Probes of flavour symmetry and violation with top quarks in ATLAS and CMS

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Top 2024 Workshop
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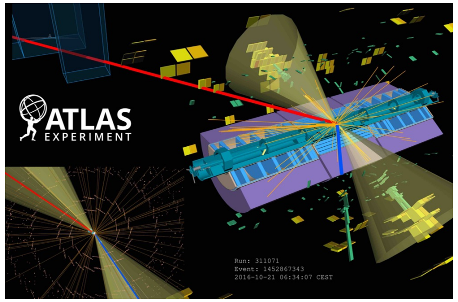
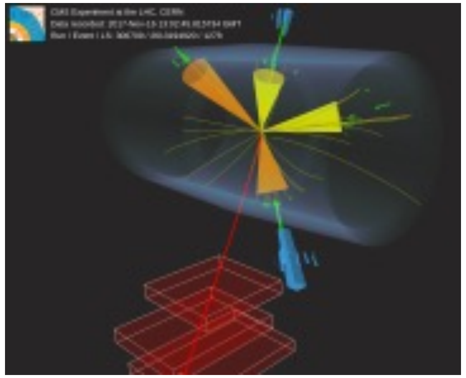
Introduction and overview

- Test universality of couplings to leptons and possible violations of the SM using top quarks





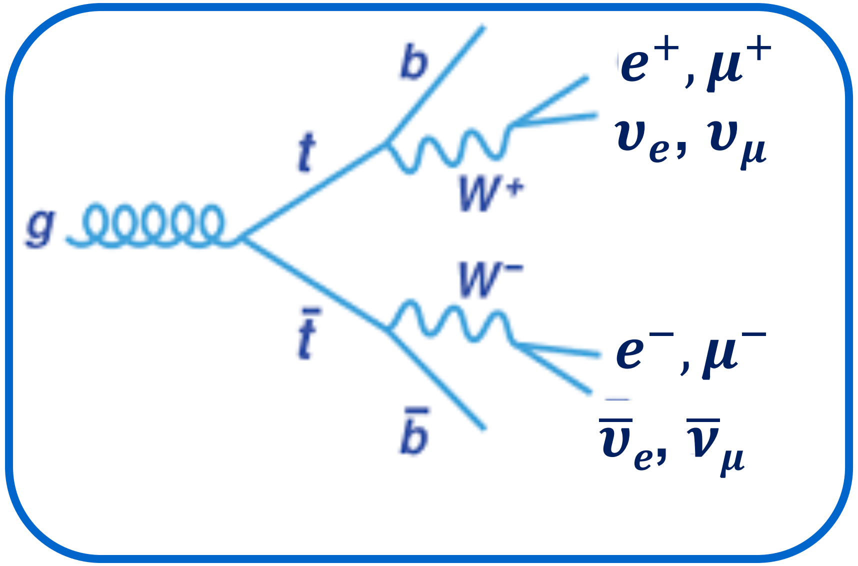
- New results in the **last year**:
  - Lepton flavour universality e/μ
  - Searches for charged-lepton flavour violation (eμ trilepton, $\mu\tau$ trilepton, $\mu\tau$ hadronic New!)
  - Search for baryon number violation
  - Search for heavy right-handed Majorana neutrinos New!

- All results shown here use the full Run 2 datasets $\mathcal{L}$ = 138-140 fb^{-1}, $\sqrt{s}$ = 13 TeV
- Detailed tables of results are given in the backup slides

Lepton flavour universality e/μ

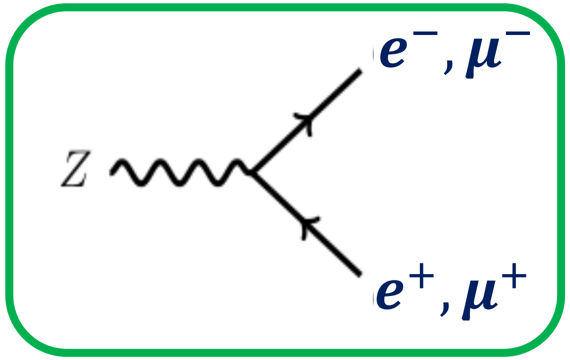
arxiv:2403.02133, accepted by EPJC

- Lepton flavour universality (LFU) is a fundamental axiom of SM:
  - Couplings of charged leptons e, μ and τ to W, Z are independent of the lepton masses
- Hints of departures from LFU in various sectors
- Test at high momentum in W bosons from top



- Overall scheme
  - Measure ratio

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} \cdot \sqrt{\frac{\mathcal{B}(Z \to ee)}{\mathcal{B}(Z \to \mu\mu)}}$$

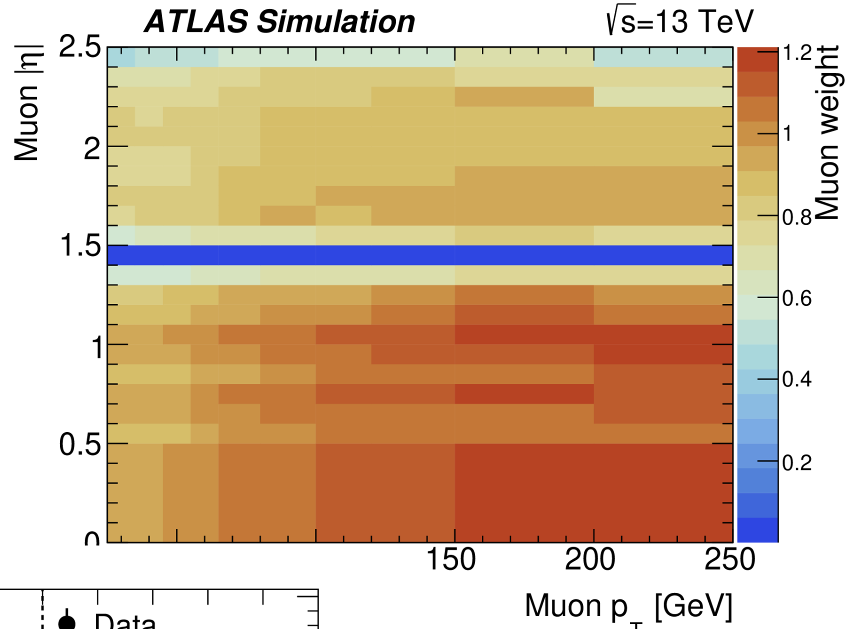


  - Ratio reduces impact of lepton identification uncertainties
  - Select $t\bar{t}$ events with $e\mu$ / ee / $\mu\mu$ and 1 or 2 b-tagged jets
  - Select inclusive Z events with ee / $\mu\mu$

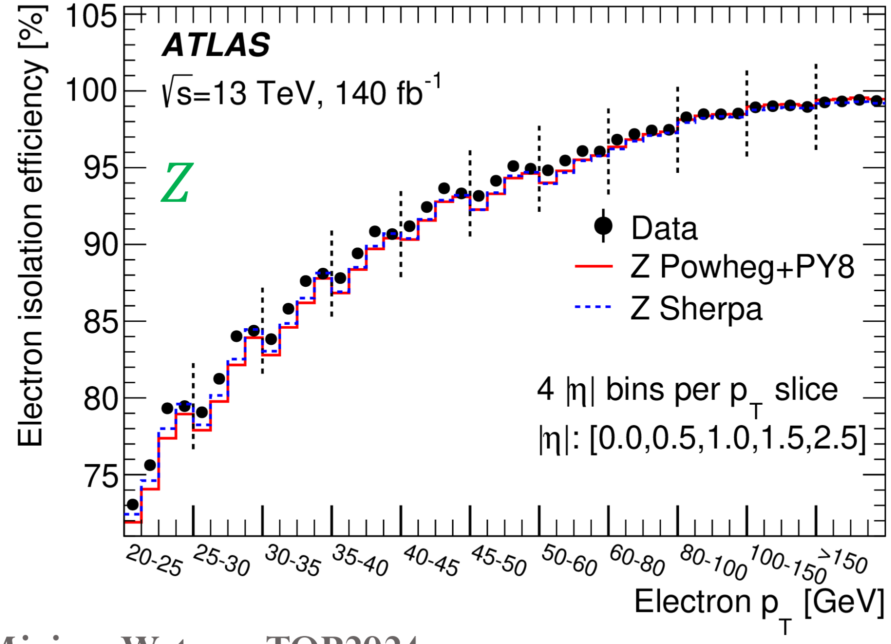
Lepton flavour universality e/μ

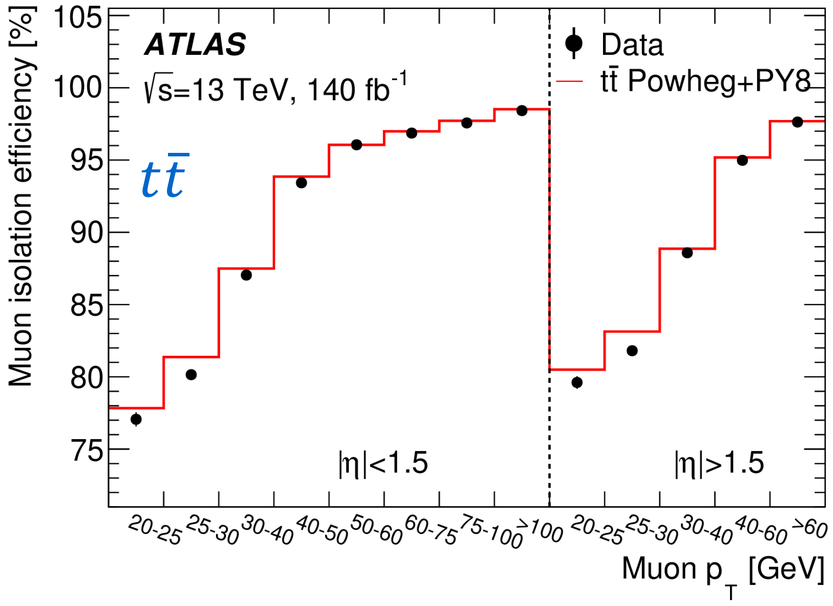
arxiv:2403.02133, accepted by EPJC

- Apply muon reweighting in (p_T, $|\eta|$) to reduce kinematic differences between e and μ



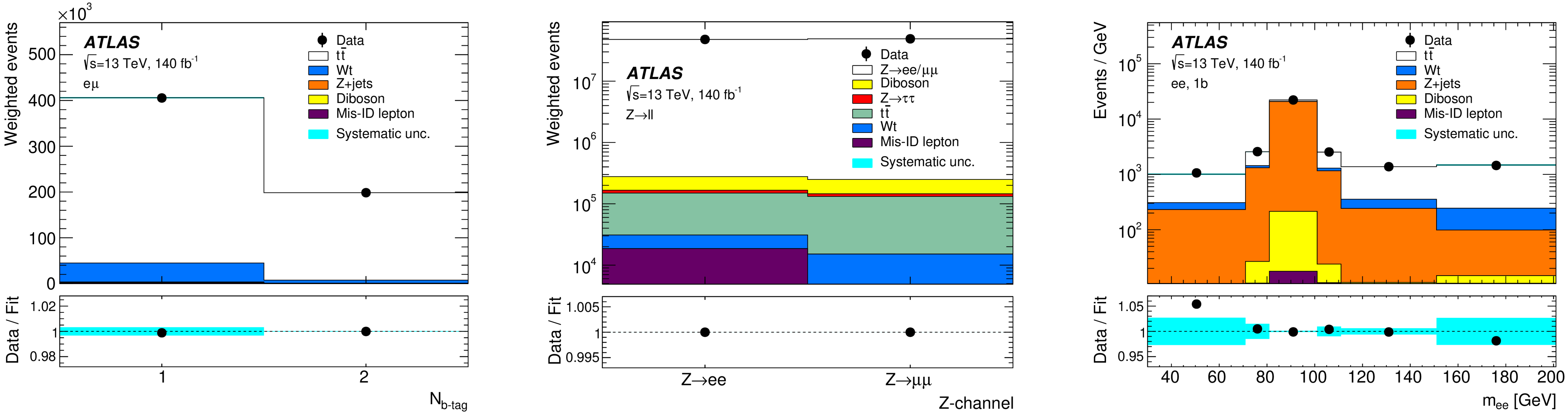
- In-situ measurement of lepton isolation efficiencies
- Particularly important due to different $t\bar{t}$ and Z environments
- Measure efficiency vs lepton p_T, $|\eta|$





Lepton flavour universality e/μ

arxiv:2403.02133, accepted by EPJC



- Simultaneous maximum likelihood fit to $t\bar{t}$ events ("b-tag counting method") and Z counts:
  - Yields in $t\bar{t} \to e\mu\ 1b/2b$ and $Z{\to}ee/\mu\mu$ regions
  - $m_{\ell\ell}$ spectrum in $t\bar{t}{\to}ee/\mu\mu\ 1b/2b$ regions
- Parametrise fitted yields using deviations in BR

Average predicted BR in SM

$$\frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)}$$

Deviations

$$\frac{\mathcal{B}(Z \to \mu\mu)}{\mathcal{B}(Z \to ee)} = \frac{\overline{Z}(1+\Delta_Z)}{\overline{Z}(1-\Delta_Z)}$$

Lepton flavour universality e/μ

arxiv:2403.02133, accepted by EPJC

ATLAS EXPERIMENT

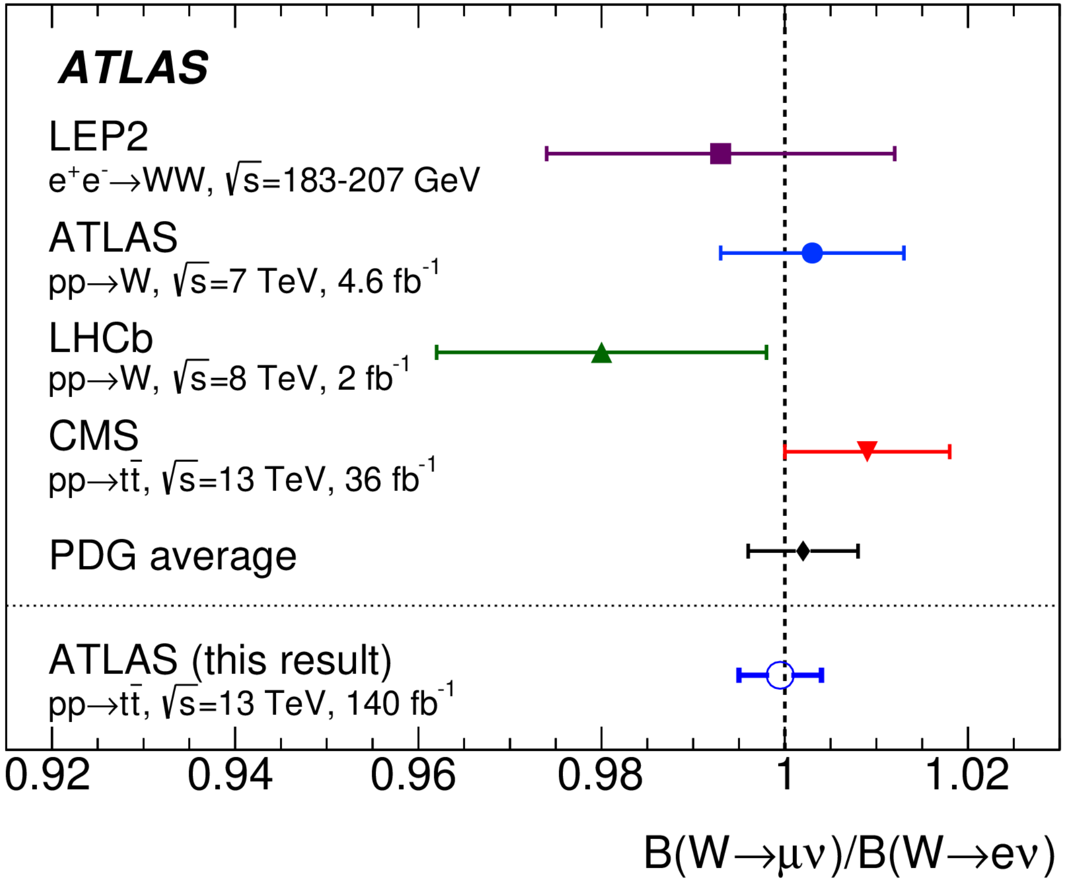
- Apply the precise external LEP+SLD Z measurement to the fitted ratio:

$$R^{\mu\mu/ee}_{Z\text{-ext}} = 1.0009 \pm 0.0028$$

$$R^{\mu/e}_{W} = R^{\mu/e}_{WZ}\sqrt{R^{\mu\mu/ee}_{Z-\text{ext}}}$$

$$= 0.9995 \pm 0.0022\,(\text{stat}) \pm 0.0036\,(\text{syst}) \pm 0.0014\,(\text{ext})$$

$$\mathcal{B}(W \to \mu\nu)/\mathcal{B}(W \to e\nu) = 0.9995 \pm 0.0045$$



- Most precise e/μ universality test (0.45%)
- Improves on the previous PDG average
- No evidence for LFU violation

