ICHEP 2022 BOLOGNA

ICHEP 2022 XLI International Conference on High Energy Physics Bologna (Italy)

6 13 07 2022

Searches for rare top quark decay and BSM top interactions in CMS

Meng Lu, SYSU

7 July, 2022

On behalf of the CMS Collaboration

Introduction

SM has been proved to be a superb model in variant tests, but we need to go beyond the SM due to there are results which couldn't be explained within the SM, i.e.,

- The long known dark matter, dark energy, neutrino masses
- Recent: 3.3 sigma violation of lepton flavour universality, muon g-2 anomaly
- ......

How to probe physics beyond SM:

- Direct search
  - Resonant or non-resonant of BSM particles (energy scale within LHC)
- Indirect search (usually search for deviations from SM)
  - Rare decay (e.g., FCNC)
  - EFT interpretation (e.g., See Reza's talk)
  - ...

BSM study using top quark events in this talk.

FCNC in t(t~)Hq (H→bb~)

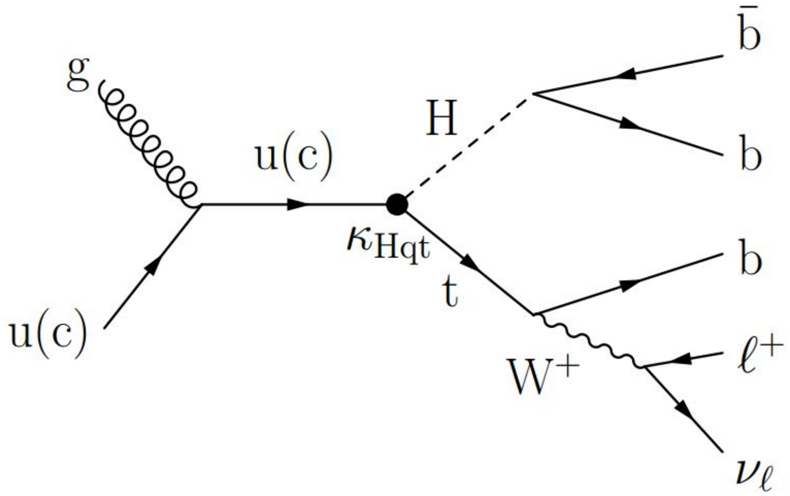
Motivation:
- FCNC decays are highly suppressed in SM, for top -> H+u/c, BR < 10^{-10}
- Several BSM allow FCNC including tHq (q = u, c) interaction

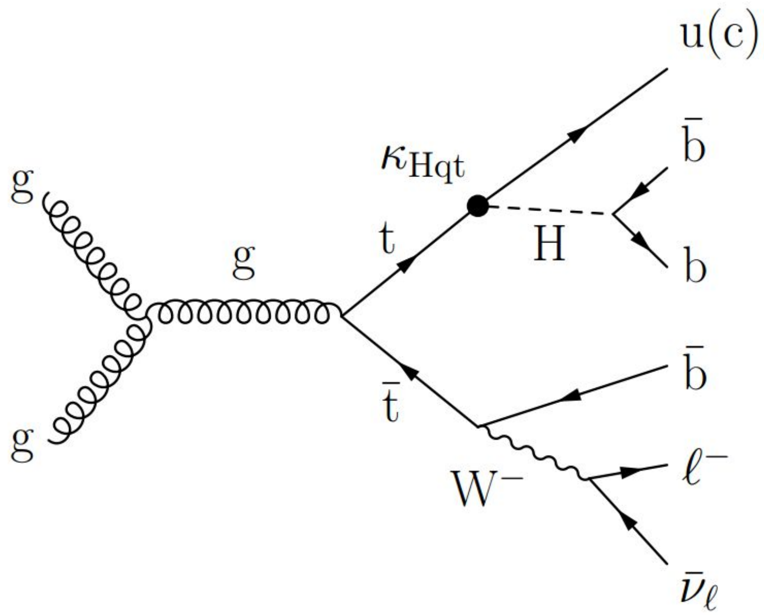
	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	$-$	10^{-5}	$\sim 10^{-6}$
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

arxiv:hep-ph/0409342

137 fb^{-1}
JHEP02(2022)169

Single top process (FCNC in the production) and double top process (FCNC in the decay) are considered.





Event selection:
- One isolated muon or electron
- At least three jets, in which at least two of them are tagged as bjets

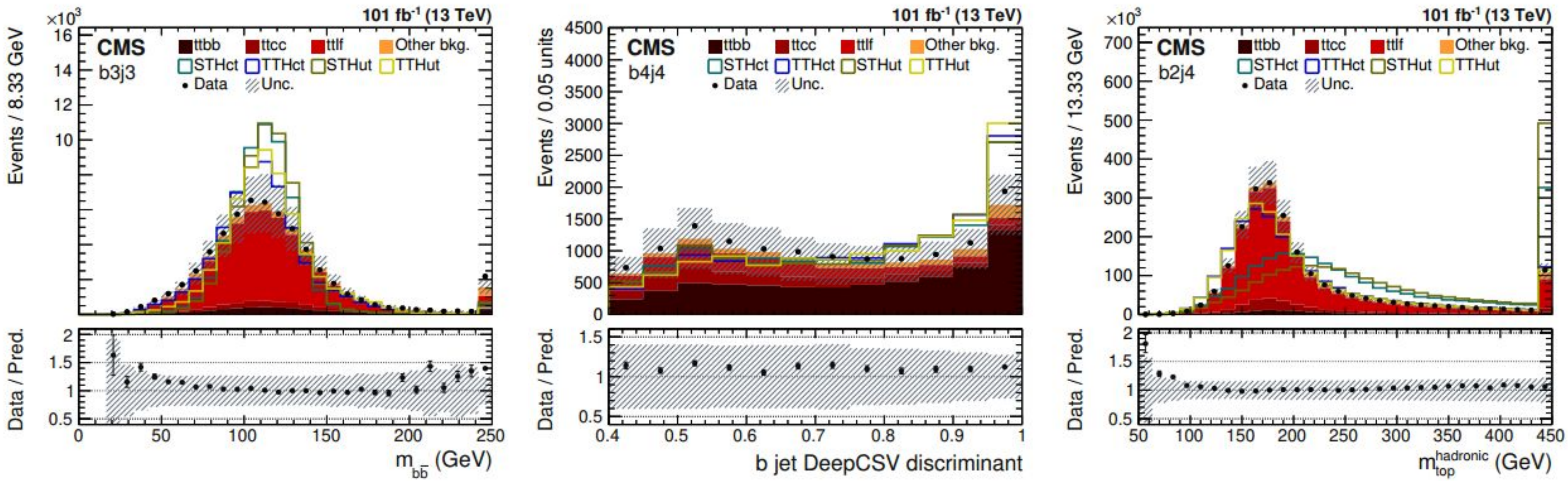
→ 5 categories: b2j3, b2j4, b3j3, b3j4, b4j4

FCNC in t(t~)Hq (H→bb~)

137 fb^{-1}
[JHEP02(2022)169]

- SM tt~ is the dominant background
- Two MVA steps are used, firstly the DNN for event reconstruction, and then BDT for signal/background separation.

Kinematics comparison between data and prediction to check the validity of the DNN.

