Search for flavor-changing neutral current interactions of the top quark and Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

Top2023

Kaitlin Salyer

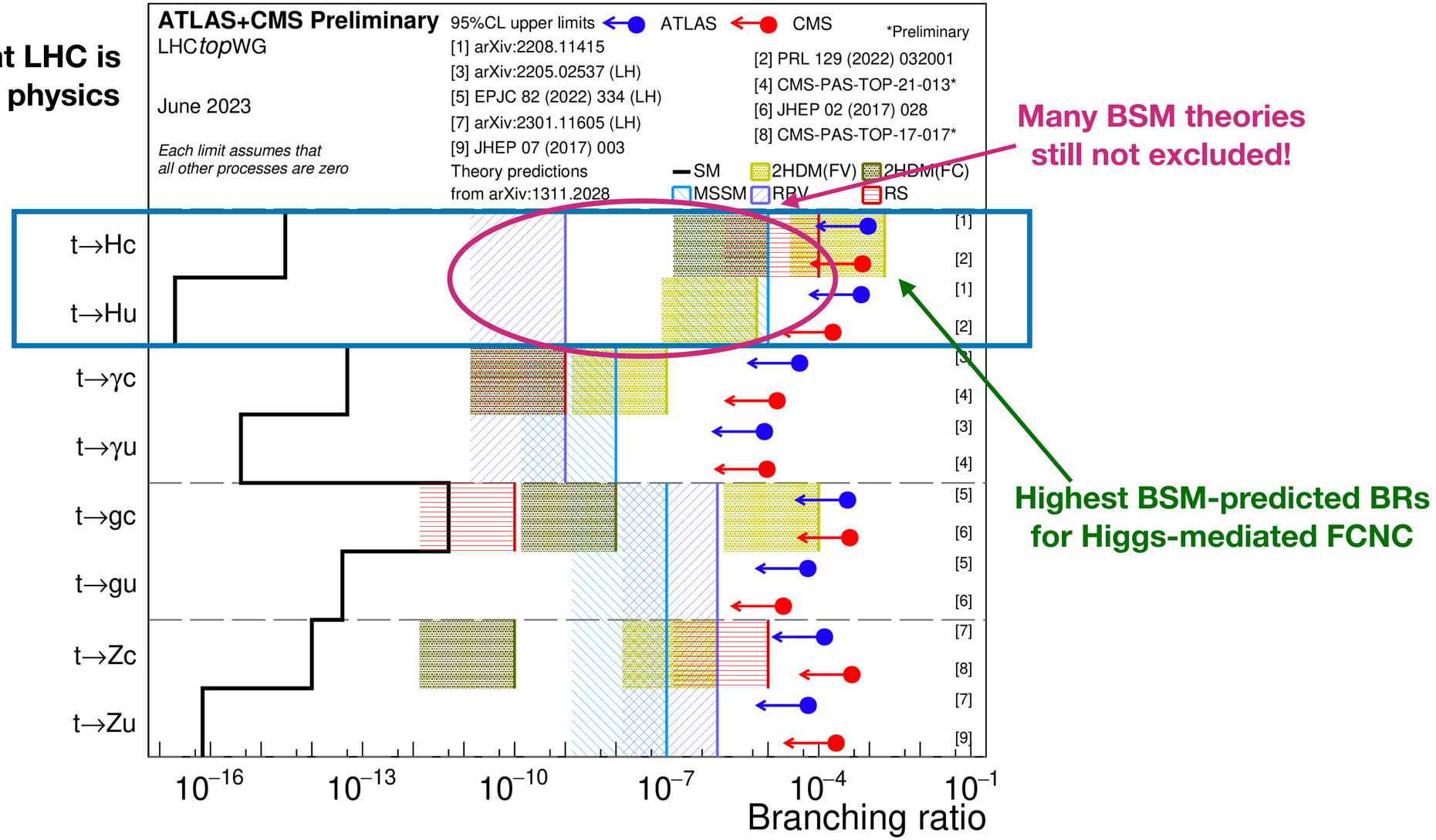
On behalf of the CMS Collaboration

CMS-PAS-TOP-22-002

Why FCNC?

Any observation of FCNC at LHC is definitive evidence of BSM physics

signals targeted by TOP-22-002

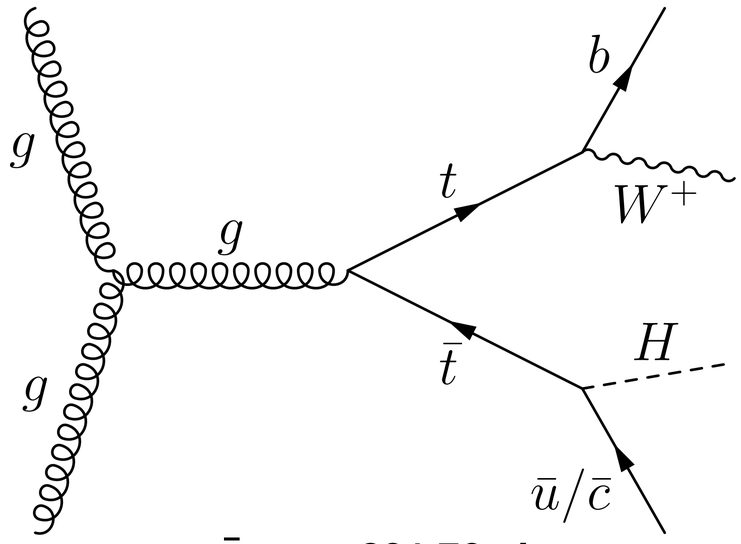


Many BSM theories still not excluded!

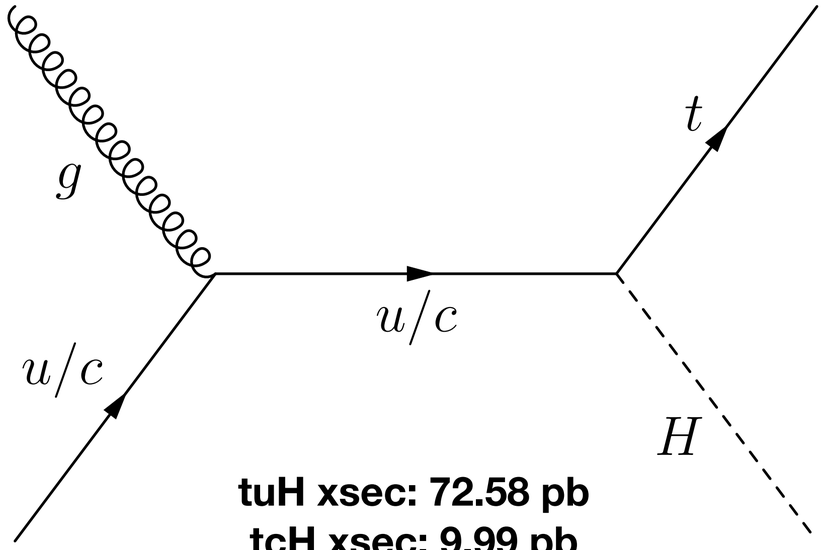
Highest BSM-predicted BRs for Higgs-mediated FCNC

