Search for extra Higgs bosons in same sign top-quark pair + jets final state

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On behalf of the CMS collaboration

International workshop on top quark physics 2023
Sep 25 2023

Introduction

- Several models introduce an extended Higgs sector i.e. supersymmetry (SUSY), Two-Higgs-Doublet Model (2HDM) in different variations etc.
- **Glashow-Weinberg condition** is usually imposed in 2HDM to avoid flavor changing neutral currents (FCNC).
- At the **alignment limit,** in a 2HDM without Glashow-Weinberg condition (type-III 2HDM / g2HDM), FCNC of 125 GeV Higgs boson are suppressed but not for exotic Higgs.
  - **Exotic Higgs in subTeV** level and **O(1) extra Yukawa couplings** are not yet excluded.
  - **Muon g-2 anomaly** and **baryogenesis** can be explained by such models.

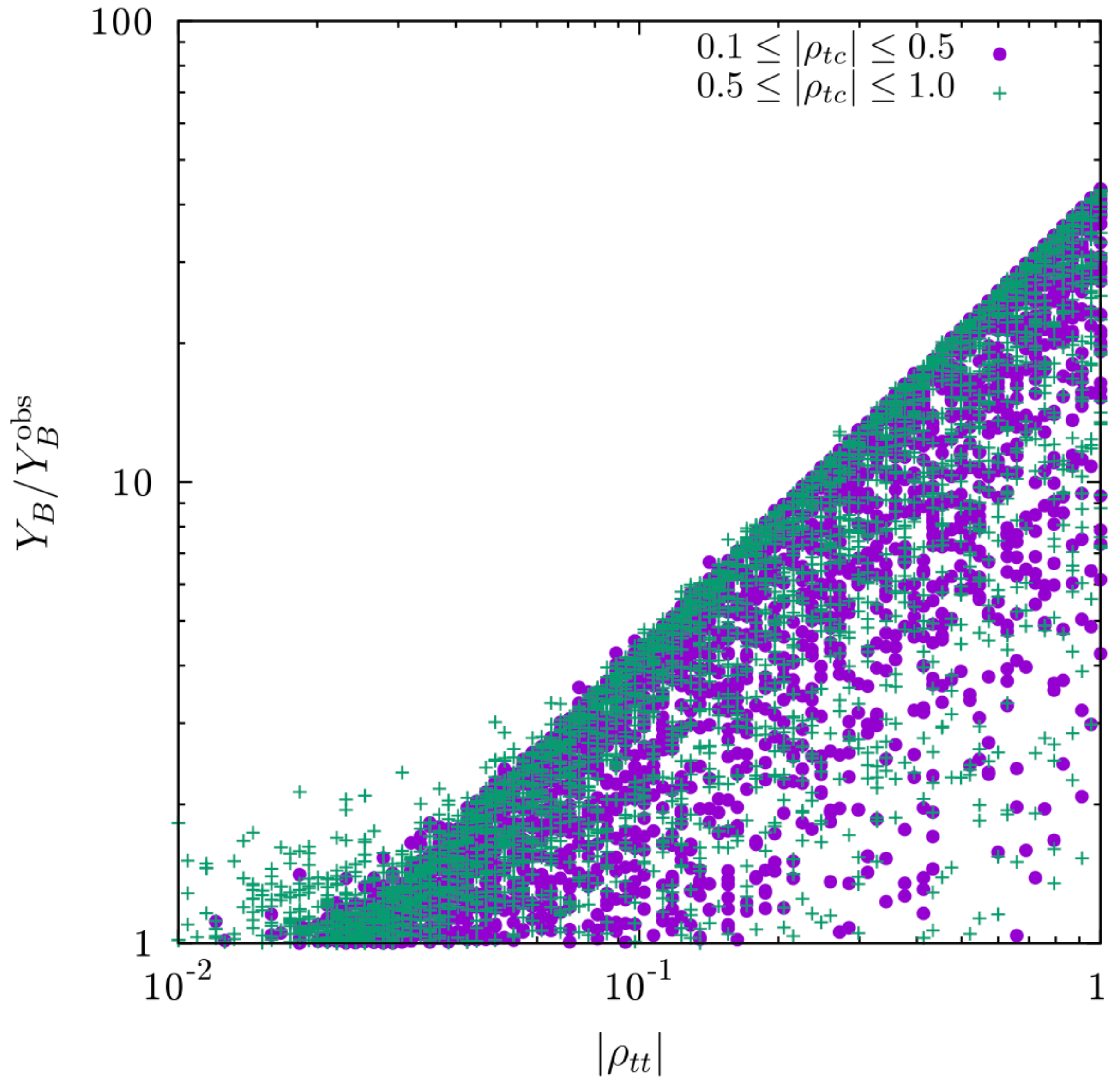
$y_{ij} = \sqrt{2} m_i \delta_{ij} / v$

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

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

Alignment limit : $cos_\gamma \to 0$

FCNC of exotic Higgs sector provides chance to observe/ exclude **subTeV** exotic Higgs and **O(1) extra Yukawa couplings**

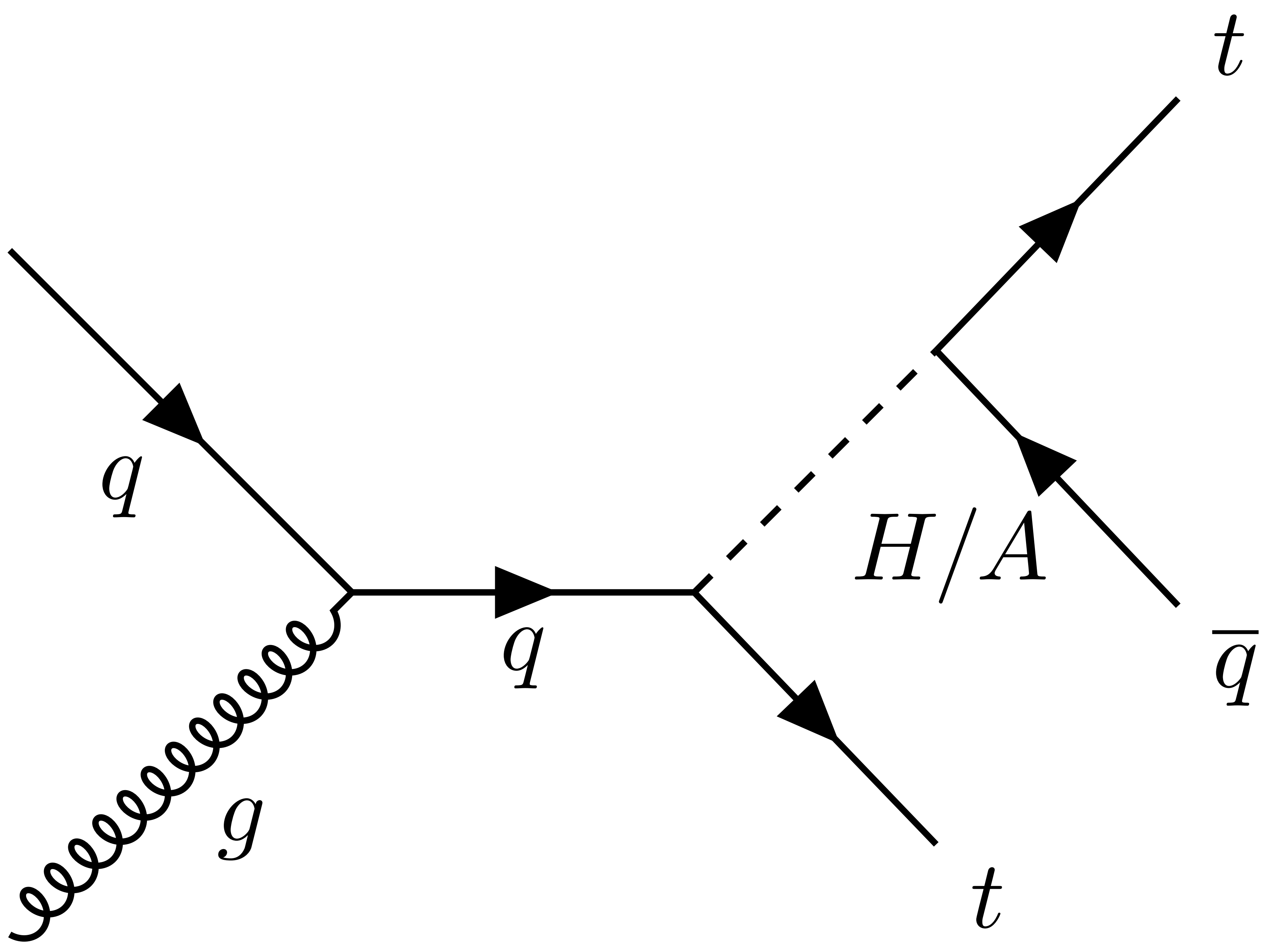


PLB 776 (2018) 402–406

Extra Yukawa coupling ρ_{tt} and ρ_{tc} are able to drive baryogenesis, which provides strong motivation to probe such phase space

Target Process

Target FCNC process



We test different mass $m_{H/A}$ and coupling strength ρ_{tu} & ρ_{tc} assumptions

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Extra Yukawa Coupling

- Probe extra Yukawa coupling involving top quark (ansatz like $\rho_{qq'} \propto \sqrt{m_q m_{q'}}$)
- Probe ρ_{tu} & ρ_{tc} through $tt\bar{u}$ & $tt\bar{c}$ processes separately
- Probe range: $0.1 \leq \rho_{tq} \leq 1.0$ (assume all other extra Yukawa couplings to be 0)

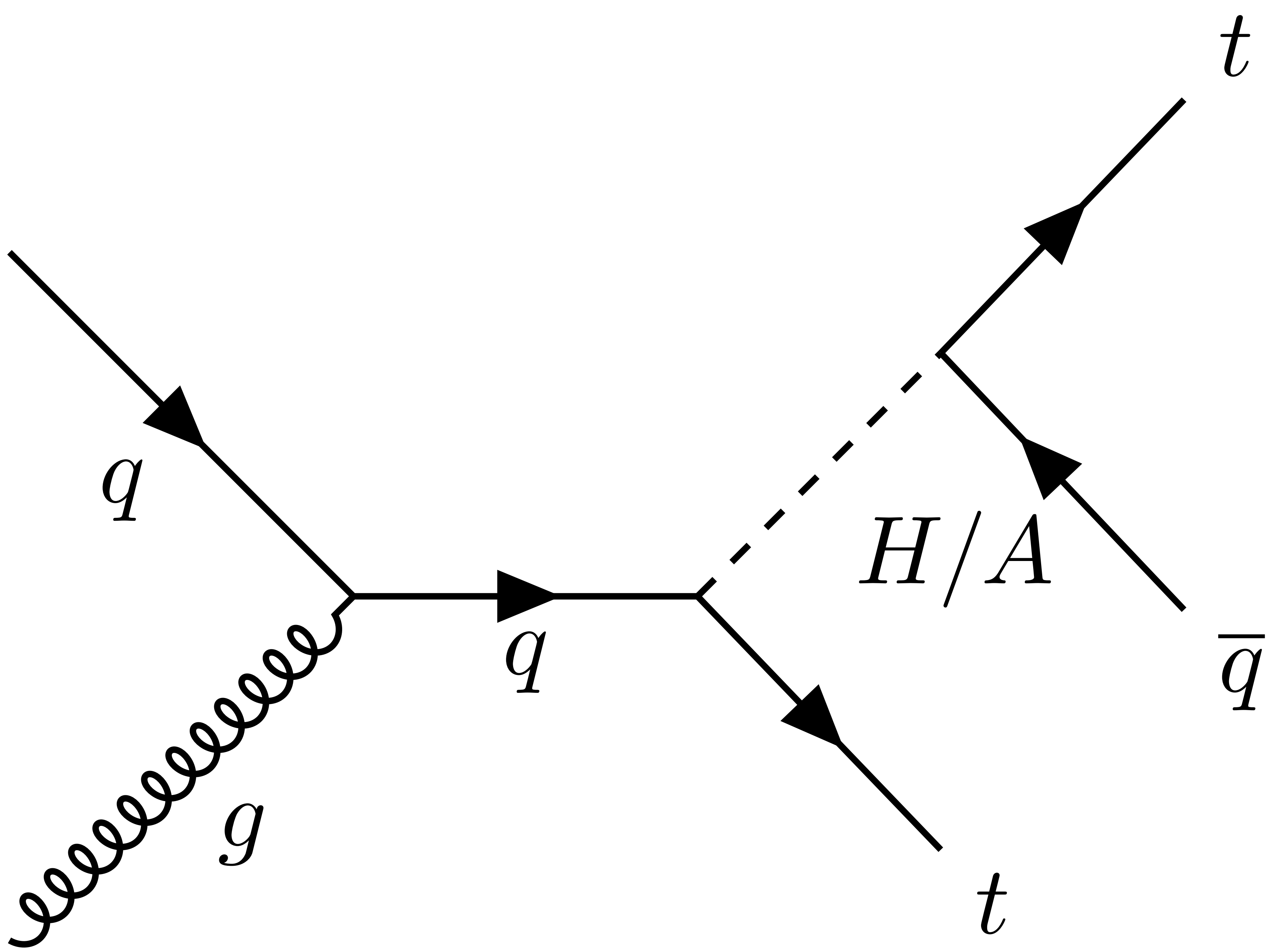
Exotic Higgs Bosons Mass

Two scenarios are considered

- **H and A non-interference**
  - Only consider A or H
  - Probe range: $200\ GeV \leq m_{A/H} \leq 1\ TeV$
- **H and A interference**
  - Take $m_A - m_H = 50\ GeV$ for demo
  - Probe range: $250\ GeV \leq m_A \leq 1\ TeV$