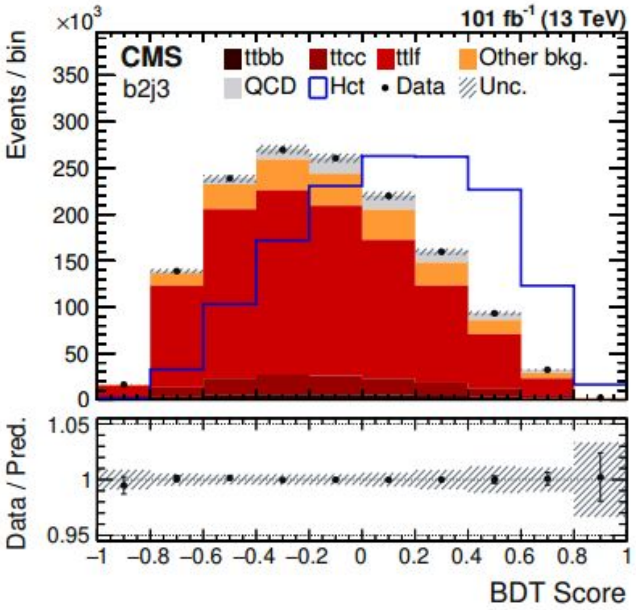


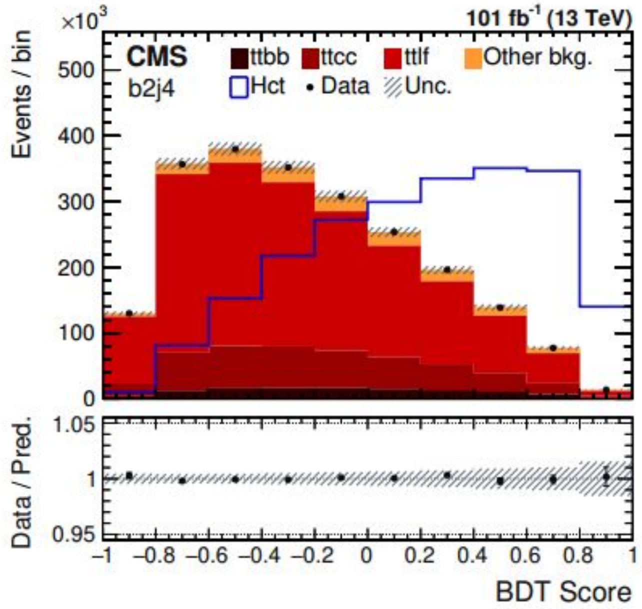
FCNC in t(t~)Hq (H→bb~)

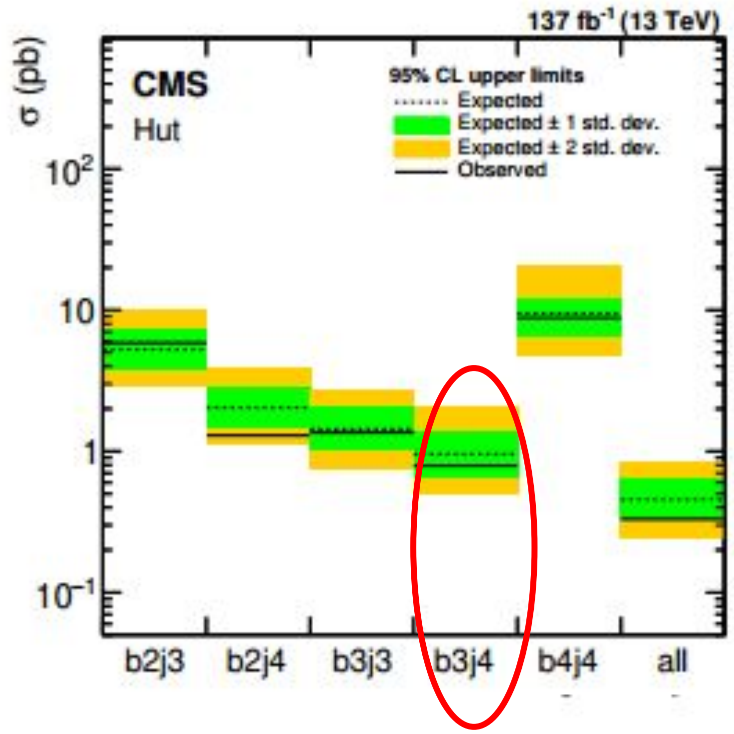
BDTs are used to separate signal and backgrounds in 5 categories.

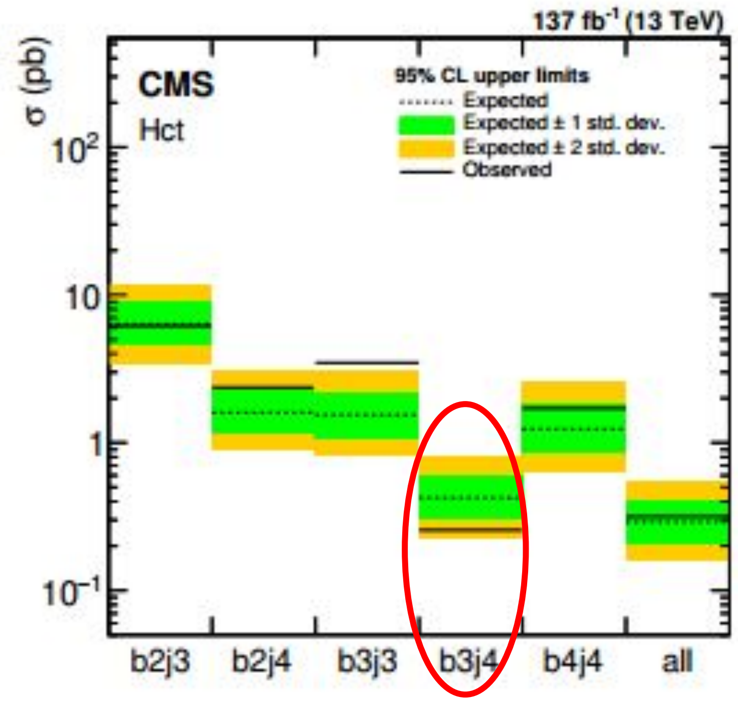
137 fb^{-1}

JHEP02(2022)169



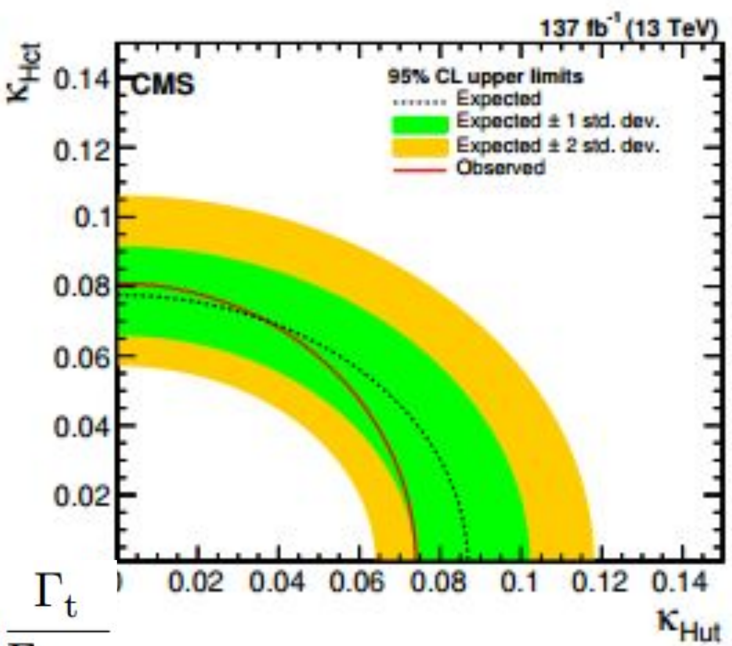


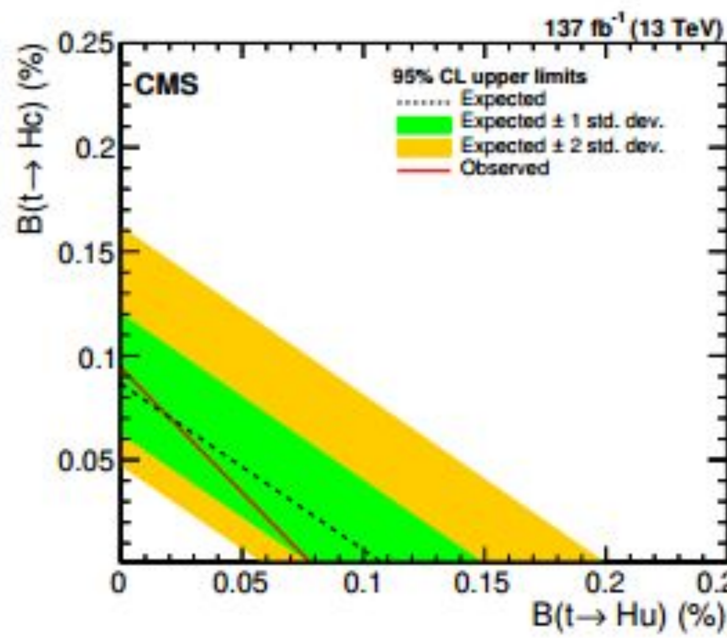




Results:

- Very good agreement between SM prediction and data, set limit on the cross sections (combined with 2016 results)
- b3j4 category contribute best constraint
- Interpreted the limit on XS in terms of exclusion on anomalous couplings (t → Hq BR)
  - 95% CL upper limit of BR(t → Hu)
    - Obs: 7.9×10^{-4}, exp: 1.1×10^{-3}
  - 95% CL upper limit of BR(t → Hc)
    - Obs: 9.4×10^{-4}, exp: 8.6×10^{-4}





$$\kappa_{Hqt}^2 = \mathcal{B}(t \to Hq)\frac{\Gamma_t}{\Gamma_{Hqt}}$$

FCNC in t(t~)Hq (H→$\gamma\gamma$)

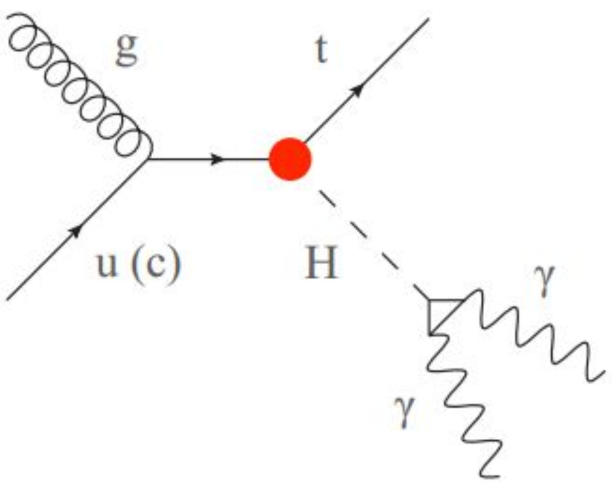
Motivation:

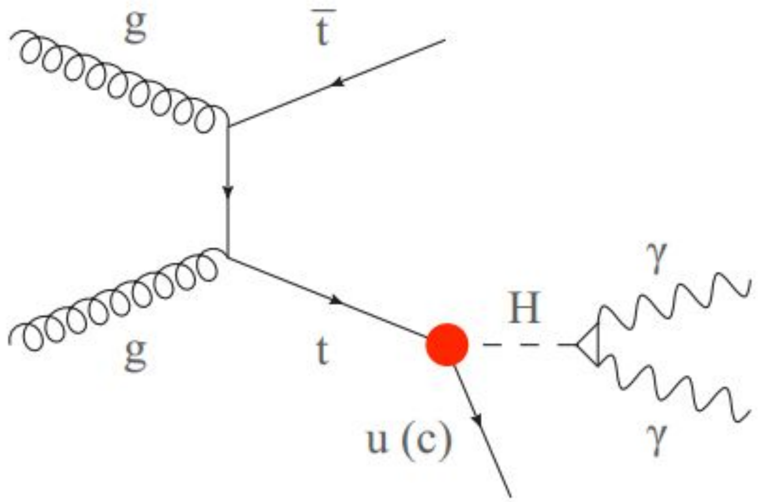
- Similar with tHq (H→ bb~) but using H→$\gamma\gamma$ channel

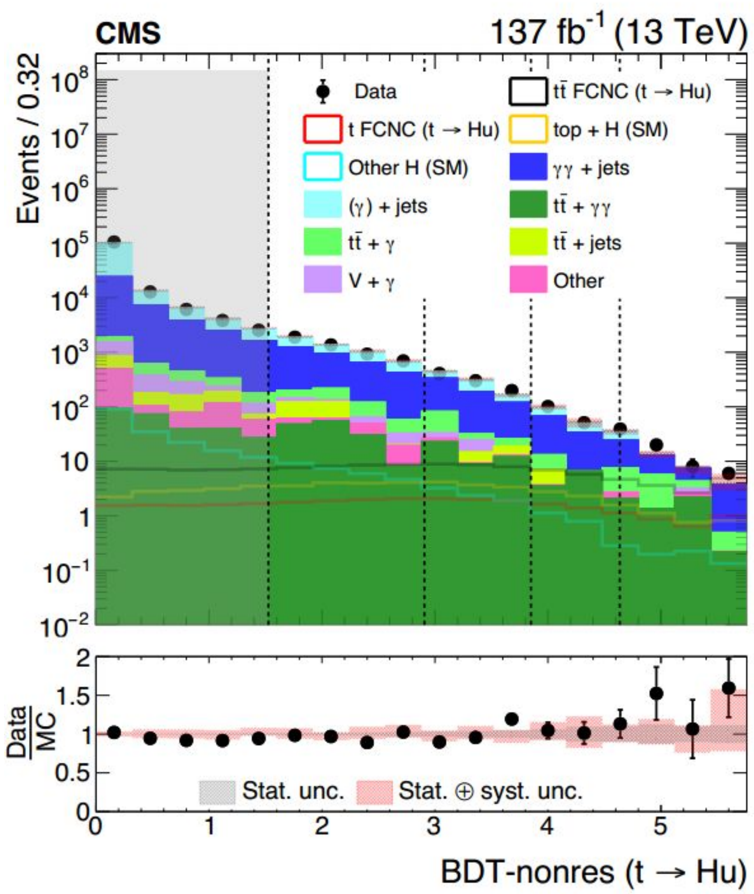
Single top process (FCNC in the production) and double top process (FCNC in the decay) are considered.

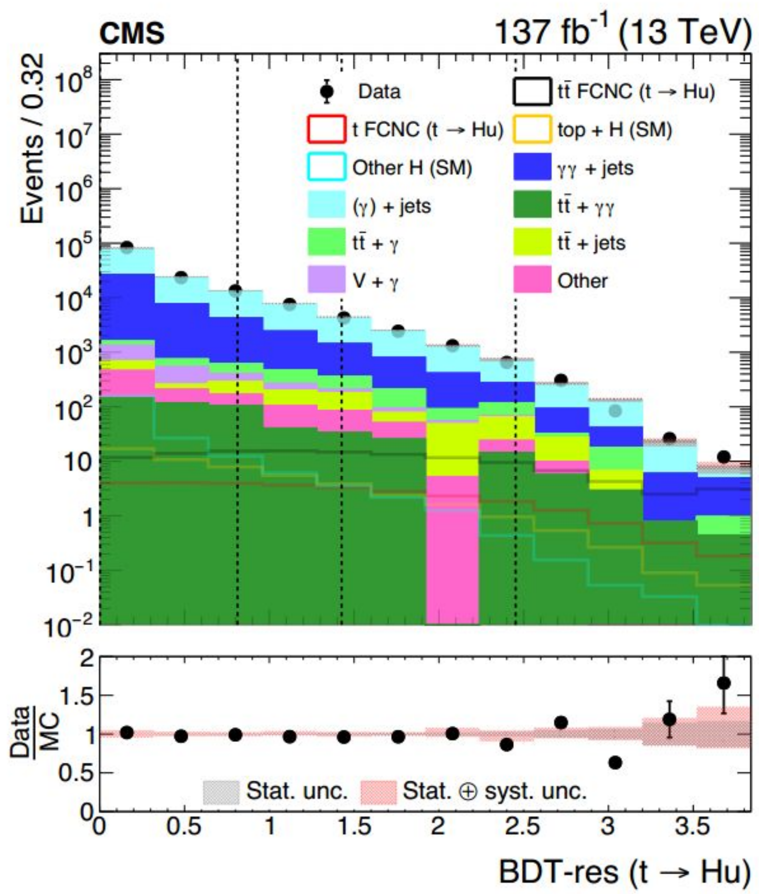
137 fb^{-1}

2111.02219, PRL accepted









Validation of BDT in m$\gamma\gamma$ sideband region

Di-photon preselection:

- Photon MVA ID derived to suppress the nonprompt photon background (π^0→$\gamma\gamma$)
- m$\gamma\gamma$ in (100, 180) GeV to reconstruct the Higgs candidates

Then two event categories:

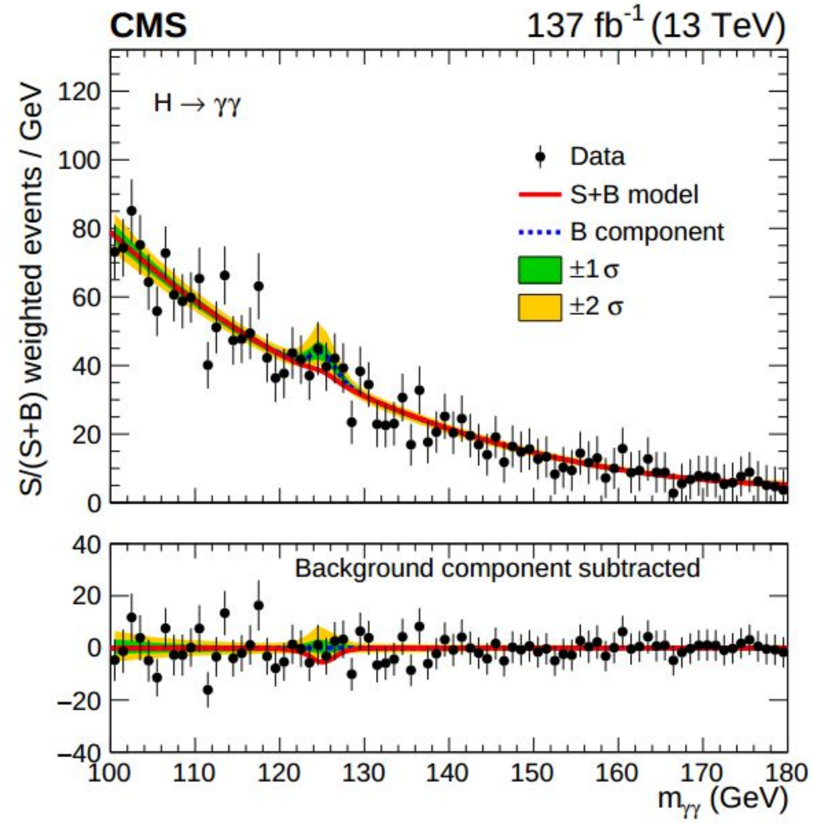
- Leptonic: >= 1 jet, >= 1 isolated lepton (e or μ)
- Hadronic: >= 3 jet, >=1 bjet, no isolated lepton

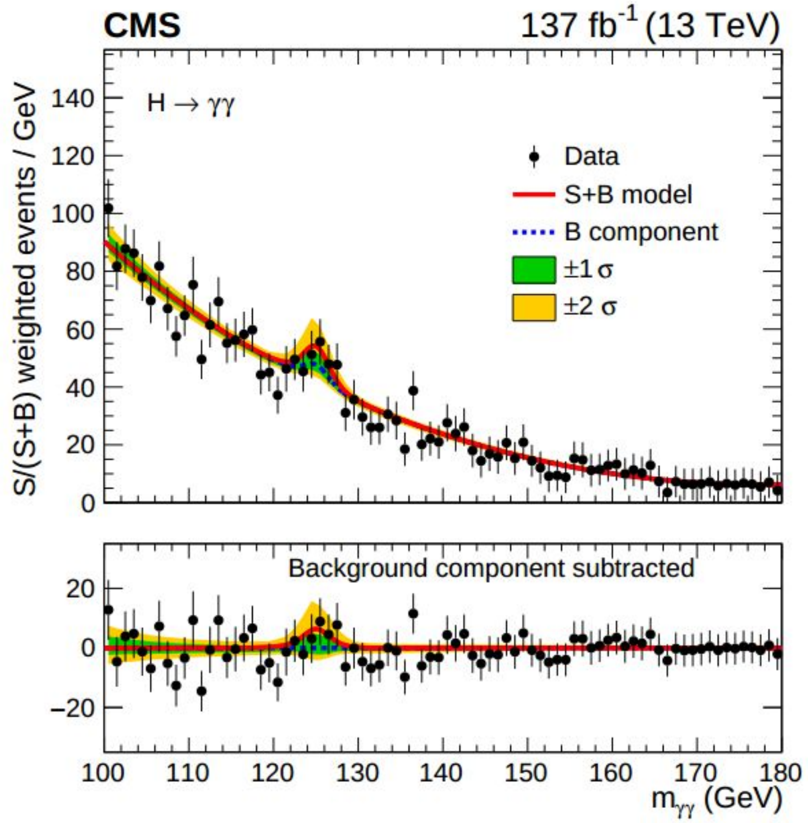
Signal extraction: BDT method is used to separate signal and backgrounds.

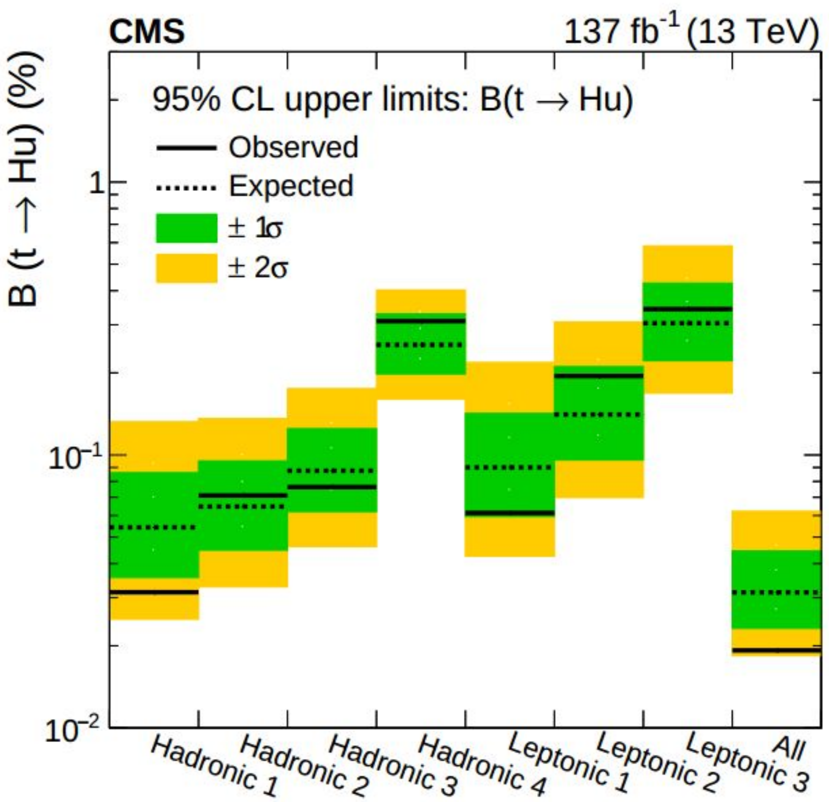
Main backgrounds:

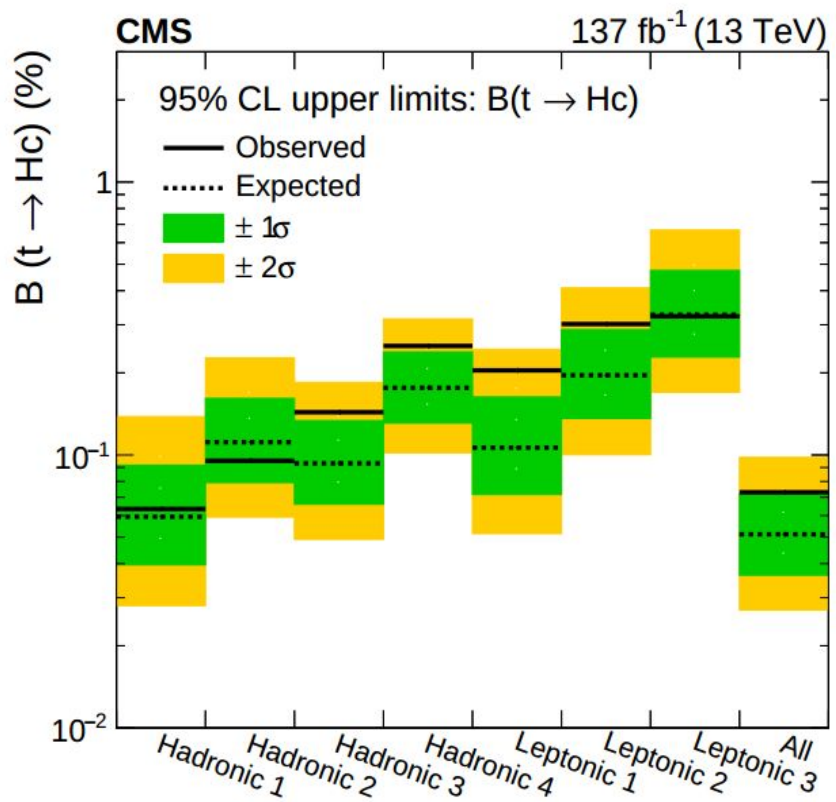
- nonresonant: γ+jet, $\gamma\gamma$+jet, tt~+jet(γ)
- resonant: ttH, WH, ZH

FCNC in t(t~)Hq (H->$\gamma\gamma$)









137 fb^{-1}

2111.02219, PRL accepted

Simultaneous fit on m$\gamma\gamma$ in 14 regions is performed. No significant excess is observed, limits are set.

