# EFT Constraints from Measurements in the Top Quark Sector

## EFT beyond Higgs

Haichen Wang

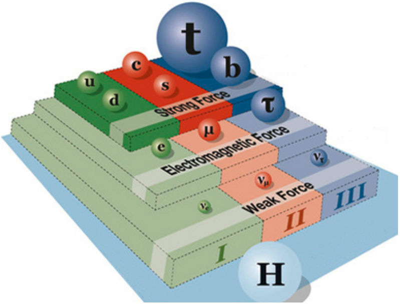
University of California, Berkeley
Lawrence Berkeley National Laboratory

on behalf of the ATLAS and CMS Collaborations

November 29, 2023

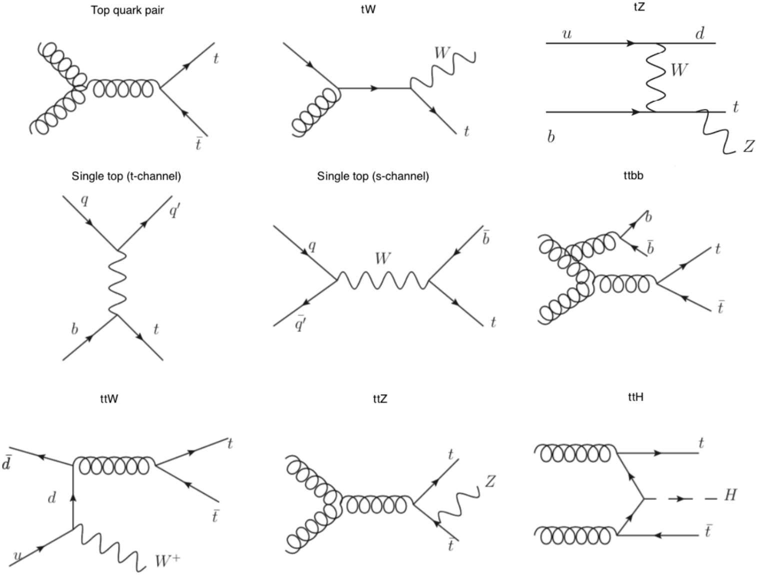
# Top Quark Sector

- The top quark is the most massive elementary particle in the Standard Model (SM)
- Its large Yukawa coupling suggests that the top quark plays a unique role in the electroweak symmetry breaking
- Measurements and searches involving top quarks could help us to uncover Beyond the SM physics



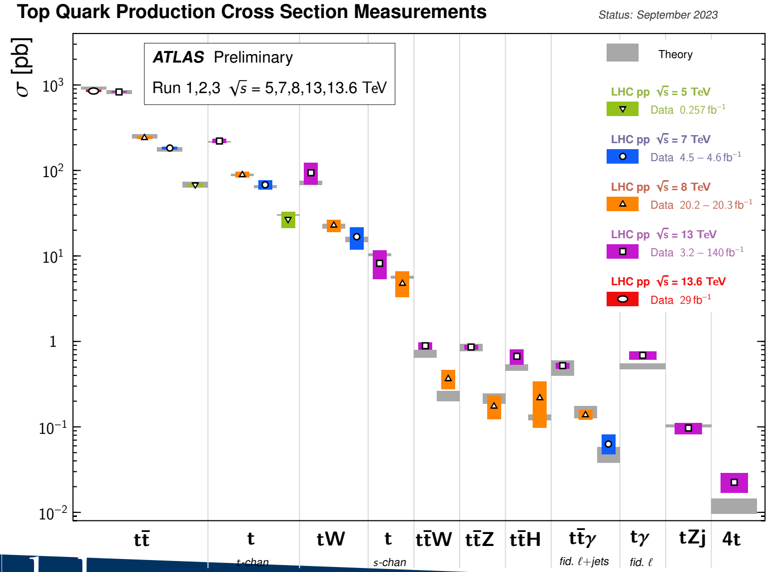

I will give an overview of CMS and ATLAS' efforts using the Effective Field Theory approach to probing BSM physics in the top quark sector