- Measurement dominated by systematic uncertainties: PDF, modelling, lepton uncertainties

CMS result Phys. Rev. D **105** (2022) 072008

Charged lepton flavour violation (cLFV)

- cLFV via neutrino oscillations is highly suppressed (BR~10^{-55})
- Some BSM processes (leptoquarks, SUSY, 2HDM) involve cLFV
- Experimental evidence for cLFV → indication of BSM physics
  - Model-independent EFT approach
  - Mass scale of new physics $\Lambda \gg$ LHC energy scale
  - Limits on vector, scalar and tensor tq$\ell\ell$' interactions from dimension-6 operators

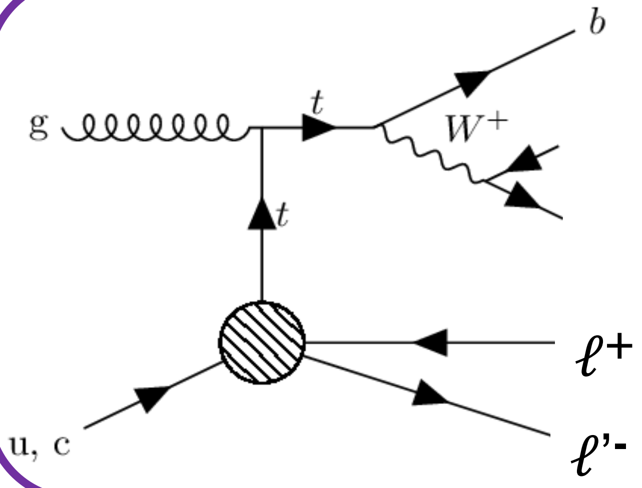
Wilson coefficients

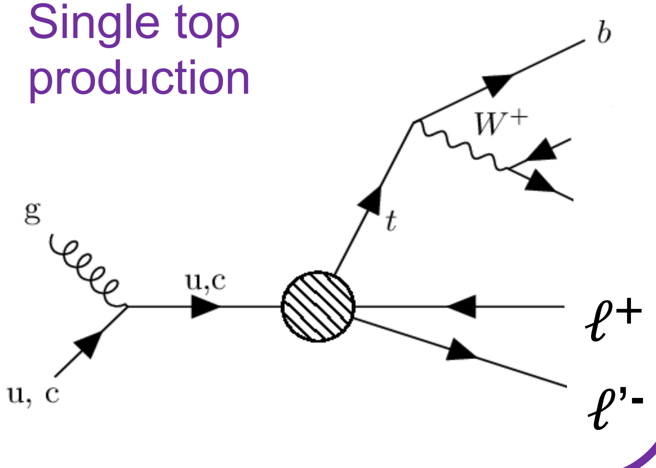
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{x} \frac{c_x}{\Lambda^2} O_x + \cdots$$

Operators

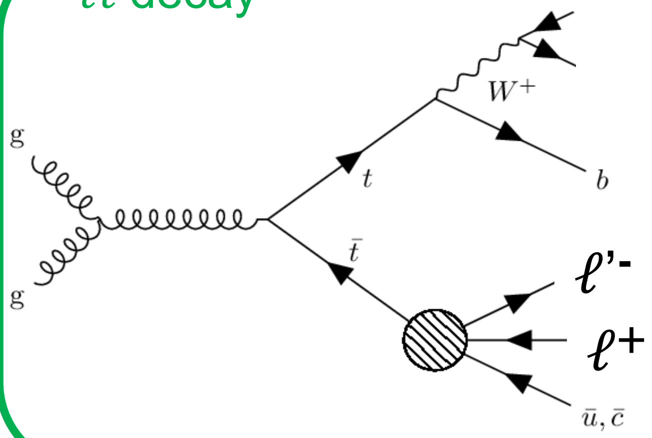
Consider production and decay channels

Single top production

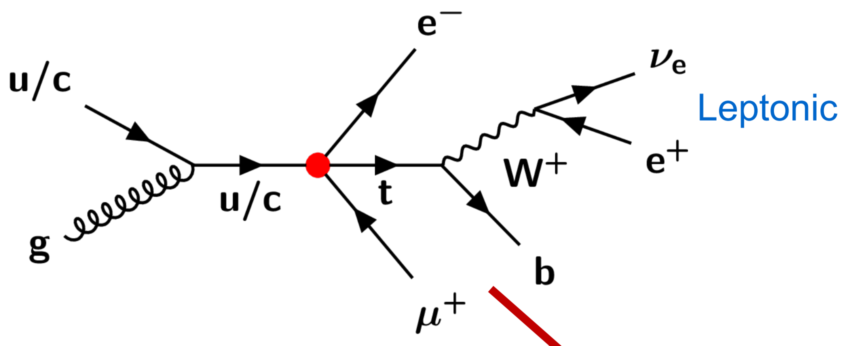


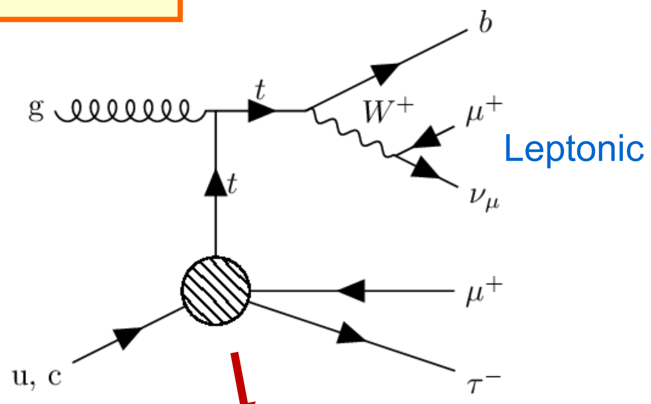


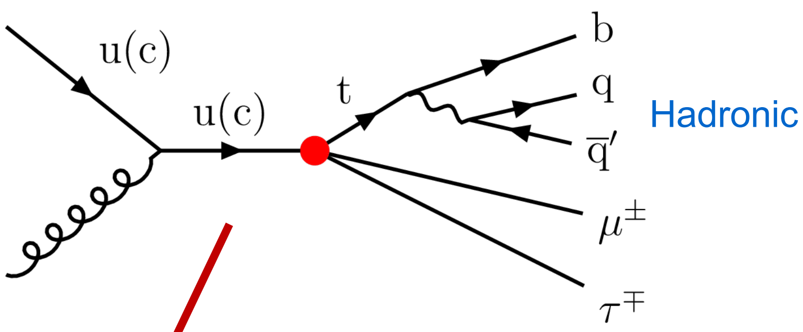
$t\bar{t}$ decay



Charged lepton flavour violation (cLFV)





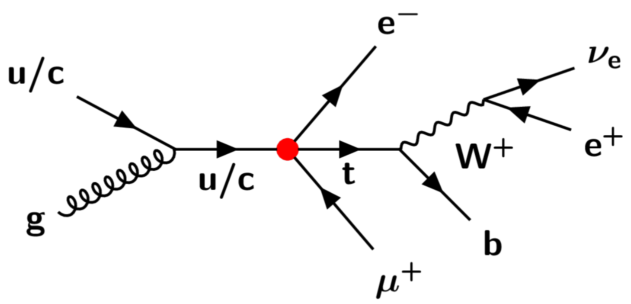


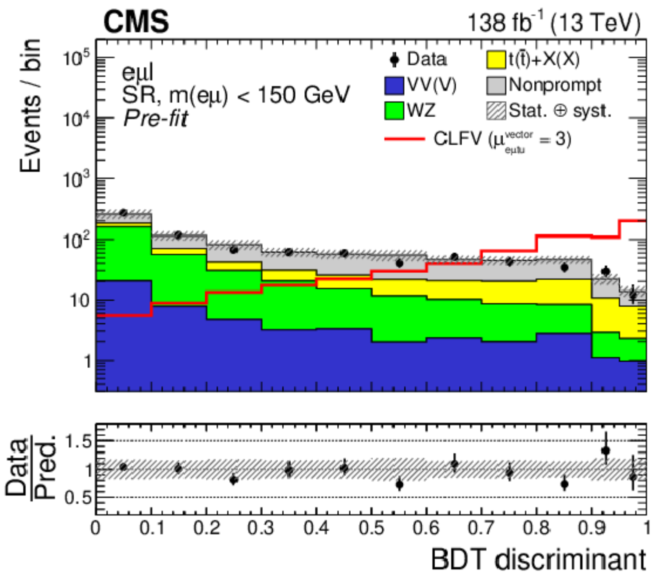
Analysis	eμ trilepton (CMS)	μτ trilepton (ATLAS EXPERIMENT)	μτ hadronic (CMS) New!
cLFV vertex	teμq (q=u,c)	tμτq (q=u,c)	tμτq (q=u,c)
cLFV leptons	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\tau^{\mp}$	$\mu^{\pm}\tau^{\mp}$
SM W decay	$e^{\pm}$ or $\mu^{\pm}$ (+ν)	$\mu^{\pm}$ (+ν)	$q\bar{q}'$
Signature	$e^{\pm}\mu^{\mp}\ell$	$\mu^{\pm}\mu^{\pm}\tau_{had}^{\mp}$	$\mu^{\pm}\tau_{had}^{\mp}jj$
+ b-tagged jets	1b	1b	1b
All jets	1 or 2	≥ 1	≥ 3
Non-prompt ℓ	Matrix method e, μ	τ scale factors, μ CR	τ ABCD method
S/B separation	BDT	H_T	DNN

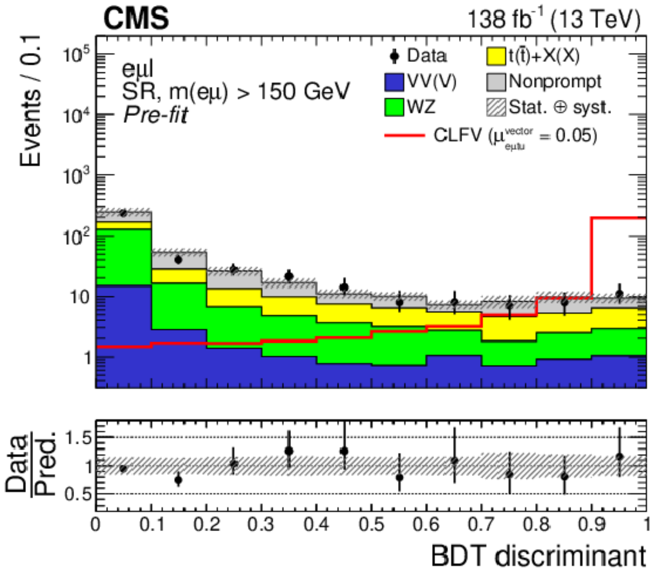
- Production and decay channels included
- Profile likehood fits with systematic uncertainties as nuisance parameters

cLFV in eμ trilepton channel

arxiv:2312.03199, submitted to PRD







- Boosted decision trees (BDT) used to separate background from signal
- Trained in 2 regions
  - m(eμ) < 150 GeV, enriched in cLFV top decay
  - m(eμ) > 150 GeV, enriched in cLFV production

- Binned likelihood fit to BDT discriminant
- Production+decay processes combined
- Each of 6 Wilson coefficients considered separately

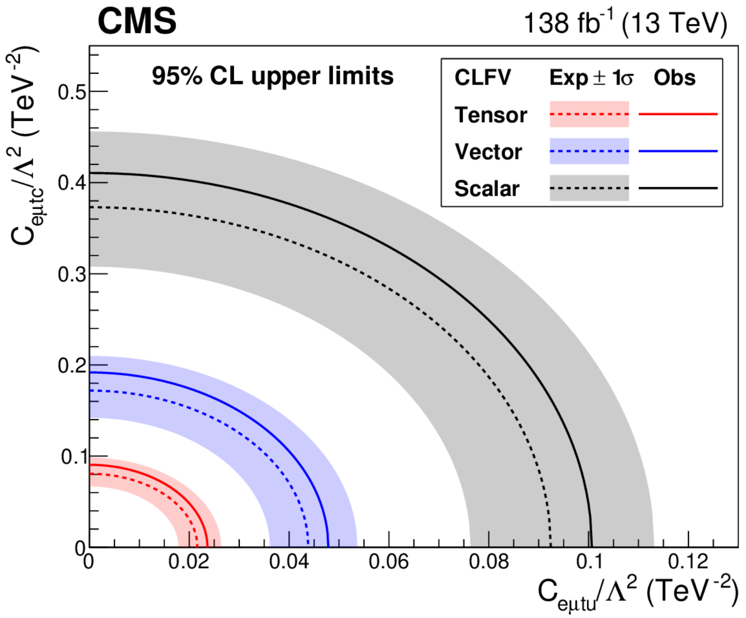
cLFV in eμ trilepton channel

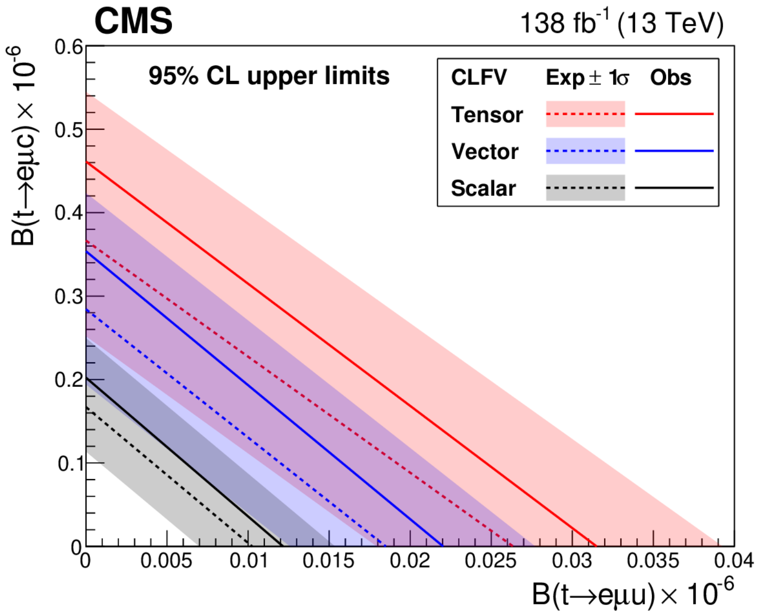
arxiv:2312.03199, submitted to PRD

- Extract 95% CL upper limits on signal strength μ, equivalent to $(C/\Lambda^2)^2$
- Convert to branching fractions, $B(t \rightarrow e\mu q)$ with q = u or c

Analysis	q	eμ trilepton
cLFV vertex		teμq (q=u,c)
c/Λ^2 [GeV^{-2}]	u	0.02-0.10
	c	0.09-0.42
BR($t \rightarrow qe\mu$) [10^{-6}]	u	0.012-0.032
	c	0.22-0.50

- No significant excess over SM
- Largest post-fit uncertainty from limited number of simulated events

