New Physics Searches with Top Quarks:

Flavor Changing Neutral Currents (FCNC)

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on behalf of the ATLAS and CMS Collaborations

Standard Model at the LHC 2024

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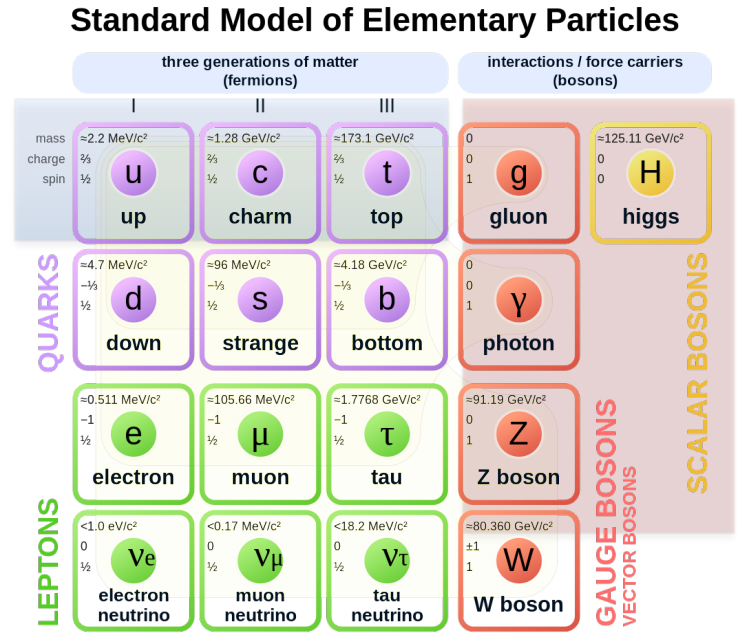
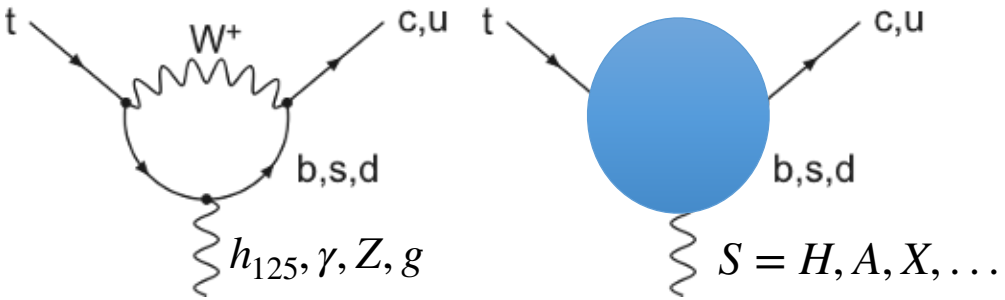
FCNCs

- Transitions that change the flavor of a fermion w/o changing charge.
- Forbidden at tree level in the SM.
- Suppressed at higher orders due to GIM mechanism.
  - Due its high mass, Top-Higgs FCNC transitions have the largest suppression in the SM.
- Occurs only at the level of quantum loop corrections.



$$\mathcal{B}(t \to Xq) \sim 10^{-17} - 10^{-12}$$

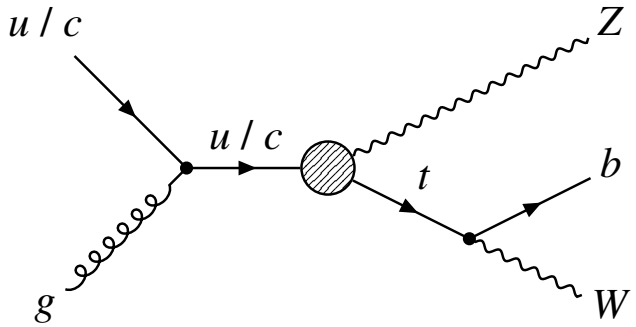


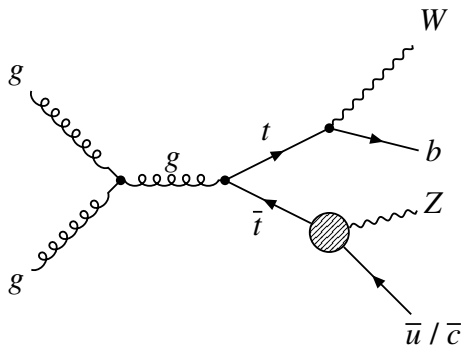
→ Any evidence of FCNC indicates the existence of new physics:
In this talk, recent searches for FCNC interactions of *both SM particles* and *new scalar particles* with « model-independent » *Effective Field Theory (EFT)* approaches and model-dependent *direct searches*.

- Charged-Lepton-Flavor Violation (cLPV)
- Baryon-Number Violation (BNV)

} covered in Sergio's talk (and in the backup)

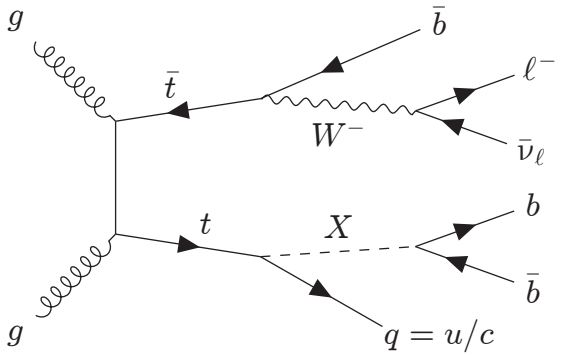
FCNC Signatures

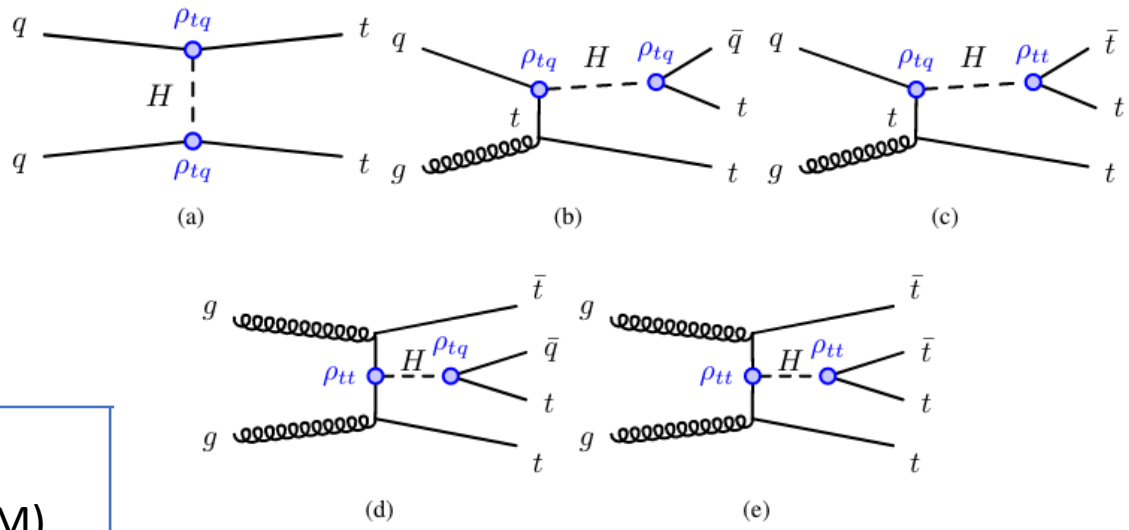




- In all searches of **FCNC interactions of SM particles in this talk**: t and $t\bar{t}$ in single analysis: in general only N_{jets} different in the signal signature.

- **FCNC interactions of new scalar particles**: 1 lepton, 2 same-sign lepton, 3, 4 leptons + jets





Signal simulation:

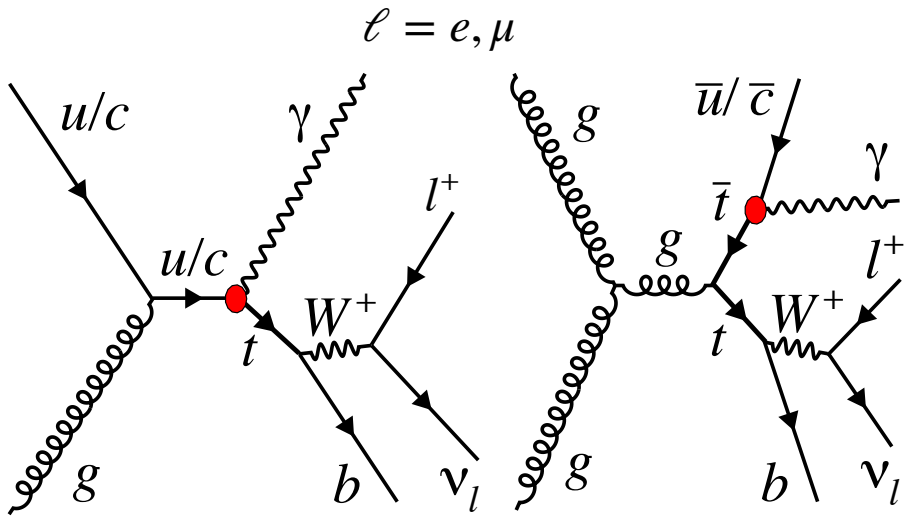
ATLAS: NLO QCD with MG5_aMC or POWHEGv2 (except g2HDM)

CMS: LO QCD with MG5_aMC.

Top-γ and Top-Z FCNC couplings

FCNC interactions of top quark with a photon

PRD 109 (2024) 072004

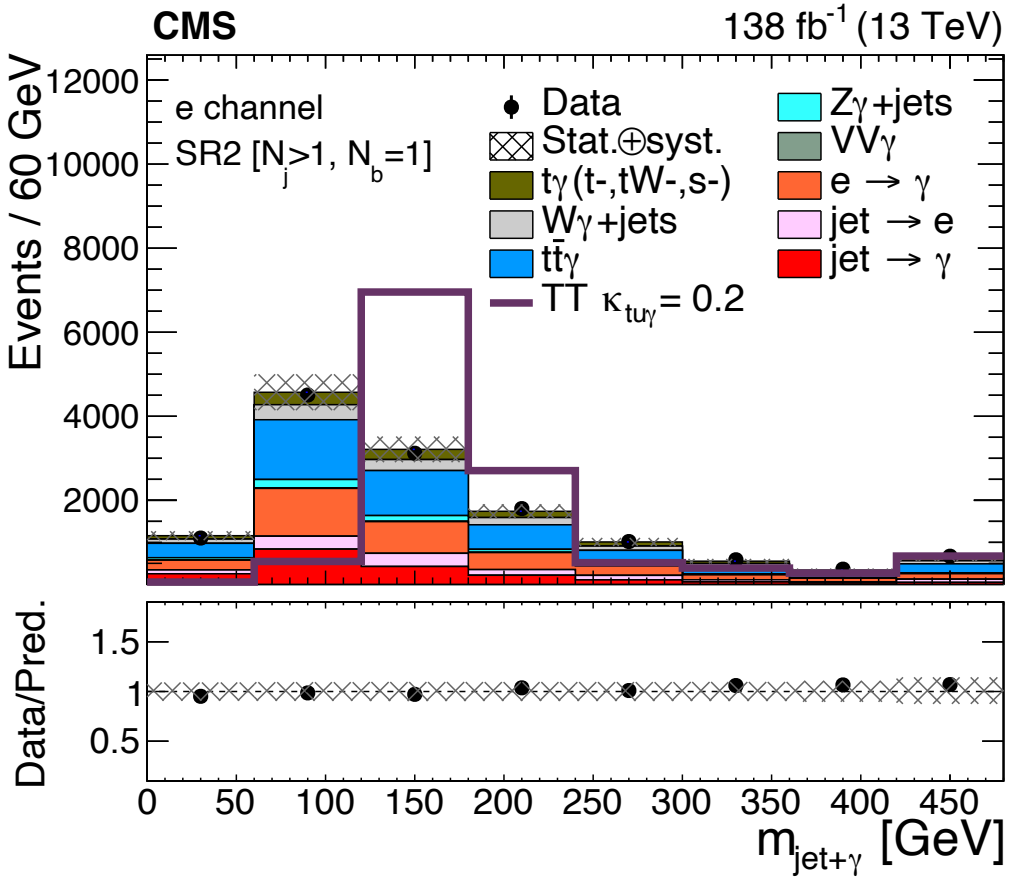


SR1 (t):
$N_b = 1$ & $N_j = 1$

more sensitivity to $t\gamma u$ (PDF effect).

SR2 ($t\bar{t}$):
$N_b = 1$ & $N_j \geq 2$

similar sensitivity to $t\gamma u$ and $t\gamma c$.



- Nonprompt lepton & photon, e misidentified as γ, and other bkgs. estimated from data except $t\gamma$ and $VV\gamma$.

