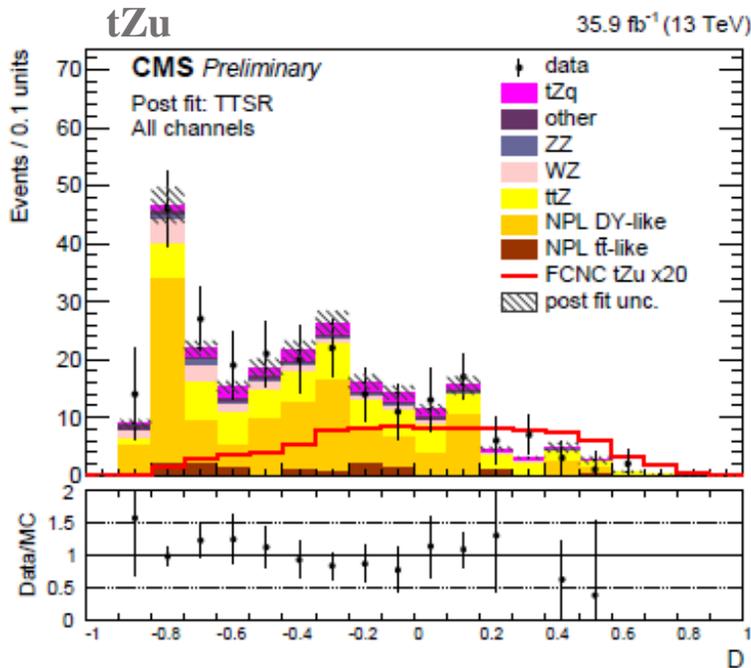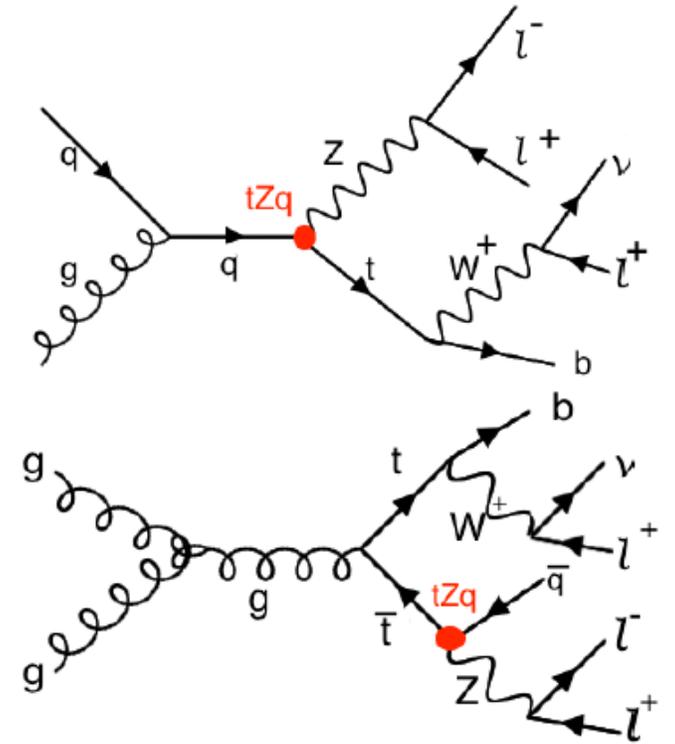
❖ **Uncertainties:**
NPL yield normalization, backgrounds cross sections, scale factors, jet energy scale, …

