Search for charged lepton flavor violation in tq$\mu\tau$ interaction at 13 TeV in CMS

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on behalf of the CMS Collaboration

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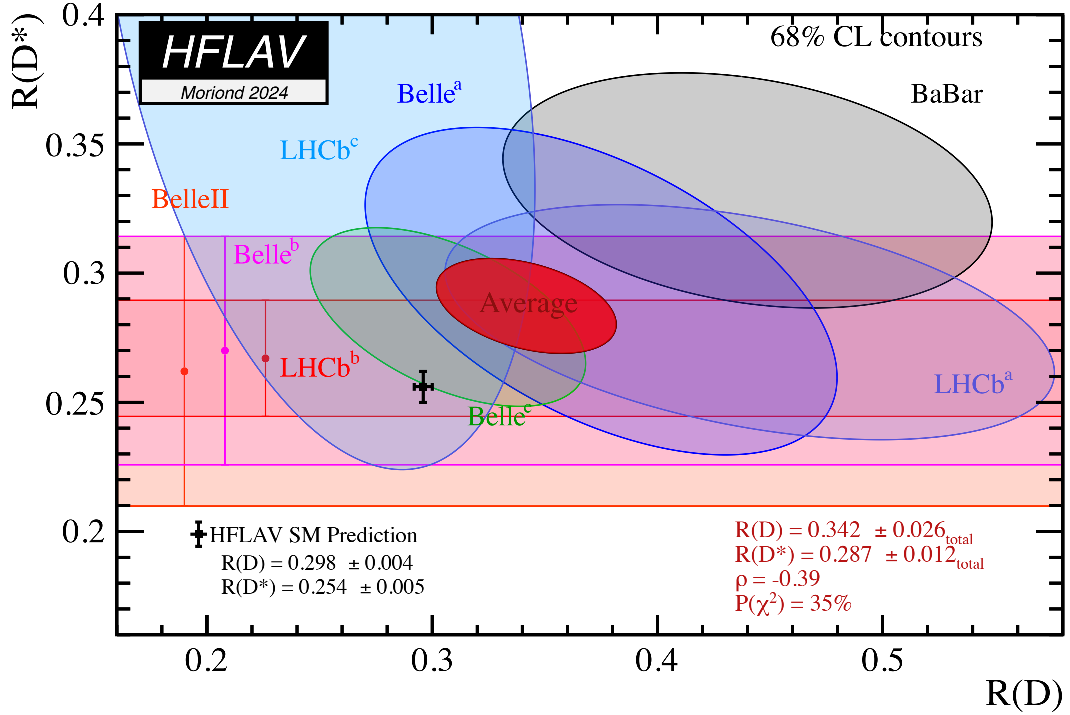
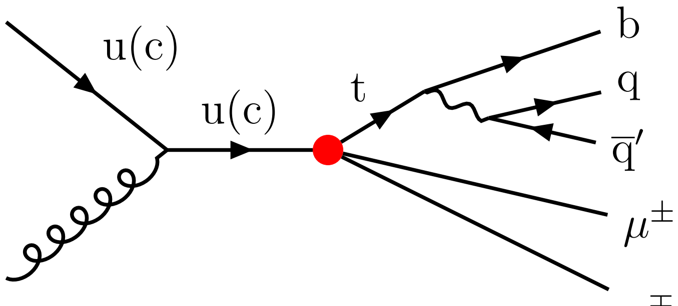
Introduction