Analysis Overview

- Search for tuH/tcH FCNC decays to same sign dilepton (SS) and $\geq 3\ell$ final states
  - Via $\mathrm{H} \rightarrow \mathrm{WW/ZZ/}\tau\tau$
  - Main backgrounds from nonprompt leptons, leptons with misidentified charge (misID), and rare SM SS events
  - Data-driven estimation methods used for nonprompt and charge misID backgrounds
  - ML techniques applied to better distinguish signal/background events



$t\bar{t}$ xsec: 831.76 pb
with tcH/tuH decay modes



tuH xsec: 72.58 pb
tcH xsec: 9.99 pb
***assumed κ_{tqH} = 1**

Event Selection

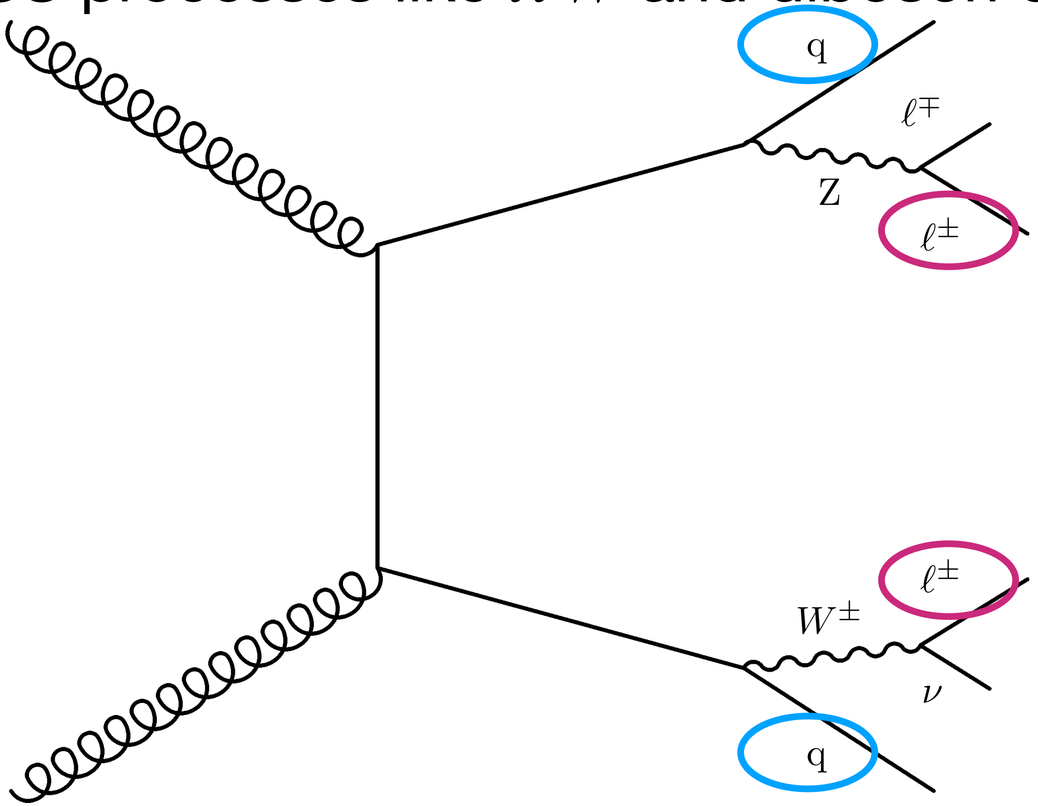
DRAFT

	Physics Object	Selection Criteria
Expected signature	Lepton	Pair of isolated SS leptons (e or μ), lead $p_T > 25$ GeV, else $p_T > 20$ GeV, $\lvert\eta_e\rvert < 2.4$, $\lvert\eta_\mu\rvert < 2.5$
	Jet	≥ 2 in SS events or ≥ 1 in multilepton events, $p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$
	b-tagged jet	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$
Reduces Z, γ^* resonances	$m_{\ell\ell}$(SF)	> 12 GeV
	$m_{\ell\ell}$(any flavor, any charge)	> 8 GeV
	m_{ee}(SS,SF)	< 75 GeV or > 105 GeV

Background Categories

Background events enter search region (SR)

1. when they have a **REAL** SS dilepton pair
   - Rare SM SS processes like $t\bar{t}W$ and diboson events

