Searches for BSM in top final states in ATLAS

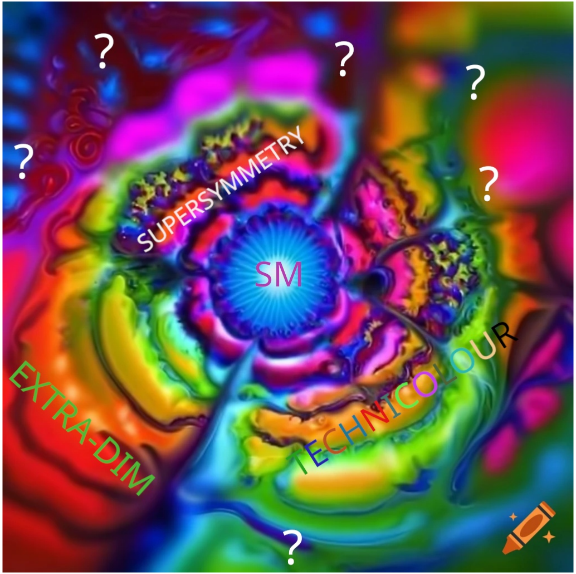
LHCP 2024, Boston, USA, June 3rd-7th

Mário José Sousa on behalf of the ATLAS Collaboration

Istituto Nazionale di Fisica Nucleare - Genova

June 5th, 2024

BSM searches in the top-quark sector



- The Standard Model is the best theory we have for explaining the universe so far.
- The "recent" discovery of the Higgs boson closes this chapter but several fundamental questions are left unanswered.
- We know that there is physics beyond the Standard Model (BSM).
- The top-quark is one of the touchstones that we can use to probe BSM theories.

Outline

t DECAY MODES

	Mode			Fraction (Γ_i/Γ)		Confidence level
Γ_1	$W q (q = b, s, d)$					
Γ_2	$W b$					
Γ_3	$e \nu_e b$			(11.10 ± 0.30) %		
Γ_4	$\mu \nu_\mu b$			(11.40 ± 0.20) %		
Γ_5	$\tau \nu_\tau b$			(10.7 ± 0.5) %		
Γ_6	$q \overline{q} b$			(66.5 ± 1.4) %		
Γ_7	$\gamma q (q=u,c)$		[a]	< 1.8	$\times 10^{-4}$	95%
Γ_8	$H^+ b,\ H^+ \to \tau \nu_\tau$					

https://pdg.lbl.gov   Page 12   Created: 12/4/2023 14:09

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022) and 2023 update

$\Delta T = 1$ weak neutral current ($T1$) modes

	Mode			Fraction		Confidence level
Γ_9	$Z q (q=u,c)$	$T1$	[b]	< 5	$\times 10^{-4}$	95%
Γ_{10}	$H u$	$T1$		< 1.9	$\times 10^{-4}$	95%
Γ_{11}	$H c$	$T1$		< 7.3	$\times 10^{-4}$	95%
Γ_{12}	$\ell^+ \overline{q} q' (q=d,s,b;\ q'=u,c)$	$T1$		< 1.6	$\times 10^{-3}$	95%

Lepton Family number (LF) violating modes

	Mode			Fraction		
Γ_{13}	$e^\pm \mu^\mp c$	LF		< 8.9	$\times 10^{-7}$	
Γ_{14}	$e^\pm \mu^\mp u$	LF		< 7	$\times 10^{-8}$	

[a] This limit is for $\Gamma(t \to \gamma q)/\Gamma(t \to W b)$.

[b] This limit is for $\Gamma(t \to Z q)/\Gamma(t \to W b)$.

- PDG (**link**) dated from last year regarding the top quark decay.
- With close to 100% of the branching ratio, $t \to Wb$.
- Some updates from ATLAS regarding:

$\mu^\pm \tau^\mp q$ Charged-lepton-flavour violation.

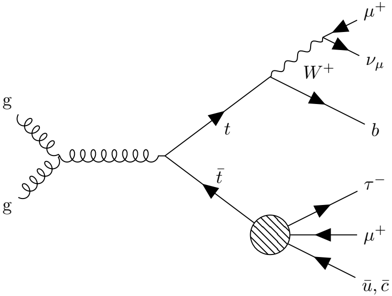
Γ_{10} Hu Flavour changing neutral currents.

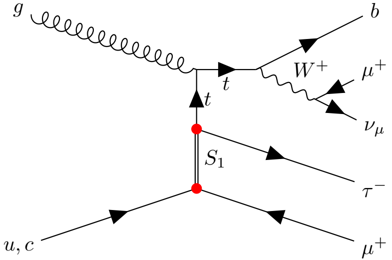
Γ_{11} Hc Flavour changing neutral currents.

  - Γ_{10} and Γ_{11} with $H \to \gamma\gamma$ and $H \to VV^*$

Charged-lepton-flavour violation

arXiv:2403.06742





- Search for $\mu\tau qt$, with $q = u, c$.
- This interaction might happen in the production or decay of the top quark.
- Analysis targets events containing:
  - Two muons with the same electric charge.
  - One hadronically decaying tau lepton.
  - Exactly one jet that is b-tagged.
  - ≥ 0 jets without b-tags.
- The observed data is interpreted:
  - within the effective field theory (EFT) framework.
  - to test a leptoquark (LQ) hypothesis.

