Searches for rare and BSM top interactions at CMS

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Introduction

- SM has been successful for many years, but recently several excesses are reported
  - Lepton flavor violation: Combined result of R(D) and R(D*) anomalies, 3.3σ deviation from SM [1]
  - W boson mass measurement from CDF II [2] reported 7.0σ of deviation
  - Muon g-2 measurement [3] showed 3.3σ discrepancy

- Considering recent experimental results, as well as theoretical motivations, various anomalous interactions have been explored in the top quark sector
  - **Flavor-changing neutral currents (FCNC)**
  - **Lepton flavor violation (LFV) in top quark interactions**
  - Effective field theory approach to the new physics -> EFT details given by Jon Wilson
  - CP violations -> Also see top properties talk of Dennis Schwarz
  - Exclusive top pair production -> Covered in joker talk of Beatriz Lopes

[1] HFLAV, Semileptonic B decay, 2021 (link)
[2] CDF Collaboration, Science 376 (2022) 6589, 170-176
[3] Muon g-2 Collaboration, Phys. Rev. Lett. 126, 141801

Flavor-changing neutral currents

- FCNC: highly suppressed in SM, due to Glashow–Iliopoulos–Maiani mechanism
  - top-related FCNC branching fractions (BF) ~ 10^{12} - 10^{17} in SM

- In BSM, BF can be enhanced as high as 10^{-4} - 10^{-6}
  - Theory predicts BF close to the sensitivity with full LHC Run2 data
  - Among various Xqt (X = H, Z, g, γ) couplings,
    Hqt where Higgs to $b\bar{b}$ and $\gamma\gamma$ final states are covered in CMS

- kappa framework is used for simulation which uses a coupling modifier κ

$$\mathcal{L} = \sum_{\mathrm{q=u,c}} \frac{g}{\sqrt{2}} \bar{\mathrm{t}}\, \kappa_{\mathrm{Hqt}} (f^{\mathrm{L}}_{\mathrm{Hq}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathrm{Hq}} P_{\mathrm{R}}) \mathrm{qH} + \mathrm{h.c.}$$

arxiv:hep-ph/0409342

	SM	2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	$-$	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	$-$	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	$-$	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	5.5×10^{-6}	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	$\sim 10^{-7}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	$\sim 10^{-6}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	$\sim 10^{-4}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	1.5×10^{-3}	10^{-5}	$\sim 10^{-6}$

Hqt FCNC in H->$b\bar{b}$

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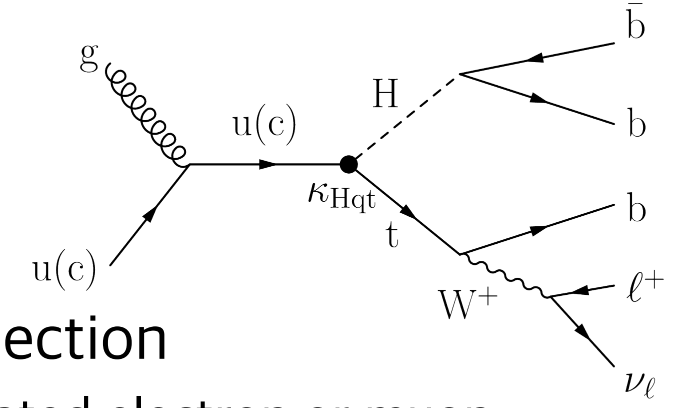
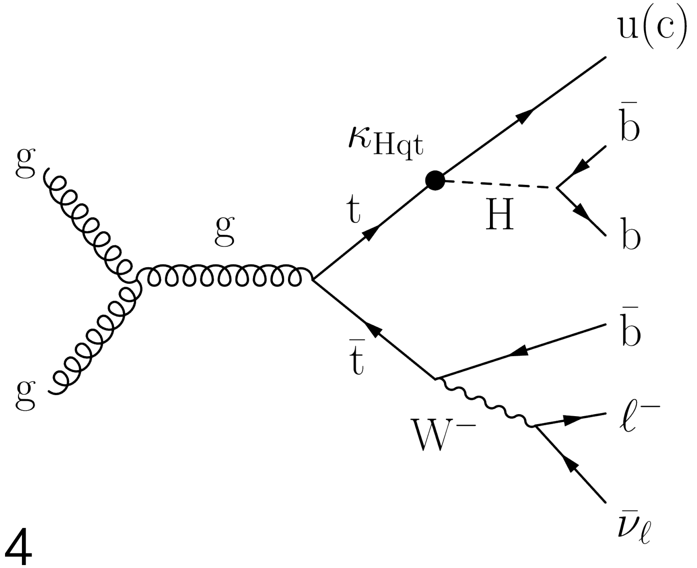
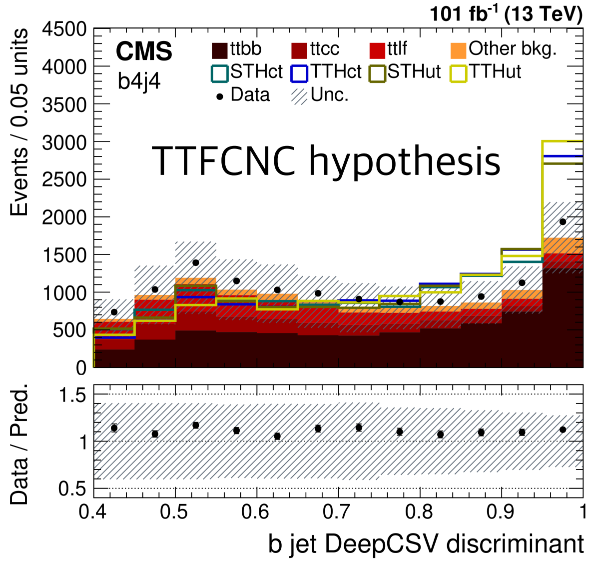
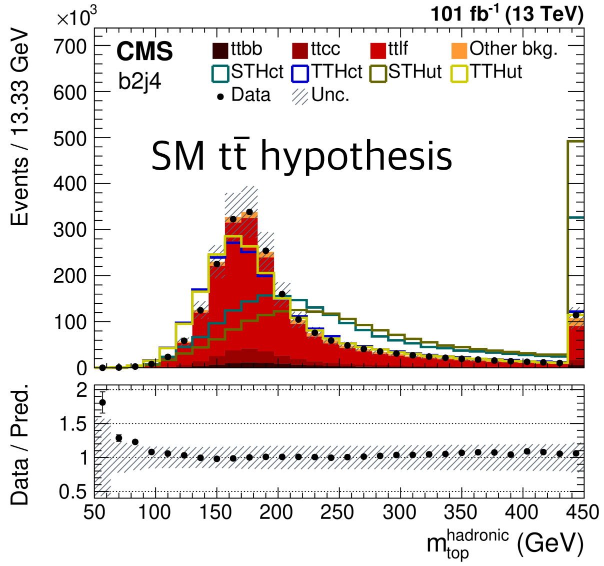
- Hqt FCNC interaction for $t\bar{t}$ or single top production, H->$b\bar{b}$ channel, 137 fb^{-1}
  - DNN event reconstruction + BDT signal extraction for 2017+2018 dataset, combine with 2016 results









