Search for charged-lepton flavor violation in the top quark sector with the CMS detector[†]

Jack Li (Northeastern University)

On behalf of the CMS Collaboration

US LUA Annual Meeting, 12-15 Dec 2023

[†] Submitted to PRD last week [arXiv:2312.03199]

Introduction

- **Charged-lepton flavor violation (CLFV) is extremely rare $\mathcal{O}(10^{-50})$ in the SM**
  - The only known way of CLFV involves W loop (massive neutrino)
  - Potential enhancements inspired by recent anomalies in the flavor sector
- **Low-energy CLFV: μ→e, μ→eee, etc**
  - Highly competitive bounds established by small but dedicated experiments (e.g. MEG)

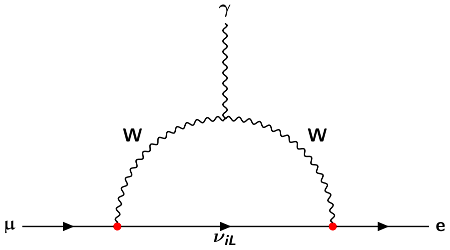


Figure 1: **μ→e transition**

- **High-energy CLFV: Z/H/t→$\ell\ell'$(X), etc**
  - Heavy particles like top quarks can be used as a good probe at the LHC

Analysis overview

- **Data collected by CMS in 2016-2018: $\sqrt{s} = 13$ TeV, $\int \mathcal{L}dt = 138$ fb^{-1}**
- **Targeting top production and decay signals in 3ℓ (e or μ) final states**
  - Three leptons selected with custom (BDT) IDs
- **Parameterising signals with Dimension-6 effective field theory (EFT) operators**

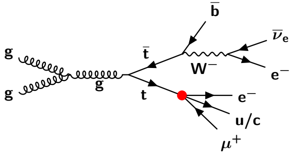


Figure 2: **Top decay**

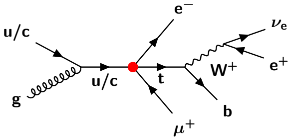


Figure 3: **Top production**

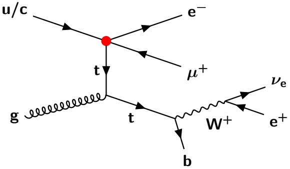
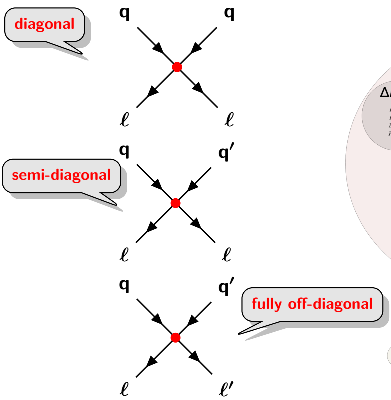


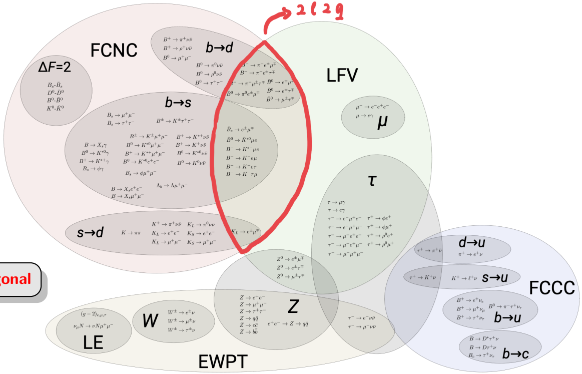
Figure 4: **Top production**

- **Nonprompt backgrounds → data-driven method**
  - At least one lepton that originates from decays of b/c hadrons, photon conversion, etc
- **Prompt backgrounds → MC simulation**

EFT signals

- **CLFV events generated by Dimension-6 “2l2q” operators**
  - Separate samples for top production and decay processes
- **Fully off-diagonal 2l2q operators sit at the crossroads between FCNC and CLFV**