Charged-lepton-flavour violation

arXiv:2403.06742

- The Wilson coefficients (c) weight the EFT operators ($\mathcal{O}$) of the effective Lagrangian, which assumes a mass scale of new physics, Λ much larger than achieved at LHC.
  - In **backup**, EFT operator basis and degrees of freedom.
  - $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_X \frac{c_X}{\Lambda^2}\mathcal{O}_X + \ldots$

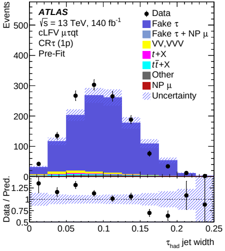
$$\Gamma(t \to \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{\text{lq}}^{-(ijk3)}|^2 + 4|c_{\text{eq}}^{(ijk3)}|^2 + 4|c_{\text{lu}}^{(ijk3)}|^2 + 4|c_{\text{eu}}^{(ijk3)}|^2 + 2|c_{\text{lequ}}^{1(ijk3)}|^2 + 96|c_{\text{lequ}}^{3(ijk3)}|^2\Big\},$$

- For the LQ interpretation, a scalar leptoquark, S_1 is introduced and may couple to multiple generations of charged leptons and up-type quarks.
  - A flavour hierarchy in the coupling strengths assumed with the magnitude in the quark and lepton generations as a constant ratio: R=0.1 where $\lambda_{t\tau}$ is the strongest coupling.

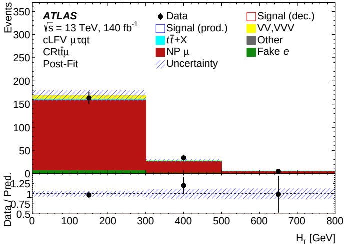
$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\text{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

- EFT-optimized analysis strategy expected to give weaker limits on couplings in LQ interpretation.

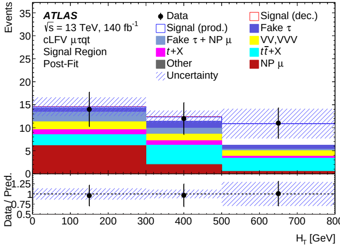
$\mathrm{CR}\tau$



$\mathrm{CR}t\bar{t}\mu$



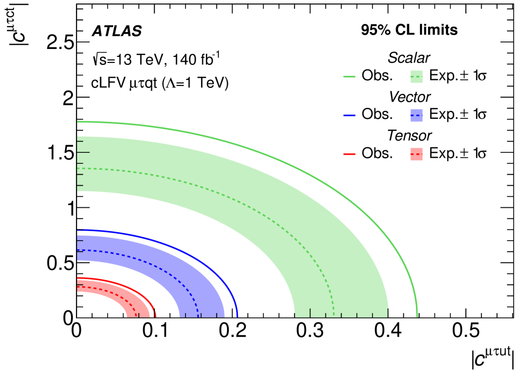
SR



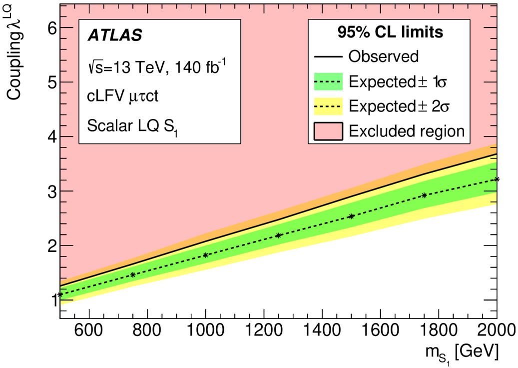
- Control region (CR) built with $\mu^{\pm}\mu^{\mp}$ events to estimate the fake-τ contribution.
  - Scale factor extracted standalone.
- CR with $t\bar{t}(\rightarrow e\mu)$ events with additional non-prompt (NP) μ to estimate the NP background in the signal region (SR).
- $H_{\mathrm{T}}\,(\equiv \sum_x |\vec{p}_{\mathrm{T}}^{\,x}|)$ distributions from $\mathrm{CR}t\bar{t}\mu$ and SR used in a binned profile-likelihood fit.
  - $x = \{$ lepton,jets $\}$
- Statistical dominated analysis.
- Leading systematic uncertainties stem from $t\bar{t}X$ and diboson processes modelling.

arXiv:2403.06742

EFT



LQ



EFT	$\lvert c_{\text{lequ}}^{1(2313)}\rvert/\Lambda^2$	$\lvert c_{\text{lequ}}^{3(2323)}\rvert/\Lambda^2$
JHEP 07 (2018) 176	> 3.4 TeV^{-2}	> 29 TeV^{-2}
This analysis	> 0.10 TeV^{-2}	> 1.8 TeV^{-2}

- Upper limits of the λ^{LQ} scalar set ranging from 1.3 to 3.7 for masses between 0.5 and 2 TeV.

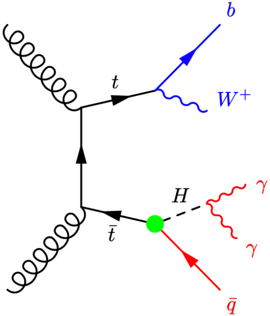
Flavour-changing neutral-currents

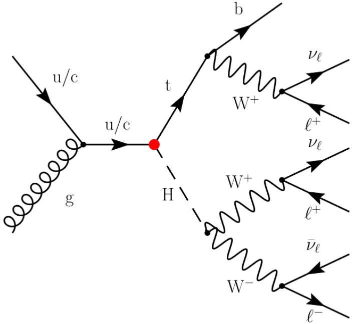
- SM states that FCNC processes, due to the GIM mechanism, are:
  - forbidden at tree level.
  - very much suppressed at the one-loop level and higher orders.
- FCNC decays of the top quark are extremely rare in the SM (Phys. Rev. D 100 (2019) 015003):
  - $\mathcal{B}(t \to cH) = 4.2 \times 10^{-15}$.
  - $\mathcal{B}(t \to uH) = 3.7 \times 10^{-17}$.
  - Observations of such processes would constitute a clear signal of BSM physics.
- Previous ATLAS limits are:

Publication	JHEP06 (2023) 155	JHEP07 (2023) 199	JHEP06 (2014) 008
H decay	$H \to \tau^+\tau^-$	$H \to b\bar{b}$	$H \to \gamma\gamma$
$\mathcal{B}(t \to cH)$	$< 9.4 \times 10^{-4}$	$< 12.0 \times 10^{-4}$	$< 7.8 \times 10^{-3}$
$\mathcal{B}(t \to uH)$	$< 6.9 \times 10^{-4}$	$< 7.7 \times 10^{-4}$	$< 7.8 \times 10^{-3}$

Flavour-changing neutral-currents: update

JHEP 12 (2023) 195





arXiv:2404.02123 [hep-ex]

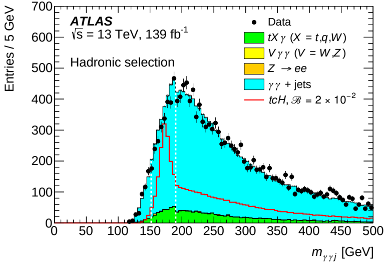
- Search for tqH coupling with diverse Higgs boson decays.
- Search in $H \to \gamma\gamma$ split primarily based on the decay of the W boson:
  - had 0 charged lepton and at least 3 jets.
  - lep 1 charged lepton and at least 1 jet.
- Search with Higgs boson decaying into multilepton final states:
  - 2LSS 2 same charged leptons.
  - 3L 3 charged leptons with $|\sum q(\ell_i)| = 1$.
- Both analyses search for FCNC in production and decay of the top quark.
- The observed data is interpreted within the EFT framework.

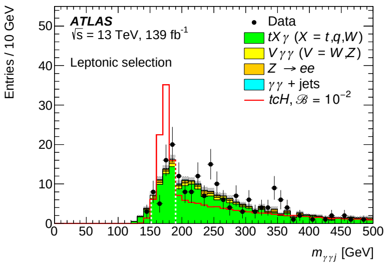
- The EFT Lagrangian ($\mathcal{L}_{\text{EFT}}$) for the tqH process can be written:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{q=u,c} \left[\frac{C_{u\phi}^{qt}}{\Lambda^2} O_{u\phi}^{qt} + \frac{C_{u\phi}^{tq}}{\Lambda^2} O_{u\phi}^{tq} \right]$$

  - with 4 FCNC operators contributing at tree level associated to 4 Wilson coefficients.
  - Notation can be found in **backup**.
- The top quarks are produced unpolarized in $t\bar{t}$ and the Higgs boson is a scalar particle:
  - no kinematic differences expected between $\mathcal{O}_{u\phi}^{tq}$ and $\mathcal{O}_{u\phi}^{qt}$.
- In the phase space considered for the single-top production, results from simulation also showed negligible differences.
- The average of the two Wilson coefficients is taken per $q = u, c$:

$$C_{u\phi}^{tq,qt} = \frac{C_{u\phi}^{tq} + C_{u\phi}^{qt}}{2}$$





- FCNC decay top: $m_{\gamma\gamma j} \in [152, 190]$ GeV.
- SM decay top: $m_{jjj} \in [120, 220]$ GeV.
- $c, \not{c}$: jet from FCNC top pass/don't pass charm-tagging.
- To improve the sensitivity these categories are fed to a boosted decision tree (BDT).
- Specific region targeting the $pp \to tH$ production.
- Profile likelihood used to fit $\mathcal{B}$ in the $m_{\gamma\gamma}$ distribution, assuming a single coupling: either tcH or tuH.
- Main systematics result from the non-resonant background from the Higgs boson $m_{\gamma\gamma}$ side-band.

Flavour-changing neutral-currents $t \to qH(\to \gamma\gamma)$

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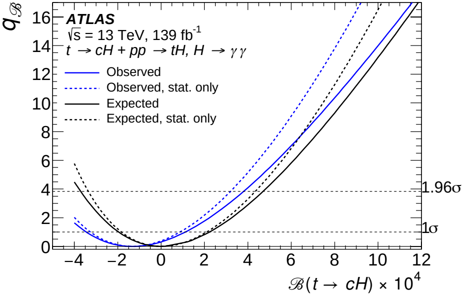
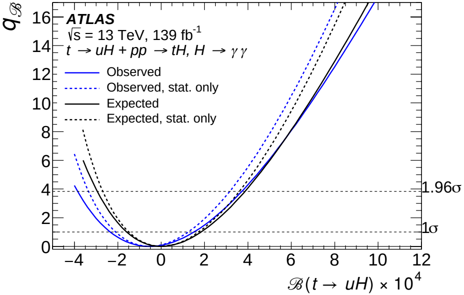
$\mathcal{B}(t \to cH)$



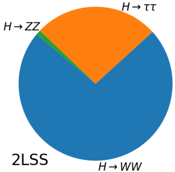
$\mathcal{B}(t \to uH)$

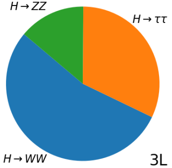


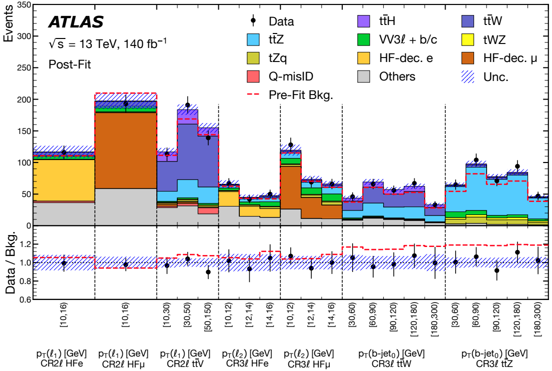
H decay	$\mathcal{B}(t \to cH)$	$\mathcal{B}(t \to uH)$
$H \to \tau\tau$	$< 9.4 \times 10^{-4}$	$< 6.9 \times 10^{-4}$
$H \to b\bar{b}$	$< 12. \times 10^{-4}$	$< 7.7 \times 10^{-4}$
$H \to \gamma\gamma$	$< 3.8 \times 10^{-4}$	$< 4.0 \times 10^{-4}$
Combined	$< 5.8 \times 10^{-4}$	$< 4.0 \times 10^{-4}$

FCNC $t \to qH$ with H multilepton decay

- In both lepton final states, the $H \to WW$ decay dominates.
- This analysis also splits between decay/production based on N_{jets}: 4 SR.
- 4 CRs to constrain the background from fake leptons (heavy flavour).
- 3 CRs to constrain the background from $t\bar{t}V$.
- Neutral network (NN) used to separate signal from background.
- Heavy flavour background modelling dominates the systematic uncertainty.







