FCNC and LFV from CMS

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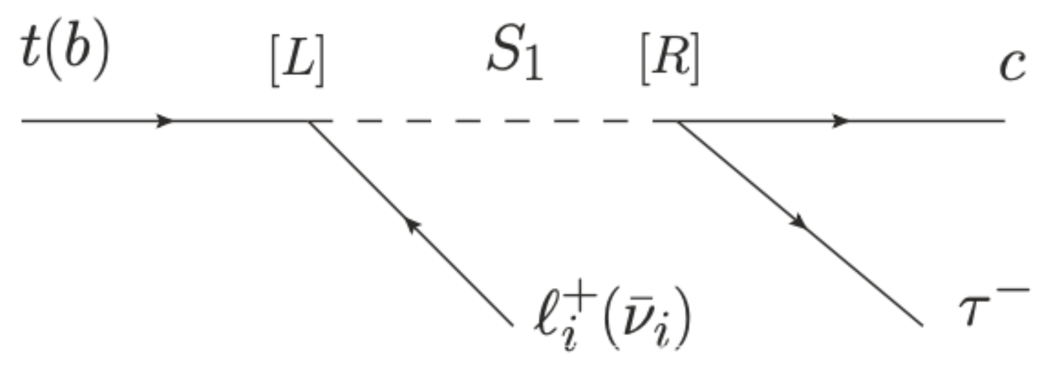
TOP2023

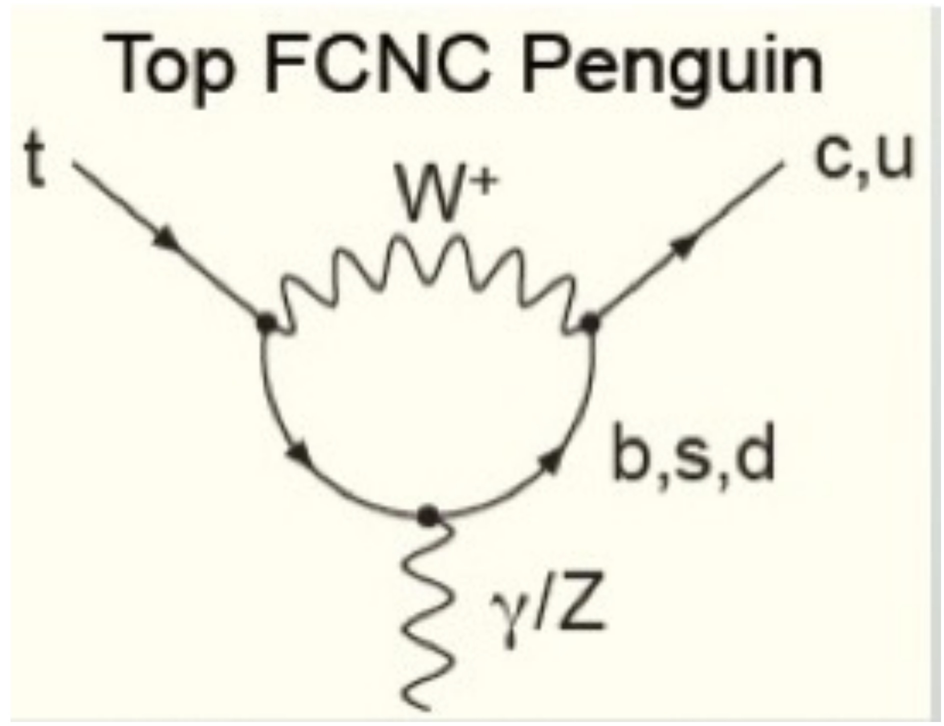
27 Sep. 2023 in Traverse City, Michigan, USA

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!



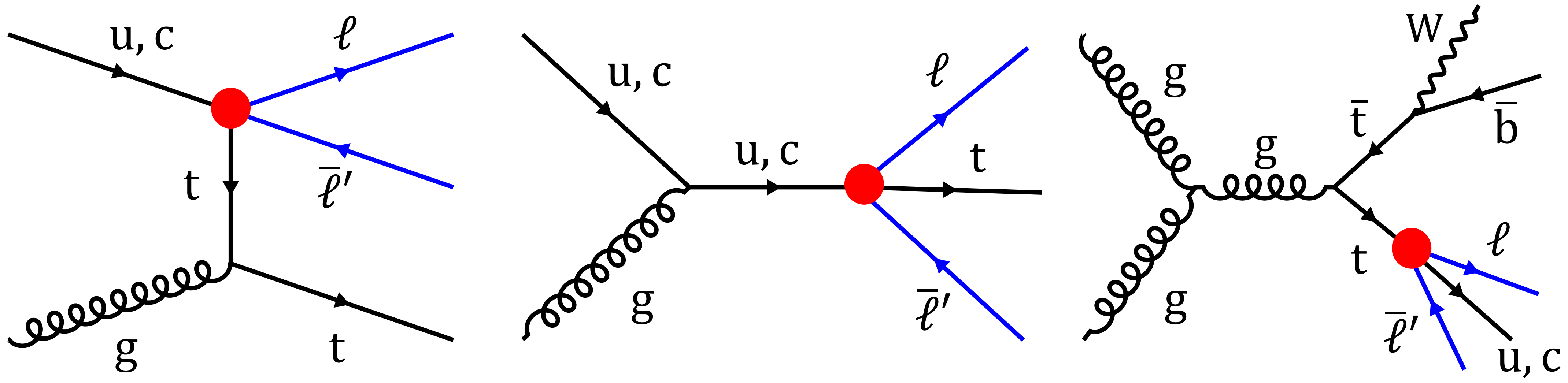
JHEP 07 (2019) 025



cLFV in dilepton final state

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

- 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)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_x \frac{C_x}{\Lambda^2} O_x + \cdots$$

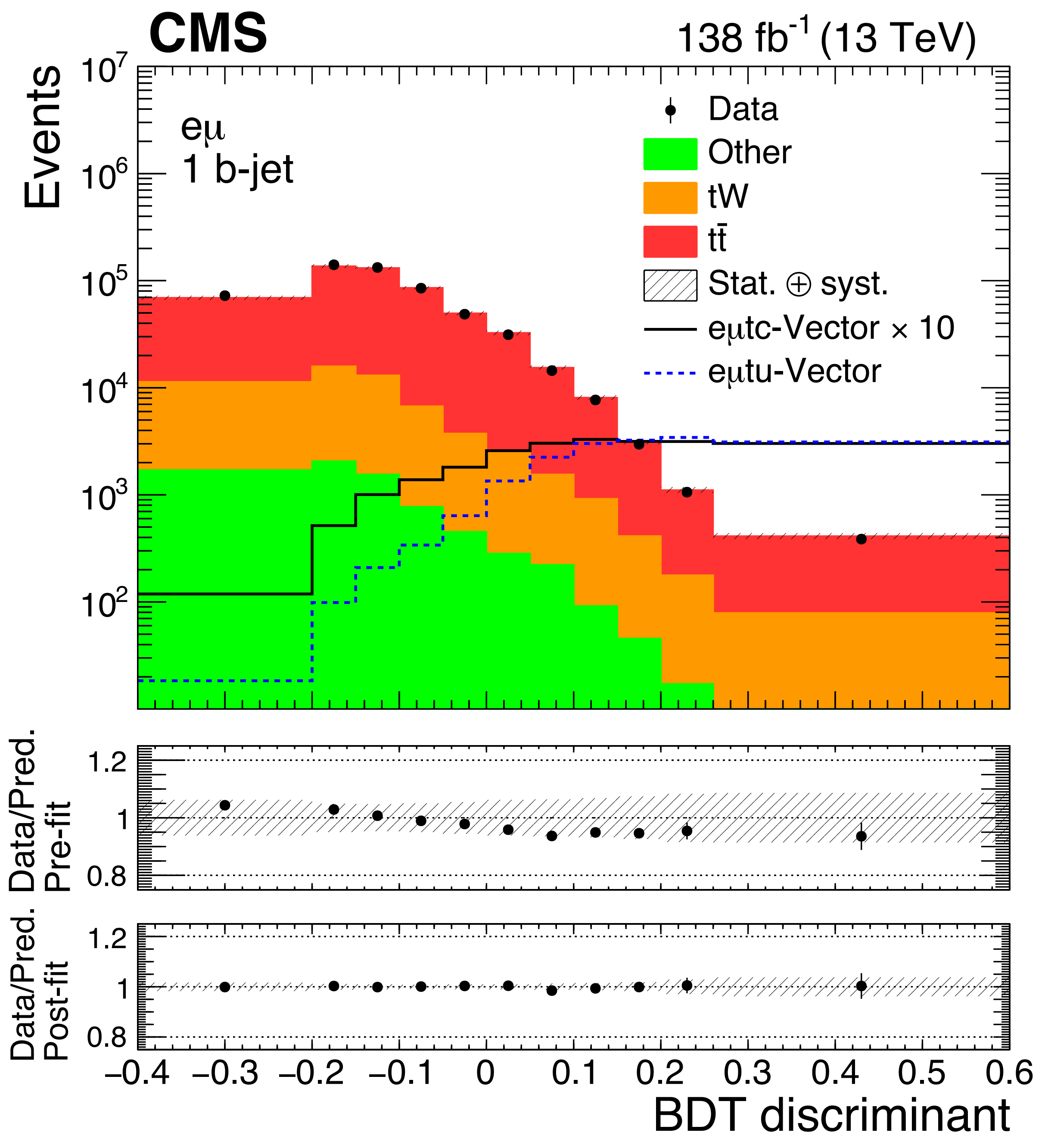
- The result is integrated in terms of limits on vector, scalar and tensor four-fermion interactions from dimension 6 operators within the EFT

- Final states: an oppositely charged $e\mu$ pair and a top quark decaying hadronically