Object & Event Selection

Target FCNC process



$$ug/cg \to tH \to tt\bar{u}/tt\bar{c}$$
$$\to (l^+ b\nu)(l^+ b\nu)\bar{u}/\bar{c}$$

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Signal Topology

Two same sign leptons
At least three jets
Missing transverse momentum

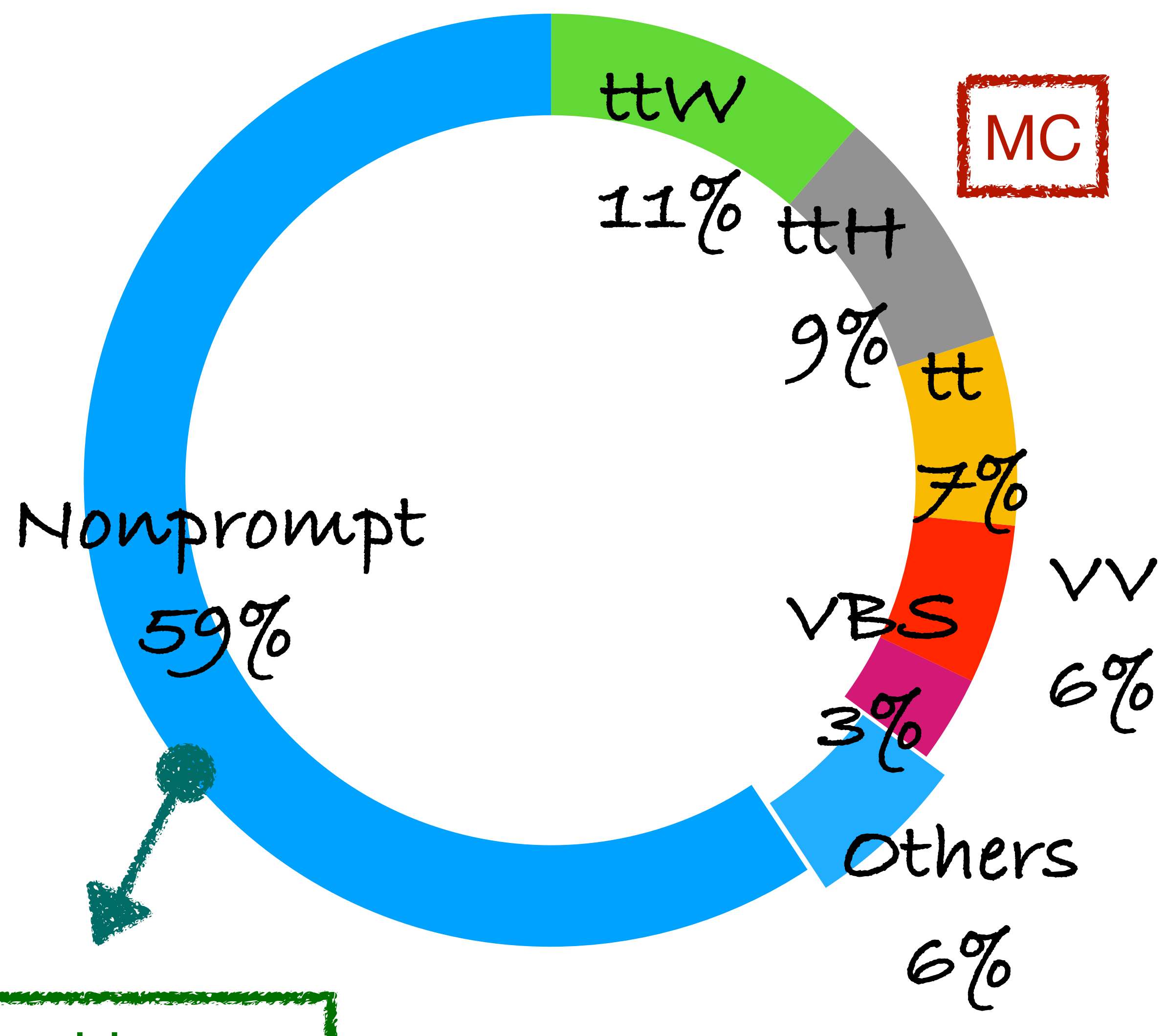
Signal cross section

Depending on the coupling value, mass and the H-A interference assumption

ttu processes range from $\sim 1\times10^{-4}$ to $\sim 7\times10^{-1}pb$

ttc processes range from $\sim 5\times10^{-6}$ to $\sim 7\times10^{-2}pb$

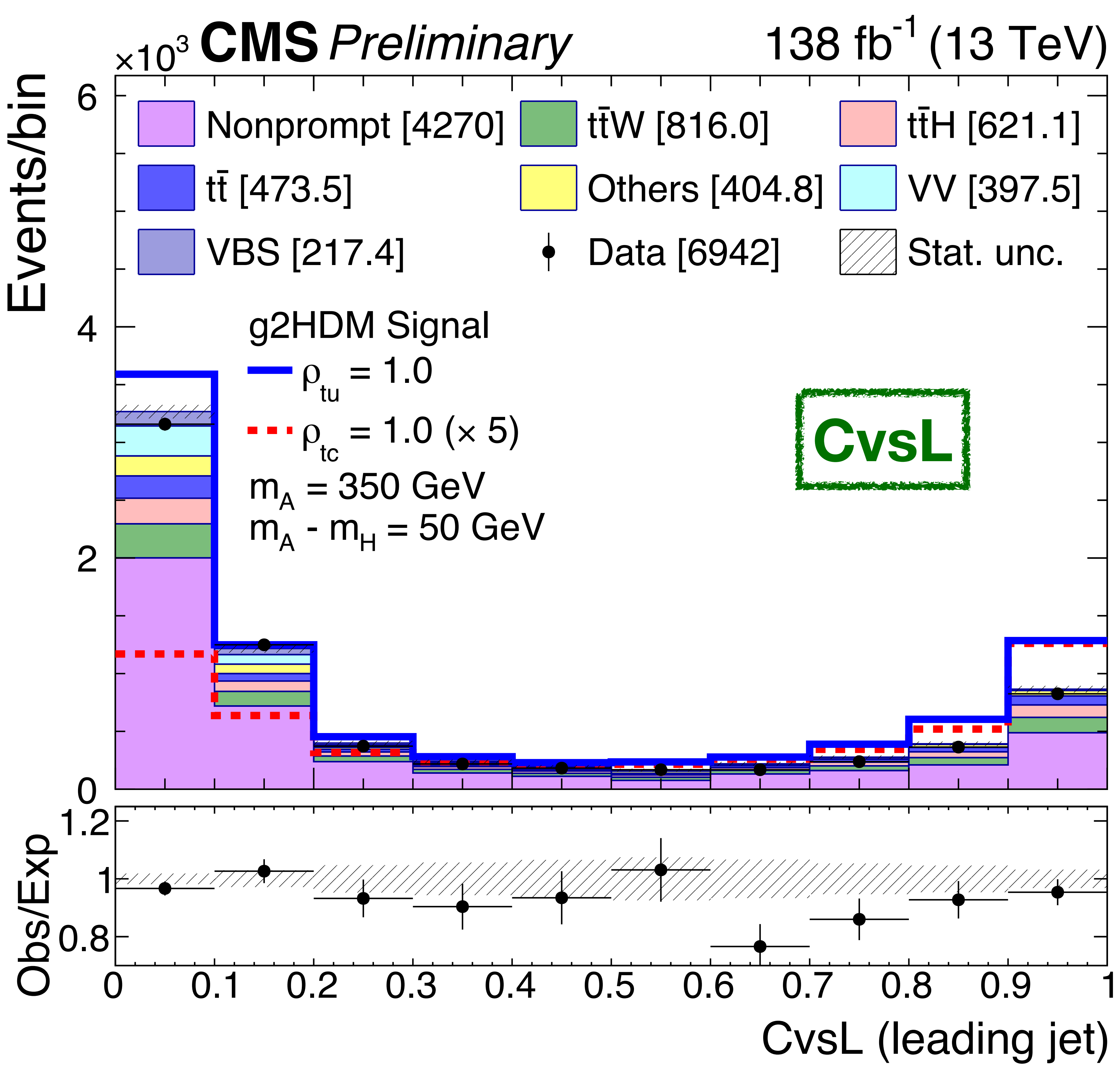
Background Contribution
(Before BDT cut)

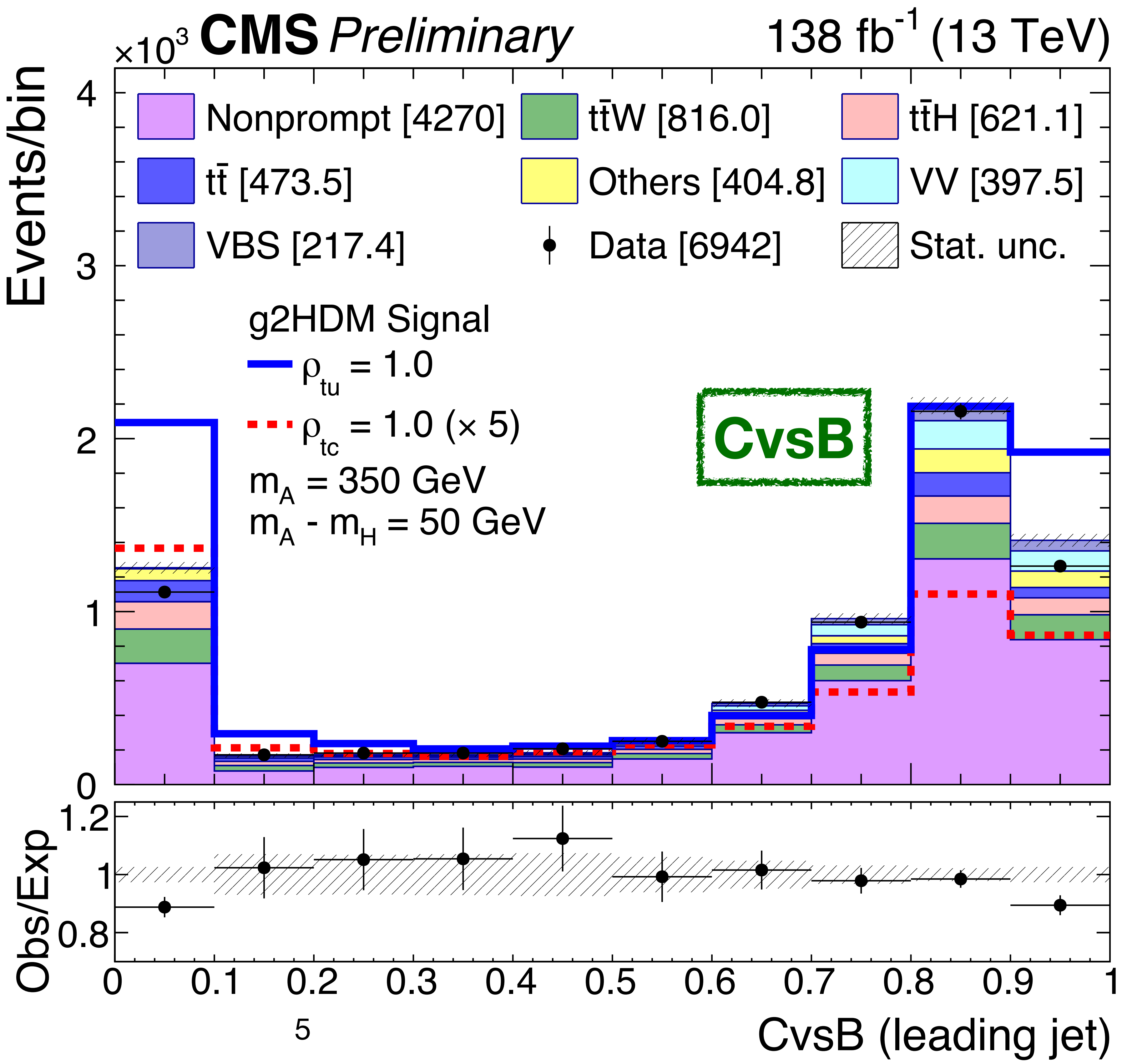


Data-driven
Details in back-up

Analysis Technique

- **DeepJet Flavor Tagging**
  - Neural network utilizes global variables, charged/neutral particle and secondary vertex features in the jets to perform flavor tagging.