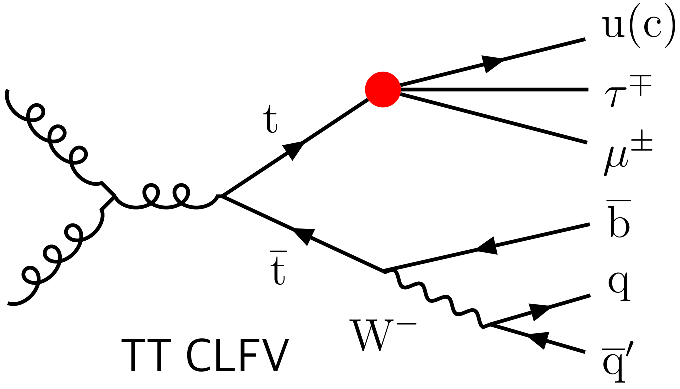
$$R\left(D^{(*)}\right) \equiv \frac{\mathrm{BF}\left(B \to D^{(*)}\tau\nu\right)}{\mathrm{BF}\left(B \to D^{(*)}\ell\nu\right)}$$ link

- Why CLFV?
  - Deviations of R(D), R(D*), and R(D)-R(D*) from SM ~ 1.6, 2.5, and 3.31σ, respectively
  - Tensions may hint CLFV interactions involving τ lepton
  - Chance to probe CLFV in top quark interactions
- Signal events are modeled with EFT framework
  - Dim-6 four-fermion operators are considered
  - Further categorized by their Lorentz structure





ST CLFV



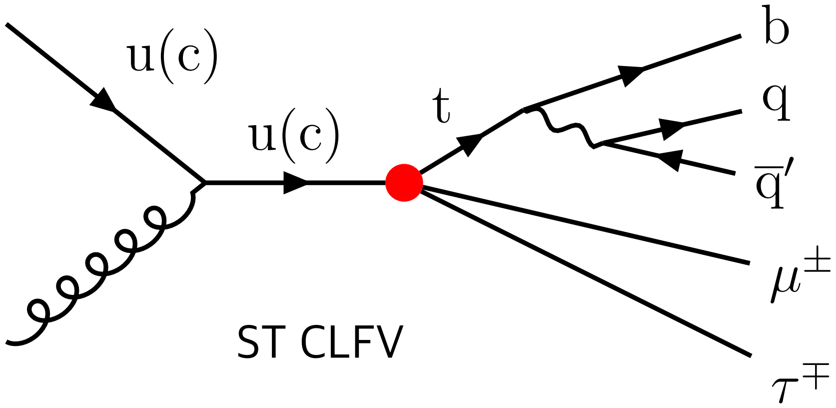
TT CLFV

Structure	Operator	Definition	Wilson coefficient
Scalar	$O^{1(ijkl)}_{\ell equ}$	$(\bar{\ell}_i e_j)\varepsilon(\bar{q}_k u_l)$	$C_{\ell equ1}$
Vector	$O^{1(ijkl)}_{\ell q} = O_{\ell q}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{q}_k\gamma^\mu q_l)$	$C_{\ell q}$
	$O^{(ijkl)}_{\ell u}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{u}_k\gamma^\mu u_l)$	$C_{\ell u}$
	$O^{(ijkl)}_{eq}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l)$	C_{eq}
	$O^{(ijkl)}_{eu}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	C_{eu}
Tensor	$O^{3(ijkl)}_{\ell equ}$	$(\bar{\ell}_i\sigma^{\mu\nu}\ell_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu}u_l)$	$C_{\ell equ3}$

- Further overview of flavor violation was covered by M. Watson

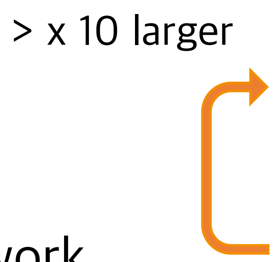
Analysis strategy

- CMS Run 2 dataset corresponding to L = 138 fb^{-1}
  - Events are collected with a set of single muon triggers



- CLFV signals with distinctive kinematics
  - OS $\mu\tau$ pair + jets from hadronic top quark
  - Higher cross sections in u-quark channel ST CLFV
  - ST CLFV signals are characterized by highly energetic μ and τ

- Strategy
  - Sensitivity on signals driven by ST CLFV
  - Optimize selections + reconstruct top quark
  - Signal discrimination using Deep Neural Network
  - Set limits if there is no significant excess