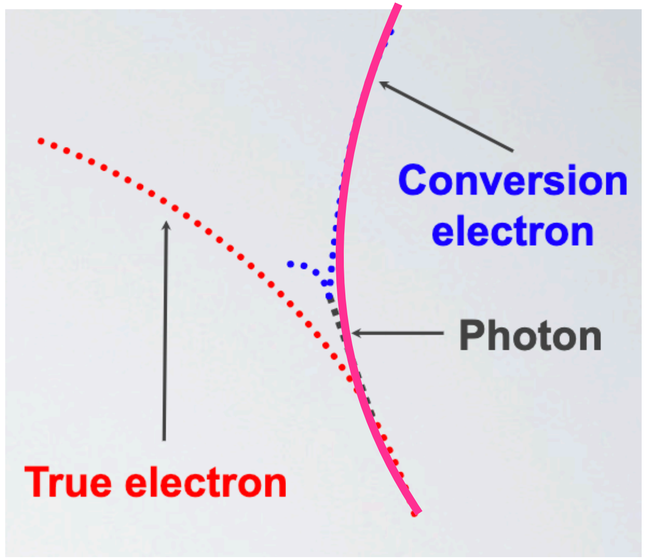


Background Categories

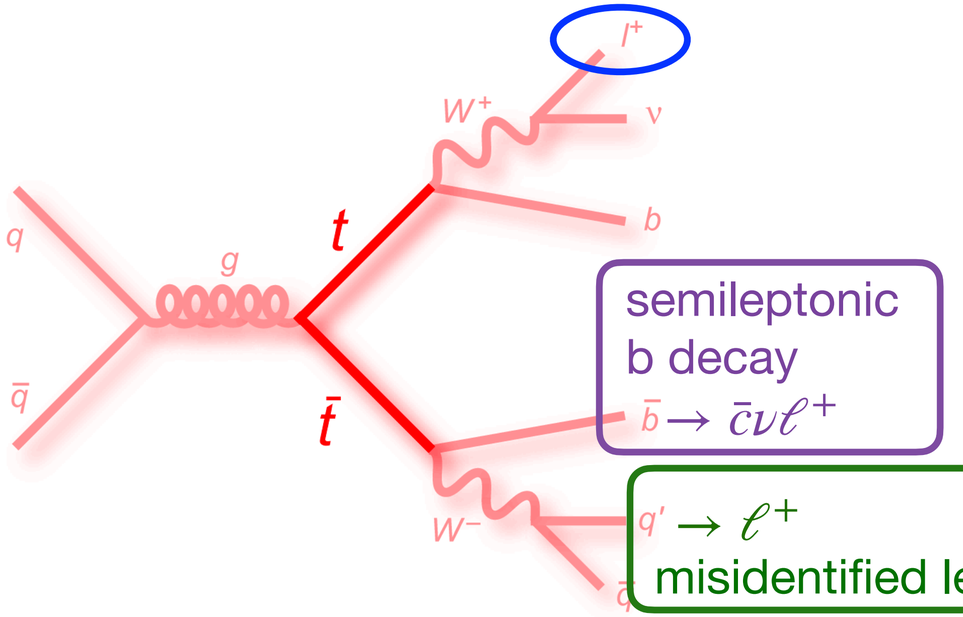
Background events enter search/signal region (SR)

2. when they have a **NOT REAL** SS dilepton pair

OS events with mismeasured charge



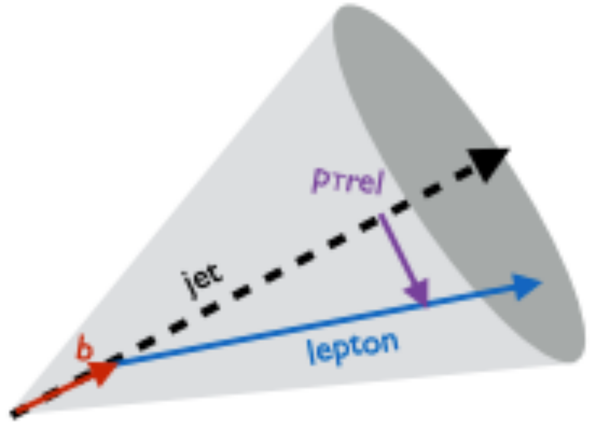
or events with something else reconstructed as a lepton



semileptonic b decay

$\bar{b} \rightarrow \bar{c}\nu\ell^+$

$q' \rightarrow \ell^+$ misidentified lepton



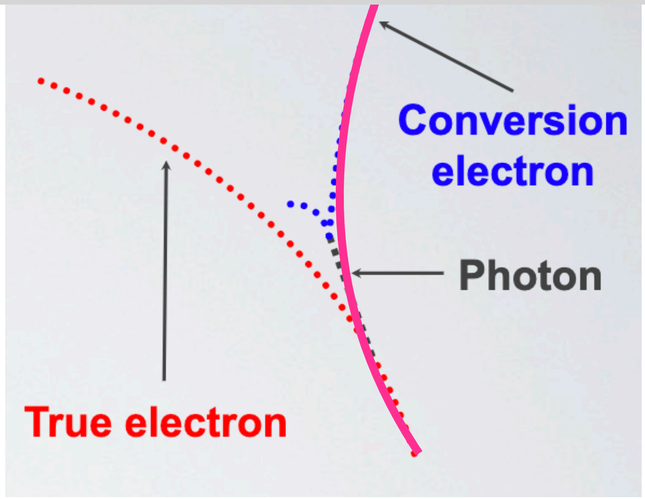
Background Categories

Background events enter search/signal region (SR)

