LFV and FCNC from CMS

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For Flavor Physics mini-workshop

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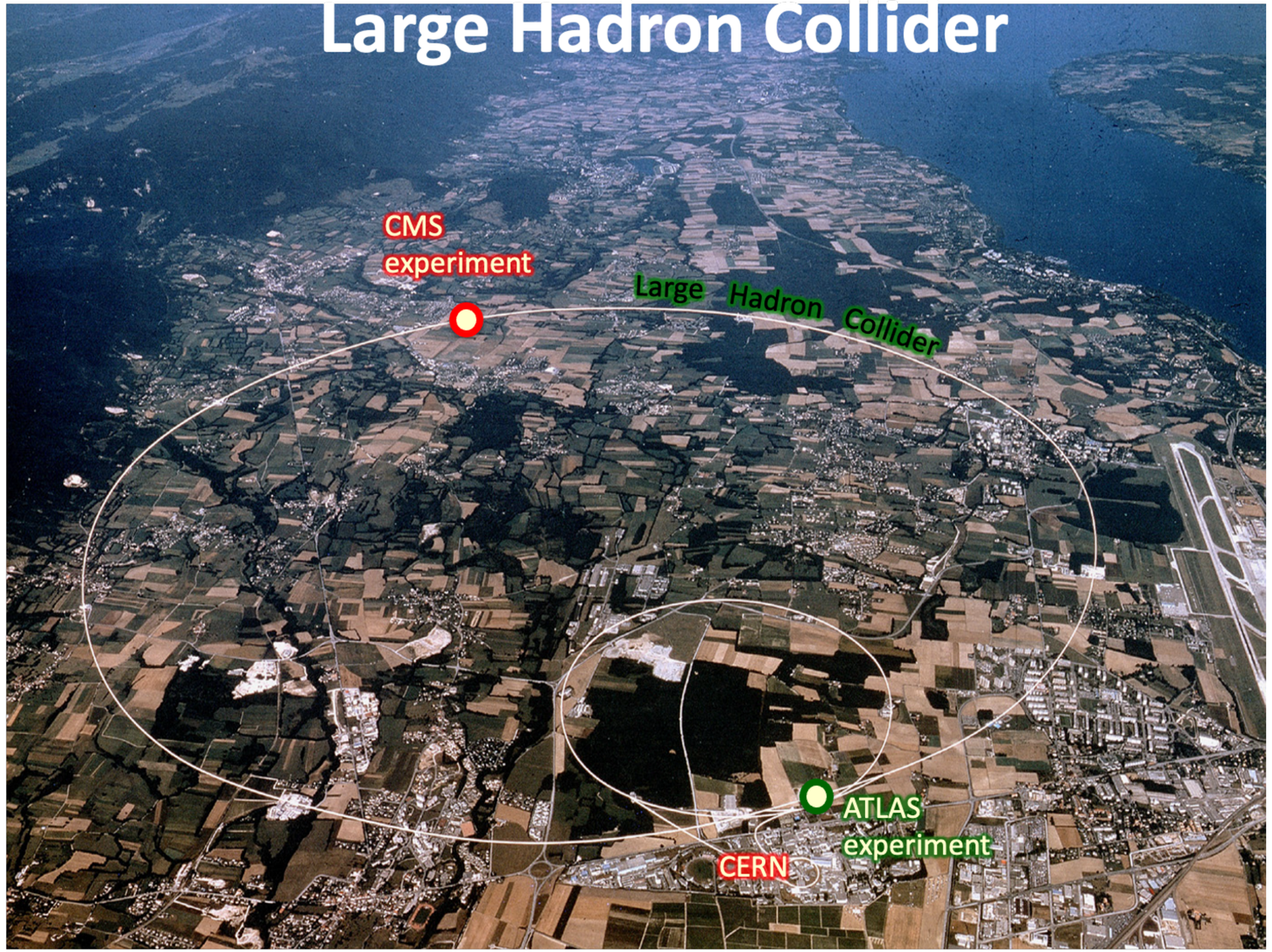
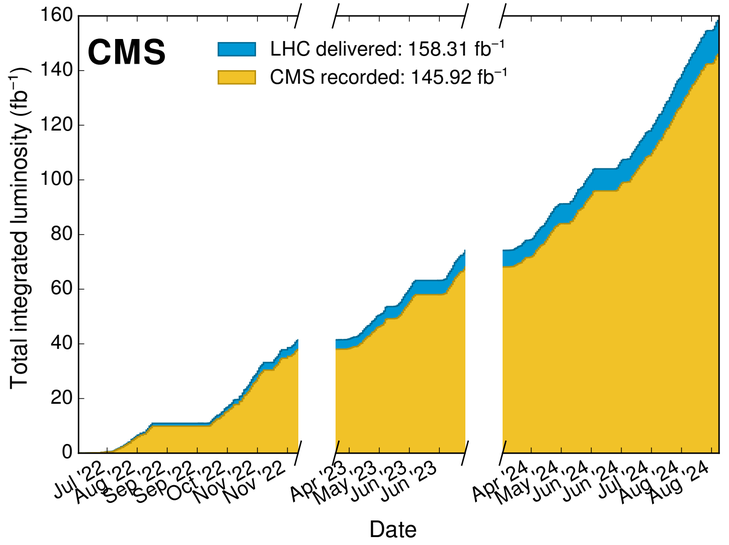
LHC

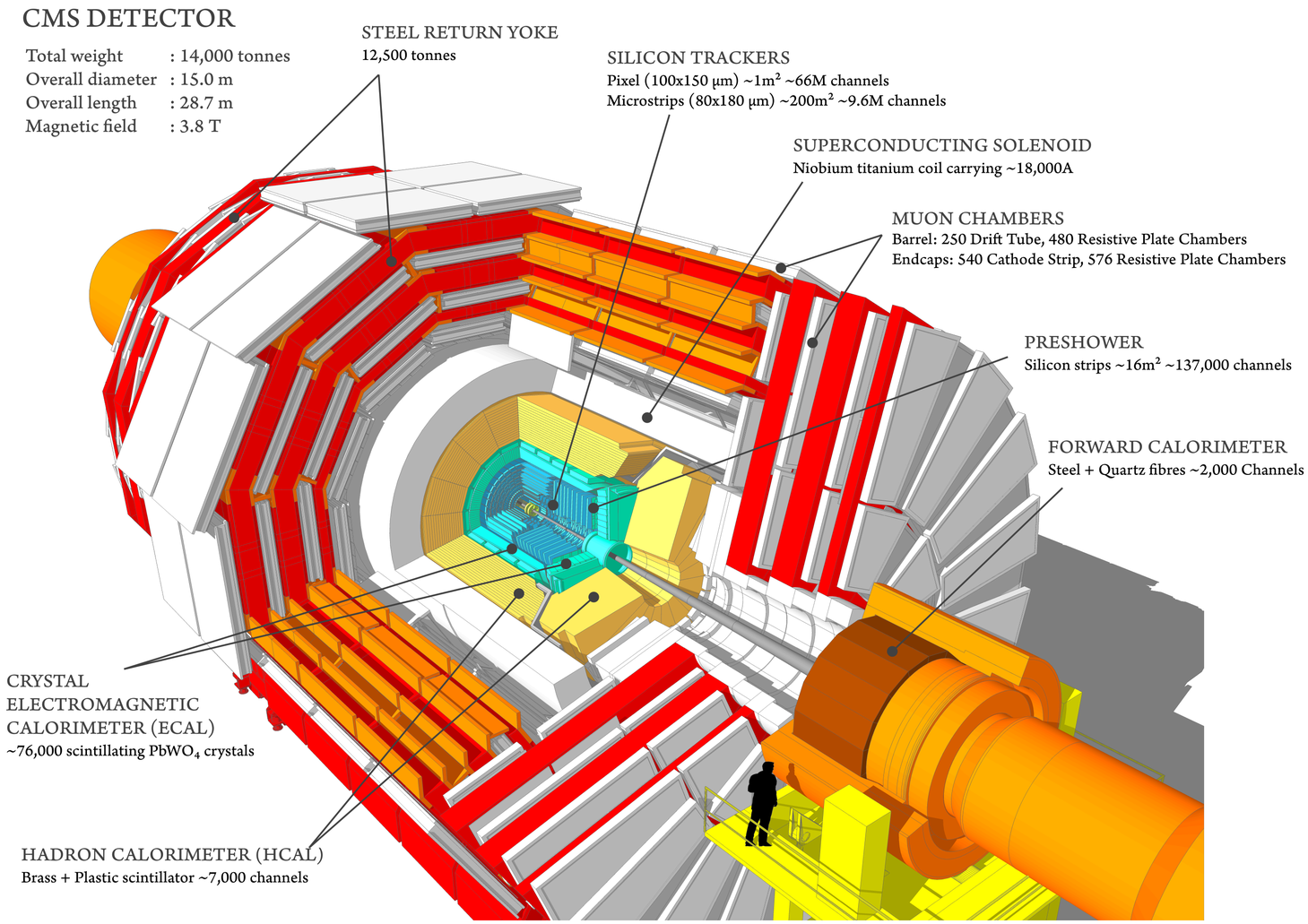


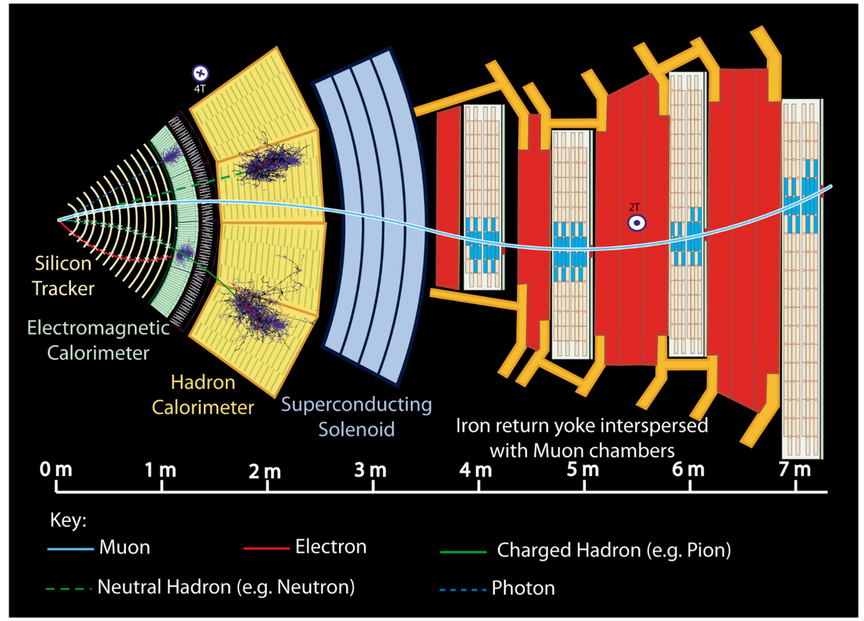
- 27 km circumference
- For Run2, operated at 13 TeV
  - Integrated L :138 fb^{-1}
- Proton-proton collisions at 13.6 TeV for Run 3
  - Integrated L :146 fb^{-1}



CMS

Compact Muon Solenoid





- 20 m long, 14 m high
- General purpose detector (same for ATLAS)
- Measure (new) particle ID, energy, direction
- Various physics programs