Process	Lorentz structure	Cross sections (fb)
ST CLFV tu$\mu\tau$	Scalar	59.14
	Vector	276.1
	Tensor	1272
ST CLFV tc$\mu\tau$	Scalar	3.74
	Vector	19.51
	Tensor	96.18
TT CLFV tq$\mu\tau$	Scalar	2.69
	Vector	21.5
	Tensor	129.0

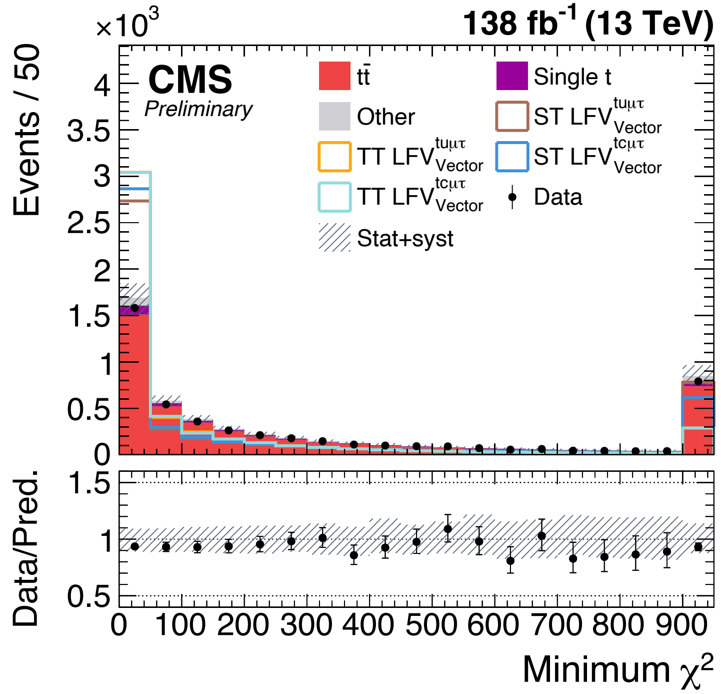
Selections and top quark reconstruction

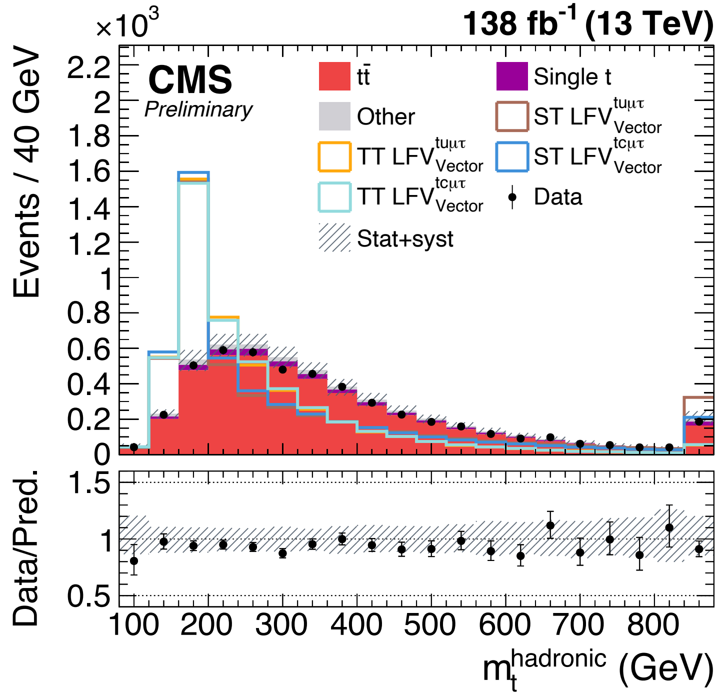
- Events are selected by requiring
  - One isolated μ, p_T > 50 GeV
  - One τ_h, p_T > 40 GeV, identified with DeepTau discriminator, ~ 50, 98, and > 99% of target efficiency vs jet, e, and μ
  - Oppositely charged μ and τ_h
  - At leaset 3 jets, including one b-tagged jet