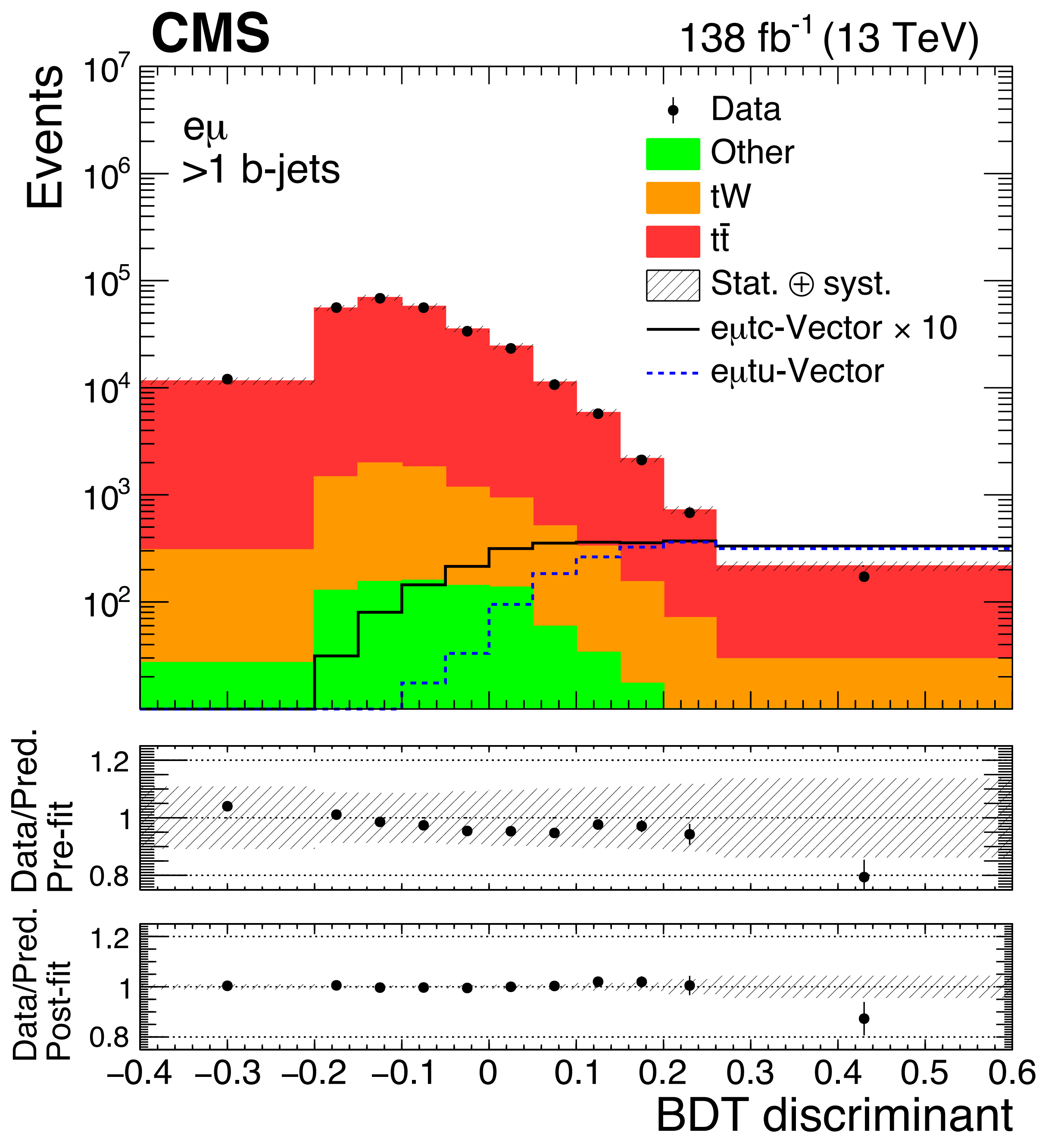
cLFV in dilepton final state

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

- 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

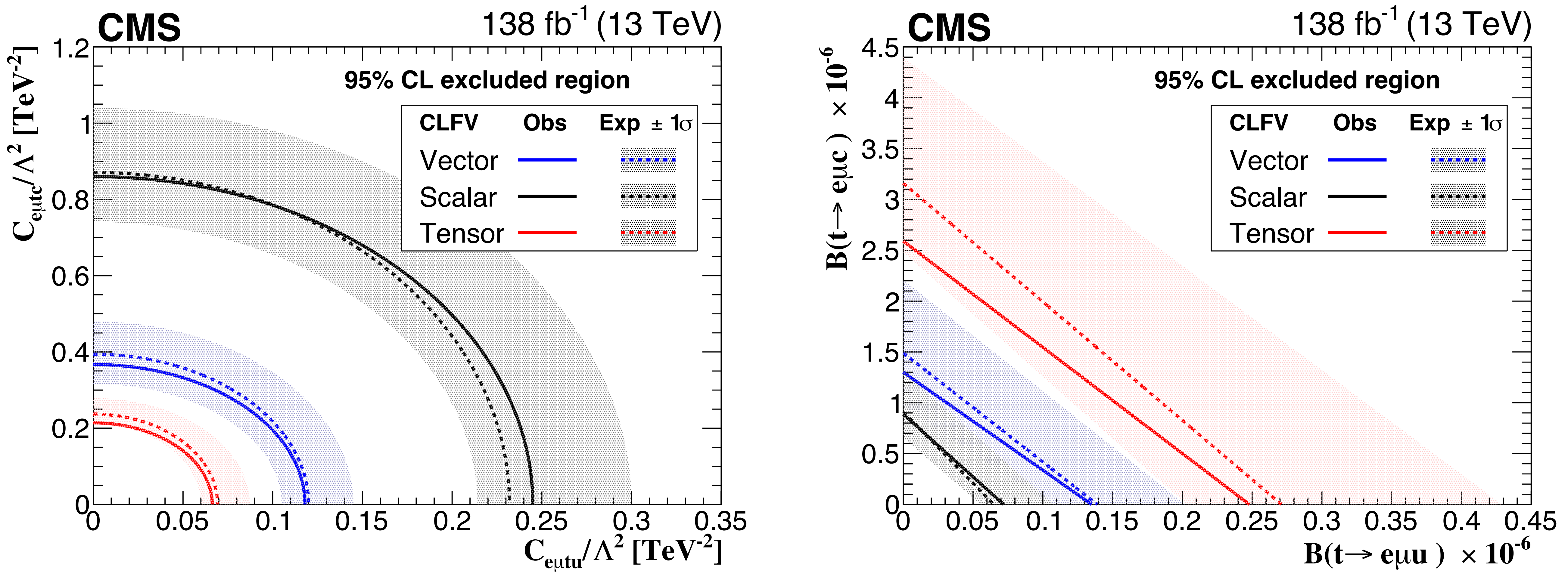


More than one b-tagged jet
$t\bar{t}$ control region

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

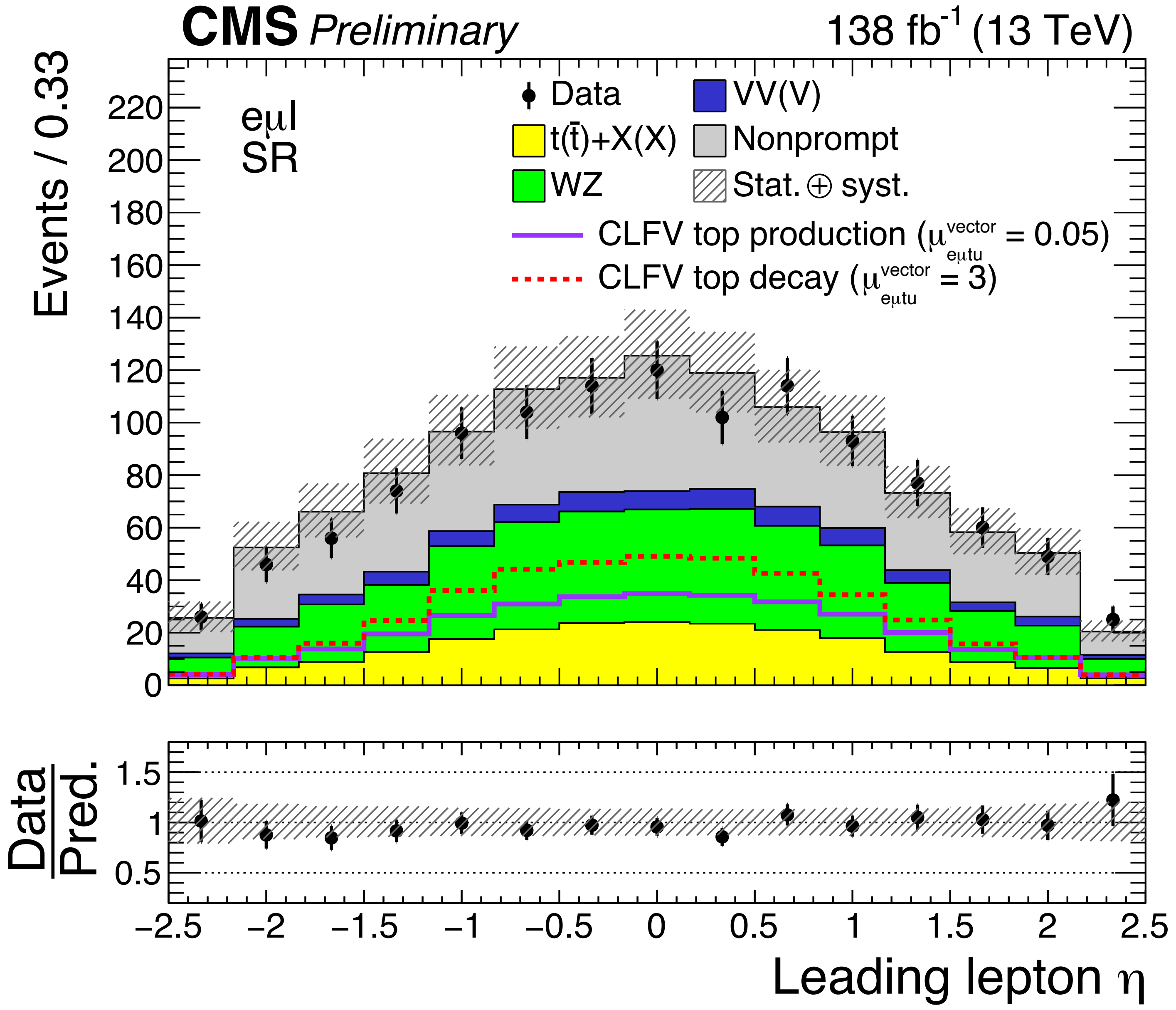


Vertex	Int. type	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
	Vector	0.12	0.12	0.14	0.13
$e\mu tu$	Scalar	0.23	0.24	0.06	0.07
	Tensor	0.07	0.06	0.27	0.25
	Vector	0.39	0.37	1.49	1.31
$e\mu tc$	Scalar	0.87	0.86	0.91	0.89
	Tensor	0.24	0.21	3.16	2.59