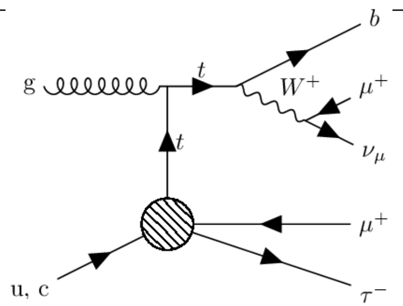




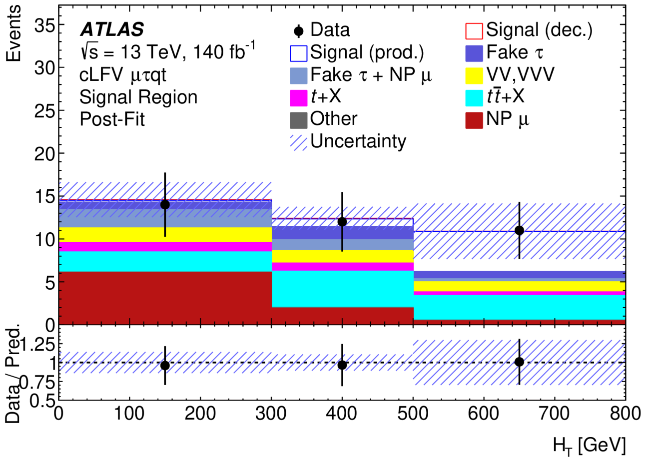
95% CL limits

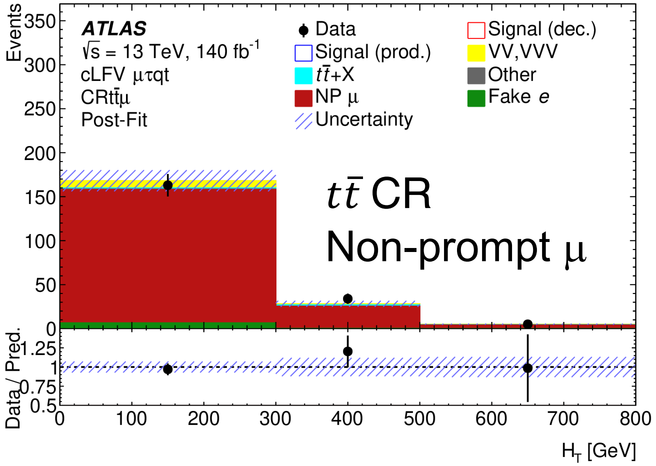
cLFV in $\mu\tau$ trilepton channel

Phys. Rev. D 110 (2024) 012014



- Fit regions binned in $H_T = \Sigma\, p_T(\text{leptons}) + p_T(\text{jets})$
- cLFV single-t production produces high-p_T leptons → high H_T
- No significant excess in data (1.6σ)
- Extract limits on effective coupling strengths
  - 7-41x better than previous indirect limits
  - Statistically limited
  - Largest systematics from signal modelling, $t\bar{t}W$ and diboson





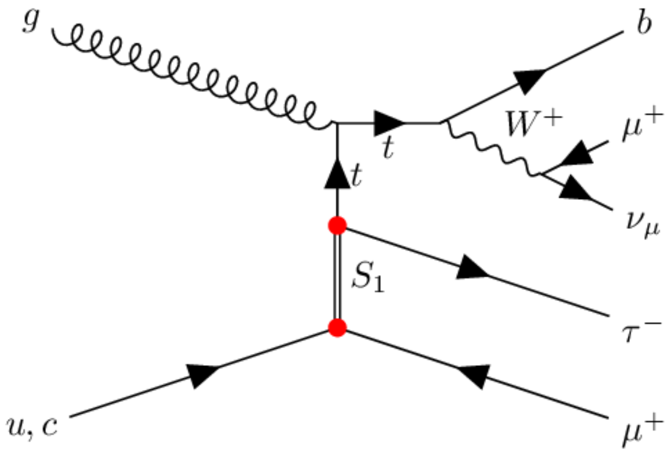
cLFV vertex		tμτq (q=u,c)
c/Λ^2 [GeV^{-2}]	u	0.10-0.44
	c	0.36-1.8
BR($t\to q\mu\tau$) [10^{-6}]	u	0.20-0.52
	c	3.4-6.7

95% CL limits

cLFV in μτ trilepton channel

Phys. Rev. D 110 (2024) 012014

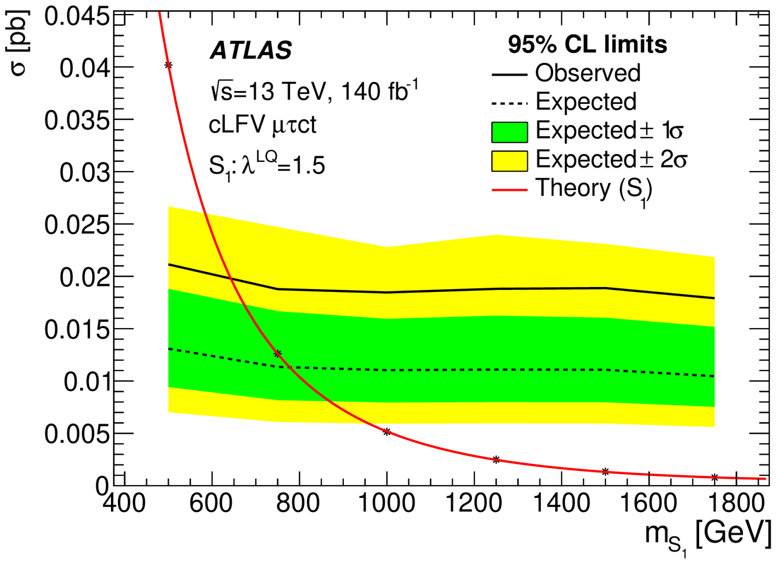
- Use same SR/CR to search for scalar leptoquark S_1
- Assume fixed hierarchical couplings, spanning generations

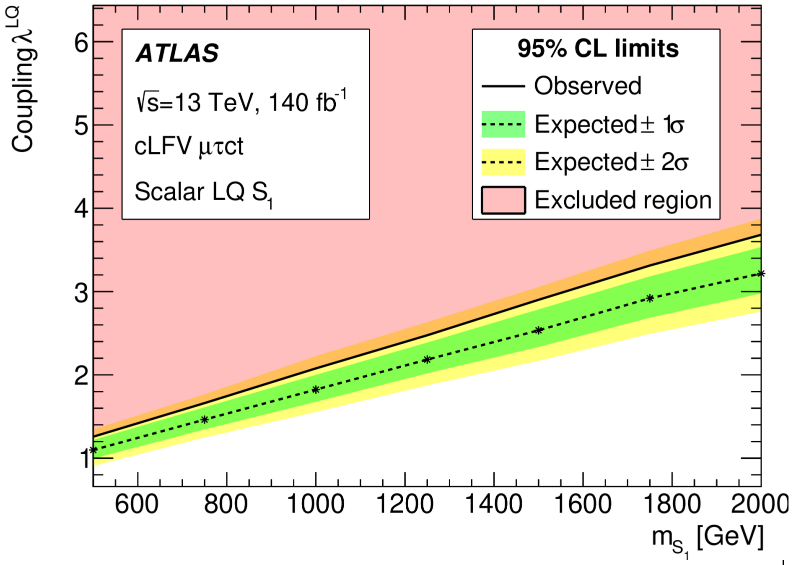


$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{LQ} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

1 coupling λ_{LQ},
1 LQ mass m_{S1}

- Limits are set on S_1 cross-section using profile-likelihood fit
- Upper 95% CL limits on LQ coupling strengths from λ_{LQ} = 1.3 to λ_{LQ} = 3.7 for masses 0.5 to 2.0 TeV

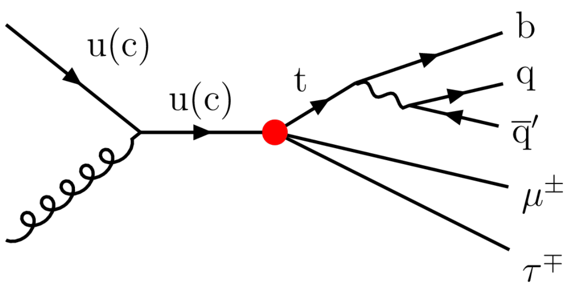




cLFV in μτ hadronic channel

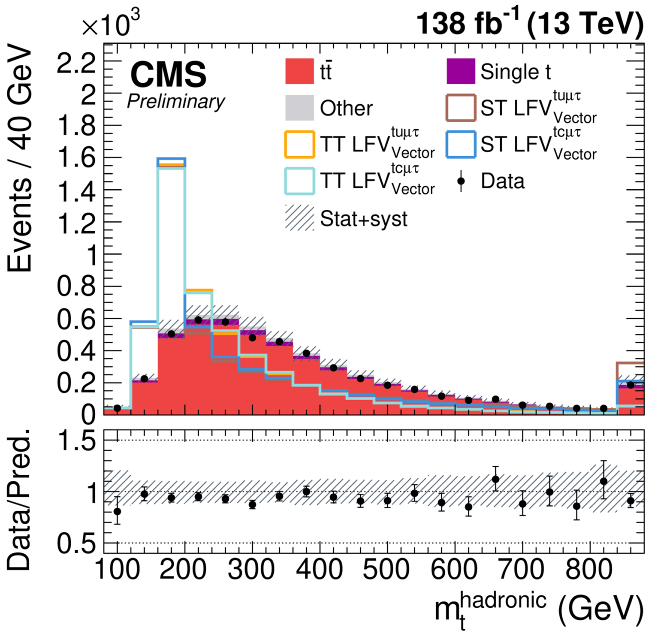
CMS-PAS-TOP-22-011

New!

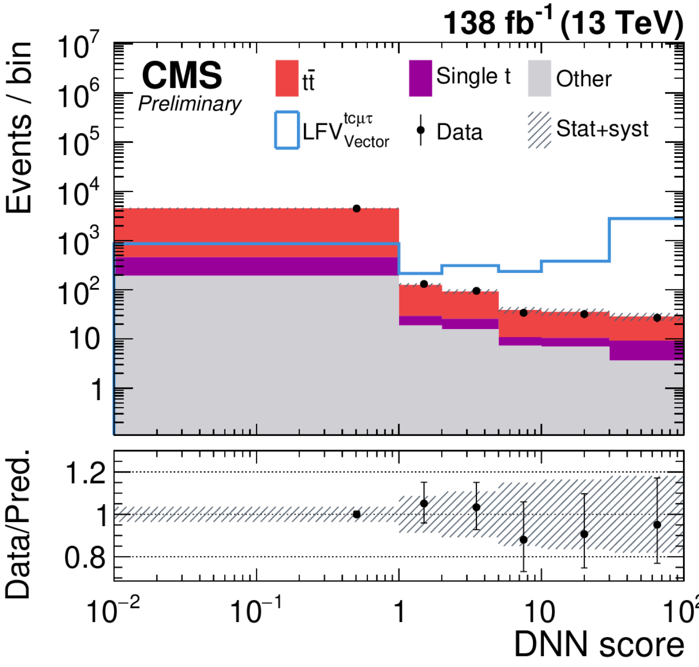


- Reconstruction of SM top and W mass
  - Background mostly from dileptonic $t\bar{t}$ channel
  - Hadronic decay reconstructed using χ^2

$$\chi^2 = \left(\frac{m_t - m_{bjj'}}{\sigma_t}\right)^2 + \left(\frac{m_W - m_{jj'}}{\sigma_W}\right)^2$$



- Multiclass deep neural network (DNN) to classify 3 nodes:
  - single top (ST) cLFV signal
  - $t\bar{t}$ (TT) cLFV signal
  - $t\bar{t}$ background events
- 28 kinematic variables, including individual particles and global features



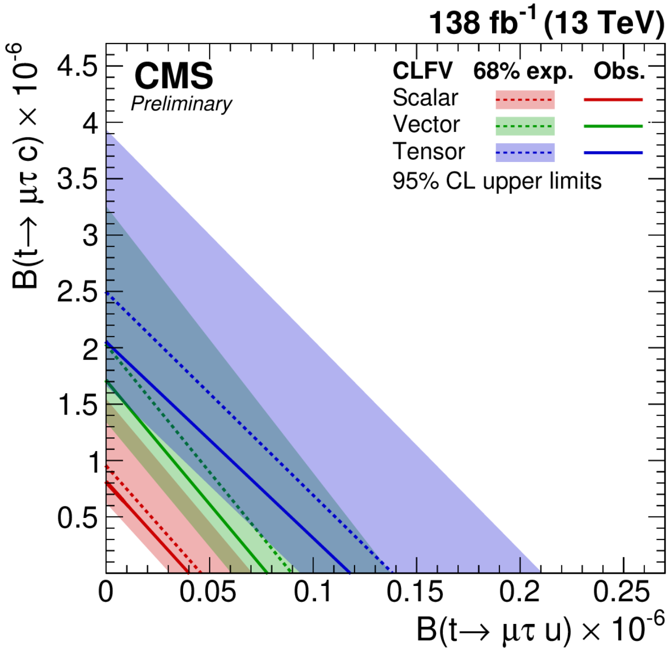
$$\text{DNN score} = \frac{0.1p(\text{TT CLFV}) + 0.9p(\text{ST CLFV})}{p(\text{background})}$$

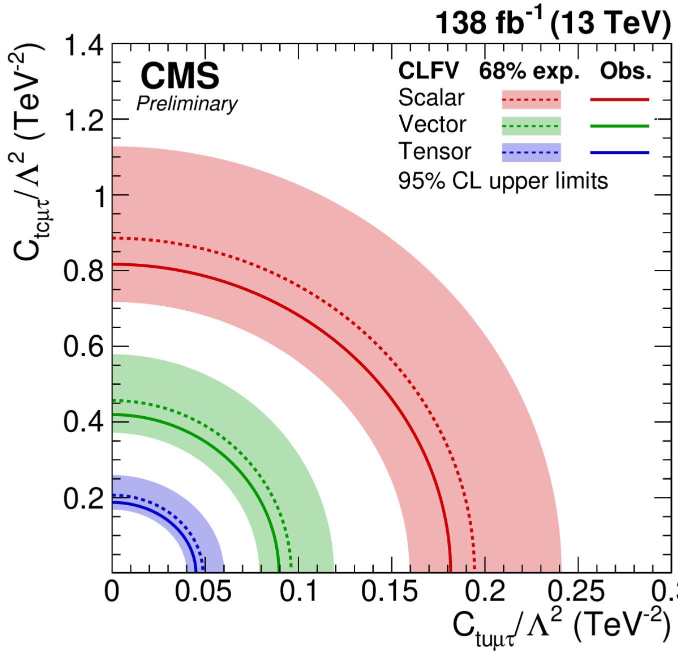
cLFV in $\mu\tau$ hadronic channel

CMS-PAS-TOP-22-011

- Data are found to be consistent with the standard model expectation.
- Upper limits at 95% CL are set for different interaction operators
- Converted into branching fractions for $t \rightarrow \mu\tau q$ process

- Improvement by factor ~2 on previous limits



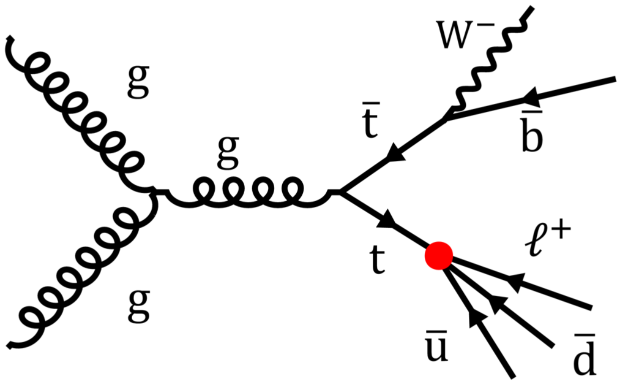


cLFV vertex		$t\mu\tau q$ (q=u,c)
c/Λ^2 [GeV^{-2}]	u	0.045–0.18
	c	0.19–0.82
BR($t\rightarrow q\mu\tau$) [10^{-6}]	u	0.04–0.12
	c	0.81–1.05