Motivation

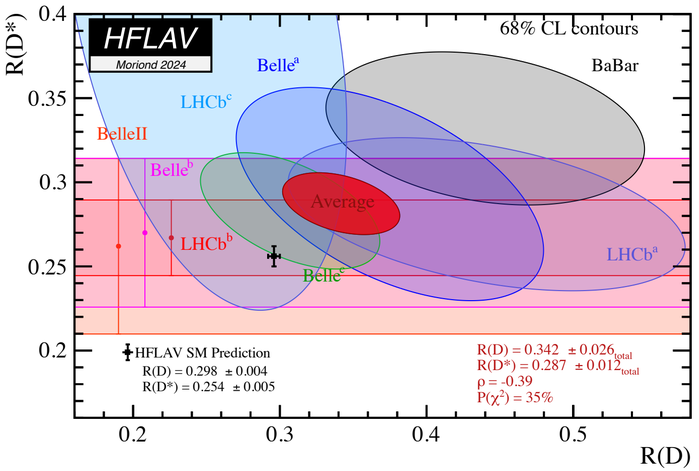
- Searching for rare processes such as charged-Lepton Flavor Violation (cLFV) and Flavor changing Neural Current (FCNC) is one of the most interesting research topic in top quark physics

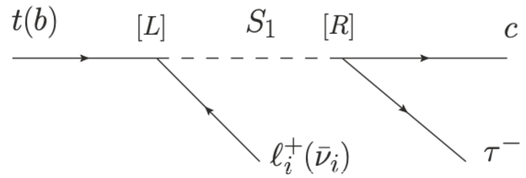
- cLFV can be the culprit for the anomalies hinted in B meson decays

- FCNC is suppressed in the SM by the GIM mechanism - branching fraction ~ 10^{-15} not accessible within the LHC

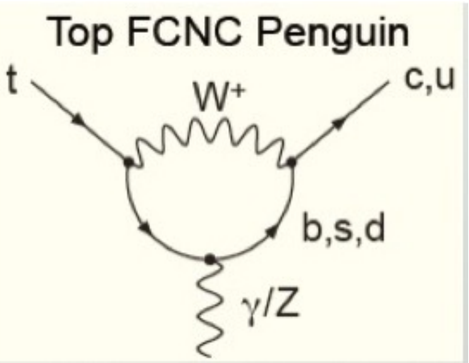
- However, many scenarios beyond the SM predict enhanced branching fraction by many orders of magnitude

- cLFV and FCNC should be sensitive to new physics!



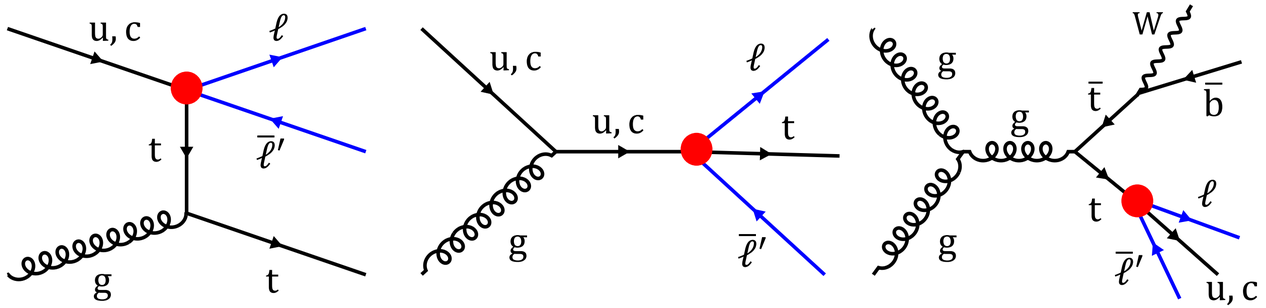


JHEP 07 (2019) 025



cLFV searches in CMS

- Assuming the mass scale of new physics is larger than the energy scale at the LHC, a model independent EFT is followed



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	$O_{lequ}^{(3)ijkl}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l)$

- D6 operators weighted by the Wilson coefficients (C_x)

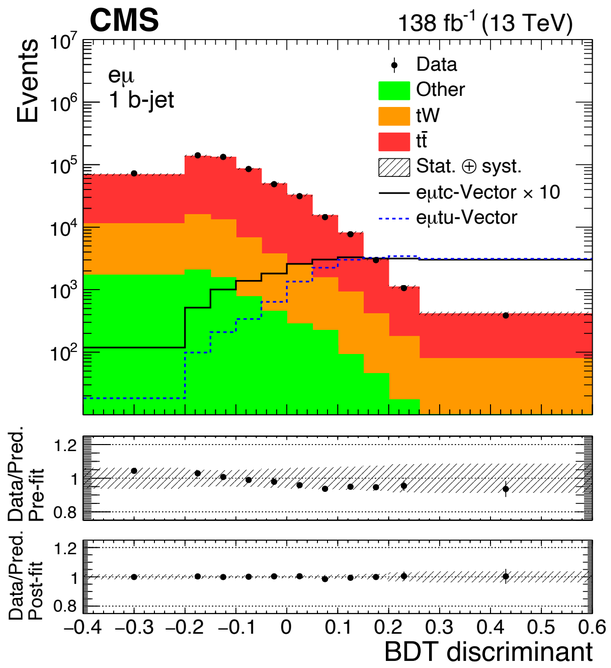
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{\mathrm{C}_x}{\Lambda^2} O_x + \cdots$$

- The result is integrated in terms of limits on vector, scalar and tensor four-fermion interactions from dimension 6 operators within the EFT

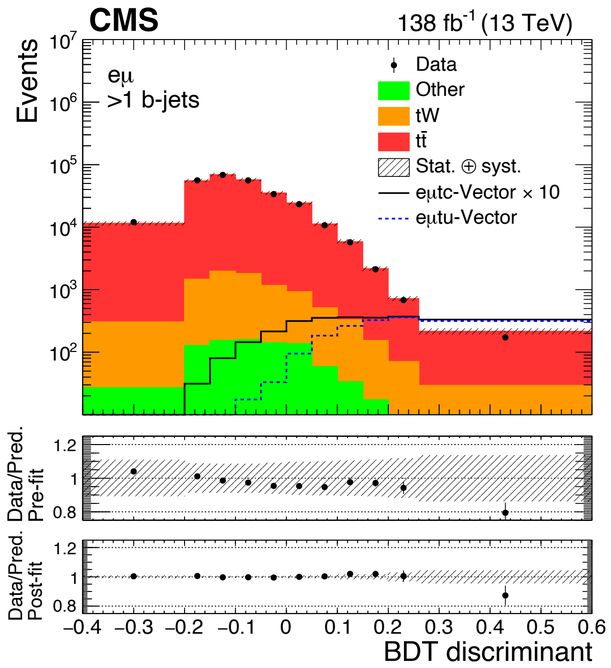
cLFV in dilepton final state

138 fb^{-1} JHEP 06 (2022) 082

- Final states: an oppositely charged $e\mu$ pair and a top quark decaying hadronically
- Event selection
  - Leptons should have opposite charge and at least one b-tagged jet
- Signal extraction
  - Boosted Decision Tree (BDT) was used to extract the LFV signal
  - 5 variables: p_{T} of leading lepton, p_{T} of jet, distance between e and μ, MET, njet
  - cLFV single top production plays a leading role



Exactly one b-tagged jet
Signal region

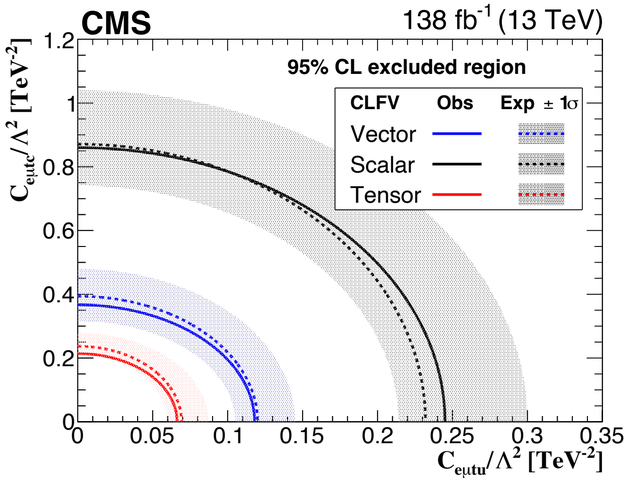


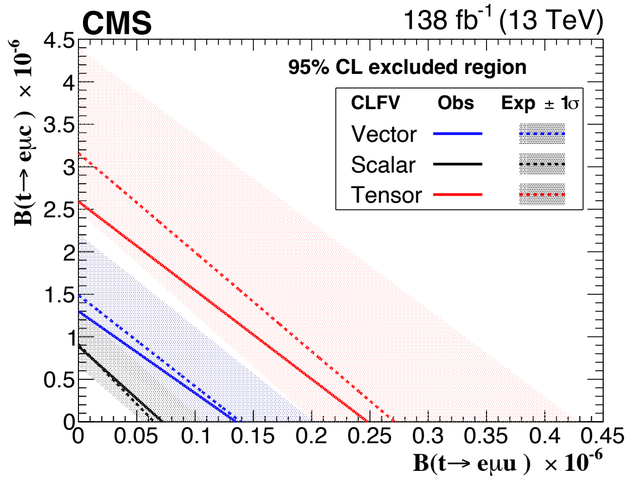
More than one b-tagged jet
$t\bar{t}$ control region

cLFV in dilepton final state

138 fb^{-1} JHEP 06 (2022) 082

- Main systematic uncertainties
  - b-tagging, ISR/FSR scale
- The limit on the tensor cLFV Wilson coefficient is more stringent than others due to its large cross section
- Translating into limits on the branching fractions, more stringent limits on scalar operator



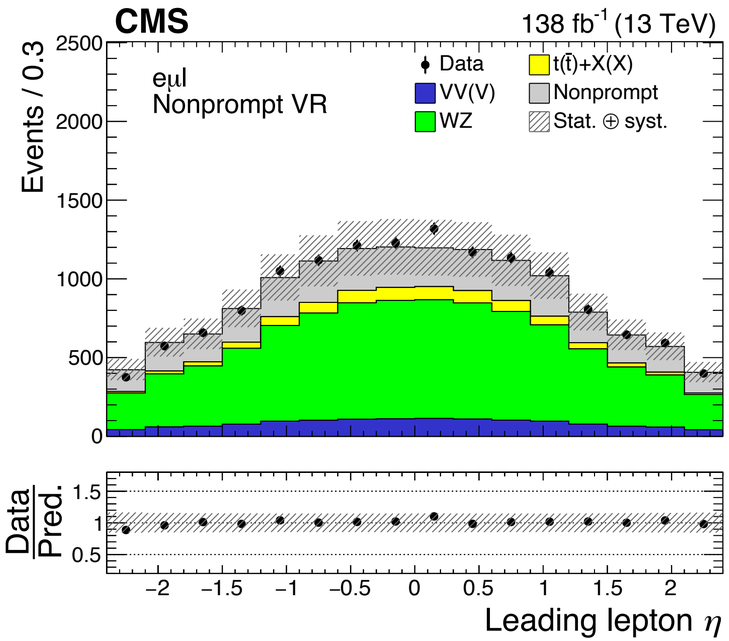


Vertex	Int. type	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
eμtu	Vector	0.12	0.12	0.14	0.13
	Scalar	0.23	0.24	0.06	0.07
	Tensor	0.07	0.06	0.27	0.25
eμtc	Vector	0.39	0.37	1.49	1.31
	Scalar	0.87	0.86	0.91	0.89
	Tensor	0.24	0.21	3.16	2.59