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FCNC *t-Z*

❖ ***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

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❖ **Not prompt-lepton bkg** coming from DY+jets, *t$\bar{t}$*
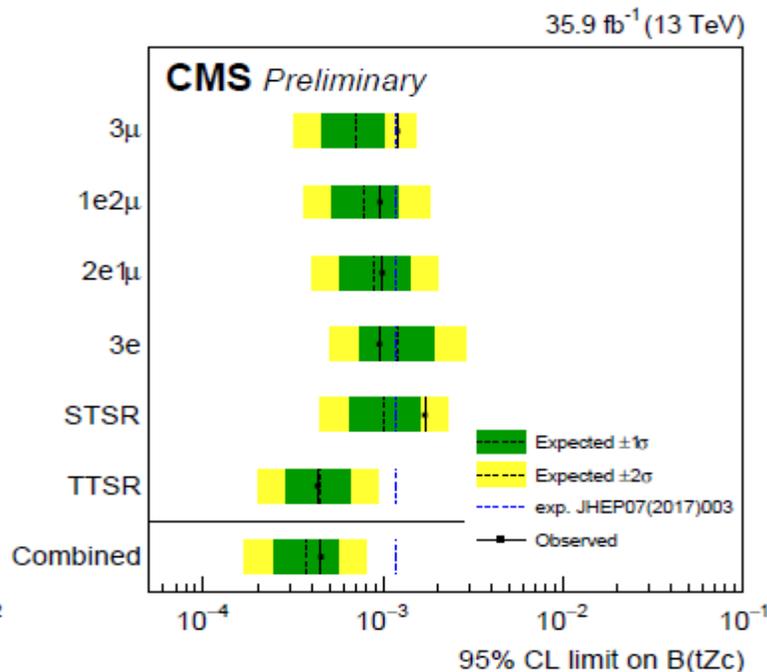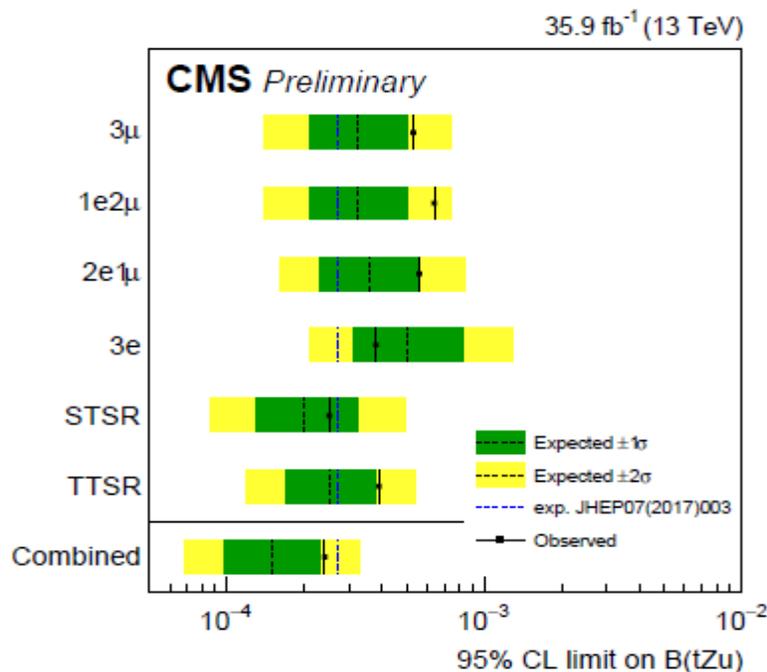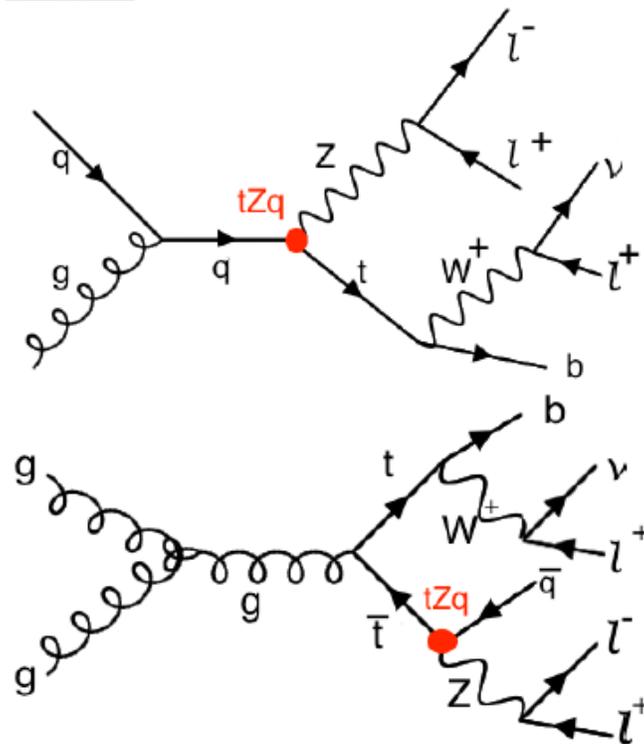
Limits	Observed	Expected
BR($t{\to}uZ$)	< 2.4×10^{-4}	(1.5×10^{-4})
BR($t{\to}cZ$)	< 4.5×10^{-4}	(3.7×10^{-4})

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})