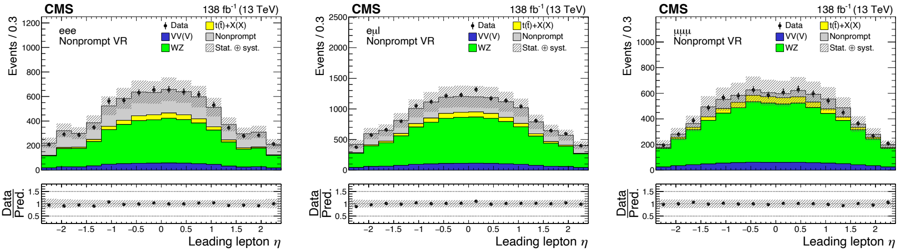


- **Underlying processes are highly suppressed by mass hierarchy**
  - Complementary to existing efforts that focus on diagonal operators

Nonprompt background estimate

[arXiv:1407.5624]

- **We use the "matrix method" to estimate nonprompt backgrounds**
- **Three validation regions (VR) are used to validate this method**
  - Defined using different lepton flavor compositions: eee, eμℓ, μμμ



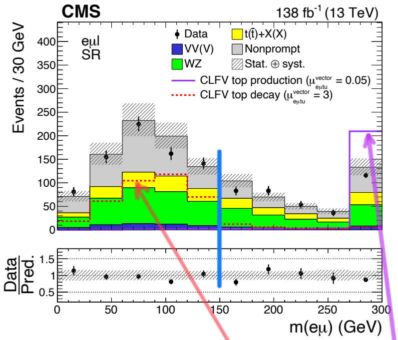
- **Good agreement between observed data and prediction in all three VRs**

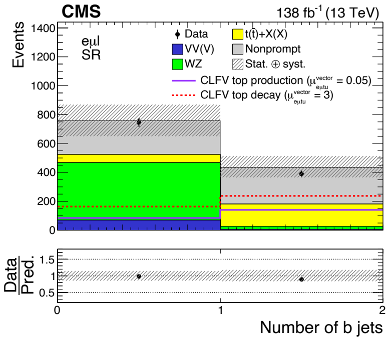
Signal region

Signal region (SR) selection

One oppositely charged eμ pair + an extra ℓ, at least one jet, no more than one b-jet, $p_T^{miss} > 20$ GeV, Z mass veto (50-106 GeV)

Dominant background: nonprompt and WZ production





- **SR is further subdivided to target different CLFV signal modes**
  - SR1: m(eμ) < 150 GeV → Top decay enriched
  - SR2: m(eμ) > 150 GeV → Top production enriched

BDT discriminant

- **One binary Boosted Decision Tree (BDT) is trained for each SR**
- **Different signal samples are combined in training**

Figure 5: **SR1: BDT targeting top decay**

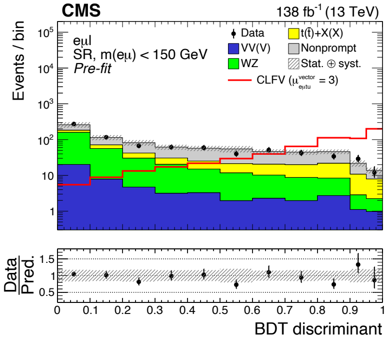
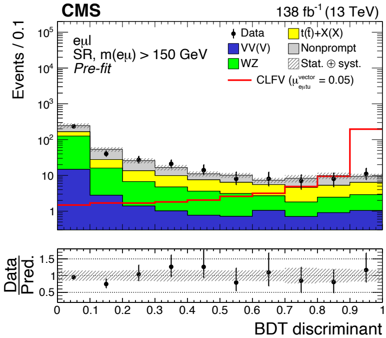


Figure 6: **SR2: BDT targeting top production**



- **No significant excess over SM expectations**
  - Full BDT distributions are used to set limits