Results:

- 95% upper limit of BR(t → Hu)
  - Obs: 1.9×10^{-4}, exp: 3.1×10^{-4}
- 95% upper limit of BR(t → Hc)
  - Obs: 7.3×10^{-4}, exp: 5.1×10^{-4}

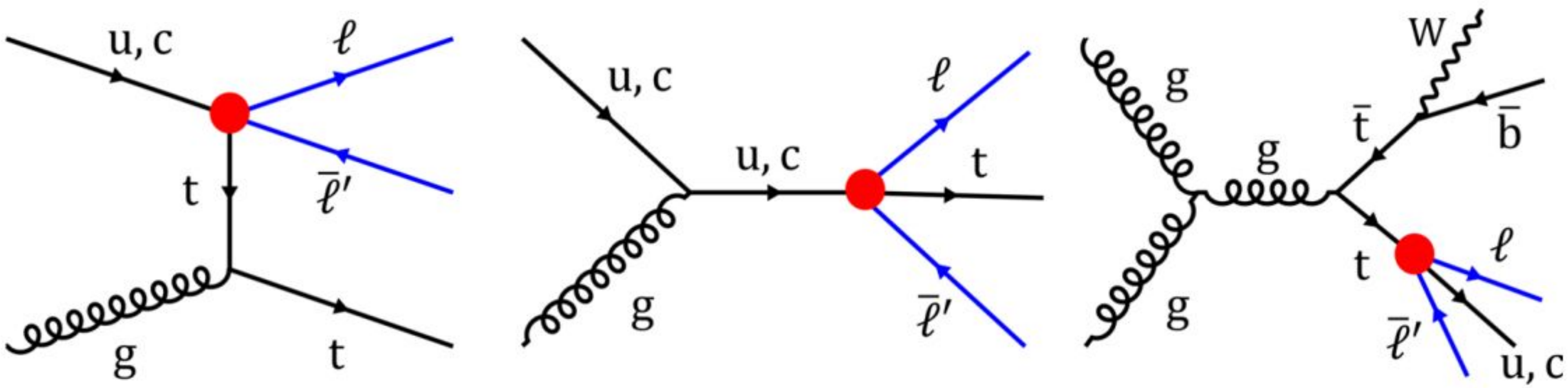
Corresponding 95% upper limit on couplings:

- $|k_{Hut}|$
  - Obs: 0.037, exp: 0.047
- $|k_{Hct}|$
  - Obs: 0.071, exp: 0.060

Motivation:

137 fb^{-1} JHEP06(2022)082

- Lepton flavor violation (LFV) processes are forbidden within the SM with massless neutrinos, but many new physics models predict sizable CLFV
- Recent B-anomaly from LHCb indicate the possibility of lepton flavor universality violation. Many models that explain the B-anomaly predict similar interactions in the top sector, e.g., JHEP07(2019)025, BR(t → ll'c) ~ 10^{-6}.



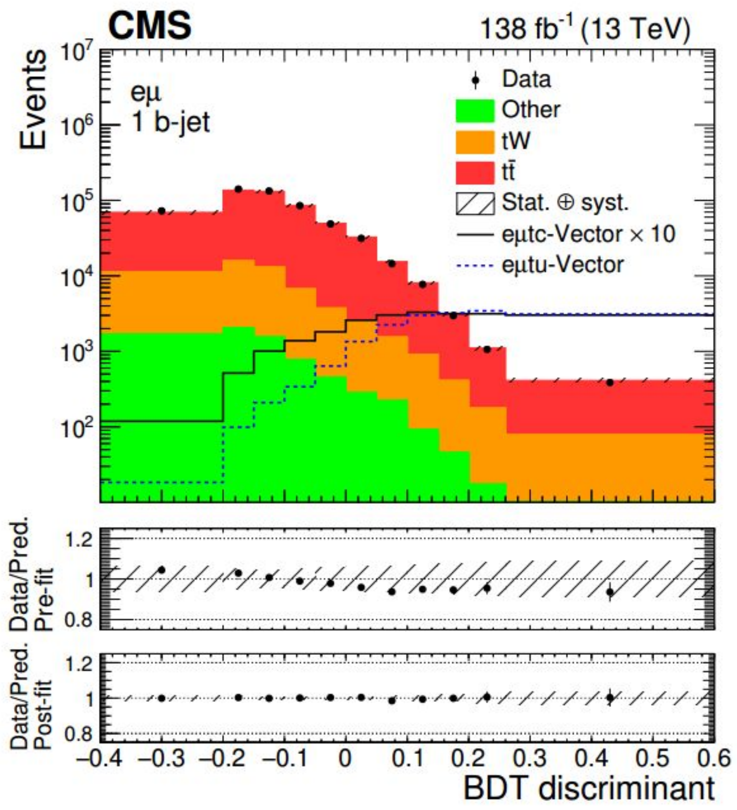
Searching for CLFV processes using top quark events could therefore shed light on anomalies seen in B meson decays.

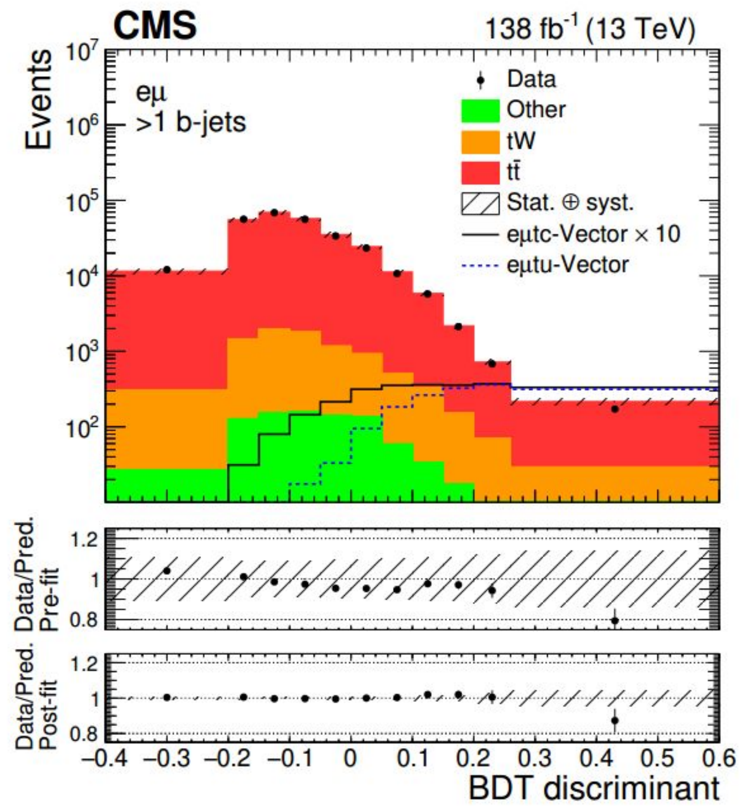
CLFV in top events

Event selection:

- Exactly one electron and one muon (oppositely charged)
- Invariant mass of $e\mu$ larger than 20 GeV
- At least one bjet

After event selection, 90% of the background events come from tt~. BDT method is used to separate signal and backgrounds.