- Event selection
  - One isolated electron or muon
  - jet >= 3 and b-jet >=2
    five categories: b2j3, b2j4, b3j3, b3j4, b4j4
- Event reconstruction
  - DNN to select a jet permutation
    - Assume three hypotheses: ST and TT FCNC, and SM $t\bar{t}$
    - Signals will have certain kinematics, while backgrounds dominated by $t\bar{t}$
    - Multiple hypotheses -> extract multiple sets of kinematic variables
    - They are combined at BDT for signal extraction
  - Trained for correct jet combination against the others, efficiency 78-86%

Hqt FCNC in H->$b\bar{b}$

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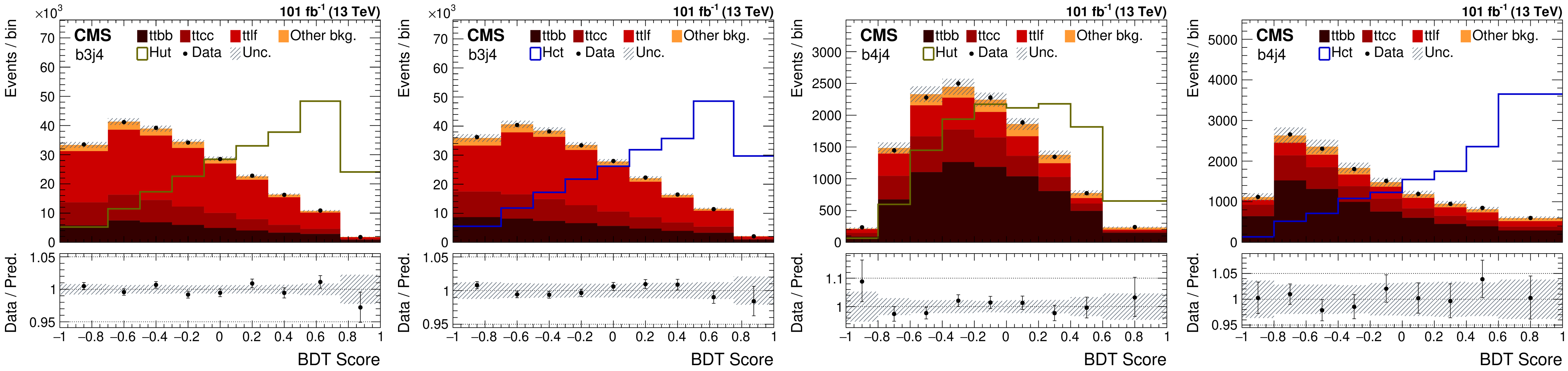
- Signal extraction
  - BDT: Signals (ST+TT) vs SM backgrounds ($t\bar{t}$), for each category/year/coupling (5*2*2 = 20 in total)
    - Inputs: lepton / jet / dijet / trijet kinematics, their angular separations, and b-tagging variables
  - Post-fit distributions:
    - Most sensitive category is b3j4 (left two), and b4j4 (right two)



- Leading systematic uncertainties
  - Theory: μ_F, μ_R
  - Experimental: b-tagging

Hqt FCNC in $H \to b\bar{b}$

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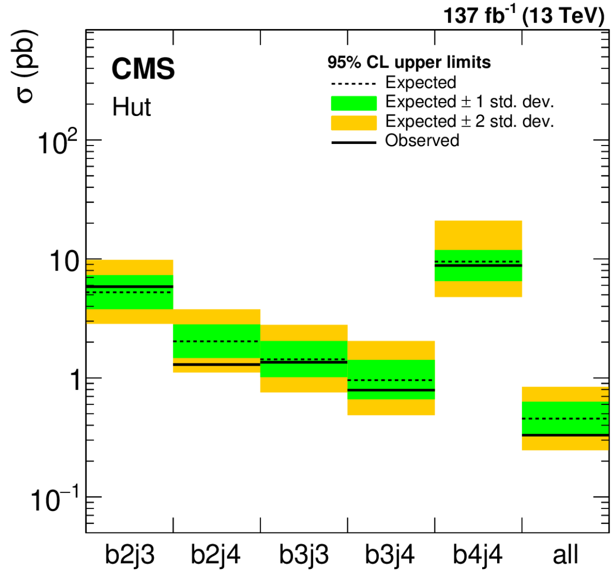
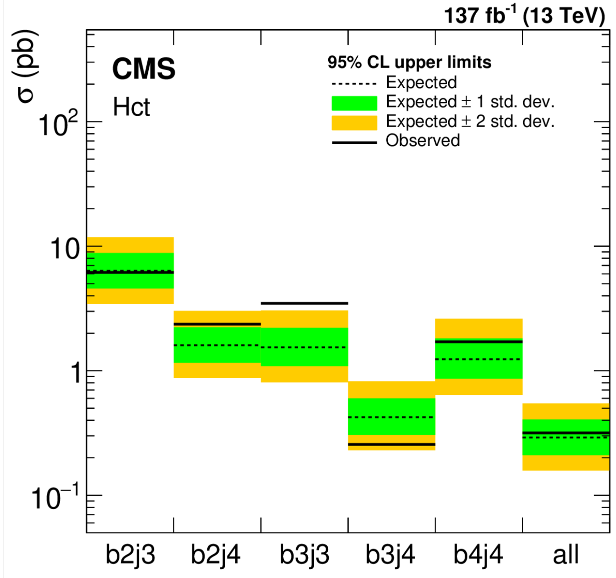
- Set limits by simultaneously fit on five BDT distribution for each coupling
  - The limits on coupling is translated to BF:

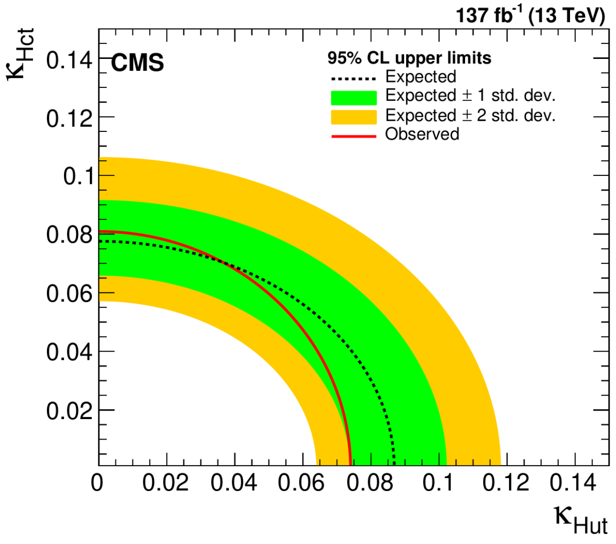
$$\kappa_{\mathrm{Hqt}}^2 = \mathcal{B}(\mathrm{t} \to \mathrm{Hq}) \frac{\Gamma_{\mathrm{t}}}{\Gamma_{\mathrm{Hqt}}}$$