Upper limits on Wilson Coefficients

- **Sensitivity is largely driven by top production mode**
  - This explains why limits on WCs involving up quarks are much better
- **Top decay mode yields a minor improvement on upper limits**

Table 1: **Upper limits at the 95% CL on various Wilson Coefficients**

CLFV coupling	Int. type	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp (68% range)	**Obs**
$e\mu tu$	tensor	0.022 (0.018-0.026)	**0.024**
	vector	0.044 (0.036-0.054)	**0.048**
	scalar	0.093 (0.077-0.114)	**0.101**
$e\mu tc$	tensor	0.084 (0.069-0.102)	**0.094**
	vector	0.175 (0.145-0.214)	**0.196**
	scalar	0.385 (0.318-0.471)	**0.424**

- **Significantly improves the previous CMS results**
  - Probing energy scale up to 6.5 TeV assuming $C = 1$

More on upper limits

- **Observed upper limits @ 95% CL on branching fractions of t→eμq, q=u/c**

Int. type	$\mathcal{B}(t\to e\mu u)\times 10^{-7}$	$\mathcal{B}(t\to e\mu c)\times 10^{-7}$
Tensor	0.32	4.98
Vector	0.22	3.69
Scalar	0.12	2.16

Figure 7: **Upper limits on branching fractions**

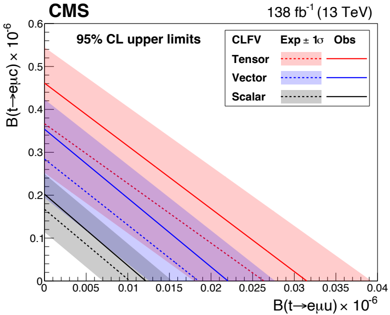
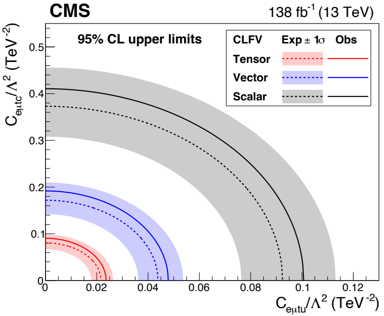


Figure 8: **Upper limits on Wilson coefficients**



- **Most stringent limits on $\mathcal{B}(t\to e\mu q)$ to date**
  - One (two) order(s) of magnitude improvement w.r.t. previous CMS[a] (ATLAS[b]) results

[a] [arXiv:2201.07859] [b] [ATLAS-CONF-2018-044]

Summary

[arXiv:2312.03199]

- **A new CMS search for charged-lepton flavor violation is presented**
  - 3ℓ (e or μ) channel
  - Targeting top production and decay
- **No significant excess is observed over the prediction from the Standard Model**
- **Improving the existing upper limits on $\mathcal{B}(t \to e\mu q)$ by one order of magnitude**

Thank you for listening!

Back up

EFT operators and signal cross sections

- **Effective Lagrangian**: $\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}^{(4)}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_a C^{(6)}_a O^{(6)}_a + O(\frac{1}{\Lambda^4})$
- **Dimension-6 “2L2Q” operators**
  - No interference with the SM terms
- **Vector operators are combined**

Lorentz Structure	Operator
Vector	$O^{(1)ijmn}_{lq} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_m\gamma_\mu q_n)$
	$O^{ijmn}_{lu} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_m\gamma_\mu u_n)$
	$O^{ijmn}_{eq} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_m\gamma_\mu q_n)$
	$O^{ijmn}_{eu} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_m\gamma_\mu u_n)$
Scalar	$O^{(1)ijmn}_{lequ} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_m u_n)$
Tensor	$O^{(3)ijmn}_{lequ} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_m\sigma_{\mu\nu} u_n)$

Table 2: **Relevant Dimension-6 EFT operators**

Channel	Tensor	Vector	Scalar
Production $\ell\ell'tu$	2140 fb	460 fb	97 fb
Production $\ell\ell'tc$	164 fb	33 fb	6.3 fb
Decay $\ell\ell'tu$	187 fb	32.0 fb	4.0 fb
Decay $\ell\ell'tc$	187 fb	32.0 fb	4.0 fb

