

Search for LFV in the top quark sector at CMS

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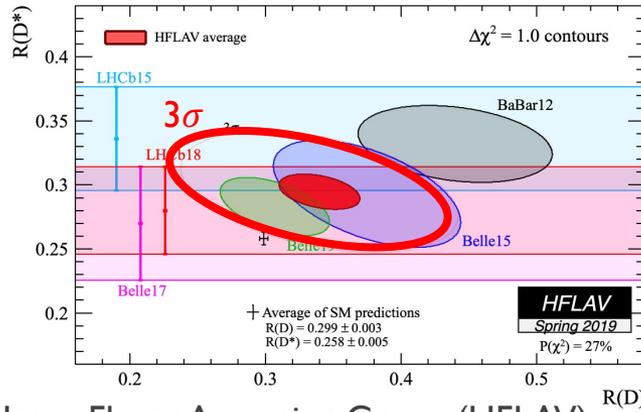
Muon Anomalies Workshop
May 21 in 2021

Theoretical motivation

- Lepton flavor violation is forbidden in the SM with massless neutrinos
- The observation of neutrino oscillation confirms the existence of non-zero mass of neutrinos and LFV in neutral leptons
- The mass terms predict charged LFV (CLFV) at loop level but this is highly suppressed due to the tiny neutrino masses
- The CLFV can be enhanced in many new physics models such multi-Higgs double models, minimal supersymmetric SM, the inverse seesaw model, etc..
- The LHC provides the best sensitivity to high-energy LFV process involving a heavy particle, such as the Z boson, Higgs boson or the top quark
- There were some searches for CLFV decays of the Z and Higgs boson
- Not much explored in data for the LFV in top quark sector - only one public note from ATLAS :[ATLAS-CONF-2018-044](#)

Experimental motivation - nnomaly in B-physics sector

Deviation observed by Belle and LHCb experiments

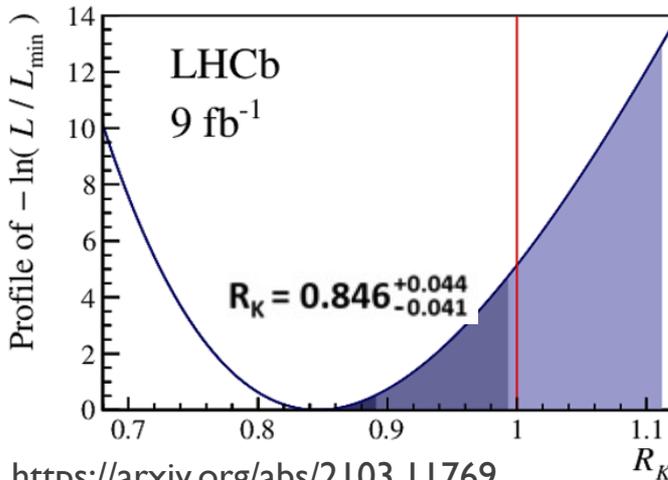


Heavy Flavor Averaging Group (HFLAV)

$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)} \tau \bar{\nu})}{Br(B \rightarrow D^{(*)} l \bar{\nu})} \quad R_{D^{(*)}}^{SM} = 0.258 \pm 0.005$$

$$R_{D^{(*)}} = 0.297 \pm 0.015$$

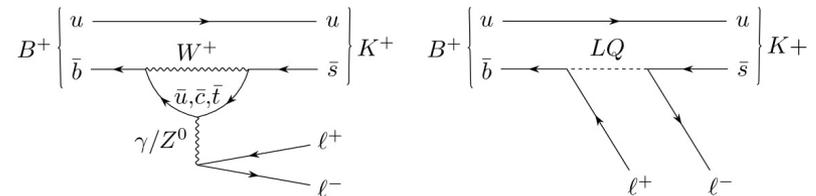
- Measured R_D (average) has 3.1 σ deviation from the SM



<https://arxiv.org/abs/2103.11769>

$$R_K = \frac{Br(B \rightarrow K \mu^+ \mu^-)}{Br(B \rightarrow K e^+ e^-)}$$

- The latest LHCb result still shows 3.1 σ deviation from the SM

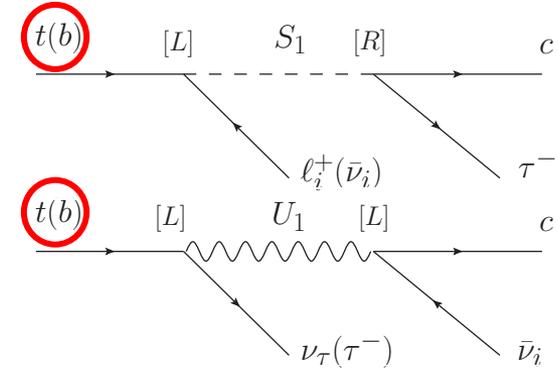


g-2 results → can be explained by Leptoquark

Search for leptoquark for R_D anomaly in top quark sector

Search for Lepton Flavor Violation (LFV)

- Models explaining the observed lepton universality violation generally also lead to LFV effects
- R_D anomaly can be explained by leptoquark (LQ) decay in B meson
- LQ can also appear in top quark sector with three body decay : $t \rightarrow c\tau\tau$, $t \rightarrow c\mu\tau$, $t \rightarrow c\nu\nu$ with $Br \approx 10^{-6}$
- CLFV in the top quark sector can shed light on the anomalies in B meson decays



Cut-and-Count

S1 : exactly 1 lepton, at least three jets (1 b-jet and two tau-jet)