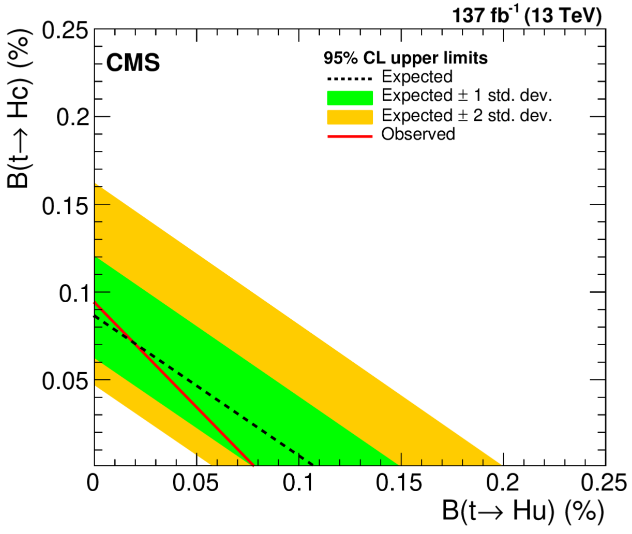
  - Corresponding observed (expected) limits are
  - B(t->Hu) < 0.079 (0.11)%
  - B(t->Hc) < 0.094 (0.86)%

  - Assuming a linear relationship between BF, limit on single nonvanishing coupling is interpolated into 2D limits







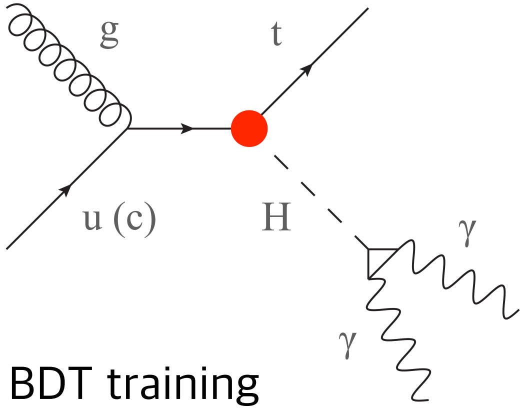


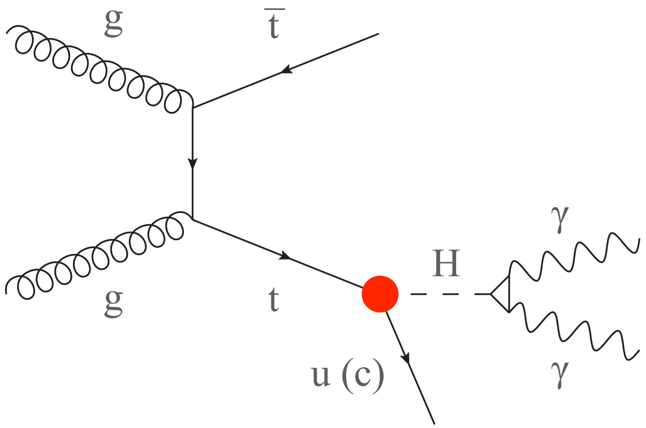
Hqt FCNC in H->γγ

PRL 129 (2022) 032001

- Hqt FCNC interaction for $t\bar{t}$ or single top production, H->γγ channel, 137 fb^{-1}

- Event selection
  - Diphoton triggers & ID, $100 < m_{\gamma\gamma} < 180$ GeV
    $p_T > 1/3\ (1/4) * m_{\gamma\gamma}$ for (sub-)leading photon
  - Leptonic channel: isolated e/μ >= 1, jet >= 1
  - Hadronic channel: jet >= 3 and b-jet >= 1
    - Use data-driven γ+jets / multijet backgrounds for BDT training
  - Resonant bkg: $120 < m_{\gamma\gamma} < 130$ GeV



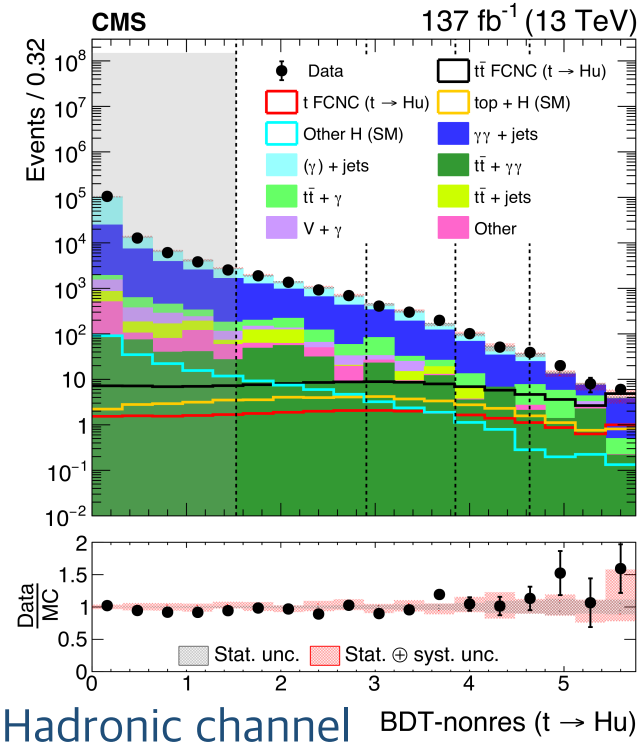


- Event reconstruction
  - Minimizing $|m_{\gamma\gamma j} - m_{top}| + |m_{jjj} - m_{top}|$, only in hadronic channel
  - Kinematic fit
  - Jet/lepton assignment using DNN, for each signal process (ST and TT) and each channel
  - Modeling of reconstructed variables are validated by comparing data and MC in res. and non-res. region
  - Reconstructed kinematic variables are used for BDT for signal extraction