- A hadronic top quark is reconstructed targeting ST CLFV while the main background component is dileptonic $t\bar{t}$
  - Determine origin of the three jets by minimizing χ^2

$$\chi^2 = \left(\frac{m_{\mathrm{t}} - m_{\mathrm{bjj'}}}{\sigma_{\mathrm{t}}}\right)^2 + \left(\frac{m_{\mathrm{W}} - m_{\mathrm{jj'}}}{\sigma_{\mathrm{W}}}\right)^2$$

  - Leads to a well discriminated top mass distribution





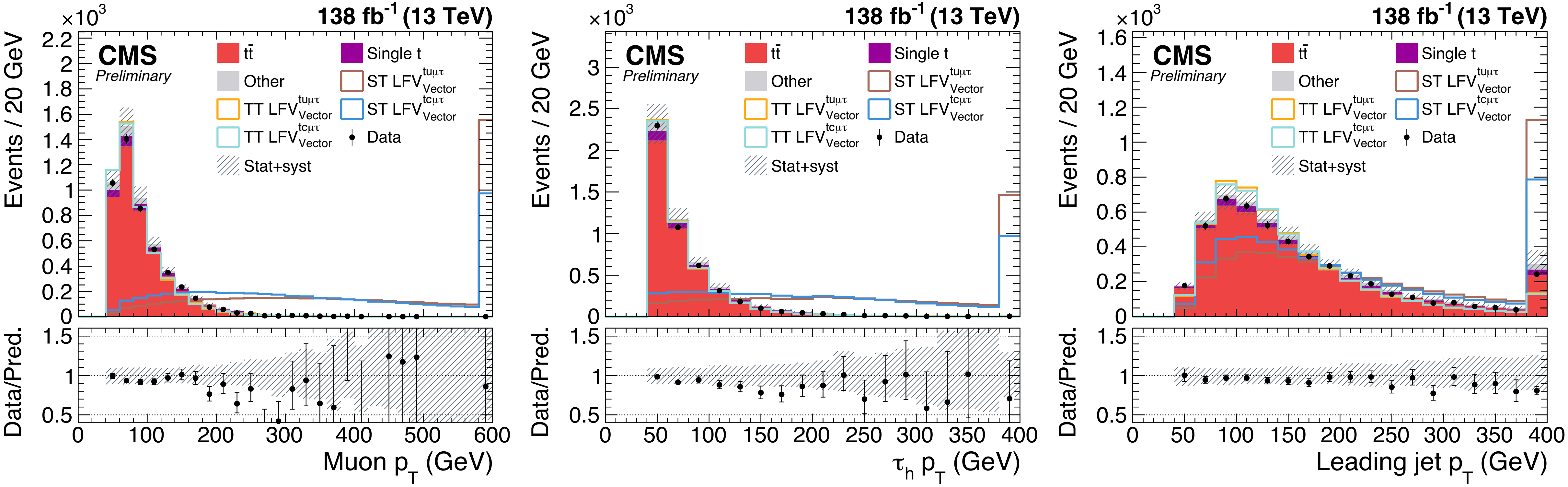
Background estimation

- Rate of jet -> τ_h misidentified events is non-negligible
- Normalizations of such backgrounds are calculated using a data-driven method
  - ABCD method is utilized by inverting τ_h ID and $\mu\tau$ charge, for each year and tau decay mode

$$\mathrm{SF} = \frac{N^D_{\text{mis-ID}}}{N^D_{\text{tot. bkg.}} - N^D_{\text{genuine}}}$$