2. when they have a **NOT REAL** SS dilepton pair

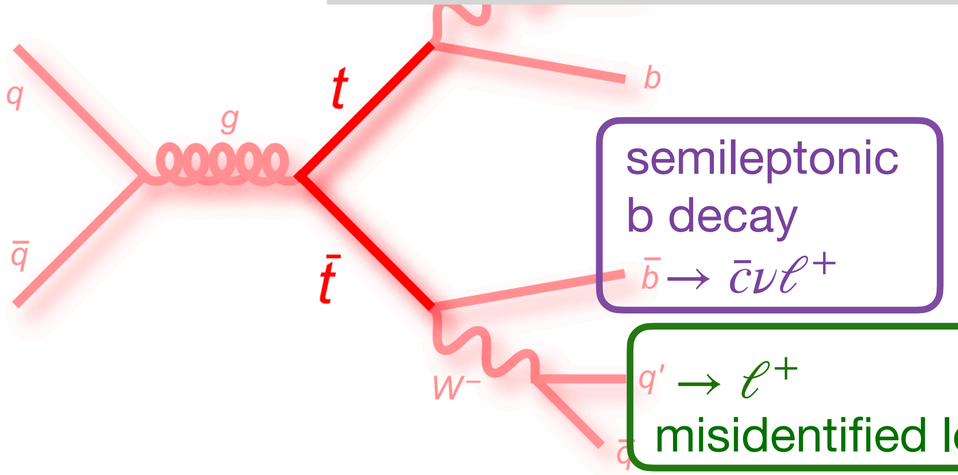
OS events with mismeasured charge

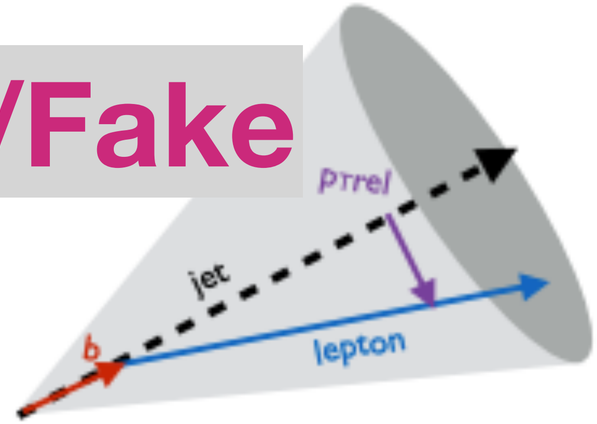
Charge MisID



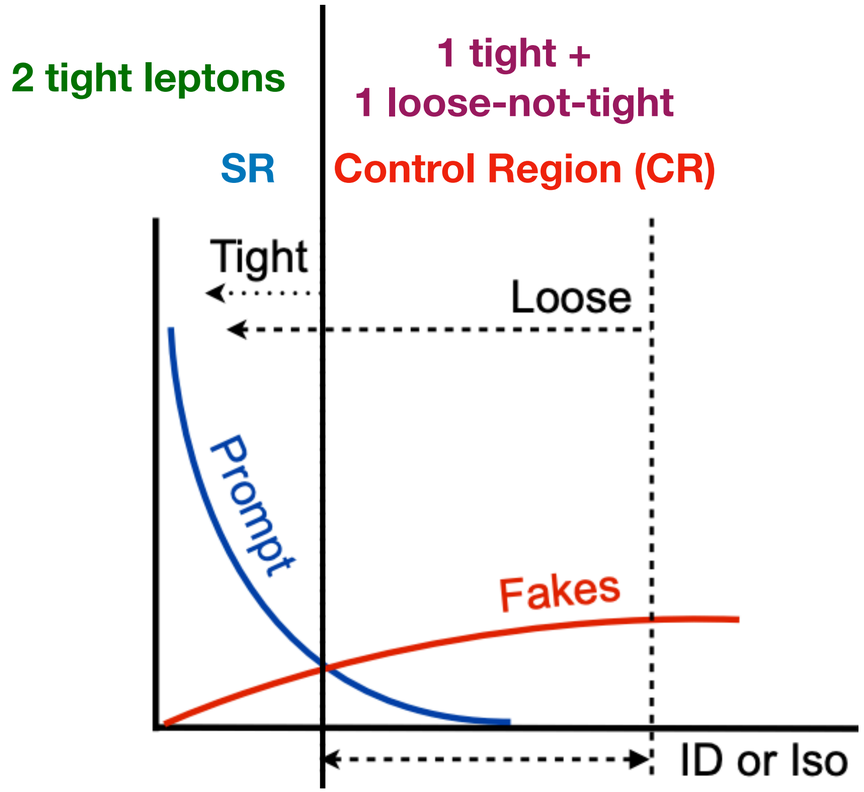
or events with something else reconstructed as a lepton

Nonprompt/Fake

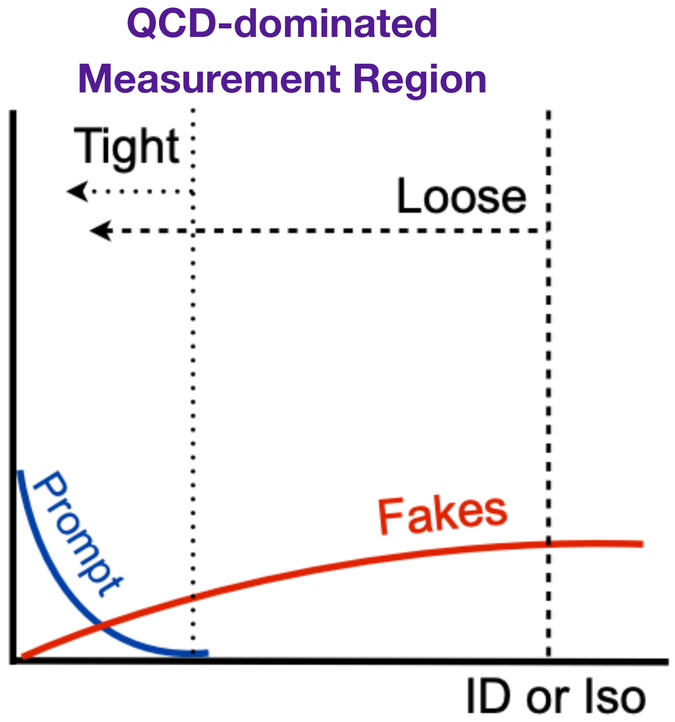




Nonprompt Estimate



Define CR: invert lepton isolation cut



Assume: Fake rate uniform across samples, regions

Weight each CR data event by $\frac{\text{fake rate}}{1 - \text{fake rate}}$

Charge MisID Estimate

- Define CR by inverting SS lepton requirement: 2 OS leptons
- Estimate background: weight CR data events by $\frac{\text{flip rate}}{1 - \text{flip rate}}$
- Measurement of flip rate in DY and $t\bar{t}2\ell$ MC:
  - Ratio of electrons with wrong charge to total number of electrons
- Apply corrective data/MC SF measured on Z-peak

Year	SF
2016	1.11
2017	1.44
2018	1.31

- Uncertainties: CR statistics, flip rate, data/MC comparison

Systematic Uncertainties

DRAFT

Source	Uncertainty in tcH Prediction	Uncertainty in tuH Prediction	Uncertainty in SM SS Prediction	Uncertainty in Nonprompt Estimate	Uncertainty in Charge Flip Estimate
Jet energy scale	1–6%	< 8%	< 5%	-	-
Theory normalization	6–10%	6–10%	5–25%	-	-
PDF shape	< 2%	< 2%	4–6%	-	-
Renormalization and factorization scale shape	7–9%	2–6%	10–15%	-	-
Pileup	< 2%	< 2%	< 2%	-	-
Trigger efficiency	2%	2%	2%	-	-
Lepton efficiency	2–3%	2–3%	2–3%	-	-
b/c tagging	10–16%	6–13%	7–14%	-	-
Estimate normalization	-	-	-	30%	30%
$\epsilon_{TL}/\epsilon_{q}$	-	-	-	7–10%	<5%
Total	14–16%	11–14%	20–28%	31–35%	29–31%

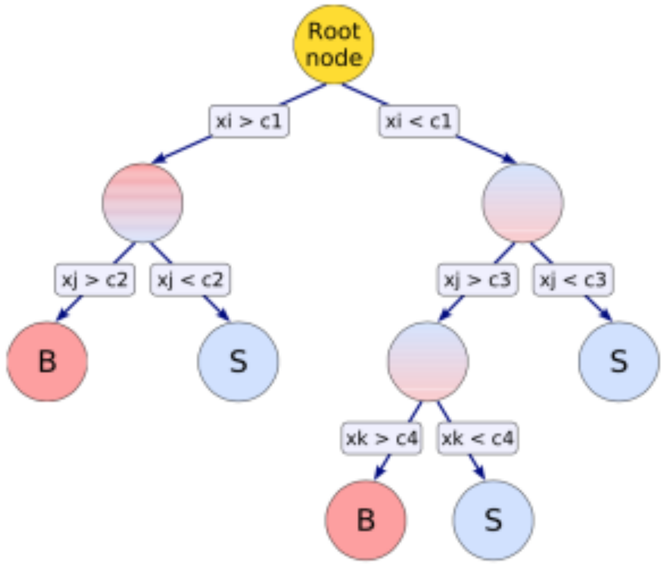
Machine Learning Strategy

- For increased sensitivity→Boosted Decision Trees (BDTs) to separate signal from background