cLFV in trilepton final state

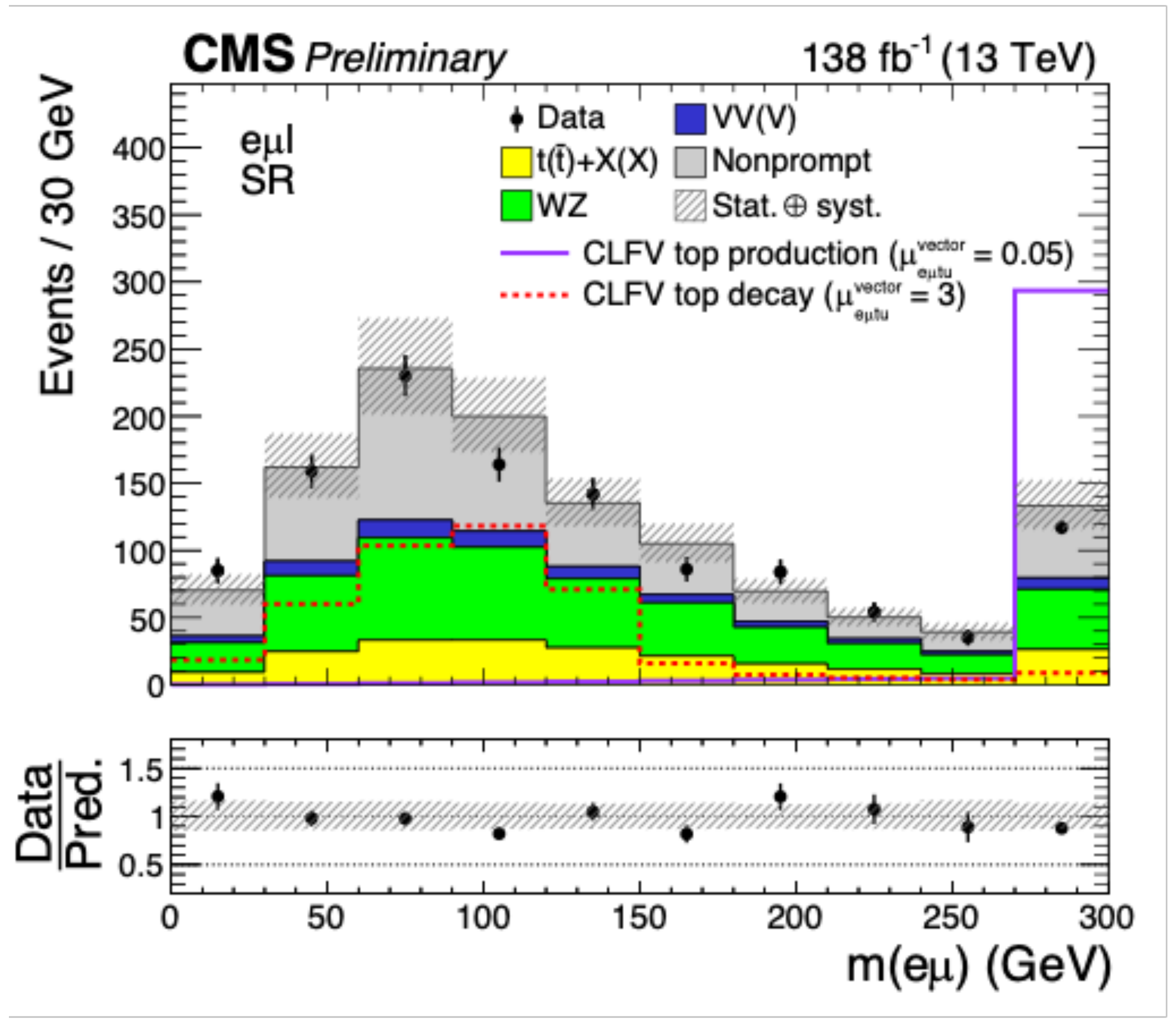
138 fb^{-1} TOP-22-005

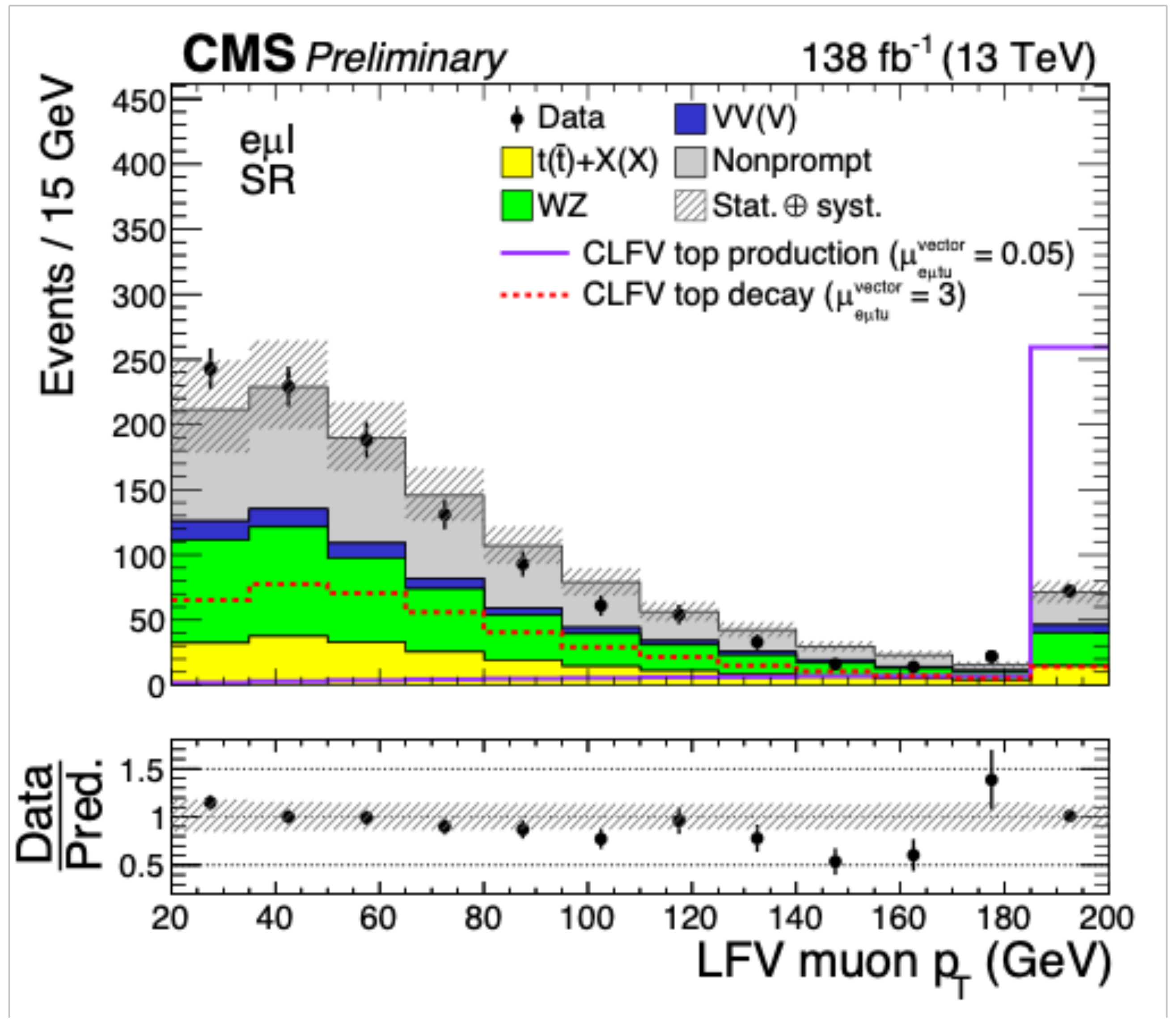
- Follows the same strategy in EFT as cLFV search in dilepton channel
- Considering W boson from top quark decays leptonically
- Event selection
  - Exactly three leptons with $p_T > 38$ GeV ($e\mu l$)
  - MET > 20 GeV
  - At least one jet and at most one b-tagged jet
  - Signal region : OffZ - !(50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