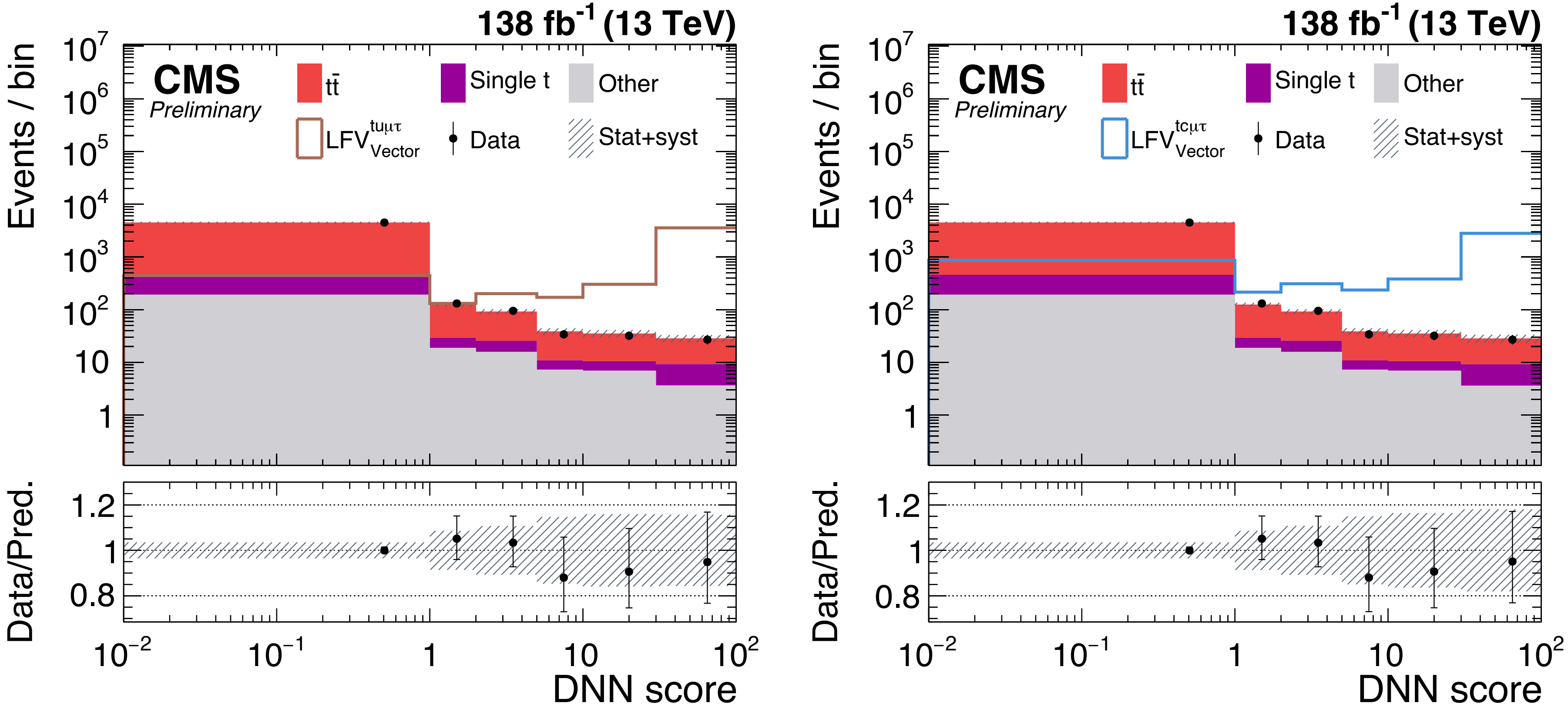
where $N^i = N^i_{\text{obs}} - N^i_{\text{genuine}}$, and

$$N^{\mathrm{D}}_{\text{mis-ID}} = N^{\mathrm{C}}\frac{N^{\mathrm{B}}}{N^{\mathrm{A}}} = N(\text{OS looseID}) \times \frac{N(\text{SS tight ID})}{N(\text{SS looseID})}$$