Input to BDTs:

p_T^γ, m_T^W, $m_{\ell\nu b}$ (common in SRs)

$\Delta R(\ell, bjet)$ (SR1)

$m_{jet+\gamma}$ (SR2)

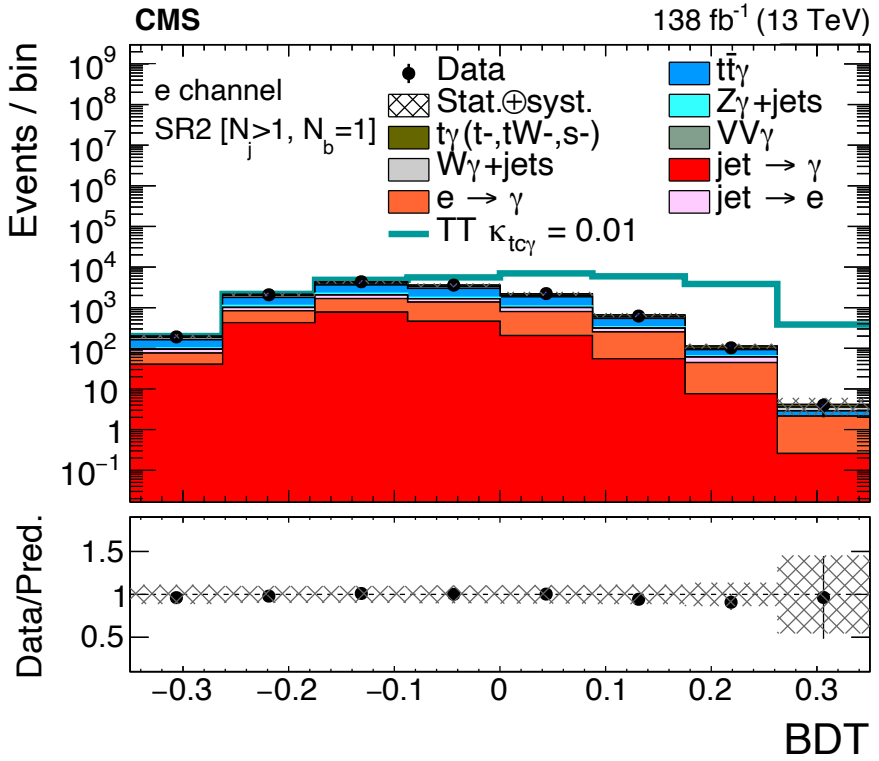
$p_T^\gamma > 30\ GeV$

$|\eta| < 1.44$

FCNC interactions of top quark with a photon

PRD 109 (2024) 072004

- Likelihood fit combining 12 BDTs: 2 channels (e, μ), 2 SRs, 3 data-taking years w/ separate nuisances for $t\gamma u$ and $t\gamma c$.



Obs.(Exp.) limits on anomalous FCNC couplings (κ) and branching ratios ($\mathscr{B}$):

$\kappa_{tu\gamma} < 6.2(6.9) \times 10^{-3}$, $\mathscr{B}(t \to u\gamma) < 0.95(1.20) \times 10^{-5}$

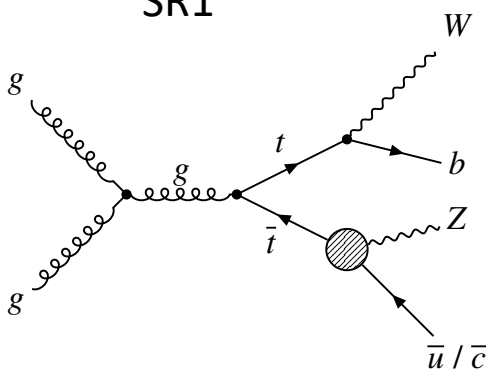
$\kappa_{tc\gamma} < 7.7(7.8) \times 10^{-3}$, $\mathscr{B}(t \to c\gamma) < 1.51(1.54) \times 10^{-5}$

- Dominant uncertainties: *nonprompt-γ, Zγ+jets and Wγ+jets normalizations, and misidentified-γ.*
- Adding another signal region, i.e. SR2 ($t\bar{t}$) and electron channel, increased cross section at 13 TeV (and larger integrated luminosity) → **limit significantly improved for** $\mathscr{B}(t \to c\gamma)$
  - $100x$ w.r.t. 8 TeV CMS JHEP 04 (2016) 035
  - $\sim 3x$ improvement w.r.t to the ATLAS previous best result PLB 842 (2023) 137379

FCNC interactions of top quark with a Z boson

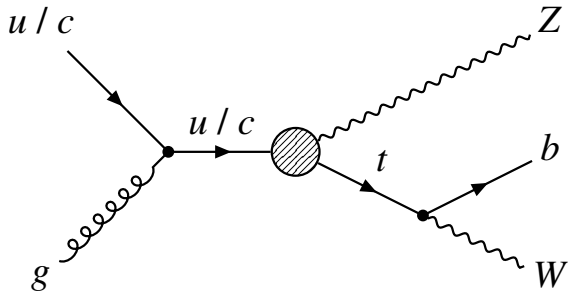
PRD 108 (2023) 032019

SR1



similar sensitivity to tZu and tZc.

SR2

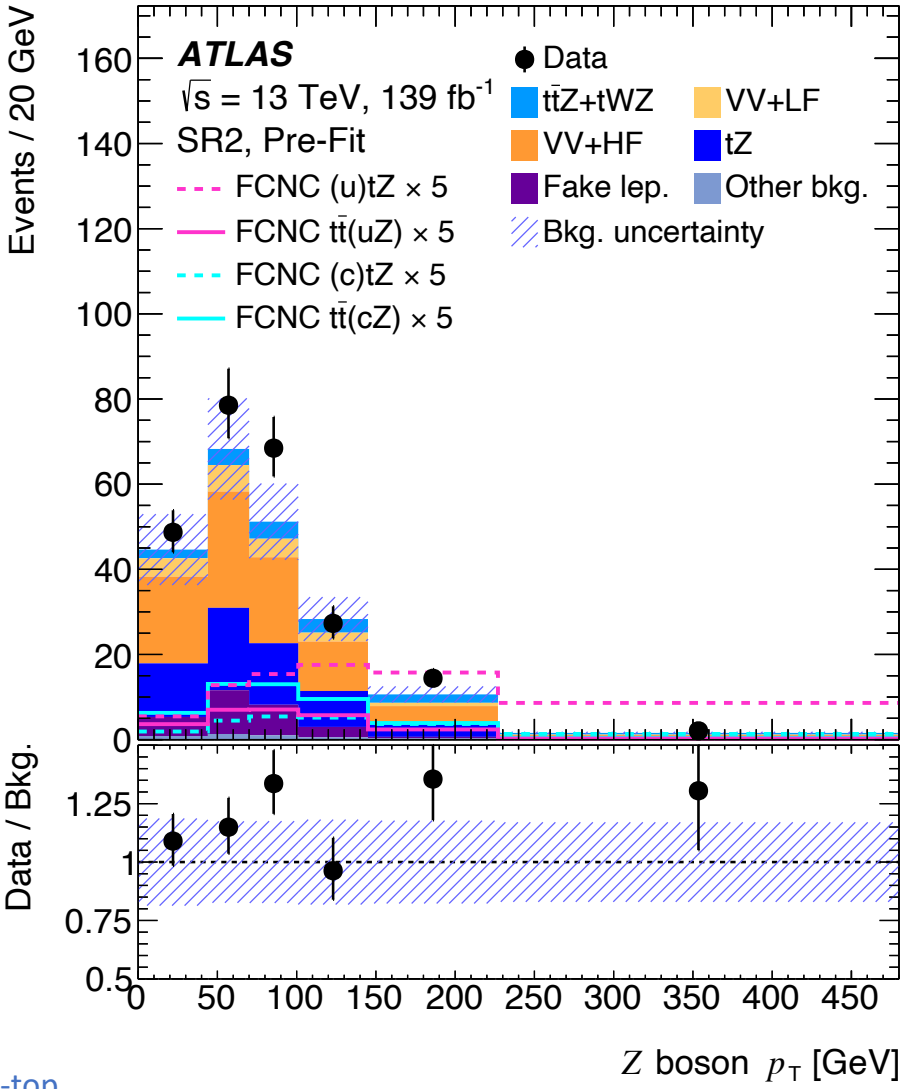


more sensitivity to tZu (PDF effect).

- 3 leptons, 1 b-tag + jets and MET.
- BDT training done separately for left-handed (LH) and right-handed (RH) FCNC operator samples in each SR.
  - D_1: Single discriminant for *tZu* and *tZc* in SR1.
  - D_2^u: Training for *tZu* *in* SR2
  - D_2^c: Training for *tZc* using FCNC in $t\bar{t}$ decay (SR1) + in single-top production (Sr2)

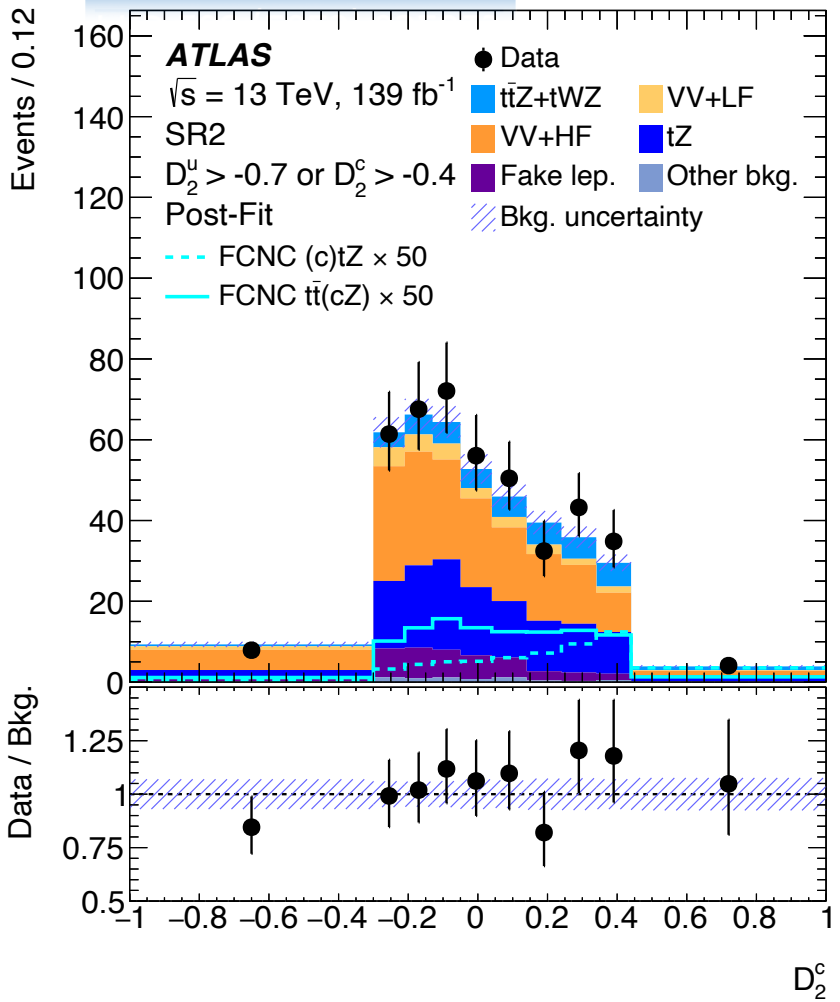
m_t^{SM}, m_t^{FCNC}
$\Delta R(m_t^{SM}, m_t^{FCNC})$
$\Delta R(\ell, \ell')$
N_{jets}
$p_T^j(u/c)$

p_T^Z, p_T^b
$\Delta R(Z, b)$
m_t^{SM}
$\Delta R(\ell, \ell')$
$\chi^2(kin.fit)$ FCNC in single-top



FCNC interactions of top quark with a Z boson

PRD 108 (2023) 032019



BDT for tZc using FCNC in $t\bar{t}$ decay *and* in single-top production (D_2^c)

- Simultaneous profile likelihood fit in SRs and CRs.
  - 4 independent fits to extract LH, RH for $\mathcal{B}$ and effective coupling strengths (Wilson coefficients C_k) for *tZu* and *tZc* couplings.
  - Dominant uncertainties: *statistical, SM tZ background normalization and diboson modeling.*

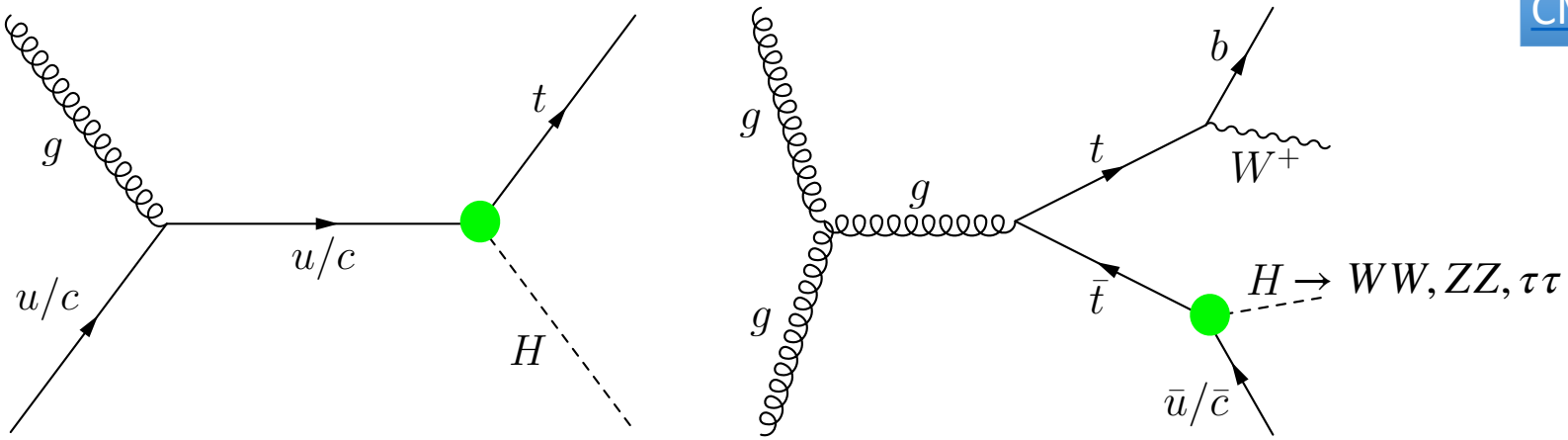
Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	*tZu*	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	*tZu*	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	*tZc*	LH	13×10^{-5}	$11\,^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	*tZc*	RH	12×10^{-5}	$10\,^{+4}_{-3}\times10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	*tZu*	LH	0.15	$0.13\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	*tZu*	RH	0.16	$0.14\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	*tZc*	LH	0.22	$0.20\,^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	*tZc*	RH	0.21	$0.19\,^{+0.04}_{-0.03}$