# The LHC is a top quark factory



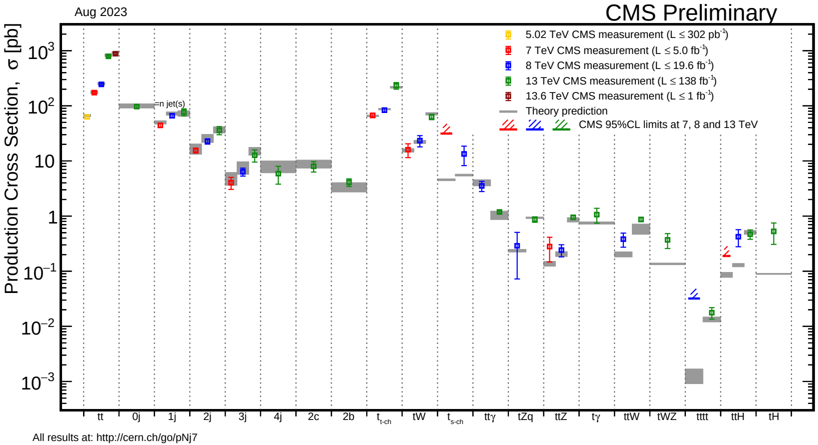

credit:arXiv:1901.05965

# The LHC is a top quark factory




Berkeley
UNIVERSITY OF CALIFORNIA

# The LHC is a top quark factory



# The Effective Field Theory Approach

- The Effective Field Theory (EFT) provides a model-independent framework for searching for new physics effects
- The SM is regarded as a low-energy approximation of a more fundamental theory involving interactions at an energy scale $\Lambda$
- New physics is then parametrised in terms of higher dimension operators which only include SM fields
- The Effective Lagrangian is given by

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{SM} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

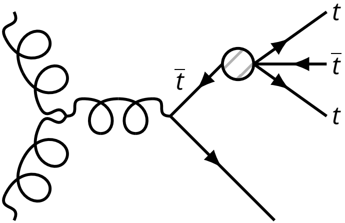
where $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, $O_i^{(d)}$ are the effective operators of dimension $d$, and the coefficients $c_i^{(d)}$ are the Wilson Coefficients (WCs) that parameterise the strength of the interaction.

# EFT in the Top Quark Sector

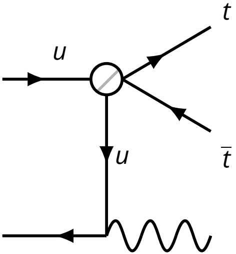
- As in the Higgs analyses, the Warsaw basis of dimension-six operators has been adopted
- In the interpretation of top quark analyses, only operators involving top quarks are considered
- There is a large number of four-fermion operators, and they are reduced by flavor assumptions:
  - The baseline scenario assumes Minimal Flavor Violation in the quark sector, i.e., a unit CKM matrix and finite Yukawa couplings only for top and bottom quarks and flavor diagonality in the lepton sector
  - two other variations are considered too
- Flavor Changing Neutral Current considered separately

More detailed information can be found in the LHC Top Working Group recommendation

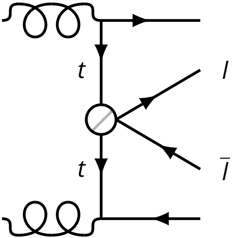
# Main Types of EFT operators:



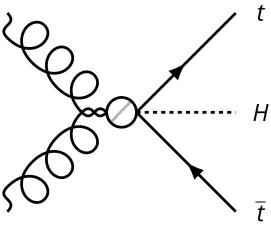

**Four-heavy-quark**




**Two-light-two-heavy**




**Two-quark-two-lepton**

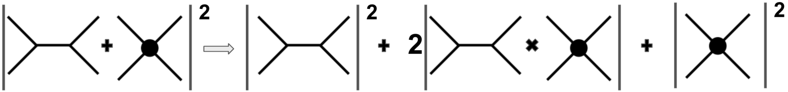



**Quark-Boson**

# Parameterization of the Observable Effects

The dimension-six operator could contribute to the rate of a process, either directly (quadratic terms), or through the interference with SM diagram (linear terms):

$$\sigma \propto \left| \mathcal{M}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i \right|^2 \propto \sigma_{SM} + \sum_i \frac{c_i}{\Lambda^2} \sigma_{SM,c_i} + \sum_i \frac{c_i^2}{\Lambda^4} \sigma_{c_i} + O(\frac{1}{\Lambda^4})$$



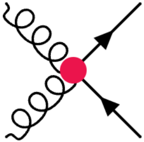

This parameterization can be applied to the inclusive event rate, differential cross section, as well as other observables such as charge asymmetry, flavor changing top decay branching ratio, etc.

