Searches for rare and beyond the Standard Model top-quark production and decay at CMS

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Why do we search for rare processes ?

Unveiling the unknown is exciting !

Rare decays and productions provide a path for probing new physics via indirect searches.

Any deviations from SM predictions in rare processes can guide theoretical developments and future experimental searches.

At the LHC we have the necessary ingredient !
The TOP quark

It is heavy, short lived and we have abundance of it :)

Introduction

In Standard Model (SM), top quark decays to b W almost with a branching fraction ~1.

Rare top quark decays such as flavour-changing neutral current (FCNC) are highly suppressed, due to Glashow-Iliopoulos-Maiani mechanism and charged lepton flavour violation (cLFV) can be predicted at loop level of neutrino mass terms.

SM has been successful for many years, but recently several excesses are reported.

- Lepton flavour violation: Combined result of R(D) and R(D*) anomalies, 3.17σ deviation from SM [1]
- W boson mass measurement from CDF II [2] reported 7.0σ of deviation
- Muon g-2 measurement [3] recently showed 5.0σ discrepancy

[1] HFLAV, Semileptonic B decay, 2023 (link)
[2] CDF Collaboration, Science 376 (2022) 6589, 170-176
[3] Muon g-2 Collaboration, arxiv:2308.06230

This talk covers …

Flavour-changing neutral currents (FCNC)

- tHq <u>CMS-PAS-TOP-22-002</u>
- tH*q <u>Phys. Lett. B 850 (2023) 138478</u>
  *with beyond standard model H

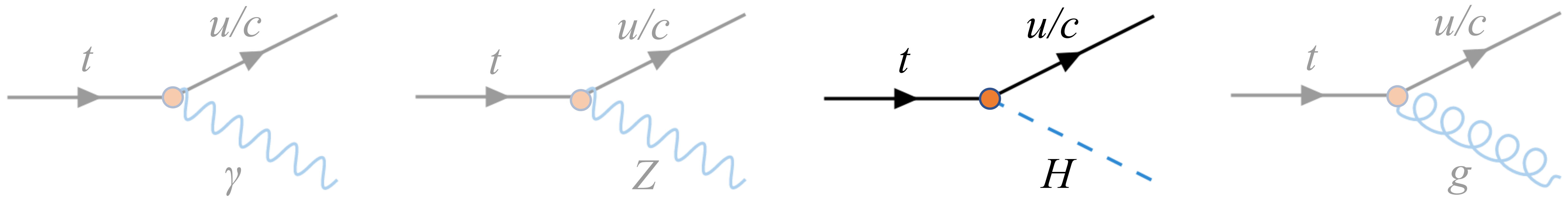
Charged lepton flavour violation (cLFV)

- $e\mu$tq <u>arXiv:2312.03199</u>
- $\mu\tau$tq <u>CMS-PAS-TOP-22-011</u>

See <u>poster</u> from Jiwon Park
Search for Lepton Flavor Violation in TOP quark sector using data from CMS Experiment

See <u>talk</u> from Barbara Alvarez Gonzalez
EFT based searches in the top-quark sector and beyond from CMS

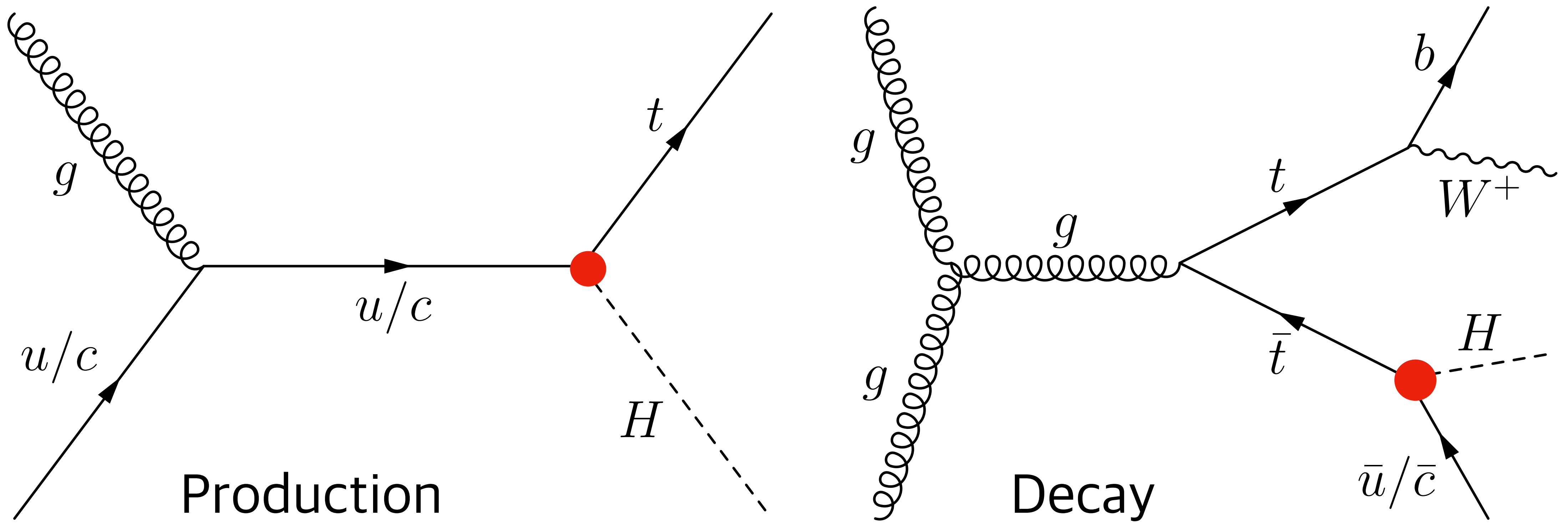
FCNC involving a top quark



- Branching fractions in SM $10^{-15} \sim -10^{-17}$
- Any excess can be a hint for Beyond the SM

Search for FCNC: tHq, H→ZZ, WW, ττ

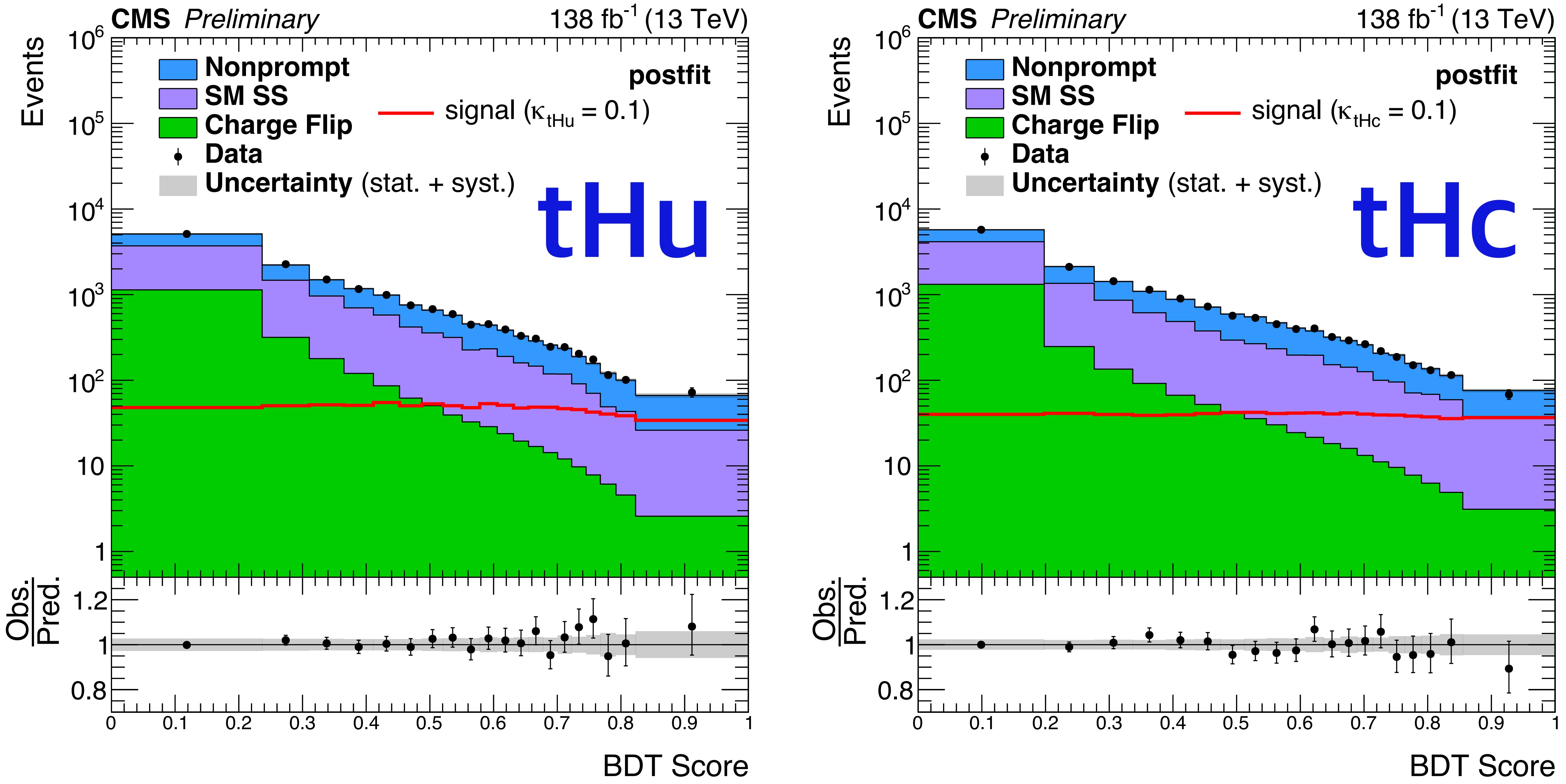
CMS-PAS-TOP-22-002



Signal and background events are classified using a boosted decision tree (BDT). Two BDTs are trained for tHu and tHc.