95% CL limits

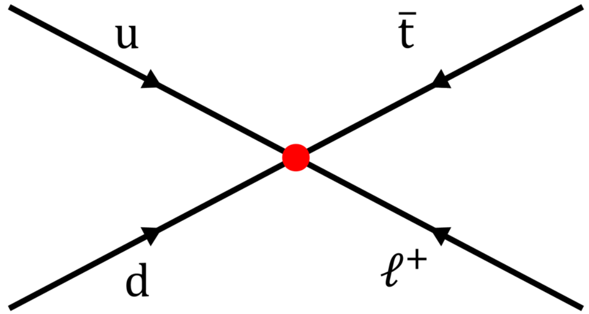
Baryon number violation (BNV)

Phys. Rev. Lett. 132 (2024) 241802



- Baryon number is conserved in SM but not a fundamental symmetry
- Can be violated by non-perturbative effects (small)
- BSM processes can enhance BNV
- tqq'ℓ vertex in 4-particle effective interaction → also LNV

- BNV contribution to single top quark production is included and dominates
- Multiple quark flavour combinations are considered: t(d,s,b)(u,c)ℓ
- Dilepton signature with W → $\ell\nu$ from the SM top



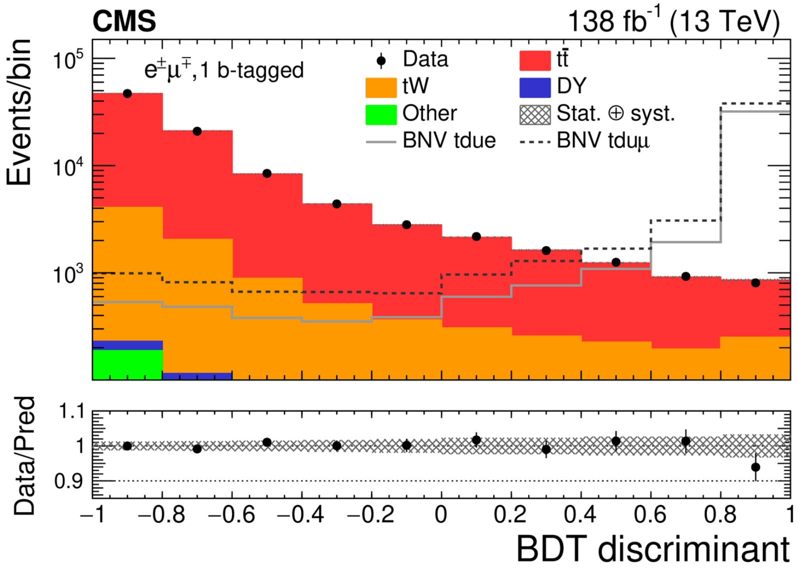
- Previous result: Phys. Lett. B 731 (2014) 173 [arXiv:1310.1618]
- 8 TeV, lepton+jets channel
- Only BNV in top quark decay

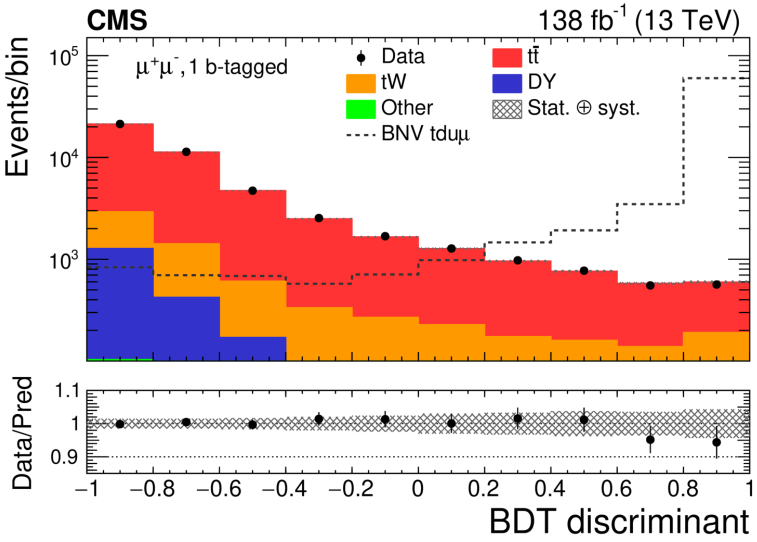
Baryon number violation (BNV)

[Phys. Rev. Lett. 132 (2024) 241802]

- Exactly one opposite-sign lepton pair ($e\mu$, ee and $\mu\mu$)
- Exactly one b-tagged jet
- $m_{\ell\ell}$ > 106 GeV and MET> 60 GeV

- Single BDT used to discriminate signal
- Max. likelihood fit to the BDT output, all 3 channels
- Uncertainties included as nuisance parameters
- No significant excess over expected background





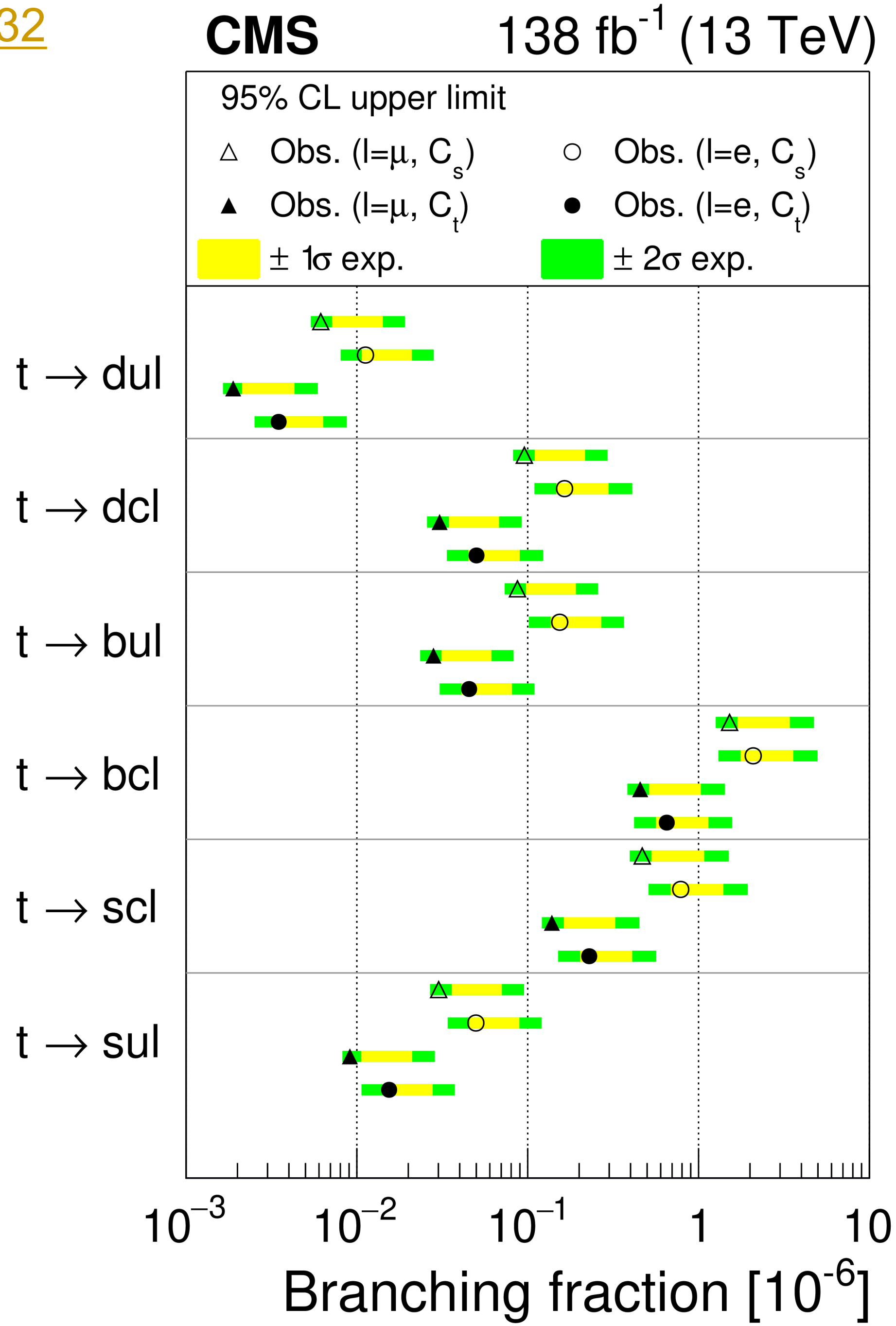
Baryon number violation (BNV)

Phys. Rev. Lett. 132 (2024) 241802

- Limits set for each BNV coupling separately
- Couplings include s-channel, t-channel exchange
- Main common sources of uncertainty:
  - tW normalisation
  - muon energy scale
  - top quark p_T modelling

- Derive limits on branching fractions for BNV top quark decays

- Coupling limits 10^3 to 10^6 better than previous measurement at 8 TeV



Heavy neutral leptons (HNL)

arxiv:2408.05000, submitted to PRD **New!**

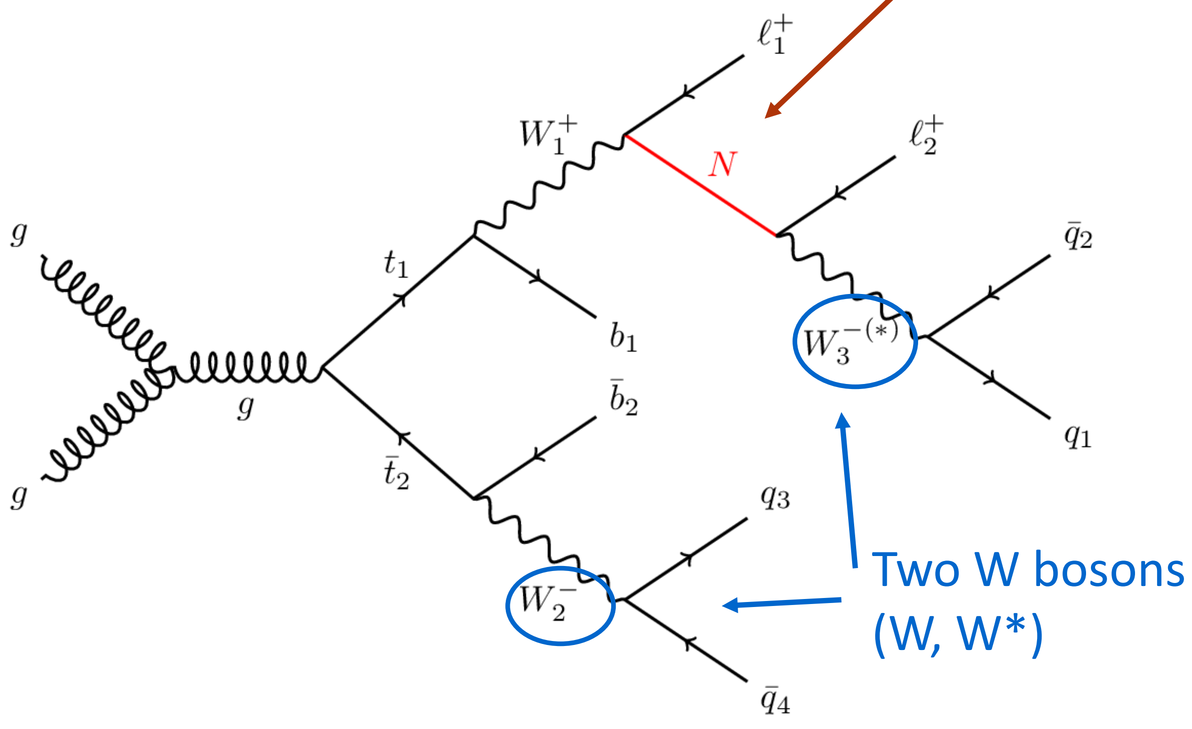
- Neutrino mixing $\Longrightarrow$ neutrinos have mass
- Type-I seesaw model adds 3 heavy right-handed Majorana neutrinos N_1, N_2, N_3
- N_i couple to SM leptons with strength V_{iN}

- Very active research field in HNL searches at the LHC
- $t\bar{t}$ is novel channel to search for HNL

- Consider only diagonal mixing terms: single N couples to one of e/μ/τ

$$V_{\ell,N} = \begin{pmatrix} V_{e,N} & 0 & 0 \\ 0 & V_{\mu,N} & 0 \\ 0 & 0 & V_{\tau,N} \end{pmatrix}$$

Neutrinoless double-beta decay: LNV of |ΔL| = 2 with Majorana neutrino exchange



Signal process: SM and BSM decays in $t\bar{t}$

Heavy neutral leptons (HNL)

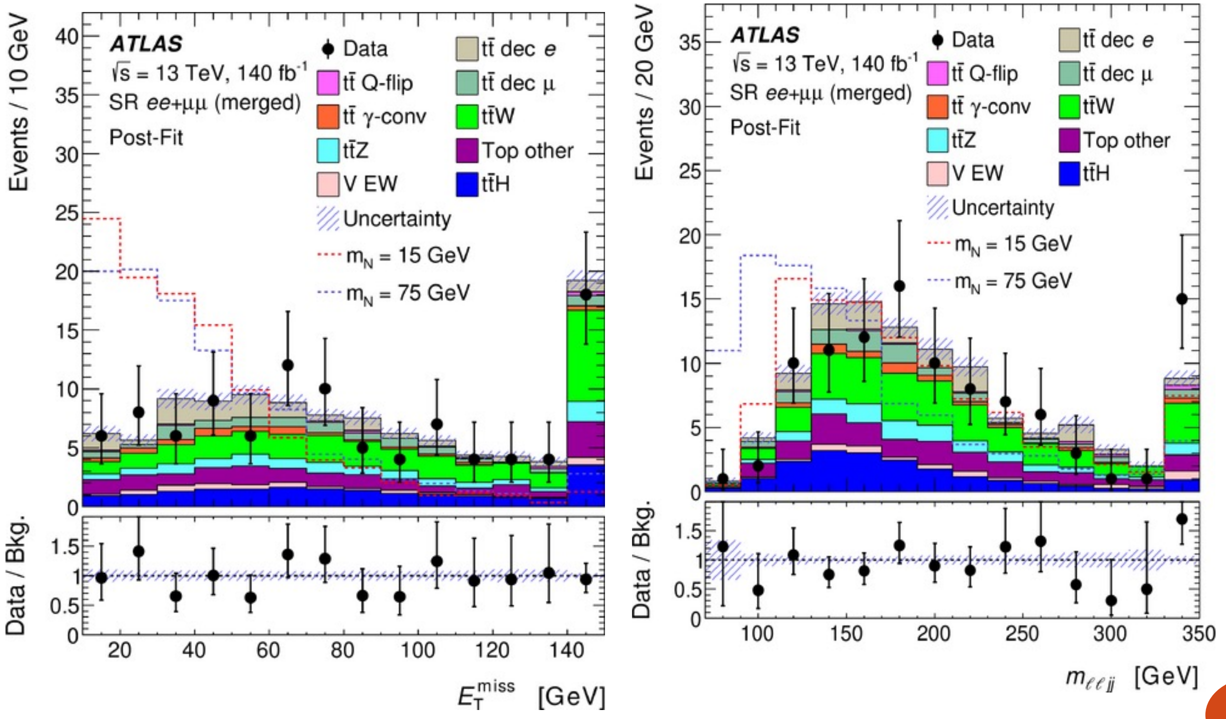
arxiv:2408.05000, submitted to PRD

- Final state: 2 leptons, hadronic decays of W, W*
- Require:
  - One same-sign $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$
  - ≥ 2 b-tagged jets, ≥ 4 other jets
- Dominant backgrounds $t\bar{t}$, $t\bar{t}$+W/Z/γ/H

$$\chi^2 = \frac{(m(t_1) - m_t)^2}{\sigma_t^2} + \frac{(m(W_1^+) - m_W)^2}{\sigma_W^2} + \frac{(m(\bar{t}_2) - m_t)^2}{\sigma_t^2} + \frac{(m(W_2^-) - m_W)^2}{\sigma_W^2}$$