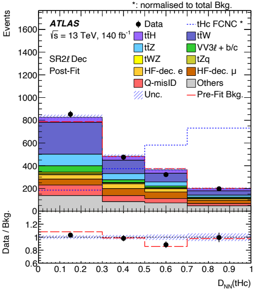
- Fits (tHu and tHc) to extract the signal strength and normalization of main backgrounds.

Process	tHu fit	tHc fit
HF-decay e	1.05 ± 0.24	1.02 ± 0.23
HF-decay μ	0.94 ± 0.18	0.92 ± 0.18
$VV3\ell + b/c$	1.41 ± 0.23	1.37 ± 0.24
$t\bar{t}W$	1.15 ± 0.14	1.19 ± 0.14
$t\bar{t}Z$	1.16 ± 0.11	1.17 ± 0.11

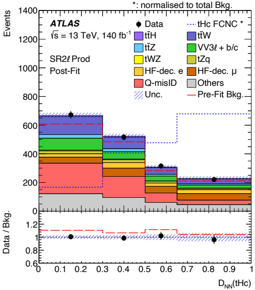
FCNC $t \to uH$ with H multilepton decay

arXiv:2404.02123 [hep-ex]

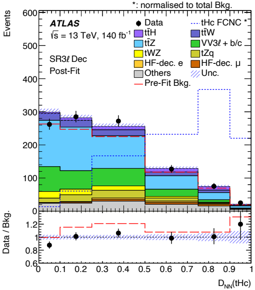
SR2ℓ Dec



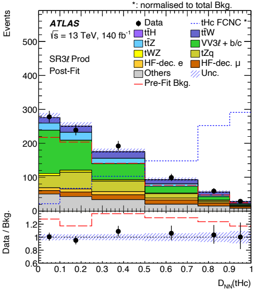
SR2ℓ Prod



SR3ℓ Dec



SR3ℓ Prod

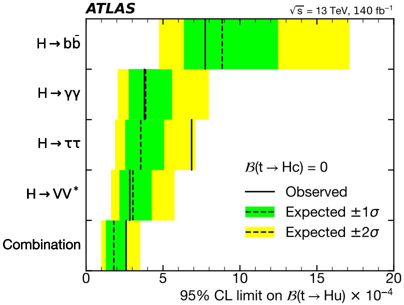


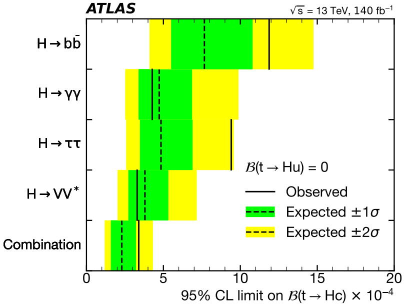
$H \to VV^*$

- $\mathcal{B}(t \to uH) < 2.8 \times 10^{-4}$
- $\mathcal{B}(t \to cH) < 3.3 \times 10^{-4}$

Full combination

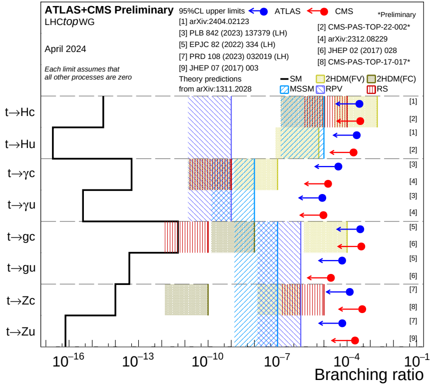
- $\mathcal{B}(t \to uH) < 2.6 \times 10^{-4}$
- $\mathcal{B}(t \to cH) < 3.4 \times 10^{-4}$