- Effective lagrangian:

$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} \left(F^{L}_{Hq} P_L + F^{R}_{Hq} P_R \right) qH + h.c..$$



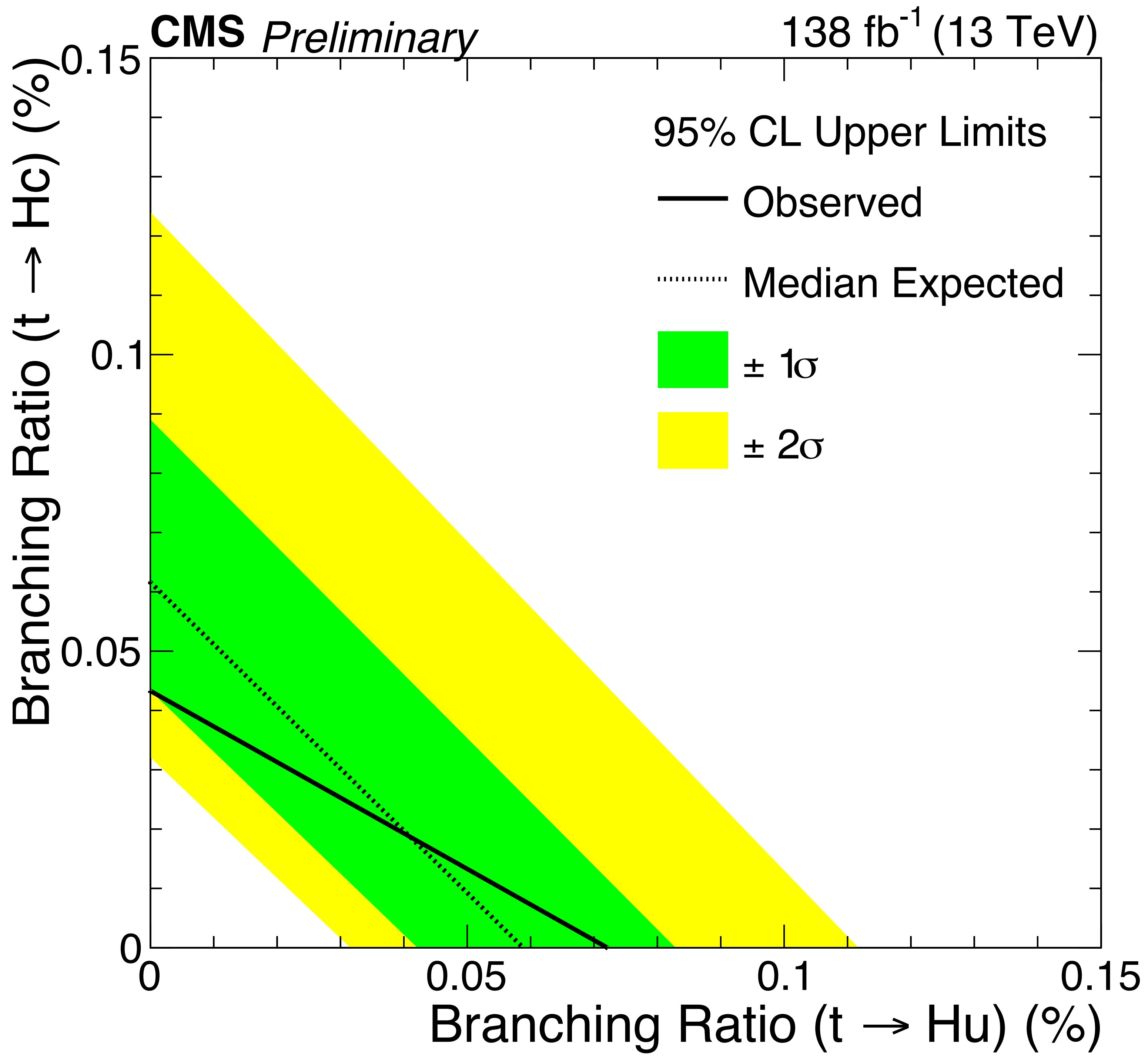
- At least two leptons (electron or muon) with the same sign (SS) electric charge and at least one jet.
- The main backgrounds are from detector effects and standard model process that produce a similar final state.

Exploiting c tagging score as one of the training inputs strengthens tHc sensitivity.

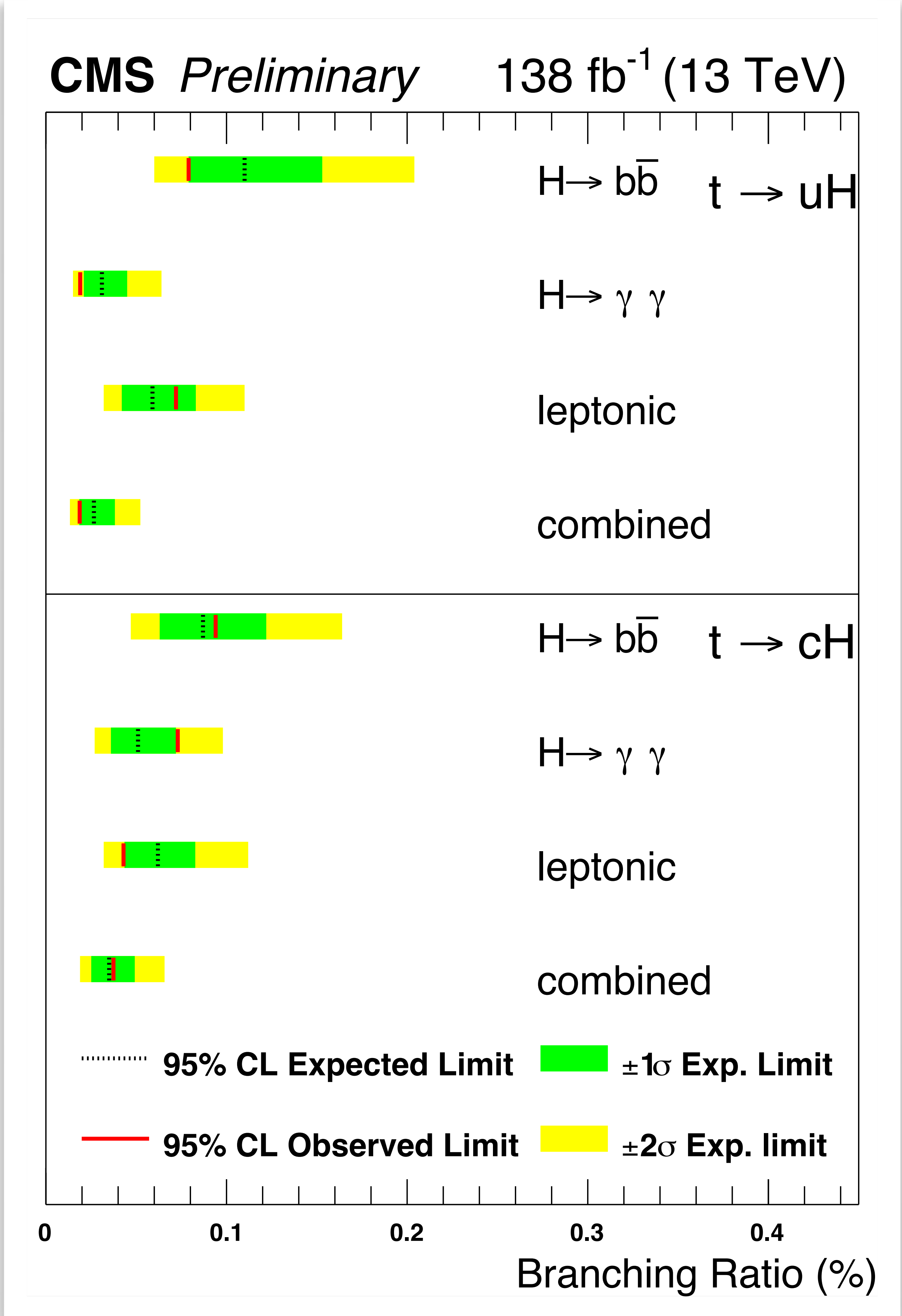
Search for FCNC: tHq, H→ZZ, WW, ττ

CMS-PAS-TOP-22-002

The data are found to be consistent with the standard model expectation.



Observable	Obs. limit	Exp. limit
$B(t \to u + H)$	7.2×10^{-4}	5.9×10^{-4}
	1.9×10^{-4}	2.7×10^{-4}
$B(t \to c + H)$	4.3×10^{-4}	6.2×10^{-4}
	3.7×10^{-4}	3.5×10^{-4}