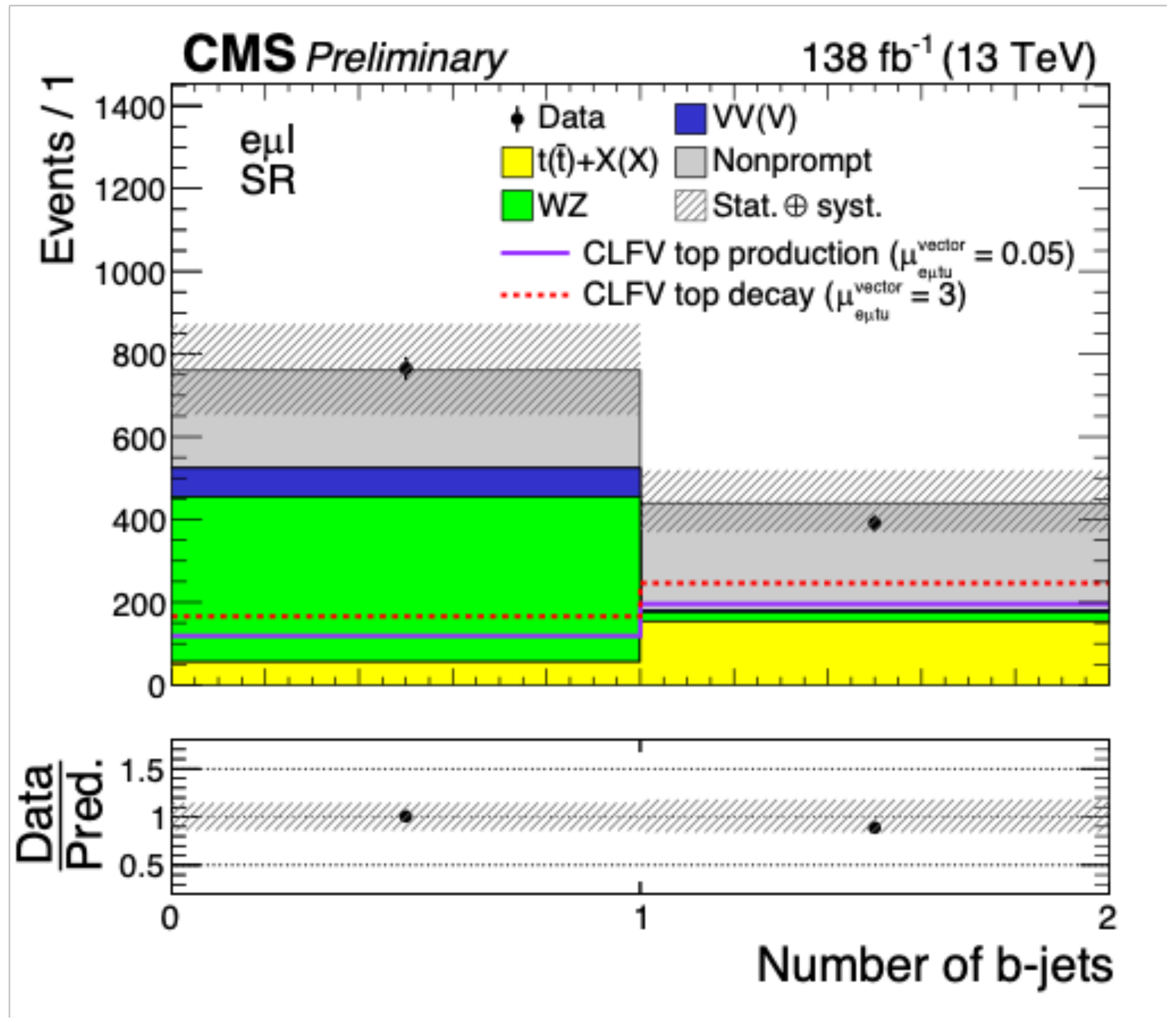


cLFV in trilepton final state

138 fb⁻¹ TOP-22-005



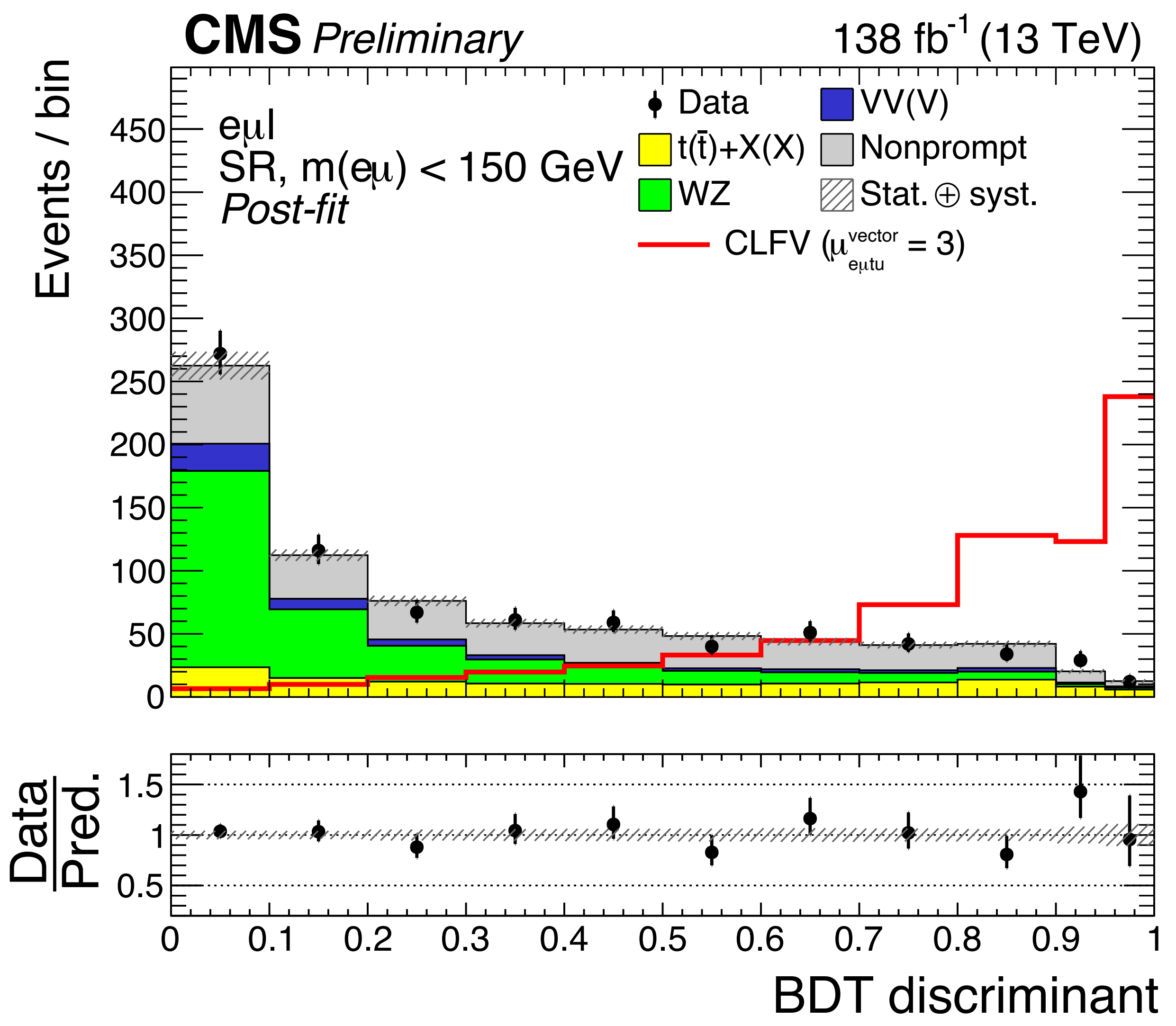


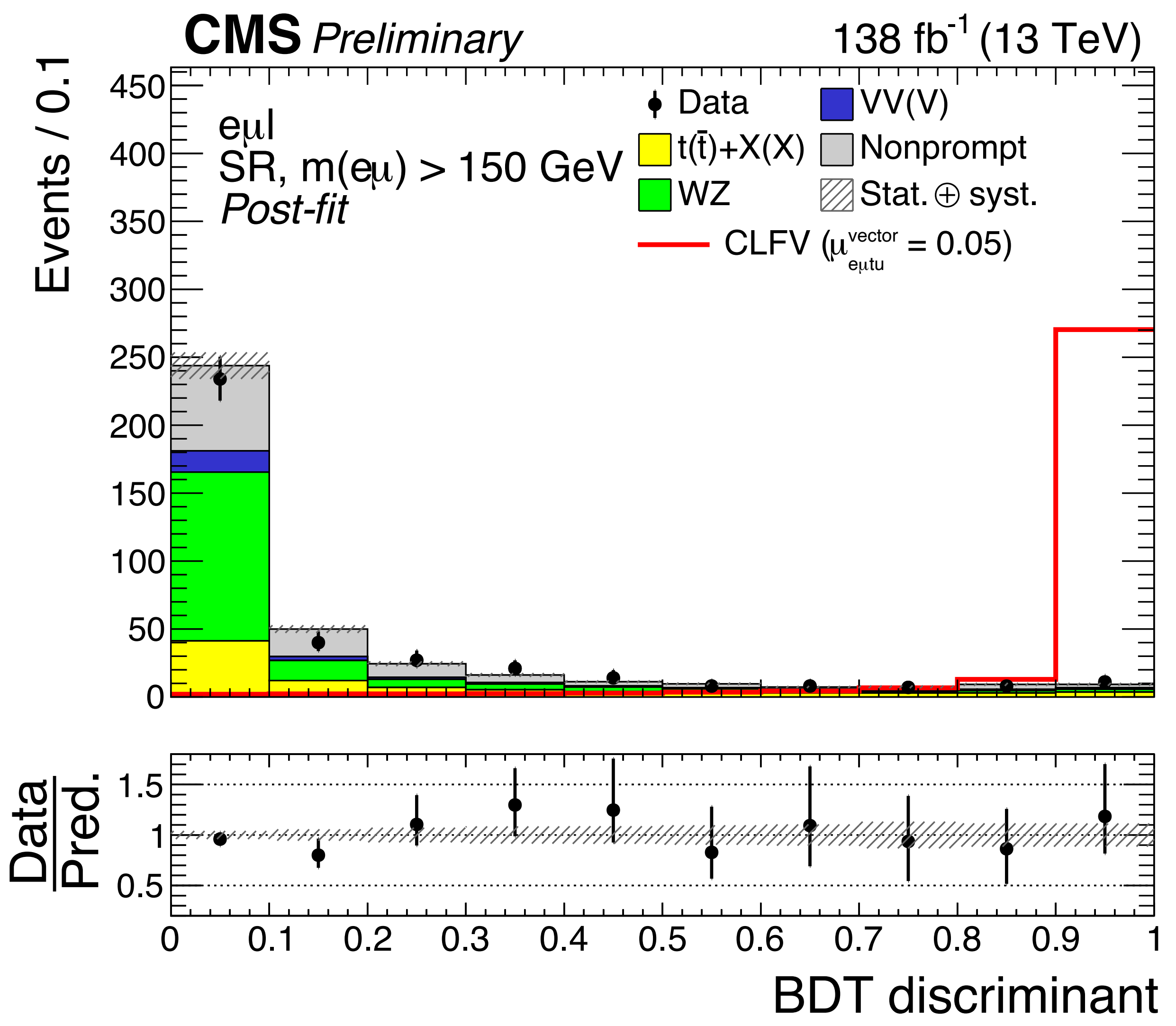


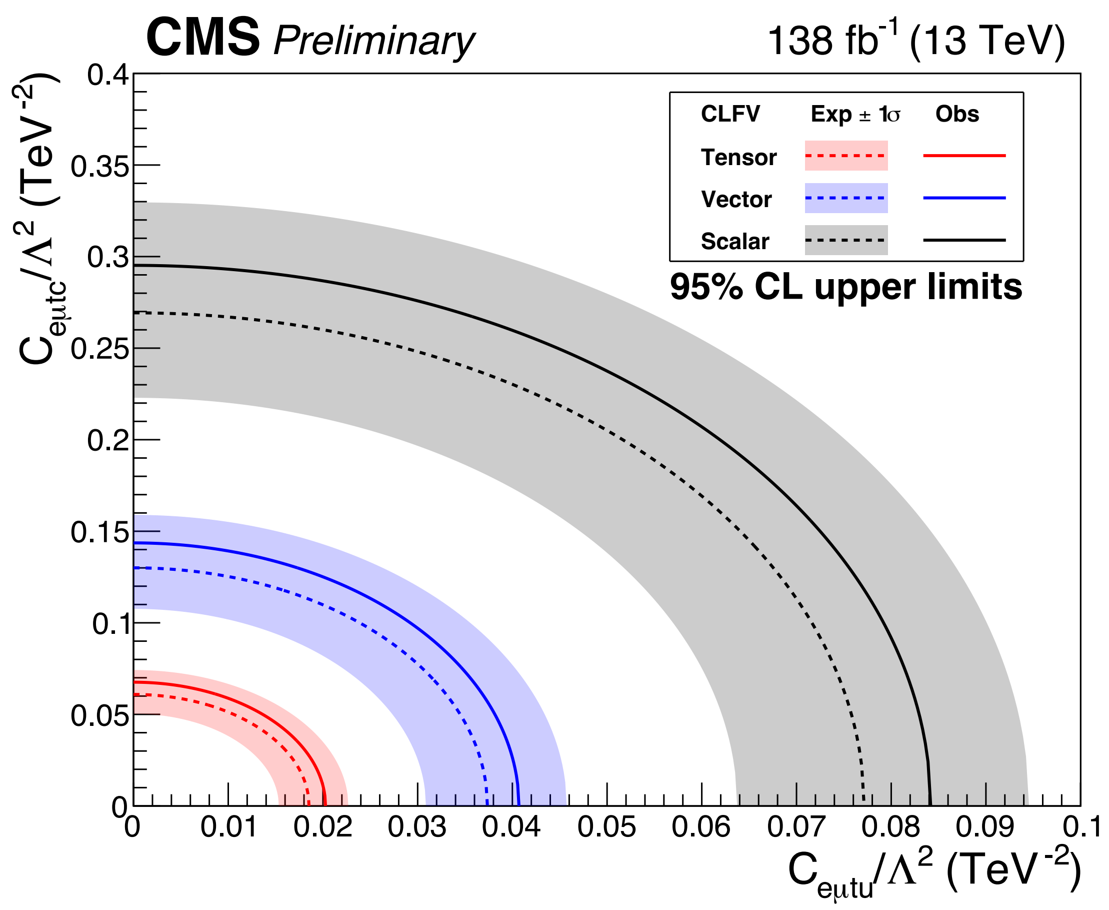
- BDT was trained in two different signal regions
  - M($e\mu$) < 150 GeV: top decay enriched, M($e\mu$) > 150 GeV: top production enriched
  - Input variables : Invariant mass of the Z boson, number of b-tagged jets and invariant mass of LFV top quark pair, p_T of LFV electron and muon

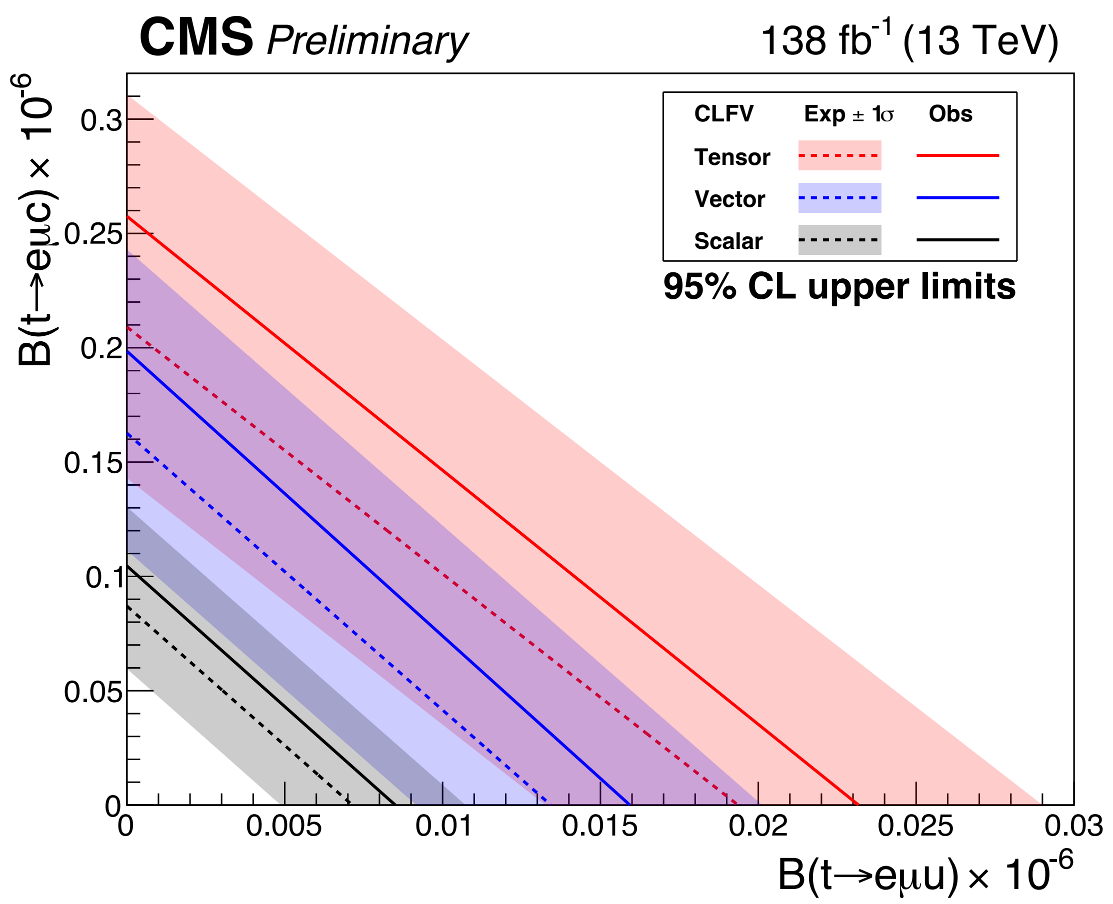
cLFV in trilepton final state

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

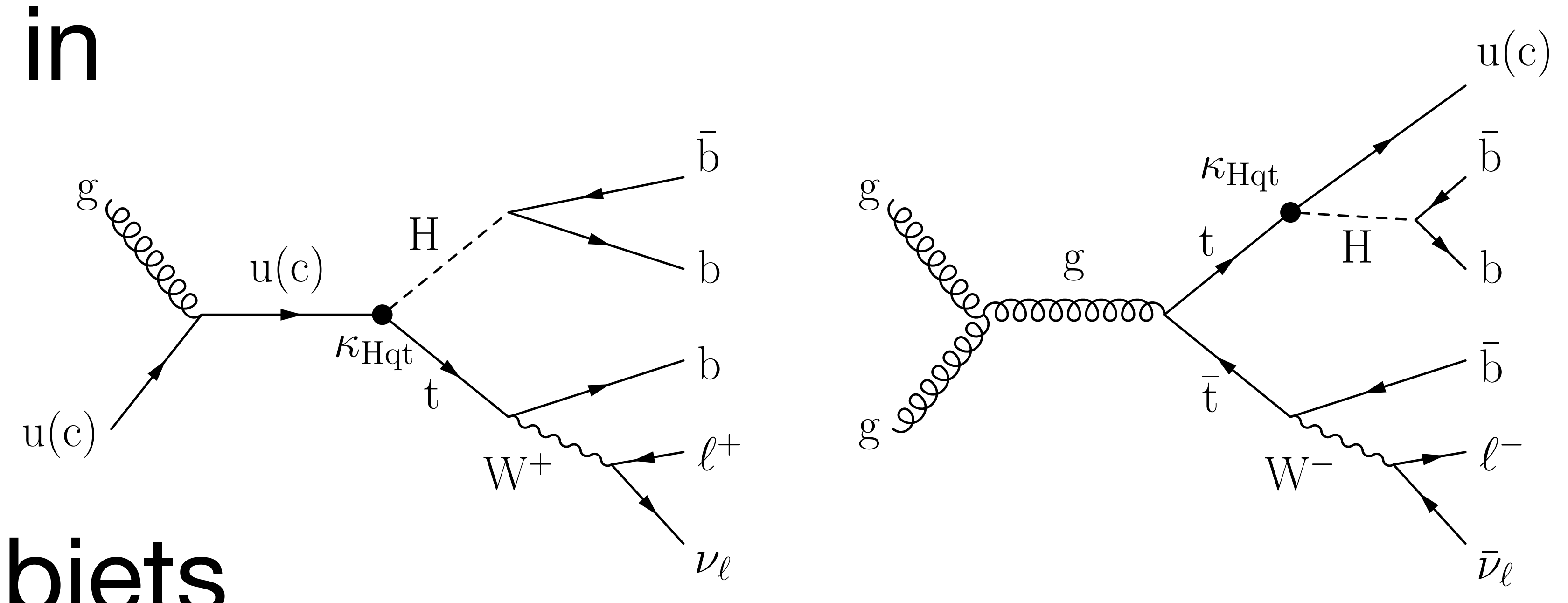
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)	**0.016**
	scalar	0.077 (0.064, 0.095)	**0.084**	0.007 (0.005, 0.011)	**0.009**
$e\mu tc$	tensor	0.061 (0.050, 0.074)	**0.068**	0.209 (0.143, 0.311)	**0.258**
	vector	0.130 (0.108, 0.159)	**0.144**	0.163 (0.111, 0.243)	**0.199**
	scalar	0.269 (0.223, 0.330)	**0.295**	0.087 (0.060, 0.130)	**0.105**

Stay tuned : fixing a bug in generator SMEFT!