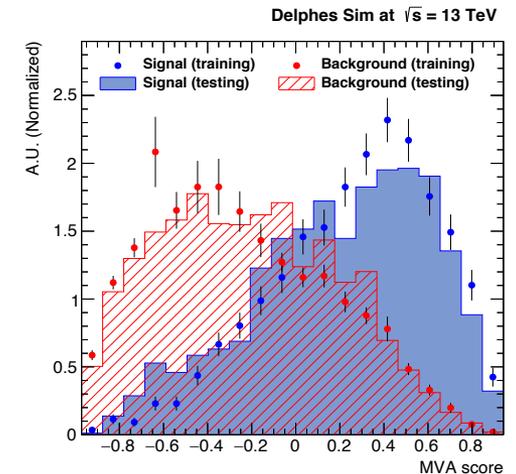
S2 : exactly two leptons, one muon, at least two jets (1 b-jet and 1 tau-jet)

S3 : exactly 1 lepton, at least three jets, one b-jet and MET > 80 GeV

	VV	DY	W+jet	$t\bar{t}$	$t \rightarrow c\mu\tau$	$t \rightarrow c\tau\tau$	$t \rightarrow c\nu\nu$
Selection 1	9559	108095	-	1189719	28	19	0.3
Selection 2	5433	54047	-	839651	39	5	0.0
Selection 3	296814	594522	16530371	64764862	140	94	102

Most sensitive channel

BDT



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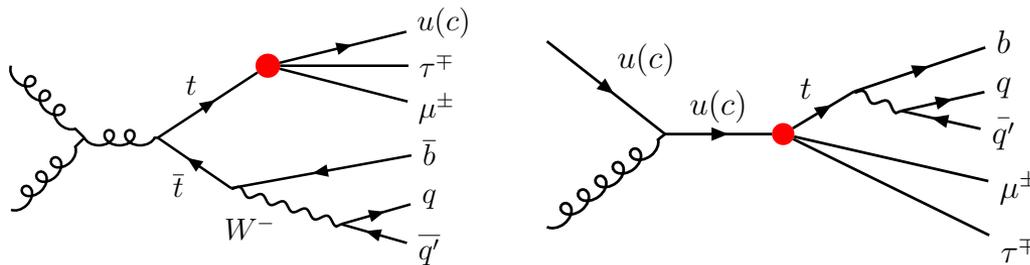
Model independent EFT approach

- Considering the SM as a low-energy approximation of a higher-energy theory, we can add higher order terms with new physics at a higher mass scales
- We follow model independent EFT approach to search for LFV
- D6 operators are used for building effective Lagrangian

<https://arxiv.org/abs/1802.07237>

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \dots,$$

C_x are dimensionless Wilson coefficients



- Search for the interaction with two quarks and two leptons of different flavors (in a top quark decay in $t\bar{t}$ or single top production)
- 6 operators can be categorized into scalar, vector and tensor types

$$O_{\text{vector}} = O_{lq} + O_{lu} + O_{eq} + O_{eu'}$$

$$O_{\text{scalar}} = O_{lequ}^{(1)}$$

$$O_{\text{tensor}} = O_{lequ}^{(3)}$$



- These four fermion interactions open up new top quark decay modes: $t \rightarrow ll'q$

$$O_{lq}^{1(ijkl)} = (\bar{l}_i \gamma^\mu l_j) (\bar{q}_k \gamma^\mu q_l)$$

$$O_{lq}^{3(ijkl)} = (\bar{l}_i \gamma^\mu \tau^I l_j) (\bar{q}_k \gamma^\mu \tau^I q_l)$$

$$O_{lu}^{(ijkl)} = (\bar{l}_i \gamma^\mu l_j) (\bar{u}_k \gamma^\mu u_l)$$

$$O_{eq}^{(ijkl)} = (\bar{e}_i \gamma^\mu e) (\bar{q}_k \gamma^\mu q_l)$$

$$O_{eu}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_j) (\bar{u}_k \gamma^\mu u_l)$$

$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j) \epsilon (\bar{q}_k u_l)$$

$$O_{lequ}^{3(ijkl)} = (\bar{l}_i \sigma^{\mu\nu} l_j) \epsilon (\bar{q}_k \sigma_{\mu\nu} q_l)$$

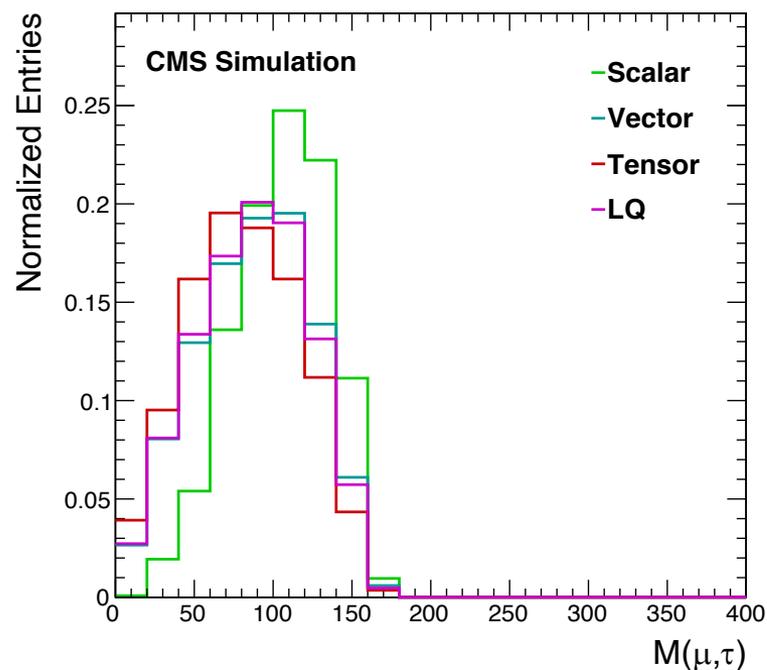
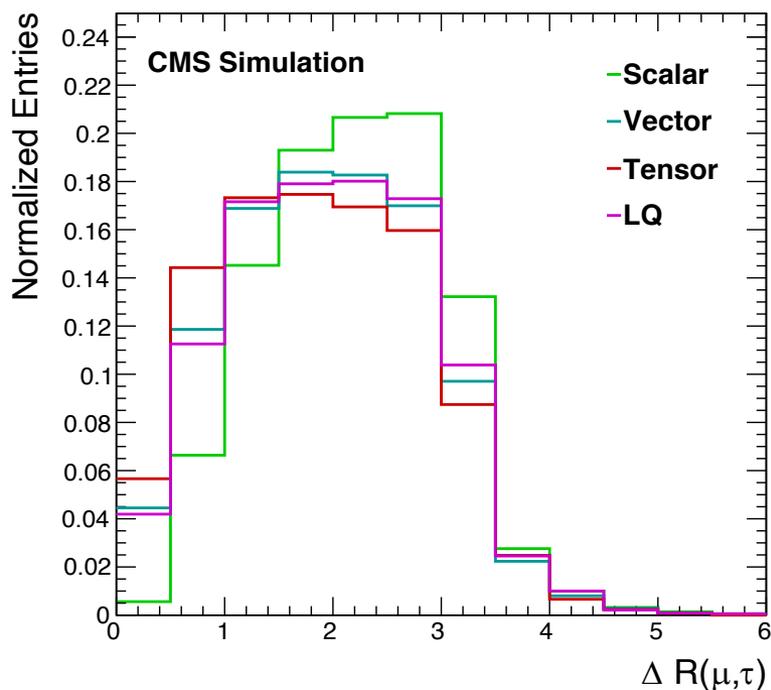
Signal cross section