Λ_{NP} = 1 TeV

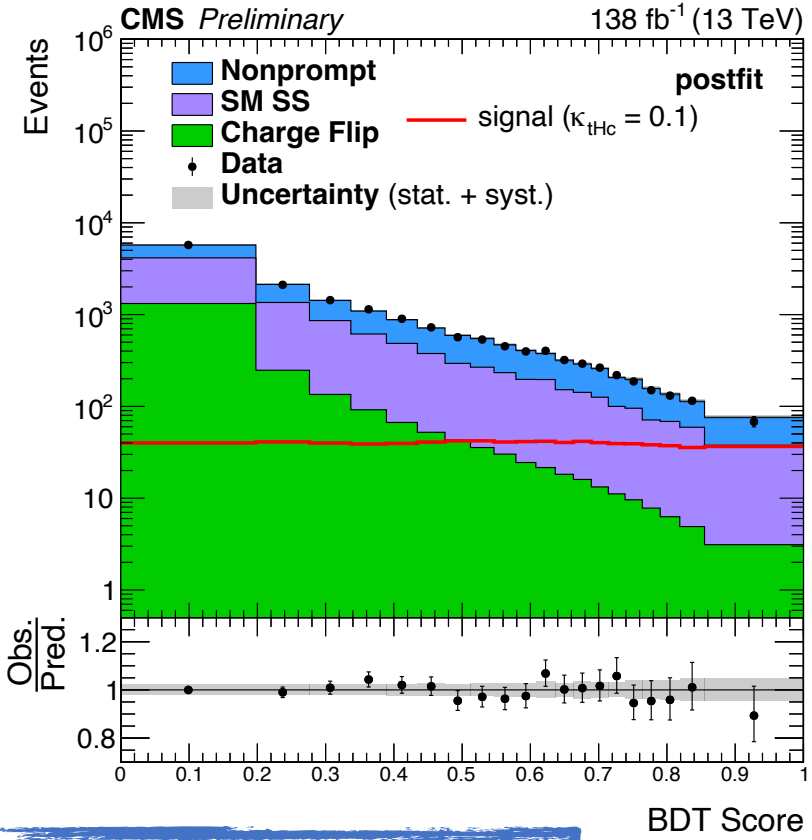
- Thanks to the added single-top quark channel, MVA, and higher integrated luminosity $5(3)x$ **improved expected limits** for $\mathcal{B}(t \to Zu)$ $(\mathcal{B}(t \to Zc))$ w.r.t. previous 13 TeV ATLAS results JHEP 07 (2018) 176.

Top-Higgs FCNC Couplings

FCNC top-Higgs-u/c couplings with multi-leptons



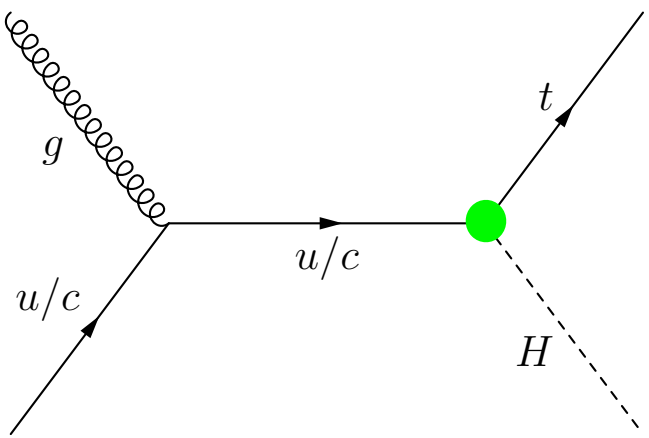
CMS-PAS-TOP-22-002

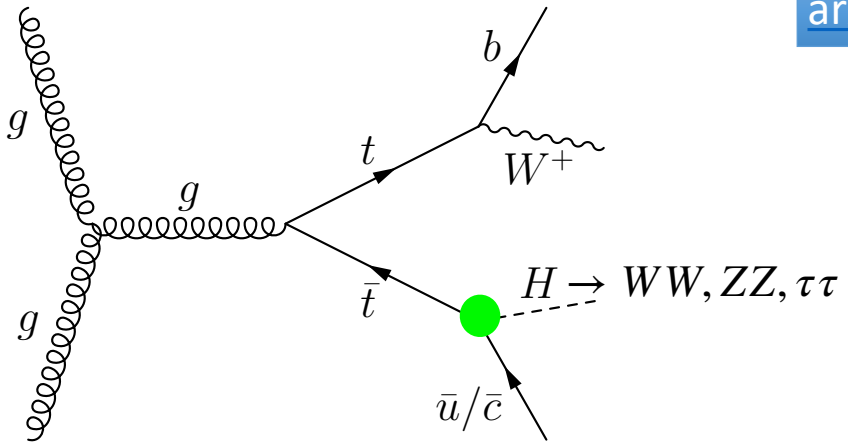


- ≥ 2 leptons (w/ same-sign charge (e, μ)) + ≥ 1 jet (w/ 1 b-tag).
- Separate BDTs for tHc and tHu signals
  - e.g. inputs: N_e, N_j, N_b, b/c tagging discriminator scores, …
- Likelihood fit including nonprompt lepton and charge mis-id control regions.
- Dominant uncertainties: *signal modeling, b/c tagging estimation, nonprompt lepton and charge-flip backgrounds.*

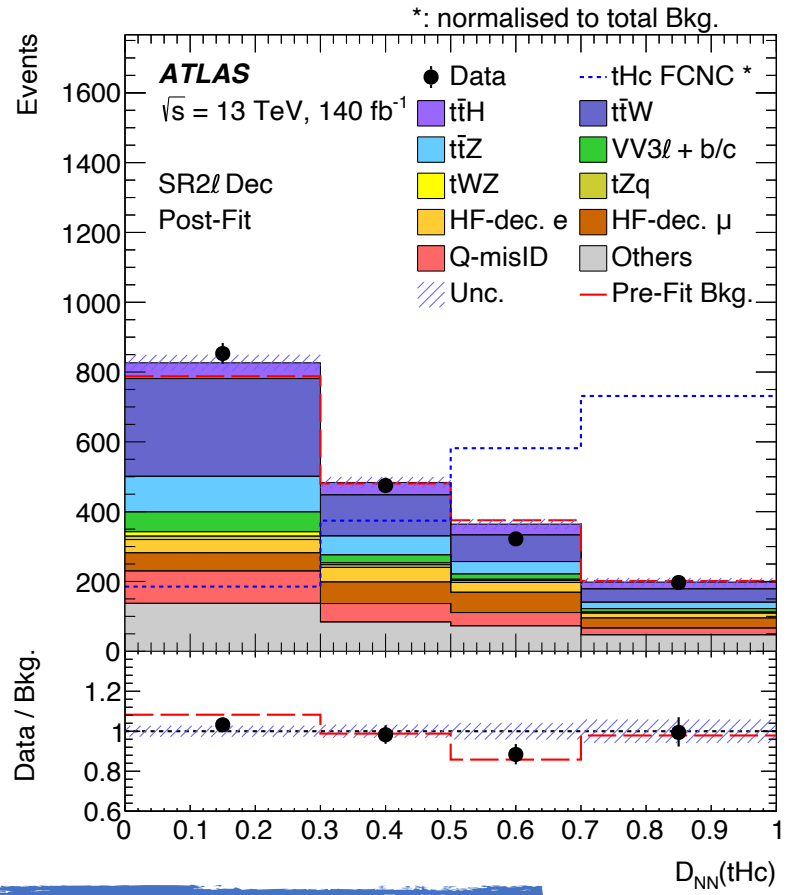
$\mathcal{B}(t \to Hu) < 0.072\,\%\,(0.059\%)$
$\mathcal{B}(t \to Hc) < 0.043\,\%\,(0.062\%)$
$\kappa_{tuH} < 0.071(0.064)$
$\kappa_{tcH} < 0.055(0.065)$

FCNC top-Higgs-u/c couplings with multi-leptons





arXiv:2404.02123

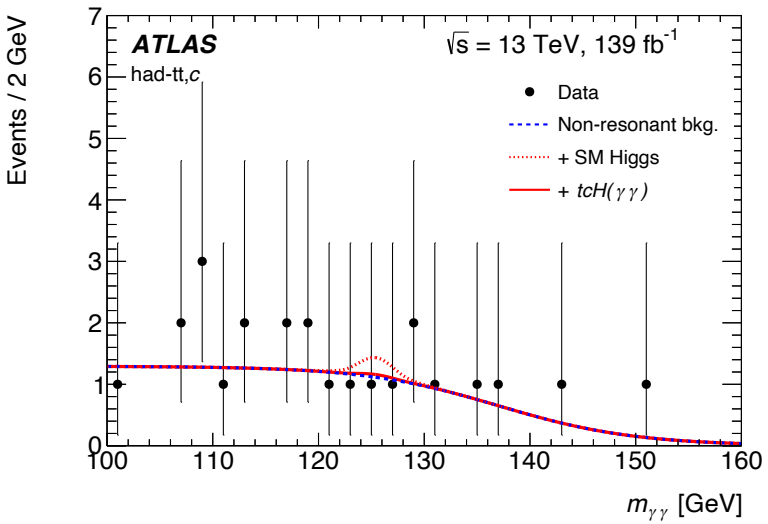


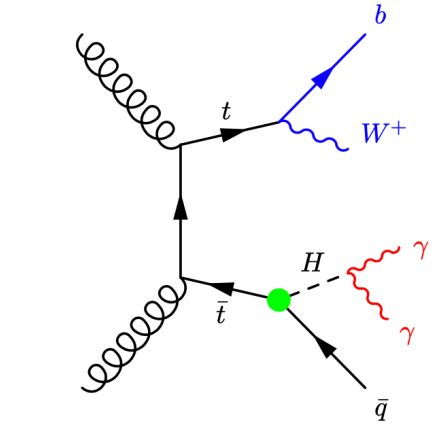
- ≥ 2 leptons (w/ same-sign charge (e, μ)) + w/ 1 b-tag.
- Separate deep neural networks (DNNs) for tcH and tuH signals and *four signal regions (2ℓ prod&decay and 3ℓ prod&decay)*.
  - e.g. inputs: $m(\ell_{OS}, \ell_{SS,1}), m(\ell_{OS}, \ell_{SS,0}), m(\ell_t, b_t), H_T, \ldots$
- Likelihood fit including nonprompt lepton and $t\bar{t}W$ and $t\bar{t}Z$ control regions.
- Dominant uncertainties: *heavy flavor bkg.*

$$\mathcal{B}(t \to Hu) < 0.028\,\%\,(0.030\%)$$
$$\mathcal{B}(t \to Hc) < 0.033\,\%\,(0.038\%)$$
$$|C_{u\phi}^{ut,tu}| < 0.71(0.73)$$
$$|C_{u\phi}^{ct,tc}| < 0.76(0.82)$$

FCNC top-Higgs-u/c couplings with di-photons

JHEP 12 (2023) 195



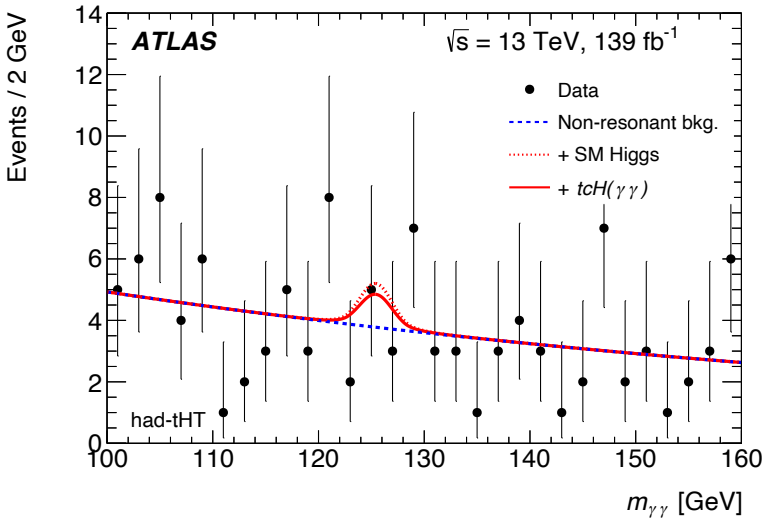


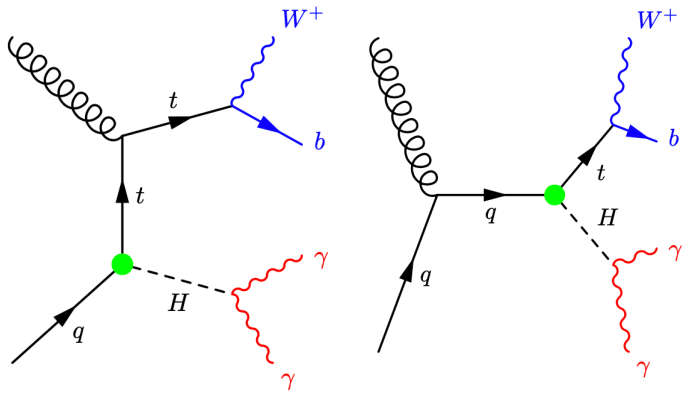
$152 < M_{\gamma\gamma j} < 190\ GeV$

(Jets charm-tagged)

$120 < M_{jjj} < 220\ GeV$

- BDT selection to improve sensitivity for hadronic and leptonic top decay channels separately.
- Likelihood fit to diphoton mass in categories based on ***hadronic and leptonic top quark decays,*** N_{jets} ***and charm-tagging***.
- Results dominated by *statistical uncertainty, photon energy resolution,* $\sigma_{t\bar{t}}$, $\mathcal{B}(H \to \gamma\gamma)$.