- 2 BDTs: tcH vs. background, tuH vs. background

- **SR binning**
  - **20 bins chosen to be evenly spaced in signal efficiency**

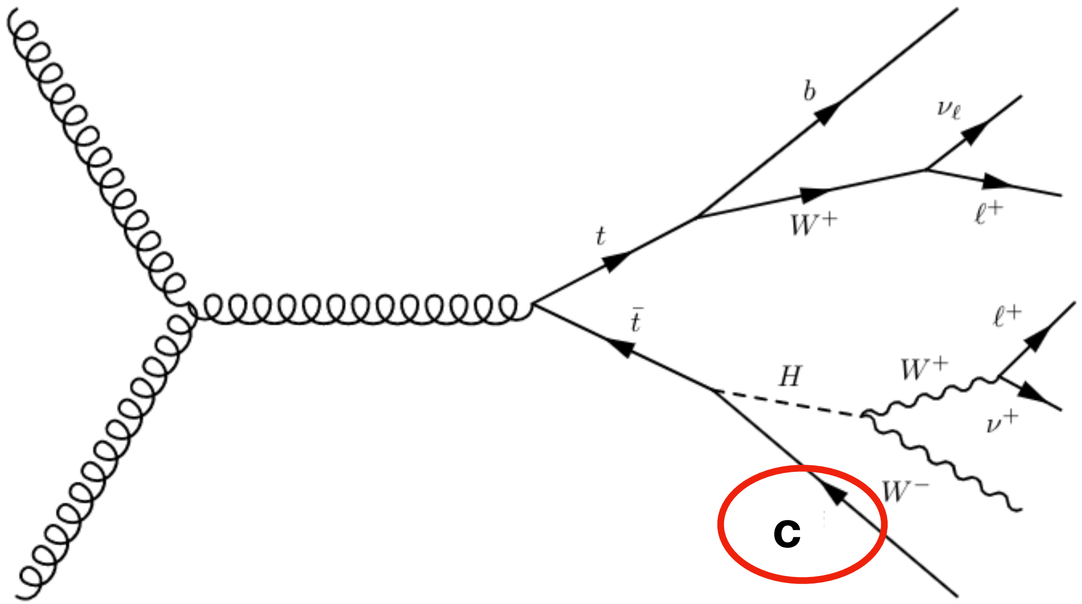
- Create training/testing samples from simulation, evaluate on third set of data to protect from biasing evaluation
  - In data-driven estimates, we evaluate on data events from CRs
  - In MC estimates, we evaluate on only half of the events, while the other half is reserved for training/testing set



BDT Training Features

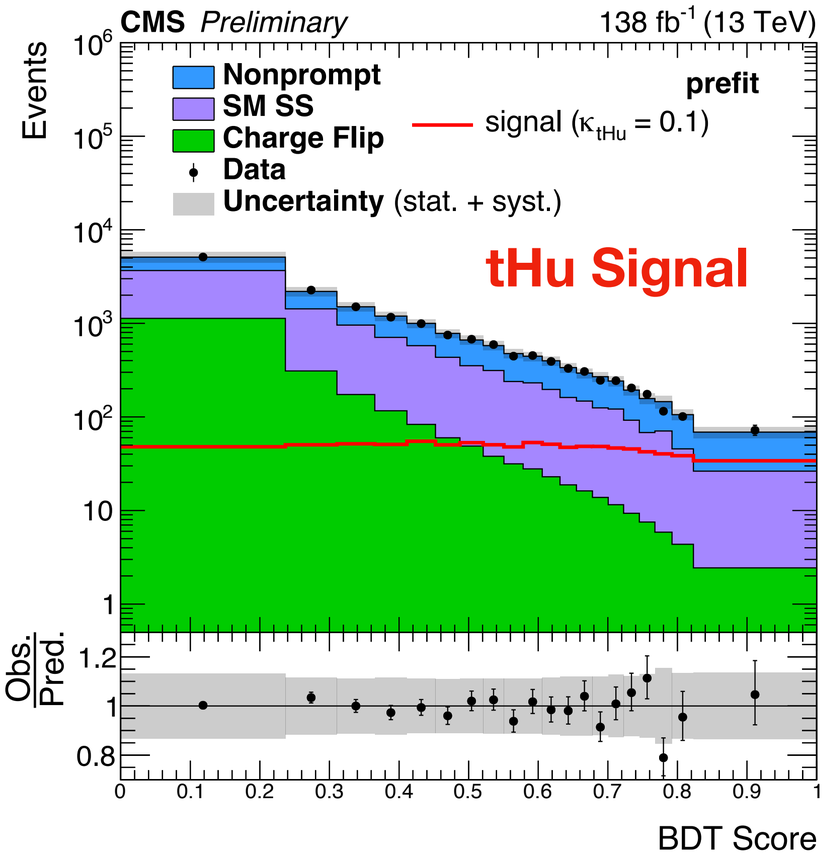
Feature			
Leading Lepton	Sublead Lepton	Sub-Sublead Lepton	pT
			abs(eta)
			abs(dxy)
			abs(dz)
			mT(lepton, MET)
Lead Jet	Sublead Jet	Sub-Sublead Jet	pT
			b tag score
			c tag score
MET pT			
Most Forward Jet pT			
HT			
nElectrons			
nJets			
nBtags			
Leading b tag score			
Leading b tag pT			
Mass of leading+subleading leptons			

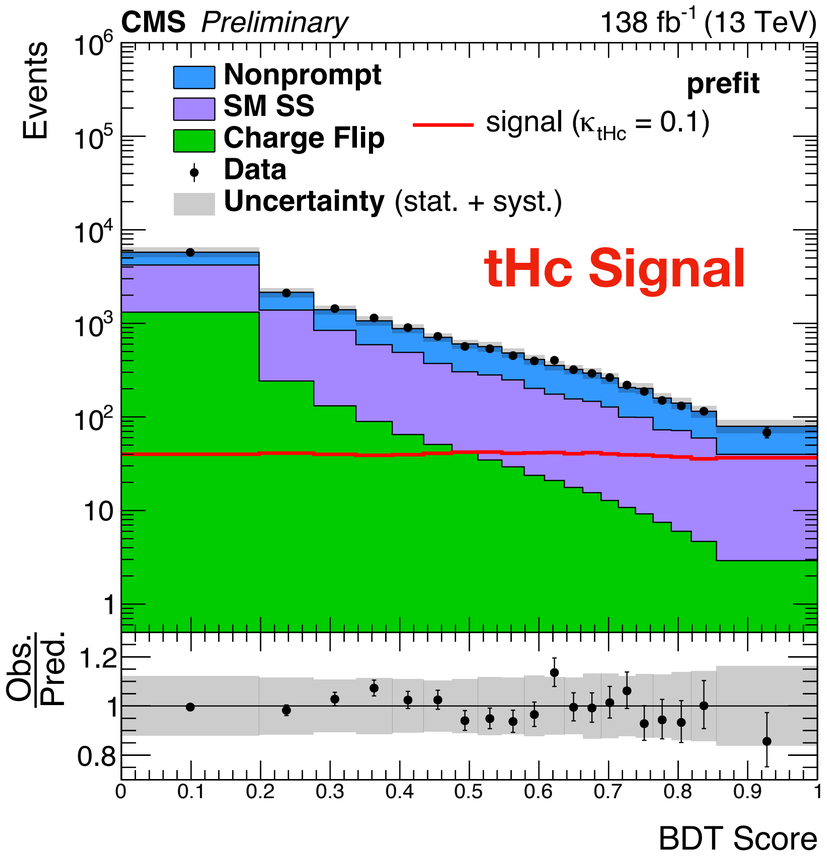
- Uniquely implemented c tagging score information as training features
- Motivation: strengthen tcH sensitivity