- Minimise χ^2 for 4 masses to give best combination: SM (t, W), BSM (t, W)

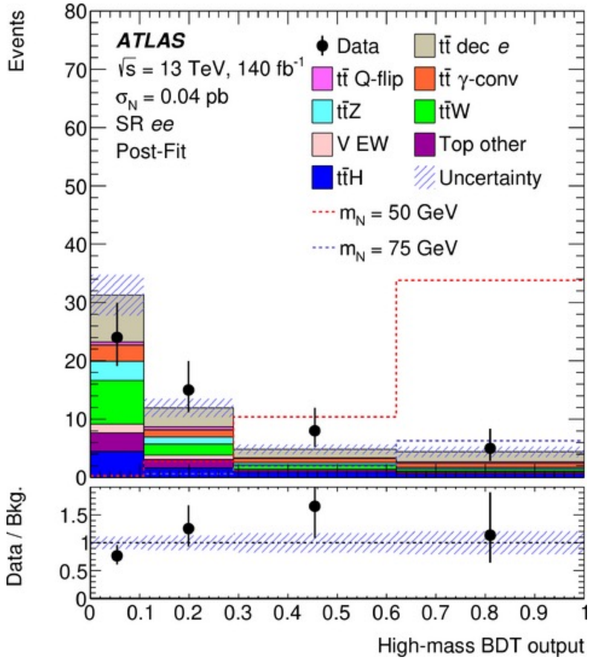
- 10 signal mass points for HNL: 15-75 GeV
- BDTs for low/high m_N to separate HNL signal using kinematic variables

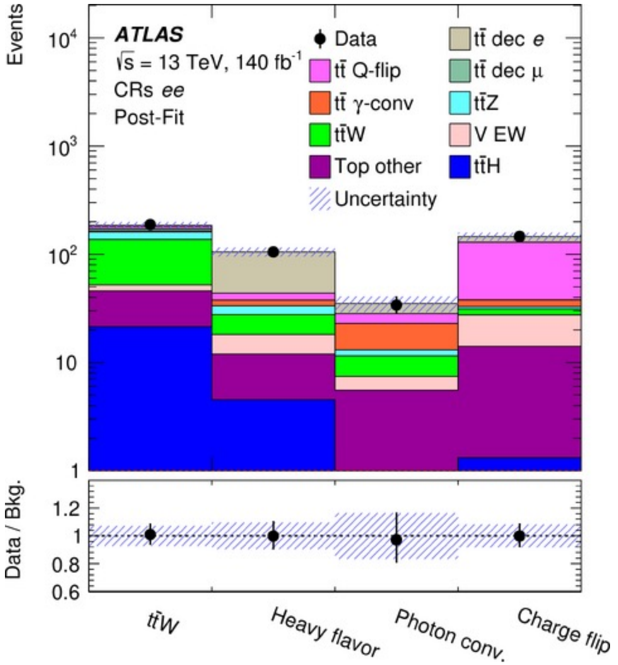


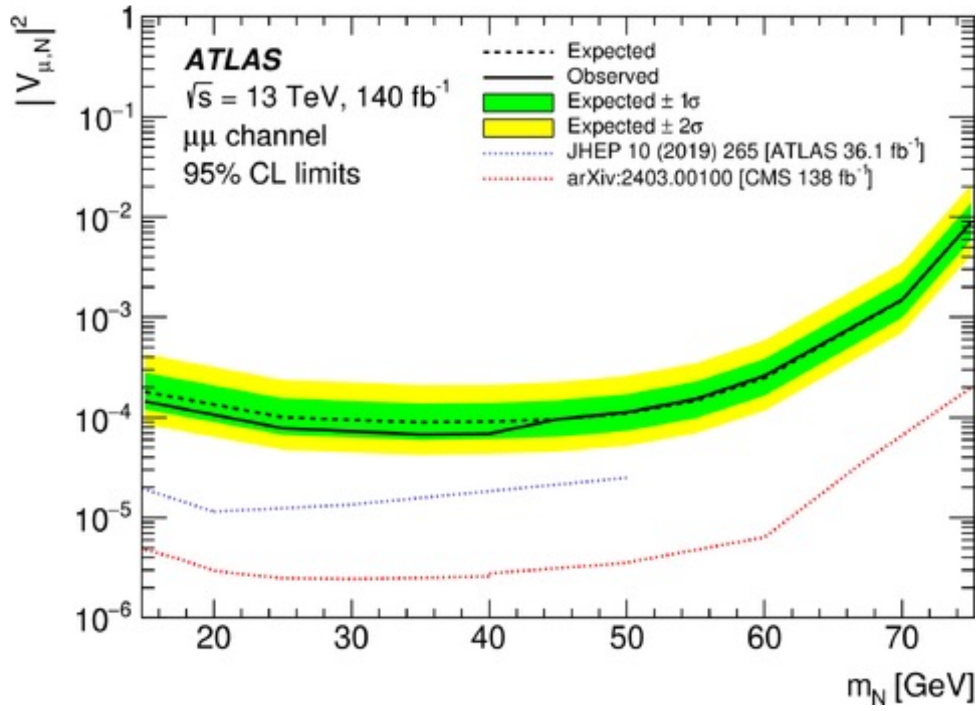
Heavy neutral leptons (HNL)

arxiv:2408.05000, submitted to PRD

- Profile likelihood fits across SR+CRs
- $ee/\mu\mu$ channel fitted separately
  - 1SR + 4CRs (charge flip, heavy flavour, γ conversion and $t\bar{t}W$) for ee
  - 1SR + 2CRs (heavy flavour and $t\bar{t}W$) for $\mu\mu$







- Set limits on HNL cross-sections and coupling parameters for all 3 generations (reinterpret for $\tau\tau \to ee$ or $\tau\tau \to \mu\mu$)
- First search for HNL in $t\bar{t}$
- $ee/\mu\mu$ limit extends the ATLAS results beyond 50 GeV to 75 GeV
- Scope for future EFT interpretation

Summary

- LFU tested very precisely via top processes: $\mathcal{B}(W \to \mu\nu)/\mathcal{B}(W \to e\nu)$ measured to 0.45%
- A large programme of top BSM searches is in progress, including:
  - Charged lepton flavour violation
  - Baryon number violation
  - Heavy neutral lepton production

Typical BR bounds for cLFV and BNV are 10^{-6} - 10^{-8}

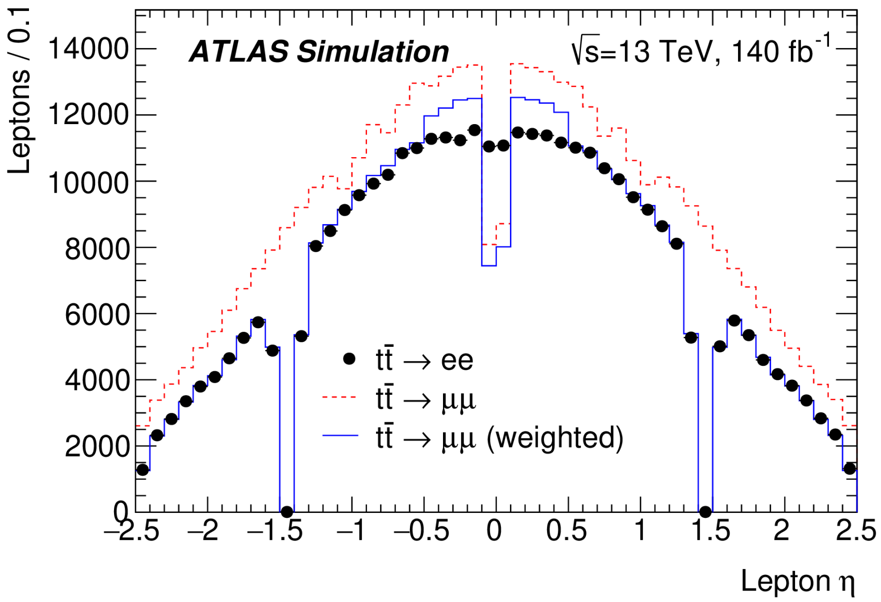
- Effective Field Theory is a useful tool for model-independent BSM searches
- Run 3 datasets will allow new probes of the top quark interactions with improved techniques and precision

Backup slides

Lepton flavour universality e/μ

arxiv:2403.02133, accepted by EPJC

Number of selected leptons as a function of η in simulated $t\bar{t}$ events with at least one b-tagged jet



Summary of the common object selection, and event selections for $t\bar{t}$ and Z final states

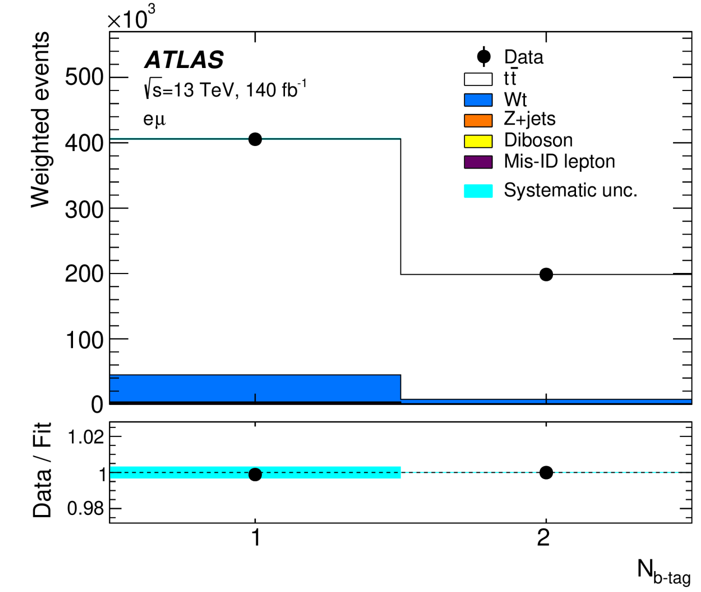
Object selection		
Electrons	$p_T > 27.3$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	
Muons	$p_T > 27.3$ GeV, $\lvert\eta\rvert < 2.5$	
b-tagged jets	$p_T > 30.0$ GeV, $\lvert\eta\rvert < 2.5$, b-tagging DL1r 70%	
Event selection	$t\bar{t} \to \ell\ell b\bar{b}\nu\bar{\nu}$	$Z \to \ell\ell$
Dilepton flavour ($\ell^+\ell^-$)	ee, $e\mu$, $\mu\mu$	ee, $\mu\mu$
Dilepton invariant mass	$m_{\ell\ell} > 30$ GeV	66 GeV $< m_{\ell\ell} < 116$ GeV
b-tagged jet multiplicity	1 or 2	–