For hadronic W channel in a SM top decay:

Process	Type / Interaction	Cross sections [fb]	Precision
$ST\ t\mu\tau$	Scalar	83.8	LO
	Vector	393	
	Tensor	1,796	
$ST\ t\mu\tau$	Scalar	7.40	LO
	Vector	36.8	
	Tensor	178.4	
$t\bar{t}\ t\mu\tau$	Scalar	2.69	NNLO
	Vector	21.5	
	Tensor	129.0	

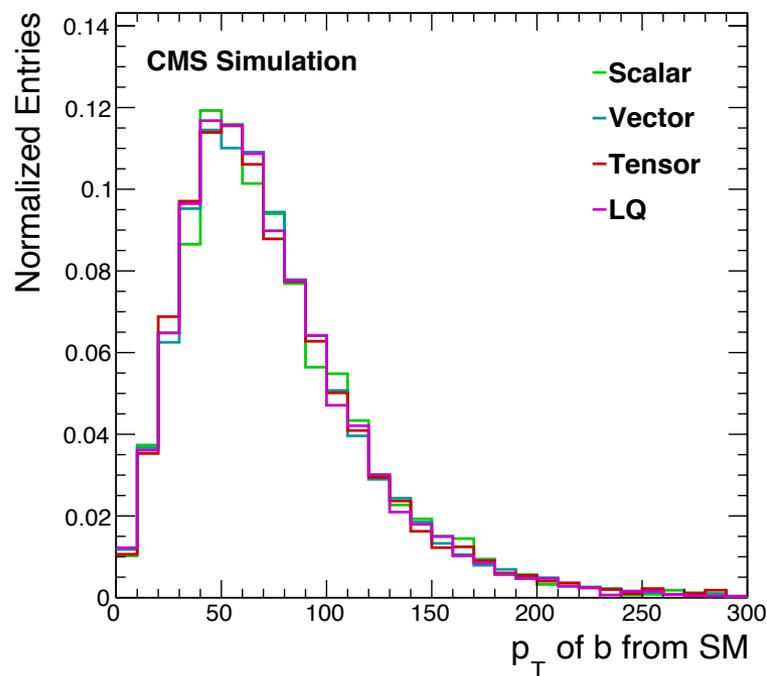
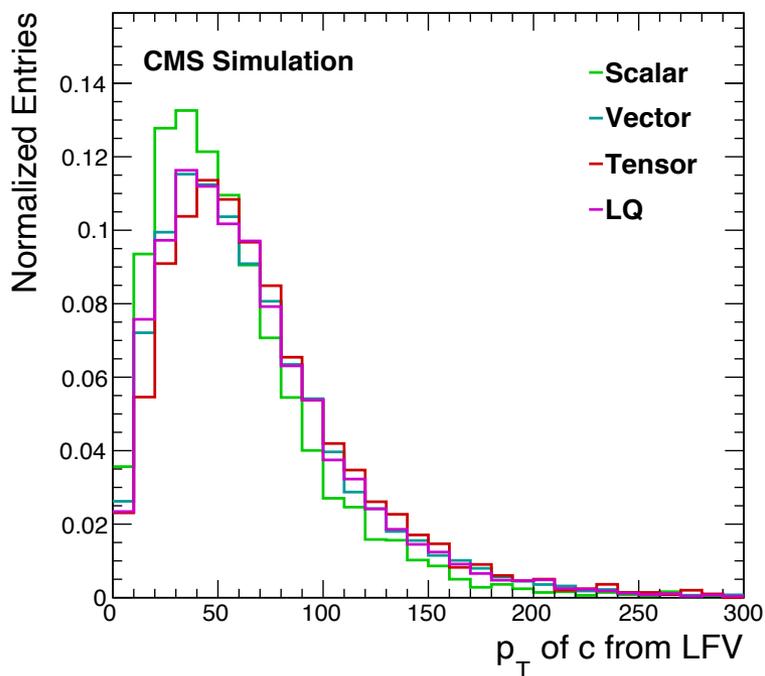
Signal distributions