Prefit SR Yields

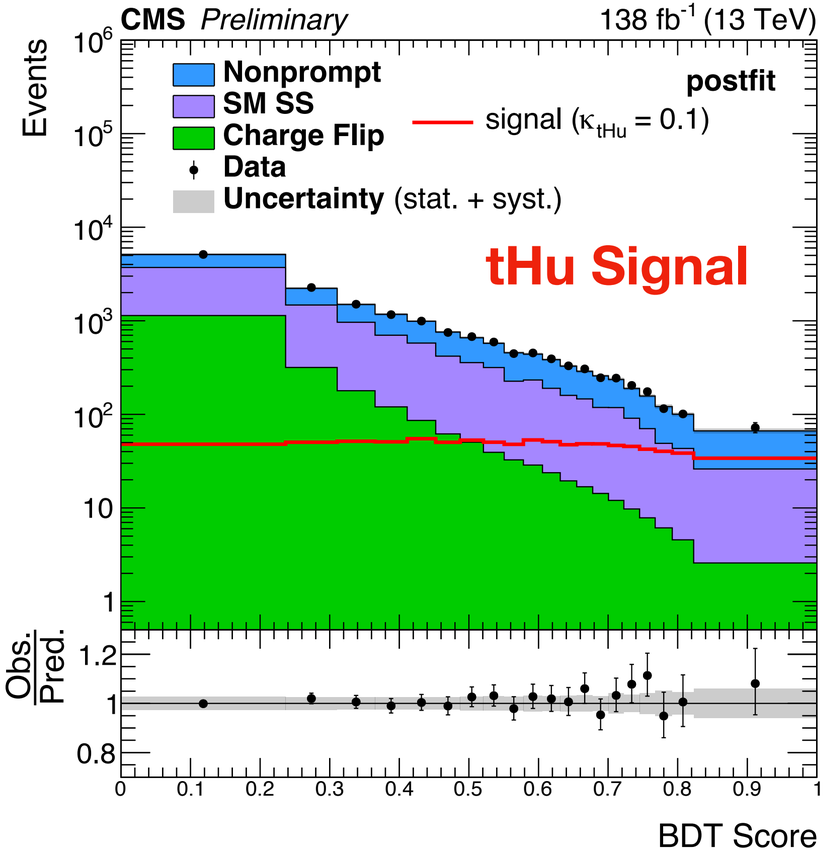
- Prefit background estimates for full run 2 and data yields
- No deviation from SM prediction