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❖ **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
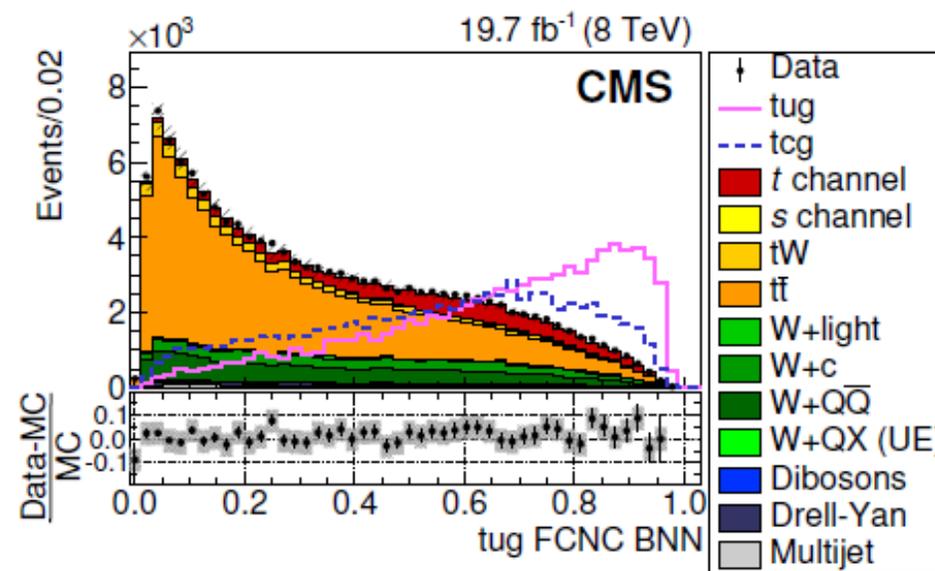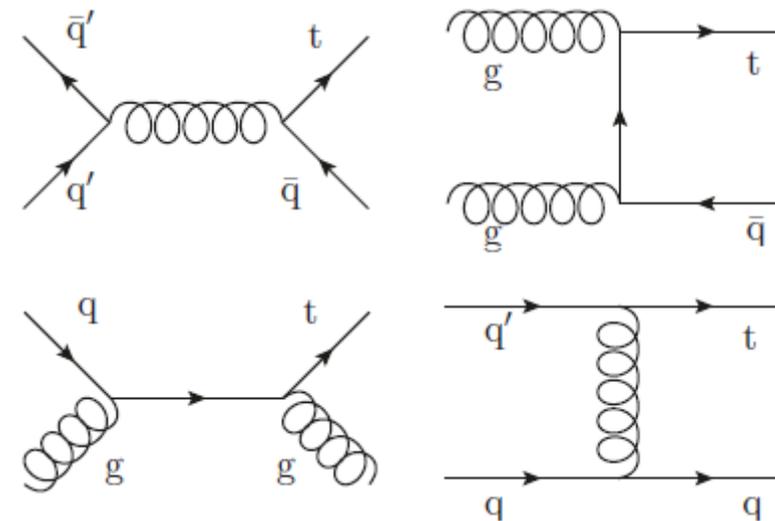**Suppressed** by imposing the cut BNN>0.7
BNN trained with $M_T(W)$, $\Delta\phi(\mu, \vec{p}_T^{\,miss})$, …