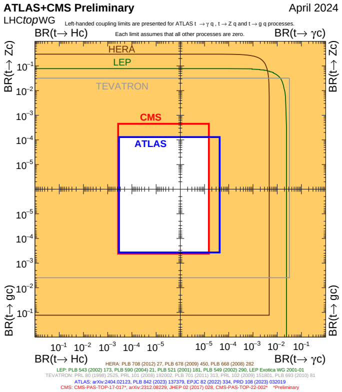


FCNC summary plots as of April 2024

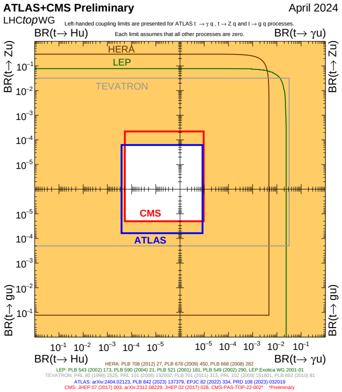
$t \to Xq$



$t \to Xc$



$t \to Xu$

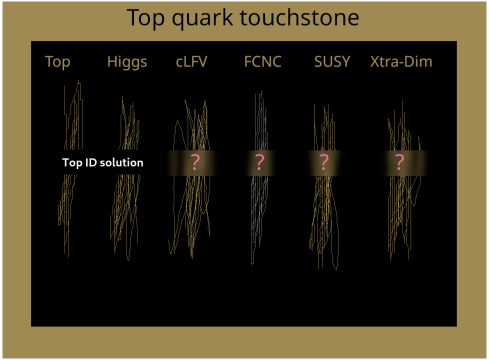


- $X \equiv \{H, \gamma, g, Z\}$

  ATL-PHYS-PUB-2024-005

Summary

- The top quark touchstone gives us already good Standard Model measurements.
- Additionally, collisions in the ATLAS detector are trying to understand it can probe physics beyond it.
- Today, a selection of this last year's analysis:
  - Charged-lepton-flavour violation: March 11$^{\mathrm{th}}$ **arXiv:2403.06742 [hep-ex]**
  - FCNC $t \to qH$ with $H \to \gamma\gamma$: September 22$^{\mathrm{nd}}$ **JHEP 12 (2023) 195**
  - FCNC $t \to qH$ with multilepton H decay: April 2$^{\mathrm{nd}}$ **arXiv:2404.02123 [hep-ex]**
- Full list of ATLAS Collaboration publications: **link**.



- An exciting time awaits as we anticipate what Run-3 of LHC data collection might reveal about the top-quark sector.

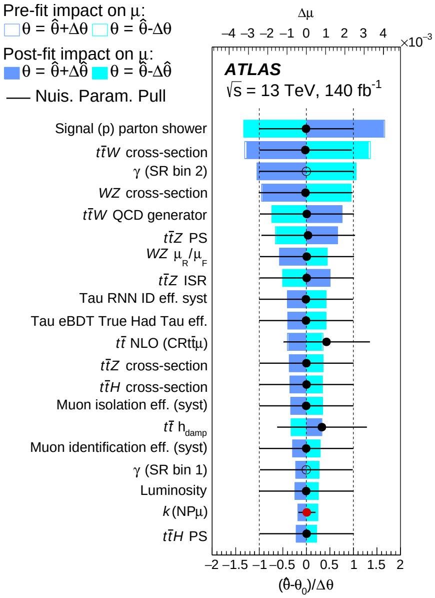
Backup: cLFV EFT operator and degrees of freedom

Table 1: EFT operator basis and degrees of freedom. In the convention used, l and q are the left-handed lepton and quark doublets, respectively, while u and e are the right-handed up-type quark and charged-lepton singlets, respectively. The indices $i, j = \{1, 2, 3\}$ represent the lepton flavour generations and $k, l = \{1, 2, 3\}$ represent the quark flavour generations, respectively. The Pauli matrices are denoted by σ^I, $\varepsilon = i\sigma^2$ is the antisymmetric $SU(2)$ tensor and $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ and γ^μ are the Dirac matrices.

Operator	Interaction	Lorentz Structure
$\mathcal{O}_{\mathsf{lq}}^{1(ijkl)}$	$(\bar{\mathsf{l}}_i\gamma^\mu \mathsf{l}_j)(\bar{\mathsf{q}}_k\gamma_\mu \mathsf{q}_l)$	Vector
$\mathcal{O}_{\mathsf{lq}}^{3(ijkl)}$	$(\bar{\mathsf{l}}_i\gamma^\mu\sigma^I \mathsf{l}_j)(\bar{\mathsf{q}}_k\gamma_\mu\sigma_I \mathsf{q}_l)$	Vector
$\mathcal{O}_{\mathsf{eq}}^{(ijkl)}$	$(\bar{\mathsf{e}}_i\gamma^\mu \mathsf{e}_j)(\bar{\mathsf{q}}_k\gamma_\mu \mathsf{q}_l)$	Vector
$\mathcal{O}_{\mathsf{lu}}^{(ijkl)}$	$(\bar{\mathsf{l}}_i\gamma^\mu \mathsf{l}_j)(\bar{\mathsf{u}}_k\gamma_\mu \mathsf{u}_l)$	Vector
$\mathcal{O}_{\mathsf{eu}}^{(ijkl)}$	$(\bar{\mathsf{e}}_i\gamma^\mu \mathsf{e}_j)(\bar{\mathsf{u}}_k\gamma_\mu \mathsf{u}_l)$	Vector
$\mathcal{O}_{\mathsf{lequ}}^{1(ijkl)}$	$(\bar{\mathsf{l}}_i \mathsf{e}_j)\varepsilon(\bar{\mathsf{q}}_k \mathsf{u}_l)$	Scalar
$\mathcal{O}_{\mathsf{lequ}}^{3(ijkl)}$	$(\bar{\mathsf{l}}_i\sigma^{\mu\nu} \mathsf{e}_j)\varepsilon(\bar{\mathsf{q}}_k\sigma_{\mu\nu} \mathsf{u}_l)$	Tensor

Preselection:	
Number of leptons	$N_\ell = 3,\ p_\mathrm{T} > 10$ GeV, $\lvert\eta\rvert < 2.5$
Leading muon / electron p_T	$p_\mathrm{T} > 27$ GeV
Trigger matching	≥ 1 trigger-matched muon / electron
Sum of lepton charges	$\sum q_i = \pm 1$

	SR	**CRτ**	**CR$t\bar{t}\mu$**
Lepton flavour	$2\mu 1\tau_\mathrm{had}$		$2\mu 1e\ (\ell_3 = \mu)$
N_jets	≥ 1	≥ 2	≥ 1
$N_{b-\mathrm{tags}}$	1	1	≤ 2
$\tau_\mathrm{had}\ p_\mathrm{T}$	> 20 GeV	> 20 GeV	–
Muon p_T	> 15 GeV	> 15 GeV	> 10 GeV
Higher p_T muon	Tight	Tight	Tight
Lower p_T muon	Tight	Tight	Loose
Muon charges	SS	OS	–
$m_{\mu\mu}^\mathrm{OS}$	–	–	>15 GeV
$\lvert m_{\mu\mu}^\mathrm{OS} - M_Z\rvert$	–	<10 GeV	>10 GeV
$3p_\mathrm{T}^{\mu_1} + \sum m_{\ell\ell}^\mathrm{OS}$	–	–	< 400 GeV