Table 3: **Signal cross sections**

- **Samples generated for top production and decay processes separately**

Implementation of the matrix method

- Key feature: efficiencies for prompt leptons are lower than 1 $\longrightarrow$ less assumptions
- Innovative implementation "3D matrix method"

Application Region

- 8 $\times$ AR are defined using different compositions of lepton requirement
- $N^{TT\overline{T}}$:leading and sub-leading leptons are *tight* while the third lepton fails *tight* requirement

Matrix

- One matrix is constructed for each event
- Matrix element is based on lepton kinematics
- Matrix is later inverted in order to evaluate non-prompt estimate

Non-prompt Estimate

- N^{TTT}_{RRF} :leading and sub-leading leptons are *prompt* while the third lepton is *nonprompt*
- $N^{TTT}_{Nonprompt} = N^{TTT}_{RRF} + N^{TTT}_{RFR} + \ldots + N^{TTT}_{FFF}$

$$
\begin{pmatrix} N^{TTT} \\ N^{TT\overline{T}} \\ N^{T\overline{T}T} \\ N^{T\overline{T}\overline{T}} \\ N^{\overline{T}TT} \\ N^{\overline{T}T\overline{T}} \\ N^{\overline{T}\overline{T}T} \\ N^{\overline{T}\overline{T}\overline{T}} \end{pmatrix}
=
\begin{pmatrix}
r_1 r_2 r_3^{\dagger} & r_1 r_2 f_3 & r_1 f_2 r_3 & r_1 f_2 f_3 & f_1 r_2 r_3 & f_1 r_2 f_3 & f_1 f_2 r_3 & f_1 f_2 f_3 \\
r_1 r_2(1-r_3) & r_1 r_2(1-f_3) & r_1 f_2(1-r_3) & r_1 f_2(1-f_3) & f_1 r_2(1-r_3) & f_1 r_2(1-f_3) & f_1 f_2(1-r_3) & f_1 f_2(1-f_3) \\
r_1(1-r_2)r_3 & r_1(1-r_2)f_3 & r_1(1-f_2)r_3 & r_1(1-f_2)f_3 & f_1(1-r_2)r_3 & f_1(1-r_2)f_3 & f_1(1-f_2)r_3 & f_1(1-f_2)f_3 \\
r_1(1-r_2)(1-r_3) & r_1(1-r_2)(1-f_3) & r_1(1-f_2)(1-r_3) & r_1(1-f_2)(1-f_3) & f_1(1-r_2)(1-r_3) & f_1(1-r_2)(1-f_3) & f_1(1-f_2)(1-r_3) & f_1(1-f_2)(1-f_3) \\
(1-r_1)r_2 r_3 & (1-r_1)r_2 f_3 & (1-r_1)f_2 r_3 & (1-r_1)f_2 f_3 & (1-f_1)r_2 r_3 & (1-f_1)r_2 f_3 & (1-f_1)f_2 r_3 & (1-f_1)f_2 f_3 \\
(1-r_1)r_2(1-r_3) & (1-r_1)r_2(1-f_3) & (1-r_1)f_2(1-r_3) & (1-r_1)f_2(1-f_3 0 & (1-f_1)r_2(1-r_3) & (1-f_1)r_2(1-f_3) & (1-f_1)f_2(1-r_3) & (1-f_1)f_2(1-f_3) \\
(1-r_1)(1-r_2)r_3 & (1-r_1)(1-r_2)f_3 & (1-r_1)(1-f_2)r_3 & (1-r_1)(1-f_2)f_3 & (1-f_1)(1-r_2)r_3 & (1-f_1)(1-r_2)f_3 & (1-f_1)(1-f_2)r_3 & (1-f_1)(1-f_2)f_3 \\
(1-r_1)(1-r_2)(1-r_3) & (1-r_1)(1-r_2)(1-f_3) & (1-r_1)(1-f_2)(1-r_3) & (1-r_1)(1-f_2)(1-f_3) & (1-f_1)(1-r_2)(1-r_3) & (1-f_1)(1-r_2)(1-f_3) & (1-f_1)(1-f_2)(1-r_3) & (1-f_1)(1-f_2)(1-f_3)
\end{pmatrix}
\begin{pmatrix} N^{TTT}_{RRR}/r_1 r_2 r_3 \\ N^{TTT}_{RRF}/r_1 r_2 f_3 \\ N^{TTT}_{RFR}/r_1 f_2 r_3 \\ N^{TTT}_{RFF}/r_1 f_2 f_3 \\ N^{TTT}_{FRR}/f_1 r_2 r_3 \\ N^{TTT}_{FRF}/f_1 r_2 f_3 \\ N^{TTT}_{FFR}/f_1 f_2 r_3 \\ N^{TTT}_{FFF}/f_1 f_2 f_3 \end{pmatrix}
$$