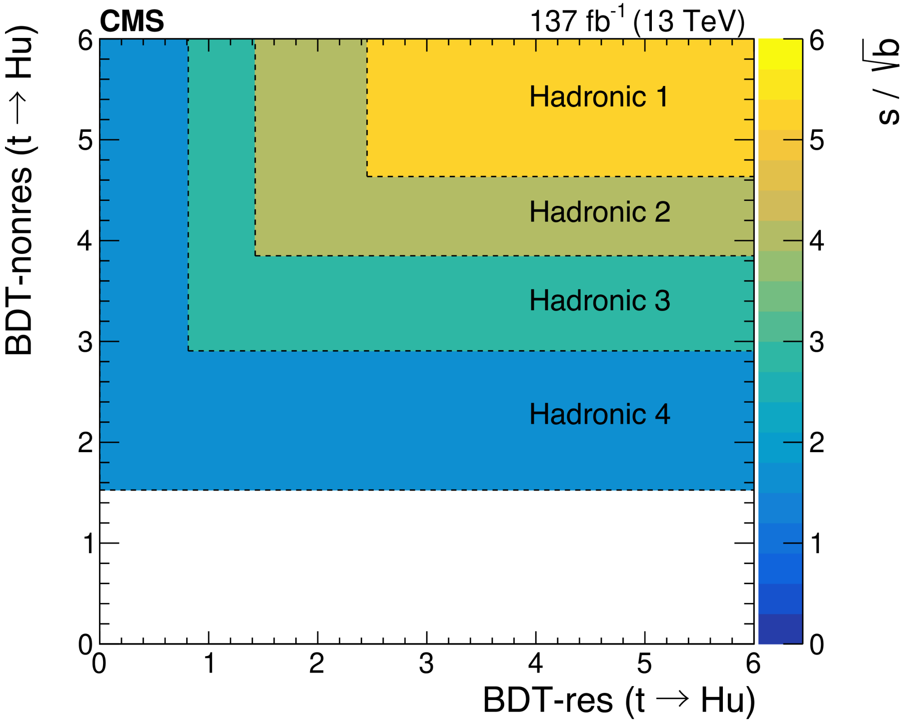
Hqt FCNC in H->γγ

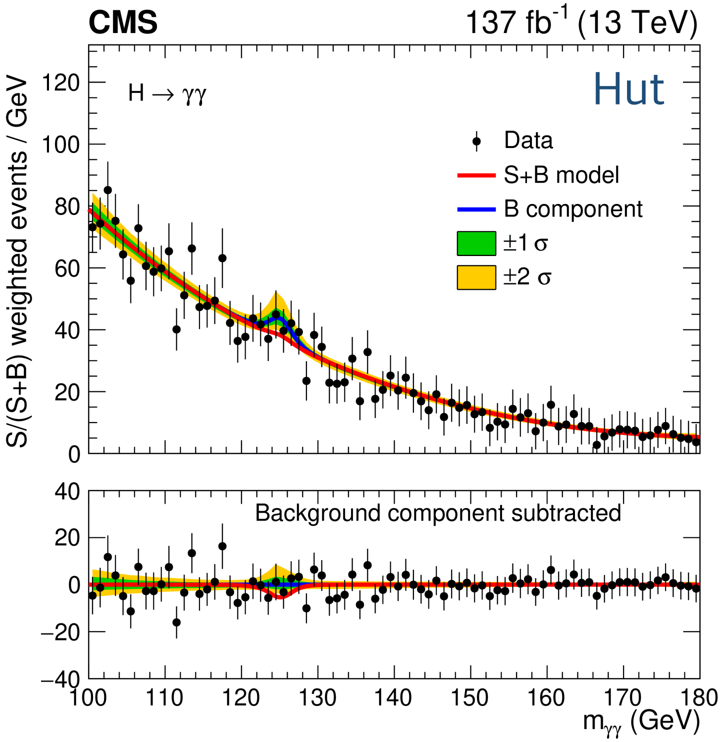
PRL 129 (2022) 032001

- Signal extraction
  - Train BDTs in resonant and non-resonant region: coupling (2) * channel (2) * (non-)res (2) = 8 BDTs
  - Using BDT scores, define 4 (had) + 3 (lep) SR



Hadronic channel

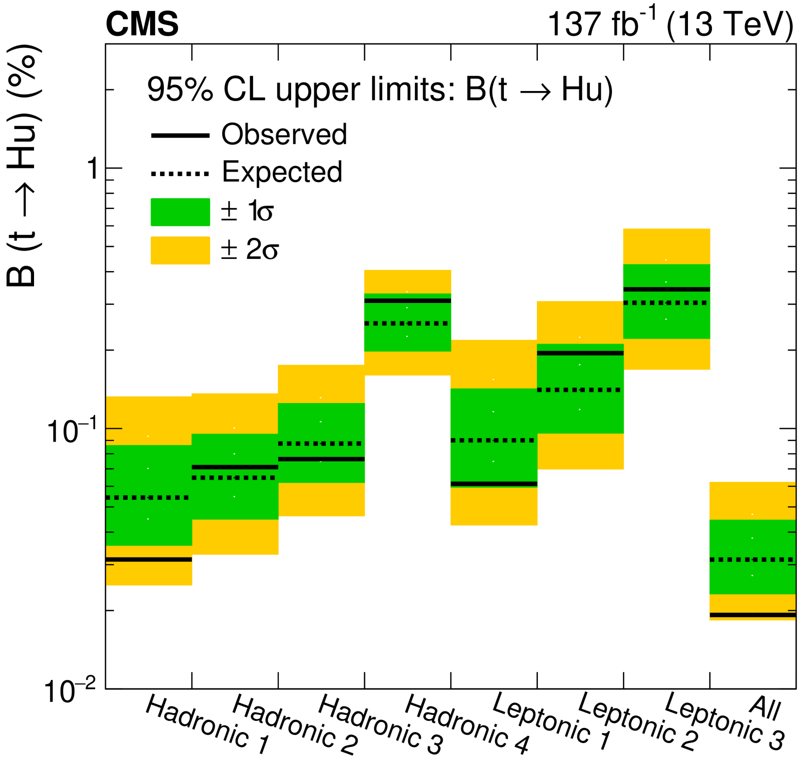


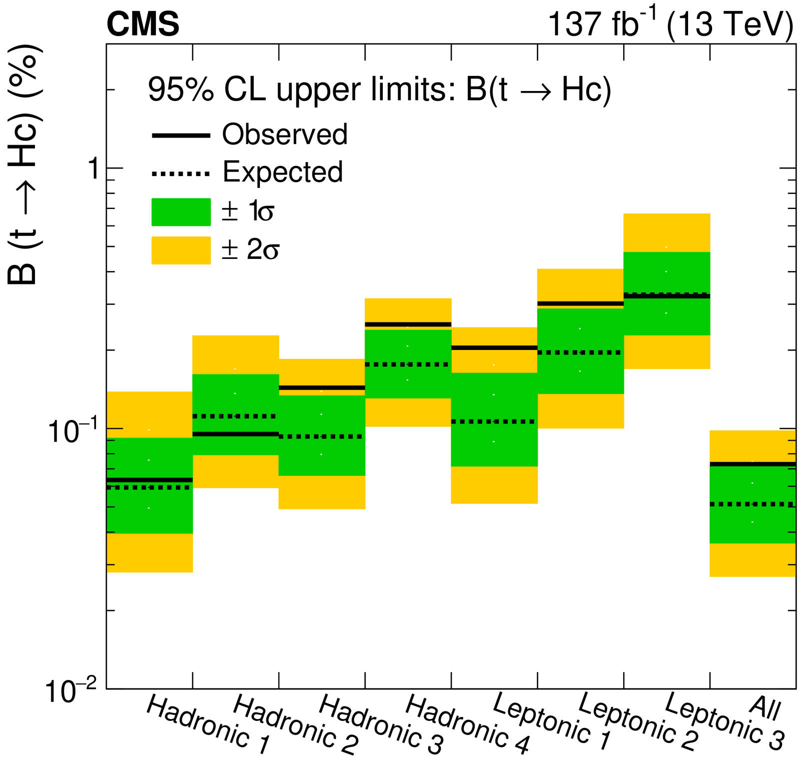


- $m_{\gamma\gamma}$ distributions with events passing the selections:
  - For fitting, $m_{\gamma\gamma}$ is drawn for each SR

Hqt FCNC in H->γγ

- Limits on branching fractions
  - Simultaneous fit on $m_{\gamma\gamma}$ distributions of SR in each coupling
  - Corresponding observed (expected) limits are
  - B(t->Hu) < 0.019 (0.031)%
  - B(t->Hc) < 0.073 (0.051)%
  - The most stringent experimental limits in Hut channel published to date.