cLFV in trilepton final state

138 fb^{-1} TOP-22-005

- Follows the same strategy in EFT as cLFV search in dilepton channel
- Considering W boson from top quark decays leptonically
- Event selection
  - Exactly three leptons with $p_{\mathrm{T}} > 38$ GeV ($\mathrm{e}\mu\mathrm{l}$)
  - MET > 20 GeV
  - At least one jet and at most one b-tagged jet
  - Signal region : OffZ - !(50 GeV < $m_{l^+l^-}$ < 106 GeV) in $\mathrm{e}\mu\mathrm{l}$ channel
- eee, $\mu\mu\mu$ channels : estimate background composition



cLFV in trilepton final state

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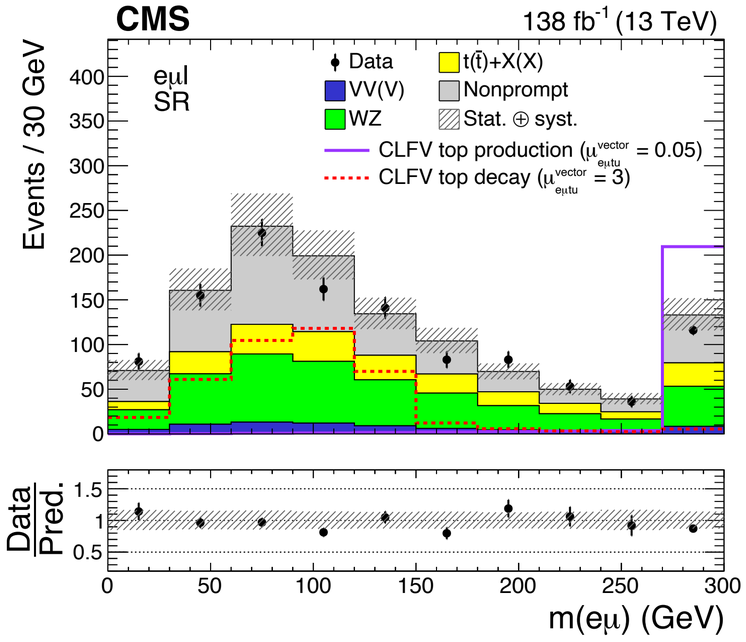
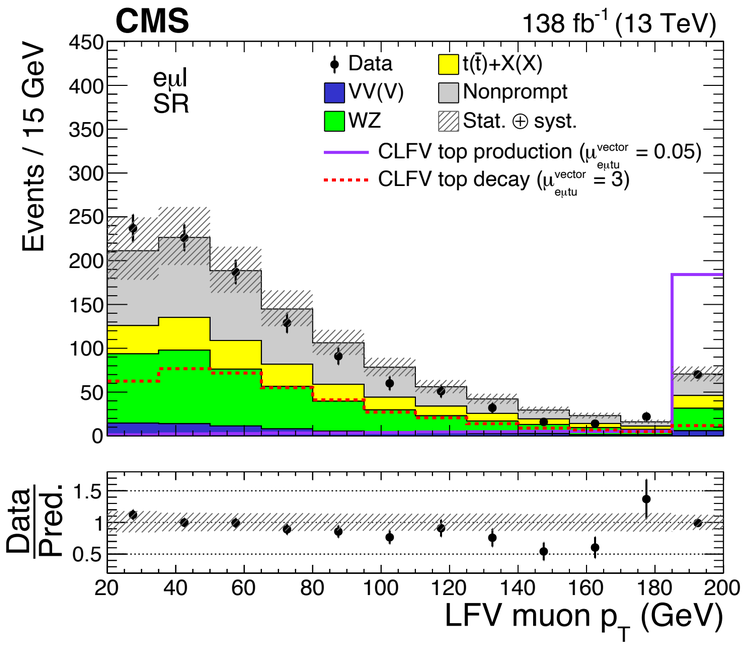
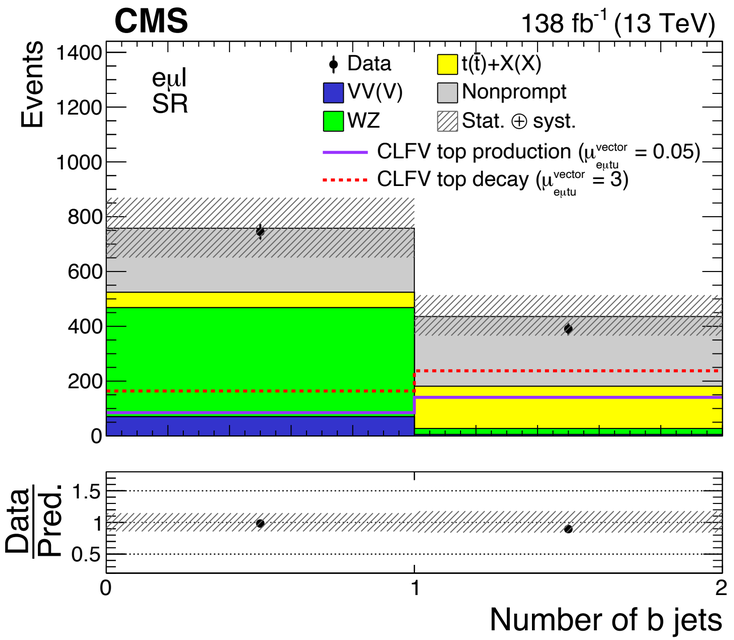


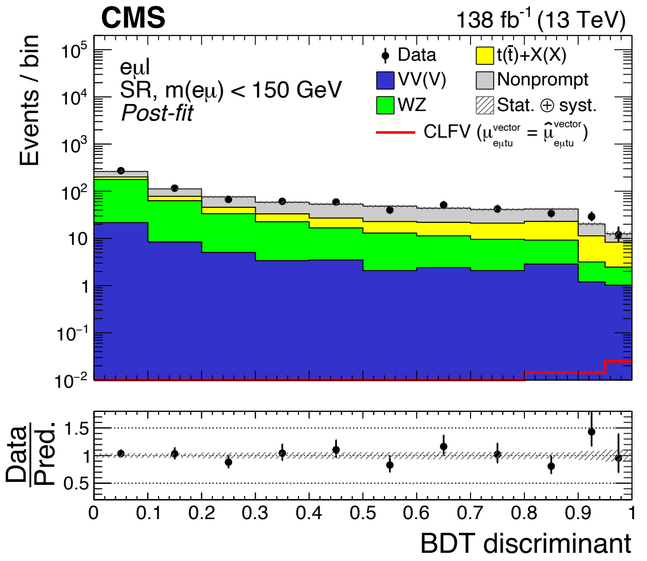


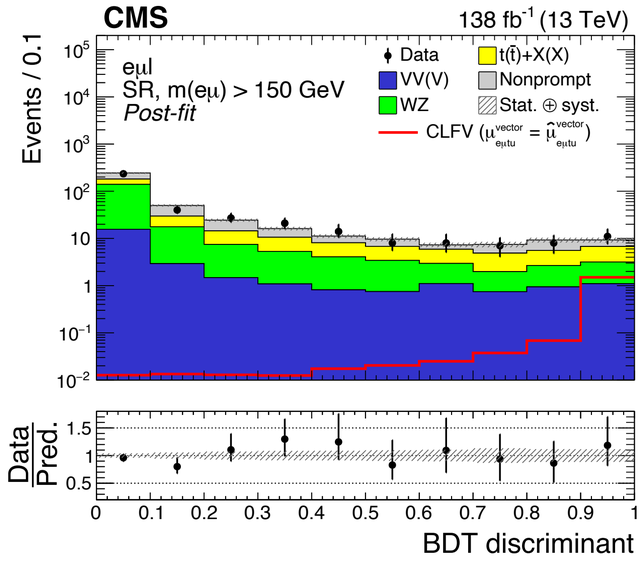


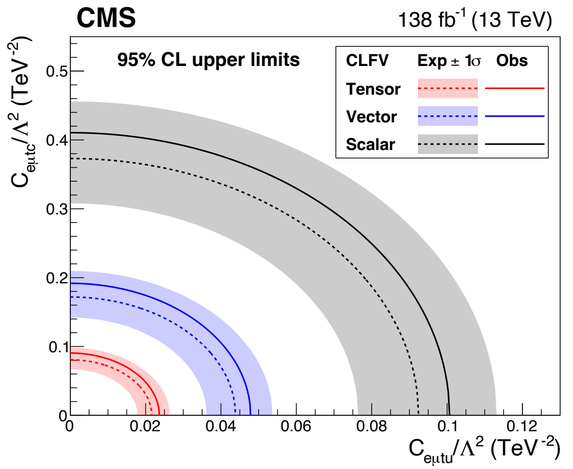
- BDT was trained in two different signal regions
  - M($e\mu$) < 150 GeV: top decay enriched, M($e\mu$) > 150 GeV: top production enriched
  - Input variables : Invariant mass of the Z boson, number of b-tagged jets and invariant mass of LFV top quark pair, p_{T} of LFV electron and muon

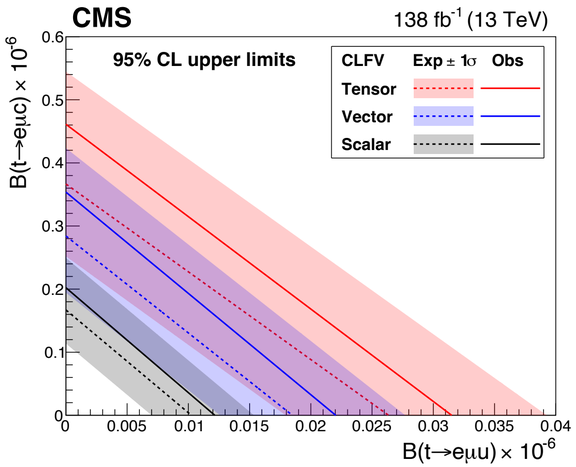
cLFV in trilepton final state

138 fb^{-1} **TOP-22-005**









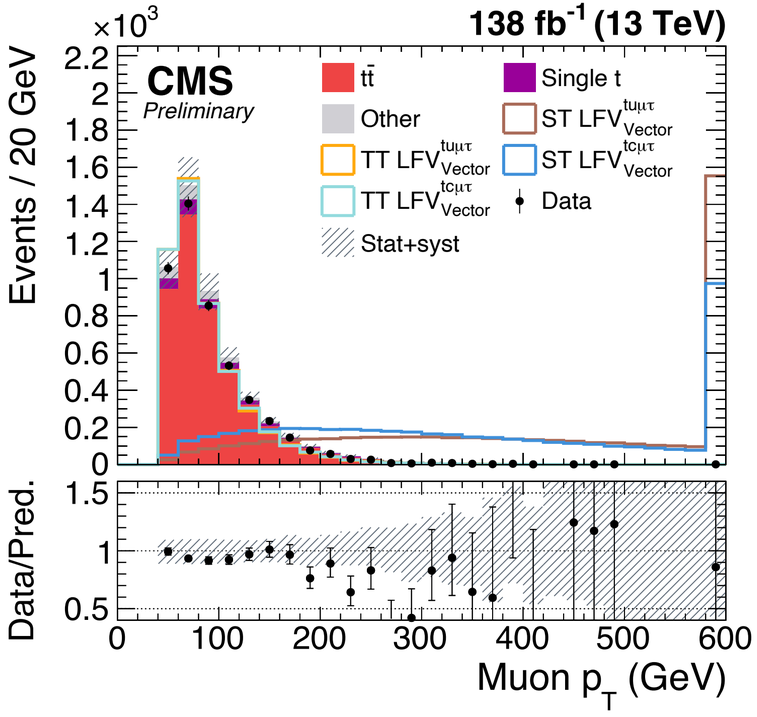
- Binned likelihood function is constructed using the BDT output
- Main systematic uncertainty - lepton ID at high p_{T}
- The most stringent limits on $B(t \to \mu^{\pm} e^{\mp} q)$ to date