Consistent results are obtained among CMS limits

Search for FCNC: tHq

with g2HDM

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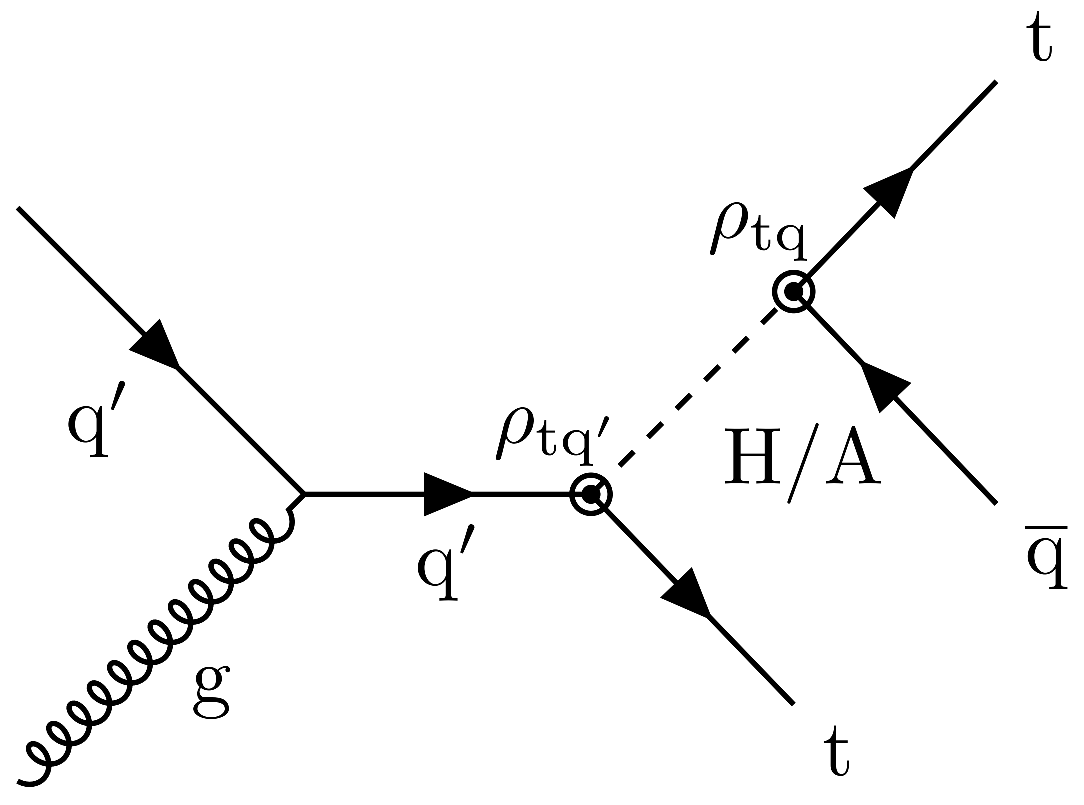
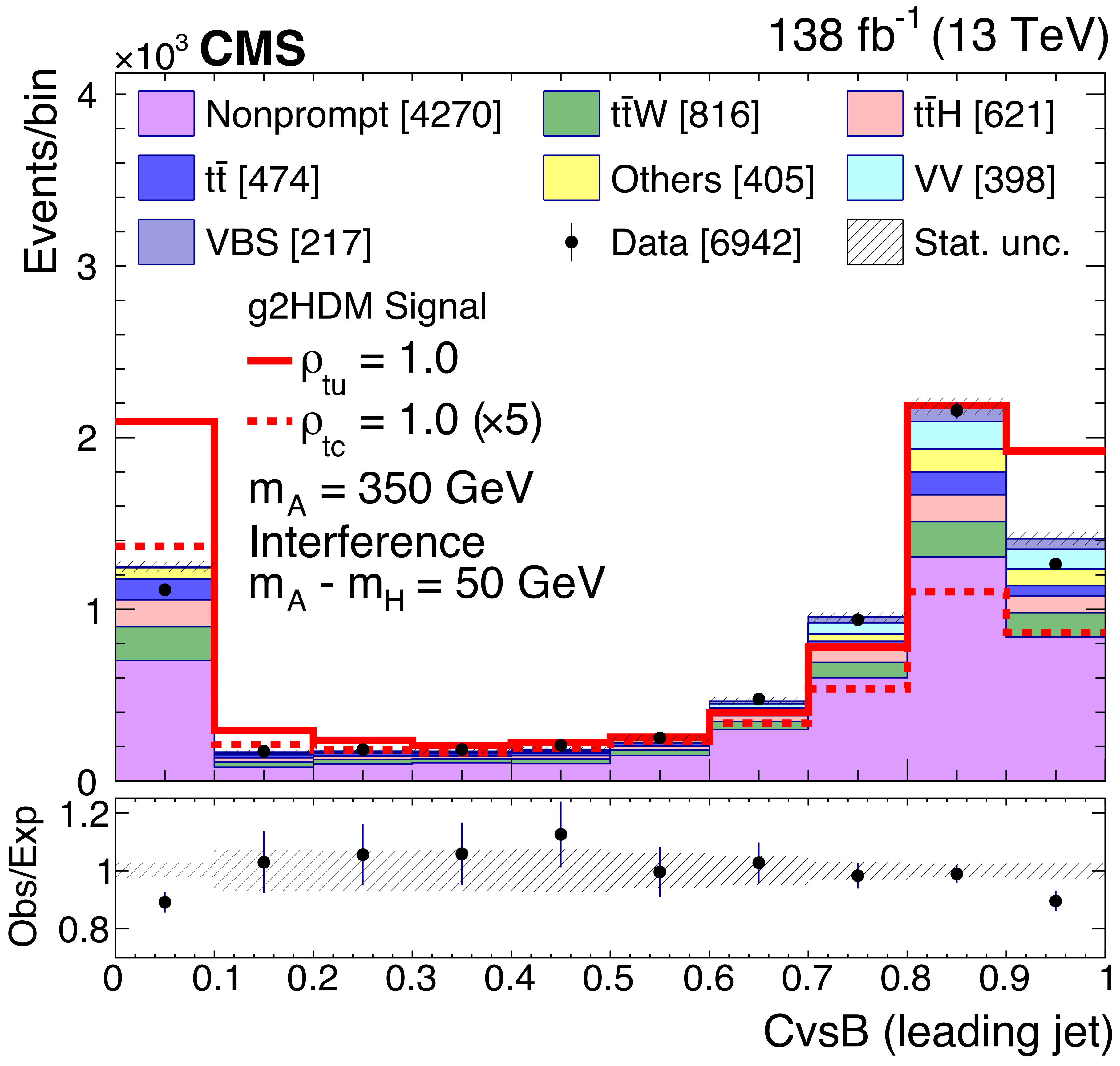
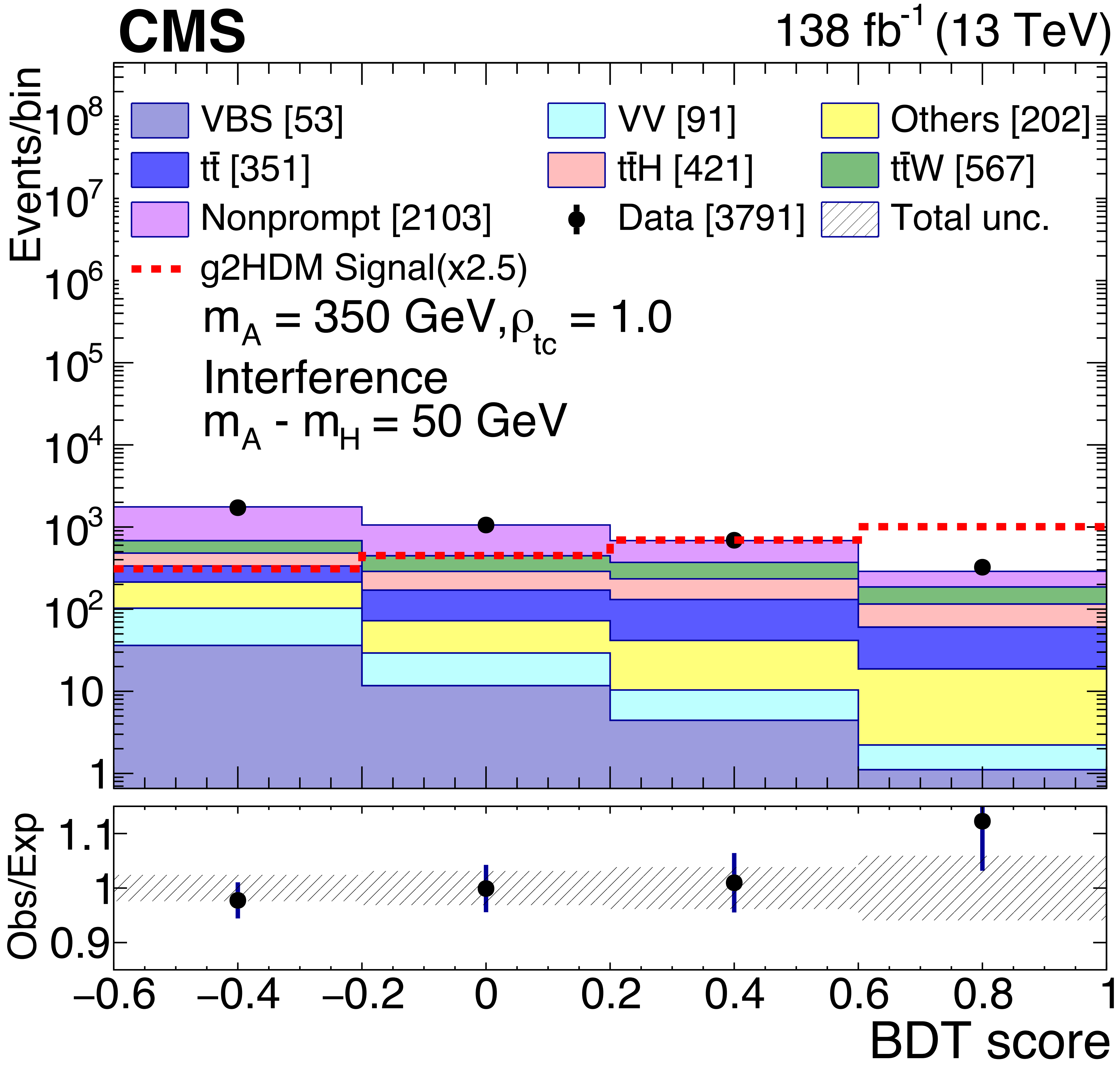


- Focus on ρ_{tu}/ρ_{tc}-induced **same-sign top quark** in **same-sign lepton** final states
- Considered **no A-H interference** and **A-H interference** cases (with $m_A - m_H = 50\,\mathrm{GeV}$) independently



- DeepJet algorithm is used.



- BDTs trained independently for each era x [10 mass (w/o interference) + 9 mass (w interference)] x(ρ_{tu}=0.4 and ρ_{tc}=0.4) —> 152 BDTs in total.

Search for FCNC: tHq

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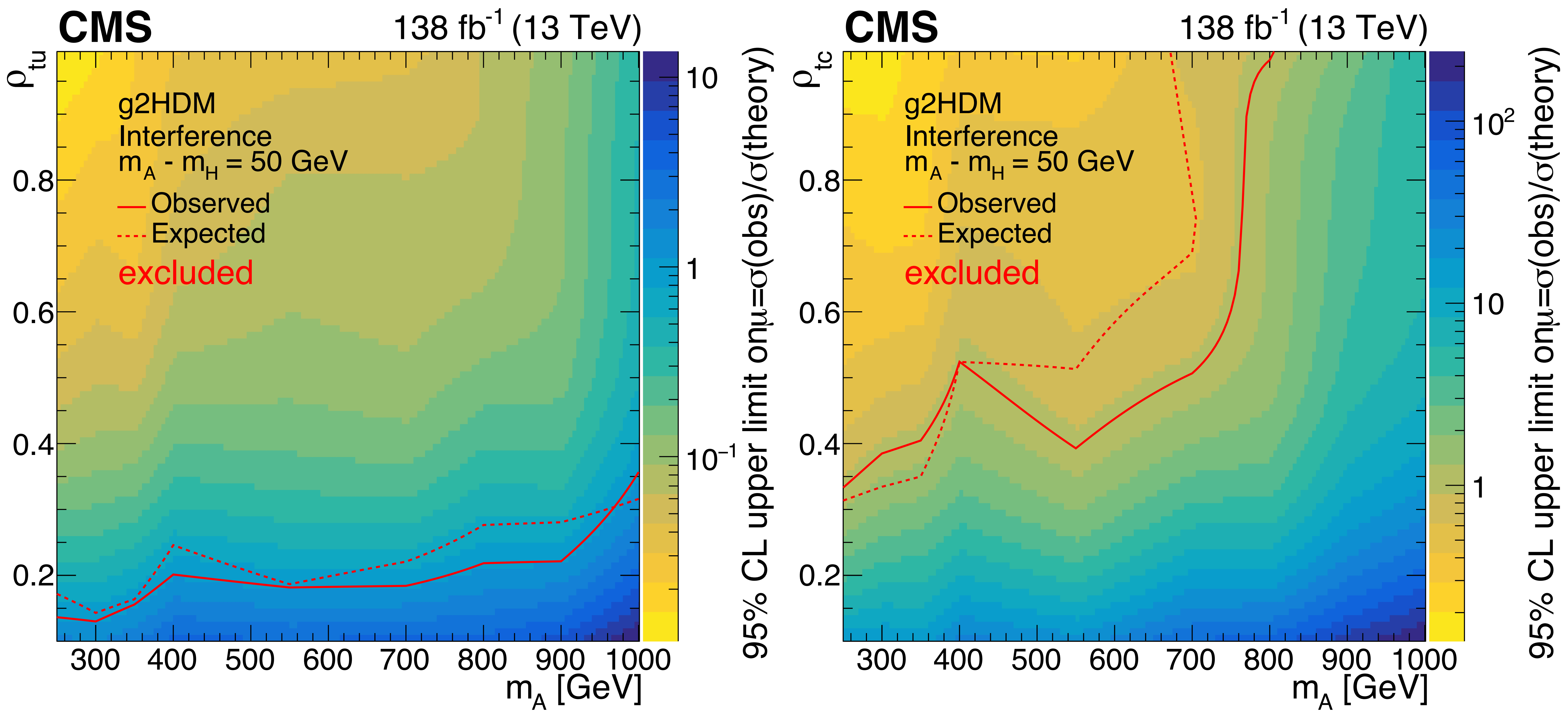
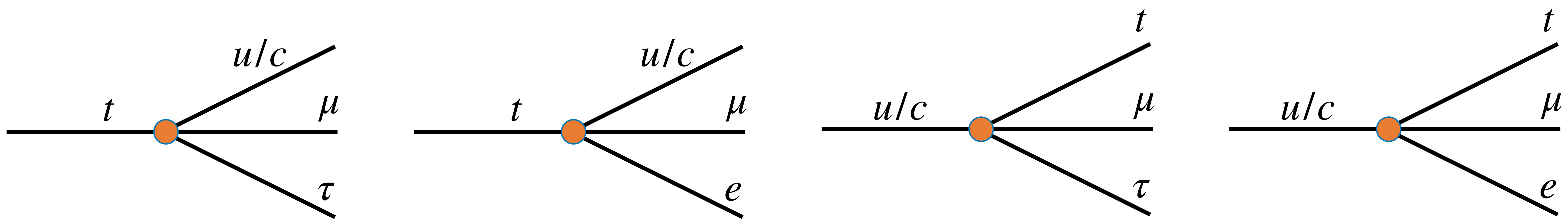
- No statistically significant excess over the SM backgrounds is observed.
- 4 bins of BDT score in each decay mode simultaneously fit to extract limits for each signal mass-coupling hypothesis.