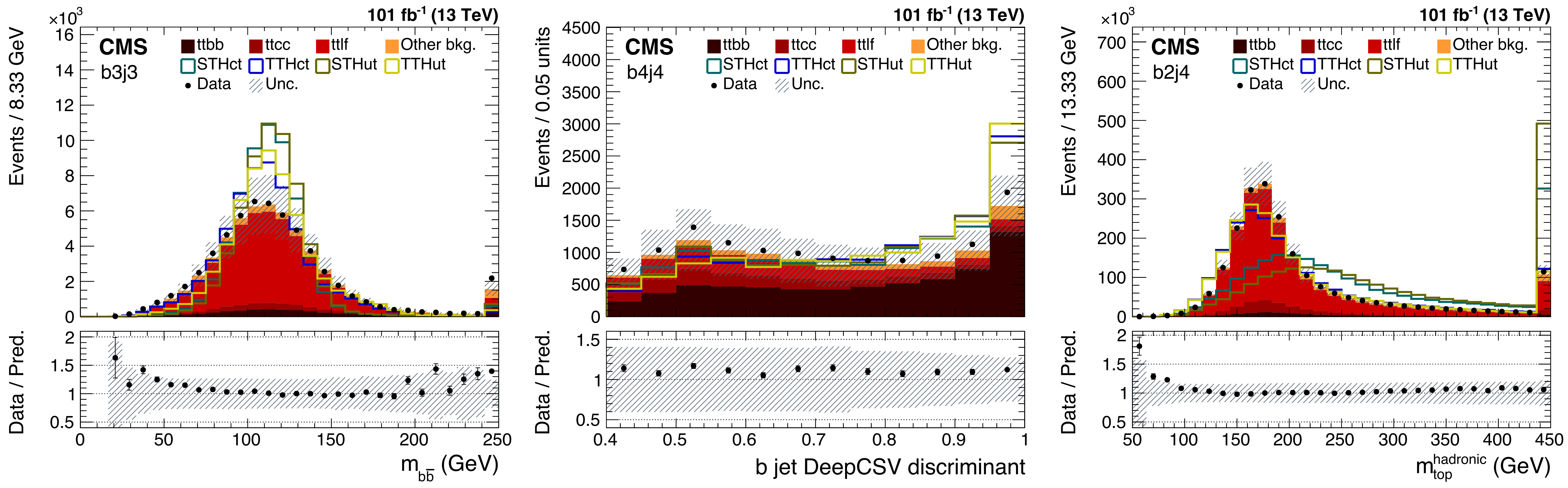
FCNC - $tu(c)H(b\bar{b})$

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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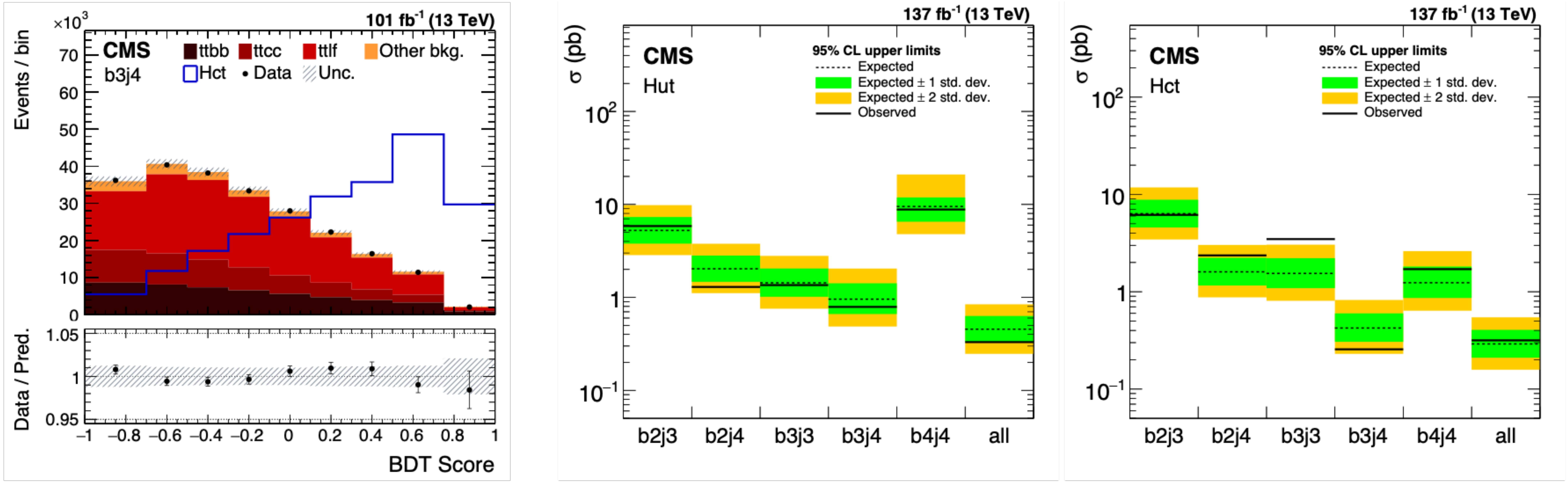
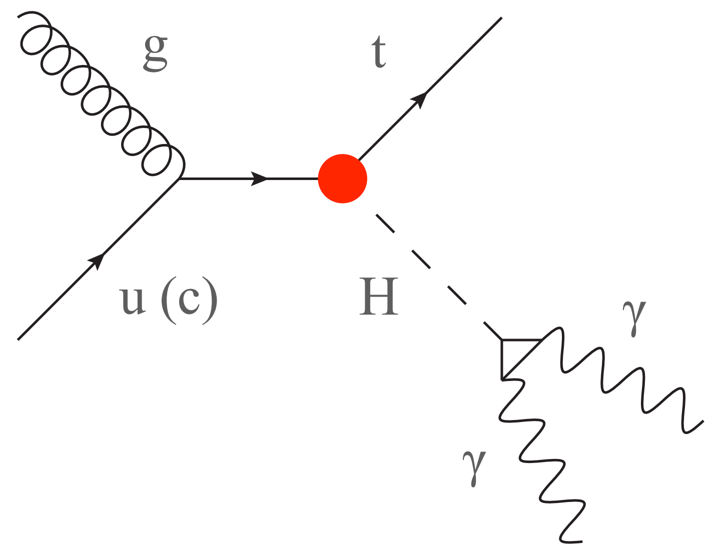


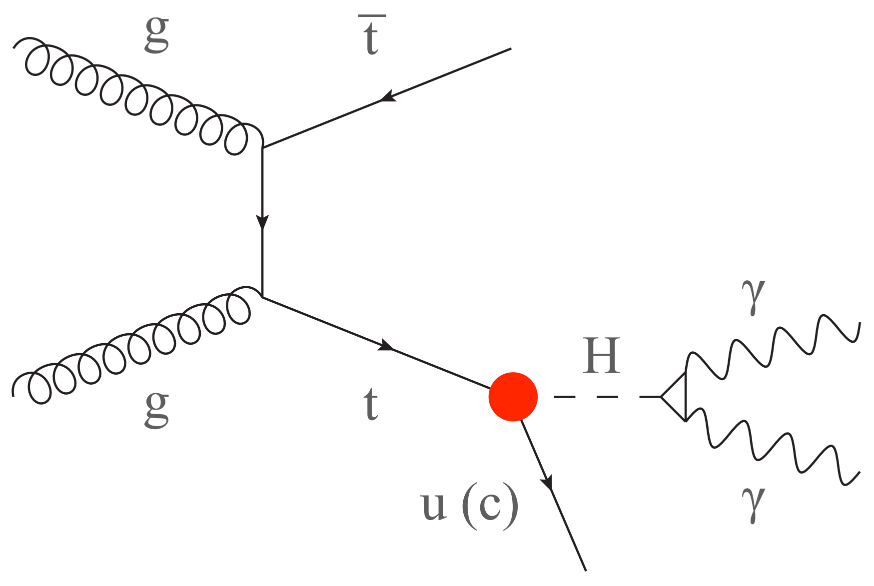
- BDT was used to distinguish FCNC signal from other backgrounds
- Main systematic uncertainties
  - b-tagging
  - Renormalization and factorization scales
- Upper limits on the branching ratio : obs.(exp.)
  - $B(t \to uH) < 0.079\ (0.11)\,\%$
  - $B(t \to cH) < 0.094\ (0.086)\,\%$

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 $p_T/m_{\gamma\gamma}$ >1/3(1/4) for leading(second) photon
- Event categorization
  - Leptonic channel : ≥ 1 isolated lep. with p_T > 10(20) GeV for electron(muon) and $|\eta|$<2.4 and ≥1 jet with p_T > 25 GeV and $|\eta|$<2.4
  - Hadronic channel: ≥three jets and ≥ 1 b-tagged jet