At least one 3-jet combination w/

$120 < M_{jjj} < 220\ GeV$

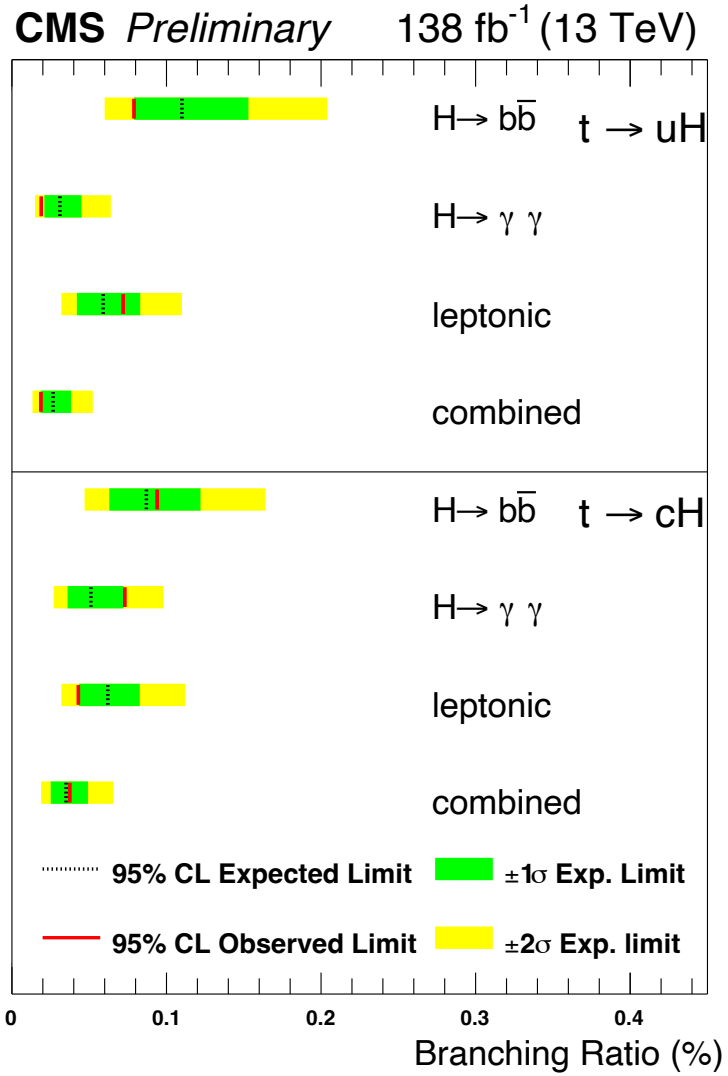
and =1 b-tag.

$$Br(t \to Hu) < 0.038\,\%\,(0.039\%)$$

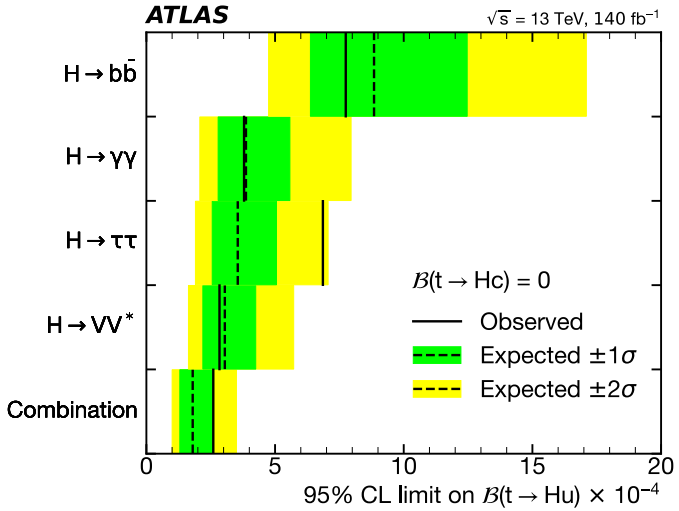
$$Br(t \to Hc) < 0.043\,\%\,(0.047\%)$$

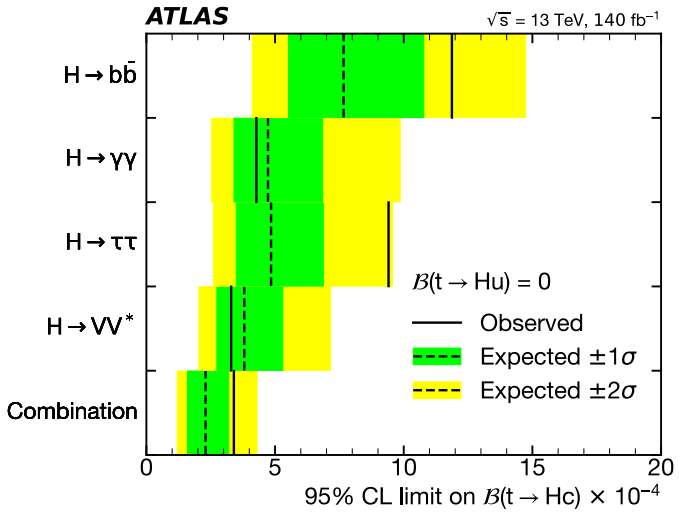
- ***tcH***: $1.5x$ better sensitivity than the ATLAS analysis with $36\ fb^{-1}$ [JHEP 10 (2017) 129] thanks to better event reconstruction and categorization & extra background rejection with BDTs.

FCNC top-Higgs-u/c couplings — Combinations



CMS-PAS-TOP-22-002





arXiv:2404.02123

95% CL observed (expected) limits

	$\mathcal{B}(t \to Hu)$	$\mathcal{B}(t \to Hc)$
ATLAS	0.026 (0.018)%	**0.034 (0.023)%**
CMS	**0.019 (0.027)%**	0.037 (0.035)%

ATLAS also provides the limits on Wilson coefficients from the combination:

$C_{u\phi}^{ut,tu}$<0.68 (0.56), $C_{u\phi}^{ct,tc}$ = 0.

$C_{u\phi}^{ct,tc}$<0.78 (0.64), $C_{u\phi}^{ut,tu}$ = 0.

λ_{NP} = 1 TeV

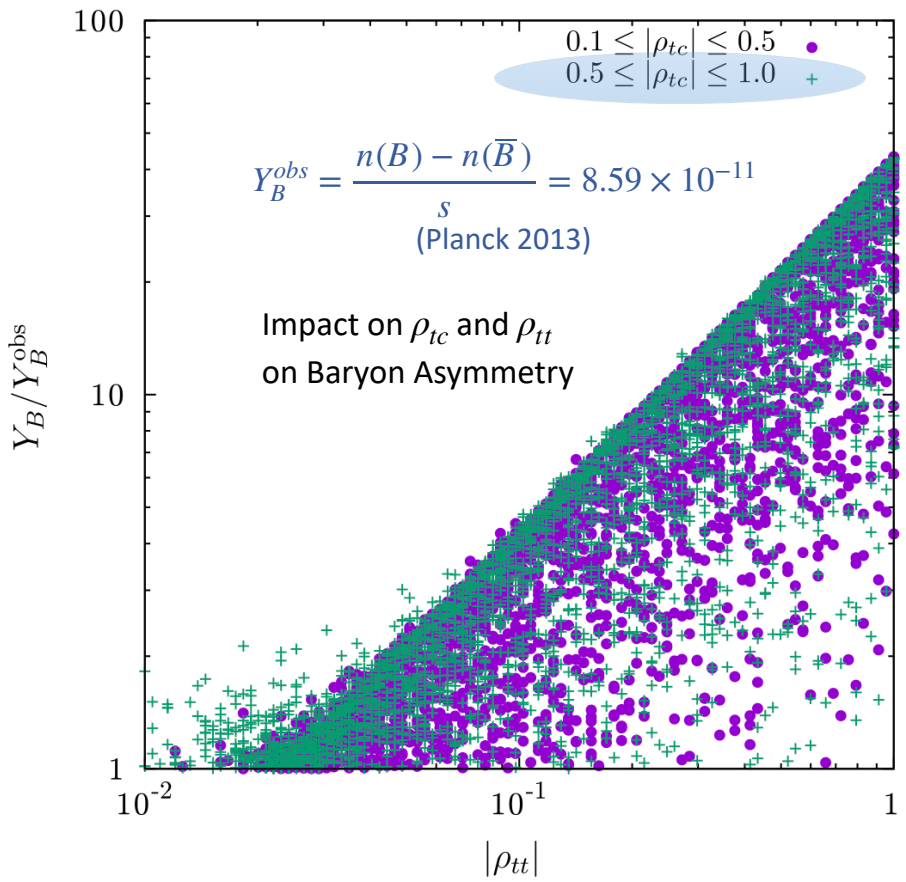
- $H \to \tau\tau$ not in CMS combination.
- $\sim 2\sigma$ fluctuation in $H \to \tau\tau$ (ATLAS both in tHu and thc).
- ATLAS *tHc* and CMS *tHu* best observed limits to date.

New scalar resonances in FCNC

New Scalar Bosons in FCNC with g2HDM

- 2HDM introduces five scalar bosons: $H^{\pm}, H, h, A$
- $\mathbb{Z}_2$ symmetry is dropped in 2HDM to allow FCNC
  → generalized 2HDM (g2HDM)
  - **Many parameters and extra processes arise.**
  - Alignment ($\cos\gamma_{H-h} \approx 0$) emerges when no $\mathbb{Z}_2$ symmetry and all extra Higgs quartic couplings are $\mathcal{O}(1)$
    - h becomes h_{125}
    - No HVV, AVV interactions.
    - Suppresses FCNC interactions for h but allows FCNC for H and A
  - *Electroweak baryogenesis, lack of FCNC (e.g. $t \to ch_{125}/uh_{125}$ or $h_{125} \to \mu\tau/e\tau$), … could be explained.*
  - **sub-TeV $H^{\pm}, H, A$ bosons may still exist**
    $\longleftrightarrow \Lambda_{NP} < \mathcal{O}(10\ TeV)$ **(opposite assumption to that of EFT).**

PLB 776 (2018) 402



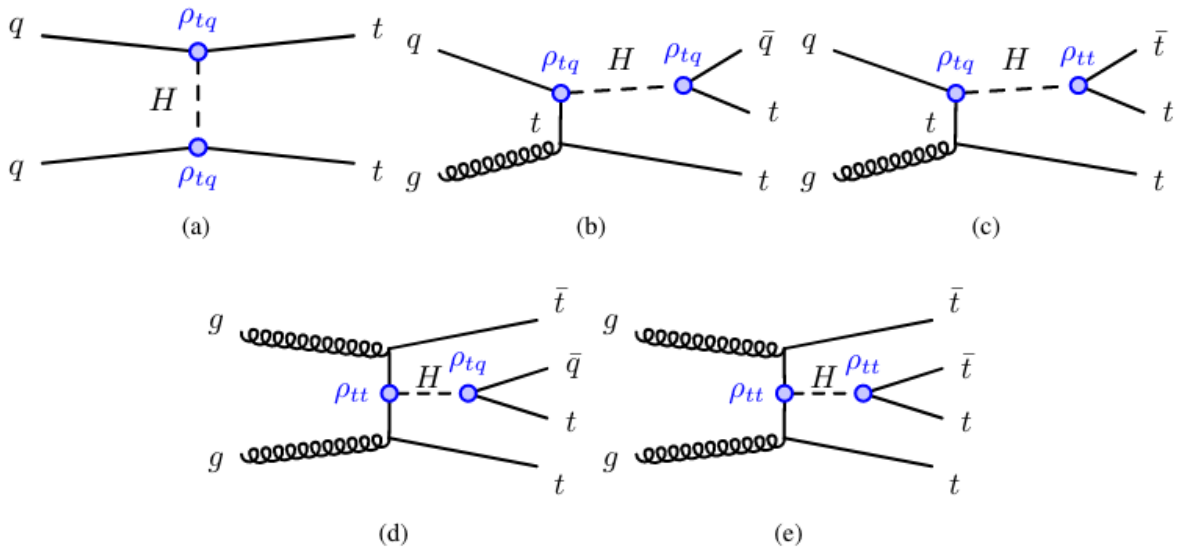
$y_{ij} = \sqrt{2} m_i \delta_{ij} / v$

$q_i q_j h$ coupling (125 GeV Higgs) $\propto -y_{ij} \sin_\gamma + \rho_{ij} \cos_\gamma$