# Top Quark Measurements and Searches with EFT Interpretations

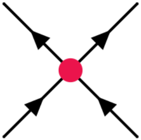
- I will focus on results released since Higgs 2022
- Go from processes with higher rates ($t\bar{t}$, $t\bar{t}Z$) to those with lower rates ($t\bar{t}t\bar{t}$)
- Direct Searches for Charged Lepton Flavor Violating processes and Flavor Changing Neural Current processes

# $t\bar{t}$ Production

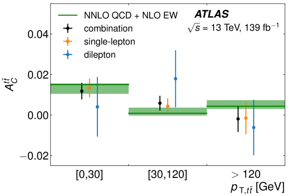
- $t\bar{t}$ process is sensitive to the $tG$ operator and four-quark operators
- a variety of measurements and searches have been used to constrain WCs



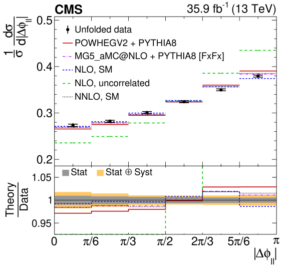
$tG$ operator



four-quark operator

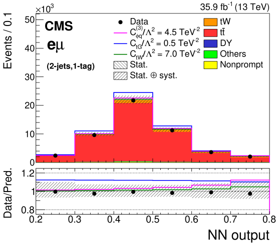



Charge Asymmetry of top quarks JHEP 08 (2023) 077




Top quark polarization and spin correlation

Phys. Rev. D 100 (2019) 072002

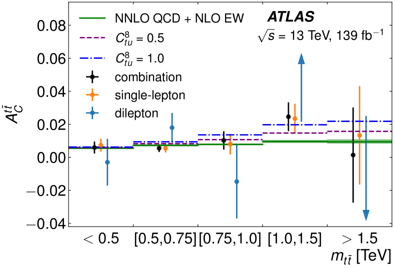


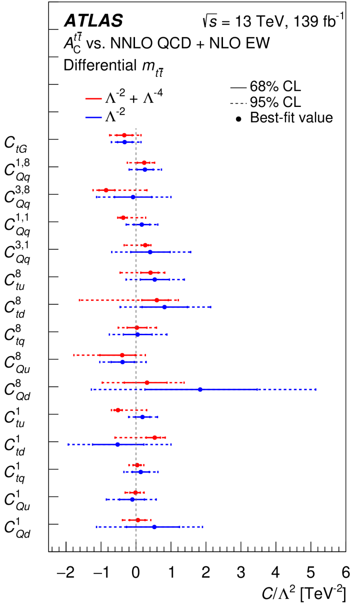

Direct search to probe excess in event rate

Eur. Phys. J. C 79 (2019) 886

# $t\bar{t}$ Production: ATLAS $t\bar{t}$ charge asymmetry measurement as an example JHEP 08 (2023) 077

- The charge asymmetry's dependences on other observables can be altered by the presence of EFT terms
- They are used to constrain WCs



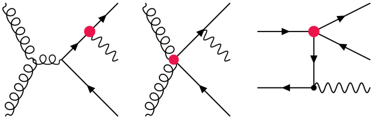



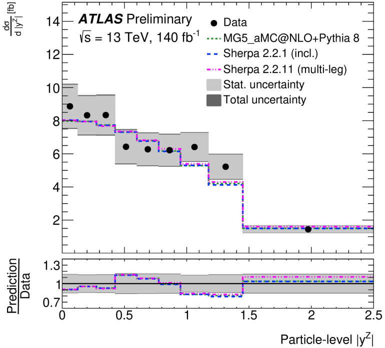
# ATLAS ttZ Measurement ATLAS-CONF-2023-065