	Observed (expected) mass limit [GeV]		
	without interference	with interference	with interference
	m_A or m_H	m_A	m_H
ρ_{tu}			
0.4	920 (920)	1000 (1000)	950 (950)
1.0	1000 (1000)	1000 (1000)	950 (950)
ρ_{tc}			
0.4	no limit	340 (370)	290 (320)
1.0	770 (680)	810 (670)	760 (620)



- ρ_{tu} largely excluded, but still a large portion of the phase space not constrained for ρ_{tc}.
- First search based on g2HDM considering A-H interference.

cLFV in top quark sector



- Observation of Neutrino oscillations -> neutrino mass & neutral lepton flavour violation.
- The neutrino mass terms predict charged lepton flavour violation
- Branching fractions in SM ~ 10^{-55}, extended SM ~ 10^{-6}
- Any excess is a hint for Beyond the SM

Lepton flavor non-universality in B Physics [link]

Interpretations of some flavor anomalies also predict a reachable CLFV rate in the top quark sector [link]

Searches for cLFV

- Takes effective field theory (EFT) interpretation for general study without model dependency.

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} O_a^{(6)} + O\left(\frac{1}{\Lambda^4}\right)$$

- c_i, O_i Wilson Coefficients and Operators:

Structure	Operator	Definition	Wilson coefficient
Scalar	$O_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l)$	C_{lequ1}
Vector	$O_{lq}^{1(ijkl)} = O_{lq}$	$(\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l)$	C_{lq}
	$O_{lu}^{(ijkl)}$	$(\bar{l}_i \gamma^\mu l_j)(\bar{u}_k \gamma^\mu u_l)$	C_{lu}
	$O_{eq}^{(ijkl)}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l)$	C_{eq}
	$O_{eu}^{(ijkl)}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l)$	C_{eu}
Tensor	$O_{lequ}^{3(ijkl)}$	$(\bar{l}_i \sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k \sigma^{\mu\nu} u_l)$	C_{lequ3}

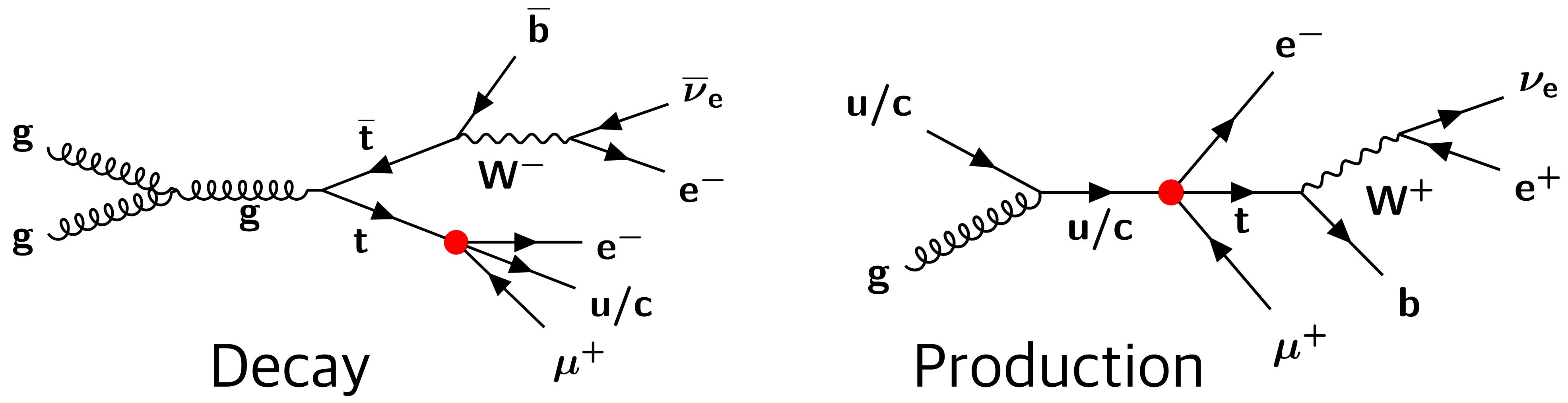
- Dimension-6 operators are used for building effective Lagrangian

- Λ : the scale of new physics is set to 1 TeV.

Search for cLFV: $e\mu tq$

arXiv:2312.03199

submitted to Phys. Rev. D



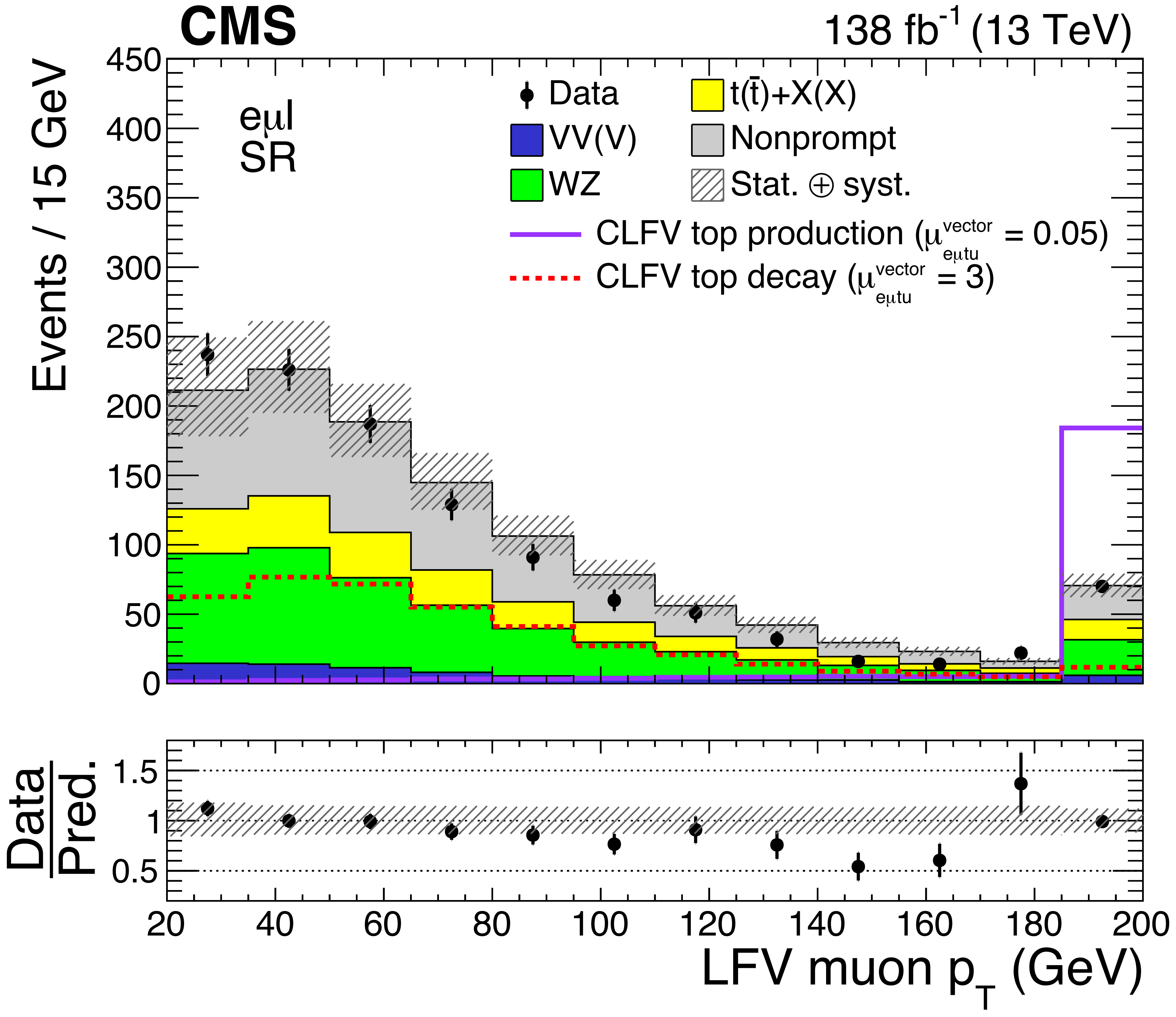
- The analysis utilizes boosted decision trees to separate background processes from a possible signal.
- Separately trained for top decay (m($e\mu$) < 150 GeV) and production (m($e\mu$) > 150 GeV) enriched regions