$q_i q_j H$ coupling (exotic Higgs) $\propto y_{ij} \cos_\gamma + \rho_{ij} \sin_\gamma$

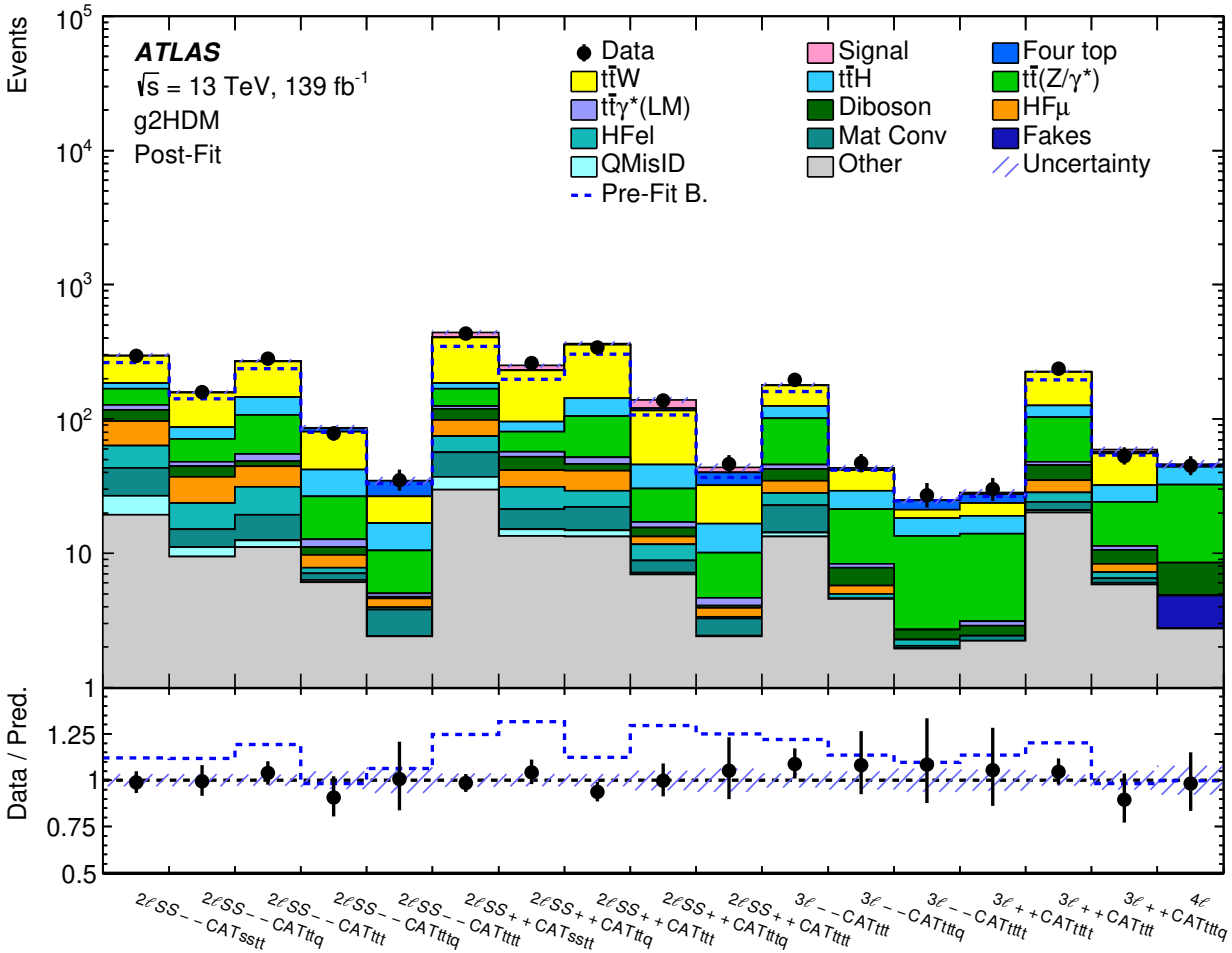
New Scalar Bosons in FCNC with g2HDM

JHEP 12 (2023) 081



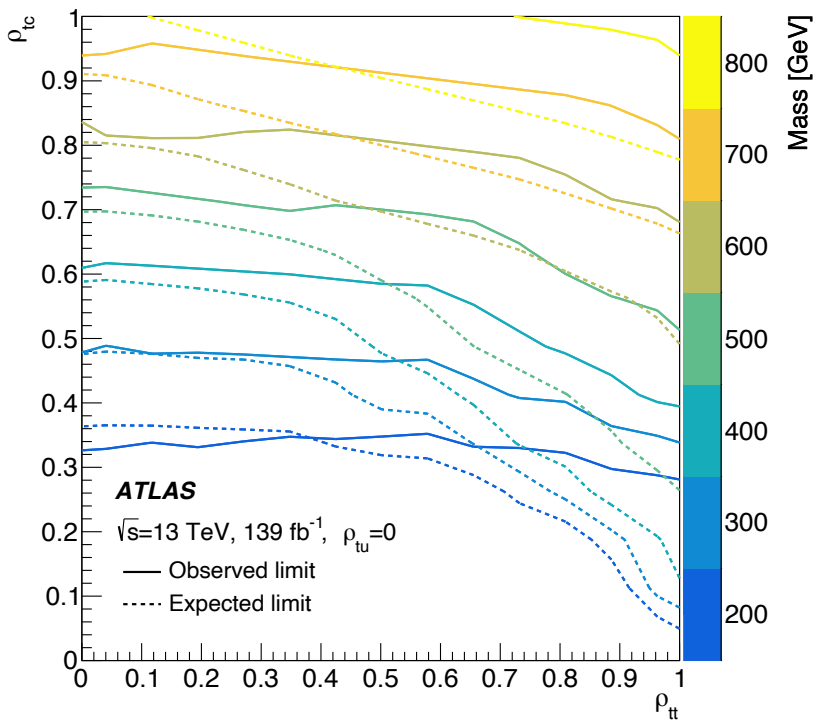
- ρ_{tu}/ρ_{tc}-induced **same-sign top quark** and ρ_{tt}**-induced triple/four-top quark** in the same umbrella with a general multi-lepton signature.
- 17 Signal categories based on lepton-multiplicity, total lepton charge, multi-output DNN classifiers (2LSS-DNN w/ 5 output nodes and 3L-DNN w/ 3 output nodes) to discriminate between different signals.
- Another DNN trained in each SR to discriminate signal from backgrounds.
- Maximum-likelihood fit performed across signal and background categories.
- **No A-H interference**

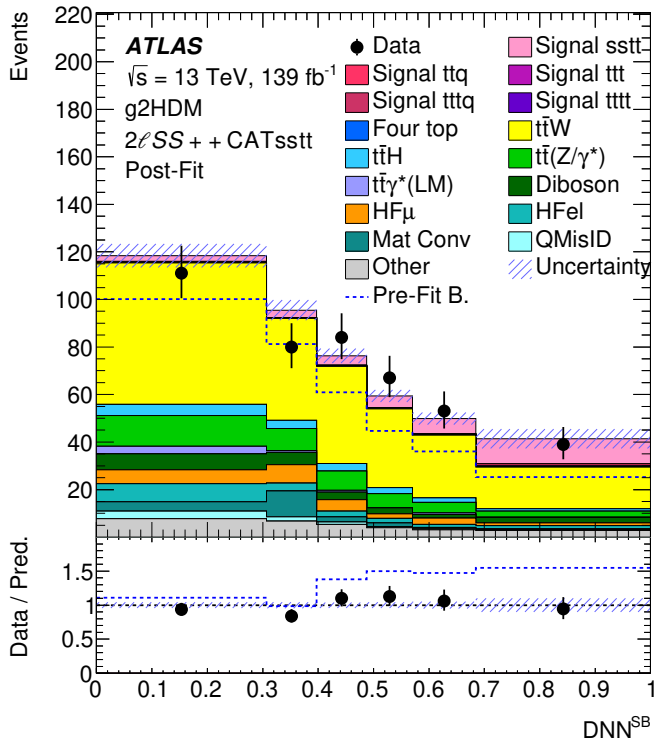
Signal: $m_H = 900$ GeV, $\rho_{tt} = 0.6$, $\rho_{tc} = 0.0$, $\rho_{tu} = 1.1$

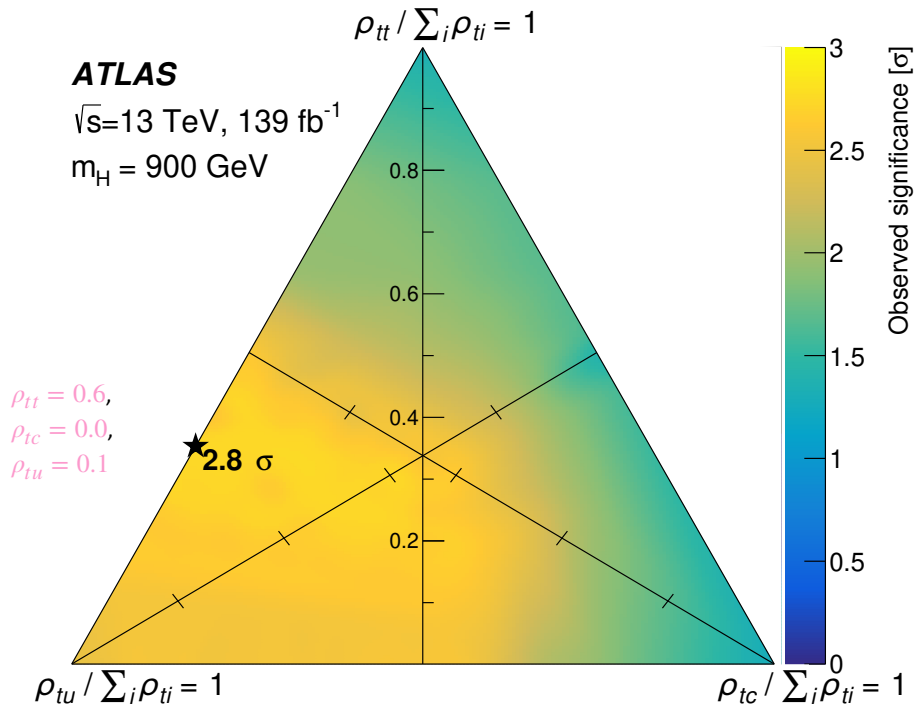


New Scalar Bosons in FCNC with g2HDM

JHEP 12 (2023) 081





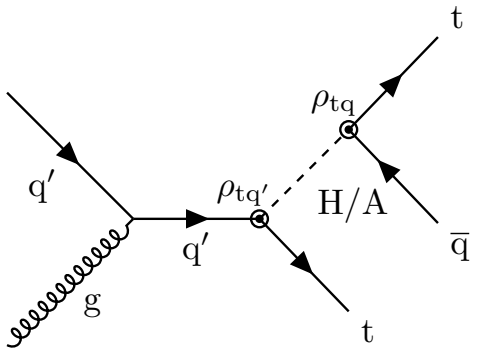


- Dominant uncertainties: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}h$, and $t\bar{t}t\bar{t}$ *modeling, statistical.*
- **Only existing search targeting BSM production of three top quarks.**
- No limit on ρ_{tt} when ρ_{tc} (or ρ_{tu})=0, but e.g. ρ_{tt}=0.4, $\rho_{tc} = \rho_{tu} = 0.2$, m_H = 200-620 (200-840) GeV excluded.