CP violation

arXiv:2205.02314, accepted to JHEP
arXiv:2205.07434, submitted to JHEP

- CP violation regarding chromoelectric dipole moment (CEDM)
  - l+jets channel, 138 fb^{-1} (TOP-18-007, 2205.07434)
  - Dilepton channel, 36 fb^{-1} (TOP-18-007, 2205.07434)

More details on asymmetry measurement
-> See Dennis's talk

$$\mathcal{L} = \frac{g_s}{2}\bar{\mathrm{t}}T^a\sigma^{\mu\nu}(a_\mathrm{t}^\mathrm{g} + i\gamma_5 d_\mathrm{t}^\mathrm{g})\mathrm{t}G_{\mu\nu}^a \quad d_\mathrm{t}^\mathrm{g} = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}(d_\mathrm{tG})$$

-> Higher CP-odd d_{tG} implies larger CP-asymmetry (A_{CP})

  - CP observables:
    - l+jets: O_3, O_6, O_{12}, O_{14} (O_3, O_6 are sensitive to b and $\bar{\mathrm{b}}$ sign)
    - dilepton: O_1, O_3

$$A_{\mathrm{CP}}(O_i) = \frac{N_{\mathrm{events}}(O_i > 0) - N_{\mathrm{events}}(O_i < 0)}{N_{\mathrm{events}}(O_i > 0) + N_{\mathrm{events}}(O_i < 0)},$$

- Event selection
  - l+jets: One isolated lepton, jets >= 4, b-jets == 2
    - Hadronic top quark is reconstructed by chi2 minimization with $\chi^2 < 20$, $m_{lb} < 150$ GeV
  - dilepton: Two opposite-signed isolated leptons, jets >= 2, b-jets >= 1
    - $m_{ll} > 20$ GeV. For same flavored pair, applied Z mass veto ($76 < m_{ll} < 106$ GeV) and $p_T^{miss} > 40$ GeV
    - Events are reconstructed by kinematic fit
- Measure asymmetry by fitting m_{lb} (l+jets) or number of events using Poisson PDF (dilep.)

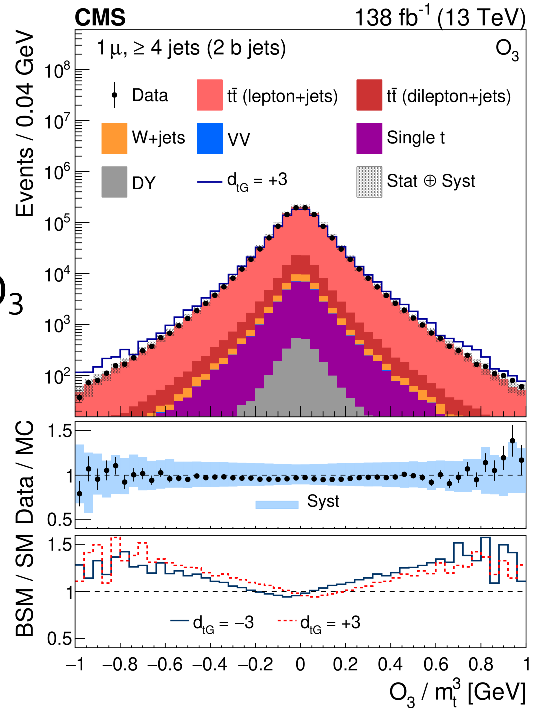
CP violation

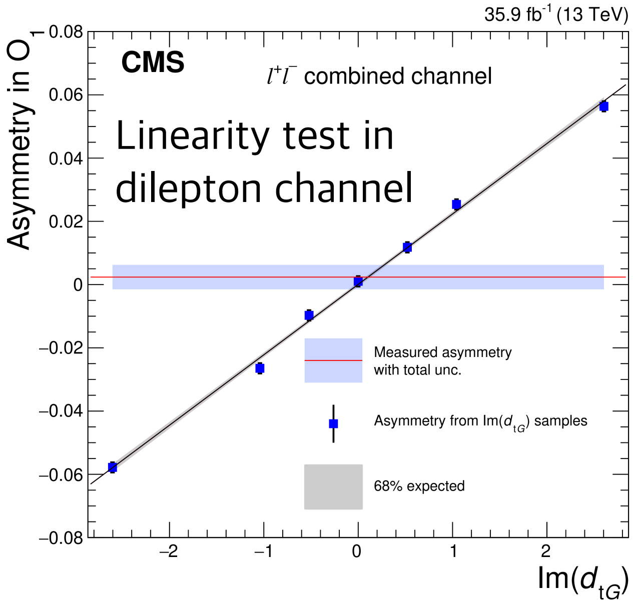
arXiv:2205.02314, accepted to JHEP
arXiv:2205.07434, submitted to JHEP

- CP observables and variations regarding CEDM parameters
- Asymmetry factor then translated in terms of CEDM
  - A_i is linearly proportional to d_{tG} (numerical tests: PhysRevD 93 014020)
  - l+jets: $A_{CP} = \frac{d_{tG} + a}{b d_{tG}^2 + c d_{tG} + d}$ and dilepton: $A = a\,\mathrm{Im}(d_{tG}) + b$
  - Dilepton channel: $d_{tG} = 0.04 \pm 0.10\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$ (combined)
  - l+jets channel:

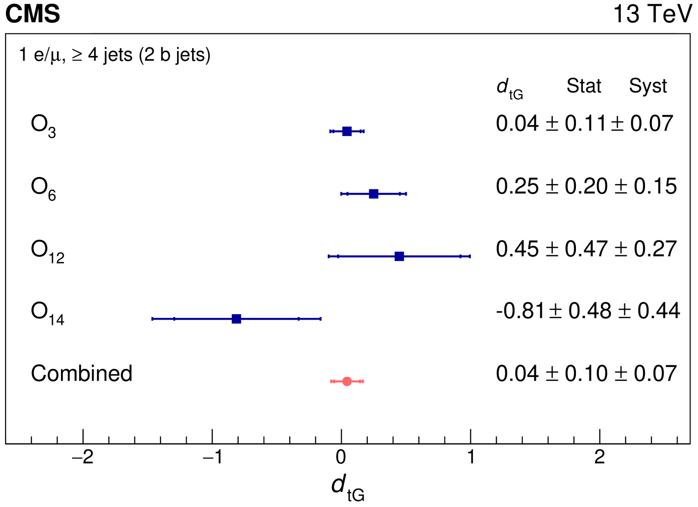
Observable	$\mathrm{Im}(d_{tG})$
$A_{\mathcal{O}_1}$	$0.10 \pm 0.12\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst})$
$A_{\mathcal{O}_3}$	$0.00 \pm 0.13\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst})$