- In this talk, we only probe tau/muon final state
- Comparisons with three different operators together with leptoquark model
- ΔR and mass between muon and tau



Signal distributions

- In this talk, we only probe tau/muon final state
- Comparisons with three different operators together with leptoquark model
- p_T of charm quark from LFV signal and bottom quark from the SM



Event selection

- Main backgrounds are dilepton events and $t\bar{t}$ events
- Following events selection is applied

- Exactly one isolated muon
 - $P_t > 30 \text{ GeV}$, $|\eta| < 2.4$
 - Should be no extra muon or electron that passes loose selection
- Exactly one tau
 - Should be identified as hadronic tau
 - $P_t > 30 \text{ GeV}$, $|\eta| < 2.3$
 - $\Delta R(\text{tau}, \text{muon}) > 0.4$
- $N_{\text{jets}} > 3$
 - $P_t > 30 \text{ GeV}$, $|\eta| < 2.4$
 - $\Delta R(\text{jet}, \text{muon}) > 0.4$ and $\Delta R(\text{jet}, \text{tau}) > 0.4$
- Exactly one b-tagged jet
- $10 < \text{MET} < 70 \text{ GeV}$ (lower MET than $t\bar{t}$ dilepton)

Expected number of events in Run 2 (2018 data only)

- With signal acceptance of 2 % level, we expect 1.5 times more sensitivity with full Run 2 data (137 fb^{-1})
- Main background is $t\bar{t}$ events from semi-leptonic and dileptonic channels

Samples (59.74 fb^{-1})	One Muon	One Tau	jet ≥ 4	b jet = 1	10 < MET < 70GeV
LFV Scalar	87.2	12.1	7.87	4.31	3.42
LFV Vector	664.0	88.0	57.8	32.1	25.5
LFV Tensor	3,980.0	521.0	353.0	193.0	157.0
$t\bar{t}$ Semileptonic	3,662,093.0	25,572.0	12,878.0	5,429.0	3,216.0
$t\bar{t}$ Dileptonic	1,256,888.0	73,129.0	21,175.0	8,275.0	3,509.0
$t\bar{t}$ Hadronic	8,268.0	93.8	56.0	31.8	24.6
DY	21,485,546.0	185,389.0	3,715.0	758.0	383.0
Single Top	1,125,780.0	11,642.0	1,729.0	833.0	394.0
W+Jets	381,959,405.0	287,612.0	3,622.0	599.0	384.0
$t\bar{t} + X$	9,489.0	354.0	233.0	93.6	35.7
VV	642,639.0	11,998.0	540.0	109.0	41.3
QCD	49,720,407.0	82,482.0	1,257.0	164.0	155.0
Total MC	459,870,515.0	678,272.0	45,206.0	16,292.0	8,143.0
Significance (S/\sqrt{B} , Scalar)	0.0041	0.0147	0.037	0.0337	0.0379
Significance (S/\sqrt{B} , Vector)	0.031	0.107	0.272	0.251	0.283
Significance (S/\sqrt{B} , Tensor)	0.186	0.633	1.66	1.51	1.74
Acceptance (% , Scalar)	54.3	7.55	4.9	2.68	2.13
Acceptance (% , Vector)	51.7	6.85	4.5	2.5	1.99
Acceptance (% , Tensor)	51.6	6.76	4.58	2.5	2.03

c=l

Main background $t\bar{t}$

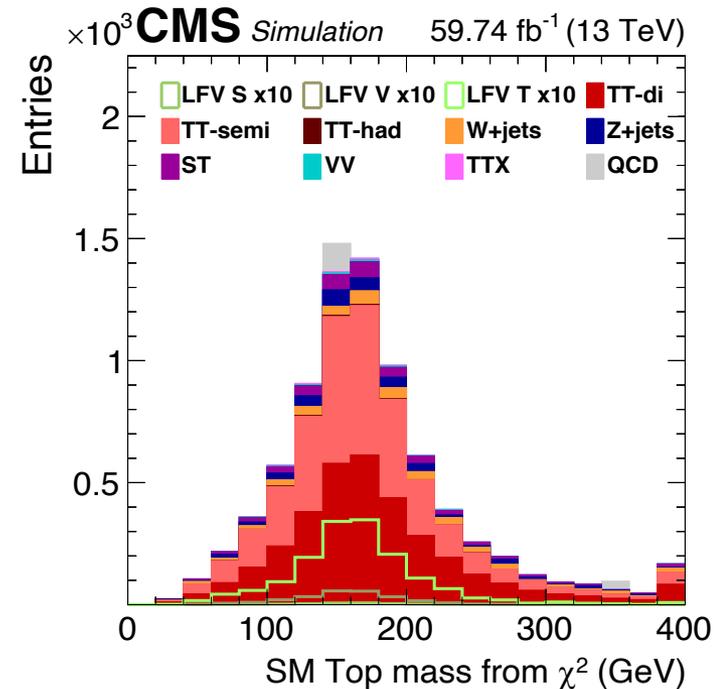
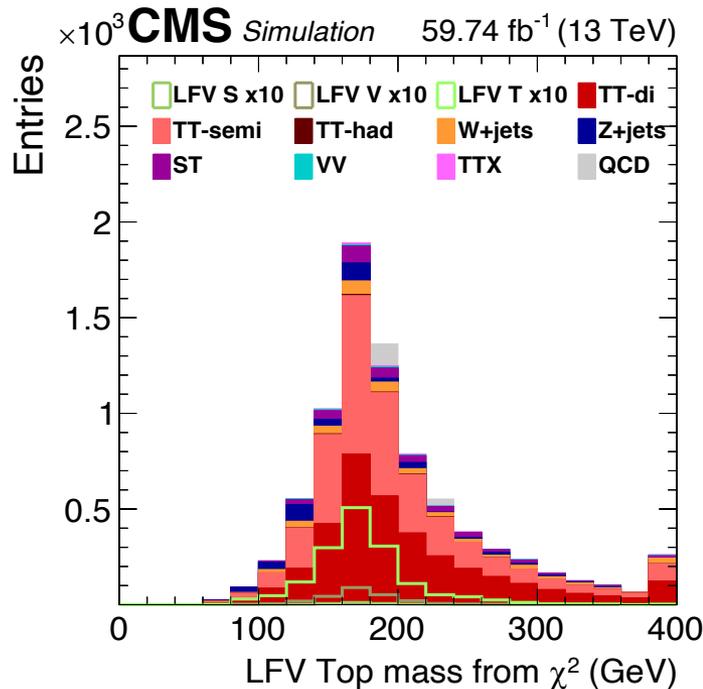
significance