† r_1/f_1 denotes the prompt/nonprompt efficiency for leading lepton in event, r_2/f_2 denotes...sub-leading...

Event yields

Process	$m(e\mu) < 150$ GeV	$m(e\mu) > 150$ GeV
Nonprompt	351 ± 92	146 ± 38
WZ	275 ± 64	145 ± 35
ZZ	33.2 ± 6.5	13.1 ± 2.6
VVV	17.0 ± 8.5	12.0 ± 6.0
$t\bar{t}W$	47.6 ± 10.0	40.0 ± 9.1
$t\bar{t}Z$	39.1 ± 7.9	25.8 ± 5.4
$t\bar{t}H$	28.2 ± 4.5	10.0 ± 1.6
tZq	5.5 ± 1.1	2.5 ± 0.5
Other	7.3 ± 3.7	4.5 ± 2.3
Total expected	805 ± 123	398 ± 57
Data	783	378
CLFV	207 ± 15	4440 ± 215

driving sensitivity

Table 4: **Expected background contributions and the number of events observed in data collected during 2016–2018. The statistical and systematic uncertainties are added in quadrature. The category "Other" backgrounds include smaller background contributions containing one or two top quarks plus a boson or quark. The CLFV signal, generated with $C^{vector}_{e\mu tu}/\Lambda^2 = 1\text{TeV}^{-2}$ is also listed for reference. The signal yields include contributions from both top production and decay modes.**

Statistical analysis

- **Profile likelihood function $\mathcal{L}(\mu, \theta)$ is constructed using binned BDT distributions**
  - μ scales the cross sections of top production and decay signals simultaneously
  - Uncertainties are incorporated as nuisance parameters θ

Systematic uncertainty	m(eμ) < 150 GeV		m(eμ) > 150 GeV	
	Background	Signal	Background	Signal
Pileup	$< 0.1\%$	0.4%	$< 0.1\%$	0.3%
Lepton reconstruction	$< 0.1\%$	0.6%	$< 0.1\%$	1.7%
Lepton identification and isolation	1.0%	1.4%	1.0%	1.3%
High p_{T} lepton	$< 0.1\%$	0.2%	$< 0.1\%$	3.4%
Muon momentum scale and resolution	$< 0.1\%$	0.3%	$< 0.1\%$	0.1%
L1 prefiring	$< 0.1\%$	0.4%	$< 0.1\%$	0.4%
Jet energy scale and resolution	$< 0.1\%$	1.0%	1.0%	0.4%
b tagging	$< 0.1\%$	0.9%	1.0%	0.5%
Jet modeling	6.0%	–	7.0%	–
Nonprompt	11.0%	–	9.0%	–
PDF	$< 0.1\%$	2.3%	$< 0.1\%$	1.3%
QCD scale	4.0%	2.8%	5%	1.4%
Initial- and final-state radiation	–	7.6%	–	1.0%

- **Maximum likelihood fit is dominated by statistical uncertainties**