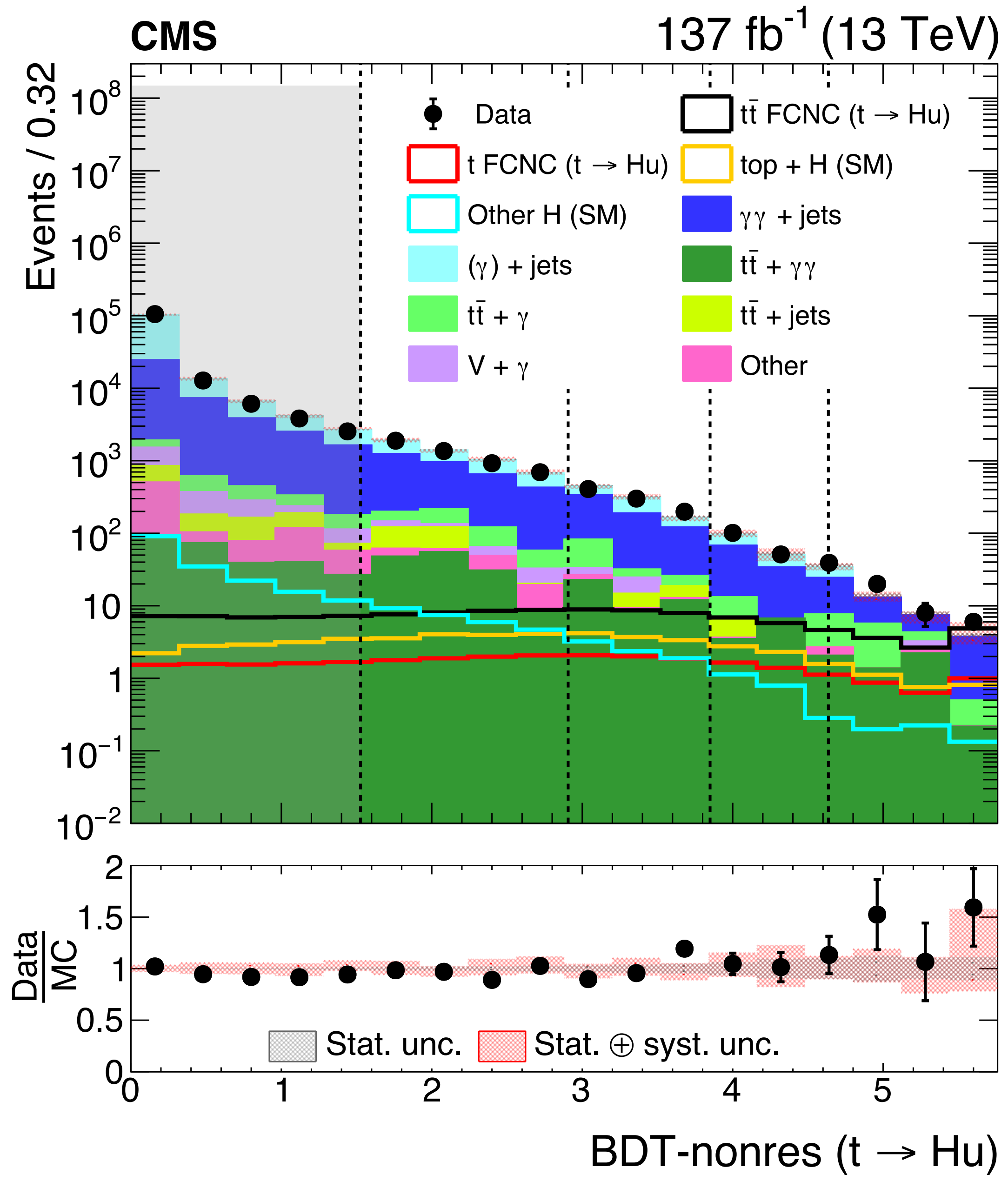


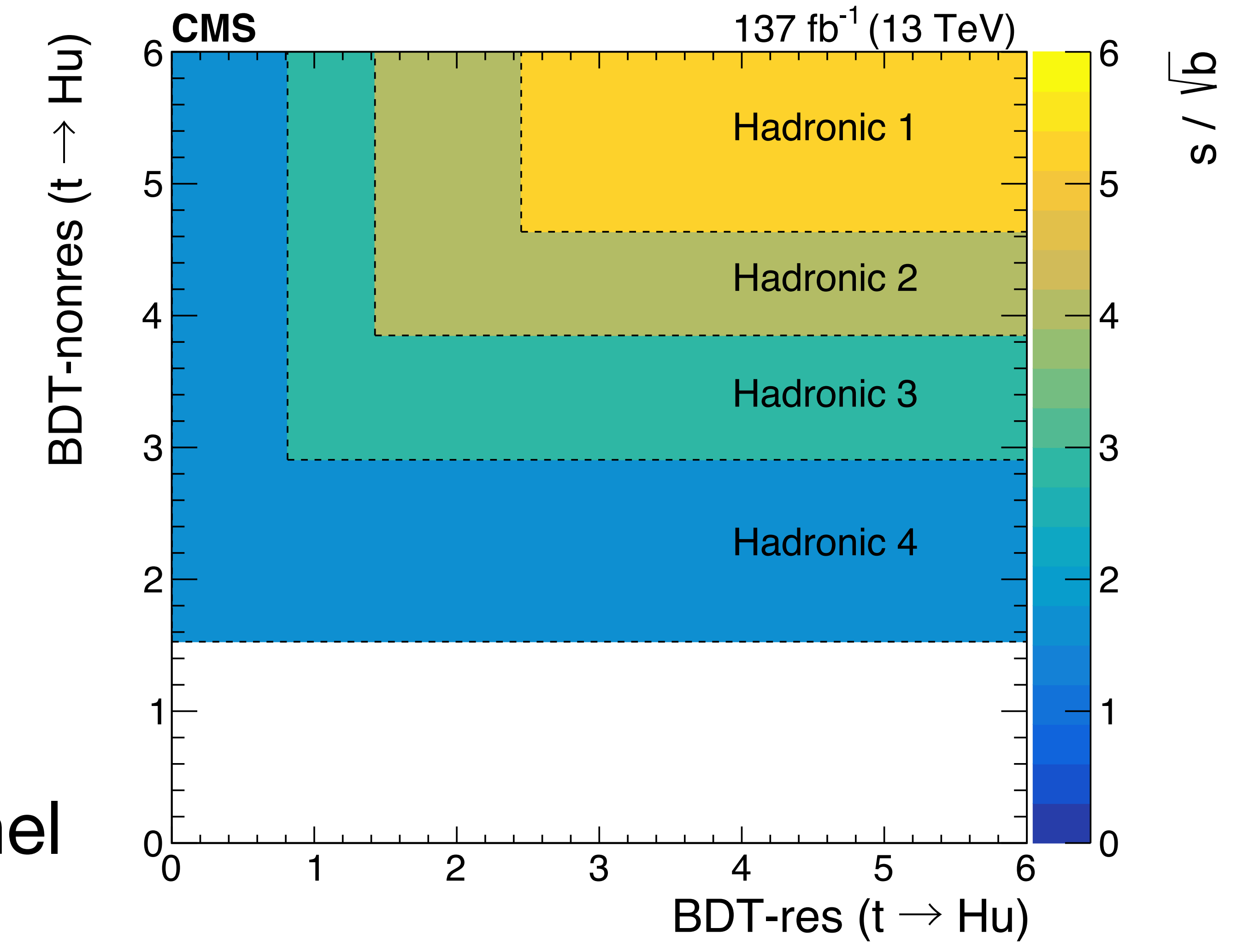


FCNC - $tu(c)H(\gamma\gamma)$

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

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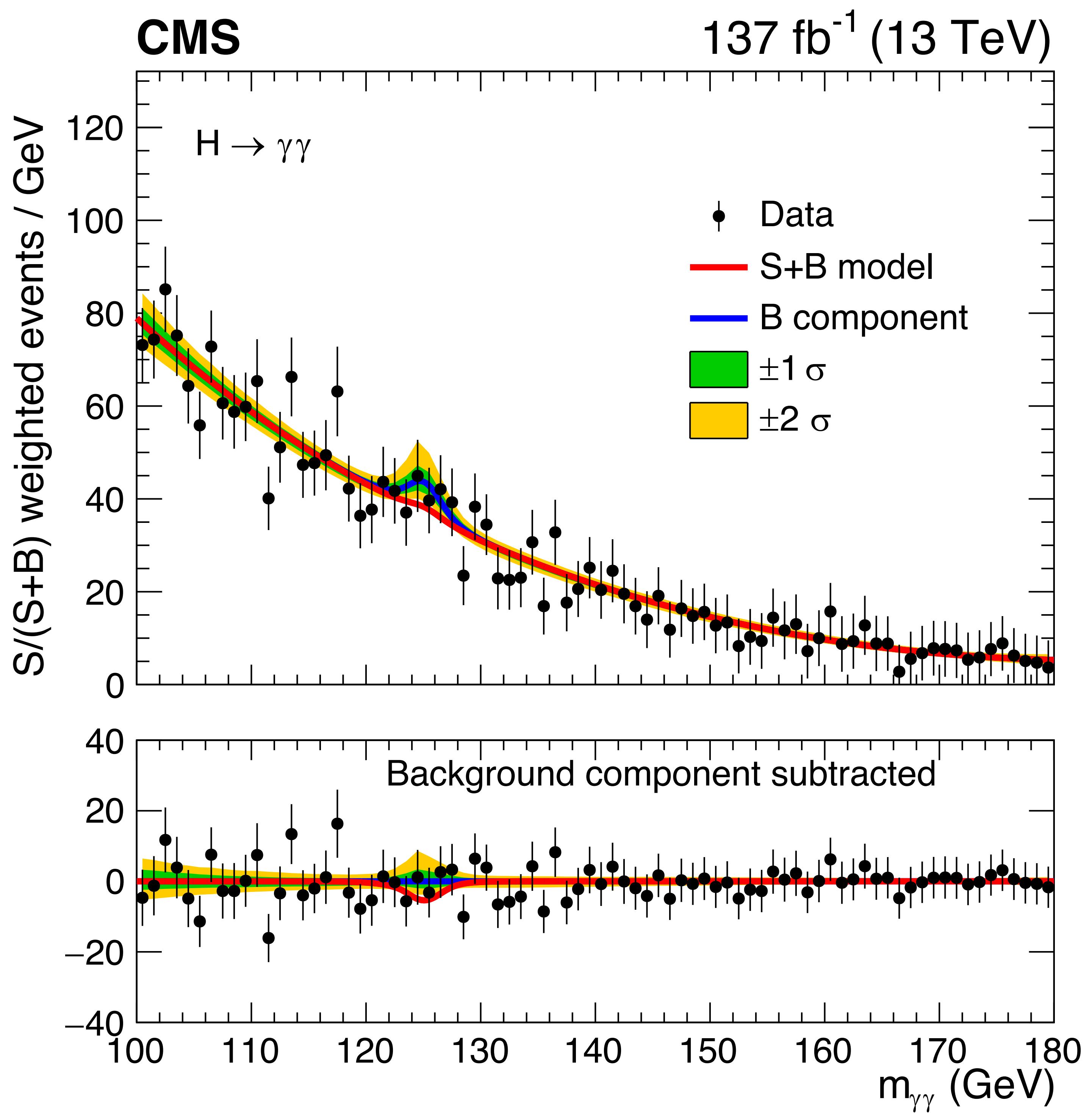
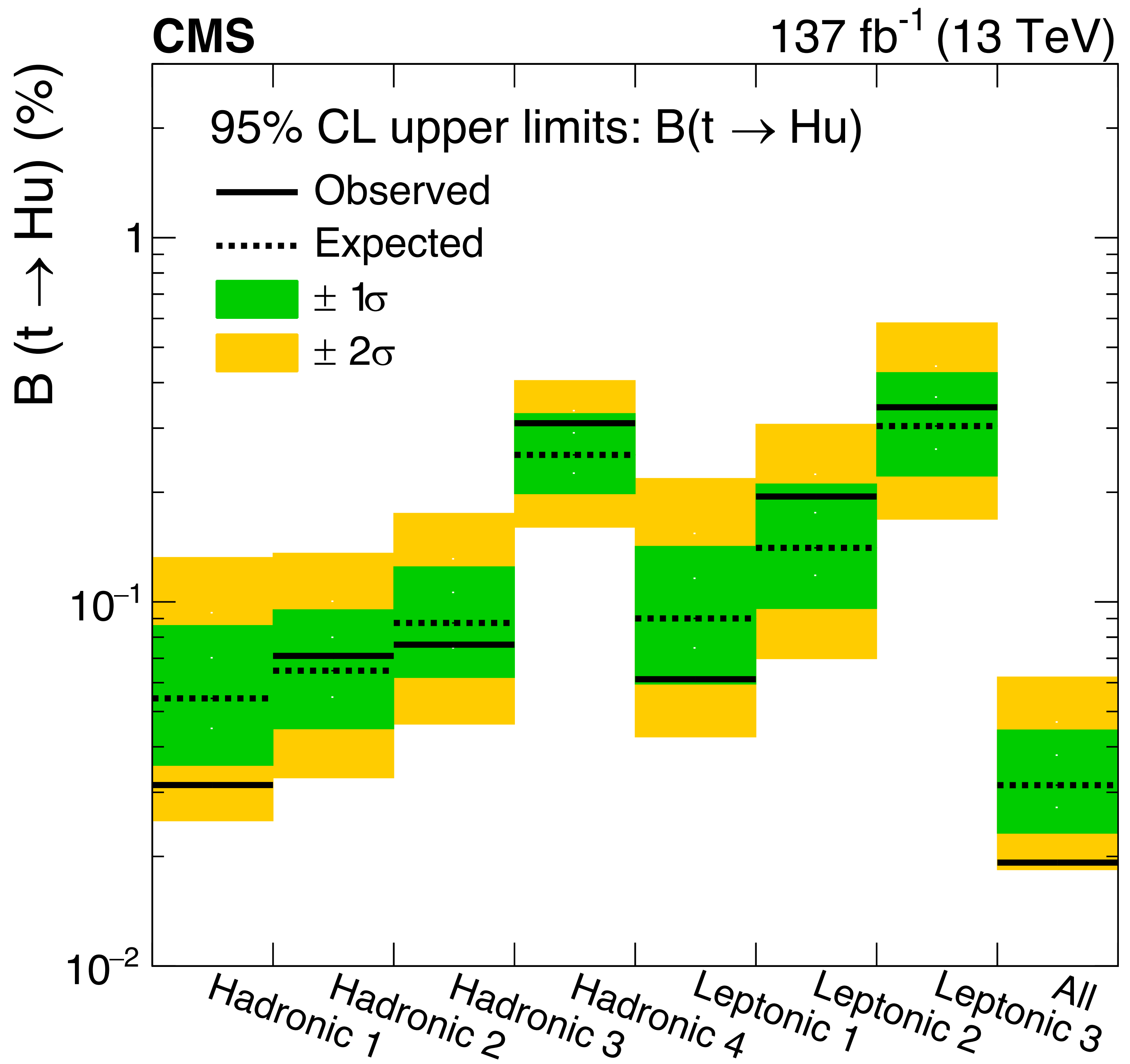




- Binned fits of $m_{\gamma\gamma}$ distribution in each category to extract the upper limit
- Main uncertainties
    - b jet, photon ID, integrated lumi., jet energy scale and resolution…