l+jets, O_3
$d_{tG}=\pm3$

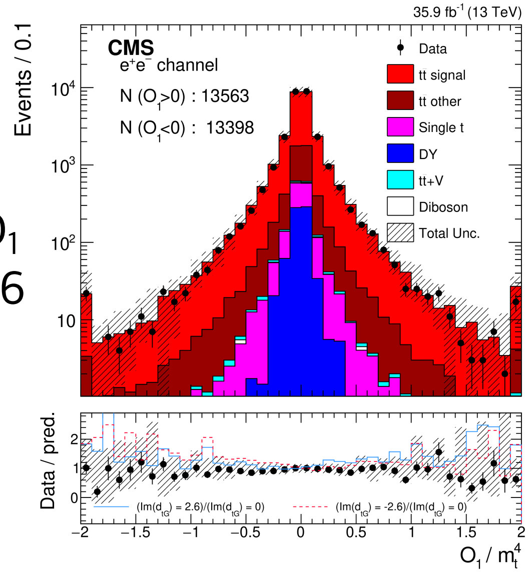




Individual and combined d_{tG} in l+jets



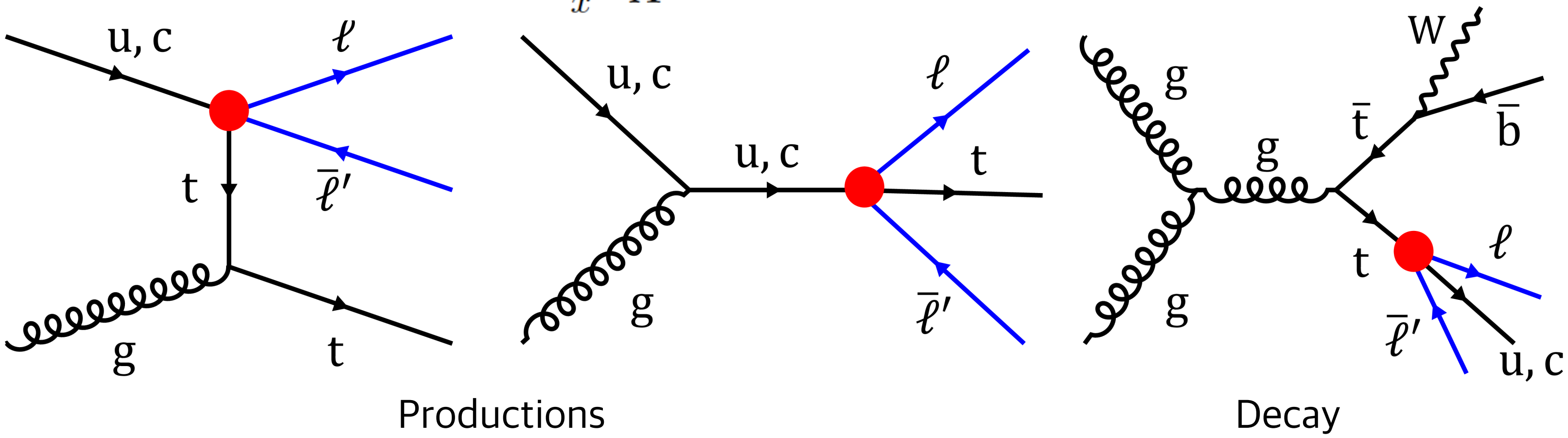
dilep, O_1
$d_{tG}=\pm2.6$



CLFV

- Charged Lepton Flavor Violation (CLFV) in $e\mu$ channel, 138 fb^{-1}
- Expect B anomaly to exist in top quark sector as well
- Event signature and relevant EFT operators: $e\mu$tu and $e\mu$tc vertices

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \cdots$$ (C: Wilson coefficient, Λ: mass scale)



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

- Predicted cross sections: Larger in production mode

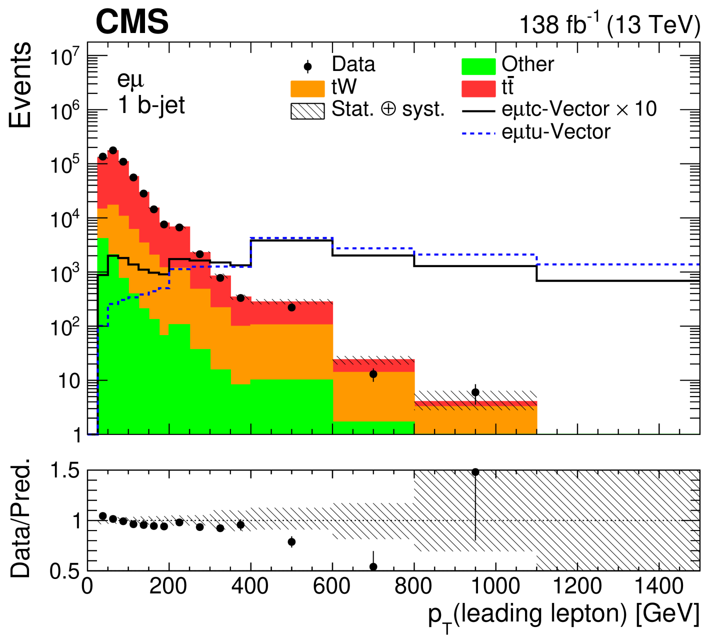
channel	Vector	Scalar	Tensor
Production ($e\mu$tu)	$634^{+113}_{-90} \pm 8$	$139^{+26}_{-20} \pm 2$	$2908^{+503}_{-401} \pm 37$
Production ($e\mu$tc)	$58^{+9}_{-7} \pm 8$	$12.1^{+2.0}_{-1.6} \pm 1.8$	$292^{+42}_{-35} \pm 37$
Decay ($e\mu$tq)	$32.0^{+0.8}_{-1.1} \pm 1.3$	$4.0^{+0.1}_{-0.1} \pm 0.2$	$187^{+5}_{-6} \pm 8$

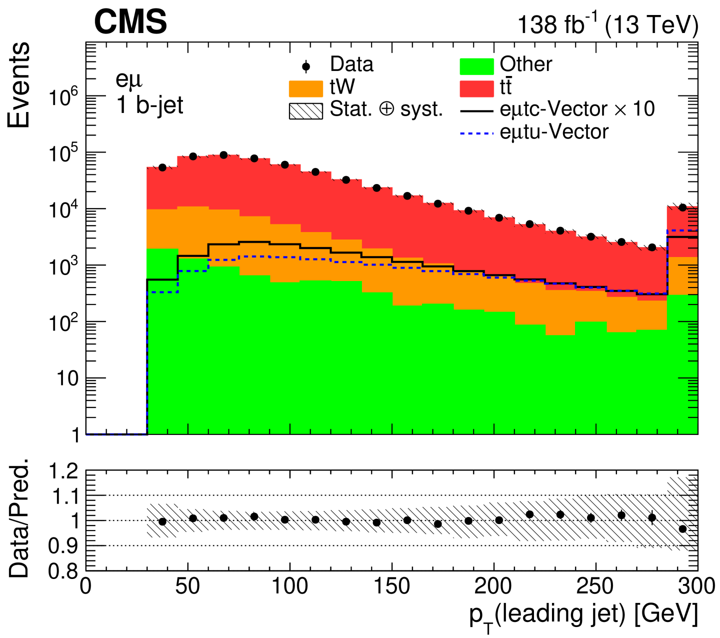
unit in fb, with Λ = 1 TeV

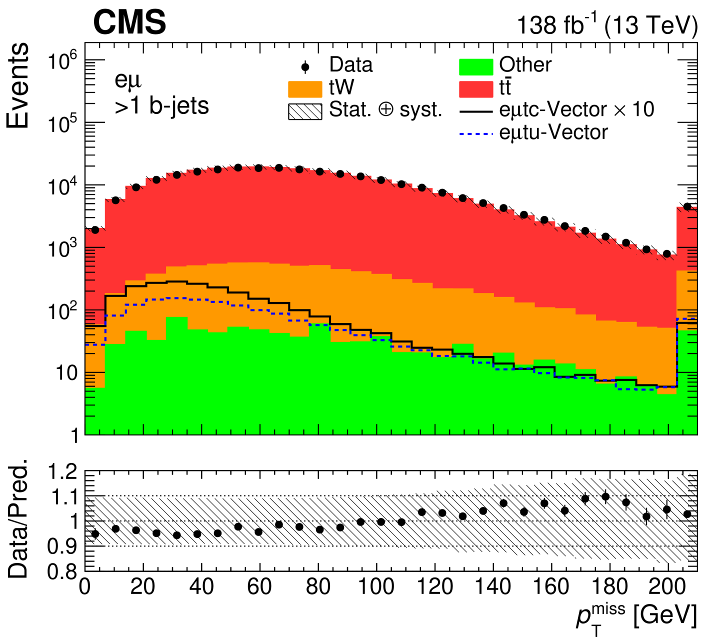
More details on EFT: check the talk given by Jon