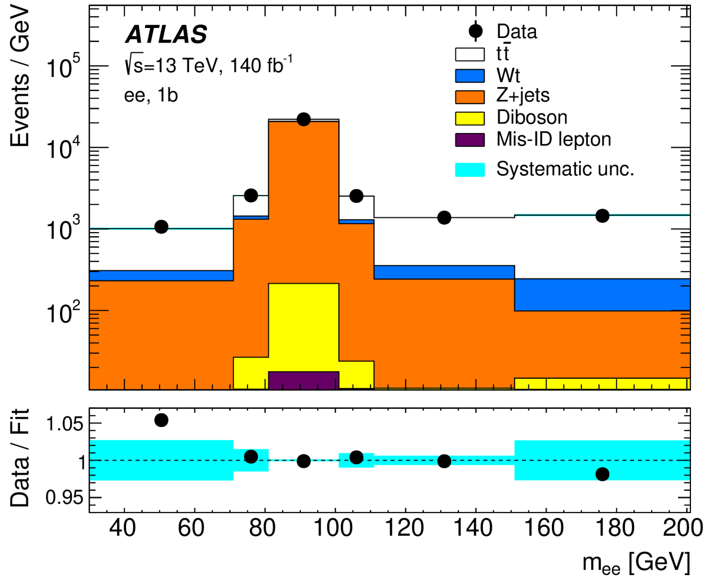
Lepton flavour universality e/μ

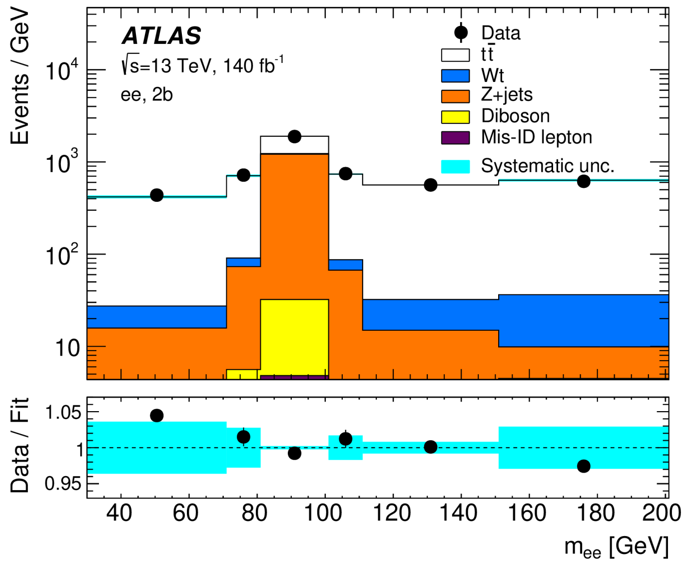
arxiv:2403.02133, accepted by EPJC

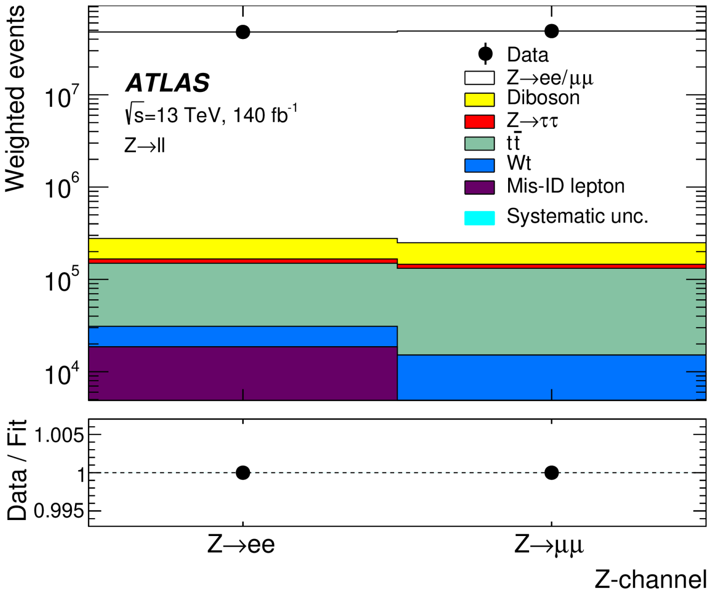
ATLAS EXPERIMENT

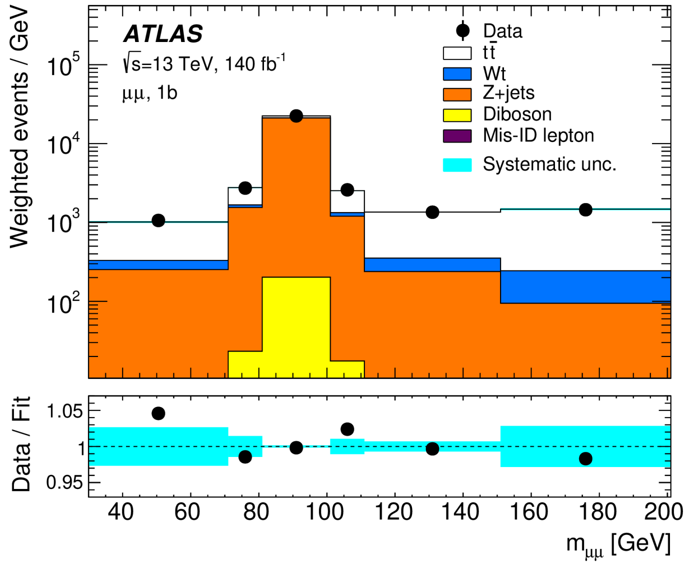
Results of the fit to data

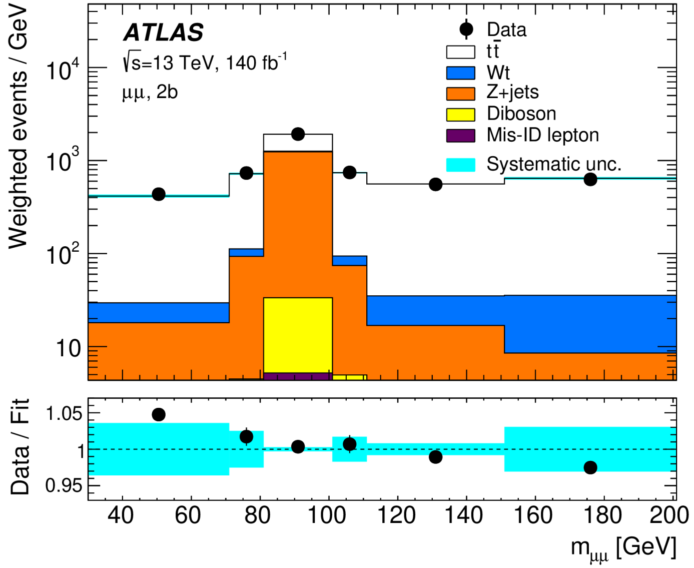












Lepton flavour universality e/μ

arxiv:2403.02133, accepted by EPJC

Breakdown of the statistical and systematic uncertainties

Uncertainty [%]	$\sigma_{t\bar{t}}$	$\sigma_{Z\to\ell\ell}$	$R_{WZ}^{\mu/e}$	$R_{Z}^{\mu\mu/ee}$
Data statistics	0.13	0.01	0.22	0.02
$t\bar{t}$ modelling	1.68	0.03	0.10	0.00
Top-quark p_T modelling	1.42	0.00	0.06	0.00
Parton distribution functions	0.67	0.68	0.15	0.03
Single-top modelling	0.65	0.00	0.05	0.00
Single-top/$t\bar{t}$ interference	0.54	0.00	0.09	0.00
Z(+jets) modelling	0.06	0.73	0.13	0.20
Diboson modelling	0.05	0.04	0.01	0.00
Electron energy scale/resolution	0.05	0.06	0.10	0.11
Electron identification	0.10	0.07	0.04	0.13
Electron charge misidentification	0.06	0.06	0.01	0.13
Electron isolation	0.09	0.02	0.08	0.04
Muon momentum scale/resolution	0.04	0.02	0.06	0.04
Muon identification	0.18	0.12	0.11	0.23
Muon isolation	0.09	0.01	0.07	0.01
Lepton trigger	0.09	0.12	0.01	0.23
Jet energy scale/resolution	0.08	0.00	0.03	0.00
b-tagging efficiency/mistag	0.14	0.00	0.00	0.00
Misidentified leptons	0.17	0.02	0.15	0.05
Simulation statistics	0.04	0.00	0.06	0.00
Integrated luminosity	0.93	0.83	0.00	0.00
Beam energy	0.23	0.09	0.00	0.00
Total uncertainty	2.66	1.32	0.42	0.45

Fit results

$$\sigma_{t\bar{t}} = 809.5 \pm 1.1 \pm 20.1 \pm 7.5 \pm 1.9\,\text{pb}$$

$$\sigma_{Z\to\ell\ell} = 2019.4 \pm 0.2 \pm 20.7 \pm 16.8 \pm 1.8\,\text{pb}$$

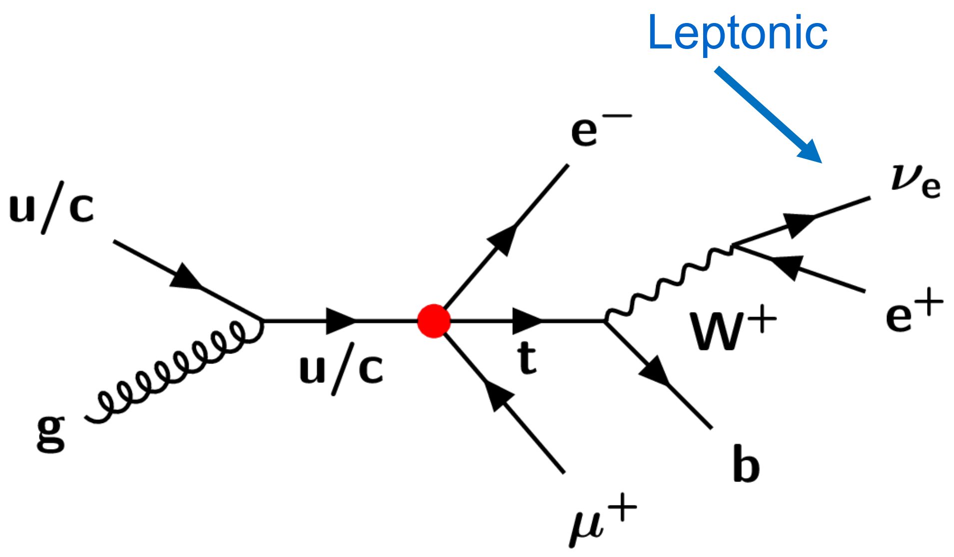
$$R_{WZ}^{\mu/e} = 0.9990 \pm 0.0022 \pm 0.0036$$

cLFV in eμ trilepton channel

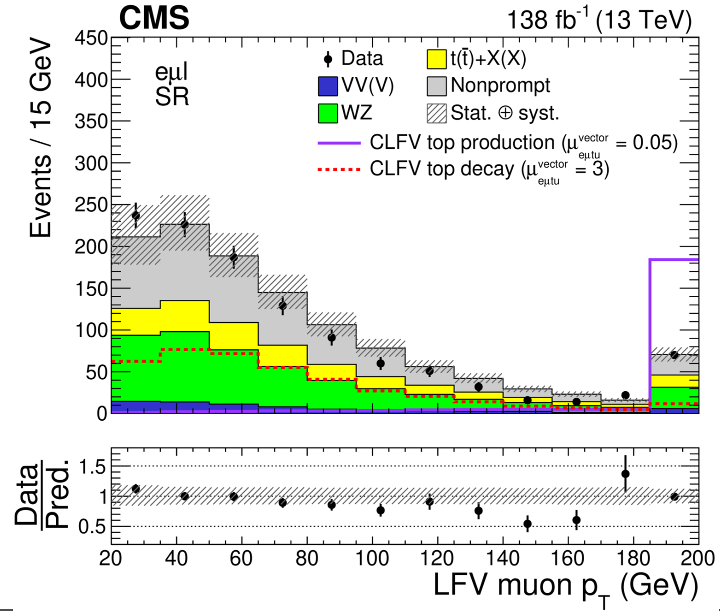
arxiv:2312.03199, submitted to PRD

- Opposite-charge eμ pair from cLFV vertex
- 3rd lepton from top decay ($e\mu\ell$) → exactly $3\ell^{\pm}$
- 1 b-jet; 0/1 light jet (u/c)
- Exclude window around Z mass

- Backgrounds
  - Prompt backgrounds from simulation
  - Non-prompt backgrounds from data-driven “Matrix method”
  - Estimated events are validated using control/validation regions (e.g. eee, μμμ)



Production and decay channels included



cLFV in eμ trilepton channel

arxiv:2312.03199, submitted to PRD

Summary of relevant dimension-6 operators

Lorentz structure	Operator		
Vector	$O_{\mathrm{lq}}^{(1)ijkl}$	=	$(\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma_\mu \mathrm{q}_l)$
	O_{lu}^{ijkl}	=	$(\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{u}}_k\gamma_\mu \mathrm{u}_l)$
	O_{eq}^{ijkl}	=	$(\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma_\mu \mathrm{q}_l)$
	O_{eu}^{ijkl}	=	$(\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma_\mu \mathrm{u}_l)$
Scalar	$O_{\mathrm{lequ}}^{(1)ijkl}$	=	$(\bar{\mathrm{l}}_i \mathrm{e}_j)\ \varepsilon\ (\bar{\mathrm{q}}_k u_l)$
Tensor	$O_{\mathrm{lequ}}^{(3)ijkl}$	=	$(\bar{\mathrm{l}}_i \sigma^{\mu\nu} \mathrm{e}_j)\ \varepsilon\ (\bar{\mathrm{q}}_k \sigma_{\mu\nu} \mathrm{u}_l)$

Theoretical cross sections for top quark production and decay for each CLFV coupling

Signal mode	Tensor	Vector	Scalar
Production ($e\mu$tu)	$2140^{+370}_{-290} \pm 30$ fb	$460^{+81}_{-64} \pm 6$ fb	$97^{+18}_{-14} \pm 1$ fb
Production ($e\mu$tc)	$164^{+22}_{-18} \pm 27$ fb	$33^{+5}_{-4} \pm 6$ fb	$6.3^{+0.9}_{-0.8} \pm 1.4$ fb
Decay ($e\mu$tq, where q = u/c)	$187^{+5}_{-6} \pm 8$ fb	$32.0^{+0.8}_{-1.1} \pm 1.3$ fb	$4.0^{+0.1}_{-0.1} \pm 0.2$ fb

cLFV in eμ trilepton channel

arxiv:2312.03199, submitted to PRD

Summary of systematic uncertainties

Systematic uncertainty	$m(e\mu) < 150$ GeV Background	$m(e\mu) < 150$ GeV Signal	$m(e\mu) > 150$ GeV Background	$m(e\mu) > 150$ GeV 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%

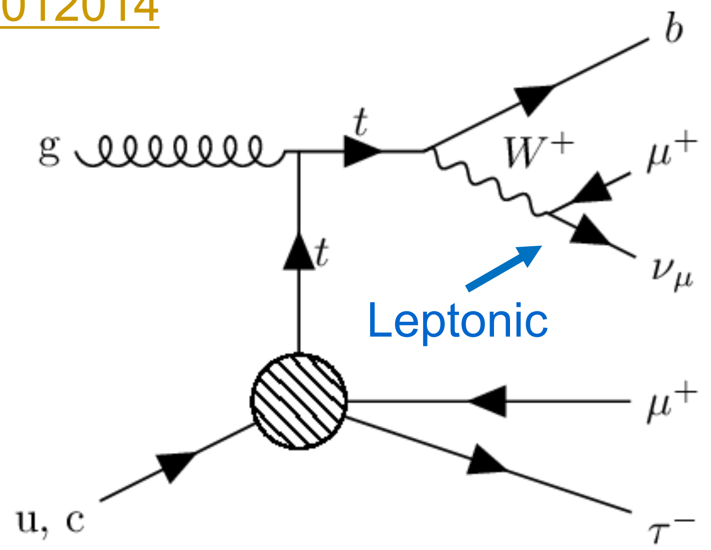
Upper limits at 95% CL on Wilson coefficients and branching fractions for tensor-, vector-, and scalar-like CLFV interactions

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) **Obs.**	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ **Obs.**
$e\mu tu$	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**
$e\mu tc$	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**

cLFV in $\mu\tau$ trilepton channel

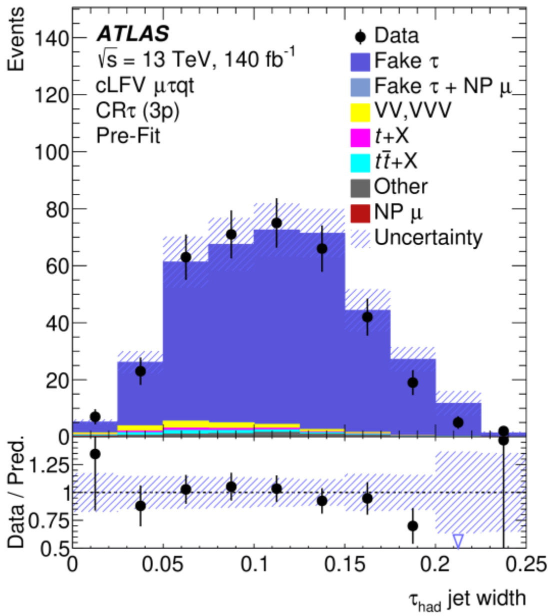
Phys. Rev. D 110 (2024) 012014

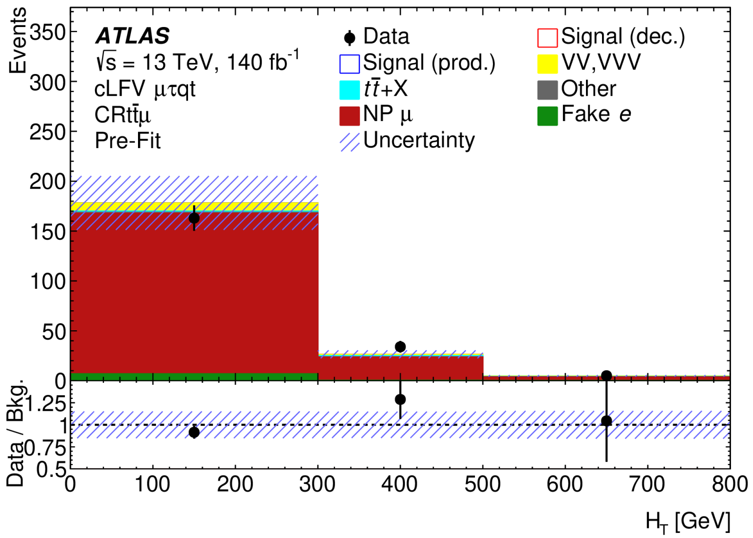
- Signal region (SR):
  - $\mu\mu\tau$ signature
  - Same-sign $\mu^{\pm}\mu^{\pm}$ to suppress backgrounds
  - Hadronic τ candidate (τ_{had})
  - ≥ 1 jet (1 b-tagged)



Production and decay channels included

- Fake lepton estimates:
  - Fake τ estimates from τ control region (CR)
    - Scale factors derived using tau-jet width, 1-,3-prong
  - Non-prompt muons from b-jets in $t\bar{t}$ CR
    - Normalisation controlled in likelihood fit