Signal extraction

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

FCNC *t-g*

❖ *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

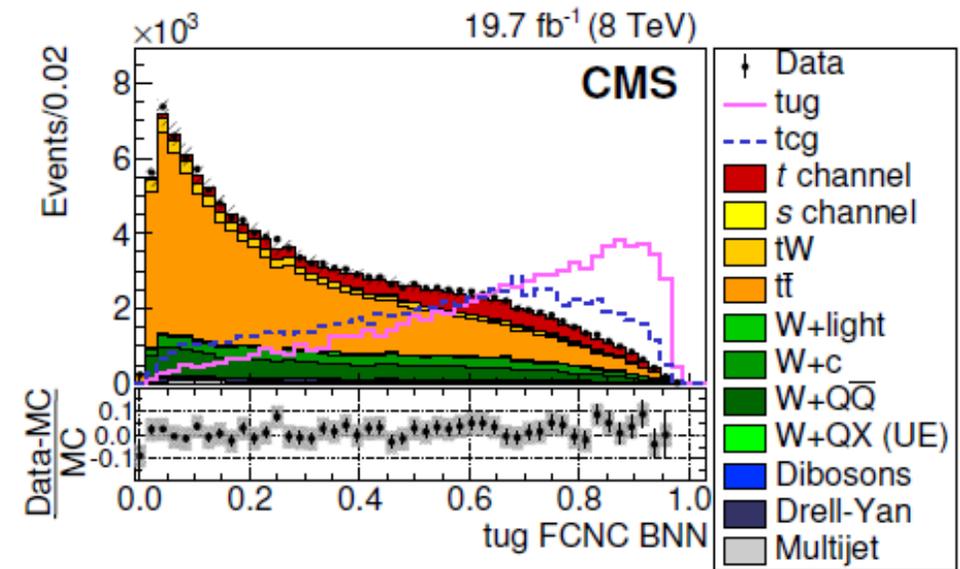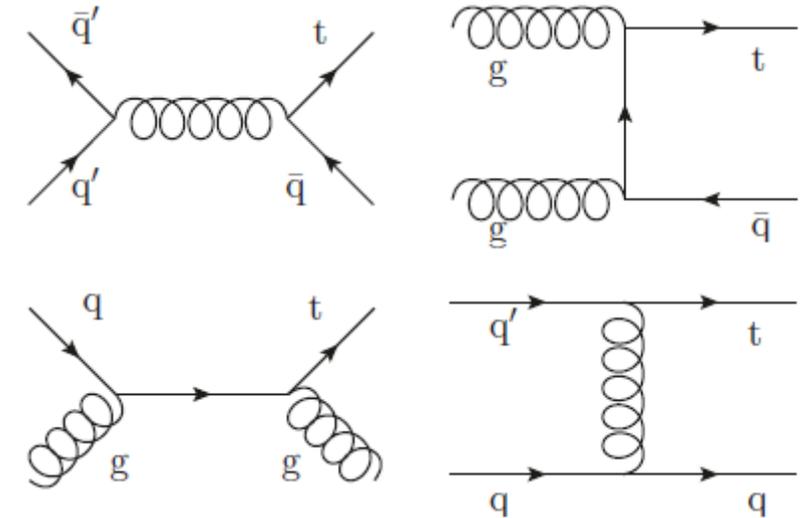➤ **W+jets, $t\bar{t}$**
Constrained using dedicated CRs
➤ **non-prompt μ**
Mostly from multijet production
Estimated using CR defined by inverted isolation criteria
Suppressed by imposing the cut BNN > 0.7
BNN trained with $M_T(W)$, $\Delta\phi(\mu, \vec{p}_T^{\text{miss}})$, …

Limits:

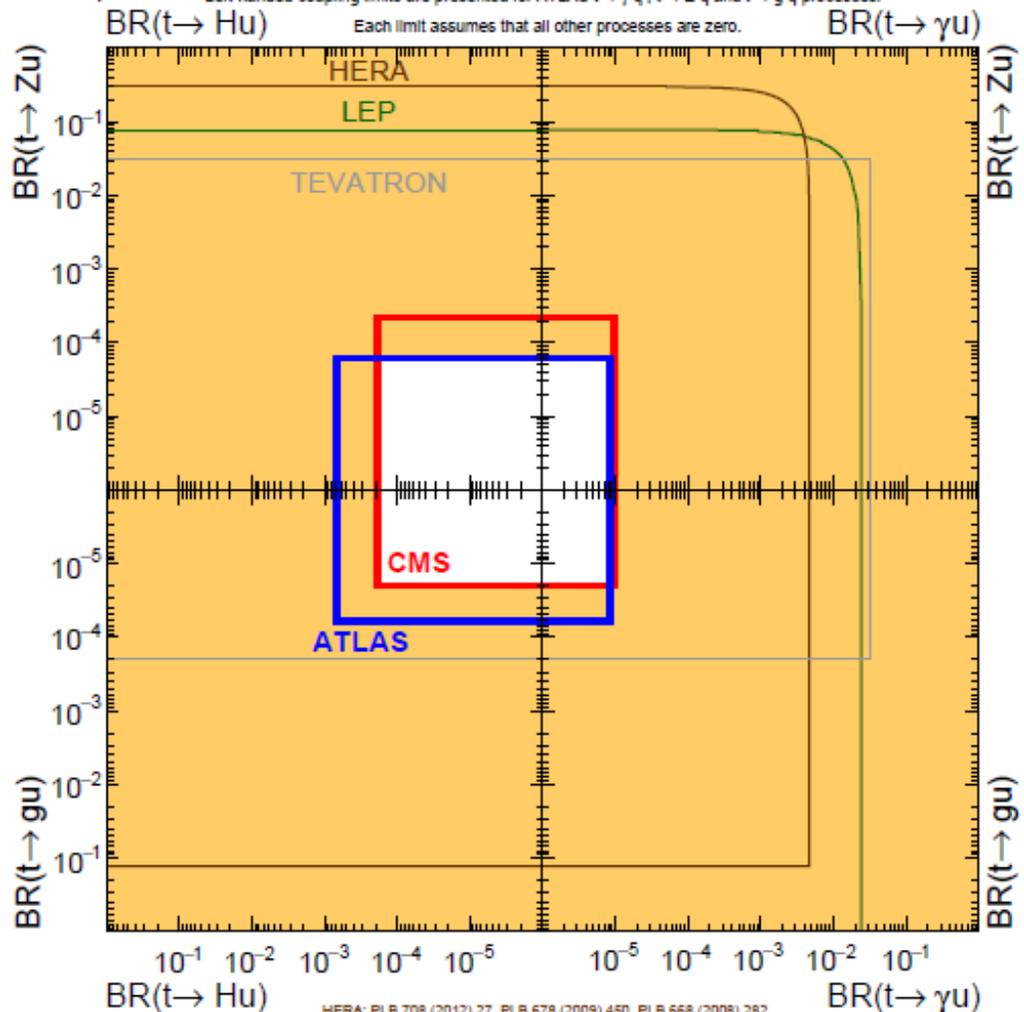|	Observed	Expected
BR($t \to ug$) <	2.0×10^{-5}	(2.8×10^{-5})
BR($t \to cg$) <	4.1×10^{-4}	(2.8×10^{-4})