- $t\bar{t}Z$ production is sensitive to top-Boson operators as well as four-quark operators
- Inclusive cross section of $t\bar{t}Z$ measured with events with 2, 3, and 4 leptons (e/$\mu$) from Run-2 data
- Six observables measured using a combination of 3l and 4l events are used as input for the EFT interpretation
- Input distributions:

$$p_T^Z,\ |y_Z|,\ \cos\theta_Z^*,\ p_T^t,\ \Delta\phi(t\bar{t},Z),\ \text{and}\ |y_{t\bar{t}Z}|$$

- EFT interpretation fitted six particle-level unfolded distributions taking into account their correlations





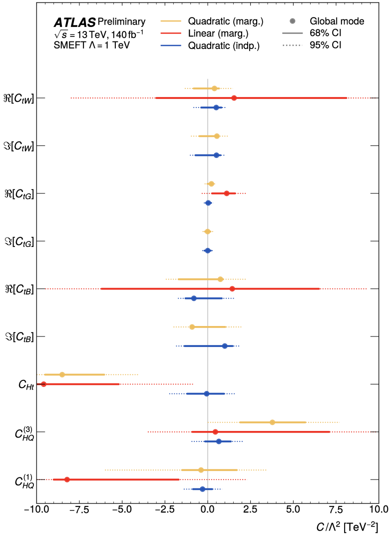
# ATLAS ttZ Measurement ATLAS-CONF-2023-065

## EFT samples

- Madgraph using SMEFTsim 3.0 UFO
- LO samples normalized to the NLO Madgraph sample

## EFT Fits

- Nominal: both lin. and quad. terms are considered. When fitting one WC, other WCs were profiled
- Only lin. terms were used
- Both lin. and quad. terms are considered. When fitting one WC, other WC's were fixed to zero




Constraints on top-boson operators

Berkeley UNIVERSITY OF CALIFORNIA

# ATLAS ttZ Measurement ATLAS-CONF-2023-065

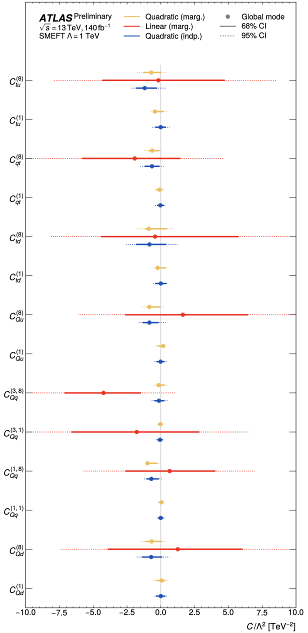
## EFT samples

- EFT samples generated with Madgraph using SMEFTsim 3.0 UFO
- These LO samples were normalized to the NLO Madgraph sample

## EFT Fits

- Nominal: both linear and quadratic terms are considered. When fitting one WC, other WCs were profiled
- Only linear terms were used
- both linear and quadratic terms are considered. When fitting one WC, other WC's were fixed to zero

⇒ Constraints on four-quark operators




Berkeley UNIVERSITY OF CALIFORNIA

# EFT motivated top plus lepton search

Accepted by JHEP

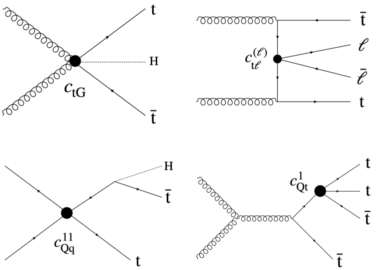
- Broadly target a large number of associated top quark production processes

  $t\bar{t}H$

  $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$

  $t\bar{t}t\bar{t}$, etc.