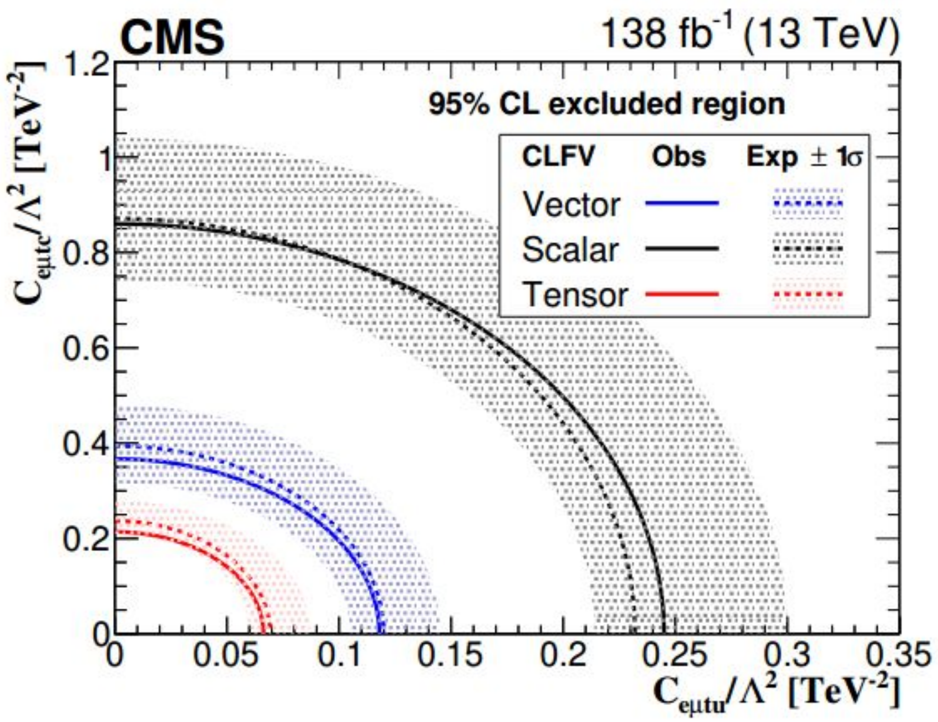


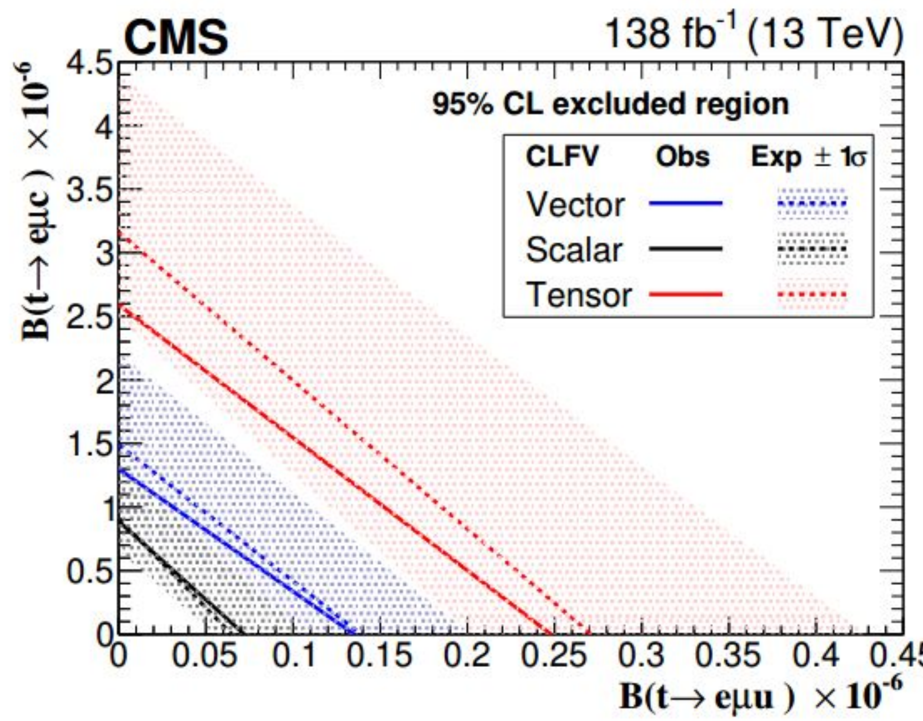


Results:

- Data is consistent with the SM prediction, set limits

Vertex	Int. type	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
eμtu	Vector	0.12	0.12	0.14	0.13
	Scalar	0.23	0.24	0.06	0.07
	Tensor	0.07	0.06	0.27	0.25
eμtc	Vector	0.39	0.37	1.49	1.31
	Scalar	0.87	0.86	0.91	0.89
	Tensor	0.24	0.21	3.16	2.59





One dimensional limits

Two dimensional limits

CP violation in top-pair events

137 fb^{-1}
arXiv:2205.02314

Motivation:

- CPV in the SM is not enough to explain the matter-dominant universe, search for CP violation using tt~ events by assuming a nonzero chromoelectric dipole moment (CEDM, d^{g}_{t}) of the top quark

$$\mathcal{L} = \frac{g_s}{2}\bar{t}T^a\sigma^{\mu\nu}(a^g_t + i\gamma_5 d^g_t)tG^a_{\mu\nu},$$

Coupling between Top and gluon after considering CEDM contribution, Reference.

Event selection: tt~ events with one decayed W→ lepton + neutrino and one decayed W→ quarks

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p}^{\,*}_b \cdot (\vec{p}^{\,*}_\ell \times \vec{p}^{\,*}_{j_1}),$$
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell(\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$
$$O_{12} = q \cdot (p_b - p_{\bar{b}})\epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z,$$
$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

4 CP observables, constructed using final status objects.

Sensitive to charge sign of bjet

$$\chi^2 = \left(\frac{m_{jjb} - m_t}{\sigma_t}\right)^2 + \left(\frac{m_{jj} - m_W}{\sigma_W}\right)^2,$$

Find the bjet from hadronic decay top, then the charge sign of bjet could be obtained by checking the charge sign of lepton.

Fit strategy:

- Signal and background contribution is estimated using fit on mlb
- Signal shape from simulation, background shape from data in a W+jets enriched region