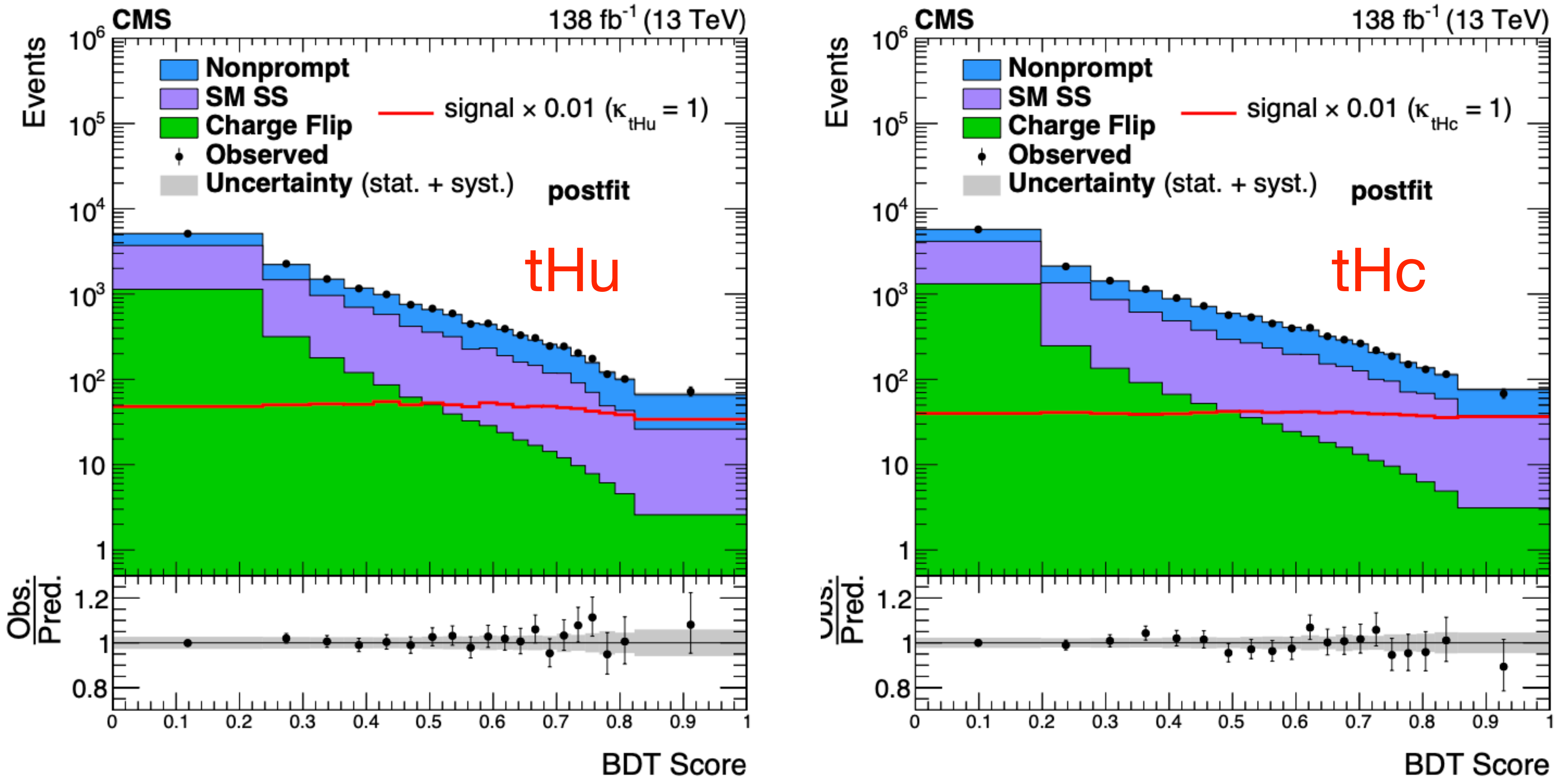
- Upper limits on the branching ratio: obs.(exp.)
    - $B(t \to Hu) < 0.019\ (0.31)\,\%$
    - $B(t \to Hc) < 0.073\ (0.051)\,\%$
- Better sensitivity than $tu(c)H(b\bar{b})$ analysis

FCNC - $tu(c)H$ in multilepton

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

- Targeting $H \to WW, ZZ, \tau\tau$ with the same sign leptons
- Event selection
  - At least a same sign pair with $p_T > 25(20)$ GeV
  - $\geq$2 jets in SS events or $\geq$1 jet in multi-lepton events with $p_T > 30$ GeV and $|\eta| < 2.4$
  - b-tagged jet with $p_T > 25$ 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.)
  - $B(t \to Hu) < 0.073\ (0.059)\ \%$
  - $B(t \to Hc) < 0.041\ (0.060)\ \%$

see Joker talk by Kaitlin Salyer on Thursday

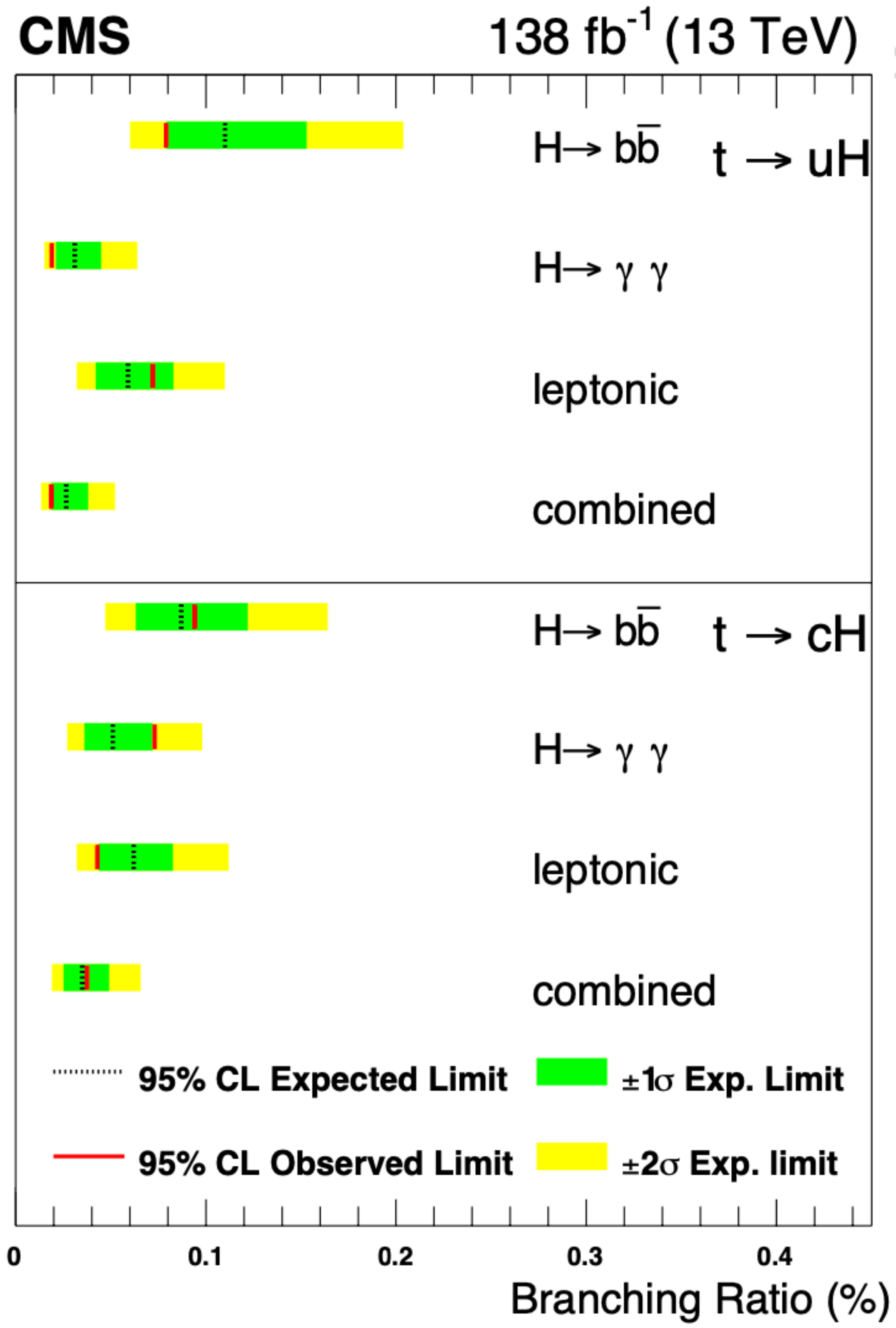
FCNC - $tu(c)H$ in combination

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

Preliminary

see Joker talk by Kaitlin Salyer on Thursday

Analysis	$\mathcal{B}(t \rightarrow Hu)$ observed (expected)	$\mathcal{B}(t \rightarrow Hc)$ observed (expected)
$b\bar{b}$ Page 9	0.079 (0.11)%	0.094 (0.086)%
Diphoton Page 11	0.019 (0.031)%	0.073 (0.051)%
Leptonic Page 14	0.073 (0.059)%	0.041 (0.060)%
Combination	0.019 (0.028)%	0.037 (0.035)%