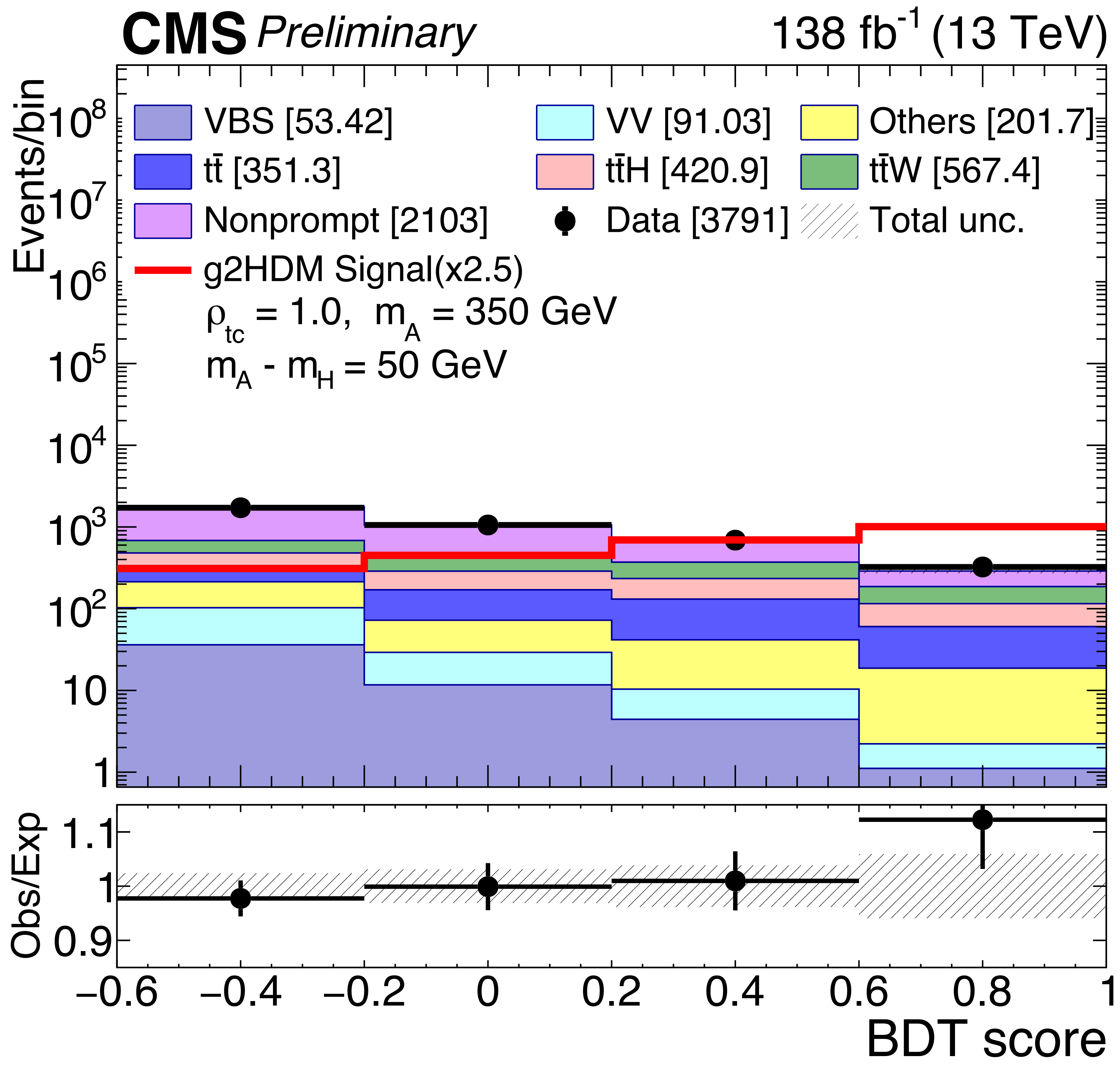


In this analysis, b/c tagging is not explicitly used. Instead, full shape information of flavor sensitive variables, CvsL & CvsB, are used as BDT inputs.

Analysis Technique

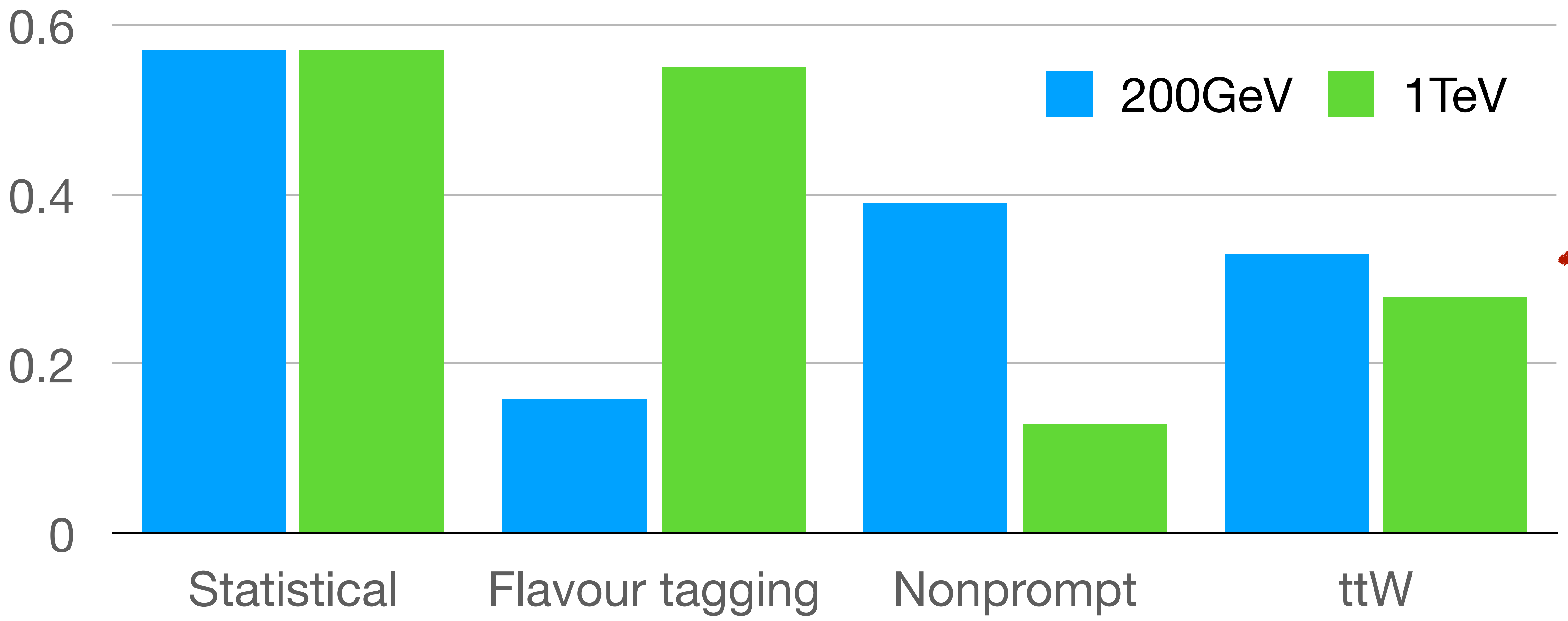
- **Boosted Decision Tree**
  - Input: Jet flavor info, lepton/jet kinematic, MET, HT, and object pair kinematic information
  - BDT > -0.6 cut is imposed in order to improve the stability of the fit and the corresponding fit uncertainties

Input features of the BDT
$p_T(\ell_i)$: i=1,2; H_T, p_T^{miss}
$CvsB(j_i)$, $CvsL(j_i)$: i=1,2,3
$m_{\ell\ell}$, $m_{\ell\ell}(j_i)$: i=1,2,3
$\Delta R(j_n, j_m)$, $m(j_n, j_m)$: $1 \leq n < m \leq 3$
$\Delta R(j_n, l_m)$, $m(j_n, l_m)$: n=1,2,3; m=1,2



Uncertainties

- Fit is performed using BDT distribution.
- Profiled uncertainty is used for analysis.
- Main uncertainties come from
  - Statistical unc. from the fit
  - Flavor tagging
  - Nonprompt background estimation
  - ttW cross section



Ratio compared to total uncertainty

Post-fit uncertainty sources with respect to the total uncertainty (given in percentages)

	$\rho_{tu} = 0.4$	
	m_A = 200 GeV (1 TeV) Without interference	m_A = 250 GeV (1 TeV) With interference
Jet flavor identification	16 (55)	26 (46)
Nonprompt leptons	39 (13)	43 (13)
$t\bar{t}W$ background	33 (28)	35 (30)
Total signal modeling	20 (16)	7 (19)
Total background modeling	67 (56)	65 (59)
Total experimental	44 (56)	55 (50)
Statistical	57 (57)	52 (61)
	$\rho_{tc} = 0.4$	
Jet flavor identification	18 (47)	24 (48)
Nonprompt leptons	35 (14)	31 (14)
$t\bar{t}W$ background	32 (32)	34 (31)
Total signal modeling	14 (12)	16 (13)
Total background modeling	66 (62)	64 (61)
Total experimental	44 (50)	46 (52)
Statistical	61 (61)	60 (59)

Results

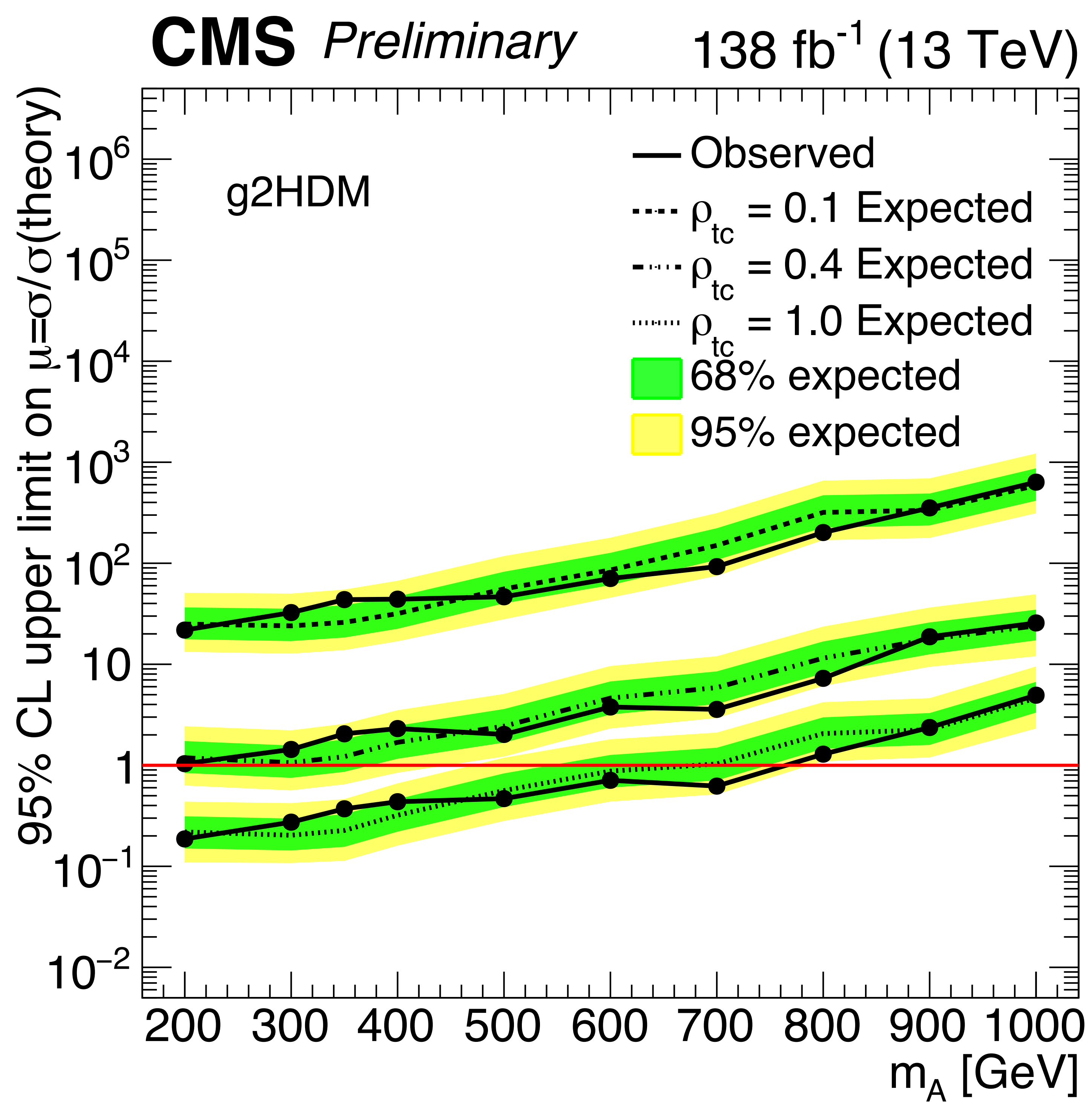
- Probe phase space with O(1) extra Yukawa couplings and sub TeV exotic Higgs mass
- Results are consistent with standard model predictions.