2.8σ local deviation from 55% $tt\bar{q}$, 31% tt, 14% $t\bar{t}t\bar{t}$

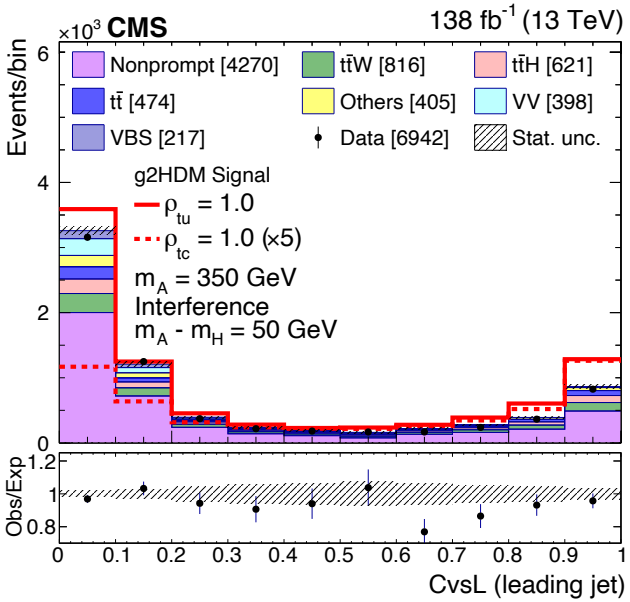
New Scalar Bosons in FCNC with g2HDM

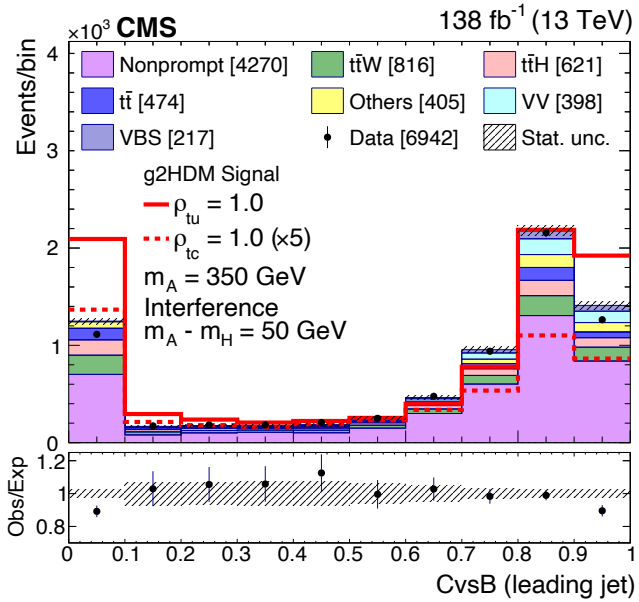
PLB 850 (2024) 138478

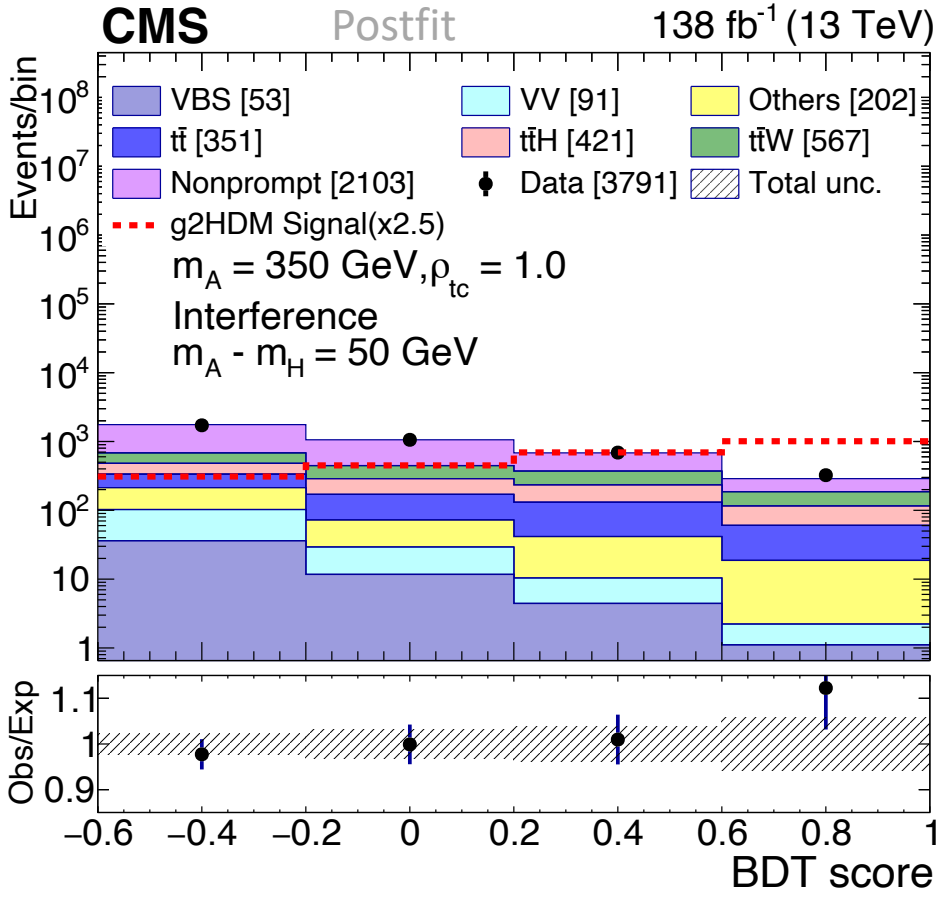


$qg \to tH \to tt\bar{q} \to (\ell^+ b\nu)(\ell^+ b\nu)\bar{q}$

- Focus on ρ_{tu}/ρ_{tc}-induced **same-sign top quark** in same-sign lepton final states
- Considered **no A-H interference** and **A-H interference** cases (with $m_A - m_H = 50$ GeV) independently.







- DeepJet algorithm: Flavor identification using global variables, charged/ neutral particle and secondary vertex kinematics in the jets. JINST 15 (2020) P12012
- For this analysis, calibrated using DY and $t\bar{t}$ control regions.

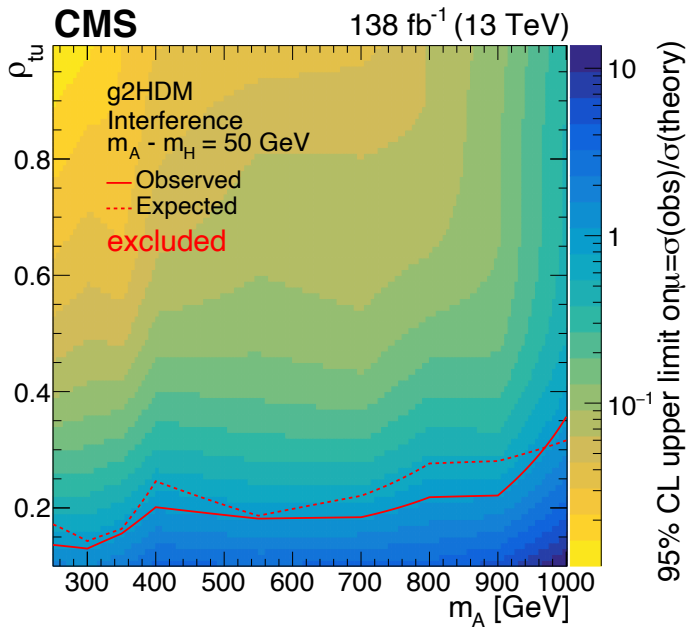
- BDTs trained independently for each era x [10 mass (w/o interference) + 9 mass (w interference)] x ($\rho_{tu} = 0.4$ and $\rho_{tc} = 0.4$) —> 152 BDTs in total.

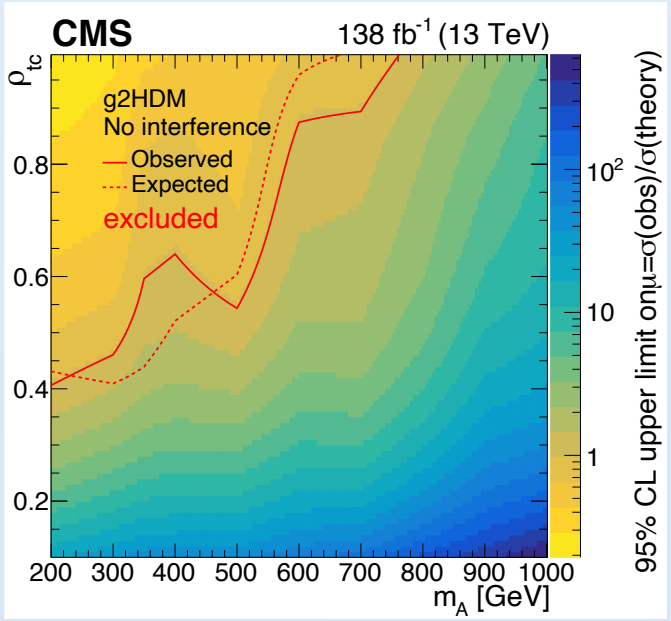
New Scalar Bosons in FCNC with g2HDM

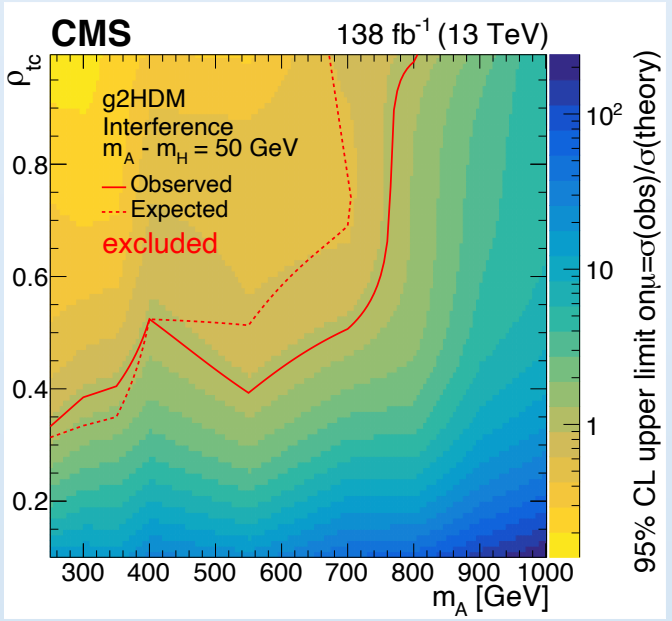
PLB 850 (2024) 138478

- 4 bins of BDT score in each decay mode simultaneously fit to extract limits for each signal mass-coupling hypothesis.
- Dominant uncertainties: *Flavor tagging, nonprompt lepton, $t\bar{t}W$ cross section, statistical.*
- *ρ_{tu} largely excluded, but still a large portion of the phase space not constrained for ρ_{tc}.*
- Final limits on (real parts of) ρ_{tu} and ρ_{tc} (**w/o A-H interference**) similar in ATLAS and CMS.
  - Limits w/o A-H interference weaker than w/ interference.
- **First search based on g2HDM considering A-H interference.**

	Observed (expected) mass limit [GeV]		
	without interference	with interference	with interference
	m_A or m_H	m_A	m_H
ρ_{tu}			
0.4	920 (920)	1000 (1000)	950 (950)
1.0	1000 (1000)	1000 (1000)	950 (950)
ρ_{tc}			
0.4	no limit	340 (370)	290 (320)
1.0	770 (680)	810 (670)	760 (620)

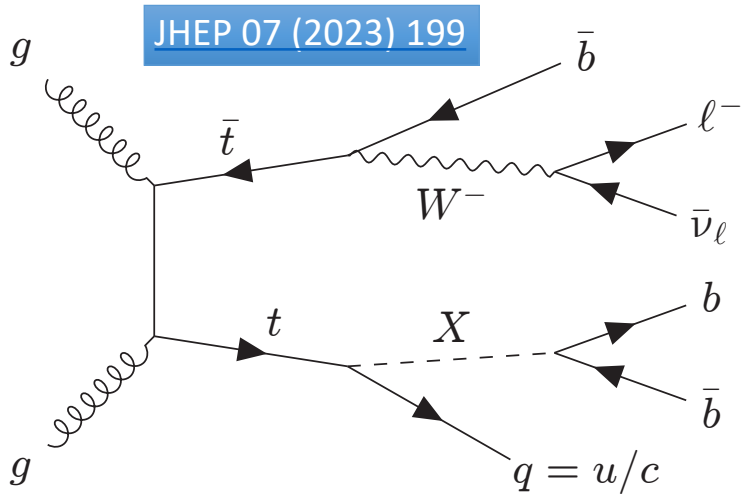




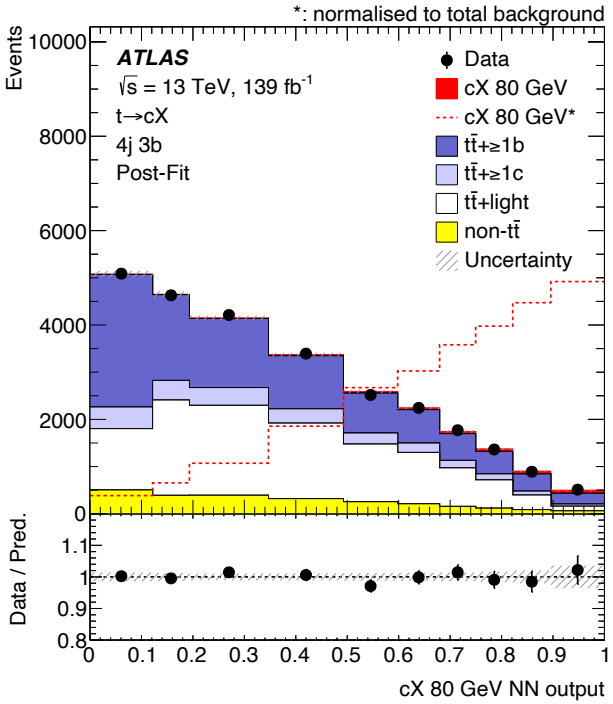


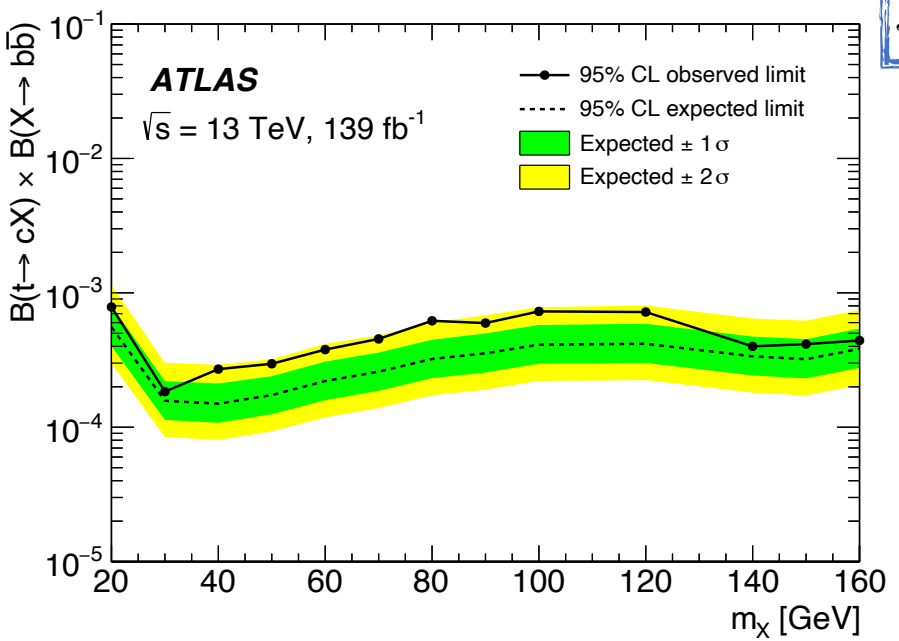
New Scalar Bosons in FCNC top-quark decays $t \to qX$ $(q = u, c)$, with $X \to b\bar{b}$

JHEP 07 (2023) 199



- Model: Higgs field X with flavor charge (flavon) → For $m_X < 200$ GeV, leading decay mode is $X \to b\bar{b}$. NPB 147 (1979) 277
- Events categorized according to N_j and N_b:
  - *3b+4/5/6j (control regions: 4b+4j, ≥4b+5j/6j)*
- NN for each mass point and signal region.
- Profile likelihood to NN output that depends on the $m(X)$.





obs.(exp.)