DNN for signal discrimination

- Utilized a multiclass DNN classifier: Discrimination of ST CLFV / TT CLFV / background
  - Inputs: Kinematic variables of μ, τ, jets, $\mu + \tau$, MET, and top reconstruction results (28 in total)
  - Final distribution is constructed by $\mathrm{DNN\,score} = \dfrac{0.1p(\mathrm{TT\ CLFV}) + 0.9p(\mathrm{ST\ CLFV})}{p(\mathrm{background})}$
- Post-fit distrubitions for the vector operators with $\mathrm{tu}\mu\tau$ (left) and $\mathrm{tc}\mu\tau$ (right) for

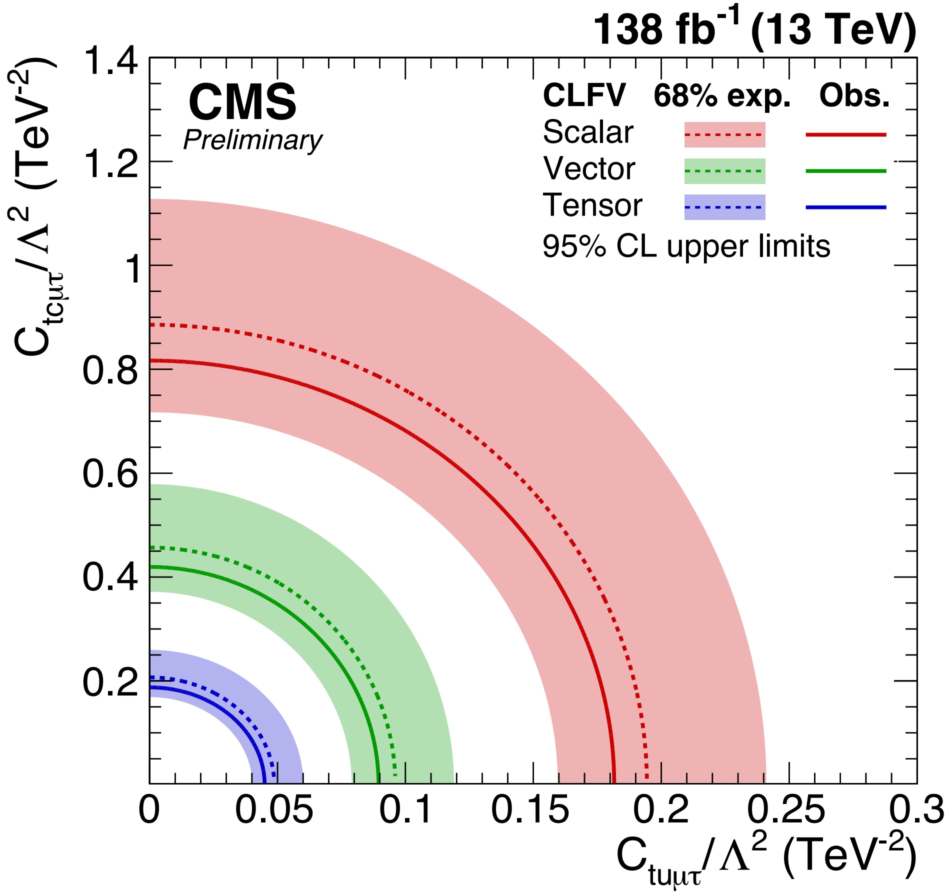


Results

- Set the most stringent limits on the $tq\mu\tau$ CLFV interactions
  - Branching fractions range from 10^{-6} to 10^{-8}
  - Exclusion contours are calculated from the tabulated results