137 fb^{-1}
arXiv:2205.02314

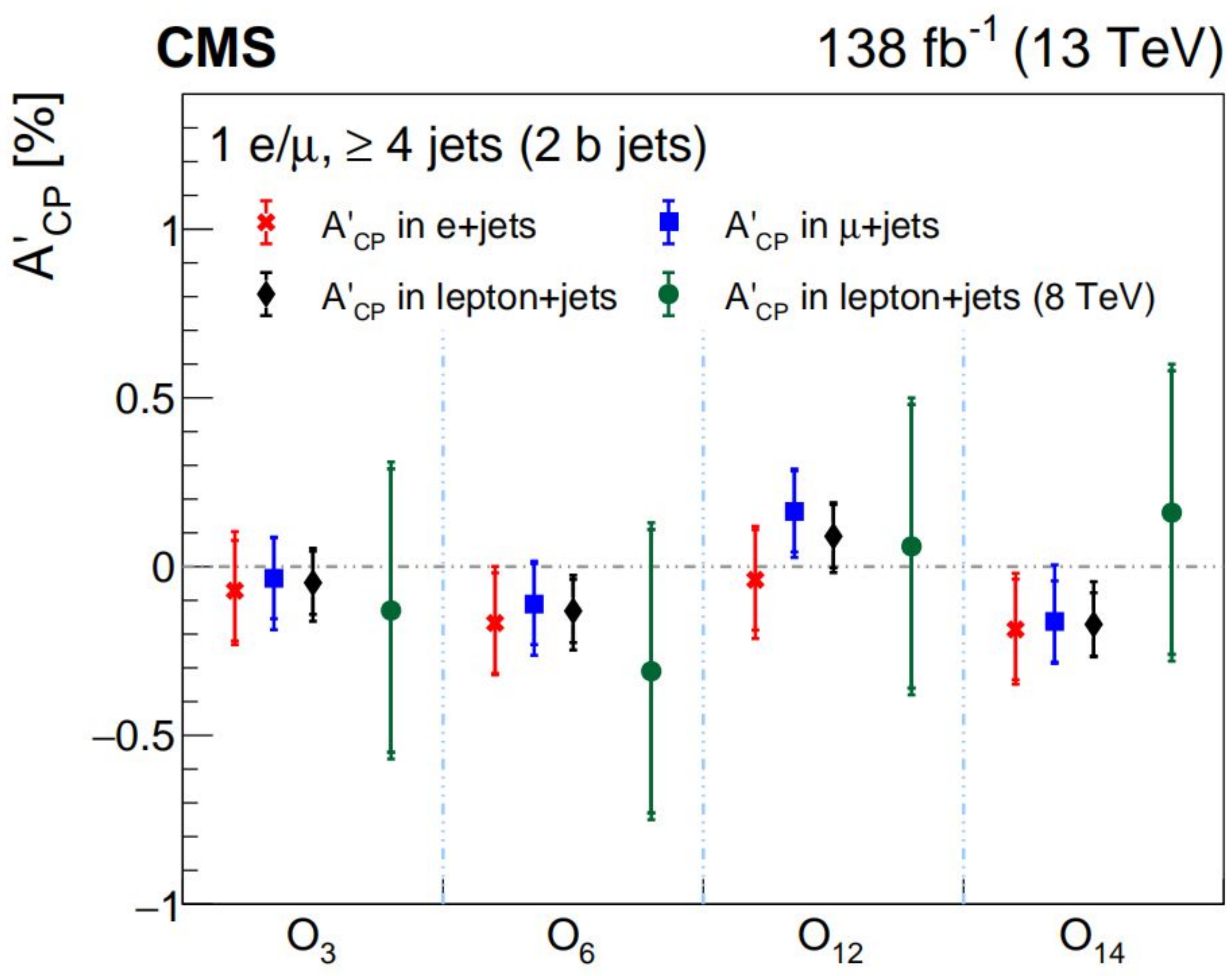
$$A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}, \quad i = 3, 6, 12, 14.$$

Zero within SM

$$A'_{CP} = D A_{CP}$$

ACP: measured from ideal detector
A'CP: measured effective asymmetry

$$D = \epsilon_c - \epsilon_w,$$



	A'_{CP} (%)		
	e+jets	μ+jets	Combined
O_3	$-0.07 \pm 0.15 ^{+0.09}_{-0.06}$	$-0.04 \pm 0.12 ^{+0.02}_{-0.09}$	$-0.05 \pm 0.09 ^{+0.04}_{-0.07}$
O_6	$-0.17 \pm 0.15 ^{+0.08}_{-0.04}$	$-0.11 \pm 0.12 ^{+0.04}_{-0.09}$	$-0.13 \pm 0.09 ^{+0.05}_{-0.07}$
O_{12}	$-0.04 \pm 0.15 ^{+0.06}_{-0.09}$	$+0.16 \pm 0.12 ^{+0.04}_{-0.07}$	$+0.09 \pm 0.09 ^{+0.03}_{-0.05}$
O_{14}	$-0.19 \pm 0.15 ^{+0.08}_{-0.07}$	$-0.16 \pm 0.12 ^{+0.12}_{-0.03}$	$-0.17 \pm 0.09 ^{+0.09}_{-0.02}$

Results:

- No significant CPV in both channels for all observables
- d^g_t = 0.04 ± 0.10 (stat) ± 0.07 (syst), Uncertainties reduced by a factor ~3 compared with 8 TeV results

Summary

- There have been many results on BSM from CMS using top quark events:
  - FCNC results from tHq events, with H→bb~ and H→$\gamma\gamma$ channels
  - CLFV results using eμ channel
  - CPV results using tt~ events
- Current results are consistent with SM, no significant deviation observed.

Thanks for your attention!

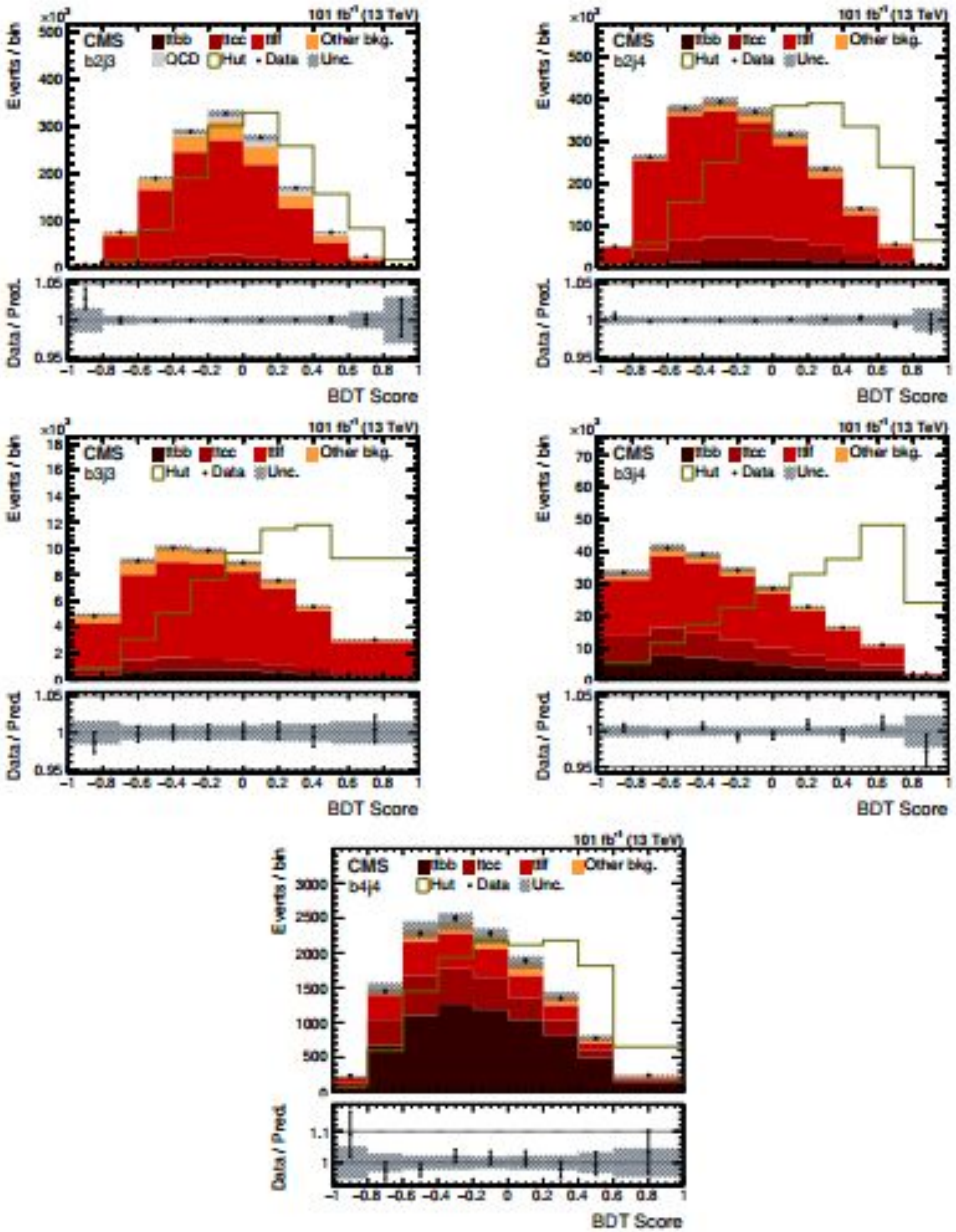
Additional slides

FCNC in t(t~)Hq (H->bb~)

BDTs are used to separate signal and backgrounds in 5 categories.