Observed (expected) lower limits on $m_A(m_H)$ at 95% CL.

Observed (expected) mass limit [GeV]

ρ_{tu}	Without interference m_A or m_H	With interference m_A	With Interference m_H
0.1	– (–)	– (–)	– (–)
0.4	900 (900)	1000 (1000)	950 (950)
1.0	1000 (1000)	1000 (1000)	950 (950)
ρ_{tc}	m_A or m_H	m_A	m_H
0.1	– (–)	– (–)	– (–)
0.4	– (–)	300 (350)	250 (300)
1.0	700 (600)	800 (550)	650 (500)

Observed and expected 95% CL upper limit on the signal strength



Results - exclusion

- Exclusions on coupling-mass plane are extracted by the 95% CL limits.

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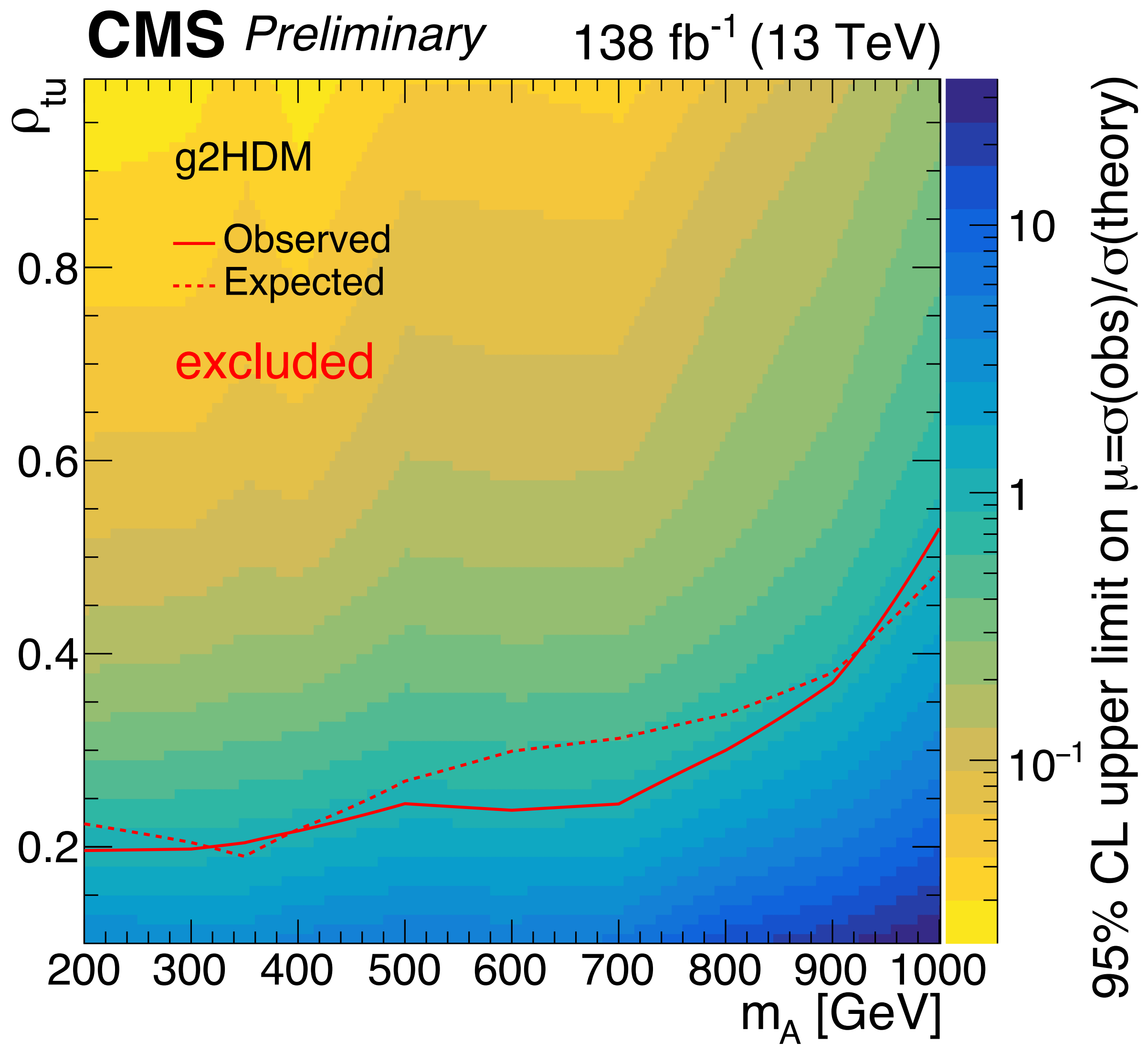
H-A non-interference
Only consider ρ_{tu}



H-A non-interference
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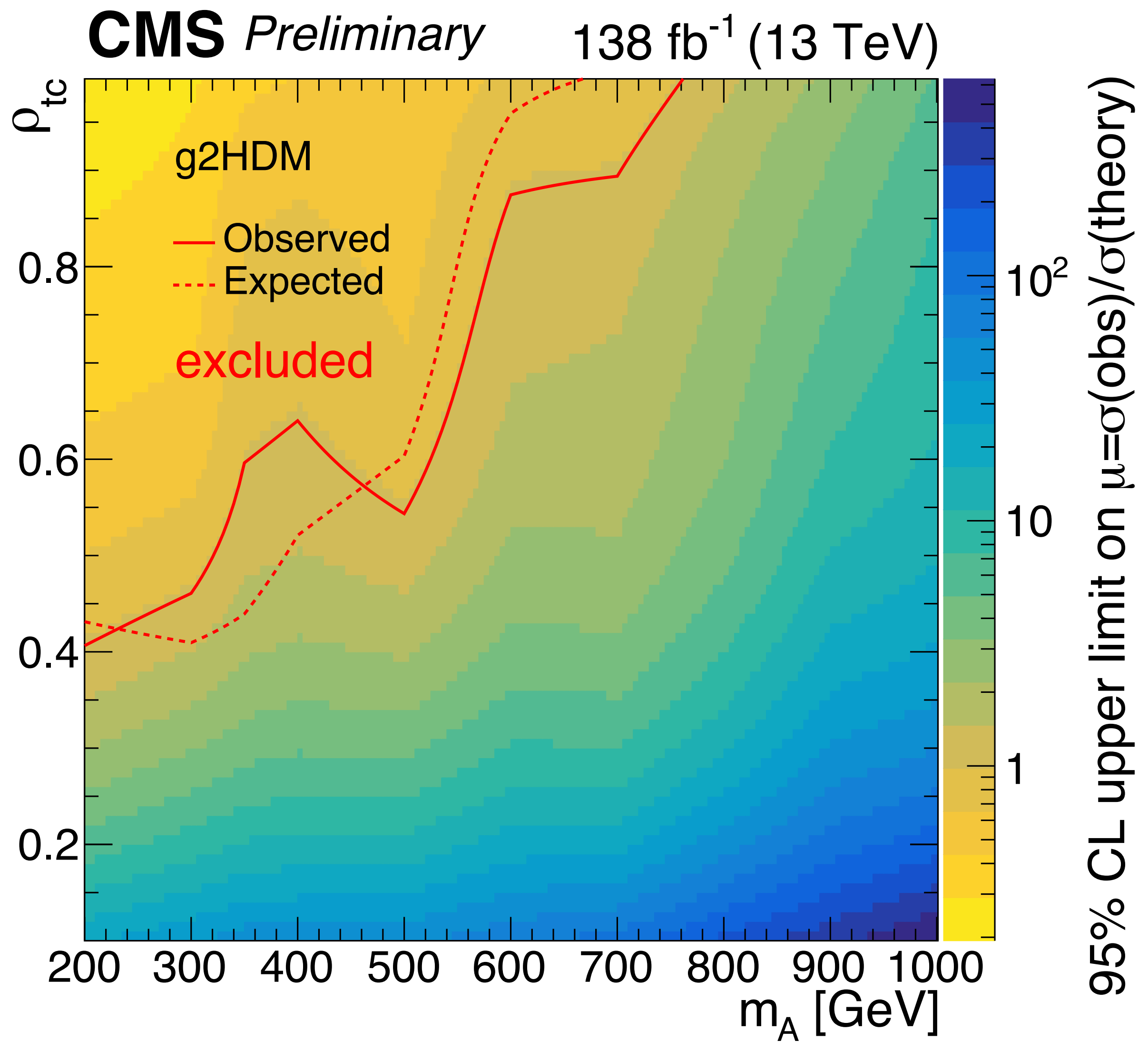

H-A interfere
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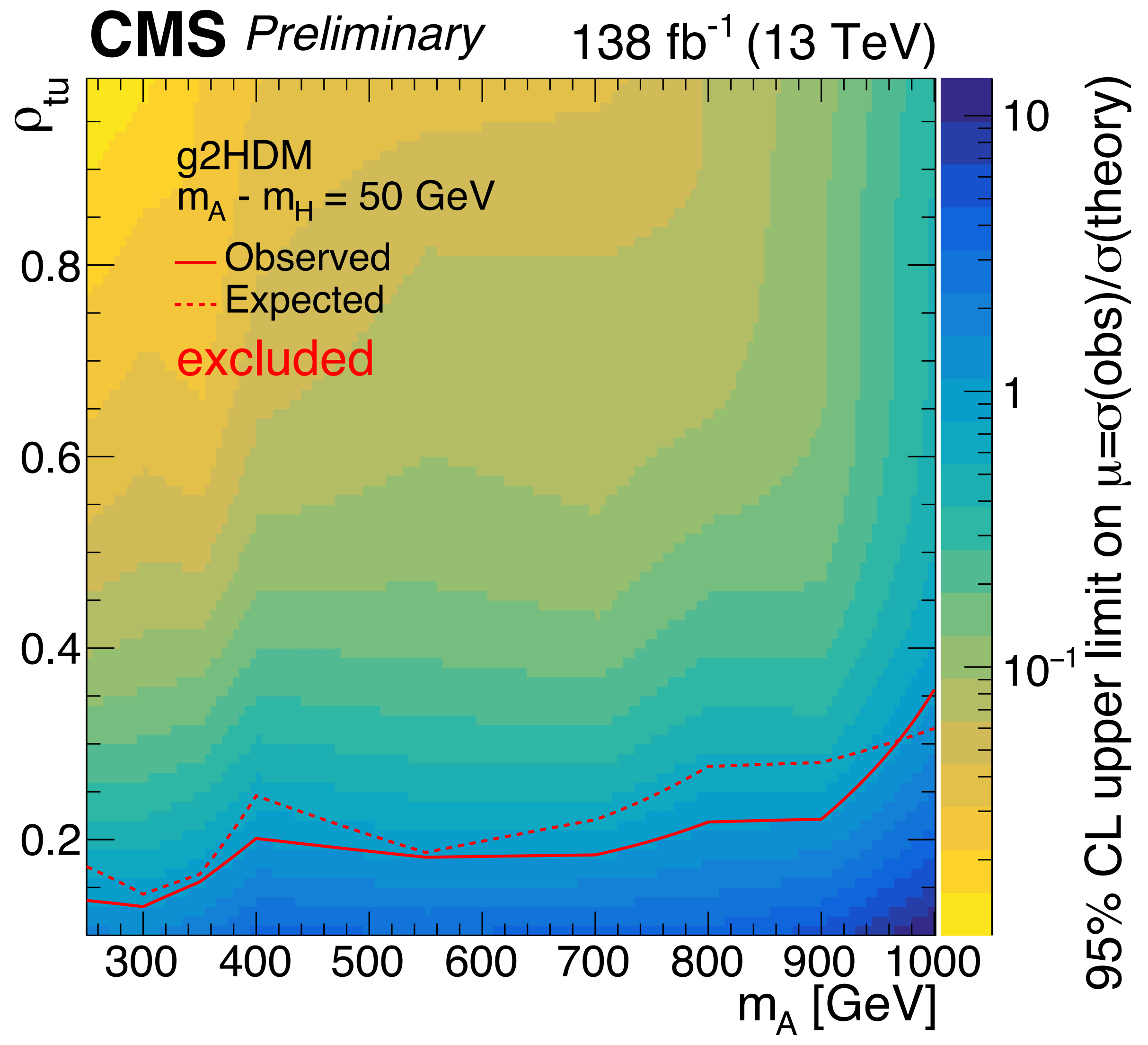