Backup: FCNC EFT operator

The FCNC interactions are introduced using an effective field theory (EFT) framework, which is used for indirect searches for new physics [29]. Here the SM is regarded as a low-energy approximation of an ultraviolet complete theory containing new particles, whose masses are characterised by an energy scale $\Lambda = 1$ TeV. The new physics contributions are parameterised in terms of operators with mass dimension greater than four containing only the SM fields, scaled by dimensionless Wilson coefficients and inverse powers of Λ. In the case where only the tHu and tHc interactions are considered, the relevant operators are

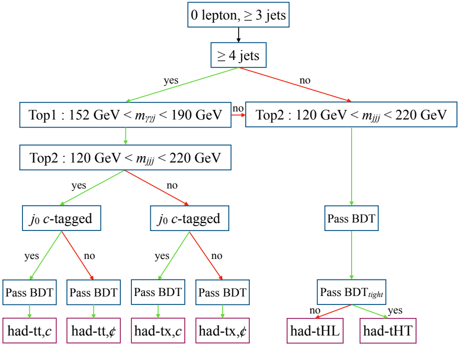
$$O_{u\phi}^{qt} = \left(\phi^\dagger\phi - \frac{v^2}{2}\right)(\bar{q}_L\, t_R)\tilde{\phi} \qquad O_{u\phi}^{tq} = \left(\phi^\dagger\phi - \frac{v^2}{2}\right)(\bar{t}_L\, q_R)\tilde{\phi}, \qquad (1)$$

where q corresponds to an up or charm quark, depending on the FCNC coupling. The index u is the coupling to any up-type quark, t is the top-quark, ϕ denotes the Higgs boson field with v corresponding to the absolute value of its vacuum expectation value. The two left-handed quark doublet fields are $\bar{q}_L$ and $\bar{t}_L$, with q_R and t_R being the corresponding right-handed singlets. The operators are scaled with Wilson coefficients $C_{u\phi}^{qt}$ and $C_{u\phi}^{tq}$, and $1/\Lambda^2$ to give the relevant Lagrangian:

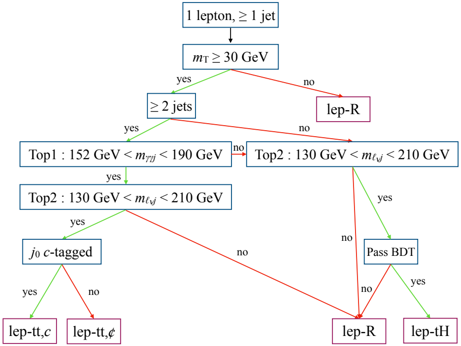
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{q=u,c}\left[\frac{C_{u\phi}^{qt}}{\Lambda^2}O_{u\phi}^{qt} + \frac{C_{u\phi}^{tq}}{\Lambda^2}O_{u\phi}^{tq}\right]. \qquad (2)$$

Backup: Event selection and systematic uncertainty for $H \to \gamma\gamma$ analysis

Hadronic selection



Leptonic selection



Source	relative impact (%)
Experimental	
Photon energy resolution	1.5
Photon identification	0.4
Luminosity, pile-up modelling	0.3
Jet energy scale and resolution, flavour tagging	< 0.2
Theoretical	
Normalisation ($\sigma(pp \to t\bar{t}, tH), \mathcal{B}(H \to \gamma\gamma)$)	1.1
Parton showering model	0.8
m_t value, NLO generator for $pp \to tH$	0.5
Resonant background	0.5
Non-resonant background	2.3

Backup: Event selection for ML analysis

Preselection

	Preselection	
N_{jets}	≥ 1	
$N_{b\text{-tags}}$	≥ 1	
$p_{\text{T}}(\text{jet})$	≥ 20 GeV	
$p_{\text{T}}(\ell)$	≥ 10 GeV	
$p_{\text{T}}(\ell_0)$	≥ 28 GeV	
	2ℓSS	3ℓ
N_ℓ	$= 2$	$= 3$
$\sum q(\ell_i)$	$= \pm 2e$	$= \pm 1e$

Signal region

	SR2ℓDec	SR2ℓProd	SR3ℓDec	SR3ℓProd
N_{jets}	≥ 4	≤ 3	≥ 3	≤ 2
$N_{b\text{-tags}}$	$= 1$	$= 1$	$= 1$	$= 1$
$p_{\text{T}}(\ell_1)$	≥ 12 GeV	≥ 16 GeV	≥ 20 GeV	≥ 20 GeV
$p_{\text{T}}(\ell_2)$	–	–	≥ 16 GeV	≥ 16 GeV
$\lvert m(e,e) - m_Z \rvert$	≥ 10 GeV	≥ 10 GeV	–	–

Control region HF

	CR2ℓHFe	CR2ℓHFμ	CR3ℓHFe	CR3ℓHFμ
N_{jets}	≤ 3	≤ 3	≥ 1	≥ 1
$N_{b\text{-tags}}$	≥ 1	≥ 1	$= 1$	$= 1$
ℓ_0 flavour	μ	μ	–	–
ℓ_1 flavour	e	μ	–	–
$p_{\text{T}}(\ell_1)$	< 16 GeV	< 16 GeV	≥ 20 GeV	≥ 20 GeV
ℓ_2 flavour	–	–	e	μ
$p_{\text{T}}(\ell_2)$	–	–	< 16 GeV	< 16 GeV