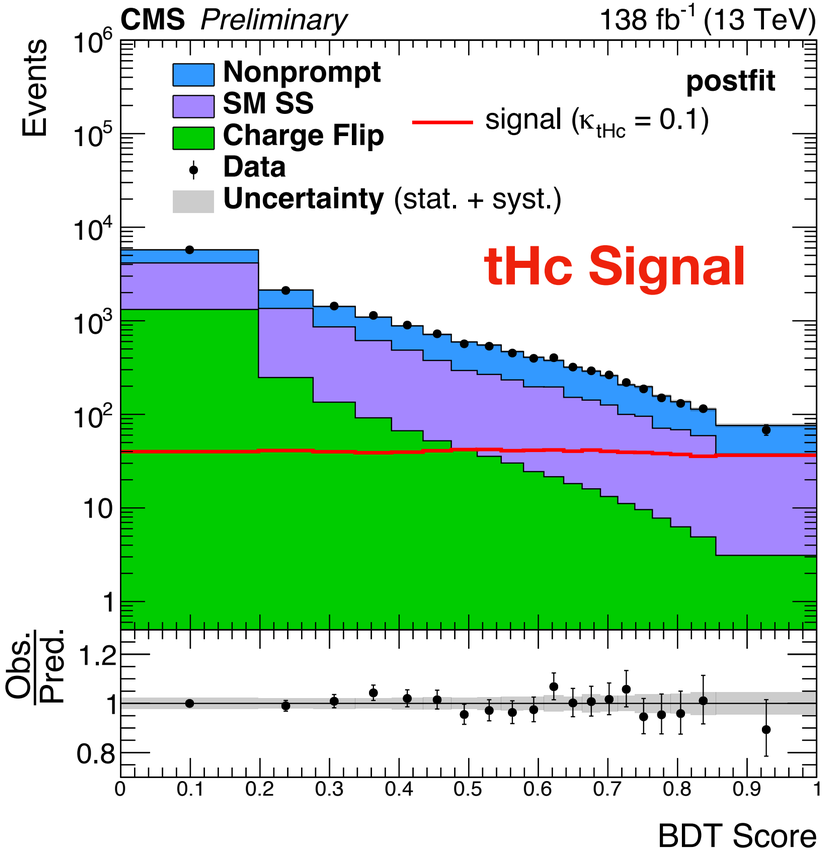




Postfit SR Yields

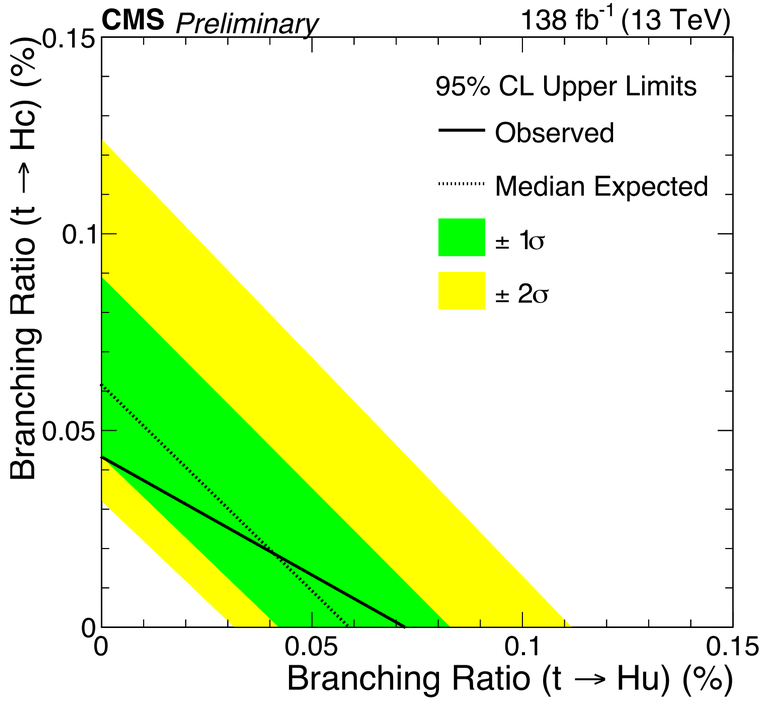
- Postfit background estimates for full run 2 and data yields
- Fit: modified frequentist approach, asymptotic approximation, CL_s criterion, log normal uncertainties
- No deviation from SM prediction

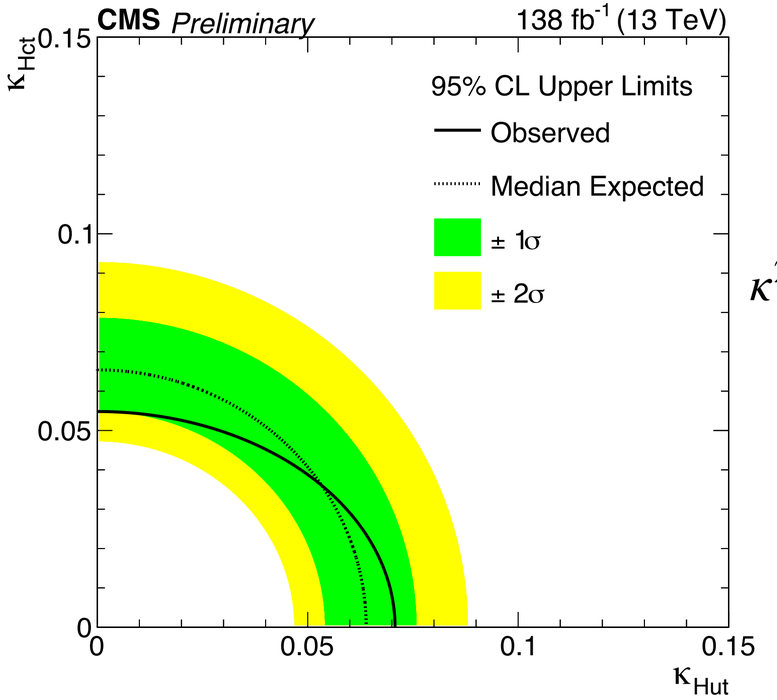




Results

- Using data-driven estimates and measured systematic uncertainties
- Observed (Expected) 95% CL upper limit:
  - $BR(tHc) < 0.043\,\%\ (0.062\%)$
  - $BR(tHu) < 0.072\,\%\ (0.059\%)$





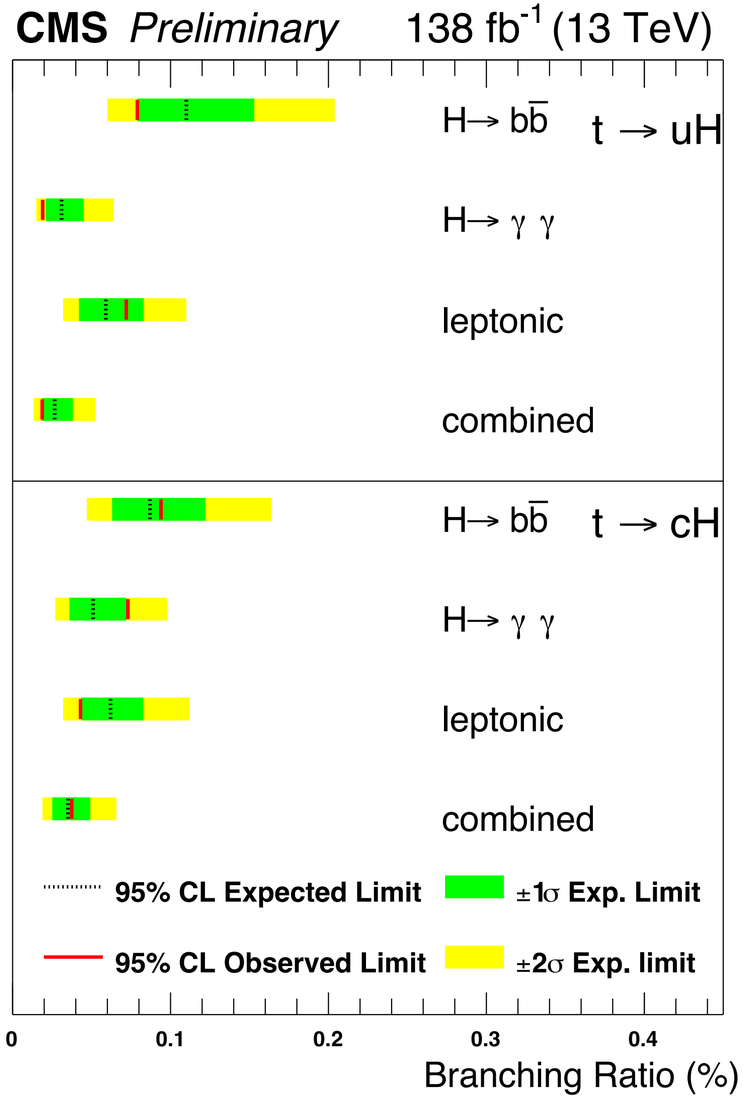
$$\kappa^2 = BR(t \to qH) \times \frac{\Gamma_t}{\Gamma_{tqH}}$$

Combination

- Performed statistical combination with 2 other CMS analyses:
  - FCNC with H→bb
  - FCNC with H→$\gamma\gamma$
- Observed (Expected) BR limits:
  - $BR(tHc) < 0.037\,\%\ (0.035\%)$
  - $BR(tHu) < 0.019\,\%\ (0.027\%)$

DRAFT

Analysis	$\mathcal{B}(t \to Hu)$ observed (expected)	$\mathcal{B}(t \to Hc)$ observed (expected)
$H \to b\bar{b}$ [24]	0.079 (0.11)%	0.094 (0.086)%
$H \to \gamma\gamma$ [25]	0.019 (0.031)%	0.073 (0.051)%
Leptonic (this note)	0.072 (0.059)%	0.043 (0.062)%
Combination	0.019 (0.027)%	0.037 (0.035)%