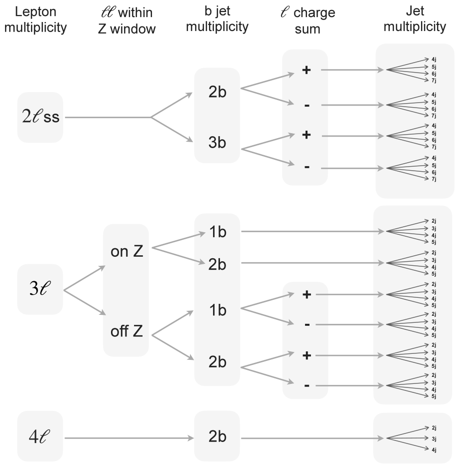
- These processes provide access to four groups of operators:




| Operator category | Wilson coefficients |
|---|---|
| Two-heavy (2hqV) | $c_{t\varphi}, c^{-}_{\varphi Q}, c^{3}_{\varphi Q}, c_{\varphi t}, c_{\varphi tb}, c_{tW}, c_{tZ}, c_{bW}, c_{tG}$ |
| Two-heavy-two-lepton (2hq2$\ell$) | $c^{3(\ell)}_{Q\ell}, c^{-(\ell)}_{Q\ell}, c^{(\ell)}_{Qe}, c^{(\ell)}_{t\ell}, c^{(\ell)}_{te}, c^{S(\ell)}_{t}, c^{T(\ell)}_{t}$ |
| Two-heavy-two-light (2hq2lq) | $c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}$ |
| Four-heavy (4hq) | $c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$ |

# CMS Top + Leptons Search [Accepted by JHEP]

- The analysis categorizes events based on the number of leptons, their charges, the invariant of dilepton system, jet and *b*-jets multiplicities
  - 43 categories defined
  - A kinematic observable is identified for each category, as input to the fit

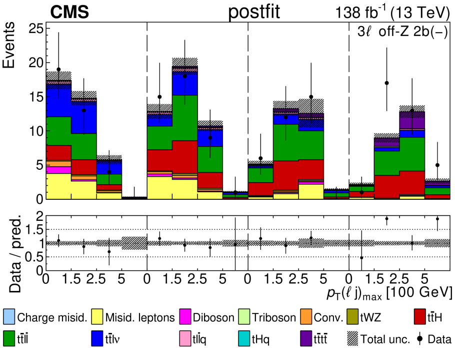


# CMS Top + Leptons Search Accepted by JHEP

- 26 Wilson coefficients are considered

  43 categories defined

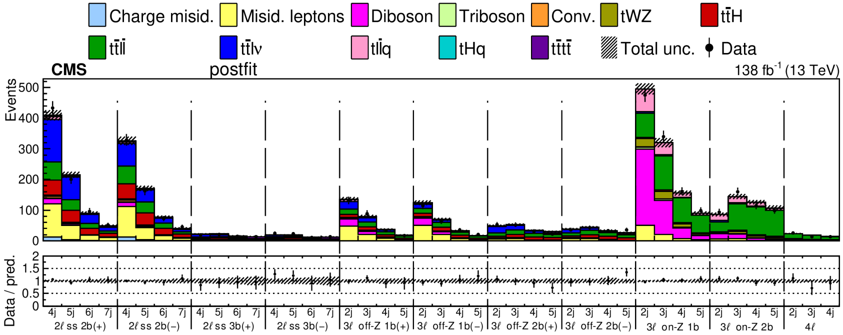
  A kinematic observable is identified for each category, as input to the fit




Major associated production modes of top quarks are captured by these categories, and their kinematics are different

# CMS Top + Leptons Search Accepted by JHEP

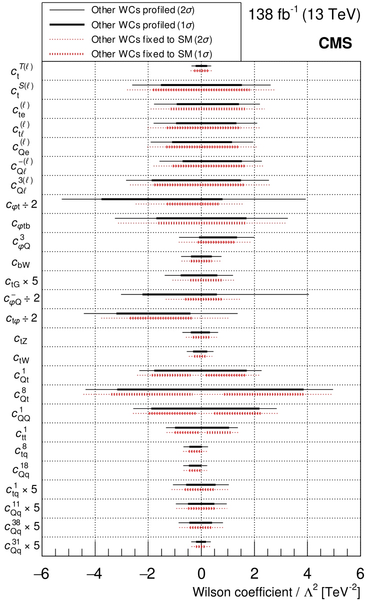
## Post-fit data and expected yields for the 43 signal regions