Control region $t\bar{t}V$

	CR2$\ell t\bar{t}V$	CR3$\ell t\bar{t}W$	CR3$\ell t\bar{t}Z$
N_{jets}	≥ 4	≥ 2	≥ 2
$N_{b\text{-tags}}$	$= 2$	$= 2$	$= 2$
ℓ_0 flavour	μ	–	–
$p_{\text{T}}(\ell_1)$	≥ 18 GeV	≥ 20 GeV	≥ 20 GeV
$p_{\text{T}}(\ell_2)$	–	≥ 16 GeV	≥ 16 GeV
$\lvert m(\ell^+,\ell^-) - m_Z \rvert$	–	≥ 10 GeV	< 10 GeV

Backup: List of NN variables for ML analysis: SR3ℓ

Variable	Description
$m(\ell_{\mathrm{OS}}, \ell_{\mathrm{SS},1})$	Invariant mass of the opposite-charge and the subleading-p_{T} same-charge lepton
$m(\ell_{\mathrm{OS}}, \ell_{\mathrm{SS},0})$	Invariant mass of the opposite-charge and the leading-p_{T} same-charge lepton
$m(\ell_t, b_t)$	Invariant mass of the b-tagged jet and the lepton assigned to the top-quark decay
N_{jets}	Number of jets
H_T(jets)	Scalar sum of the p_{T} of all jets
$m(t_{\mathrm{SM}}, H)$	Invariant mass of the RJR top quark decaying via $t \to Wb$ and the Higgs boson
$\Delta R(\ell_{\mathrm{SS},0}, \ell_{\mathrm{SS},1})$	Angular separation between the leading and subleading-p_{T} same-charge lepton
$m(\ell_{H,0}, \ell_{H,1})$	Invariant mass of the two leptons assigned to the Higgs-boson decay
$m(b\text{-jet}, \ell_{\mathrm{SS},0})$	Invariant mass of the b-tagged jet and the leading-p_{T} same-charge lepton
$\Delta R(\ell_t, b_t)$	Angular separation between the b-tagged jet and the lepton assigned to the top-quark decay
$p_{\mathrm{T}}(t_{\mathrm{SM}})$	Transverse momentum of the RJR top quark decaying via $t \to Wb$
$p_{\mathrm{T}}(b\text{-jet})$	Transverse momentum of the b-tagged jet
$\eta(\ell_{\mathrm{SS},1})$	Pseudorapidity of the subleading-p_{T} same-charge lepton
$p_{\mathrm{T}}(\ell_{\mathrm{SS},1})$	Transverse momentum of the subleading-p_{T} same-charge lepton
$m(H, \ell_{\mathrm{SS},1})$	Invariant mass of the RJR Higgs boson and the subleading-p_{T} same-charge lepton
$\Delta R(t_{\mathrm{SM}}, \ell_{\mathrm{OS}})$	Angular separation between the RJR top quark decaying via $t \to Wb$ and the opposite-charge lepton
$\Delta R(H, \ell_{\mathrm{OS}})$	Angular separation between the RJR Higgs boson and the opposite-charge lepton
$\Delta R(\ell_{\mathrm{OS}, \ell_{\mathrm{SS},1}})$	Angular separation between the opposite-charge and the subleading-p_{T} same-charge lepton

↑ Production Decay →

Variable	Description
$m(\ell_{\mathrm{OS}}, \ell_{\mathrm{SS},1})$	Invariant mass of the opposite-charge and the subleading-p_{T} same-charge lepton
$m(\ell_{\mathrm{OS}}, \ell_{\mathrm{SS},0})$	Invariant mass of the opposite-charge and the leading-p_{T} same-charge lepton
NICE $m(\ell_t, b_t)$	Invariant mass of the b-tagged jet and the lepton assigned to the top-quark decay with a fulfilled NICE Reco condition
H_T(jets)	Scalar sum of the p_{T} of all jets
$m(b\text{-jet}, \ell_{\mathrm{SS},0})$	Invariant mass of the b-tagged jet and the leading-p_{T} same-charge lepton
$m(t_{\mathrm{SM}}, H)$	Invariant mass of the RJR top quark decaying via $t \to Wb$ and the RJR Higgs boson
$m(\ell_{H,0}, \ell_{H,1})$	Invariant mass of the two leptons assigned to the Higgs-boson decay
$m(H, \ell_{\mathrm{SS},1})$	Invariant mass of the RJR Higgs boson and the subleading-p_{T} same-charge lepton
$\Delta R(b\text{-jet}, t_{\mathrm{SM}})$	Angular separation between the b-tagged jet and the RJR top quark decaying via $t \to Wb$
$m(\ell_0, t_{\mathrm{SM}})$	Invariant mass of the leading-p_{T} lepton and the RJR top quark decaying via $t \to Wb$
$p_{\mathrm{T}}(t_{\mathrm{SM}})$	Transverse momentum of the RJR top quark decaying via $t \to Wb$
$m(t_{\mathrm{SM}}, \ell_{\mathrm{SS},1})$	Invariant mass of the RJR top quark decaying via $t \to Wb$ and the subleading-p_{T} same-charge lepton
$\Delta R(\ell_{\mathrm{OS}}, \ell_{\mathrm{SS},0})$	Angular separation between the opposite-charge and the leading-p_{T} same-charge lepton
$p_{\mathrm{T}}(\ell_{\mathrm{OS}})$	Transverse momentum of the opposite-charge lepton
$m(b\text{-jet}, \ell_{\mathrm{OS}})$	Invariant mass of the b-tagged jet and the opposite-charge lepton
$m(b\text{-jet}, H)$	Invariant mass of the b-tagged jet and the RJR Higgs boson
$p_{\mathrm{T}}(\ell_2)$	Transverse momentum of the third-leading-p_{T} lepton
$\eta(\ell_0)$	Pseudorapidity of the leading-p_{T} lepton
$m(W_t)$	Mass of the RJR W boson from the top-quark decay
$m(\ell_t, b_t)$	Invariant mass of the b-tagged jet and the lepton assigned to the top-quark decay