acceptance

Top quark mass reconstruction

- Looping over the correct jets for top quark reconstruction
- Take the combination with the minimum χ^2

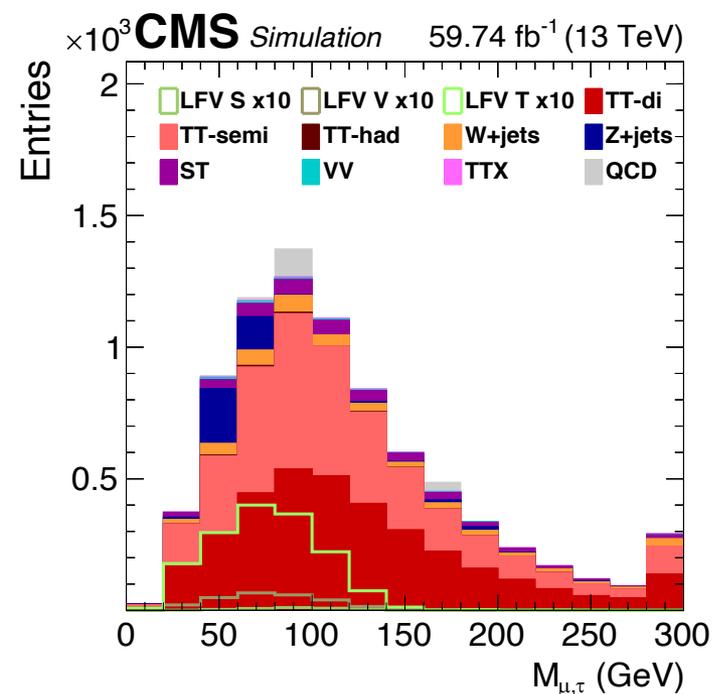
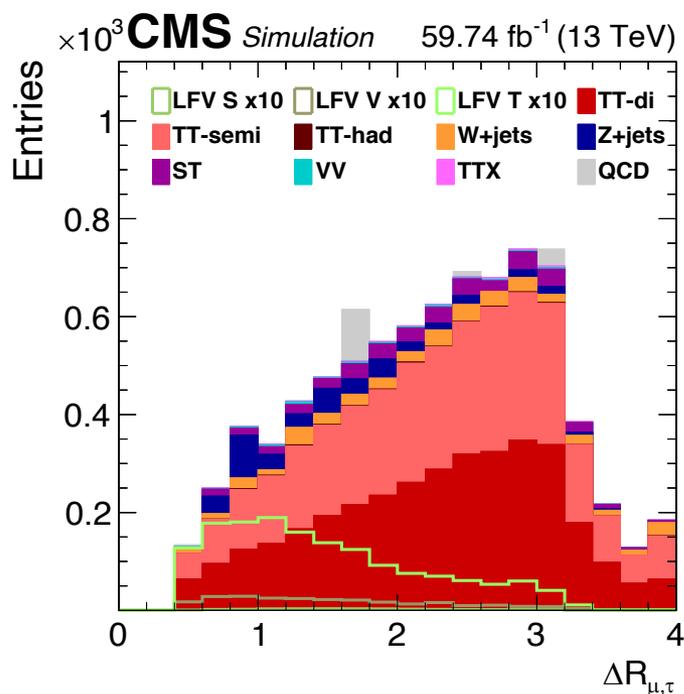
$$\chi^2 = \left(\frac{M_{j\mu\tau} - M_{Top}}{\Gamma_{Top}} \right)_{LFV,Top}^2 + \left(\frac{M_{bjj} - M_{Top}}{\Gamma_{Top}} \right)_{SM,Top}^2 + \left(\frac{M_{jj} - M_W}{\Gamma_W} \right)_{SM,W}^2$$