H-A interfere
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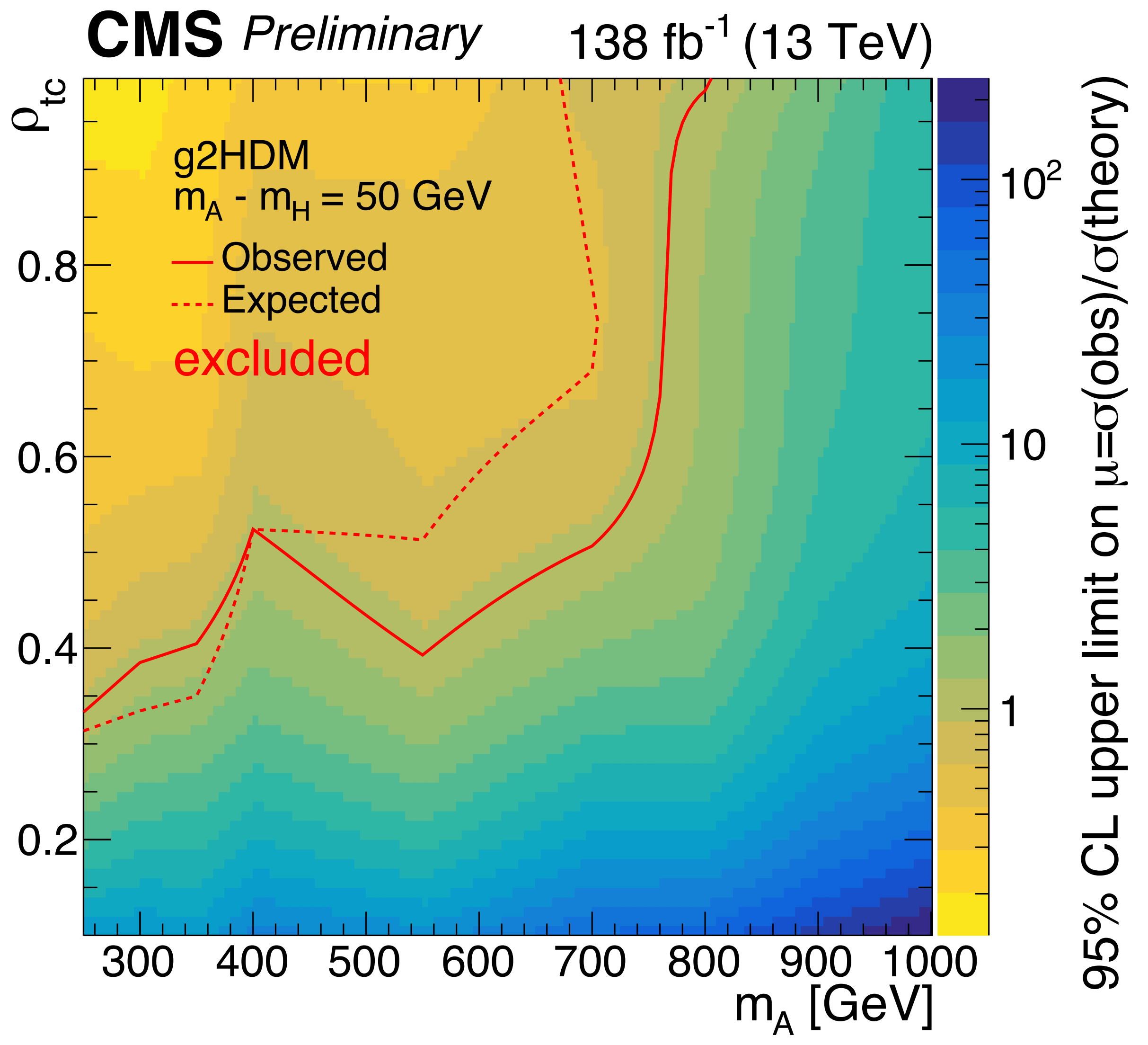

Summary

- Search for top quark related flavor changing neutral current in extended Higgs sector using full run2 CMS data
- Good agreement with standard model predictions.
- Exclude certain phase space of O(1) extra Yukawa couplings and sub TeV exotic Higgs mass with/without considering H/A interference.

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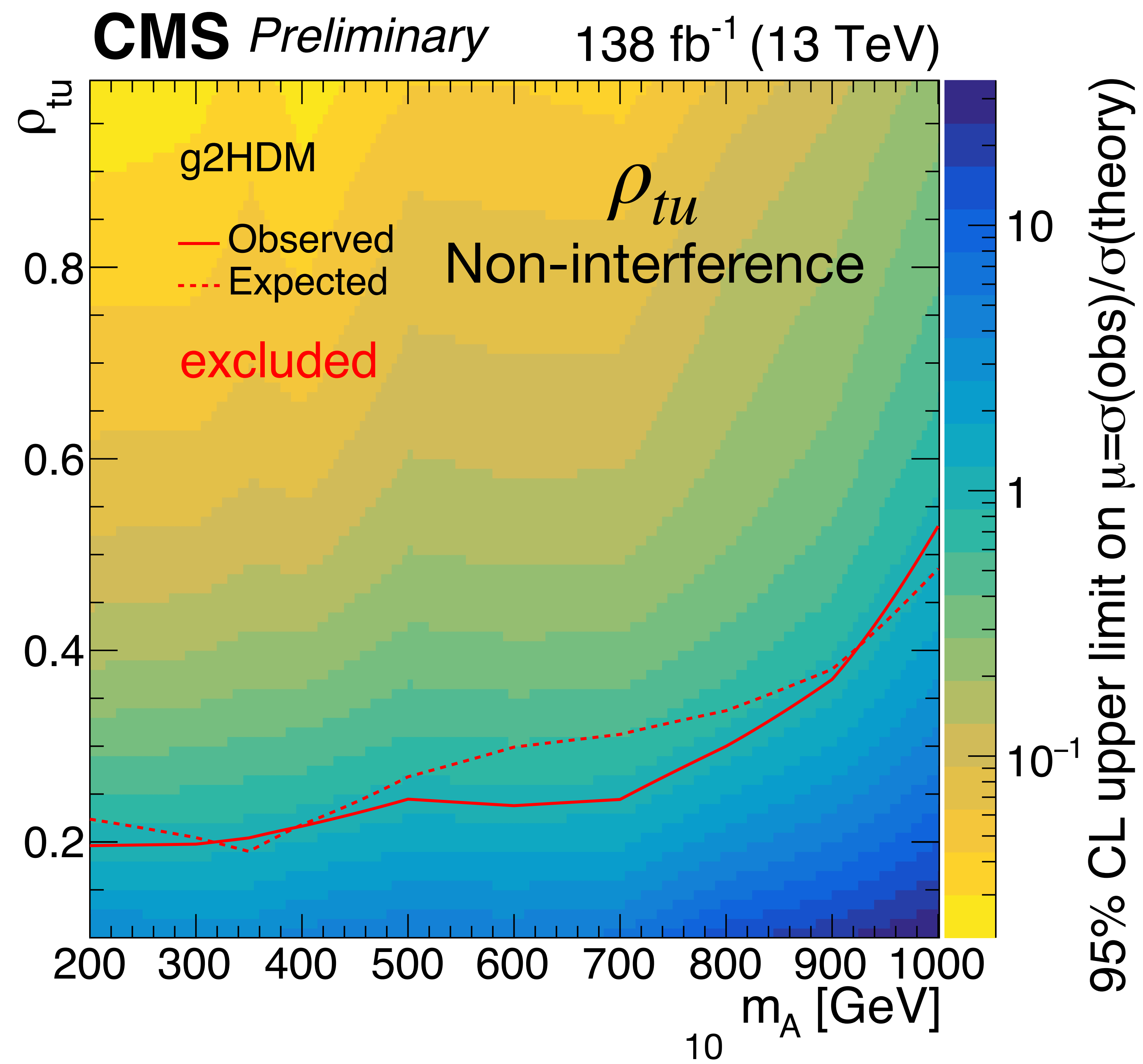
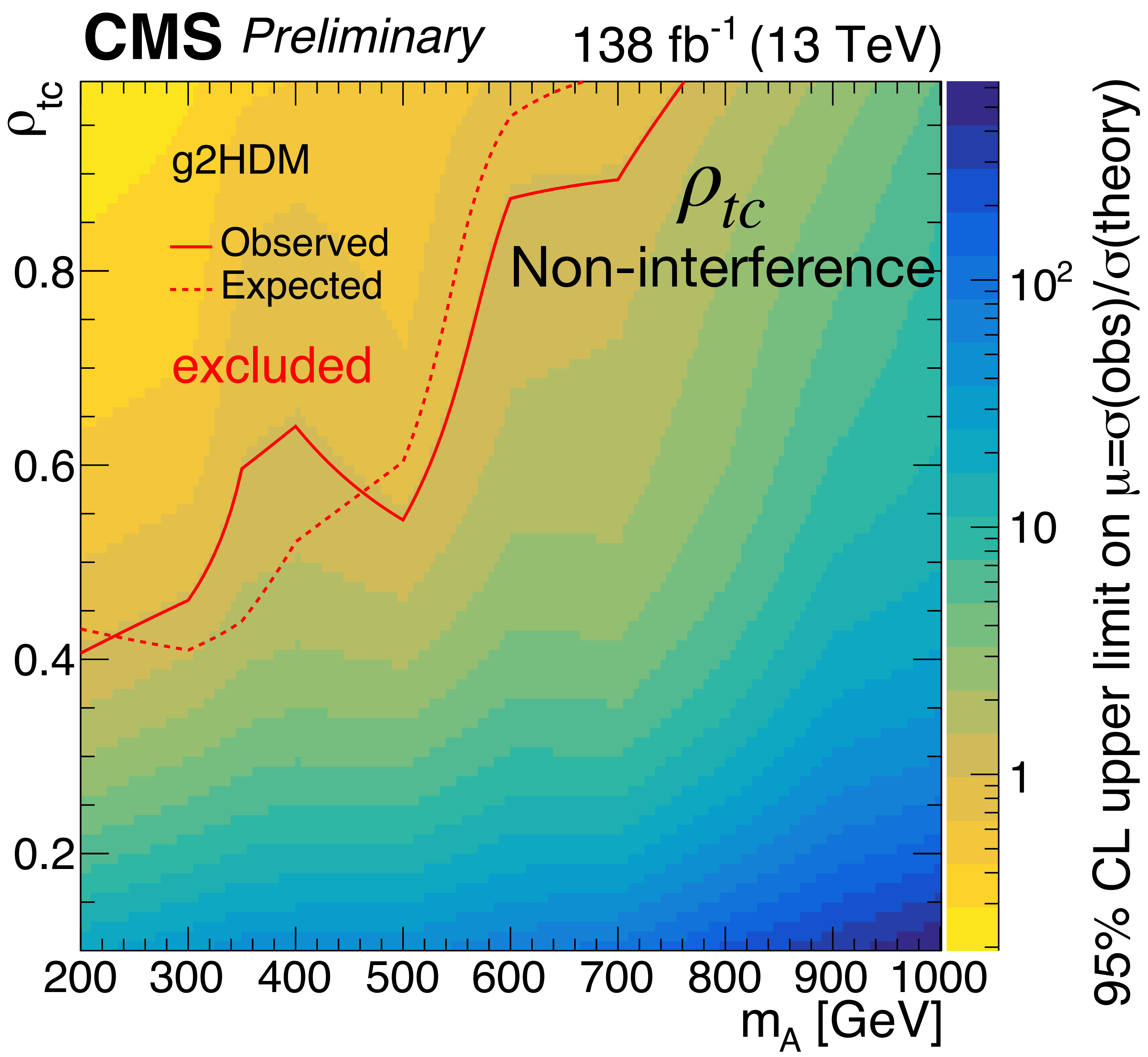