JHEP 06 (2022) 082

- Event selection
  - Combination of single and dilepton ($e\mu$) triggers
  - Oppositely charged $e\mu$ pair, $m_{e\mu} > 20$ GeV, jets >= 1, b-jets >= 1,
  - Two categories: b-jets = 1 and b-jets > 1 for signal extraction using BDT
  - Signals: three types of operators (scalar, vector, and tensor) * two flavors of quarks (u / c)
- Utilize BDT to distinguish signals over backgrounds
  - Inputs: p_T of leading jet and lepton, MET, $\Delta R(e,\mu)$, # of jets
  - Leading lepton p_T well characterizes signal kinematics

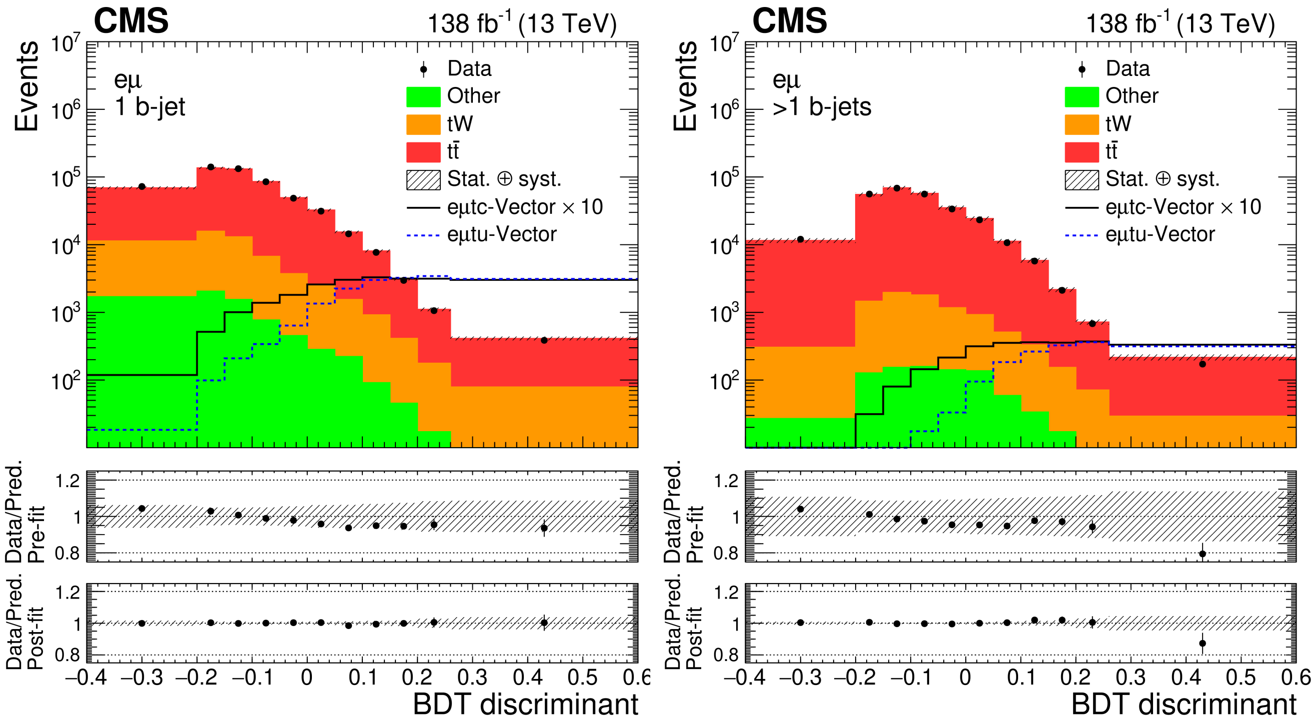




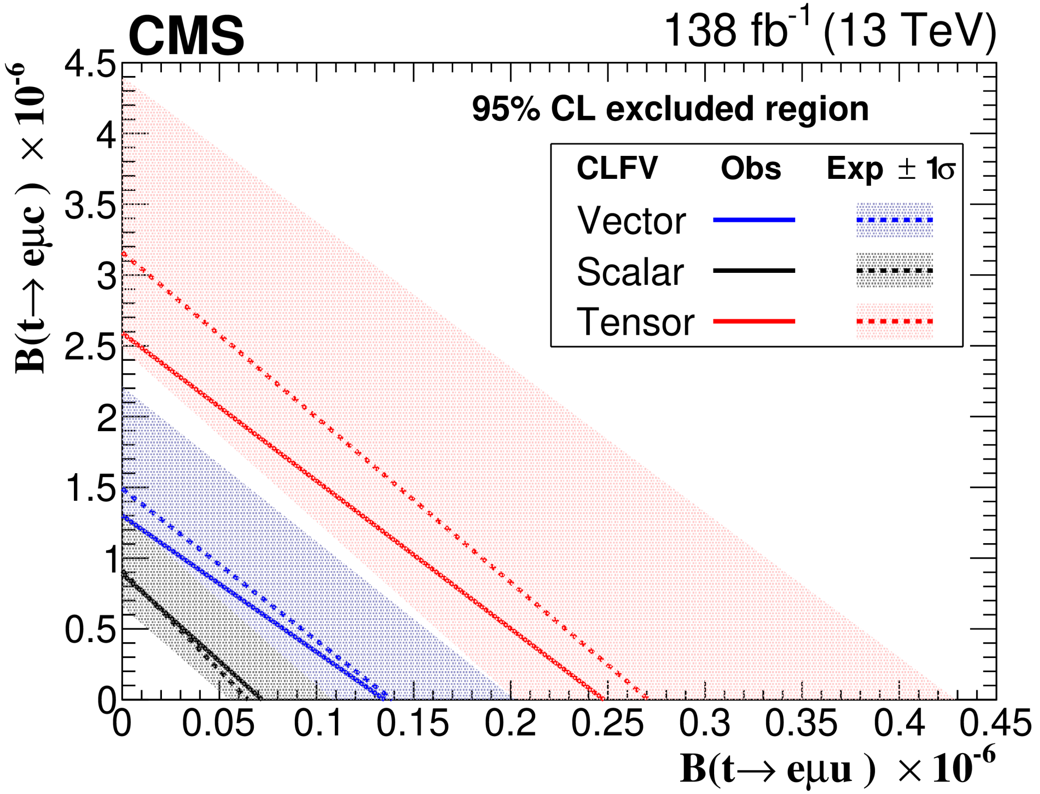


JHEP 06 (2022) 082

- Fit BDT distributions to data and set upper limit on Wilson coefficients
  - Limits are calculated for scalar, vector, and tensor operators, individually
  - Limits on Wilson coefficients then translated to branching fractions



- 2D limits assuming both flavor of quarks at the same time



- Limits on BF reach O(10^{-6} – 10^{-8}), setting the most restrictive bounds to date.