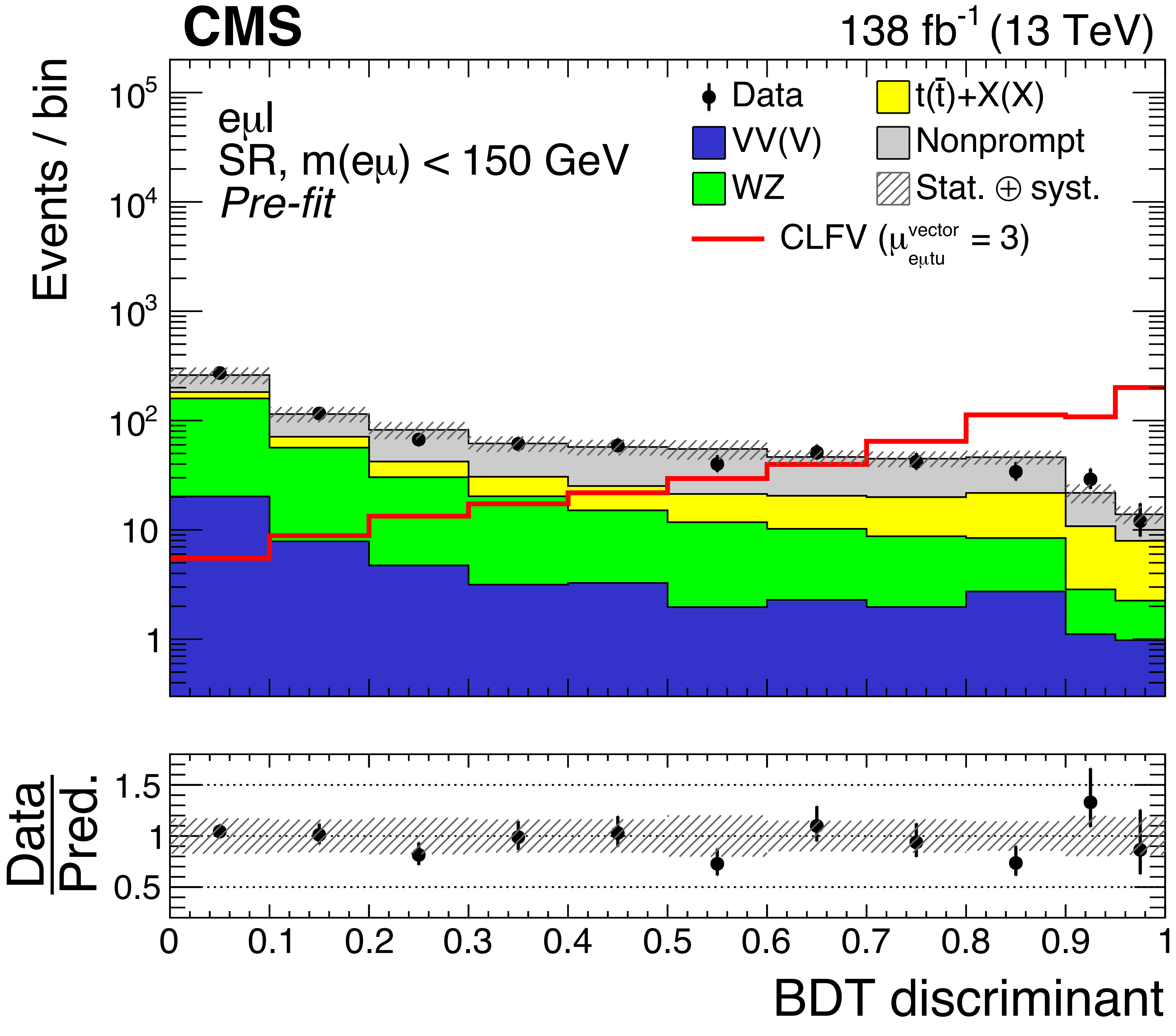
Analysis signature

- Opposite-Charge eμ pair
- Third lepton coming from leptonic top quark decay
- One b-jet,
- one/zero light jet (u/c)

Background estimation

- Prompt backgrounds rely on the simulation
- Nonprompt backgrounds estimated by data-driven “Matrix method”
- Estimated events are validated using control/validation regions





Search for cLFV: $e\mu$tq

arXiv:2312.03199

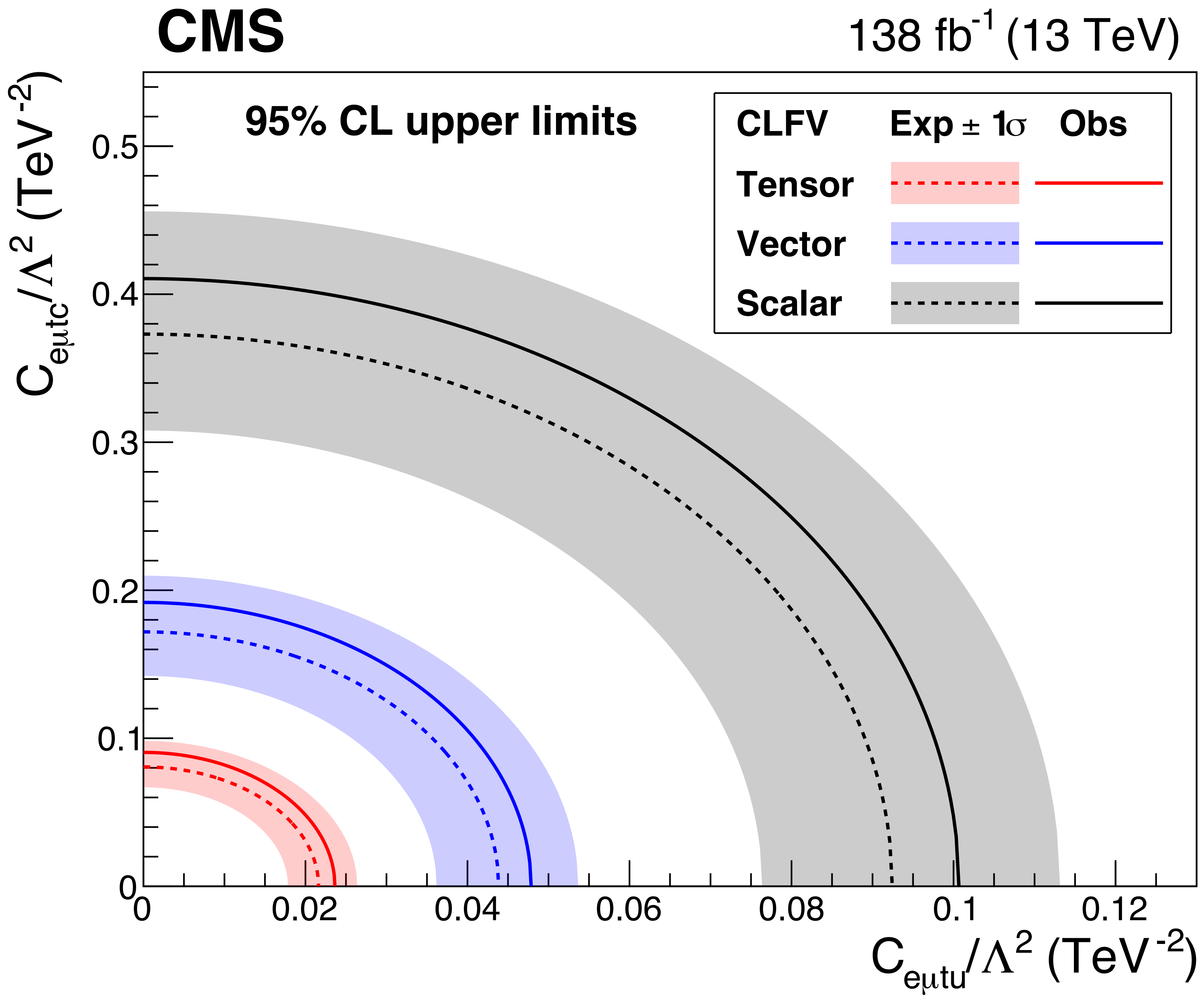
submitted to Phys. Rev. D

The data are found to be consistent with the standard model expectation.

The upper limits:

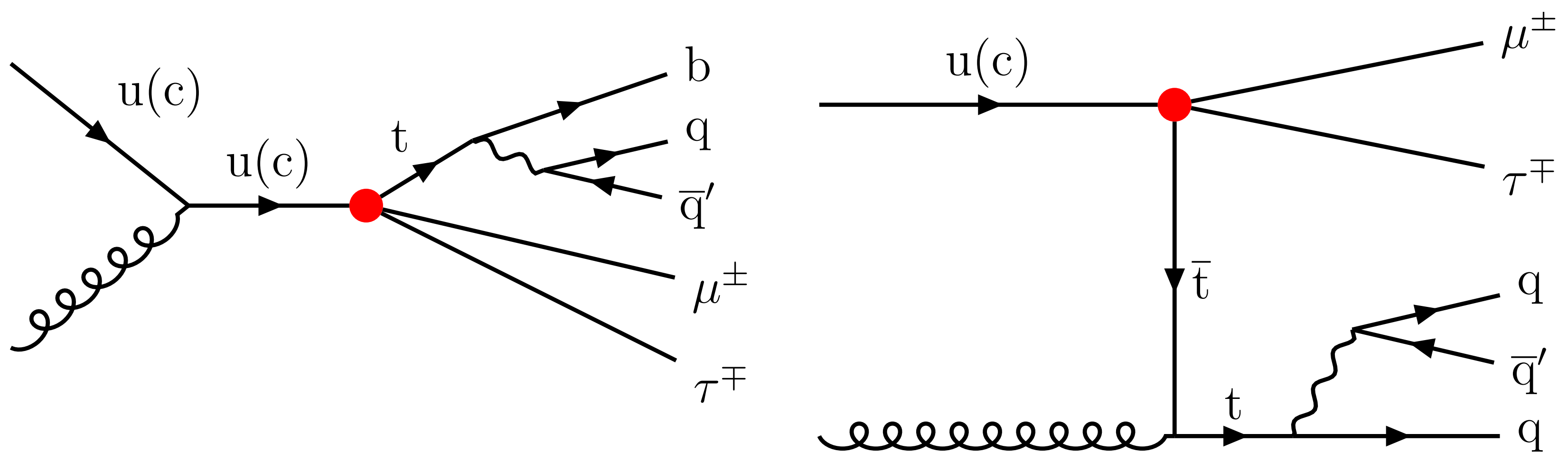
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	**Obs.**	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	**Obs.**
$e\mu tu$	Tensor	0.022 (0.018–0.026)	**0.024**	0.027 (0.018–0.040)	**0.032**
	Vector	0.044 (0.036–0.054)	**0.048**	0.019 (0.013–0.028)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

The exclusion contours of one dimensional limits on Wilson coefficients:

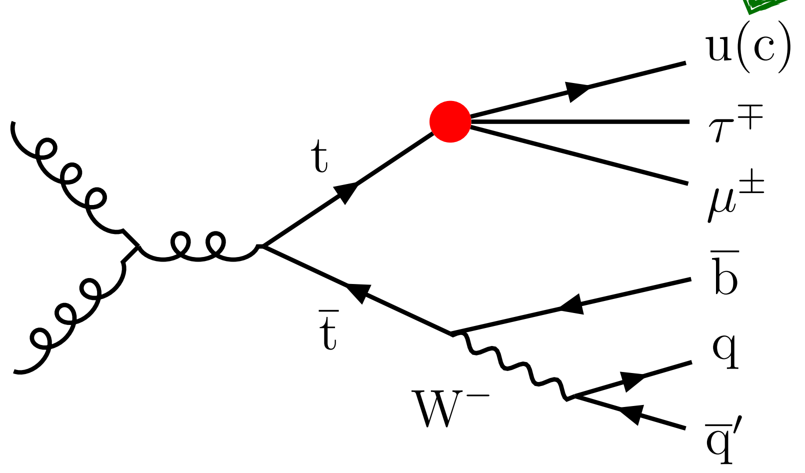


Search for cLFV: $\mu\tau$tq

CMS-PAS-TOP-22-011



Single top production



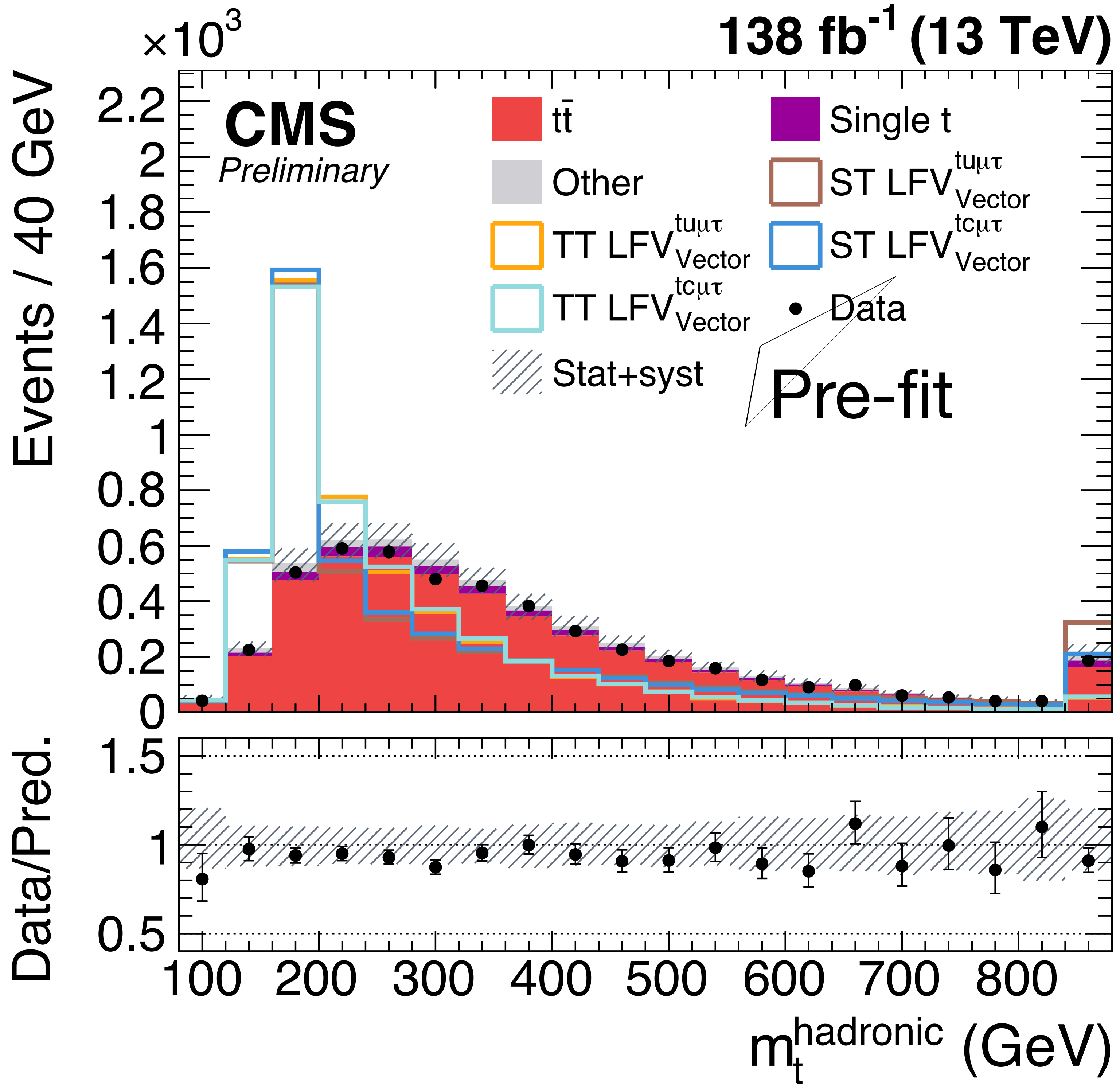
$t\bar{t}$ decay

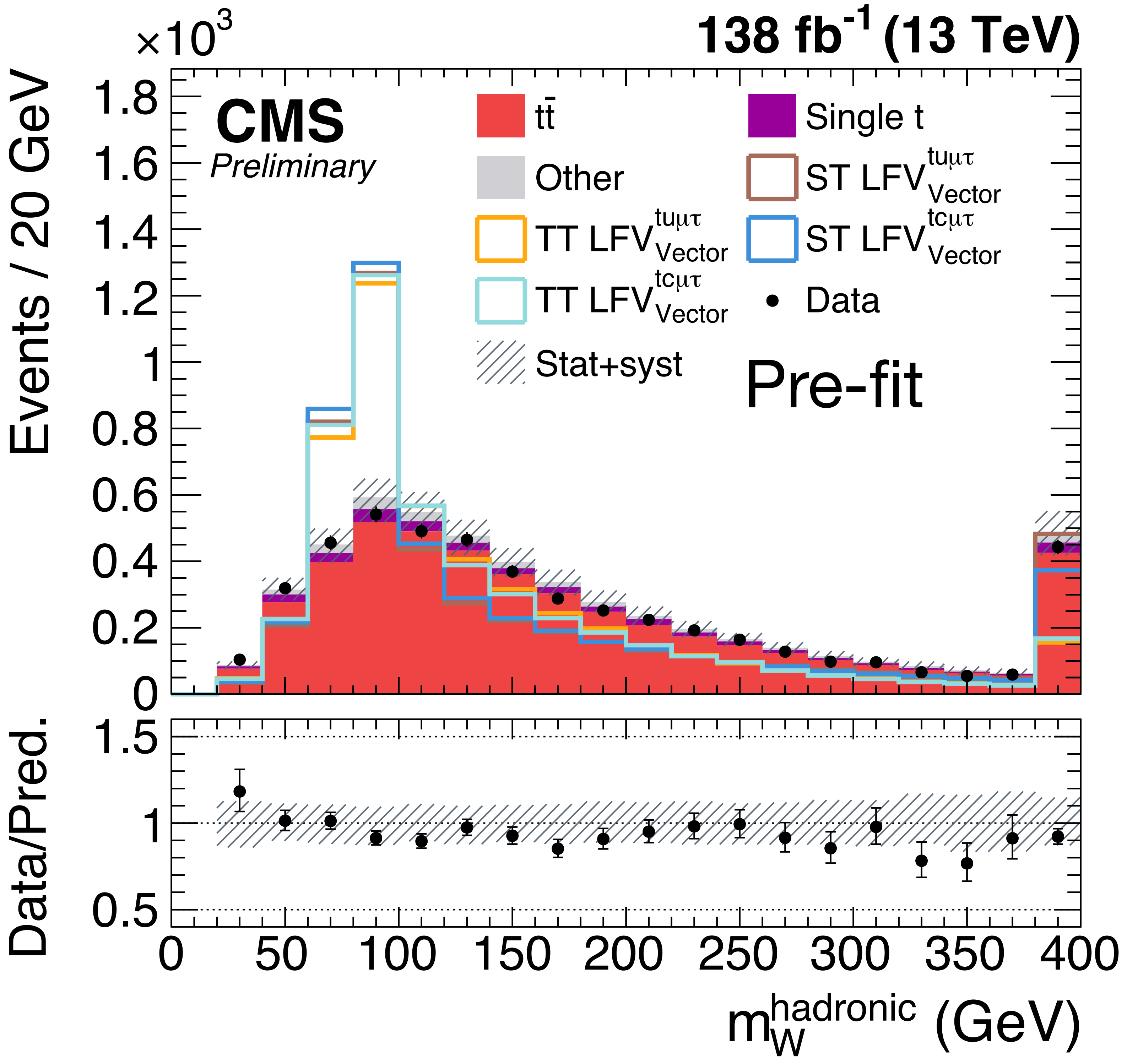
- Events Selection:

  one muon, one tau, opposite sign (OS) electric charge of the two leptons, Jets ≥ 3, one b-tagged jet.

- Background Estimation:
  - Prompt backgrounds rely on the simulation
  - Jets mis-identified as hadronic taus is estimated with **data based** estimation