Normalized to 59.7 fb⁻¹

ΔR and mass of charm and muon

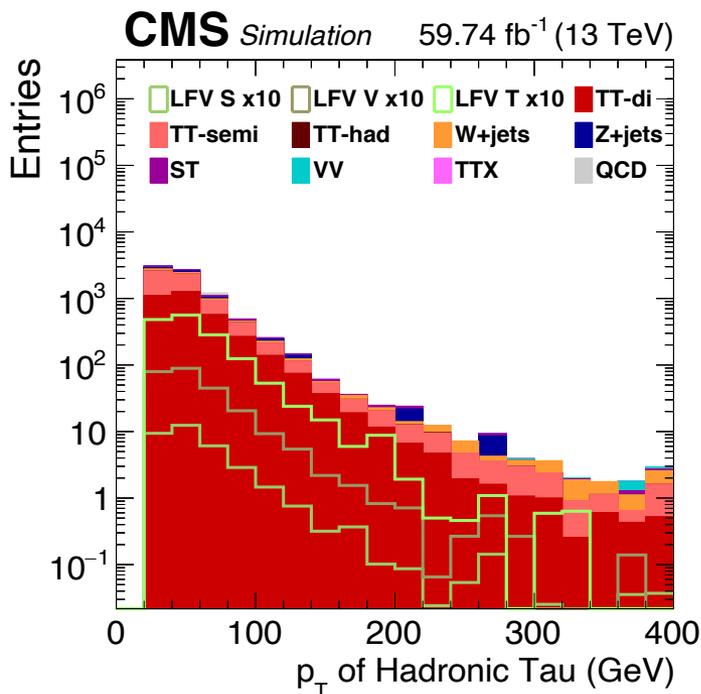
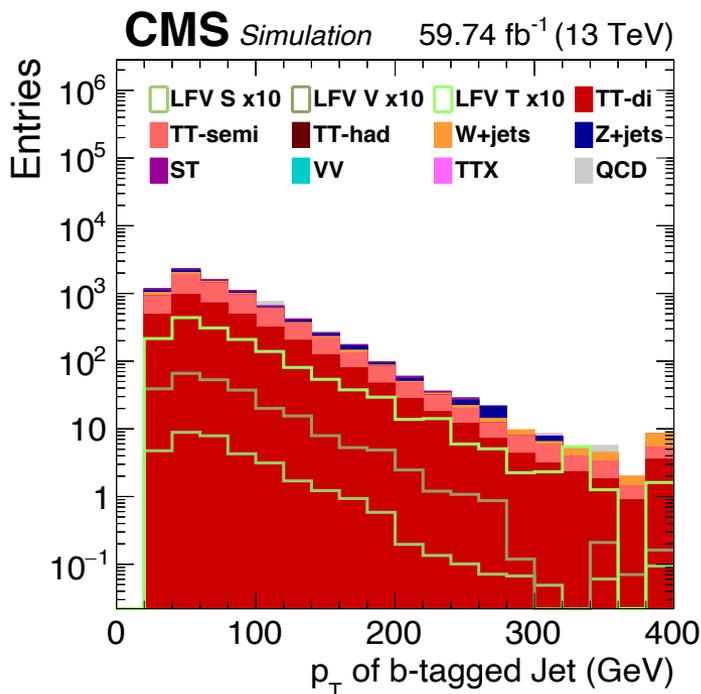
- One of the best discriminant variables
- LFV signal shows narrow angle between tau and muon



Normalized to 59.7 fb⁻¹

p_T of b-jet and tau-jet

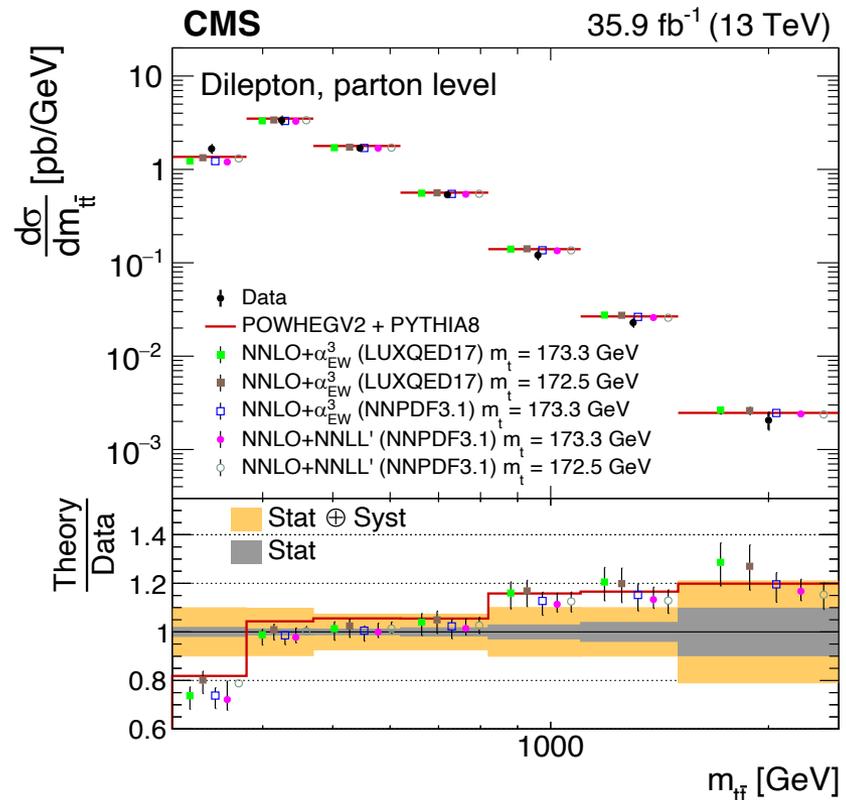
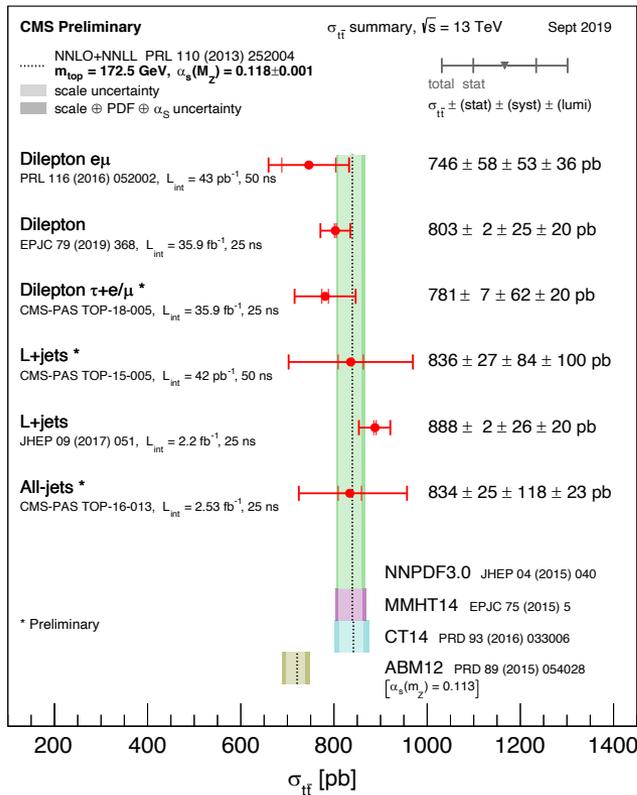
- Hadronic tau from LFV has harder distribution