$\mathcal{B}(t \to uH) \times \mathcal{B}(X \to b\bar{b}) < 0.019(0.017) - 0.062(0.056)\,\%$

$\mathcal{B}(t \to cH) \times \mathcal{B}(X \to b\bar{b}) < 0.018(0.015) - 0.078(0.056)\,\%$

Using the same NN:

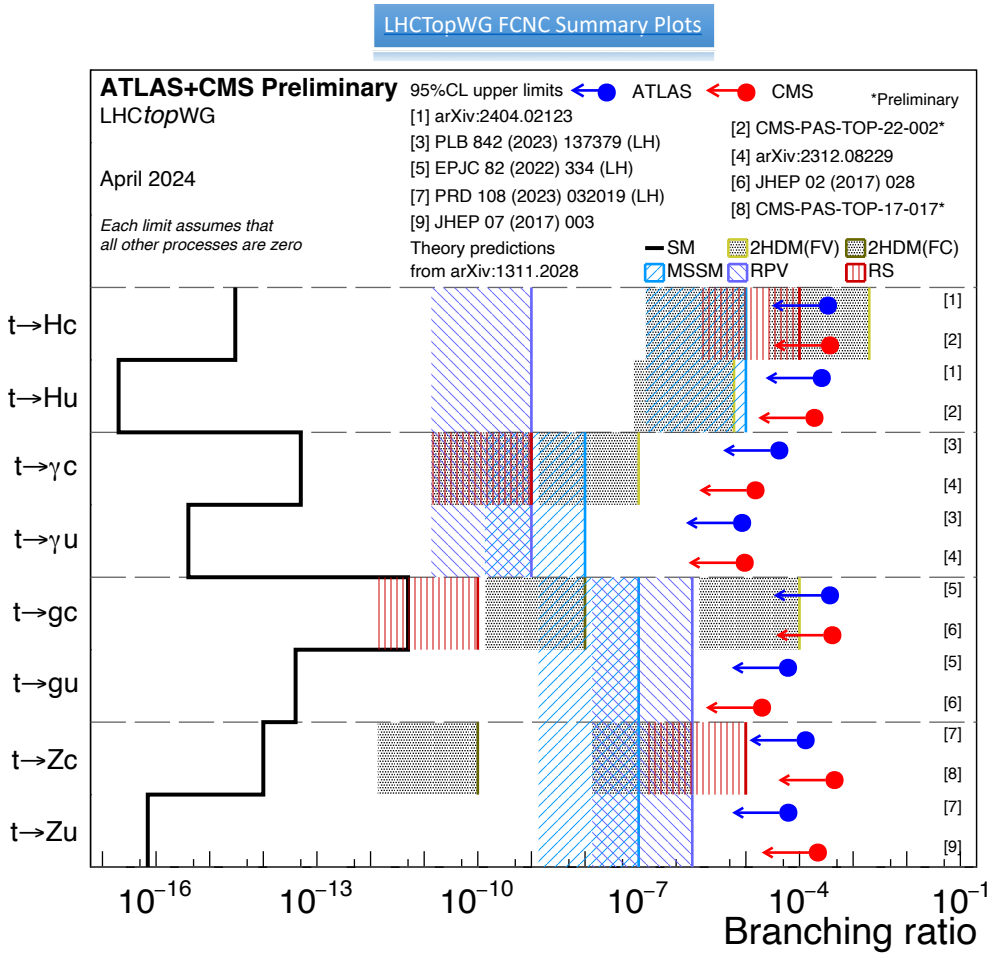
$\mathcal{B}(t \to uH) < 0.077\,\%\,(0.088\%)$

$\mathcal{B}(t \to cH) < 0.12\,\%\,(0.076\%)$

- Dominant uncertainties: *$t\bar{t}$ modeling, jet energy scale and resolution, heavy flavor tagging.*
- Expected limits $3x$ better than the previous ATLAS result scaled to the same integrated luminosity.

Conclusions

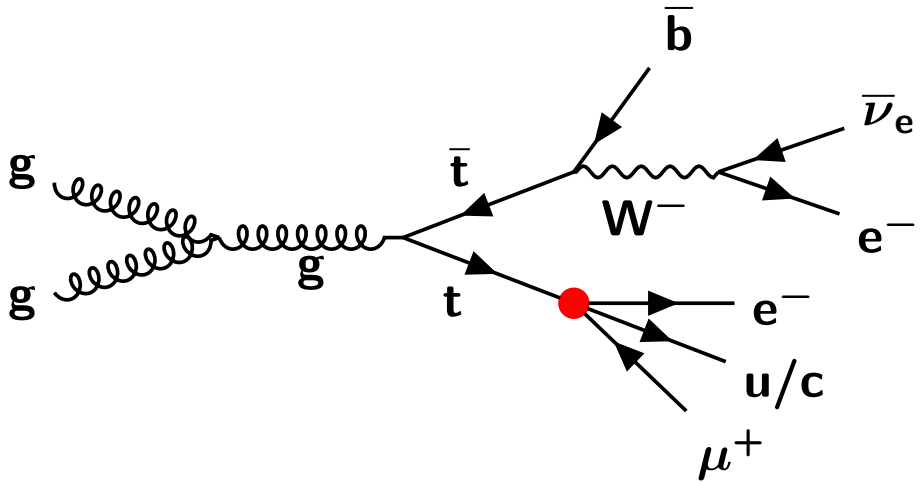
- Top quark continues to be an important particle to look for new physics effects.
- All results in good agreement with the Standard Model.
- No sign of *Flavor Changing Neutral Currents (Charged Lepton Flavor Violation, or Baryon Number Violation)*.
- Significant improvements in many searches thanks to
  - considering interactions both in top quark production and decay,
  - improved signal extraction techniques,
  - combinations, or increased collision energy.
- Top quark modeling and heavy flavor tagging crucial in many searches.
- Limits getting closer to the predictions from specific models.
- Many searches performed for FCNCs and extra Higgs bosons but *FCNC in extended Higgs sector* still remains to be studied in more detail.



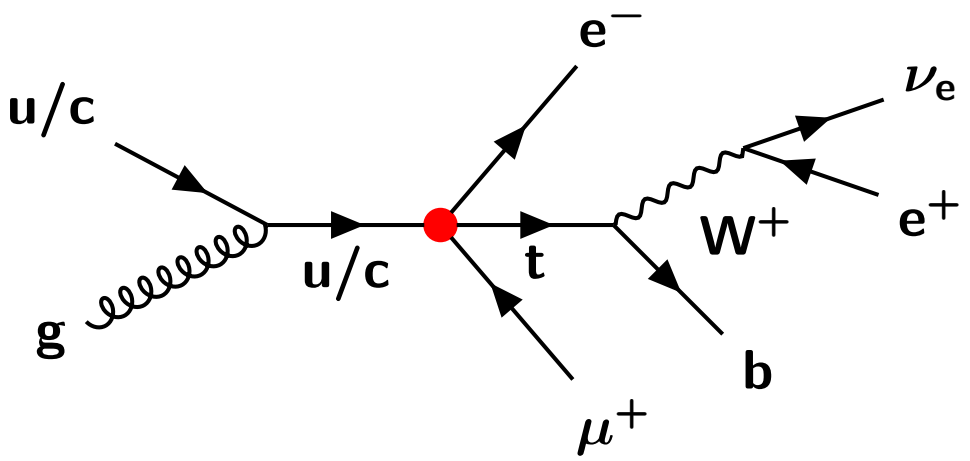
Additional Slides

Charged Lepton Flavor Violation (CLFV)

- Neutrino oscillations → CLFV but might be unobservable as CLFV suppressed by the « negligible » m_ν^2 [PRD 95 (2017) 015022]
- Many BSM scenarios predict significant LFV [arXiv:2209.00142].
- In SM EFT, CLFV appears at dim. 6. → used for parametrizing the CLFV interactions.



In decay

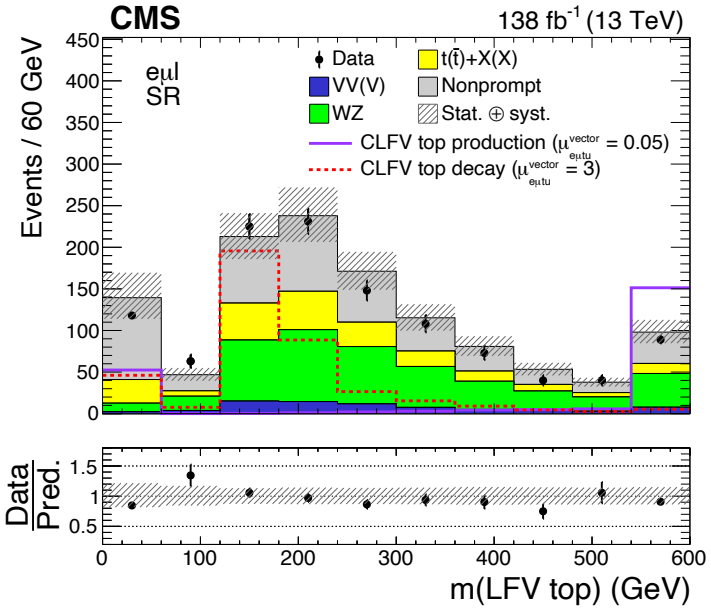


In production (High p_T leptons)

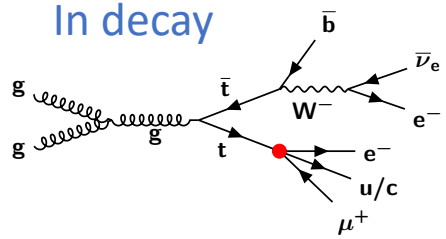
Charged Lepton Flavor Violation (CLFV)

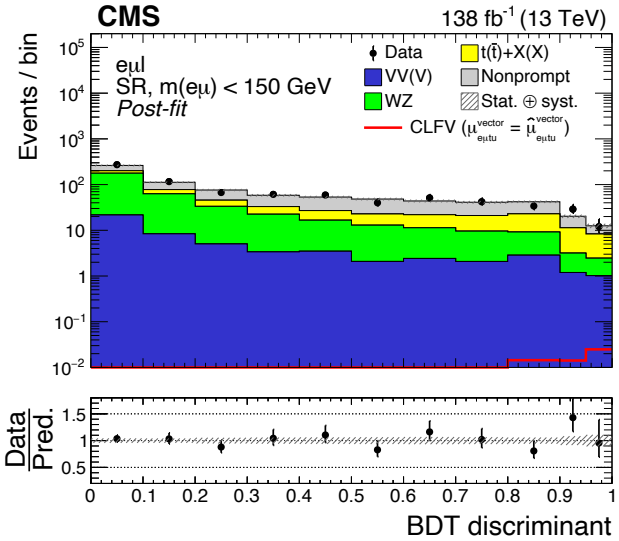
arXiv:2312.03199

- **Triple-lepton final states**: $e^{\pm}\mu^{\mp}$ + another e or μ + ≥ 1 jet (with ≤ 1 b-jet).
- Profile likelihood fit to separate BDTs trained for the « decay » and « production » regions and 3 data-taking years, simultaneously.