# CMS Top + Leptons Search

Accepted by JHEP

- 26 Wilson coefficients were measured
  - solid lines: fitting one WC, while other WCs profiled
  - dashed lines: fitting one WC, while other WCs fixed to 0






Berkeley UNIVERSITY OF CALIFORNIA

# ATLAS Four Top Production

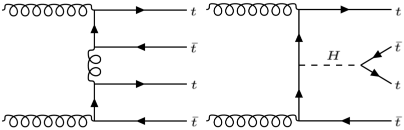
Eur. Phys. J. C 83 (2023) 496

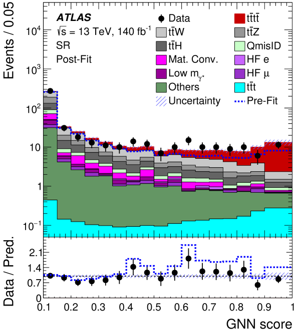
The simultaneous production of four top quarks at the LHC is one of the rarest processes observed by ATLAS and CMS

## Analysis

- Events with two leptons with same signs or three leptons
- A Graph Neural Network was used as the event classifier and observable
- ATLAS observed the $t\bar{t}t\bar{t}$ at $> 6\ \sigma$ level

CMS also established the observation of the $t\bar{t}t\bar{t}$ process
(Phys. Lett. B 847 (2023) 138290)



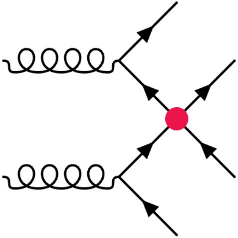



# ATLAS Four Top Production Eur. Phys. J. C 83 (2023) 496

The $t\bar{t}t\bar{t}$ process is sensitive to a large number of four-fermion operators, and they are ***uniquely sensitive to four-heavy-fermion operators***

## EFT Interpretation

- The expected GNN distribution is parametermized as functions of these WCs
- Both linear and quadratic terms are included in the interpretation



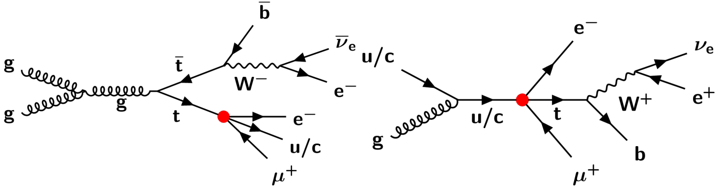
| Operators | Expected $C_i/\Lambda^2$ [TeV $^{-2}$] | Observed $C_i/\Lambda^2$ [TeV $^{-2}$] |
|---|---|---|
| $O^1_{QQ}$ | [-2.4, 3.0] | [-3.5, 4.1] |
| $O^1_{Qt}$ | [-2.5, 2.0] | [-3.5, 3.0] |
| $O^1_{tt}$ | [-1.1, 1.3] | [-1.7, 1.9] |
| $O^8_{Qt}$ | [-4.2, 4.8] | [-6.2, 6.9] |

# CMS Search for charged lepton flavor violation in the top quark sector

CMS-PAS-TOP-22-005

Targeting interactions involving a top quark, a light quark (up or charm), and an electron and a muon

- testing **two-quark-two-lepton operators**



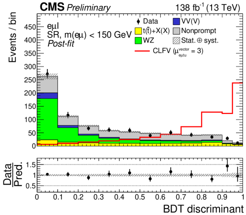

- The signature consists of
  - three leptons
  - at least one electron and one muon
  - One top quark that decays semi-leptonically

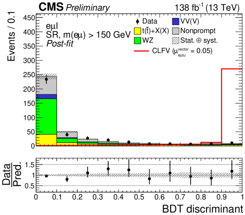
| | | |
|---|---|---|
| vector | $O_{lq}^{(1)ijkl}$ | $(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l)$ |
| | $O_{lu}^{ijkl}$ | $(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l)$ |
| | $O_{eq}^{ijkl}$ | $(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l)$ |
| | $O_{eu}^{ijkl}$ | $(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l)$ |
| scalar | $O_{lequ}^{(1)ijkl}$ | $(\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l)$ |
| tensor | $O_{lequ}^{(3)ijkl}$ | $(\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l)$ |