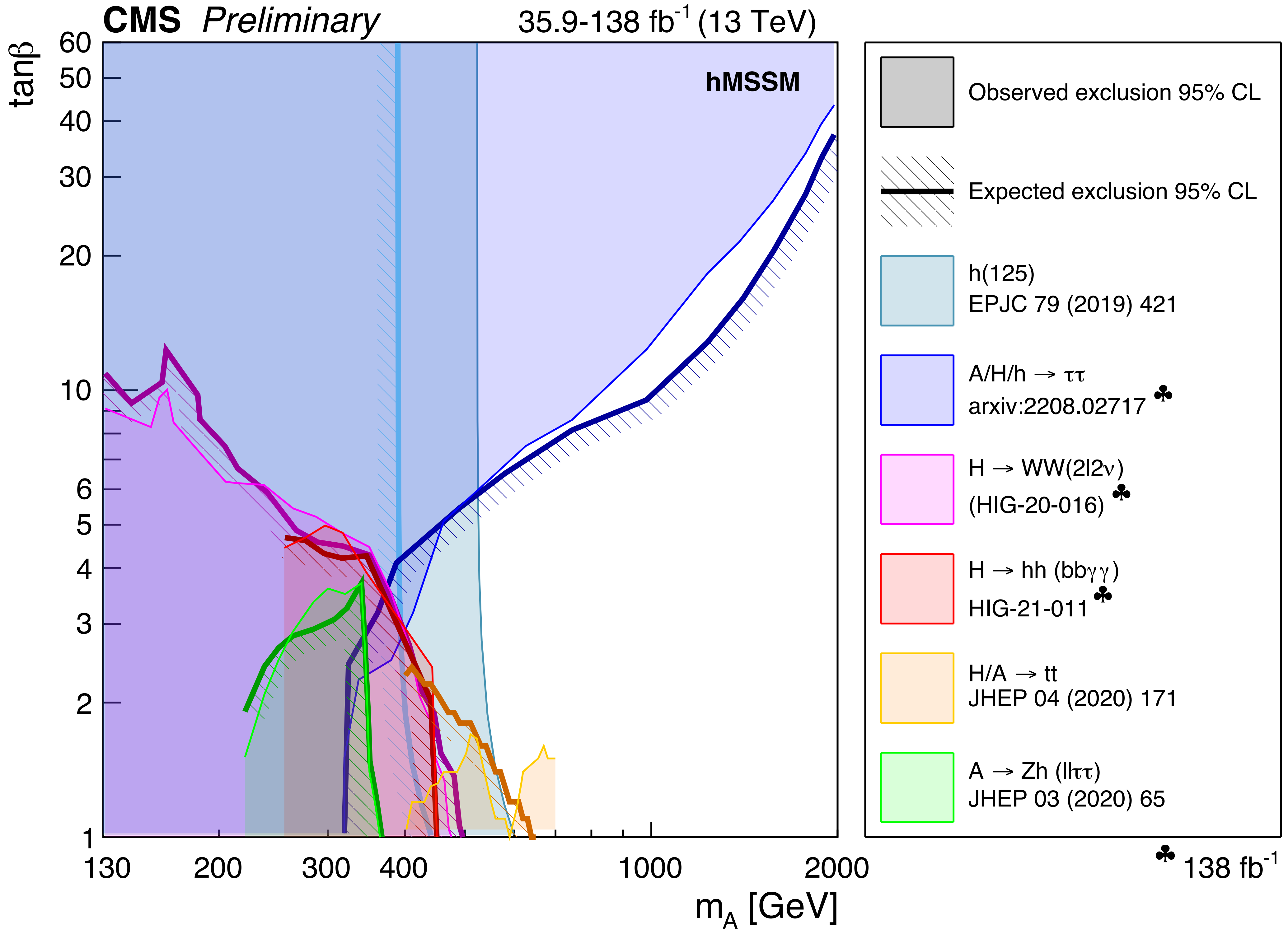
Thank you for your attention

Back up

Introduction to Extra Higgs Bosons

- Standard model still has several unsolved puzzles i.e. (anti)matter imbalance, g-2 muon anomaly etc.
- Several models introduce an extended Higgs sector i.e. supersymmetry (SUSY), Two-Higgs-Doublet Model (2HDM) in different variations etc.
- The second Higgs doublet in a 2HDM-like model introduces 5 scalar bosons
  - Charged scalar: $H^{\pm}$
  - Neutral scalar: H, h
  - Neutral pseudoscalar: A
- Many searches have been performed for extra Higgs Bosons

CMS Higgs Group Summary



EPS-HEP Conference 2023

Previous CMS results

- Many researches have been performed regarding to extra Higgs Bosons

$H/A \to tt$: Eur. Phys. J. C 77 (2017) 578

$H/A \to bb$: JHEP 08 (2018) 113

$H/A \to \tau\tau$: JHEP 09 (2018) 007

$H/A \to \mu\mu$: Phys. Lett. B 798 (2019)

$A \to Zh \to (ll, \nu\nu)bb$: Eur. Phys. J. C 79 (2019)

$H/A \to Z(ll)A/H(bb)$: JHEP 03 (2020) 055

$H \to WW$: JHEP 03 (2020) 034

$X \to YH \to b\bar{b}b\bar{b}$: Phys. Lett. B 842 (2023) 137392

$\phi \to \tau\tau$: JHEP 07 (2023) 073

$H \to AA \to 4\gamma$: Accepted pub. In Phys. Rev. Lett.

$H \to e\mu$: Submitted to Phys. Rev. D

$H \to \gamma\gamma$: CMS-PAS-HIG-20-002

$\phi \to ll$: CMS-PAS-EXO-21-018

$H^{\pm} \to \tau_h\nu$: JHEP 2019:142

$H^{\pm} \to Wa$: Phys. Rev. Lett. 123 131802 (2019)

$H^{\pm} \to tb$: JHEP 2020:096, JHEP 2020:126

$H^{\pm} \to cs, cb$: Phys. Rev. D 102, 072001 (2020)

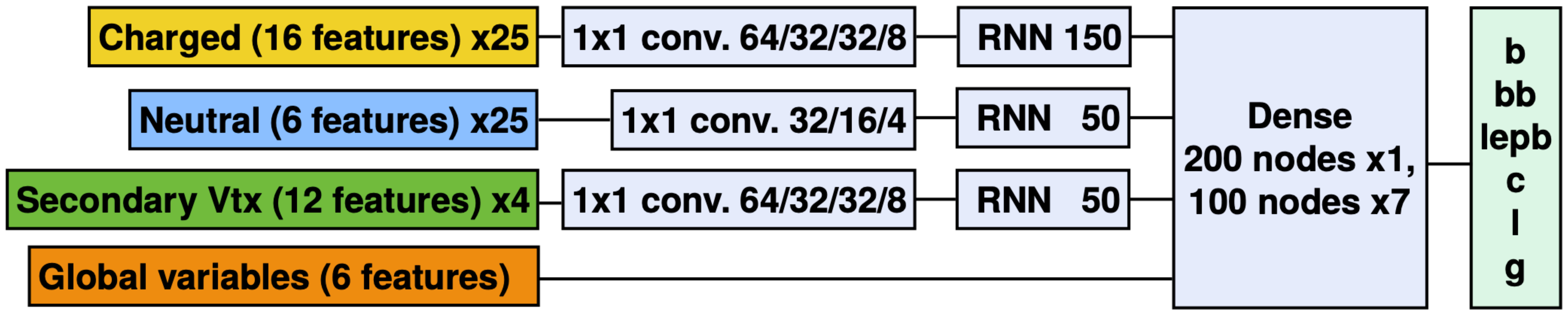
$H^{\pm} \to H(\tau\tau)W$: Accepted pub. In JHEP

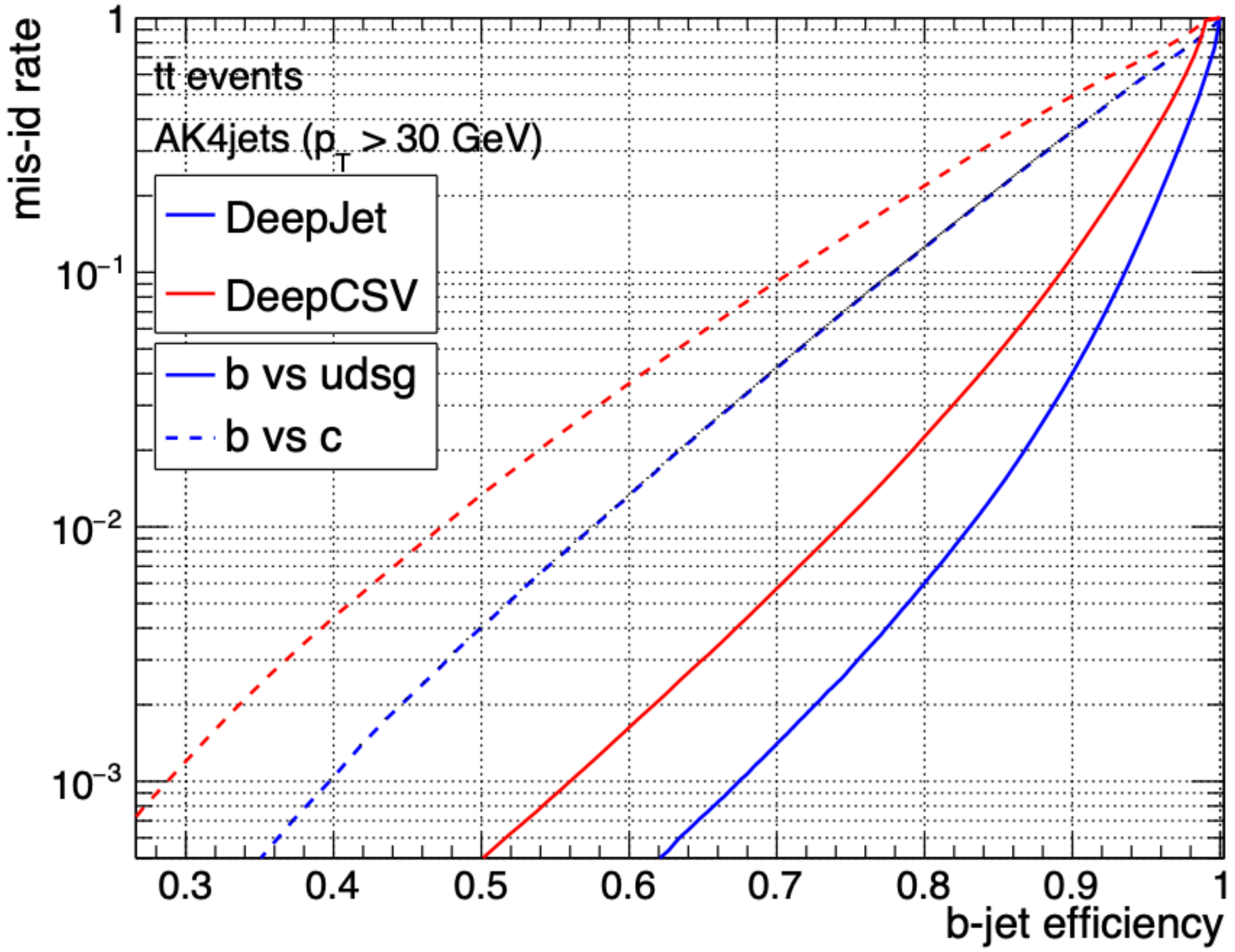
FCNC in extended Higgs sector still remains to be studied.

Analysis Technique - DeepJet

arXiv:2008.10519

- DeepJet Flavor Tagging
  - Neural network utilizing global variables, charged/neutral particle and secondary vertex features in the Jets to perform flavor tagging.