- Reconstruction of SM top and W mass

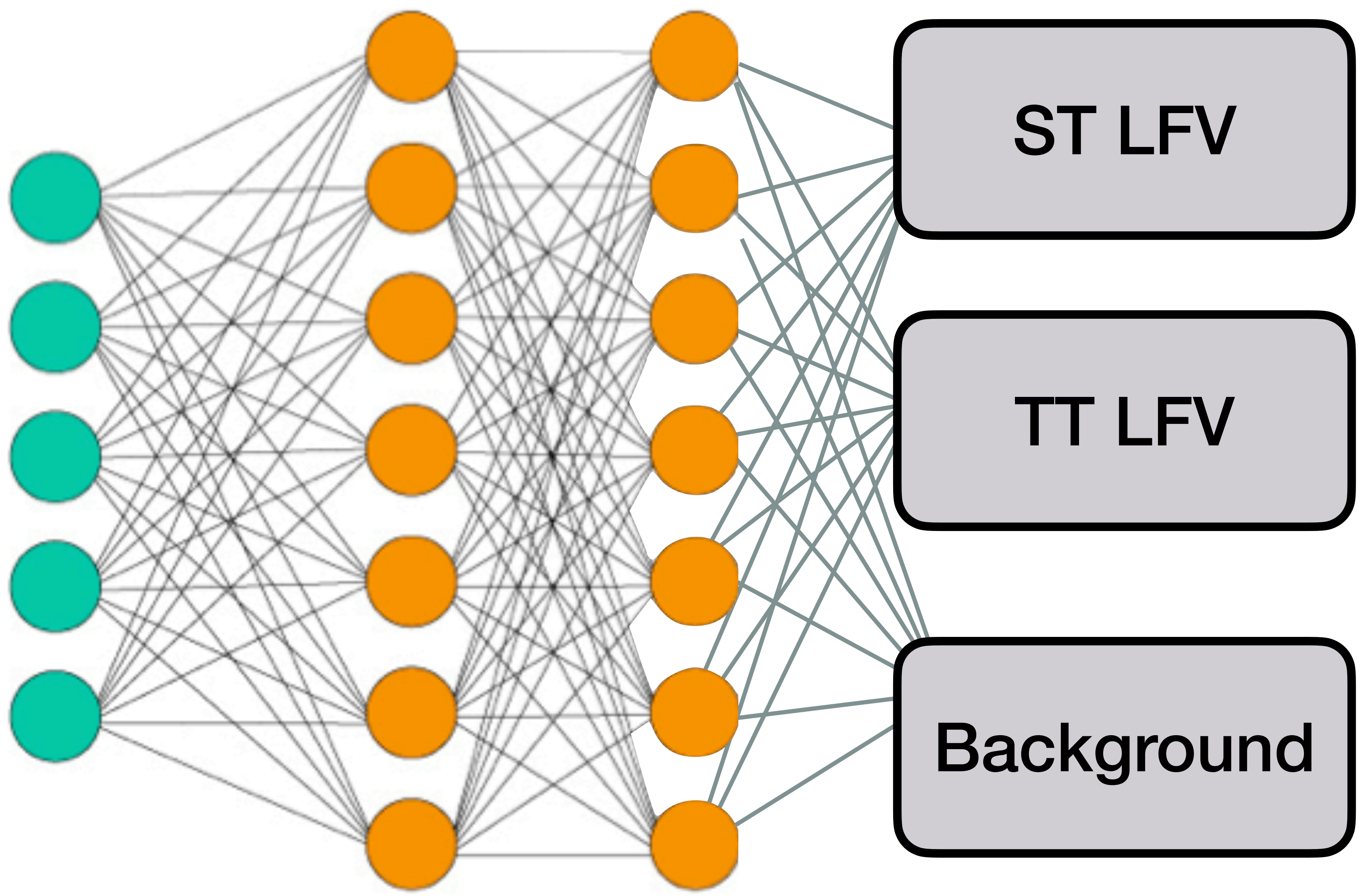




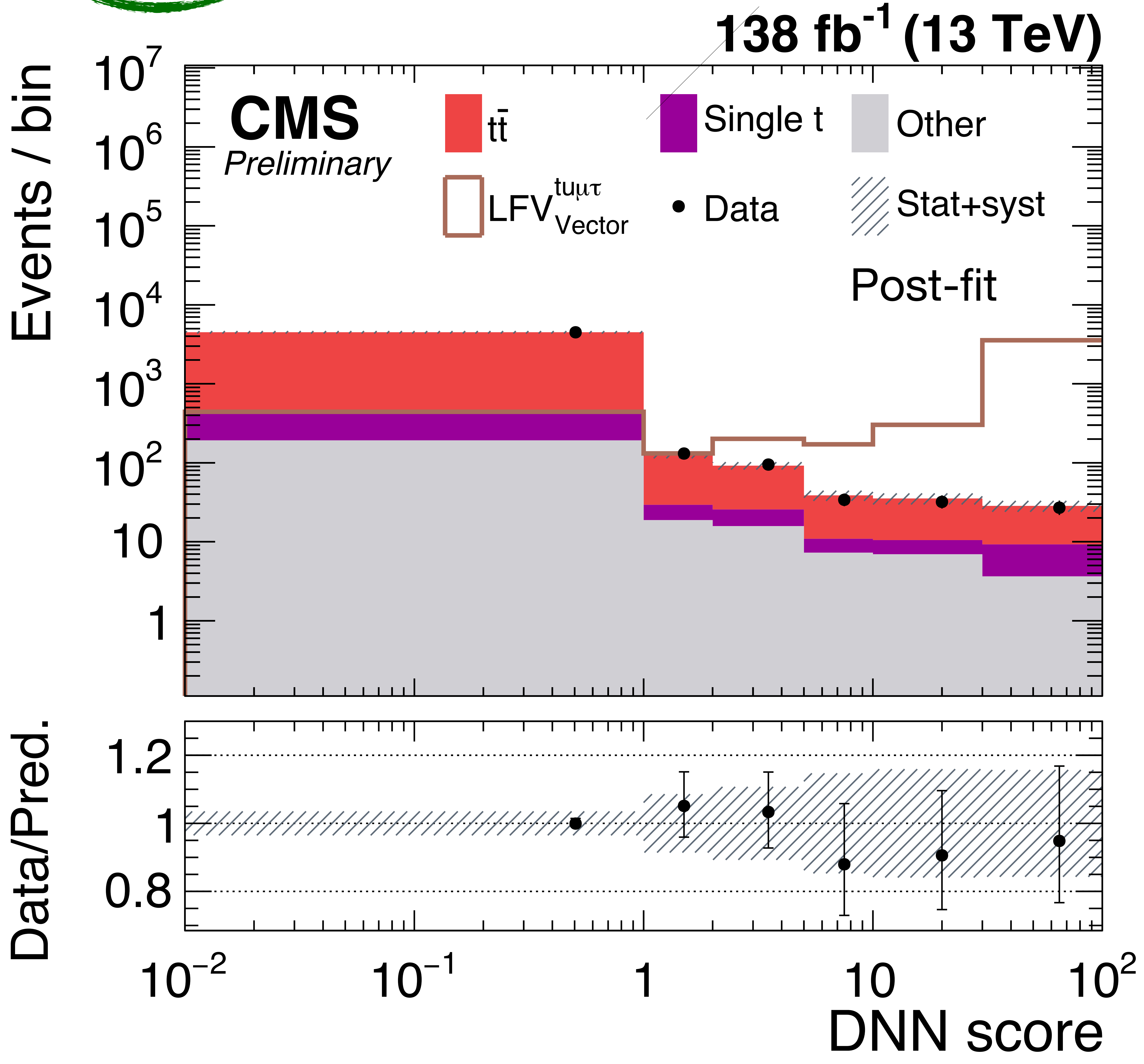
Search for cLFV: $\mu\tau tq$

CMS-PAS-TOP-22-011

Signal and background events are classified using a single deep neural network (DNN).



$$\text{DNN Score} = \frac{0.1 \times \text{P(TT LFV)} + 0.9 \times \text{P(ST LFV)}}{\text{P(SM Background)}}$$



Search for cLFV: $\mu\tau$tq

CMS-PAS-TOP-22-011

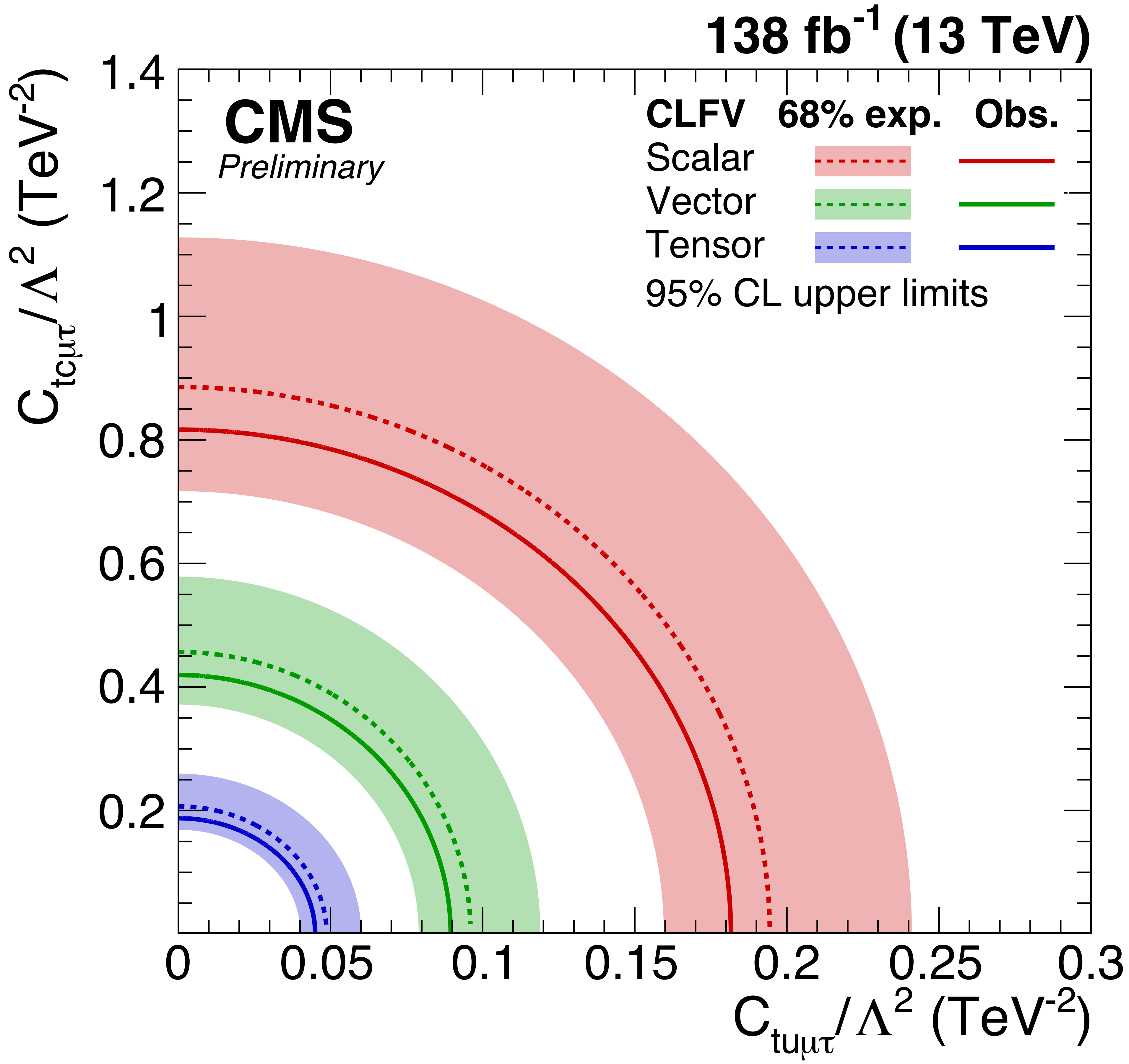
The data are found to be consistent with the standard model expectation.

- Upper limits at 95% CL are set for different interaction operators

The upper limits:

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

The exclusion contours of one dimensional limits on Wilson coefficients:



Conclusion

LHC as a top quark factory provides excellent opportunity to search for rare top quark decays.

We searched for FCNC and cLFV, so far the results are in agreement with SM.

Limits on the branching fractions of $O(10^{-6})$ or even smaller have been derived.

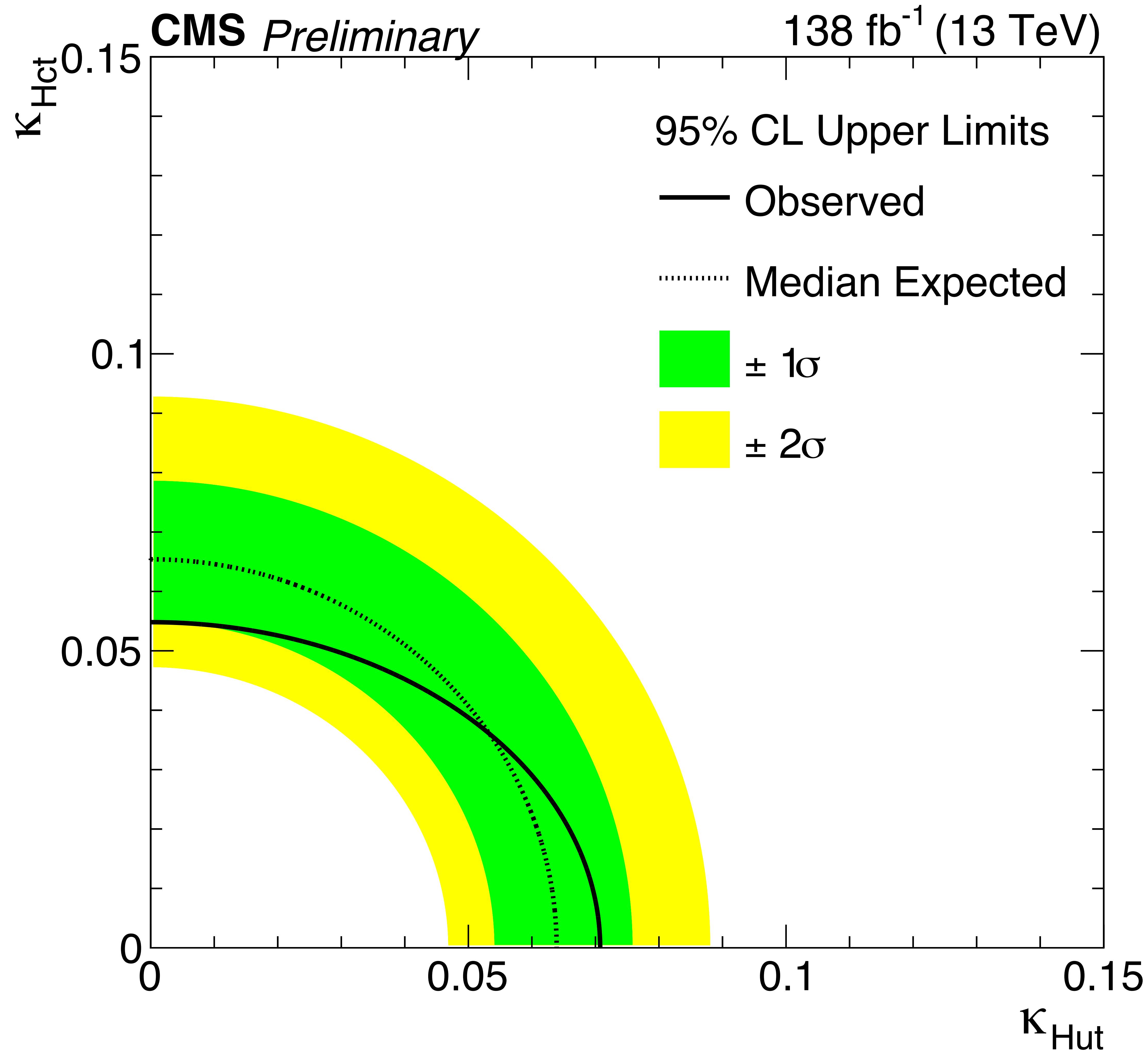
CMS collaboration continue analysing events with top quark production and decays.