Comparison with ATLAS Results

- ATLAS best result: arXiv 2309.12817
  - Combination results:
    - $B(tHu) < 4.0 \times 10^{-4}$ (2.4×10^{-4})
    - $B(tHc) < 5.8 \times 10^{-4}$ (3.0×10^{-4})
  - H→$\gamma\gamma$ results:
    - $B(tHu) < 3.8 \times 10^{-4}$ (3.9×10^{-4})
    - $B(tHc) < 4.3 \times 10^{-4}$ (4.7×10^{-4})
- CMS best result:
  - $BR(tHu) < 1.9 \times 10^{-4}$ (2.8×10^{-4})
  - $BR(tHc) < 3.7 \times 10^{-4}$ (3.5×10^{-4})

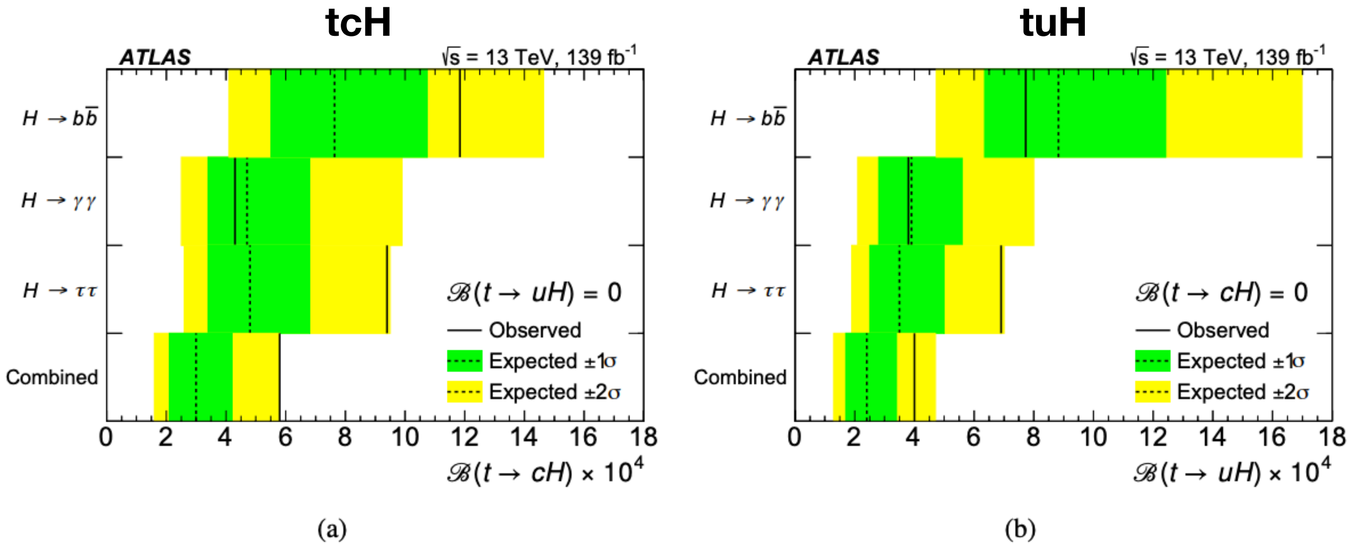


Figure 11: 95% CL upper limits on (a) $\mathcal{B}(t \to cH)$ assuming $\mathcal{B}(t \to uH) = 0$ and (b) $\mathcal{B}(t \to uH)$ assuming $\mathcal{B}(t \to cH) = 0$ for the individual searches and their combination. The observed limits (solid lines) are compared with the expected (median) limits under the background-only hypothesis (dotted lines). The surrounding shaded bands correspond to the 68% and 95% CL intervals around the expected limits, denoted by $\pm 1\sigma$ and $\pm 2\sigma$, respectively.

Summary

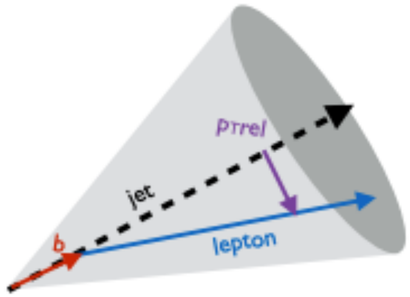
- Robust **data-driven estimation methods** for nonprompt and charge misID backgrounds
- Increased sensitivity due to **multivariate approach**
- Results show good agreement between observation and SM prediction
- Results of combination with two previous CMS analyses provide **most stringent observed constraints** on these interactions to date

Thank you!
Questions?

Backup

Objects and Triggers

- Same lepton selections as $t\bar{t}t\bar{t}$ SS analysis [TOP-18-003]
- **Multi-isolation (WPs for each year):**
  - I_{mini}: relative isolation in p_T-dependent cone
  - pTratio: lepton energy dominates jet
  - pTrel: recovers efficiency lost when jet is near a lepton



$$I_{\text{mini}} < I_1 \wedge \left(\frac{p_{\text{T}}(\ell)}{p_{\text{T}}(\text{jet})} > I_2 \vee \frac{|(\vec{p}(\text{jet}) - \vec{p}(\ell)) \times \vec{p}(\ell)|}{|\vec{p}(\text{jet}) - \vec{p}(\ell)|} > I_3 \right)$$

Electrons	$\|\eta\| < 2.4$, transition region excluded dxy < 0.05; dz < 0.1 Tight pT and η dependent MVA
Muons	$\|\eta\| < 2.5$ dxy < 0.05; dz < 0.1 Medium Muon POG ID
Jets	$\|\eta\| < 2.4$ pT > 30 GeV Tight jet ID Cleaned to remove overlap with leptons (dR < 0.4)
bTags	$\|\eta\| < 2.4$ pT > 25 GeV Medium WP for Deep Flavor
MET	PF MET type 1 corrected (EE fix for 2017) All recommended filters applied
Triggers	Dilepton triggers: lepton pT thresholds different for each year HLT_Mu*Ele*, HLT_Mu*Mu*, HLT_Ele*Ele*

Flavor	p_T Threshold 1	p_T Threshold 2
$\mu\mu$	17 GeV	8 GeV
ee	23 GeV	12 GeV
$e\mu$	23 GeV	8 GeV
μe	23 GeV	12 GeV

Correlation Schemes

- Leptonic analysis
  - All correlated between SR bins
  - Correlated between signal/background except: R&F scales, cross section uncertainties
  - Correlated between years except: lumi, trigger efficiencies

- Combination
  - Fully correlated: JES/JER, lumi, lepton ID, per-process theoretical uncertainties
  - Everything else uncorrelated