Normalized to 59.7 fb⁻¹

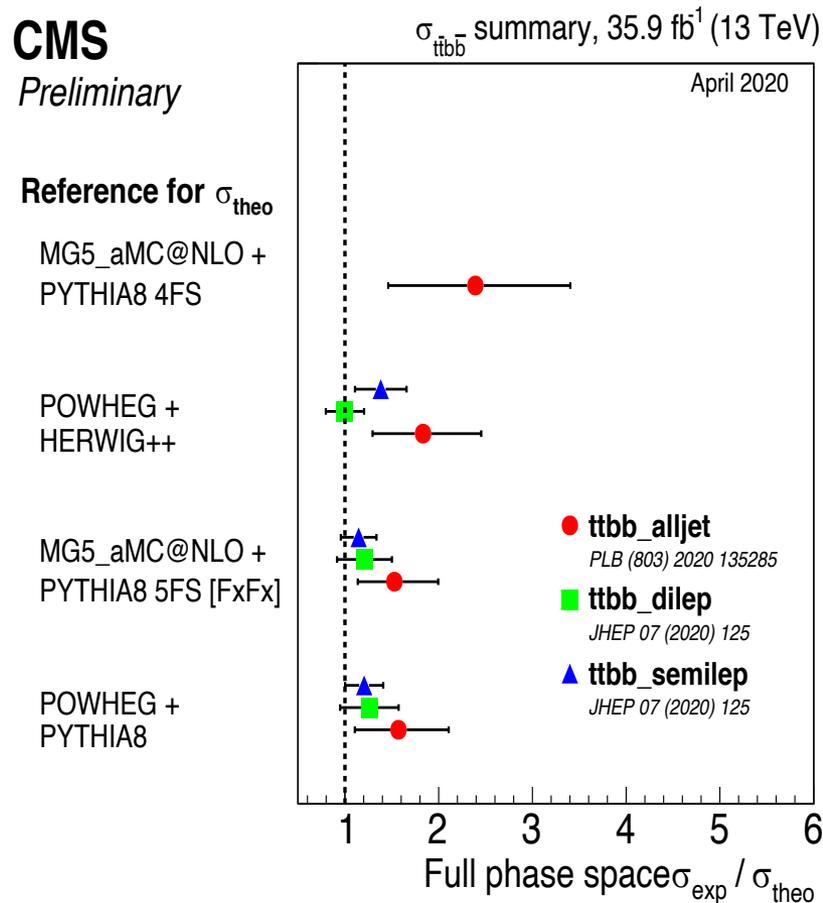
$t\bar{t}$ is the main background for LFV searches in top sector

- We should understand $t\bar{t}$ process precisely: we are already at the NNLO level
- If you see any deviation in the $t\bar{t}$ dominant area, it could be possible new physics



How much do we understand $t\bar{t} + \text{heavy flavor}$?

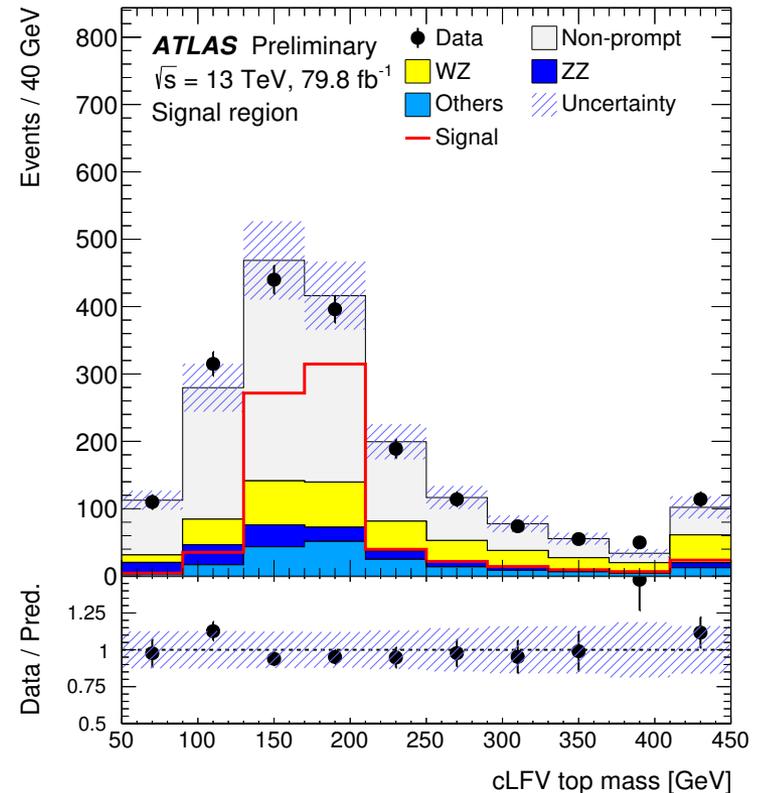
- $t\bar{t} + b\bar{b}$ is the main background for most of BSM searches and available at NLO
- The measured ratio of $t\bar{t} + b\bar{b}$ is consistently higher than prediction
- Consistently shows deviation from the SM in the $t\bar{t} + b\bar{b}$ process though