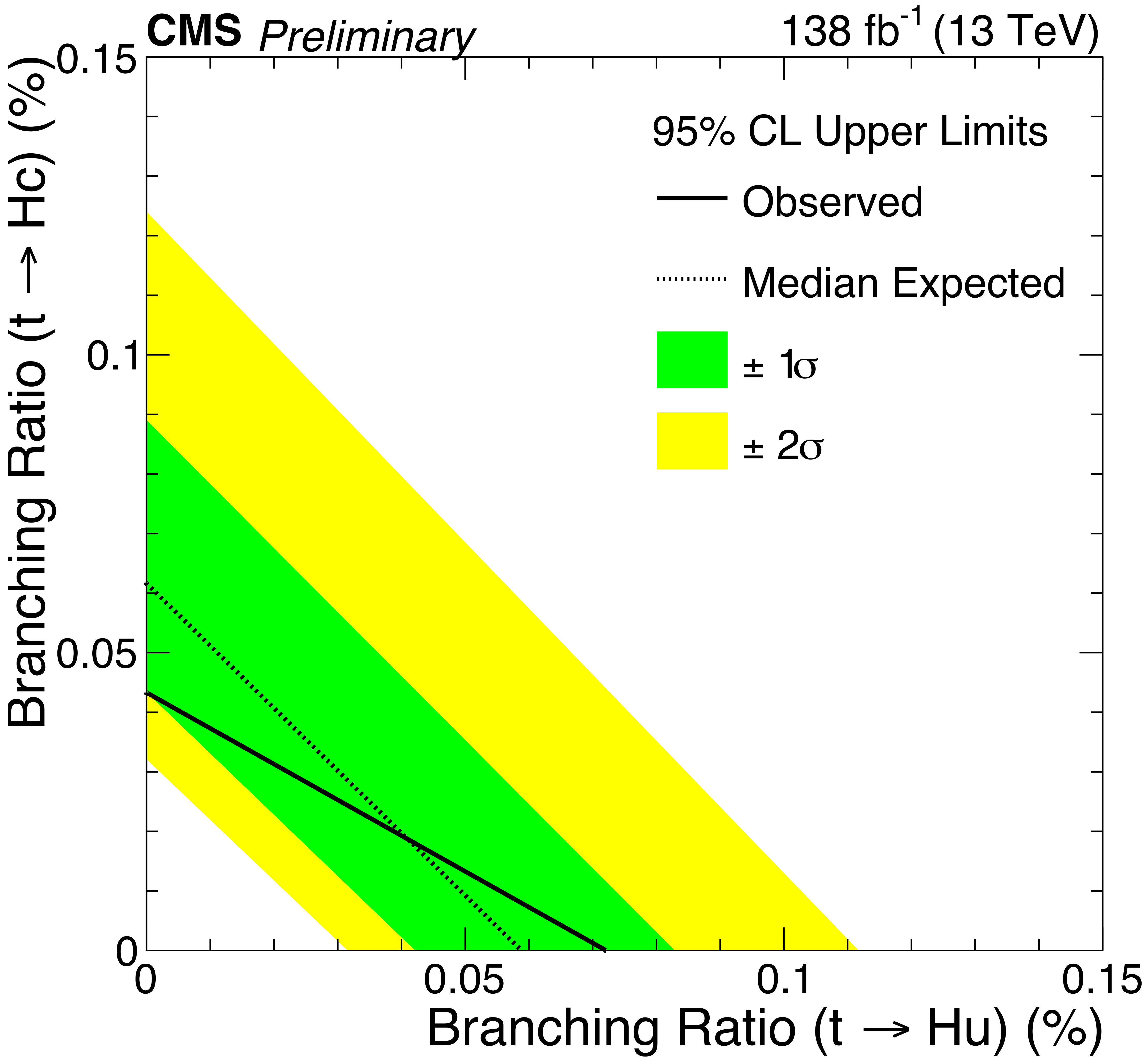
Stay tuned for Run3 results !

Search for FCNC: tHq, H→ZZ, WW, ττ

CMS-PAS-TOP-22-002

The data are found to be consistent with the standard model expectation.





Search for FCNC: tHq

with g2HDM

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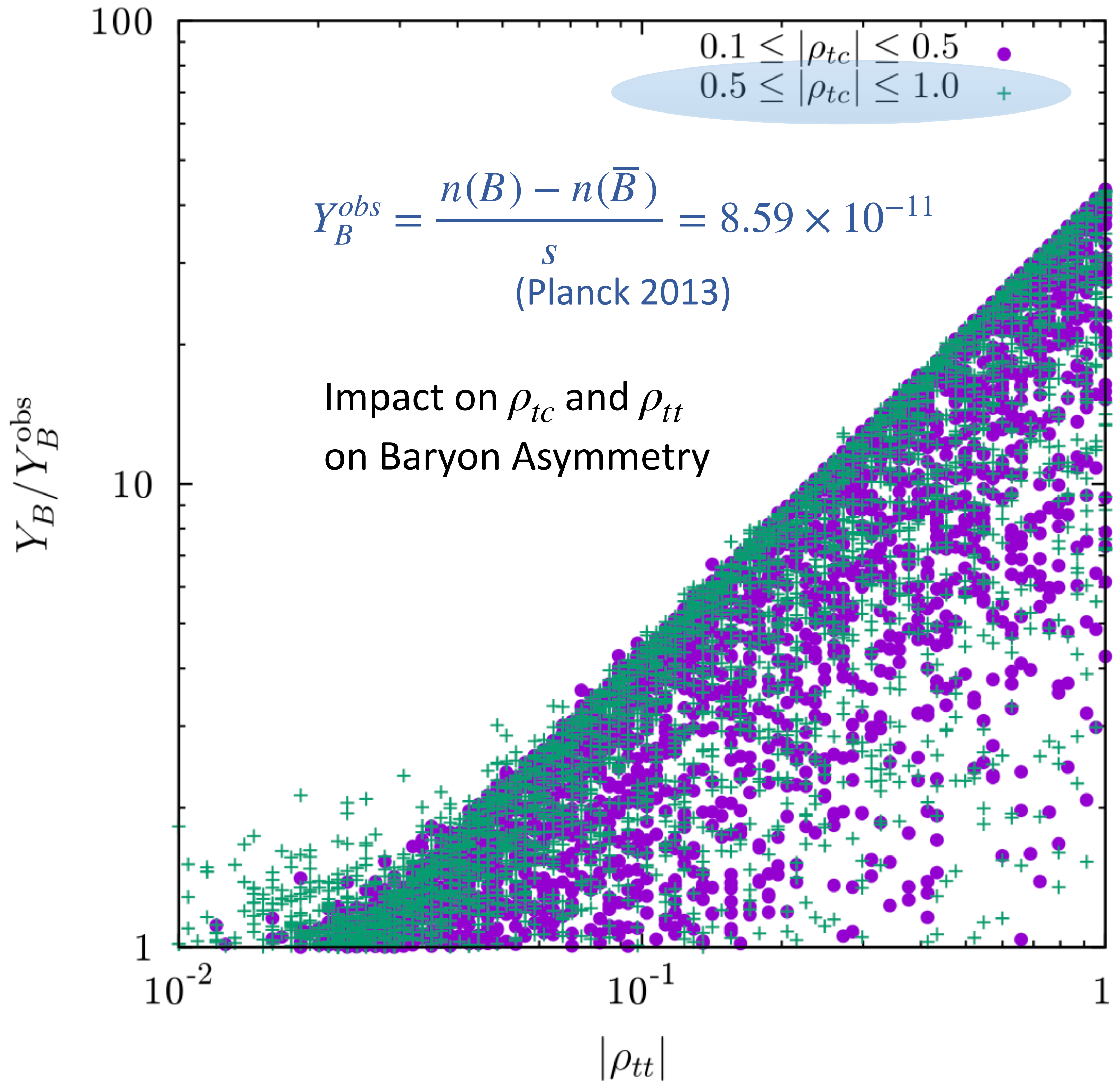
- 2HDM introduces five scalar bosons: $H^{\pm}, H, h, A$
- $\mathbb{Z}_2$ symmetry is dropped in 2HDM to allow FCNC
  $\rightarrow$ generalized 2HDM (g2HDM)
  - **Many parameters and extra processes arise.**
  - Alignment ($\cos\gamma_{H-h} \approx 0$) emerges when no $\mathbb{Z}_2$ symmetry and all extra Higgs quartic couplings are $\mathcal{O}(1)$
    - h becomes h_{125}
    - No HVV, AVV interactions.
    - Suppresses FCNC interactions for h but allows FCNC for H and A
  - *Electroweak baryogenesis, lack of FCNC (e.g. $t \rightarrow ch_{125}/uh_{125}$ or $h_{125} \rightarrow \mu\tau/e\tau$), … could be explained.*
  - **sub-TeV $H^{\pm}, H, A$ bosons may still exist**
    $\longleftrightarrow \Lambda_{NP} < \mathcal{O}(10\ TeV)$ **(opposite assumption to that of EFT).**

PLB 776 (2018) 402



$y_{ij} = \sqrt{2} m_i \delta_{ij}/v$

$q_i q_j h$ coupling (125 GeV Higgs) $\propto -y_{ij}\sin_\gamma + \rho_{ij}\cos_\gamma$

$q_i q_j H$ coupling (exotic Higgs) $\propto y_{ij}\cos_\gamma + \rho_{ij}\sin_\gamma$

Slide from Efe Yazgan