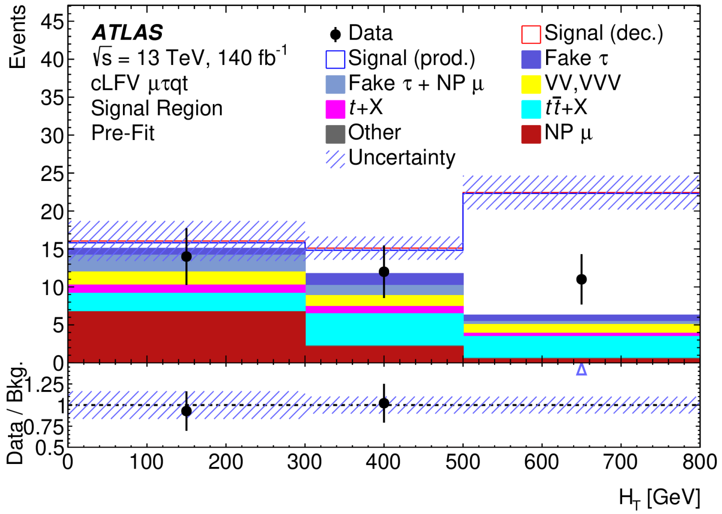


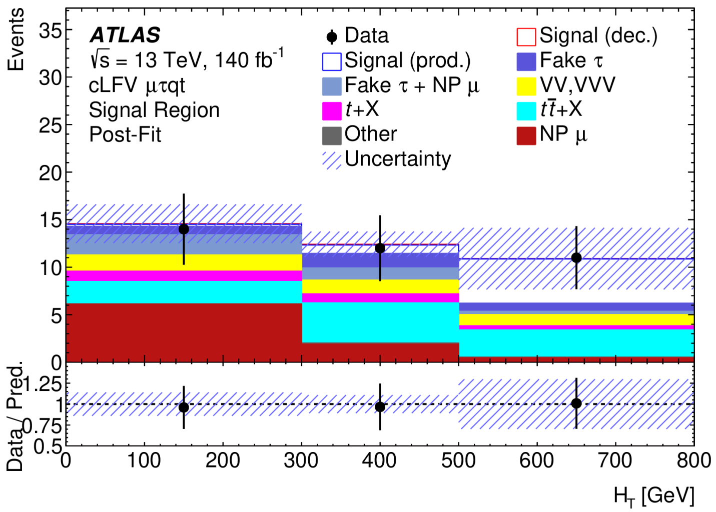
- Binned profile-likelihood fit over across SR + $t\bar{t}$ CR with systematic uncertainties

cLFV in $\mu\tau$ trilepton channel

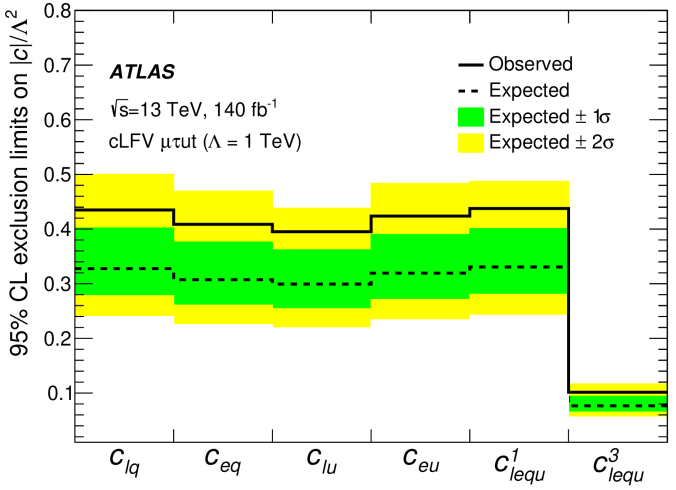
Phys. Rev. D 110 (2024) 012014

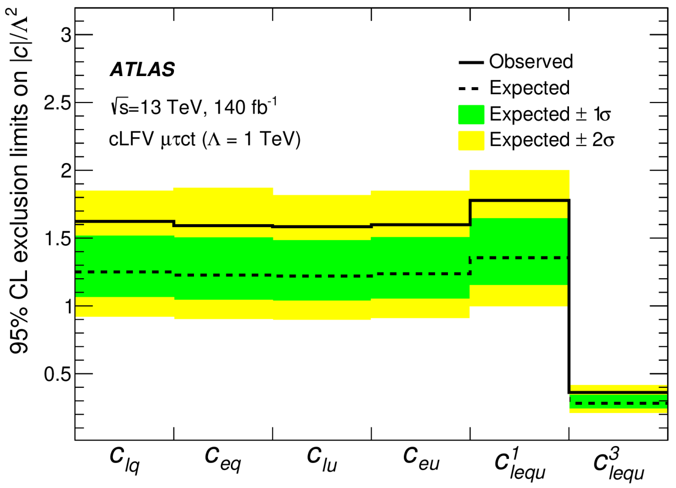
- Fit regions binned in H_T (scalar sum of lepton and jet p_T)
- H_T separates EFT signal from SM backgrounds: cLFV single-t production produces high-p_T leptons





- No significant excess in data (1.6σ)
- Extract limits on effective coupling strengths (Wilson coefficients)
  - Factor 7-41 better than previous indirect limits
  - Statistically limited
  - Largest systematics are signal modelling, $t\bar{t}W$ and diboson





cLFV in μτ trilepton channel

Phys. Rev. D 110 (2024) 012014

EFT operator basis

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

Theoretical cross-sections

	Cross-section $\sigma^{+\text{scale}}_{-\text{scale}} \pm$ PDF [fb]		
	$c_{\text{vector}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Production $\ell\ell' ut$	$118^{+24}_{-19} \pm 1$	$101^{+21}_{-16} \pm 1$	$2150^{+410}_{-320} \pm 20$
Production $\ell\ell' ct$	$7.9^{+1.2}_{-1.0} \pm 1.6$	$6.1^{+1.0}_{-0.8} \pm 1.5$	$153^{+21}_{-18} \pm 29$
Decay $\ell\ell' q_k t$	$6.9^{+1.8}_{-1.3} \pm 0.1$	$3.46^{+0.90}_{-0.66} \pm 0.03$	$166^{+43}_{-32} \pm 2$

Requirements for each analysis region

	SR	CRτ	CR$t\bar{t}\mu$
Lepton flavour	$2\mu 1\tau_{\text{had}}$		$2\mu 1e$ $(\ell_3 = \mu)$
N_{jets}	≥ 1	≥ 2	≥ 1
$N_{b\text{-tags}}$	1	1	≤ 2
τ_{had} p_{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	–
$m_{\mu\mu}^{\text{OS}}$	–	–	>15 GeV
$\lvert m_{\mu\mu}^{\text{OS}} - M_Z\rvert$	–	<10 GeV	>10 GeV
$3p_{\text{T}}^{\mu_1} + \sum m_{\ell\ell}^{\text{OS}}$	–	–	< 400 GeV

cLFV in μτ trilepton channel

Phys. Rev. D 110 (2024) 012014

ATLAS EXPERIMENT

Expected and observed 95% CL upper limits on Wilson coefficients

	95% CL upper limits on $\|c\|/\Lambda^2$ [TeV^{-2}]					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Previous (u)	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33	0.08
Observed (u)	0.43	0.41	0.4	0.42	0.44	0.10
Previous (c)	14	14	14	14	21	2.6
Expected (c)	1.3	1.2	1.2	1.2	1.4	0.28
Observed (c)	1.6	1.6	1.6	1.6	1.8	0.36

m_{S_1} [GeV]	Limit on λ^{LQ} (95% CL)	
	Observed	Expected
500	1.3	1.1
750	1.7	1.5
1000	2.1	1.8
1250	2.5	2.2
1500	2.9	2.5
1750	3.3	2.9
2000	3.7	3.2

Observed and expected exclusion 95% CL upper limits on the leptoquark coupling strength

Expected and observed 95% CL upper limits on the branching ratios for specific Wilson coefficients

	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$ $(\times 10^{-7})$					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Expected (u)	2.3	2.0	1.9	2.2	1.2	3.0
Observed (u)	4.0	3.6	3.3	3.8	2.0	5.2
Expected (c)	33	32	32	33	20	41
Observed (c)	56	54	53	54	34	67

Expected and observed 95% CL upper limits on the inclusive branching ratio

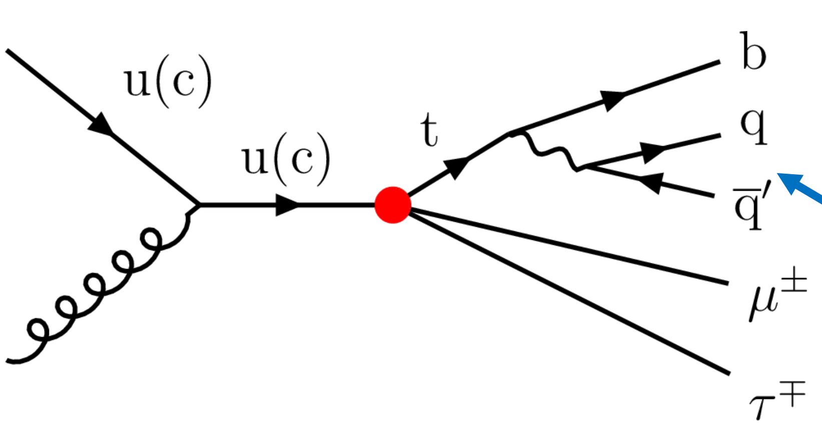
	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$	
	Stat. uncertainty	**Stat.+syst. uncertainties**
Expected	4.6×10^{-7}	5.0×10^{-7}
Observed	8.2×10^{-7}	8.7×10^{-7}

cLFV in $\mu\tau$ hadronic channel

CMS-PAS-TOP-22-011

New!

- Event selection:
  - 1 μ, 1 τ_{had}, opposite charges
  - ≥ 3 jets (hadronic W decay), 1 b-tagged jet



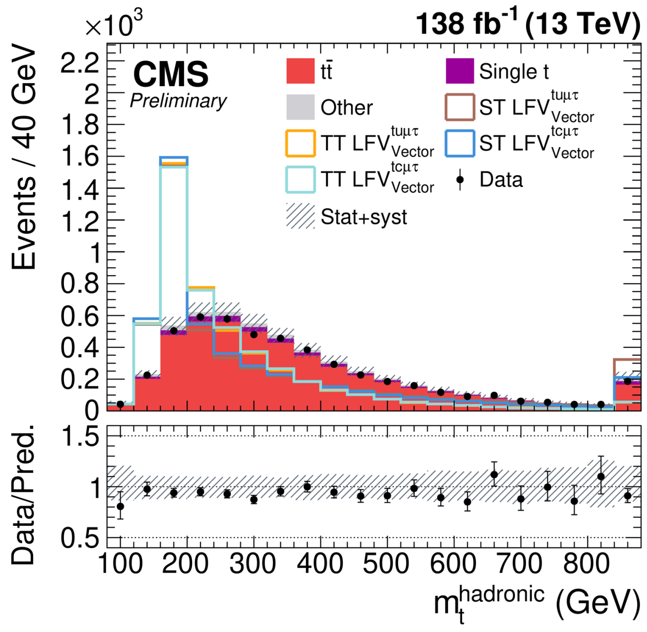
Hadronic

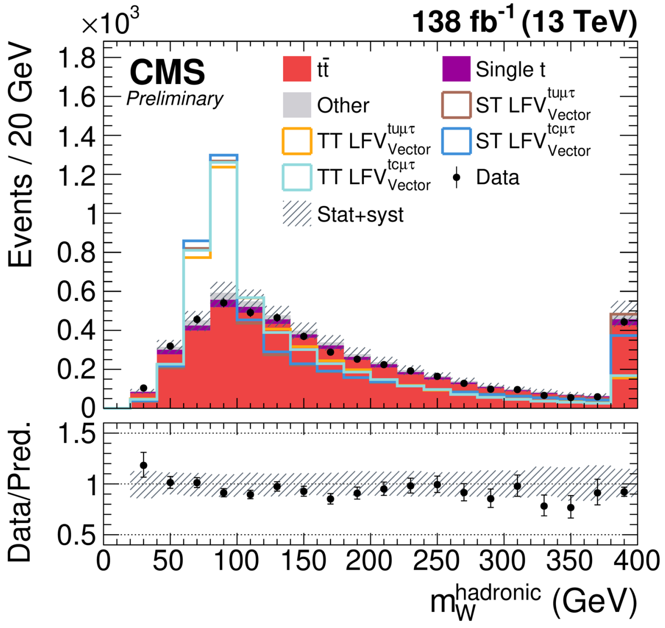
Production and decay channels included

- Background estimation:
  - Prompt backgrounds from simulation
  - Data-driven estimation of jets misidentified as τ_{had}

- Reconstruction of SM top and W mass
  - Background events mostly from dileptonic $t\bar{t}$ channel.
  - Hadronic decay reconstructed using χ^2

$$\chi^2 = \left(\frac{m_t - m_{bjj'}}{\sigma_t}\right)^2 + \left(\frac{m_W - m_{jj'}}{\sigma_W}\right)^2$$

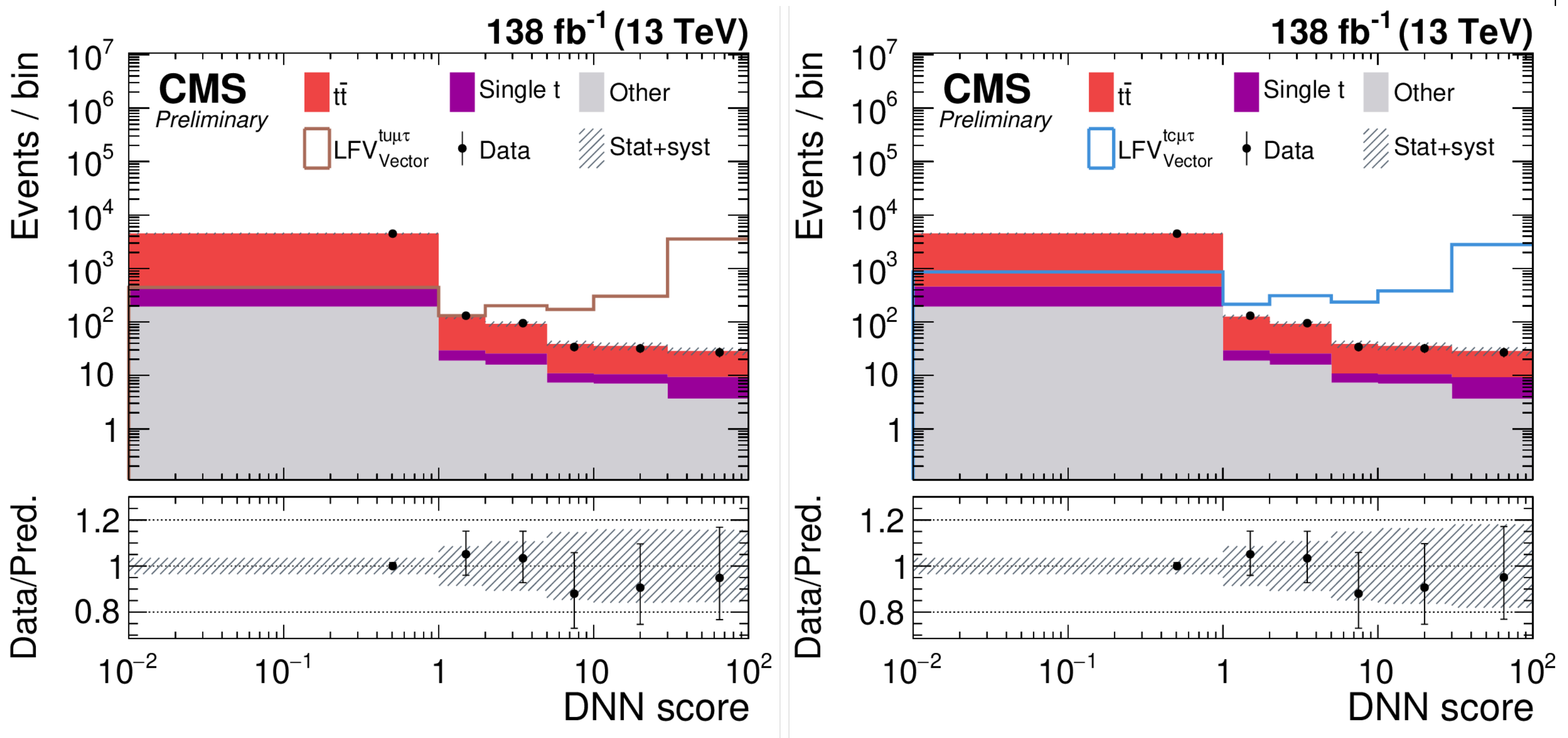




cLFV in μτ hadronic channel

CMS-PAS-TOP-22-011

- A deep neural network (DNN) is used to classify signal and $t\bar{t}$ background events
- Includes single top (ST) and $t\bar{t}$ (TT) cLFV channels
- 28 kinematic variables, including individual particles and global features