Summary

- CMS collaboration continues searching for rare and BSM top quark interaction searches
  - Flavor-changing neutral currents
  - Lepton flavor violations
  - CP violation
  - Effective field theory approaches
  - And other rare processes

- Experimental results suggest no significant excess from the SM predictions so far

- The last set of analyses with the 138 fb^{-1} data are coming soon, stay tuned!

Backup

CPV in dilepton channel

- Parameterization of A_{CP}
  - From Phys. Rev. D 93, 014020 (2016): $$\mathcal{A}_i = \frac{\sigma(\mathcal{O}_i > 0) - \sigma(\mathcal{O}_i < 0)}{\sigma_{SM}}$$

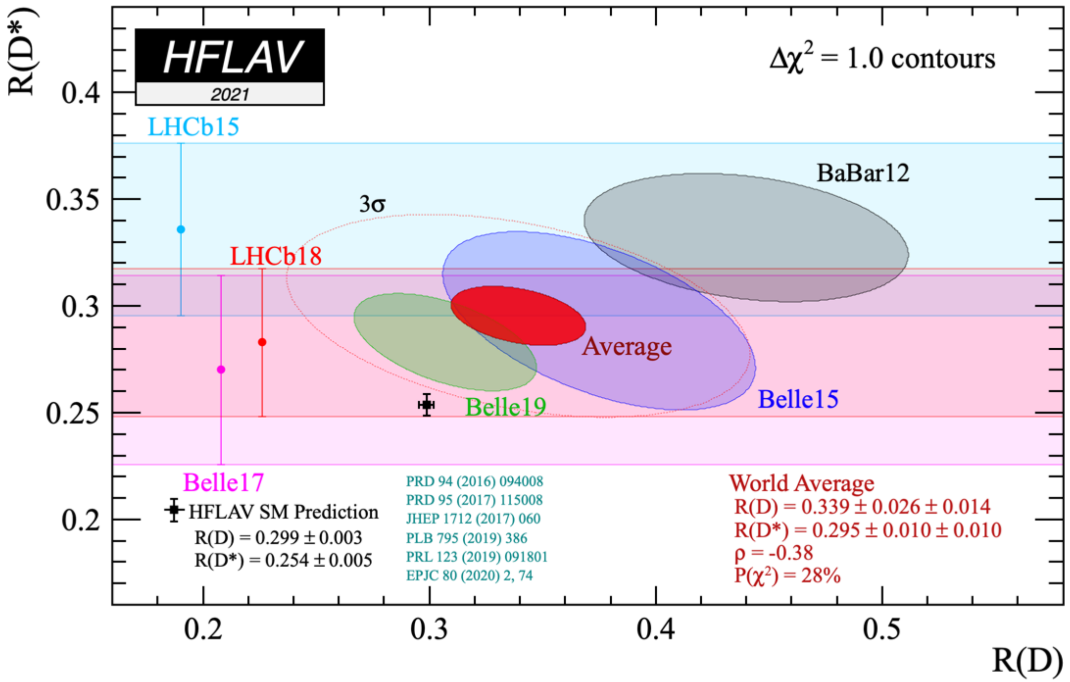
$$A_{\mathrm{CP}}(O_i) = \frac{N_{\mathrm{events}}(O_i > 0) - N_{\mathrm{events}}(O_i < 0)}{N_{\mathrm{events}}(O_i > 0) + N_{\mathrm{events}}(O_i < 0)},$$

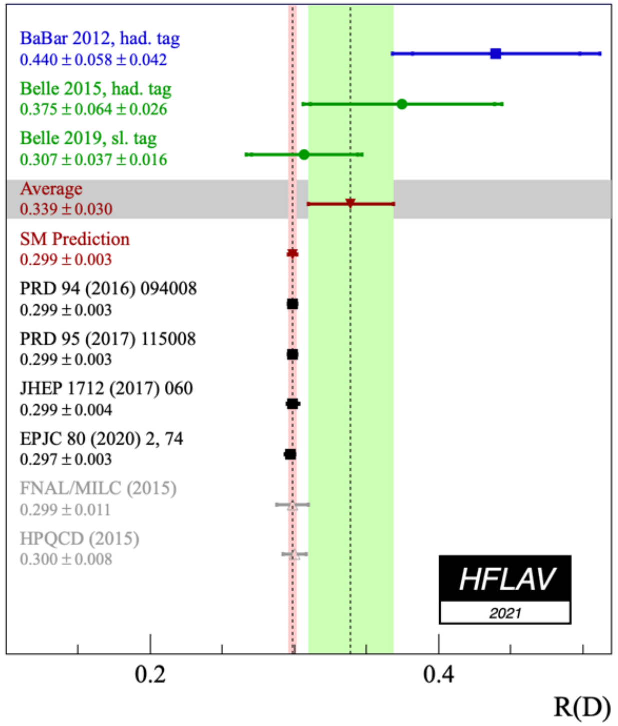
  - As CEDM cross section is proportional to d_{tG}^2

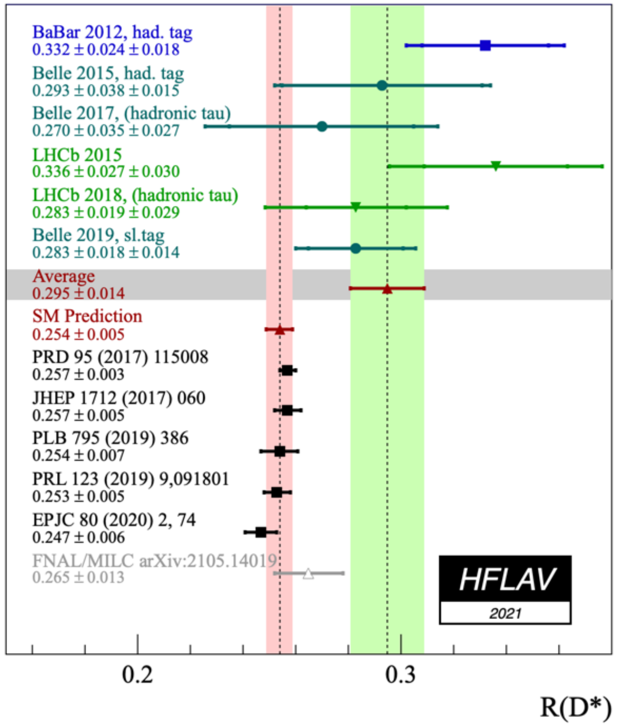
$$A_{CP} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{\sigma_+ - \sigma_-}{\sigma_{SM}} \frac{\sigma_{SM}}{\sigma_{CEDM}}$$
$$= A_i \times \frac{\sigma_{SM}}{\sigma_{CEDM}} = (a \cdot d_{tG} + b) \times \frac{\sigma_{SM}}{\sigma_{CEDM}}$$
$$= \frac{a \cdot d_{tG} + b}{c \cdot d_{tG}^2 + d \cdot d_{tG} + e}$$

R(D) and R(D*) anomalies

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \, \nu_\tau)}{\mathcal{B}(B \to D^* l \, \nu_l)}$$







CLFV

- List of operators and yield (C/Λ^2 = 1 TeV^{-2}), limits on operators and BF

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

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

Vertex	Int. type	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
$e\mu tu$	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
$e\mu tc$	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