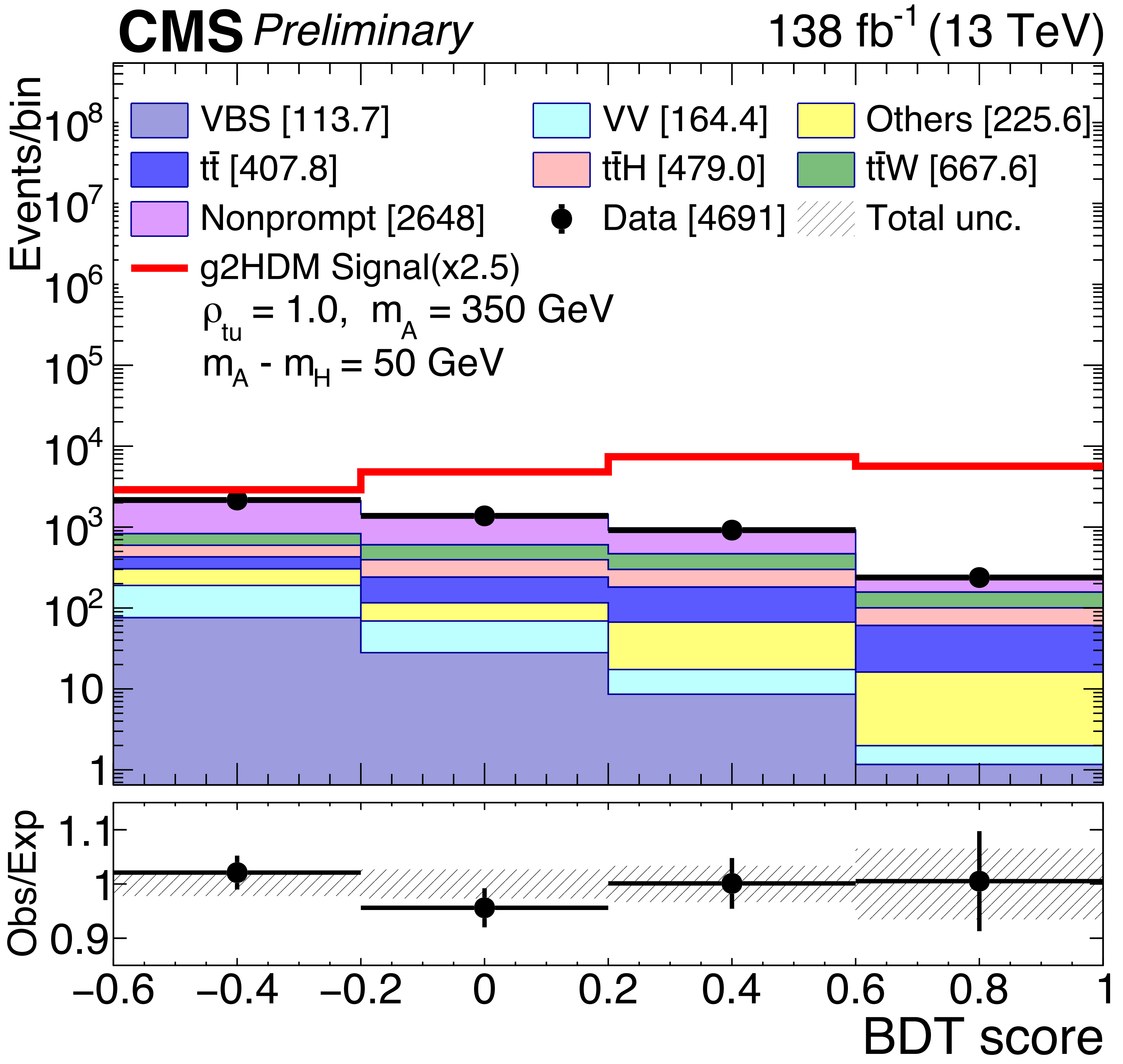




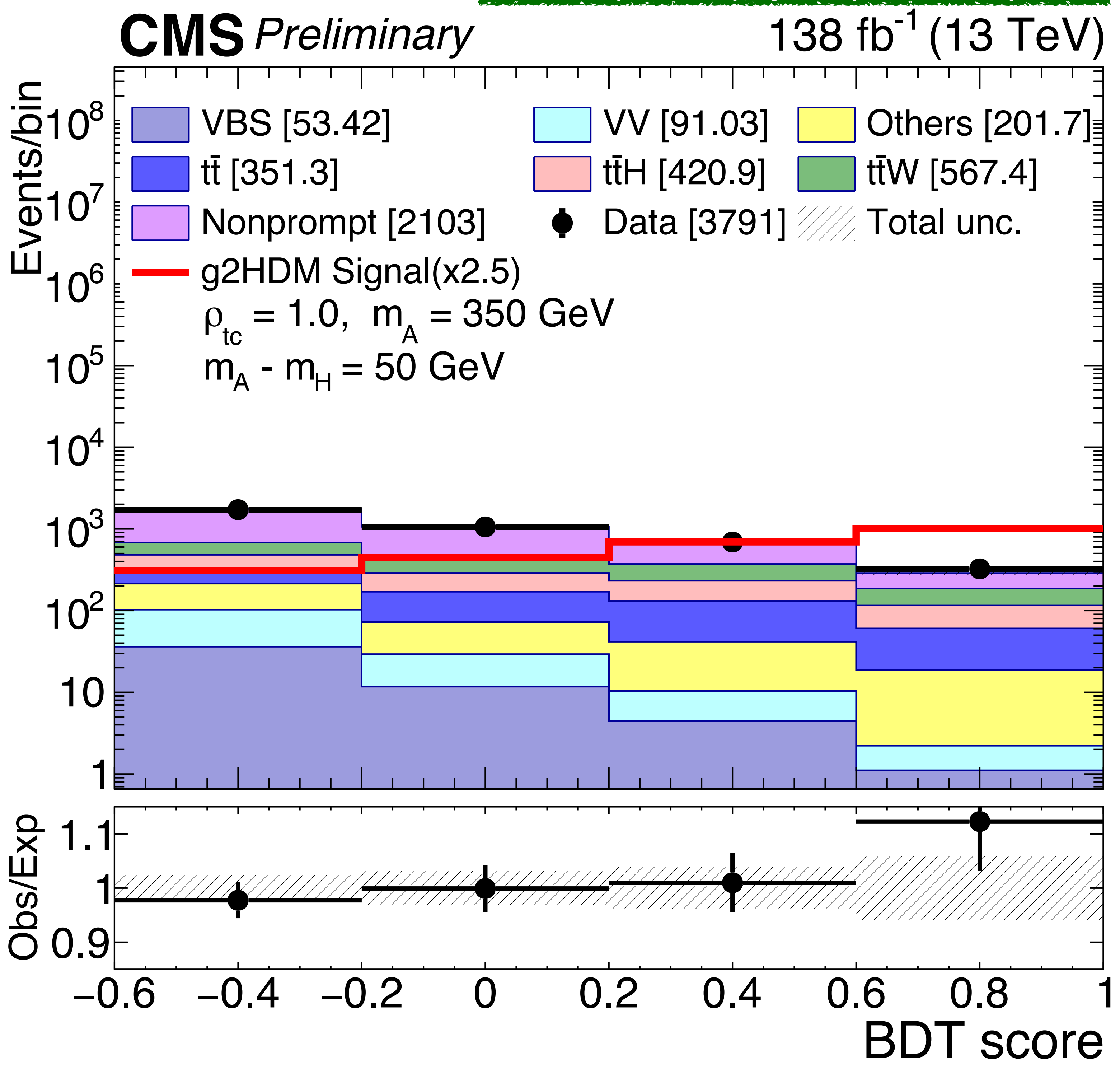
BDT distribution

- **Boosted Decision Tree**
  - Input: Jet flavor info, lepton/jet kinematic, MET, HT, and object pair kinematic information
  - BDT > -0.6 cut is imposed in order to improve the stability of the fit and the corresponding fit uncertainties

BDT focuses on ttu



BDT focuses on ttc



Results

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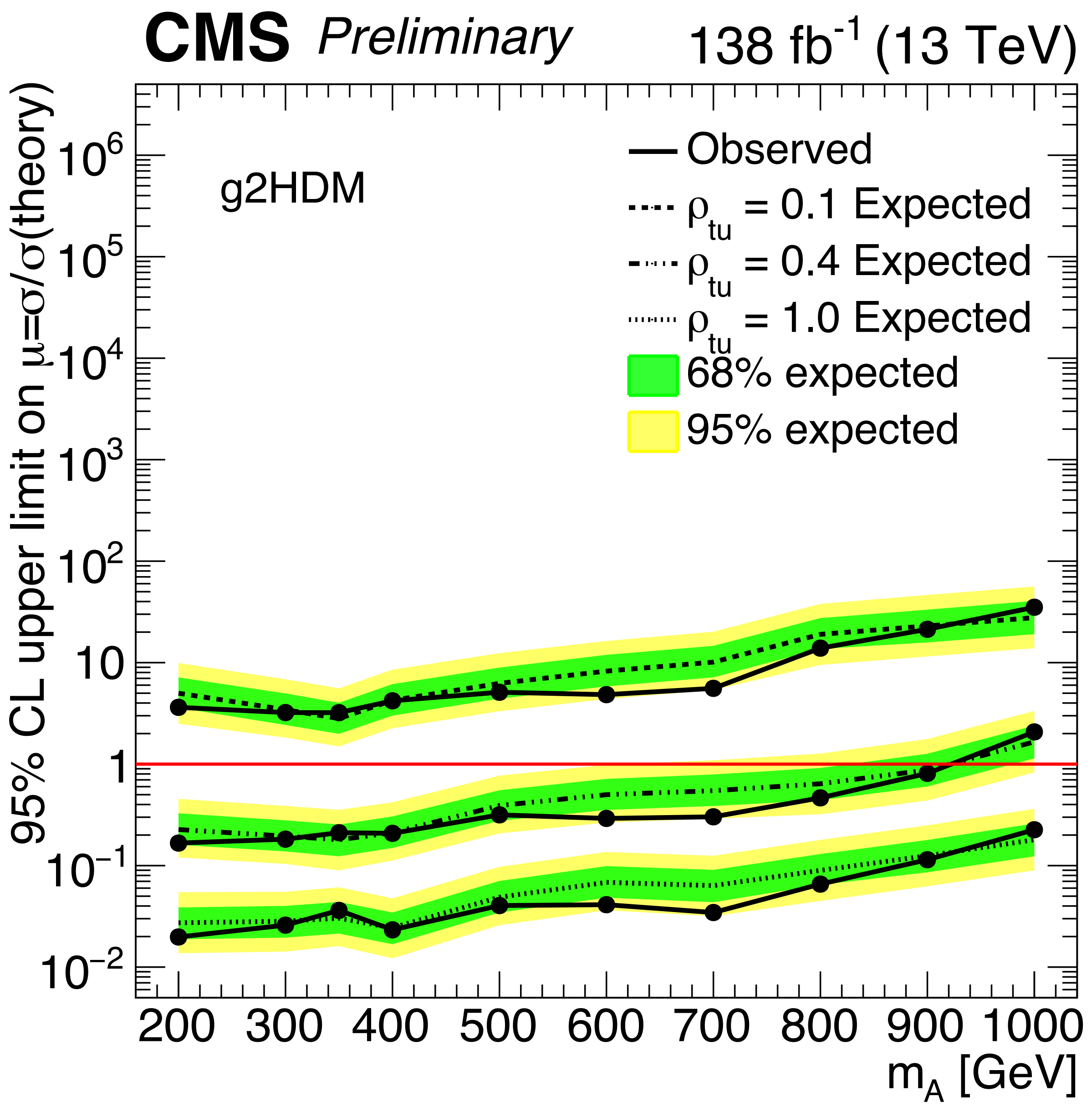
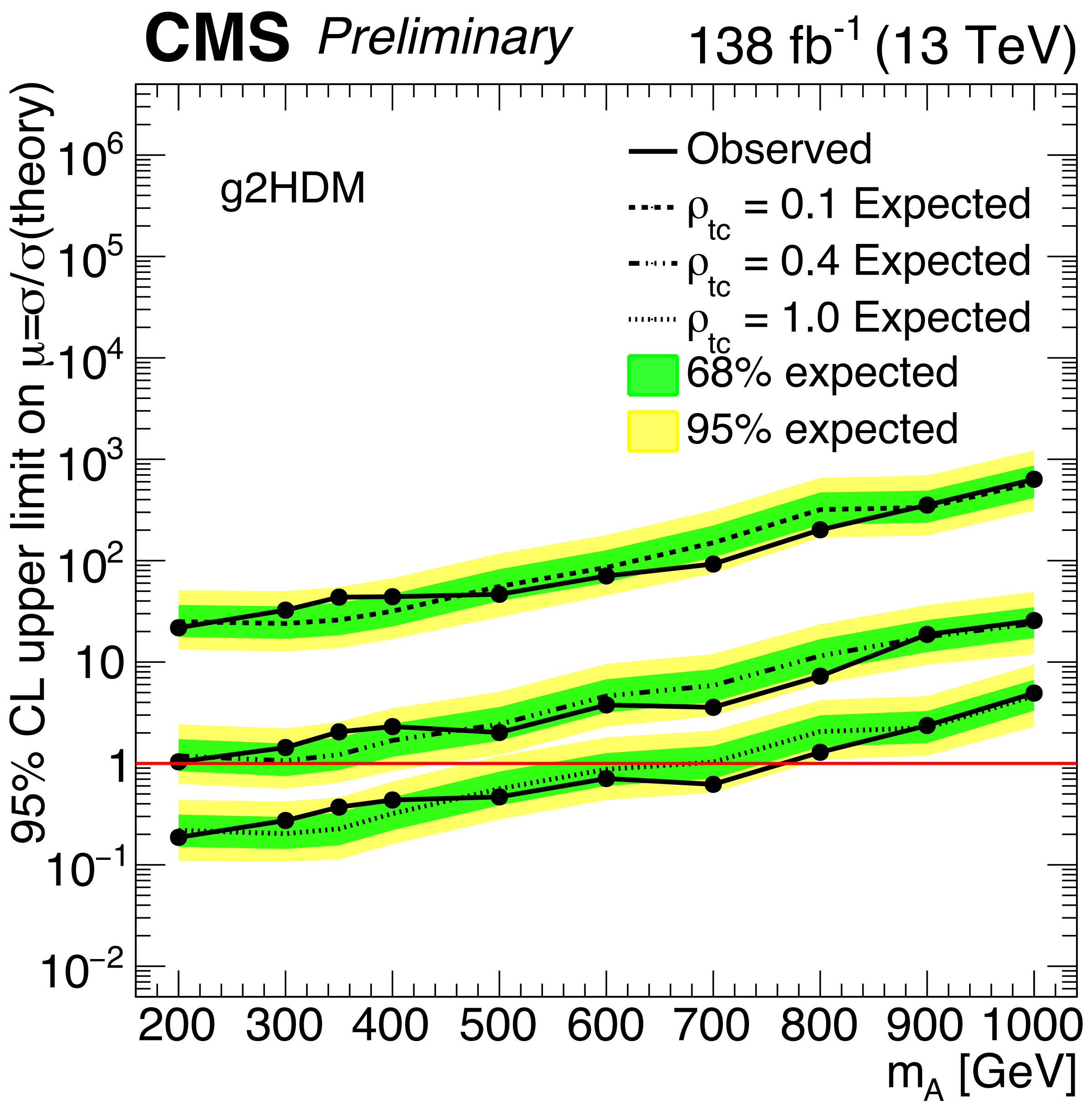
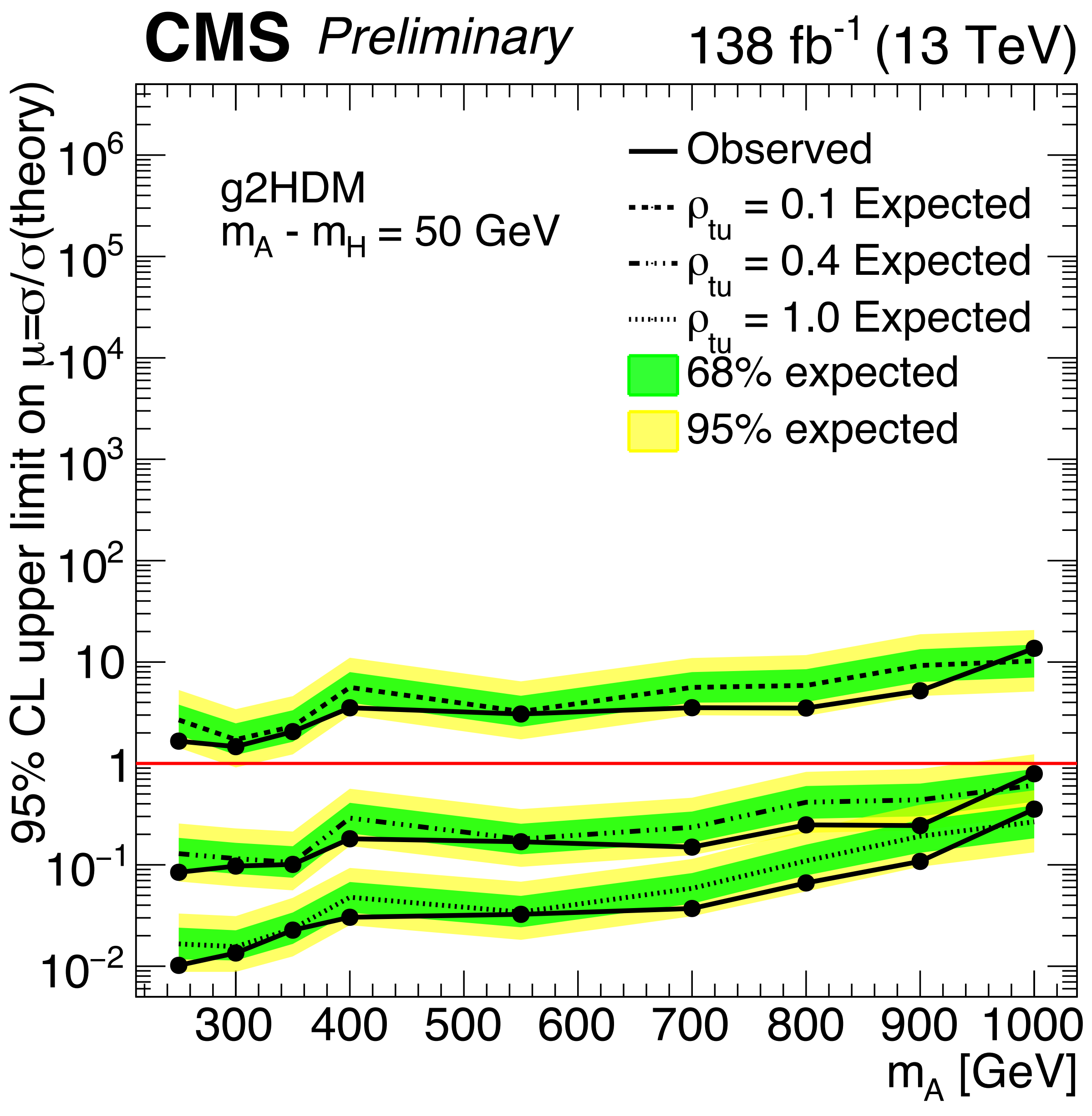
H-A non-interference
Only consider ρ_{tu}