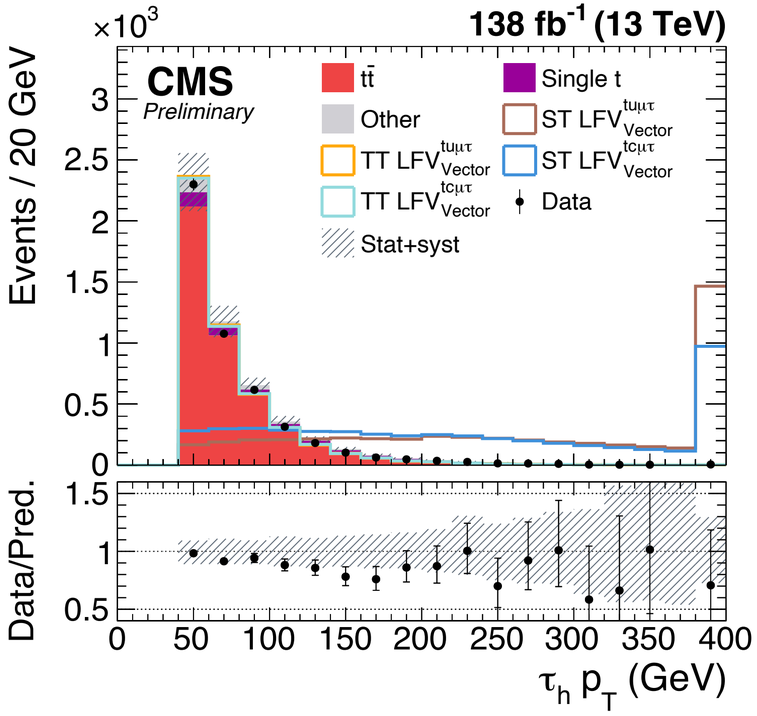
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	**Obs.**	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	**Obs.**
$e\mu tu$	Tensor	0.022 (0.018–0.026)	**0.024**	0.027 (0.018–0.040)	**0.032**
	Vector	0.044 (0.036–0.054)	**0.048**	0.019 (0.013–0.028)	**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 tau final state

138 fb-1 TOP-22-011

- Event selection
  - exactly one muon with p_T > 50 GeV, $|\eta|$<2.4
  - hadronic tau with p_T > 40 GeV, $|\eta|$<2.3 - opposite charge with μ, overlap removal with a selected μ (ΔR < 0.4)
  - at least 3 jets with p_T > 40 GeV, $|\eta|$<2.4 (overlap removal with muon and tau), one b-tagged jets





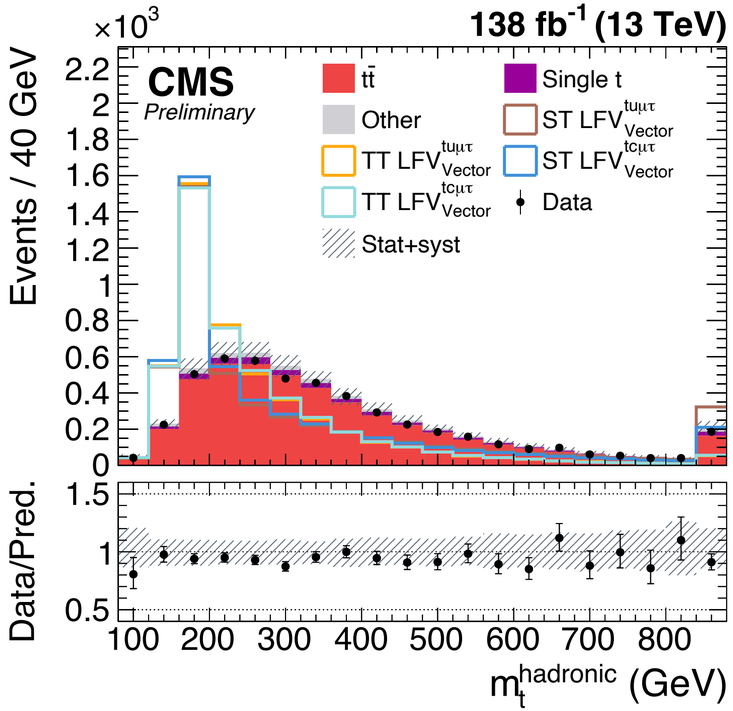
138 fb-1 TOP-22-011

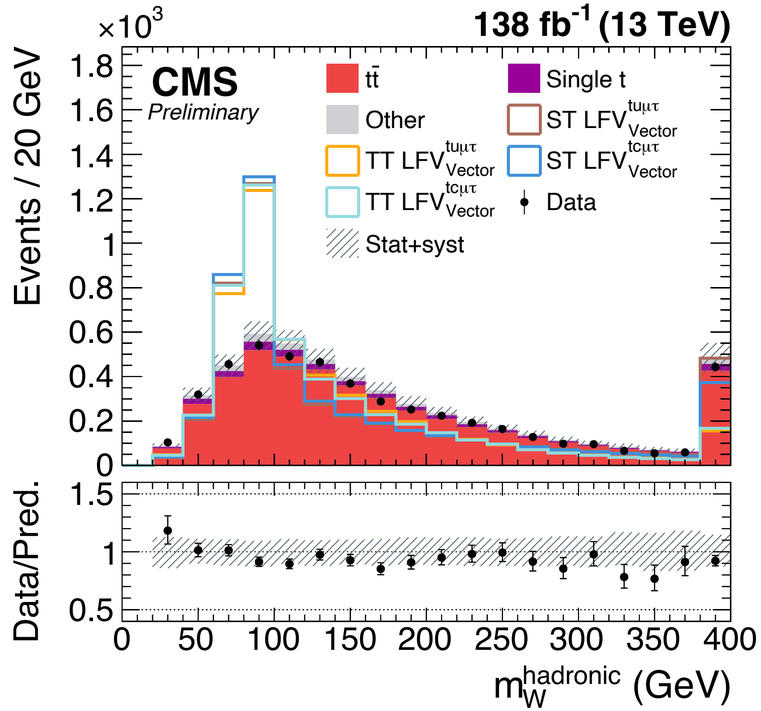
cLFV in tau final state

Reconstruction of top quark and W boson

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

- Hadronic top quark and is reconstructed
- Used as one of the input variables for the Deep Neural Network



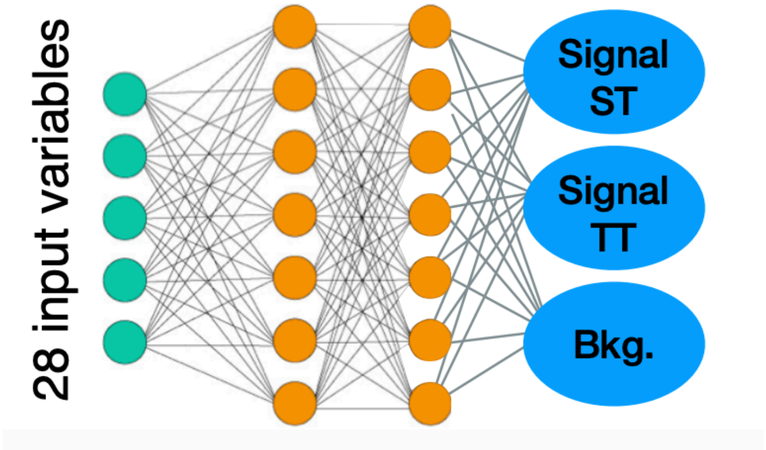


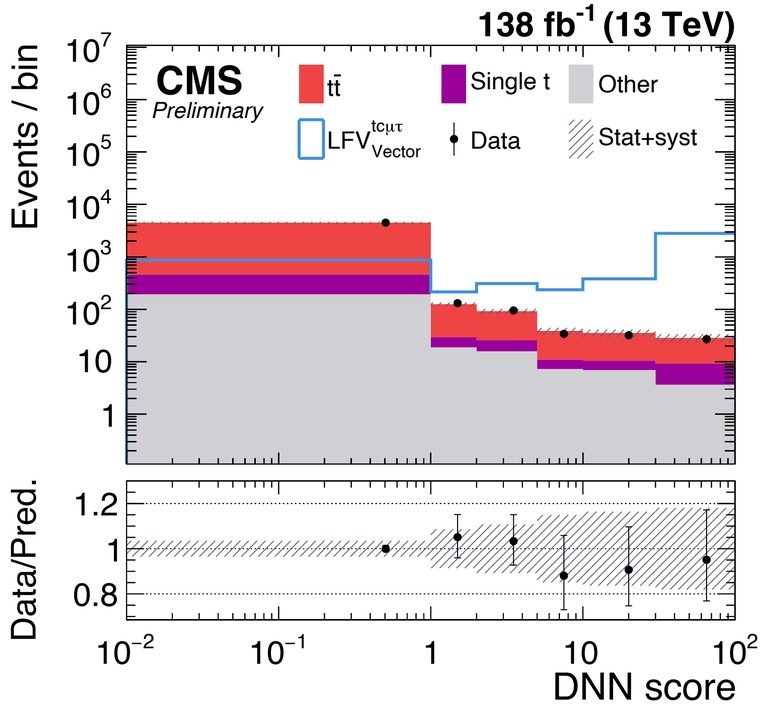
cLFV in tau final state

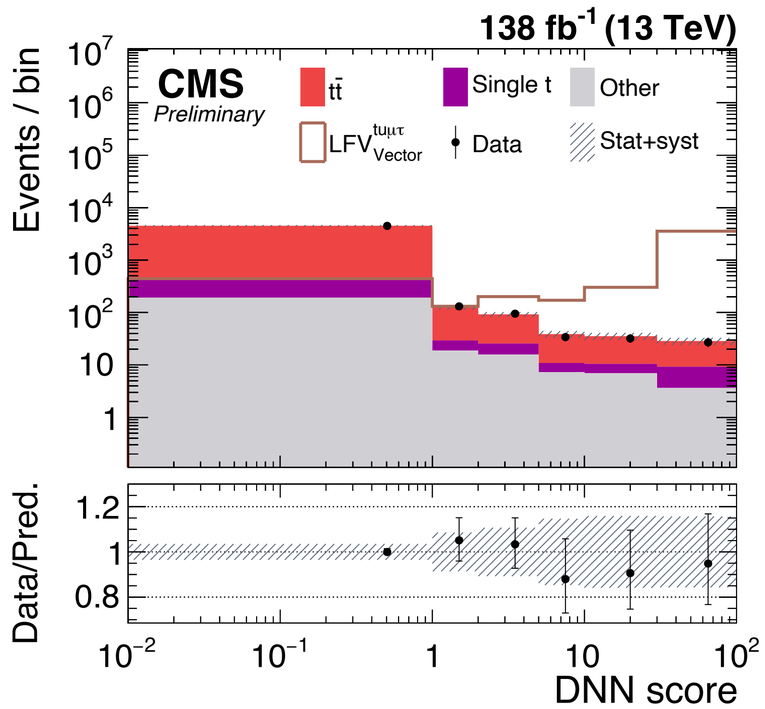
138 fb^{-1} TOP-22-011

Signal extraction

- Multi-classification: TT LFV, ST LFV and background
- new output discriminant: $$\text{DNN score} = \frac{0.1 \times P(\text{TT LFV}) + (0.9) \times P(\text{ST LFV})}{P(\text{Background})}$$