Observed (expected) limits and 68% interval containing expected limits

Interaction	Type	σ [fb]	$C_{tq\mu\tau}/\Lambda^2$ [TeV^{-2}]	$\mathcal{B}(t \to \mu\tau q)[10^{-6}]$
$tu\mu\tau$	Scalar	2.039 (2.337) [1.574, 3.594]	0.182 (0.194) [0.16, 0.241]	0.040 (0.046) [0.031, 0.071]
	Vector	2.384 (2.746) [1.857, 4.213]	0.09 (0.096) [0.079, 0.119]	0.078 (0.09) [0.061, 0.138]
	Tensor	2.834 (3.326) [2.257, 5.063]	0.045 (0.049) [0.04, 0.06]	0.118 (0.138) [0.094, 0.211]
$tc\mu\tau$	Scalar	4.269 (5.02) [3.291, 8.142]	0.817 (0.886) [0.717, 1.128]	0.81 (0.953) [0.625, 1.545]
	Vector	7.213 (8.552) [5.663, 13.734]	0.419 (0.457) [0.372, 0.579]	1.71 (2.027) [1.342, 3.255]
	Tensor	7.927 (9.633) [6.427, 15.2]	0.188 (0.207) [0.169, 0.26]	2.052 (2.494) [1.664, 3.936]

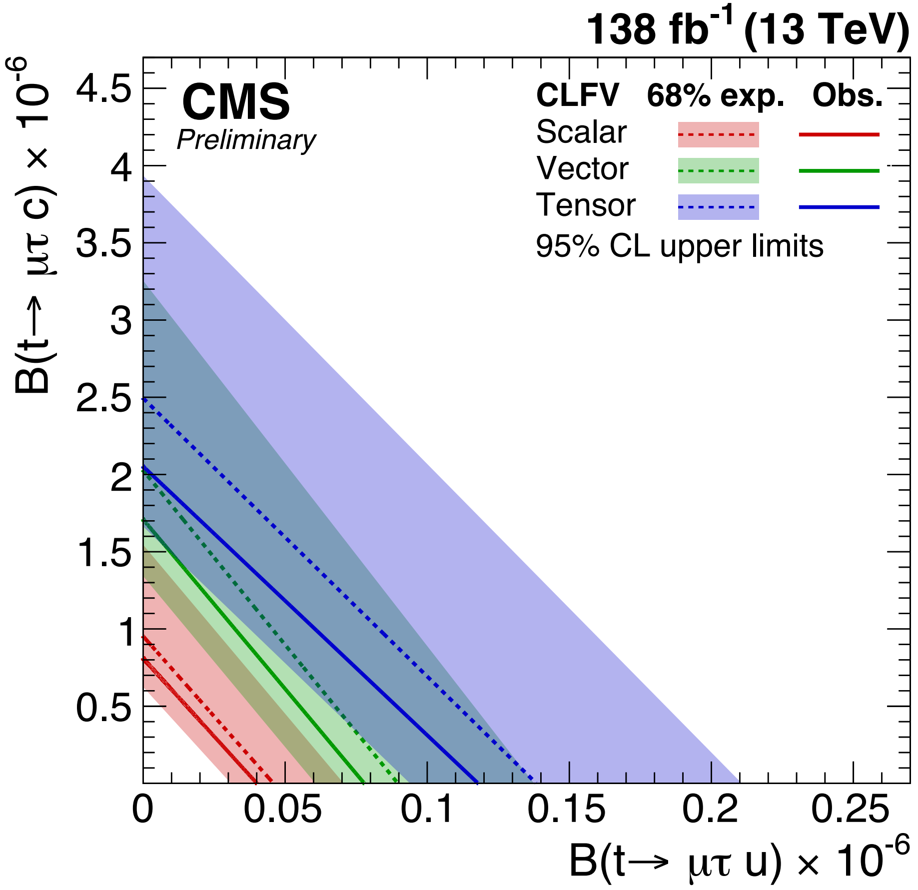


Summary

- Presented a search for CLFV in $tq\mu\tau$ interactions at 13 TeV
  - Signals are modeled using an EFT framework
  - DNN is used to further discriminate signals from background prediction

- No significant excess is found, an upper limits are set
  - $B(t \to \mu\tau u) \sim 10^{-7}$–$10^{-8}$
  - $B(t \to \mu\tau c) \sim 10^{-6}$–$10^{-7}$

- Complements CMS $e\mu$ channel analysis*
- Set more than × 2 better limits on branching fractions compared to ATLAS results†



*JHEP 06 (2022) 082, CMS-TOP-22-005 (sub. to PRD)
†Phys. Rev. D 110 (2024) 012014


Thanks!