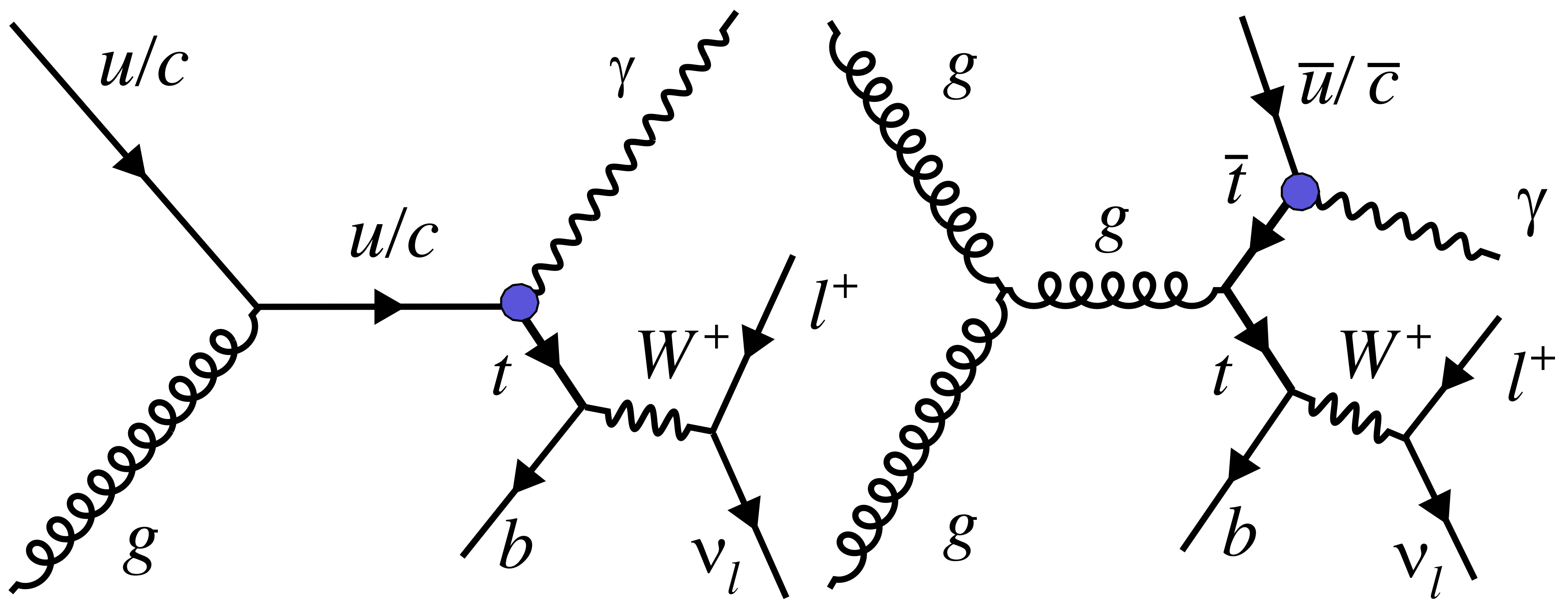


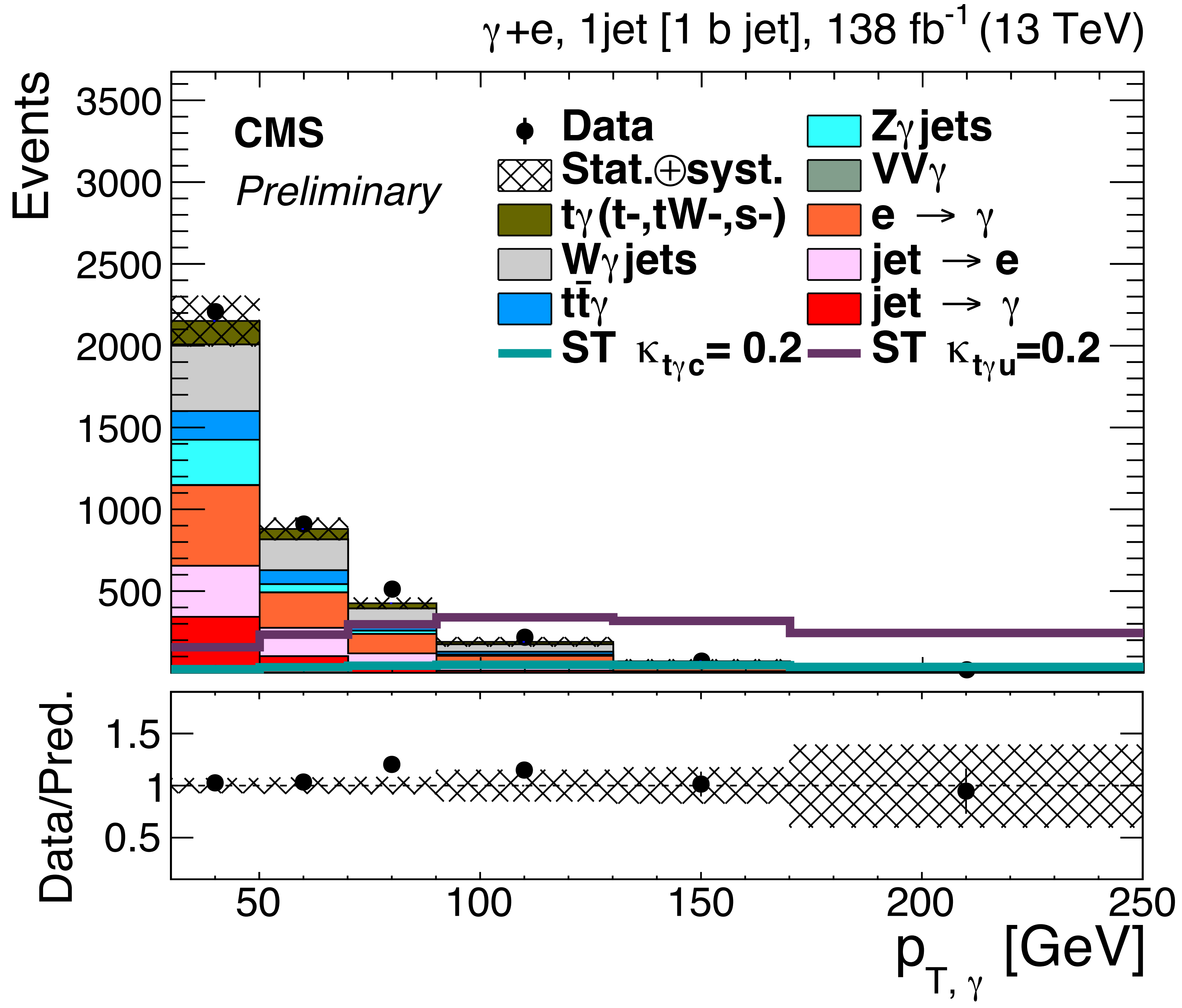
- Correlation
  - Combination jet energy scale and MET resolution, luminosity , lepton ID, theoretical uncertainties are treated as fully correlated
  - Remaining uncertainties are treated as uncorrelated
- The combination with the $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$ gives the most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

FCNC - $tu(c)\gamma$

138 fb^{-1} TOP-21-013

- 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

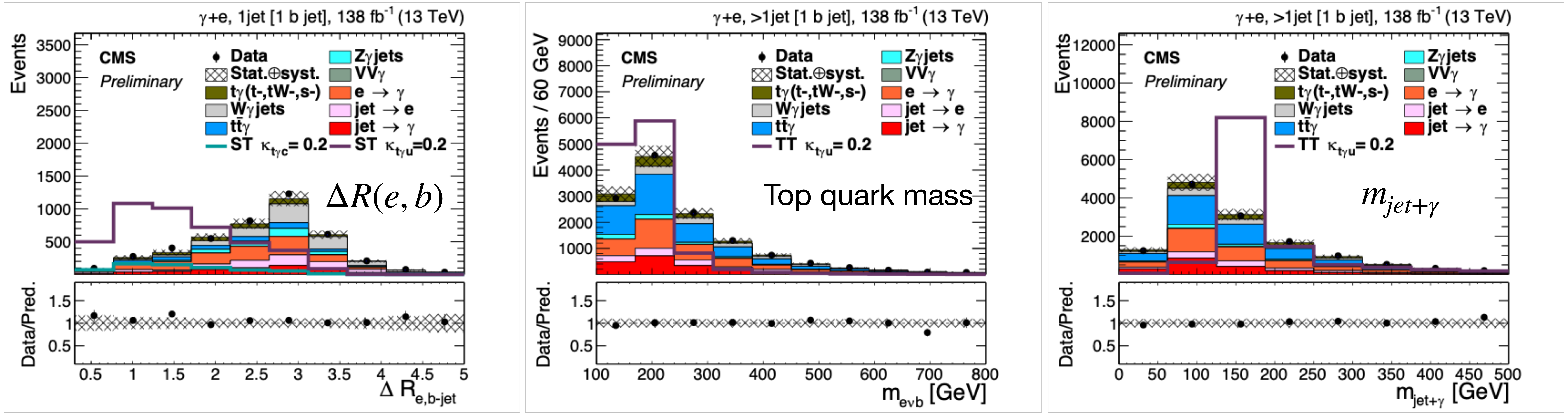




FCNC - $tu(c)\gamma$

138 fb^{-1} TOP-21-013

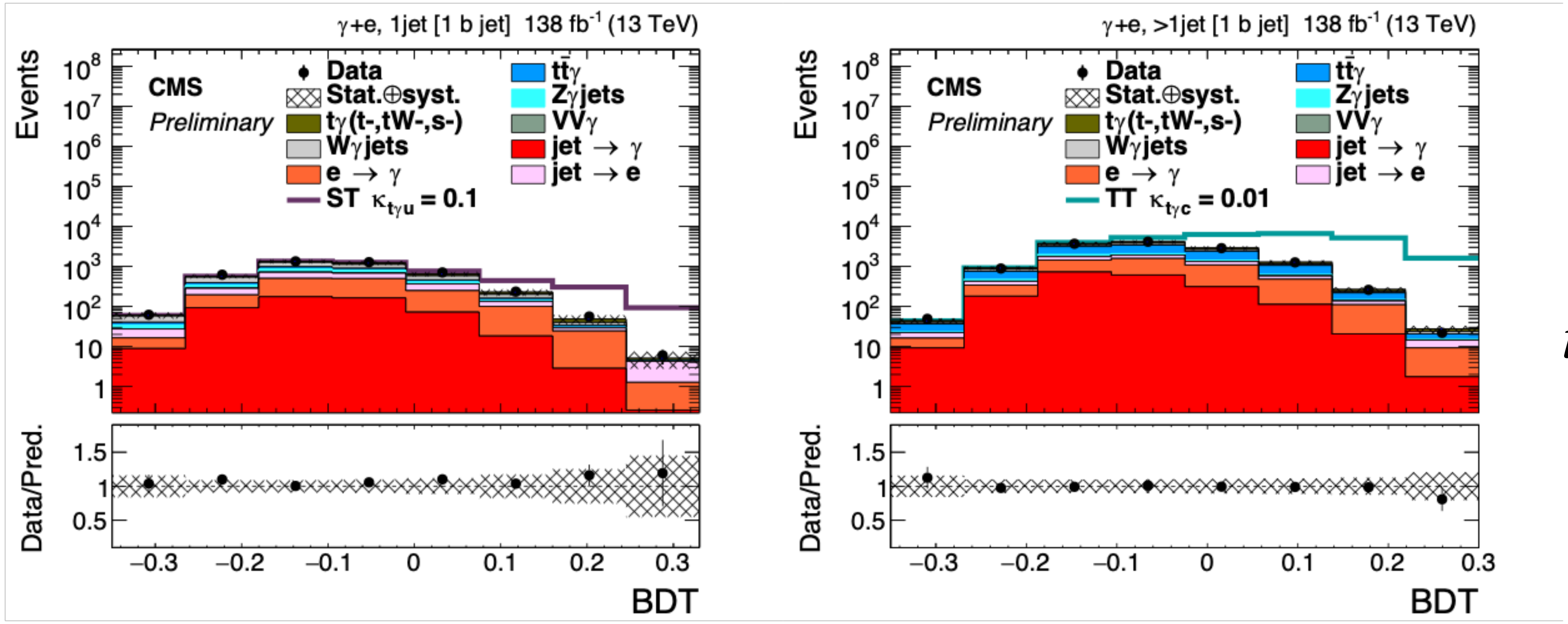
- BDT is used to maximize the sensitivity
- Separately trained for $tu\gamma$ and $tc\gamma$ signal scenarios (SR1 and SR2)
- 13 input variables
  - p_T and η of photon, η and charge of lepton, m_t, m_{WT}, $m_{j+\gamma}$,MET, $\Delta R(l,\gamma)$,$\Delta R(t,\gamma)$, njets, $\Delta R(l,b)$, $\Delta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



FCNC - $tu(c)\gamma$

138 fb^{-1} TOP-21-013

$tu\gamma$ 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}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$

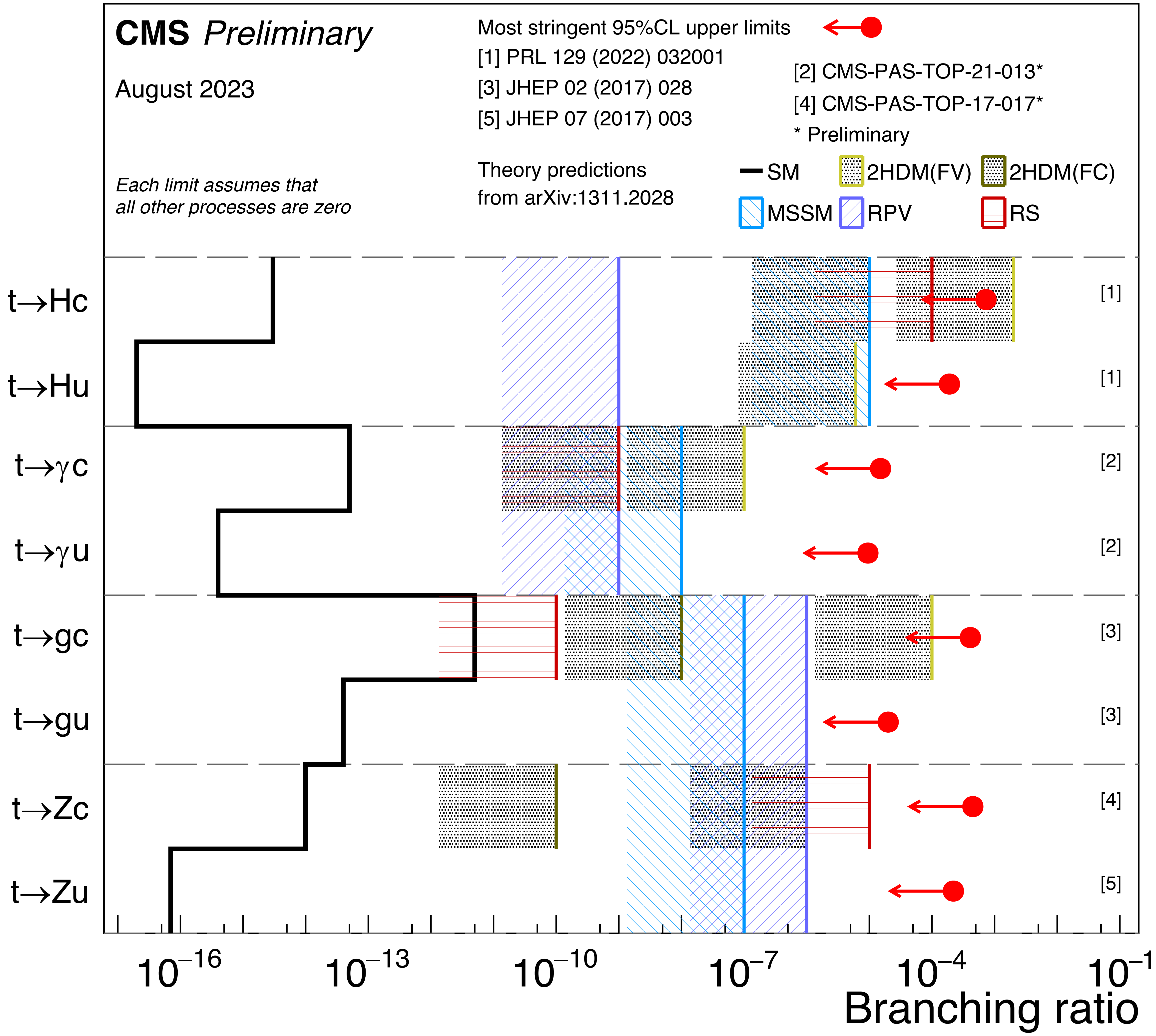
- For $B(t \to u + \gamma) < 0.95 \times 10^{-5}$, compatible with ATLAS results - PLB 842 (2023) 137379
- Limit for $B(t \to c + \gamma) < 1.51 \times 10^{-5}$ is significantly tighter

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