cLFV in tau final state

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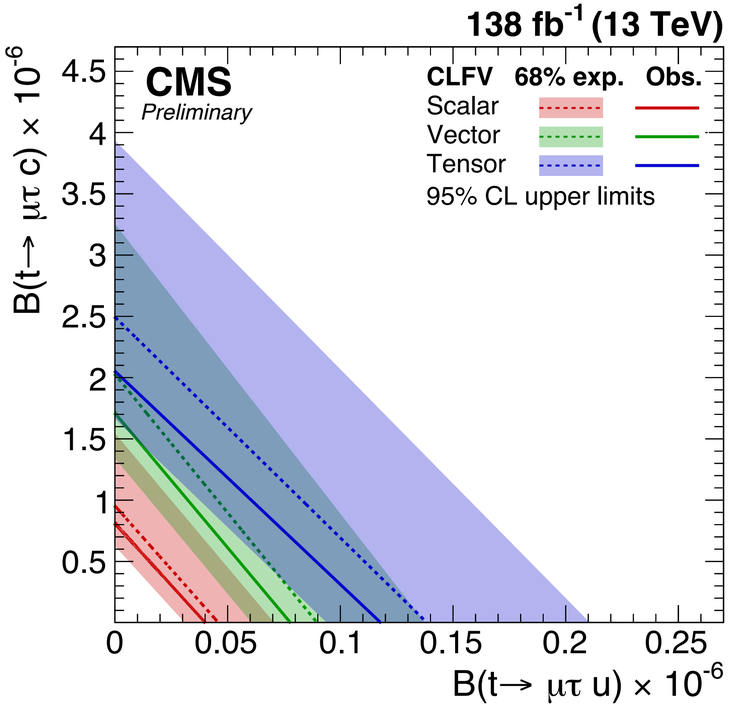
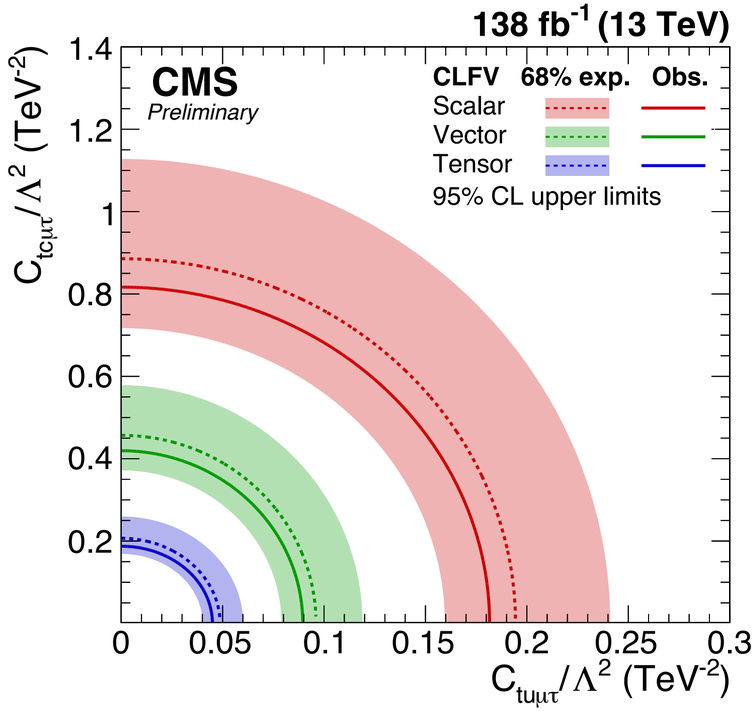
Interaction	Type	Obs. (exp.) σ (fb)	Obs. (exp.) $C_{tq\mu\tau}/\Lambda^2$ (TeV^{-2})
$tu\mu\tau$	Scalar	2.039 (2.337)	0.182 (0.194)
		[1.574, 3.594]	[0.16, 0.241]
	Vector	2.384 (2.746)	0.09 (0.096)
		[1.857, 4.213]	[0.079, 0.119]
	Tensor	2.834 (3.326)	0.045 (0.049)
		[2.257, 5.063]	[0.04, 0.06]
$tc\mu\tau$	Scalar	4.269 (5.02)	0.817 (0.886)
		[3.291, 8.142]	[0.717, 1.128]
	Vector	7.213 (8.552)	0.419 (0.457)
		[5.663, 13.734]	[0.372, 0.579]
	Tensor	7.927 (9.633)	0.188 (0.207)
		[6.427, 15.2]	[0.169, 0.26]



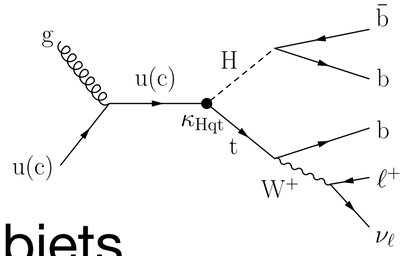


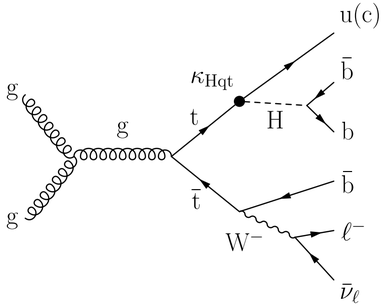
- The upper limits on the Wilson coefficients is more stringent than the ATLAS results with the final state of tau and muon [ATLAS-TOPQ-2023-23]

FCNC - $tu(c)H(b\bar{b})$

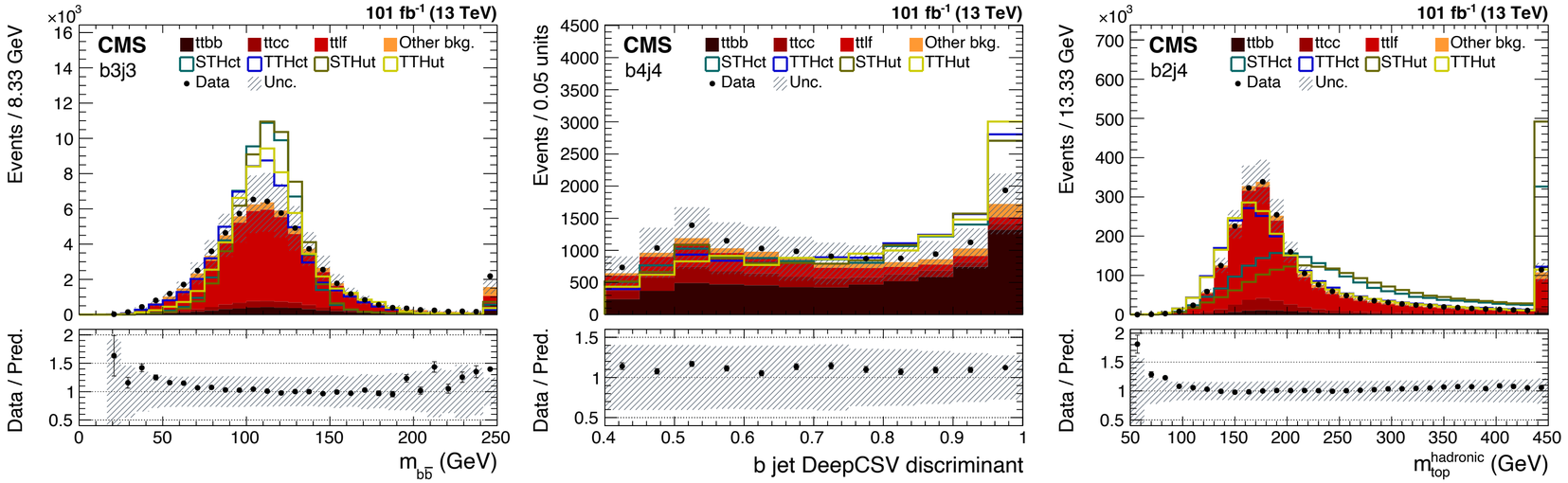
138 fb^{-1} JHEP 02 (2022) 169

- FCNC Single Top (ST) production mode and FCNC decay mode in top quark pair are considered





- Event selection
  - Exactly one lepton and categorized depending on njets and nbjets



- Depending on the event categories, different assumptions of event processes ($t\bar{t}$, $t \to qH$,single top) are made
  - Deep neural network (DNN) was used for the correct jet assignment

FCNC - $tu(c)H(b\bar{b})$

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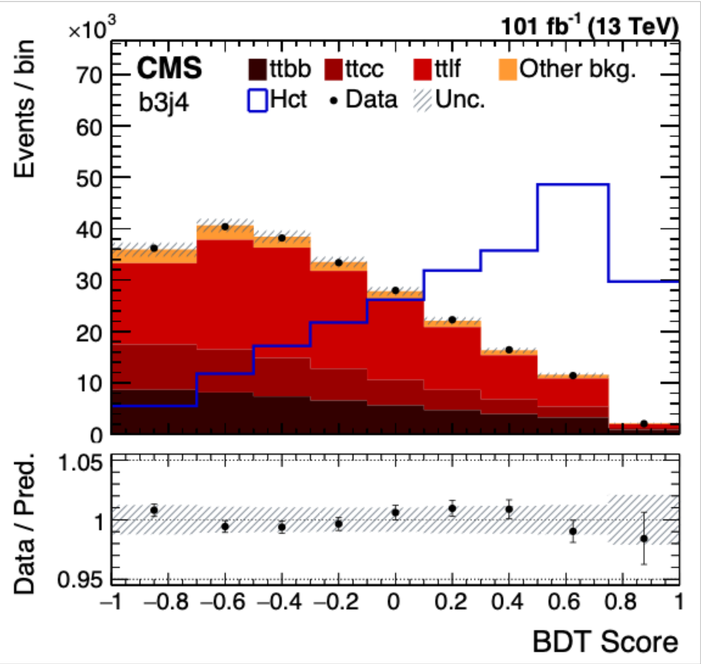
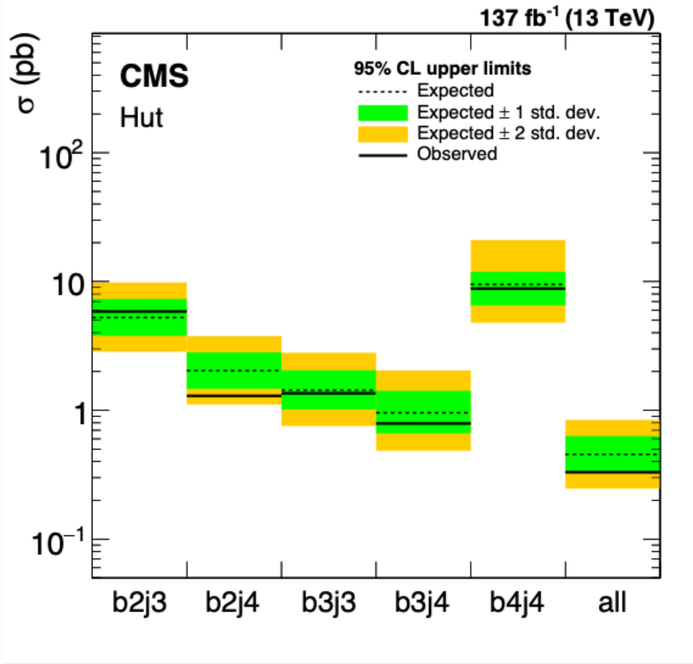
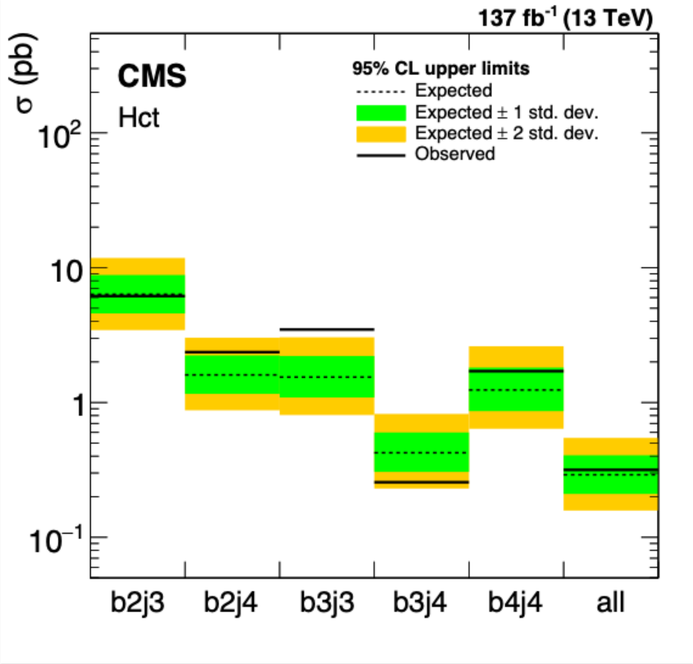