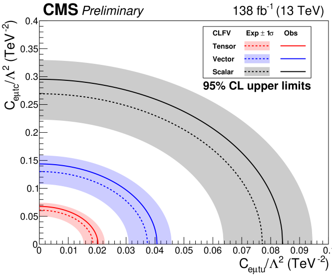
# CMS Search for charged lepton flavor violation in the top quark sector

CMS-PAS-TOP-22-005

- cLFV top quark decay and cLFV top quark production targeted with different signal regions
- Boosted Decisions Trees (BDTS) used as event classifiers



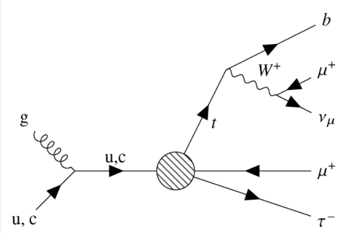

Left: CLFV decay BDT; Right: CLFV production BDT

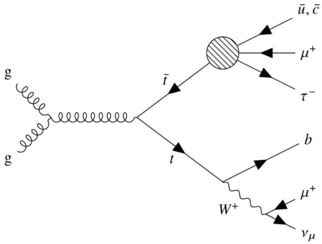
Caveat: this result used SMEFTfr v2 for event generation, which has known issues. An update is expected when the paper is to submitted for publication.

# ATLAS Search for charged lepton flavor violation in the top quark sector

ATLAS-CONF-2023-001

## Targeting interactions involving a top quark, a light quark (up or charm), a muon and a tau lepton




| Operator | Lorentz Structure | |
|---|---|---|
| $\mathcal{O}_{lq}^{1(ijkl)}$ | $(\bar{l}_i\gamma^{\mu}l_j)(\bar{q}_k\gamma_{\mu}q_l)$ | Vector |
| $\mathcal{O}_{lq}^{3(ijkl)}$ | $(\bar{l}_i\gamma^{\mu}\sigma^I l_j)(\bar{q}_k\gamma_{\mu}\sigma^I q_l)$ | Vector |
| $\mathcal{O}_{eq}^{(ijkl)}$ | $(\bar{e}_i\gamma^{\mu}e_j)(\bar{q}_k\gamma_{\mu}q_l)$ | Vector |
| $\mathcal{O}_{lu}^{(ijkl)}$ | $(\bar{l}_i\gamma^{\mu}l_j)(\bar{u}_k\gamma_{\mu}u_l)$ | Vector |
| $\mathcal{O}_{eu}^{(ijkl)}$ | $(\bar{e}_i\gamma^{\mu}e_j)(\bar{u}_k\gamma_{\mu}u_l)$ | Vector |
| $^{\ddagger}\mathcal{O}_{lequ}^{1(ijkl)}$ | $(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$ | Scalar |
| $^{\ddagger}\mathcal{O}_{lequ}^{3(ijkl)}$ | $(\bar{l}_i\sigma^{\mu\nu}e_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu}u_l)$ | Tensor |

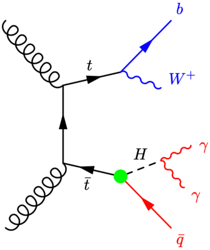
| | **95% CL upper limits on Wilson coefficients** $c/\Lambda^2$ **[TeV$^{-2}$]** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $c_{lq}^{-(ijk3)}$ | $c_{eq}^{(ijk3)}$ | $c_{lu}^{(ijk3)}$ | $c_{eu}^{(ijk3)}$ | $c_{lequ}^{1(ijk3)}$ | $c_{lequ}^{1(ij3k)}$ | $c_{lequ}^{3(ijk3)}$ | $c_{lequ}^{3(ij3k)}$ |
| **Previous (u)** [22] | 12 | 12 | 12 | 12 | 26 | 26 | 3.4 | 3.4 |
| **Expected (u)** | 0.47 | 0.44 | 0.43 | 0.46 | 0.49 | 0.49 | 0.11 | 0.11 |
| **Observed (u)** | 0.49 | 0.47 | 0.46 | 0.48 | 0.51 | 0.51 | 0.11 | 0.11 |
| **Previous (c)** [22] | 14 | 14 | 14 | 14 | 29 | 29 | 3.7 | 3.7 |
| **Expected (c)** | 1.6 | 1.6 | 1.5 | 1.6 | 1.8 | 1.8 | 0.35 | 0.35 |
| **Observed (c)** | 1.7 | 1.6 | 1.6 | 1.6 | 1.9 | 1.9 | 0.37 | 0.37 |