Backup: List of NN variables for ML analysis: SR2ℓSS

Variable	Description
$m(\ell_1, H)$	Invariant mass of the subleading-p_T lepton and the RJR Higgs boson
N_jets	Number of jets
$m(b\text{-jet}, t_\mathrm{SM})$	Invariant mass of the b-tagged jet and the RJR top quark decaying via $t \to Wb$
$m(H, b\text{-jet})$	Invariant mass of the RJR Higgs boson and the b-tagged jet
$p_\mathrm{T}(W_\mathrm{had})$	Transverse momentum of the hadronically decaying RJR W boson
$\Delta R(\ell_1, H)$	Angular separation between the subleading-p_T lepton and the RJR Higgs boson
$m(W_\mathrm{had})$	Mass of the hadronically decaying RJR W boson
$p_\mathrm{T}(\ell_1)$	Transverse momentum of the subleading-p_T lepton
$\eta(\ell_1)$	Pseudorapidity of the subleading-p_T lepton
$\Delta R(H, W_t)$	Angular separation between the RJR Higgs boson and the RJR W boson from the top-quark decay
$\Delta R(\ell_0, \ell_1)$	Angular separation between leading and subleading-p_T lepton
$m(\ell_1, b\text{-jet})$	Invariant mass of the subleading-p_T lepton and the b-tagged jet
$\eta(b\text{-jet})$	Pseudorapidity of the b-tagged jet
$\Delta R(\ell_0, t_\mathrm{SM})$	Angular separation between the leading-p_T lepton and the RJR top quark decaying via $t \to Wb$
$E_\mathrm{T}^\mathrm{miss}$	Missing transverse momentum
fl.(ℓ_0)	Flavour of the leading-p_T lepton
$\eta(\ell_0)$	Pseudorapidity of the leading-p_T lepton
$p_\mathrm{T}(\ell_0)$	Transverse momentum of the leading-p_T lepton
$\Delta R(\ell_1, t_\mathrm{SM})$	Angular separation between the subleading-p_T lepton and the RJR top quark decaying via $t \to Wb$
$m(H, W_t)$	Invariant mass of the RJR Higgs boson and the RJR W boson from the top-quark decay
$\Delta R(\ell_1, W_t)$	Angular separation between the subleading-p_T lepton and the RJR W boson from the top-quark decay
$m(\ell_0, H)$	Invariant mass of the leading-p_T lepton and the RJR Higgs boson
$p_\mathrm{T}(b\text{-jet})$	Transverse momentum of the b-tagged jet

$\uparrow$ Production

Decay $\rightarrow$

Variable	Description
$H_T(\text{jets})$	Scalar sum of the p_T of all jets
$m(\ell_0, b\text{-jet})$	Invariant mass of the leading-p_T lepton and the b-tagged jet
$\Delta R(\ell_1, H)$	Angular separation between the subleading-p_T lepton and the RJR Higgs boson
$p_\mathrm{T}(\ell_1)$	Transverse momentum of the subleading-p_T lepton
$m(\text{jets}_{\min\Delta R})$	Invariant mass of the two non-b-tagged jets with the smallest ΔR
$m(t_\mathrm{SM}, l\text{-jet}_0)$	Invariant mass of the RJR top quark decaying via $t \to Wb$ and the leading-p_T non-b-tagged jet
$\eta(\ell_1)$	Pseudorapidity of the subleading-p_T lepton
$\Delta R(\ell_0, l\text{-jet}_1)$	Angular separation between the leading-p_T lepton and the subleading-p_T non-b-tagged jet
$m(\ell_1, l\text{-jet}_0)$	Invariant mass of the subleading-p_T lepton and the leading-p_T non-b-tagged jet
$m(\ell_0, l\text{-jet}_0)$	Invariant mass of the leading-p_T lepton and the leading-p_T non-b-tagged jet
$\Delta R(\ell_0, l\text{-jet}_2)$	Angular separation between the leading-p_T lepton and the third-leading-p_T non-b-tagged jet
$\Delta R(\ell_1, l\text{-jet}_2)$	Angular separation between the subleading-p_T lepton and the third-leading-p_T non-b-tagged jet
$m(t_\mathrm{FCNC}, l\text{-jet}_0)$	Invariant mass of the RJR top quark decaying via $t \to Hq$ and the leading-p_T non-b-tagged jet
$m(\ell_1, l\text{-jet}_1)$	Invariant mass of the subleading-p_T lepton and the subleading-p_T non-b-tagged jet
$m(\ell_1, t_\mathrm{FCNC})$	Invariant mass of the subleading-p_T lepton and the RJR top quark decaying via $t \to Hq$
$m(W_t, W_\mathrm{had})$	Invariant mass of the RJR W boson from the top-quark decay and the hadronically decaying RJR W boson
$\Delta R(\ell_0, l\text{-jet}_0)$	Angular separation between the leading-p_T lepton and the leading-p_T non-b-tagged jet
$m(\ell_1, b\text{-jet})$	Invariant mass of the subleading-p_T lepton and the b-tagged jet
N_jets	Number of jets
$m(H, b\text{-jet})$	Invariant mass of the RJR Higgs boson and the b-tagged jet
$H_T(\ell_0, \ell_1)$	Scalar sum of the p_T of all leptons
$p_\mathrm{T}(\ell_0)$	Transverse momentum of the leading-p_T lepton
$m(W_t, t_\mathrm{FCNC})$	Invariant mass of the RJR W boson from the top-quark decay and the RJR top quark decaying via $t \to Hq$

Backup: Leading systematics uncertainties for ML analysis