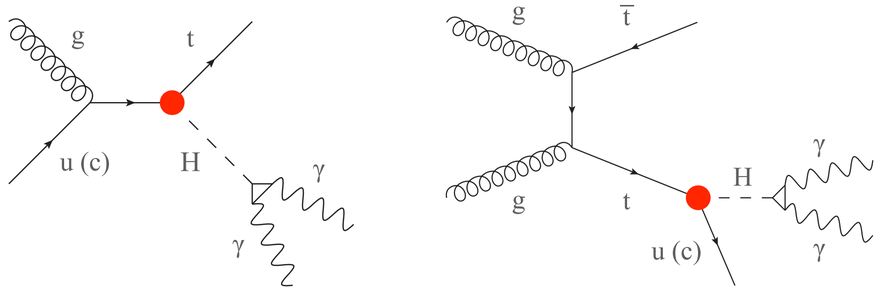


- BDT was used to distinguish FCNC signal from other backgrounds
- Main systematic uncertainties
  - b-tagging
  - Renormalization and factorization scales
- Upper limits on the branching ratio : obs.(exp.)
  - $B(t \to uH) < 0.079\ (0.11)\,\%$
  - $B(t \to cH) < 0.094\ (0.086)\,\%$

FCNC - $tu(c)H(\gamma\gamma)$

138 fb^{-1} PRL 129 (2022) 032001

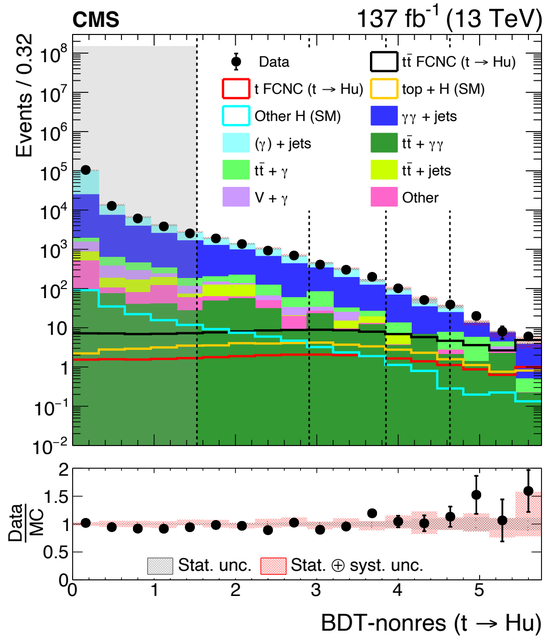
- ST production mode and FCNC decay mode in top quark pair are considered
- Event selection
  - Leading(second) photon p_{T} > 35 (25) GeV, $|\eta|$<2.5
  - 100 GeV < $m_{\gamma\gamma}$ < 180 GeV
  - Mass-dependent $p_{\mathrm{T}}/m_{\gamma\gamma}$ >1/3(1/4) for leading(second) photon
- Event categorization
  - Leptonic channel : $\geq$ 1 isolated lep. with p_{T} > 10(20) GeV for electron(muon) and $|\eta|$<2.4 and $\geq$1 jet with p_{T} > 25 GeV and $|\eta|$<2.4
  - Hadronic channel: $\geq$three jets and $\geq$ 1 b-tagged jet

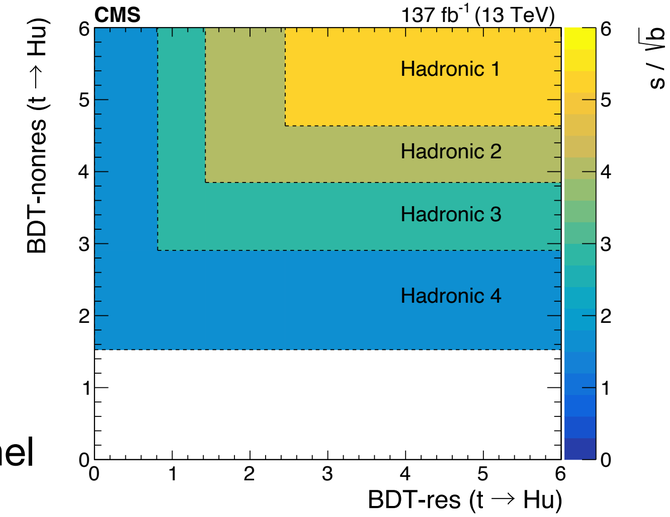


FCNC - $tu(c)H(\gamma\gamma)$

138 fb^{-1} | PRL 129 (2022) 032001

- BDT is used to extract the signal
- Input for BDT
  - kinematic properties of the jets, leptons, photons, diphotons, njet, nlepton, MET,b-tag output, photon ID BDT
  - Output of the algorithms aimed at reconstructing top quarks
- BDTs are trained for each of two k_{Hqt} couplings (k_{Hct}, k_{Hut}), each of two channel (hadronic or leptonic) and two SM backgrounds (resonant or non-resonant) - 8 BDTs in total

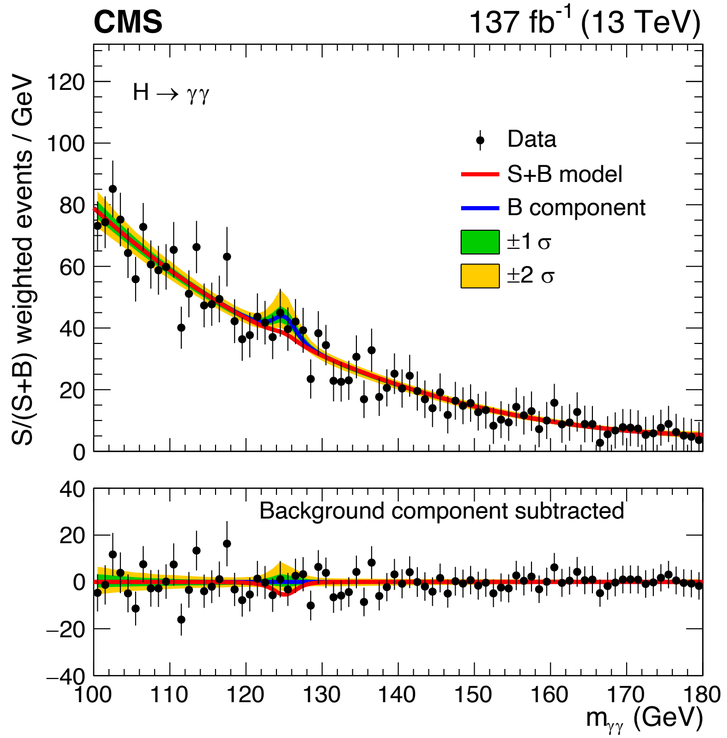


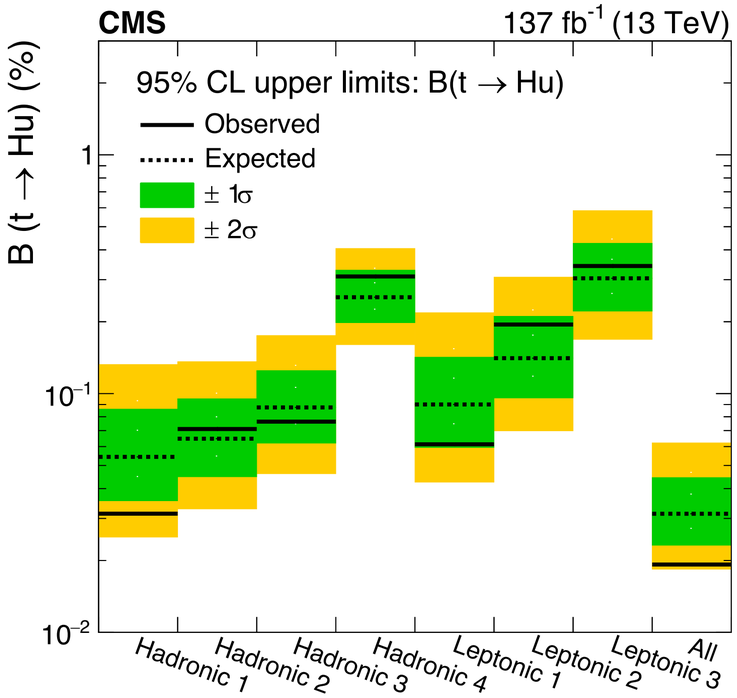


Hadronic channel

FCNC - $tu(c)H(\gamma\gamma)$

138 fb^{-1} **PRL 129 (2022) 032001**





- Binned fits of $m_{\gamma\gamma}$ distribution in each category to extract the upper limit (4 in hadronic, 3 in leptonic)
- Main uncertainties
  - b jet, photon ID, integrated lumi., jet energy scale and resolution…

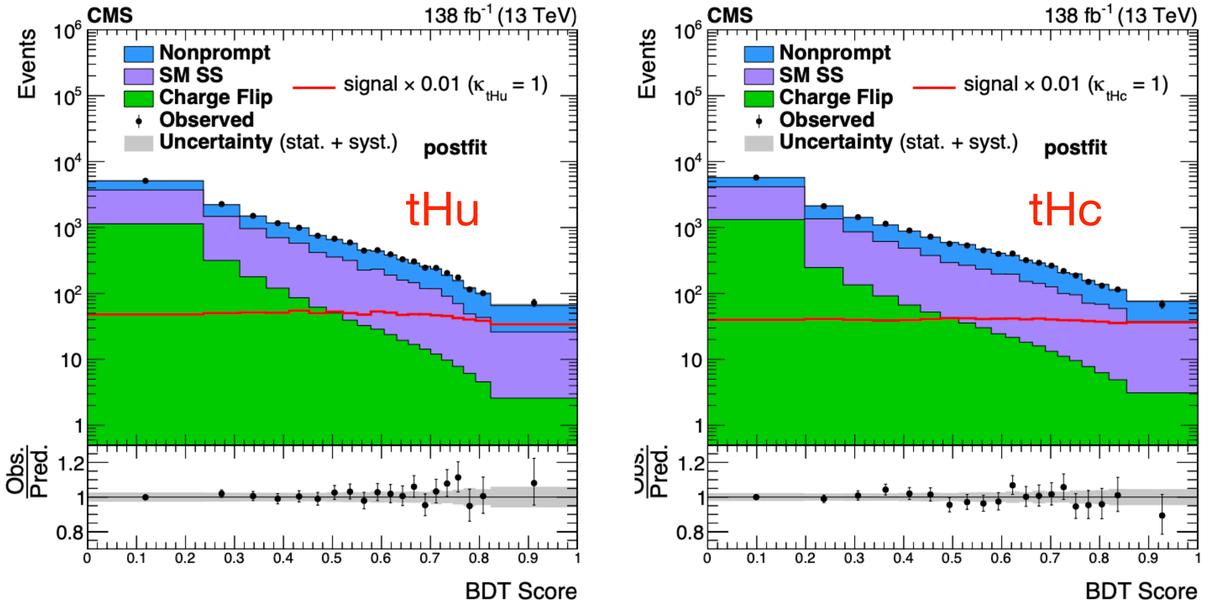
- Upper limits on the branching ratio: obs.(exp.)
  - $B(t \to Hu) < 0.019\ (0.31)\,\%$
  - $B(t \to Hc) < 0.073\ (0.051)\,\%$
- Better sensitivity than $tu(c)H(b\bar{b})$ analysis