- DNN score is weighted towards single top

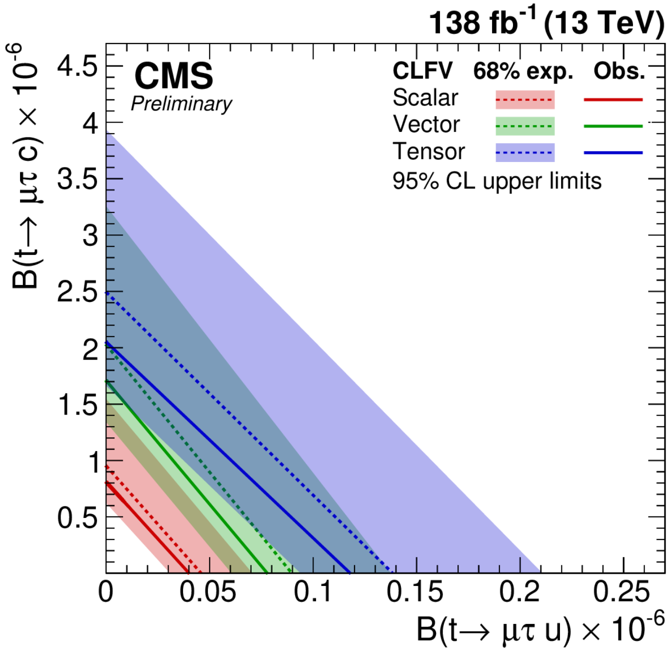
$$\text{DNN score} = \frac{0.1p(\text{TT CLFV}) + 0.9p(\text{ST CLFV})}{p(\text{background})}$$

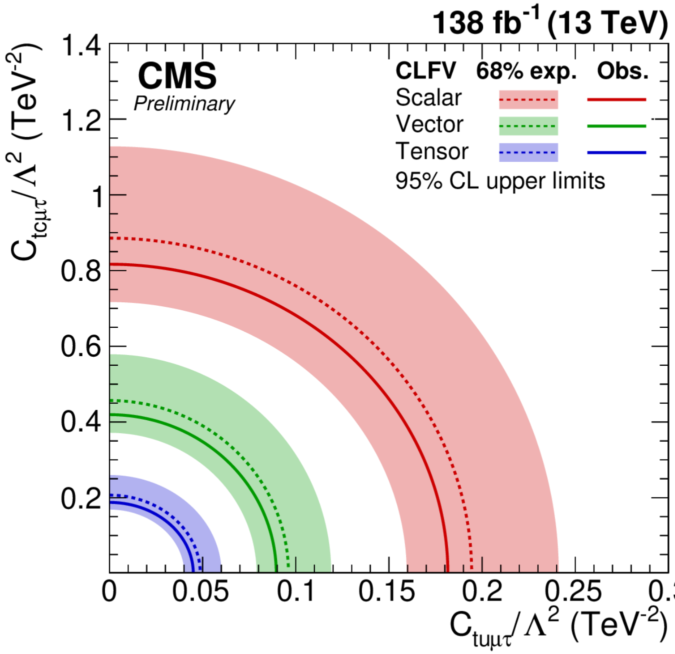
cLFV in μτ hadronic channel

CMS-PAS-TOP-22-011

- Data are found to be consistent with the standard model expectation.
- Upper limits at 95% CL are set for different interaction operators
- Converted into branching fractions for $t \to \mu\tau q$ process

- Improvement by factor ~2 on previous 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]

cLFV in μτ hadronic channel

CMS-PAS-TOP-22-011

EFT operators and their definition

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	$O^{3(ijkl)}_{\ell equ}$	$(\bar{\ell}_i \sigma^{\mu\nu} \ell_j)\varepsilon(\bar{q}_k \sigma_{\mu\nu} u_l)$	$C_{\ell equ3}$

Predicted cross sections for CLFV signal processes

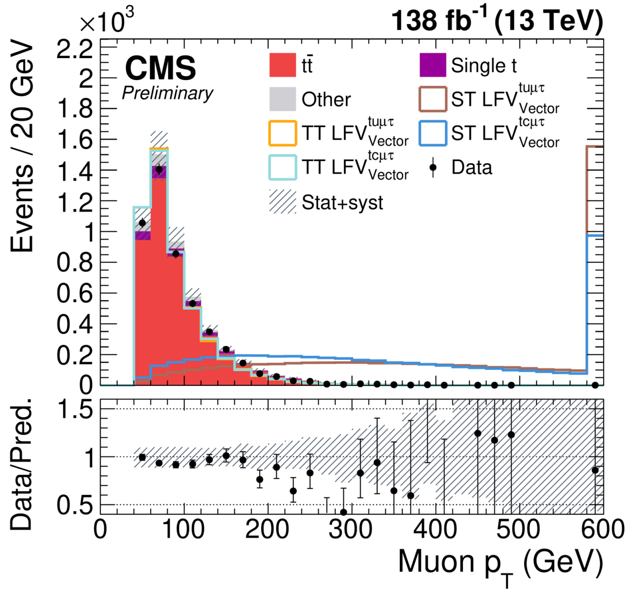
Process	Lorentz structure	Cross sections (fb)
ST CLFV tu$\mu\tau$	Scalar	59.14
	Vector	276.1
	Tensor	1272
ST CLFV tc$\mu\tau$	Scalar	3.74
	Vector	19.51
	Tensor	96.18
TT CLFV tq$\mu\tau$	Scalar	2.69
	Vector	21.5
	Tensor	129.0

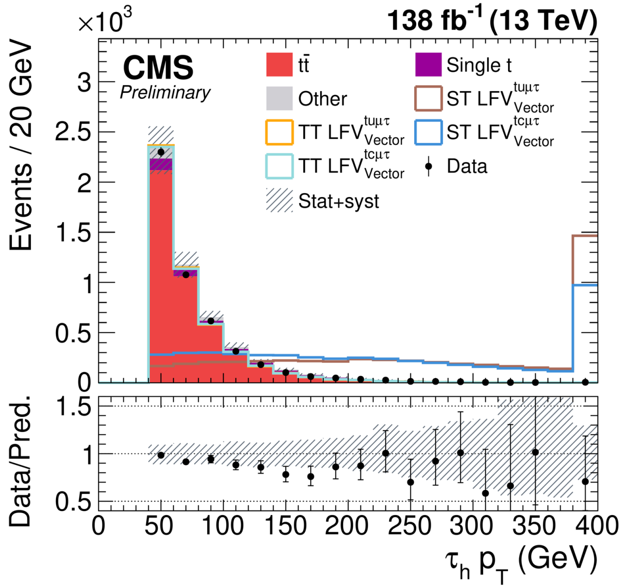
cLFV in μτ hadronic channel

CMS-PAS-TOP-22-011

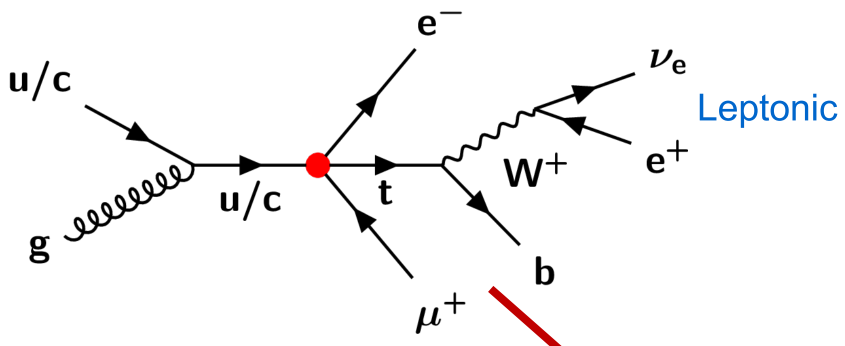
Input features of the DNN

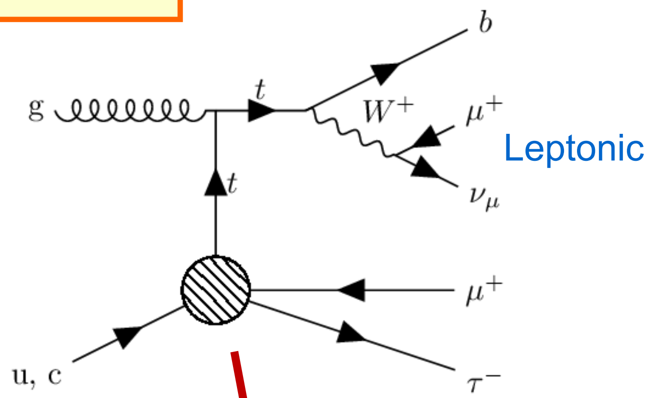
Group	Variables	Description
Muon (μ)	$p_{T\mu}$, η_μ	p_T and η of selected muon
Tau (τ_h)	$p_{T\tau_h}$, η_{τ_h}, m_{τ_h}	p_T, η, and mass of selected τ_h
Muon+Tau ($\mu\tau_h$)	$m_{\mu\tau_h}$, $\Delta\eta_{\mu\tau_h}$, $\Delta\phi_{\mu\tau_h}$, $\Delta R_{\mu\tau_h}$	Mass and angular differences of $\mu\tau_h$ 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.

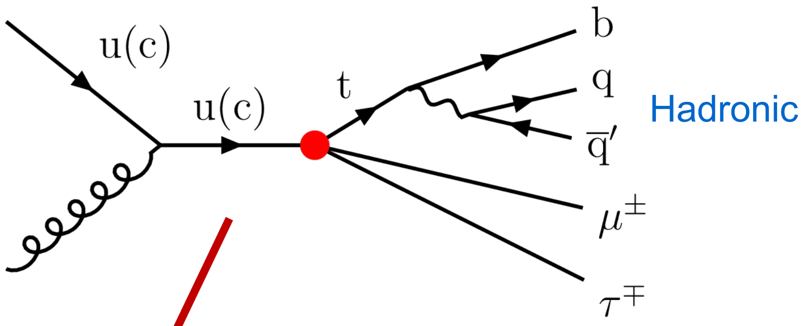




Charged lepton flavour violation (cLFV)







Analysis	q	eμ trilepton (CMS)	μτ trilepton (ATLAS)	μτ hadronic (CMS)
cLFV vertex		teμq (q=u,c)	tμτq (q=u,c)	tμτq (q=u,c)
c/Λ^2 [GeV^{-2}]	u	0.02-0.10	0.10-0.44	0.045–0.18
	c	0.09-0.42	0.36-1.8	0.19–0.82
BR($t \to q\ell\ell'$) [10^{-6}]	u	0.012-0.032	0.20-0.52	0.04–0.12
	c	0.22-0.50	3.4-6.7	0.81–1.05

- Tight limits on Wilson coefficients
- Branching ratios 10^{-6} – 10^{-8}

Baryon number violation (BNV)

Phys. Rev. Lett. 132 (2024) 241802

Theoretical inclusive cross sections for single top quark production (ST) and top quark-antiquark pair production with the decay (TT) via BNV interactions

Process	$\sigma(C_t = 1)$ [pb]	$\sigma(C_s = 1)$ [pb]
ST ($t\ell ud$)	$31.5 \pm 2.1 \pm 1.0$	$10.7 \pm 0.7 \pm 0.4$
ST ($t\ell us$)	$8.1 \pm 0.3 \pm 0.5$	$2.8 \pm 0.1 \pm 0.2$
ST ($t\ell ub$)	$3.31 \pm 0.13 \pm 0.06$	$1.14 \pm 0.05 \pm 0.02$
ST ($t\ell cd$)	$2.77 \pm 0.22 \pm 0.01$	$0.96 \pm 0.01 \pm 0.07$
ST ($t\ell cs$)	$0.79 \pm 0.02 \pm 0.11$	$0.27 \pm 0.01 \pm 0.04$
ST ($t\ell cb$)	$0.28 \pm 0.03 \pm 0.04$	$0.10 \pm 0.01 \pm 0.01$
TT	$0.007 \pm 0.002 \pm 0.001$	$0.007 \pm 0.002 \pm 0.001$

Expected and observed 95% CL upper limits on the BNV effective couplings and top quark BNV branching fractions

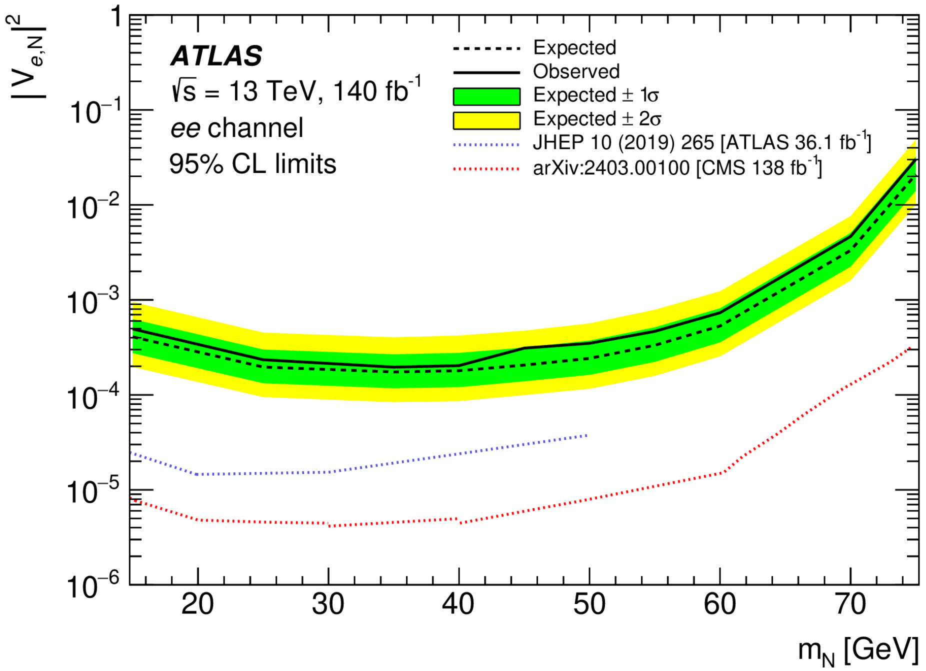
Vertex	C_x	C_x/Λ^2 [TeV^{-2}] Exp.	C_x/Λ^2 [TeV^{-2}] Obs.	$\mathcal{B}_x$ [10^{-6}] Exp.	$\mathcal{B}_x$ [10^{-6}] Obs.
teud	s	0.055	0.048	0.015	0.011
	t	0.031	0.027	0.005	0.003
tμud	s	0.046	0.036	0.010	0.006
	t	0.025	0.020	0.003	0.002
tecd	s	0.207	0.184	0.208	0.164
	t	0.114	0.102	0.063	0.050
tμcd	s	0.178	0.141	0.153	0.095
	t	0.100	0.080	0.048	0.030
teus	s	0.115	0.101	0.063	0.050
	t	0.064	0.056	0.019	0.015
tμus	s	0.102	0.079	0.050	0.030
	t	0.056	0.043	0.015	0.009
tecs	s	0.448	0.403	0.973	0.786
	t	0.243	0.218	0.286	0.229
tμcs	s	0.394	0.311	0.752	0.468
	t	0.217	0.169	0.228	0.138
teub	s	0.199	0.178	0.191	0.154
	t	0.109	0.097	0.057	0.045
tμub	s	0.168	0.134	0.136	0.087
	t	0.095	0.076	0.044	0.028
tecb	s	0.718	0.657	2.503	2.090
	t	0.405	0.367	0.795	0.652
tμcb	s	0.703	0.564	2.393	1.521
	t	0.386	0.307	0.722	0.455

Heavy neutral leptons (HNL)

arxiv:2408.05000, submitted to PRD

Expected and observed upper limits on the signal cross-sections at 95% CL

m_N [GeV]	15	25	35	40	45	50	55	60	70	75
Exp. $\sigma_{e,N}$ [fb]	21	9.8	7.3	6.9	6.9	6.7	7.2	8.5	18	36
Obs. $\sigma_{e,N}$ [fb]	26	12	8.2	7.8	10	9.7	10	12	26	52
Exp. $\sigma_{\mu,N}$ [fb]	9.3	5.0	3.7	3.5	3.2	3.1	3.2	4.0	8.2	15
Obs. $\sigma_{\mu,N}$ [fb]	7.5	3.9	2.8	2.6	3.2	3.1	3.3	4.2	8.3	15
Exp. $\sigma_{\tau,N}$ [pb]	8.9	2.6	2.1	1.7	1.8	1.8	2.0	3.7	7.0	19
Obs. $\sigma_{\tau,N}$ [pb]	13	3.6	2.7	2.3	2.5	2.2	3.2	5.5	7.3	20



Expected and observed upper limits on the strength of HNL mixing with (left) electron neutrinos, (right) τ-neutrinos at 95% CL