Lepton Flavor Violation in top quark decays at the LHC

ATLAS-CONF-2018-044

- ATLAS showed the first direct search for charged lepton flavor violation (cLFV) :
 $t \rightarrow \ell \ell' q, q = u, c$
- Other top decays in the SM
- Model independent direct search
- Three isolated charged leptons are required
- Top quark in cLFV is reconstructed from two opposite sign different flavor leptons and a jet
- Main background : $t\bar{t}$, Z+jets



Signal normalized to
 $B(t \rightarrow \ell \ell' q) = 3 \times 10^{-4}$

Lepton Flavor Violation in top quark decays

ATLAS-CONF-2018-044

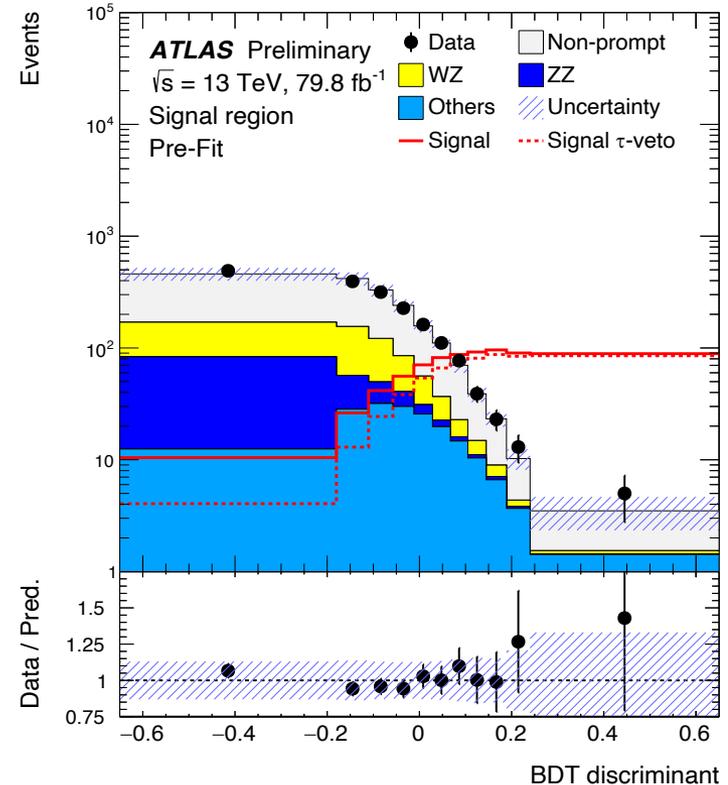
- Background samples are modelled mostly at NLO and NNLO level

Sample	Generator	ME PDF	Shower	Tune	Normalisation
$t\bar{t} \rightarrow \ell\ell + \text{jets}$	PowHEG	NNPDF3.0	PYTHIA 8	NNPDF2.3 A14	NNLO+NNLL
$t\bar{t}\gamma$	MG5_aMC	NNPDF2.3	PYTHIA 8	NNPDF2.3 A14	NLO
$Z \rightarrow \ell\ell + \text{jets}$	SHERPA 2.2.1	NNPDF3.0			NNLO
$Z\gamma$	SHERPA 2.2.2	NNPDF3.0			NLO
$3\ell\nu$	SHERPA 2.2.2	NNPDF3.0			NLO
4ℓ	SHERPA 2.2.2	NNPDF3.0			NLO
$t\bar{t}Z (Z \rightarrow \ell\ell)$	MG5_aMC	NNPDF3.0	PYTHIA 8	NNPDF2.3 A14	NLO
$t\bar{t}W$	MG5_aMC	NNPDF3.0	PYTHIA 8	NNPDF2.3 A14	NLO
$t\bar{t}H$	MG5_aMC	NNPDF3.0	PYTHIA 8	NNPDF2.3 A14	NLO
$tZ (3\ell)$	MG5_aMC	NNPDF3.0	PYTHIA 8	NNPDF2.3 A14	LO
tW	PowHEG	CT10	PYTHIA 6	CTEQ6L1 P2012	LO
tWZ	MG5_aMC	NNPDF3.0	PYTHIA 8	MMHT2014	NLO
$tH (H \rightarrow WW, ZZ, \tau\tau)$	MG5_aMC	CT10	PYTHIA 8	NNPDF23 A14	LO
Triboson	SHERPA 2.2.2	NNPDF3.0			LO
Others:					
$2\ell 2\nu$	SHERPA 2.2.2	NNPDF3.0			NLO
$2\ell 2q$	SHERPA 2.2.1	NNPDF3.0			NLO
$4t$	MG5_aMC	NNPDF2.3	PYTHIA 8	NNPDF2.3 A14	NLO
$3t$	MG5_aMC	NNPDF2.3	PYTHIA 8	NNPDF2.3 A14	NLO
$t\bar{t}WW$	MG5_aMC	NNPDF3.0	PYTHIA 8	NNPDF2.3 A14	NLO
WH, ZH	PYTHIA 8	NNPDF2.3	PYTHIA 8	NNPDF2.3 A14	NLO

- Can constrain axial-vector, scalar, pseudo-scalar and lepton-quark EFT operators

$$\mathcal{B}(t \rightarrow \ell\ell'q) < 1.86 \times 10^{-5} \quad (\text{observed})$$

$$\mathcal{B}(t \rightarrow e\mu q) < 6.6 \times 10^{-6} \quad (\text{no } \tau \text{ in cLFV vertex, observed})$$



Conclusion

- Deviations from LHCb and Belle experiments and also from $g-2$ experiment need to be also confirmed by CMS
- Instead of B sector, we can also search for the LFV in top quark sector as the LHC is a top quark factory
- Pursued model independent approach to search for LFV
- There must be something going in these deviations
- Should have better idea with our CMS data soon in coming years