FCNC - $tu(c)H$ in multilepton

138 fb^{-1} TOP-22-002

- Targeting $H \rightarrow WW, ZZ, \tau\tau$ with the same sign leptons
- Event selection
  - At least a same sign pair with $p_{\mathrm{T}} > 25$ (20) GeV
  - $\geq$2 jets in SS events or $\geq$1 jet in multi-lepton events with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$
  - b-tagged jet with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.4$
  - $m_{ll}(SF) > 12$ GeV, m_{ll}(any flavor, any charge) > 8 GeV, $m_{ll}(SS, SF) < 75$ GeV or > 105 GeV
- Background estimation
  - SM SS events : estimated by the simulation
  - Non-prompt and fake leptons : tight-to-loose ratio
  - Charge flip for election : $10^{-5} \sim 10^{-3}$
- Main uncertainty : b-tagging, background estimation
- Signal extraction : BDT was used for tuH and tcH

Preliminary



- Upper limits on the branching ratio: obs.(exp.)
  - $B(t \rightarrow Hu) < 0.073\ (0.059)\,\%$
  - $B(t \rightarrow Hc) < 0.041\ (0.060)\,\%$

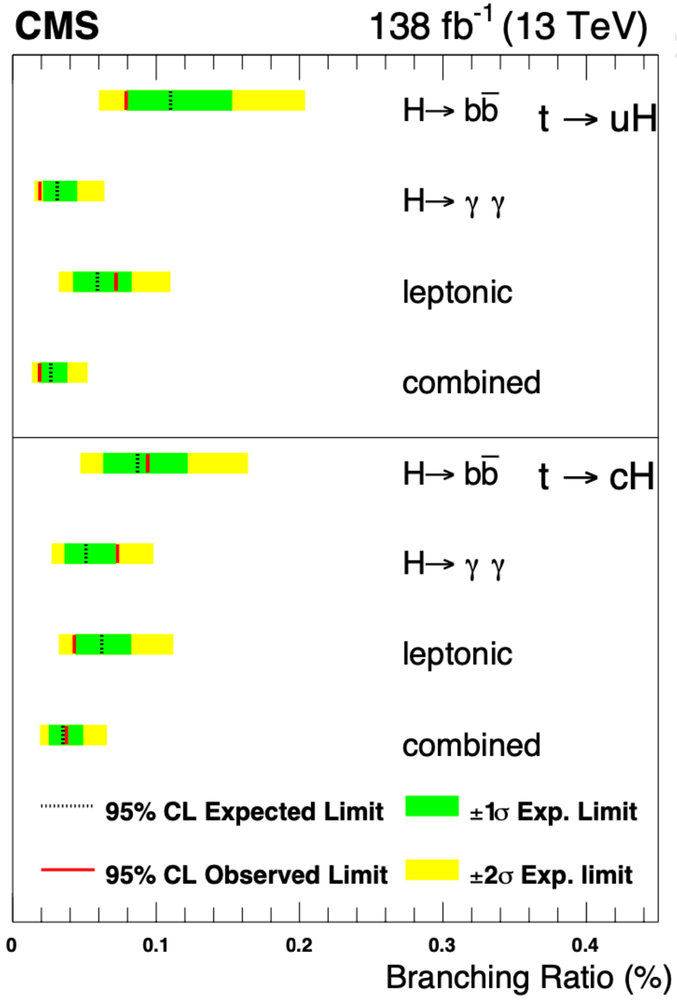
FCNC - $tu(c)H$ in combination

138 fb^{-1} TOP-22-002

Analysis	$\mathcal{B}(t \to Hu)$ observed (expected)	$\mathcal{B}(t \to Hc)$ observed (expected)
$b\bar{b}$ Page 13	0.079 (0.11)%	0.094 (0.086)%
Diphoton Page 15	0.019 (0.031)%	0.073 (0.051)%
Leptonic Page 18	0.073 (0.059)%	0.041 (0.060)%
Combination	0.019 (0.028)%	0.037 (0.035)%

- Correlation
  - Combination jet energy scale and MET resolution, luminosity , lepton ID, theoretical uncertainties are treated as fully correlated
  - Remaining uncertainties are treated as uncorrelated
- The combination with the $H \to \gamma\gamma$ and $H \to b\bar{b}$ gives the most stringent limits on $tu(c)H$ interactions

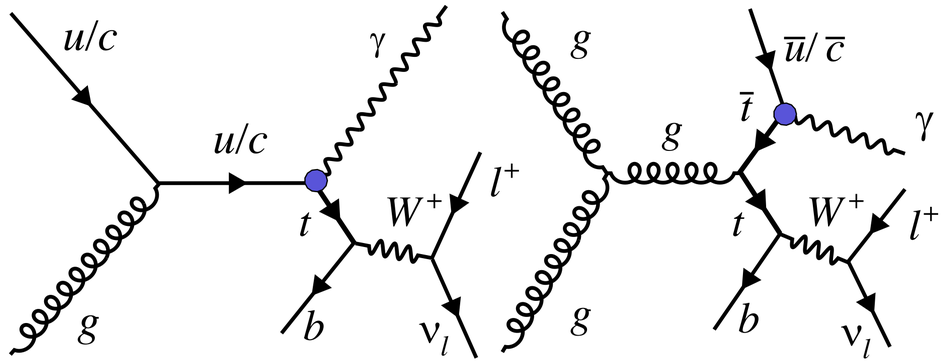
Preliminary

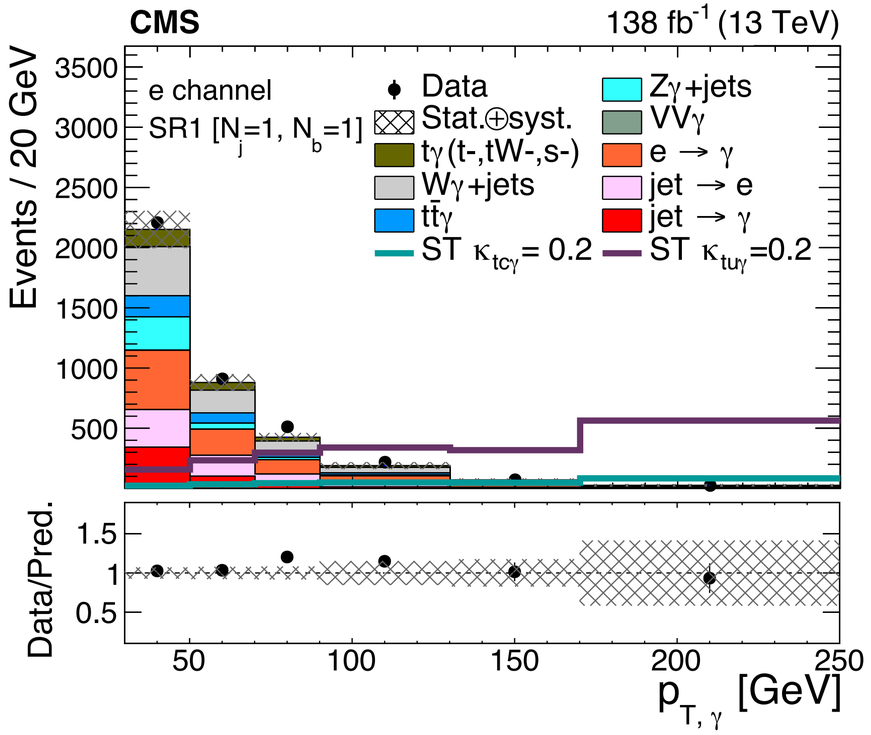


FCNC - $tu(c)\gamma$

138 fb^{-1} | PRD 109 (2024) 072004

- Event selection
  - Electron (p_T > 35 GeV and $|\eta|$ < 2.5) or Muon (p_T > 30 GeV and $|\eta|$ < 2.4)
  - Photons (p_T > 30 GeV and $|\eta|$ < 1.44)
  - SR1 : njets =1 and nbjets = 1 (FCNC single top)
  - SR2 : njets ≥2 and nbjets = 1 (FCNC decay of top quark)
- Background estimation
  - $t\bar{t}\gamma$, $W\gamma$+jets, $Z\gamma$+jets, $VV\gamma$+jets are estimated from simulation and normalization is corrected using data
  - Jets misidentified as photons
  - Misidentified lepton background
  - Electrons misidentified as photons