Backup

Pre-fit yields

- Pre-fit expected event yields for the data, simulated backgrounds and signals
  - Signals are normalized by their cross section and luminosity (138 fb^{-1})

Process	Event yield
ST CLFV tu$\mu\tau$ Scalar	535 $\pm$ 1
ST CLFV tu$\mu\tau$ Vector	2327 $\pm$ 3
ST CLFV tu$\mu\tau$ Tensor	9909 $\pm$ 13
ST CLFV tc$\mu\tau$ Scalar	32 $\pm$ $<$ 1
ST CLFV tc$\mu\tau$ Vector	129 $\pm$ $<$ 1
ST CLFV tc$\mu\tau$ Tensor	701 $\pm$ 1
TT CLFV tu$\mu\tau$ Scalar	1.1 $\pm$ $<$ 0.1
TT CLFV tu$\mu\tau$ Vector	8.2 $\pm$ $<$ 0.1
TT CLFV tu$\mu\tau$ Tensor	48 $\pm$ $<$ 1
TT CLFV tc$\mu\tau$ Scalar	1.1 $\pm$ $<$ 0.1
TT CLFV tc$\mu\tau$ Vector	7.9 $\pm$ $<$ 0.1
TT CLFV tc$\mu\tau$ Tensor	45 $\pm$ $<$ 1
$t\bar{t}$	4573 $\pm$ 13
Single Top	306 $\pm$ 9
Other	258 $\pm$ 5
Total $\pm$ (stat)	5136 $\pm$ 17
Data	4810
Data / Background prediction	0.94 $\pm$ 0.01

DNN input variables

- 28 input variables for DNN training and evaluation are listed

Group	Variables	Description
Muon (μ)	$p_{T\mu}$, η_μ	p_T and η of selected muon
Tau (τ_h)	$p_{T\tau_h}$, η_{τ_h}, m_{τ_h}	p_T, η, and mass of selected τ_h
Muon+Tau ($\mu\tau_h$)	$m_{\mu\tau_h}$, $\Delta\eta_{\mu\tau_h}$, $\Delta\phi_{\mu\tau_h}$, $\Delta R_{\mu\tau_h}$	Mass and angular differences of $\mu\tau_h$ system
Jets	p_{T1}, p_{T2}, p_{T3}	p_T of jets ordered in increasing p_T
	η_1, η_2, η_3	η of jets ordered in increasing p_T
	m_1, m_2, m_3	Mass of jets ordered in increasing p_T
	b_1, b_2, b_3	b tagging discriminant of jets ordered in increasing p_T
Event	p_T^{miss}	Missing transverse momentum
t and W reco.	χ^2, $m_{bjj'}$, $m_{jj'}$	$minimum \chi^2$ and reconstructed t and W masses
	$\Delta\eta_{jj'}$, $\Delta\phi_{jj'}$, $\Delta R_{jj'}$	Angular differences of jets used in W reco.

Systematic uncertainties

- Experimental uncertainties
  - Luminosity: 1.6% for Run 2
  - Pileup
  - Muon: ID, isolation, trigger (as well as L1 prefiring), high-pt extrapolation 0-10% for [200, 1000] GeV
  - Tau: energy scale and ID
    - Separated sources are used for the vsJet ID
    - Dedicated vsJet ID uncertainties for pT > 140 GeV
  - Jet energy scale (JES) and resolution (JER)
  - b tagging shape correction
- Background estimation
  - Statistical uncertainty from SF calculation
  - Closure between data and MC driven SFs (2-3% on total pre-fit yield)
- Modeling uncertainties
  - Background cross sections
  - ME scales (muR and muF)
  - PS scales (ISR, FSR)
  - ME-PS matching (hdamp)
  - Underlying events (PY8 tune)
  - PDF (NNPDF31, 100 eigenvector + aS)
  - top pT reweighting