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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:

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

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

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

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

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*

❖ ***$tu\gamma/tc\gamma$ 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*
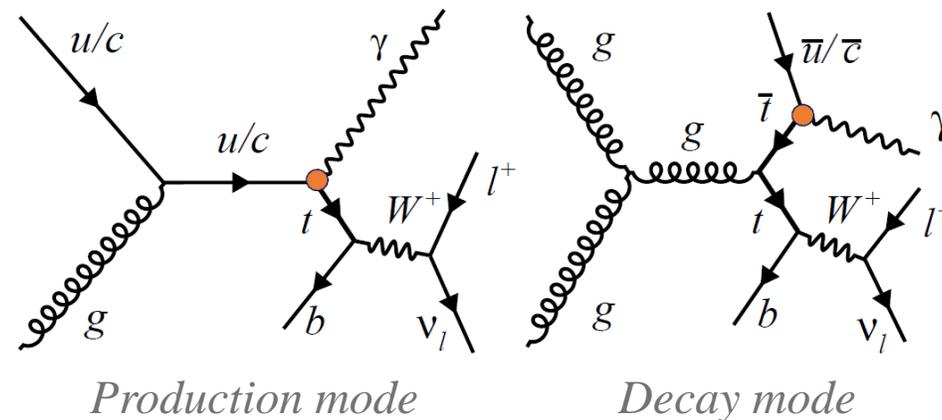
Signal Regions

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 → γ)**
➢ **Jets misidentified as electron/muon (jet → e/μ)**
➢ **Electrons misidentified as photon ($e → \gamma$)**

Jets misidentified as photon (jet→γ) ⟹ *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

Jets misidentified as electron/muon (jet → e/μ)

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 → e/μ 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, …

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

Modeling

Simulation-based (rec. γ matched to gen. e)

Scale Factors applied to correct the simulation

Control Regions $\begin{cases} \textbf{DY} + \textbf{jets CR} \implies 2 \text{ tight electrons, } |m_{ee} - m_Z| < 10 \text{ GeV} \\ \boldsymbol{e \rightarrow \gamma} \textbf{ CR} \implies 1 \text{ tight electron, 1 medium photon, } |m_{e\gamma} - m_Z| < 10 \text{ GeV} \end{cases}$

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

Dominated by $\begin{cases} \boldsymbol{e} \text{ channel: DY} + \text{jets, } t\bar{t}, \text{ single top } tW\text{-channel, diboson (} ee \text{ decay mode)} \\ \boldsymbol{\mu} \text{ channel: } t\bar{t}, \text{ single top } tW\text{-channel, diboson (} e\mu \text{ decay mode)} \end{cases}$

Strategy ⟹ **Multivariate classification based on BDT**

➢ 13 input variables

Most important ones $\begin{cases} \textbf{SR1: } p_T^\gamma, \Delta R(\ell, b\text{-jet}), m_{top}, \Delta R(top, \gamma) \\ \textbf{SR2: } m_{jet+\gamma}, p_T^\gamma, m_{top}, \Delta R(\ell, b\text{-jet}), \Delta R(\ell, \gamma) \end{cases}$

➢ Separate BDTs for *tuγ/tcγ* 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→uγ*)/BR(*t→cγ*)**