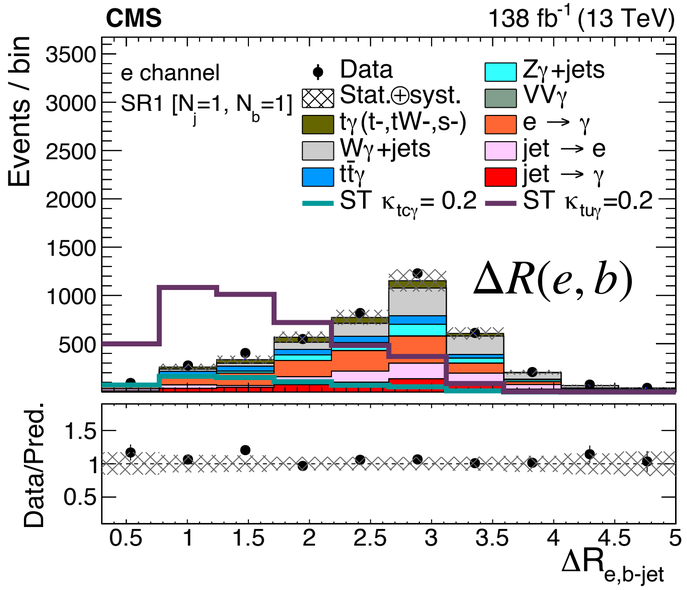


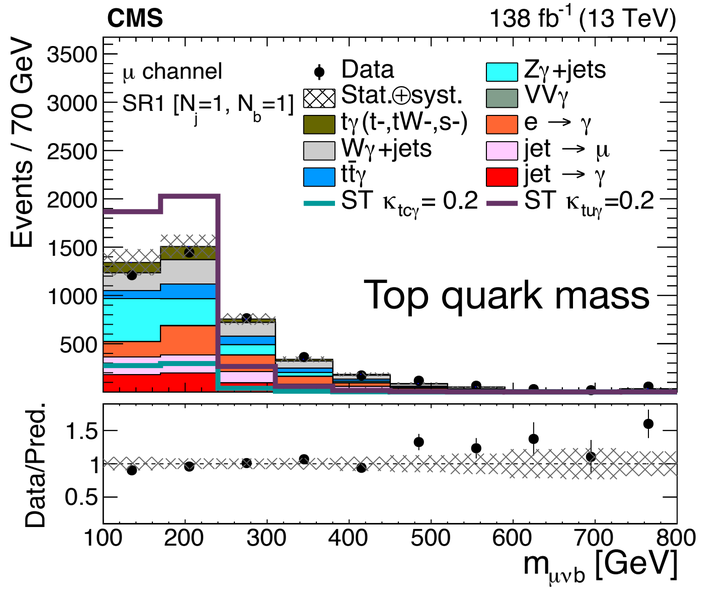


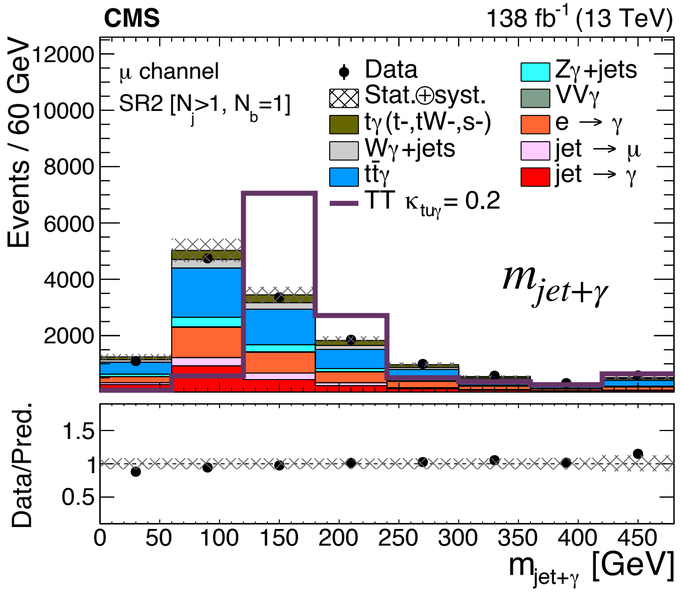
FCNC - $tu(c)\gamma$

138 fb^{-1} PRD 109 (2024) 072004

- BDT is used to maximize the sensitivity
- Separately trained for $tu\gamma$ and $tc\gamma$ signal scenarios (SR1 and SR2)
- 13 input variables
  - p_{T} and η of photon, η and charge of lepton, m_t, m_{WT}, $m_{j+\gamma}$,MET, $\Delta R(l,\gamma)$,$\Delta R(t,\gamma)$, njets, $\Delta R(l,b)$, $\Delta R(b,\gamma)$



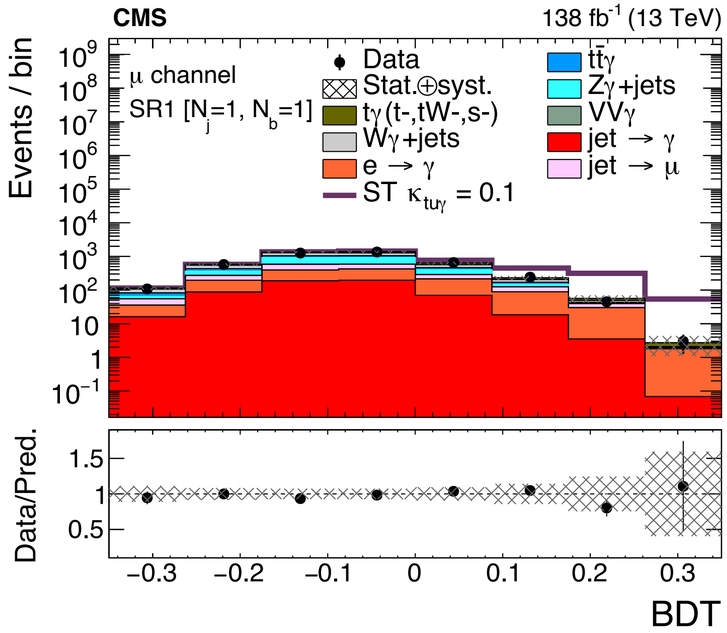


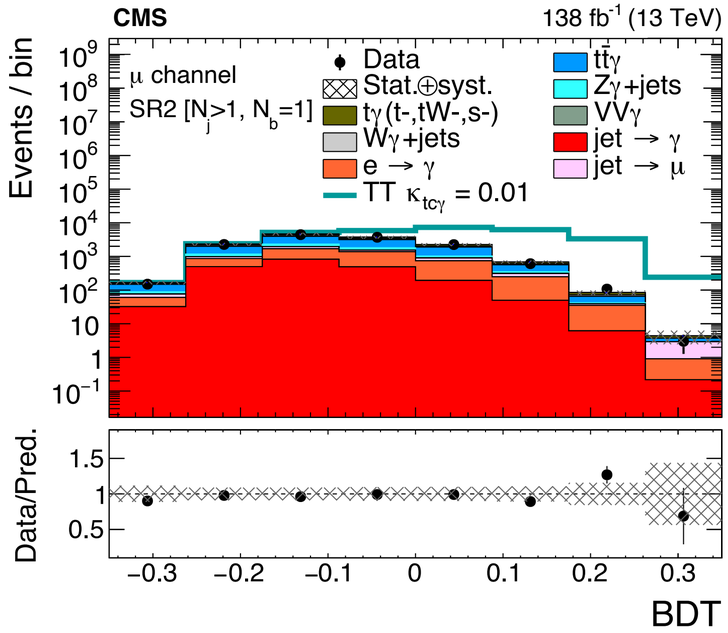


FCNC - $tu(c)\gamma$

138 fb^{-1} **PRD 109 (2024) 072004**

$tu\gamma$ for single top production





$tc\gamma$ for SR2

Combined	Obs. limit	Exp. limit	$\pm1\sigma$ (exp. limit)	$\pm2\sigma$ (exp. limit)
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9 - 8.4) \times 10^{-3}$	$(5.1 - 10.1) \times 10^{-3}$
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7 - 9.7) \times 10^{-3}$	$(5.7 - 11.5) \times 10^{-3}$
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89 - 1.78) \times 10^{-5}$	$(0.64 - 2.57) \times 10^{-5}$
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$

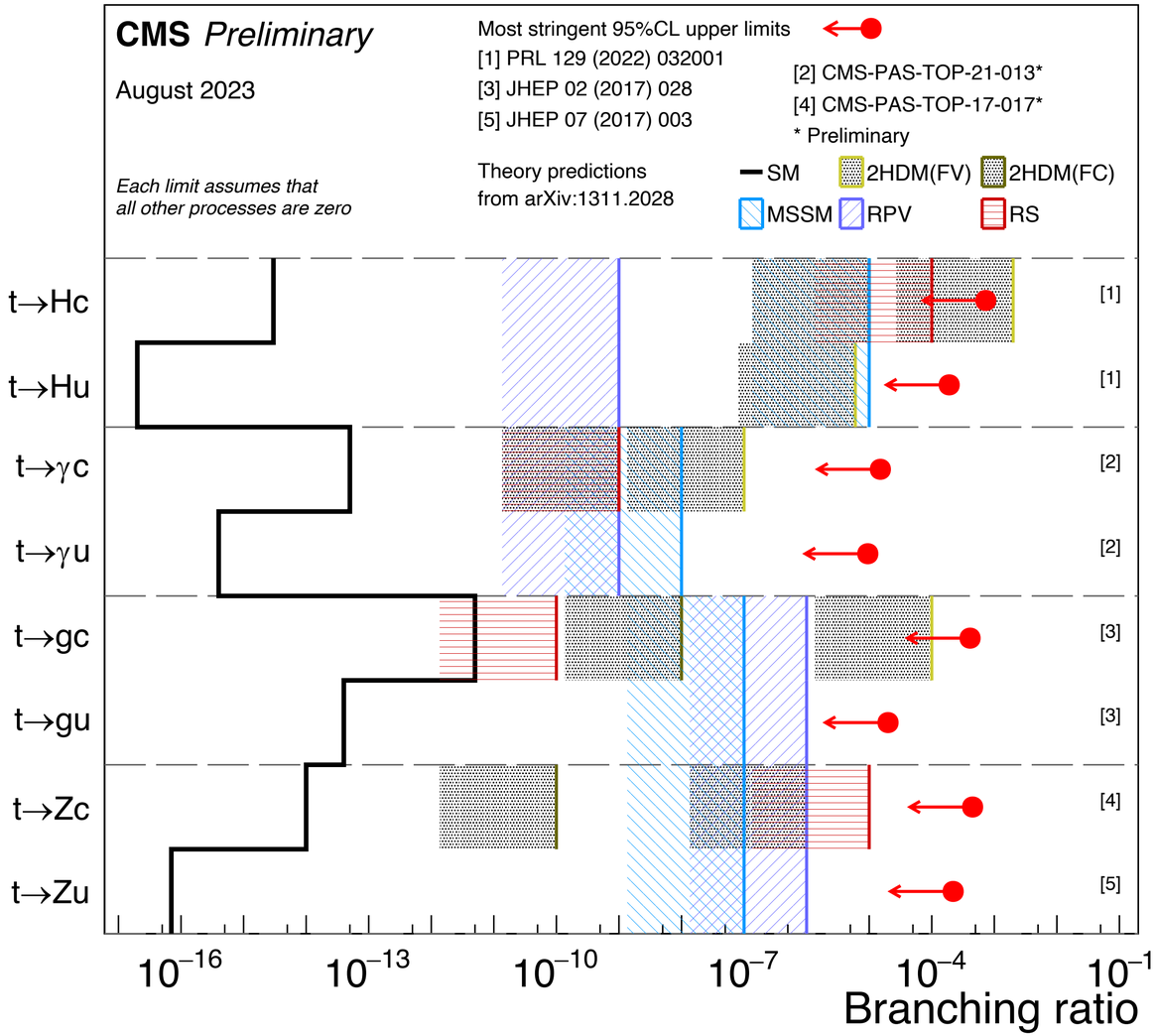
- For $B(t \to u + \gamma) < 0.95 \times 10^{-5}$, compatible with ATLAS results - PLB 842 (2023) 137379
- Limit for $B(t \to c + \gamma) < 1.51 \times 10^{-5}$ is significantly tighter

Summary of FCNC

In this talk at 13 TeV!

- $B(t \to Hc) < 3.7 \times 10^{-4}$ [TOP-22-002]
- $B(t \to Hu) < 1.9 \times 10^{-4}$ [TOP-22-002]
- $B(t \to \gamma c) < 1.51 \times 10^{-5}$ [TOP-21-013]
- $B(t \to \gamma u) < 0.95 \times 10^{-5}$ [TOP-21-013]
- $B(t \to gc) < 4.1 \times 10^{-4}$ [JHEP 02(2017) 028]
- $B(t \to gu) < 2.0 \times 10^{-5}$ [JHEP 02(2017) 028]
- $B(t \to Zc) < 4.5 \times 10^{-4}$ [TOP-17-017]
- $B(t \to Zu) < 2.2 \times 10^{-4}$ [JHEP 07(2017) 003]

latest results from TOP-22-002 are not included



Conclusion

- Rare processes of FCNC and LFV have been extensively searched at CMS
- FCNC searches started to exclude some BSM predictions
- cLFV searches has been started and gets more attention to explain the anomaly shown in B-physics
- Better reconstruction technology and more date will allow these FCNC and cLFV to be more sensitive in coming years