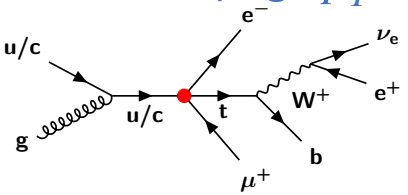


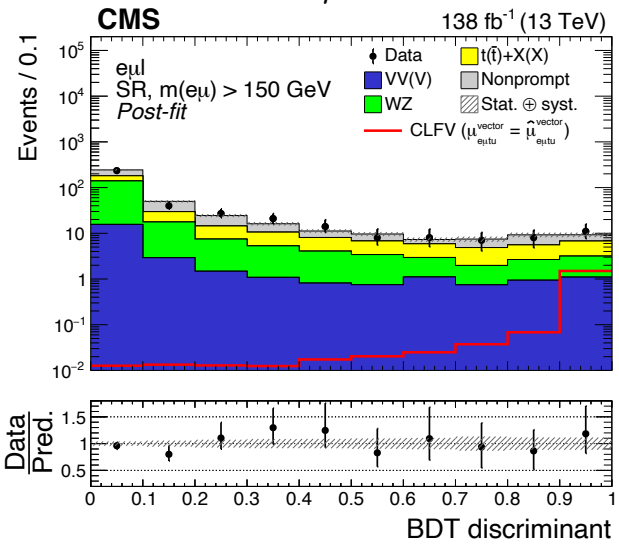
In decay





In production (High p_T leptons)





$$\mu(C/\Lambda^2) = \frac{\sigma_{CLFV}(C/\Lambda^2)}{\sigma_{CLFV}(1\ TeV^{-2})} \propto (C/\Lambda^2)^2$$

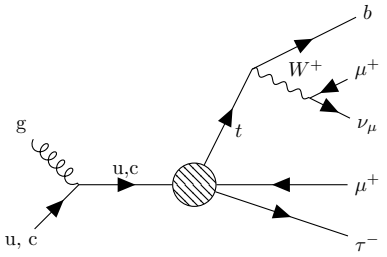
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	Obs.	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	Obs.
eμtu	Tensor	0.022 (0.018–0.026)	**0.024**	0.027 (0.018–0.040)	**0.032**
	Vector	0.044 (0.036–0.054)	**0.048**	0.019 (0.013–0.028)	**0.022**
	Scalar	0.093 (0.077–0.114)	**0.101**	0.010 (0.007–0.016)	**0.012**
eμtc	Tensor	0.084 (0.069–0.102)	**0.094**	0.396 (0.272–0.585)	**0.498**
	Vector	0.175 (0.145–0.214)	**0.196**	0.296 (0.203–0.440)	**0.369**
	Scalar	0.385 (0.318–0.471)	**0.424**	0.178 (0.122–0.266)	**0.216**

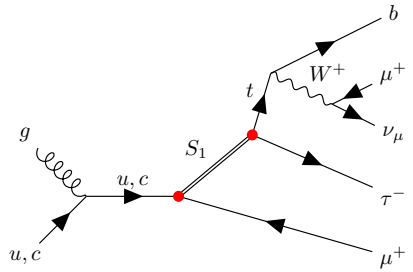
- Dominant uncertainties: *nonprompt lepton., additional jets mismodeling in WZ/ZZ samples, QCD scales, and parton shower initial/final state radiation.*
- Limits most stringent to date w/ an order of magnitude improvement!

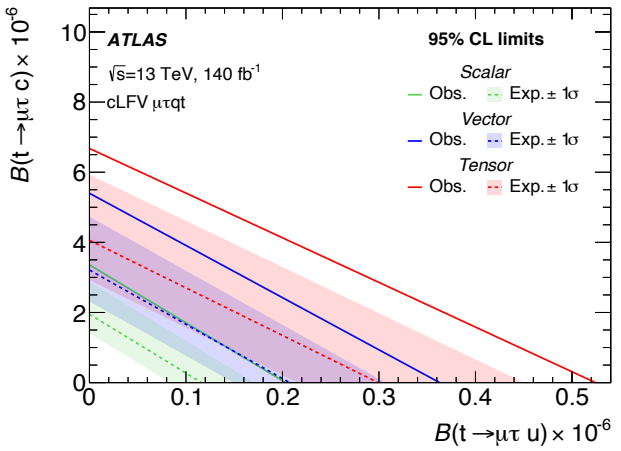
CLFV — ATLAS

arXiv:2403.06742

- Same processes but in (hadronic) τ and μ final states: $\mu^{\pm}\mu^{\pm}\tau^{had}$+1 bjet.
- Results with EFT and also assuming a scalar leptoquark (S_1) obtained from a simultaneous profile-likelihood fit to H_T in signal and control regions. High p_T leptons → High H_T → CLFV
- **Result limited by statistical uncertainty**
- Dominant systematic unc.: $t\bar{t} + X$ *and VV modeling.*

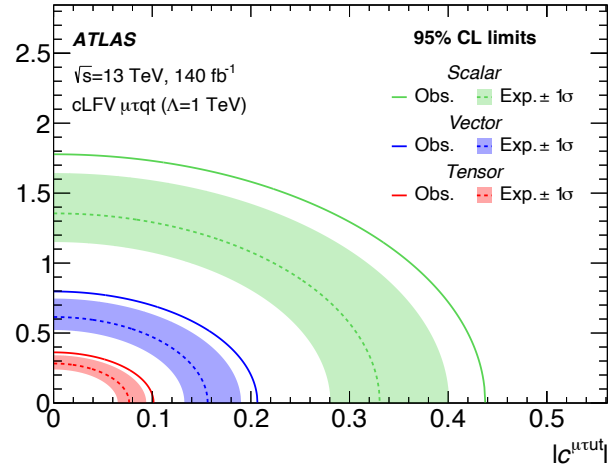




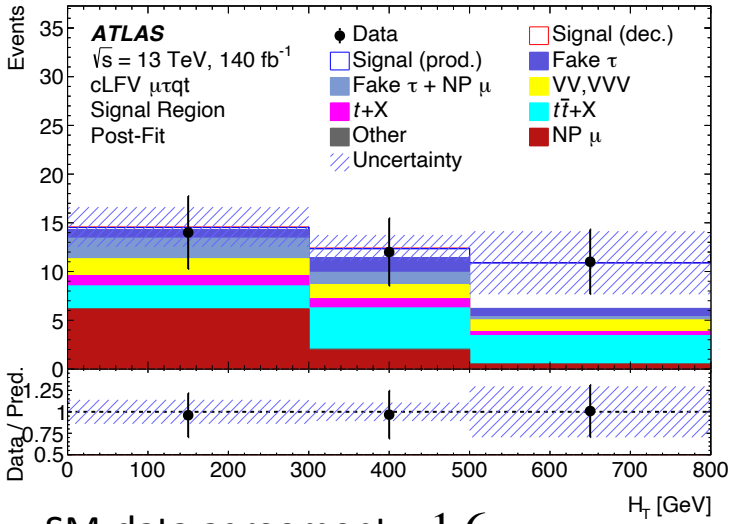


$\mathcal{B}(t \to \mu\tau q) < 0.87\ (0.50) \times 10^{-6}$

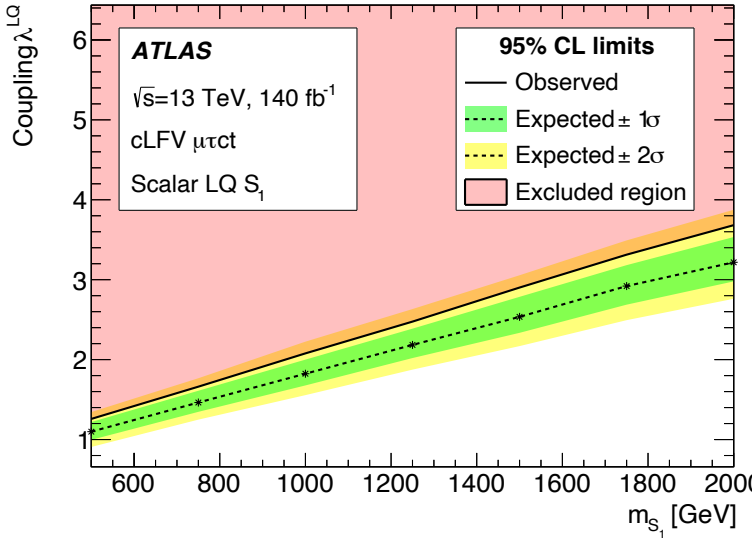
(Assuming all EFT operators are equal)



First limits on EFT couplings w/ μ and τ flavors.



SM-data agreement = 1.6σ

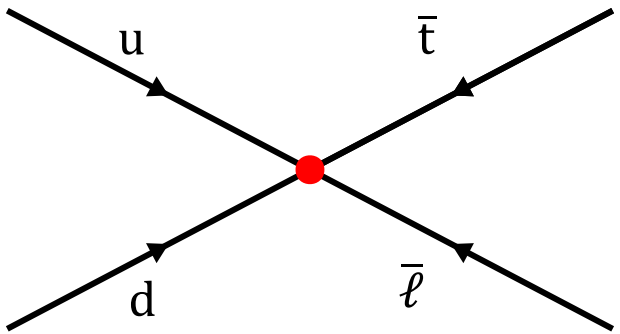


← Couplings of S_1 to each generation of quarks and leptons fixed relative to one another → reduces 10 degrees of freedom to only 2 to set limits on coupling-mass.

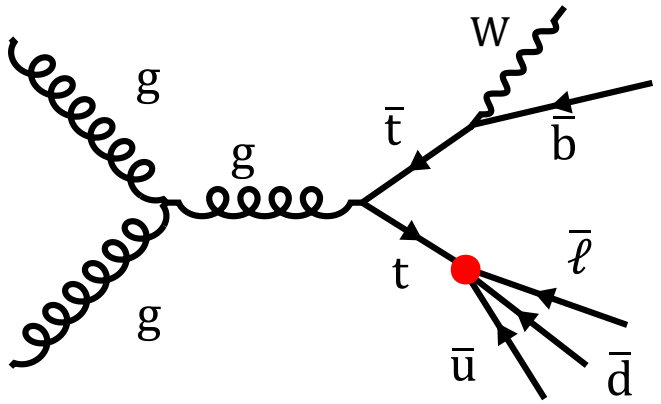
Baryon Number Violation (BNV)

- Baryon number conservation
  - Needed for *absolute* stability of matter.
  - An approximate symmetry
    - (a global symmetry w/o an associated mediator — unlike stability of electron based on charge conservation)
  - Even tiny BNV would have deep implications in the evolution of the Universe. e.g. see PRD85(2012)016006, PRD72(2005)095001

Fermion-flavor-dependent effective BNV interactions.



Single-top production

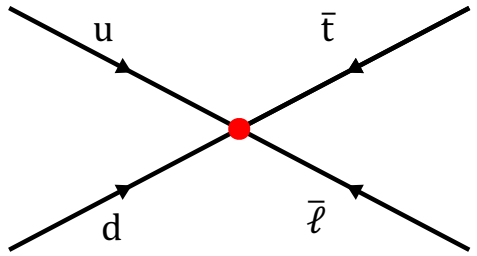


$t\bar{t}$ decay

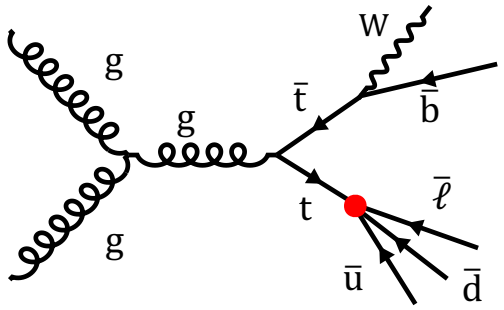
Baryon Number Violation (BNV)

arXiv:2402.1862

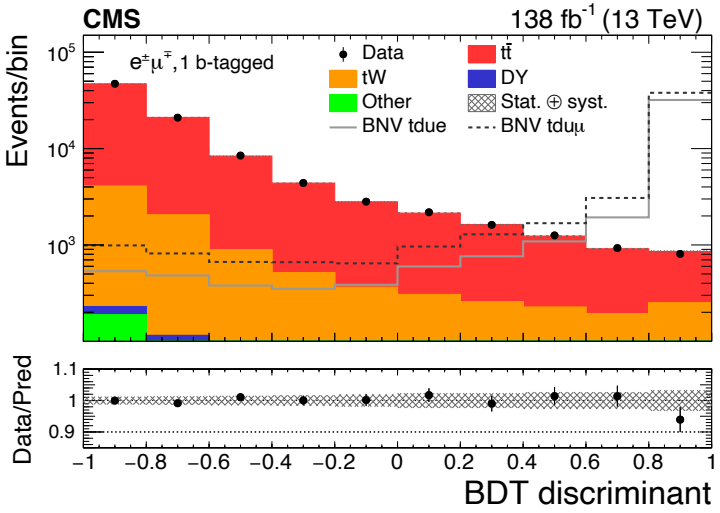
Fermion-flavor-dependent effective BNV interactions.



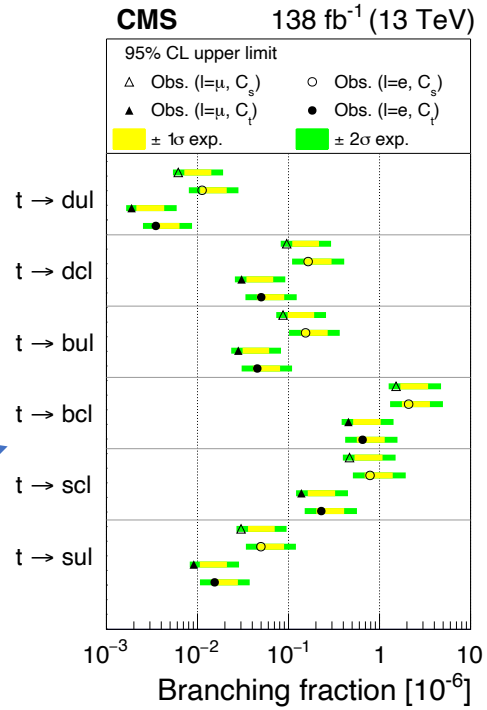
Single-top production *for the first time.*
Dominant signal process, and harder final state.



$t\bar{t}$ decay
(Added for completeness)



Different quark flavor combinations for the first time.



- Dilepton ($e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$) + 1 b-tagged jet.
- Maximum likelihood fit performed in the signal region for three years and three channels simultaneously.
- Dominant uncertainties:
  - *tW modeling, muon energy scale, top quark p_T in $t\bar{t}$*

The results improve the previous bounds [PLB 02 (2014) 033] by 3 to 6 orders of magnitude.

Most stringent limits on BRs.