137 fb^{-1}

JHEP02(2022)169



137 fb^{-1}
JHEP06(2022)082

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{\mathrm{C}_x}{\Lambda^2} O_x + \cdots$$

$$O_{\mathrm{lq}}^{(3)abcd} = (\bar{\mathrm{l}}_a \gamma^\mu \tau^I \mathrm{l}_b)(\bar{\mathrm{q}}_c \gamma_\mu \tau^I \mathrm{q}_d),$$
$$O_{\mathrm{lq}}^{(1)abcd} = (\bar{\mathrm{l}}_a \gamma^\mu \mathrm{l}_b)(\bar{\mathrm{q}}_c \gamma_\mu \mathrm{q}_d),$$
$$O_{\mathrm{lu}}^{abcd} = (\bar{\mathrm{l}}_a \gamma^\mu \mathrm{l}_b)(\bar{\mathrm{u}}_c \gamma_\mu \mathrm{u}_d),$$
$$O_{\mathrm{eq}}^{abcd} = (\bar{\mathrm{e}}_a \gamma^\mu \mathrm{e}_b)(\bar{\mathrm{q}}_c \gamma_\mu \mathrm{q}_d),$$
$$O_{\mathrm{eu}}^{abcd} = (\bar{\mathrm{e}}_a \gamma^\mu \mathrm{e}_b)(\bar{\mathrm{u}}_c \gamma_\mu \mathrm{u}_d),$$
$$O_{\mathrm{lequ}}^{(1)abcd} = (\bar{\mathrm{l}}_a \mathrm{e}_b)\, \varepsilon\, (\bar{\mathrm{q}}_c \mathrm{u}_d),$$
$$O_{\mathrm{lequ}}^{(3)abcd} = (\bar{\mathrm{l}}_a \sigma^{\mu\nu} \mathrm{e}_b)\, \varepsilon\, (\bar{\mathrm{q}}_c \sigma_{\mu\nu} \mathrm{u}_d),$$

$$O_{\mathrm{vector}} = O_{\mathrm{lq}} + O_{\mathrm{lu}} + O_{\mathrm{eq}} + O_{\mathrm{eu}},$$
$$O_{\mathrm{scalar}} = O_{\mathrm{lequ}}^{(1)} + \mathrm{h.c},$$
$$O_{\mathrm{tensor}} = O_{\mathrm{lequ}}^{(3)} + \mathrm{h.c},$$

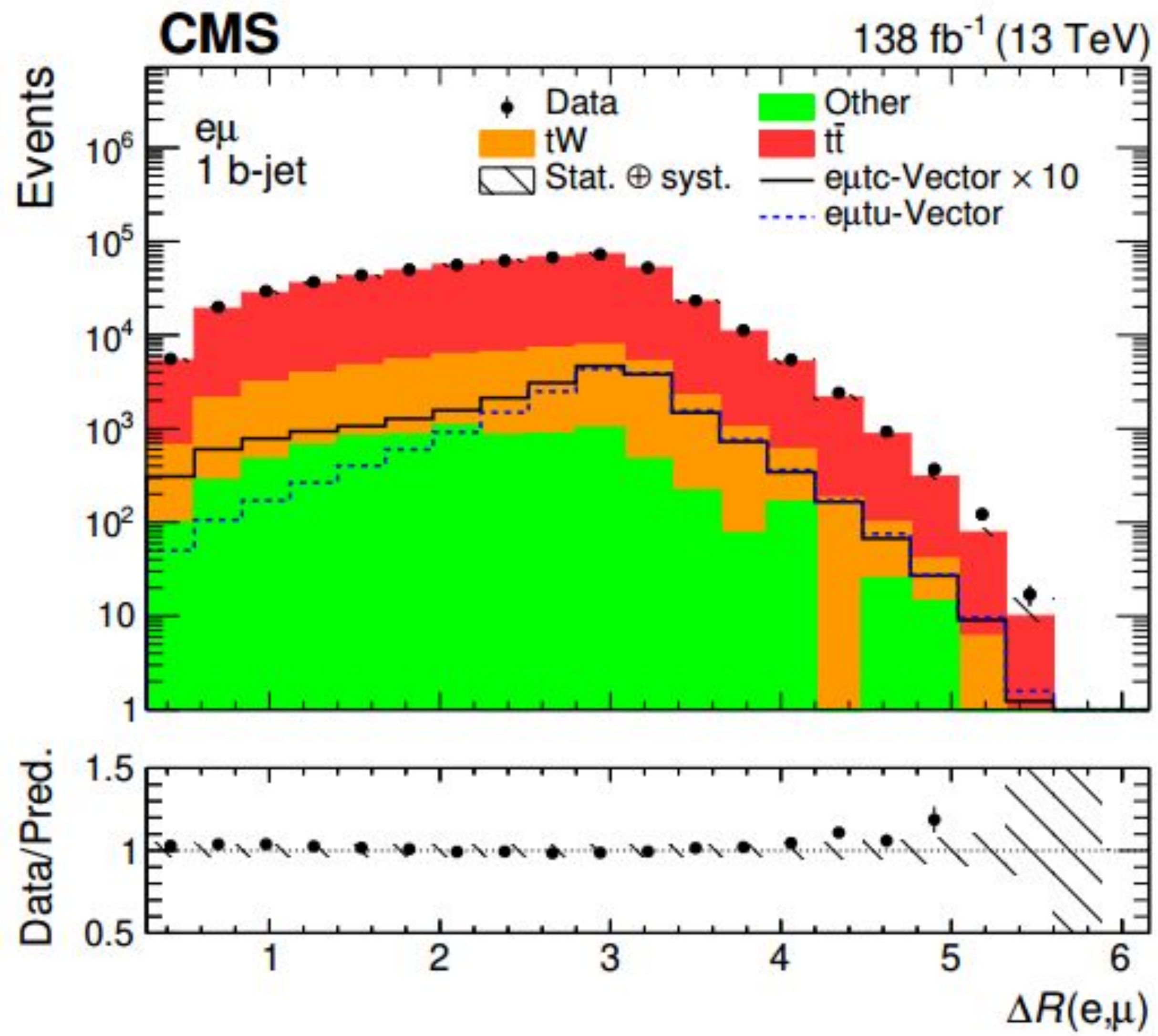
Operators that give rise to top quark CLFV interactions.

CLFV in top events

Channel			1 b tagged	>1 b tagged
$t\bar{t}$			477800 ± 7900	265000 ± 7100
tW			49100 ± 1300	7710 ± 250
Other			7950 ± 670	850 ± 70
Total background prediction			534900 ± 8000	273600 ± 7100
Data			537236	268781
eμtu	Vector	t decay	604 ± 2	45.2 ± 0.4
		t production	17103 ± 29	1557 ± 9
	Scalar	t decay	78.2 ± 0.2	6.1 ± 0.1
		t production	3670 ± 6	336 ± 2
	Tensor	t decay	3499 ± 9	266 ± 2
		t production	61011 ± 107	5567 ± 33
eμtc	Vector	t decay	596 ± 2	90.4 ± 0.5
		t production	1711 ± 3	166 ± 1
	Scalar	t decay	77.7 ± 0.2	11.4 ± 0.1
		t production	294 ± 1	28.5 ± 0.2
	Tensor	t decay	3467 ± 8	534 ± 3
		t production	6329 ± 13	621 ± 4

137 fb^{-1}

JHEP06(2022)082



CP violation in top-pair events

137 fb^{-1}
arXiv:2205.02314

$$A_{\mathrm{CP}}(O_i) = \frac{N_{\mathrm{events}}(O_i > 0) - N_{\mathrm{events}}(O_i < 0)}{N_{\mathrm{events}}(O_i > 0) + N_{\mathrm{events}}(O_i < 0)}, \quad i = 3, 6, 12, 14.$$

Zero within SM

$$A'_{\mathrm{CP}} = D A_{\mathrm{CP}}$$

ACP: measured from ideal detector
A'CP: measured effective asymmetry

$$D = \epsilon_c - \epsilon_w,$$

CP observable	Dilution factor D
O_3	$0.46\,^{+0.01}_{-0.02}$
O_6	$0.44\,^{+0.01}_{-0.02}$
O_{12}	$0.74\,^{+0.01}_{-0.02}$
O_{14}	$0.60\,^{+0.01}_{-0.01}$

where ϵ_c is the fraction of events where the measured CP observable has the correct sign, and ϵ_w is the fraction with the wrong sign. Events are classified into the correct-sign (wrong-sign) type when the sign of the CP observable at the reconstruction level agrees with (differs from) that at the POWHEG generator level.