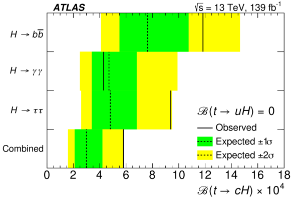
# ATLAS FCNC search with $H \to \gamma\gamma$

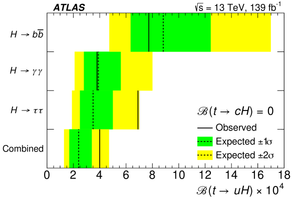
ATLAS-TOPQ-2019-04, submitted to JHEP

Flavor Changing Neural Current searches have been done in top quark productions associated with a photon, a Z boson, or a Higgs boson

- This search focuses on $H \to \gamma\gamma$
- Targets vertices connecting a top quark, a Higgs boson, and a light quark (up or charm)
- A combination with $b\bar{b}$, $\tau\tau$ to constrain the FCNC decays



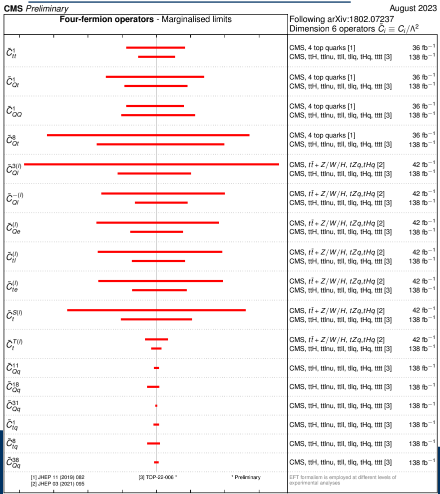

- *tcH* interaction: $c_{u\phi}^{23,32} < 1.07$ at 95% CL
- *tuH* interaction: $c_{u\phi}^{13,31} < 0.88$ at 95% CL
- When one WC is tested, the other WC is fixed to

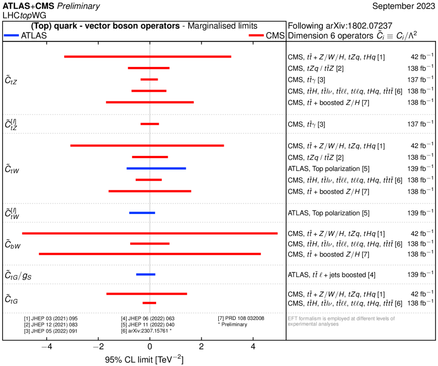
# EFT Summary Plots

Both CMS and ATLAS maintain public websites to keep track of their results

- [CMS Top Physics Results]
- [ATLAS Top Physics Results]

EFT Summary plots are also available on these sites



# Summary and Outlook

- The SMEFT framework has been widely used in LHC top quark measurements and searches
- CMS and ATLAS now interpret their results following the LHC Top WG's recommendation, making these EFT interpretations comparable bewteen experiments
- It is challenging to work out a coherent approach to use this large variety of measurements and searches to maximize the sensitivity to the large number of WCs in the top sector
  - consistent Monte Carlo generation
  - harmonization of object and event selection between different analyses within an experiment
  - how to combine analyses with overlapping signal and control regions?
- Both experiments are actively addressing these challenges, e.g., ATLAS roadmap for future combination and EFT interpretation of top + X processes ATL-PHYS-PUB-2023-030
- Stay tuned with new data and analyses!