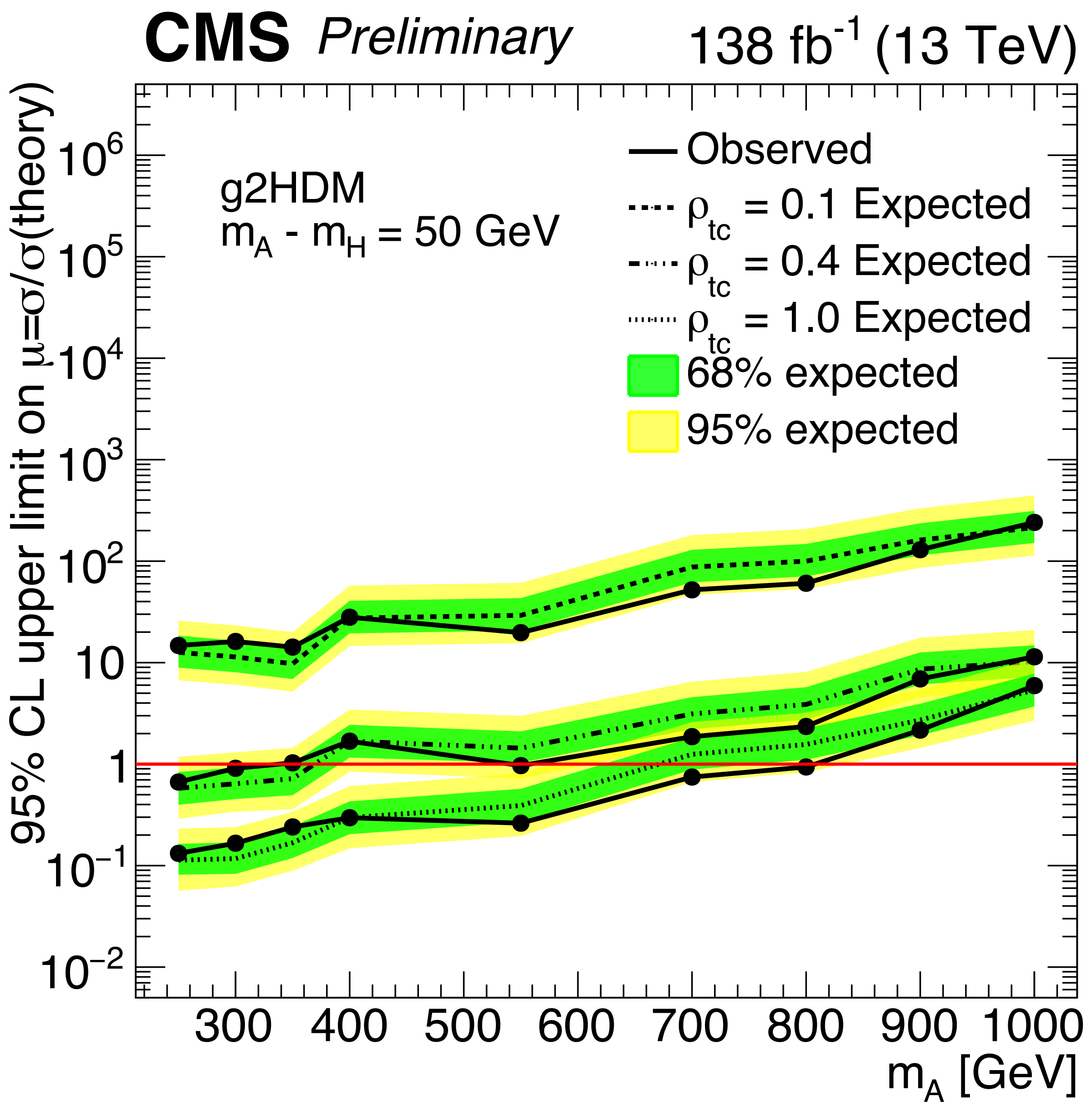
H-A non-interference
Only consider ρ_{tc}



H-A interfere
Only consider ρ_{tu}

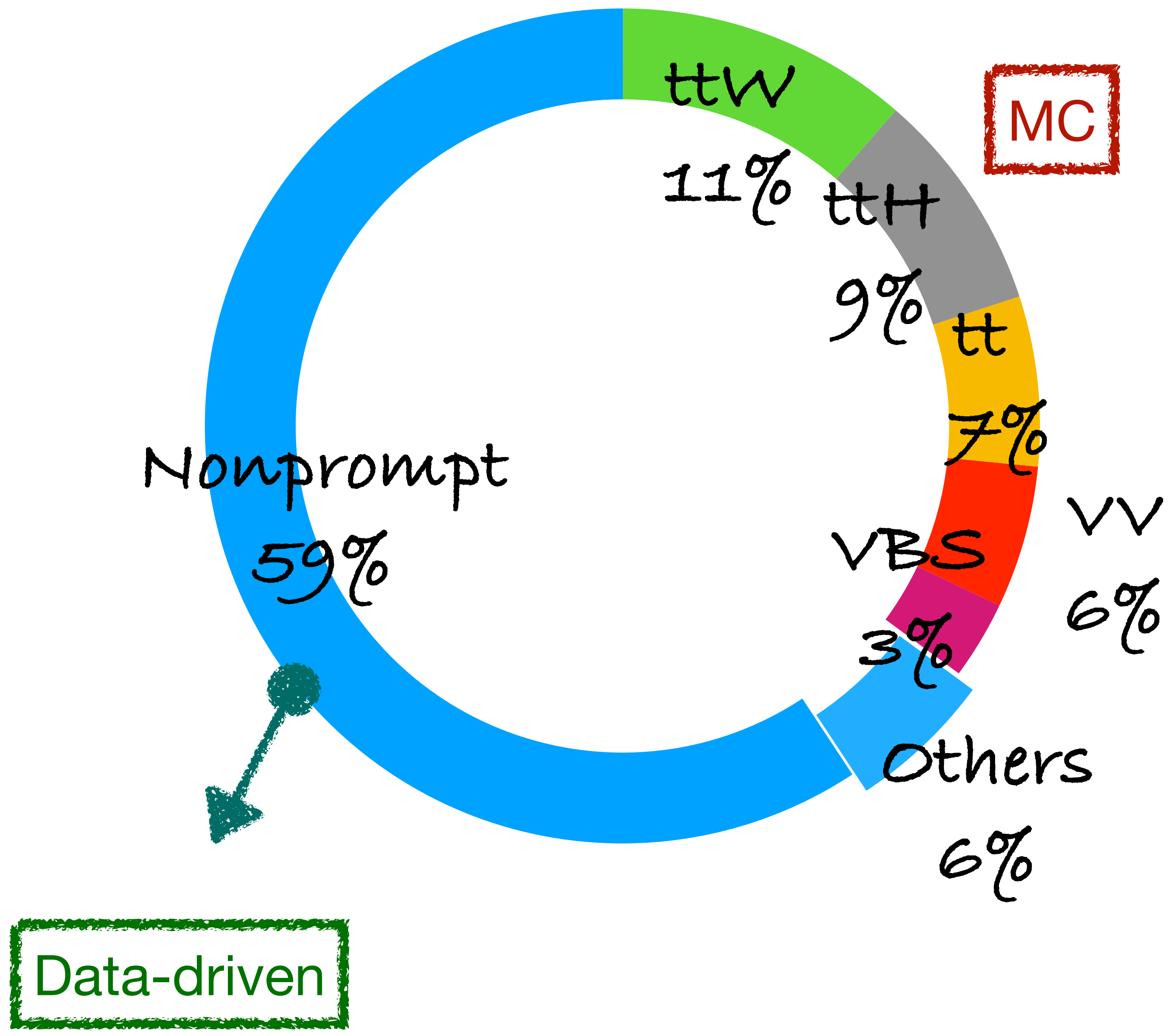


H-A interfere
Only consider ρ_{tc}

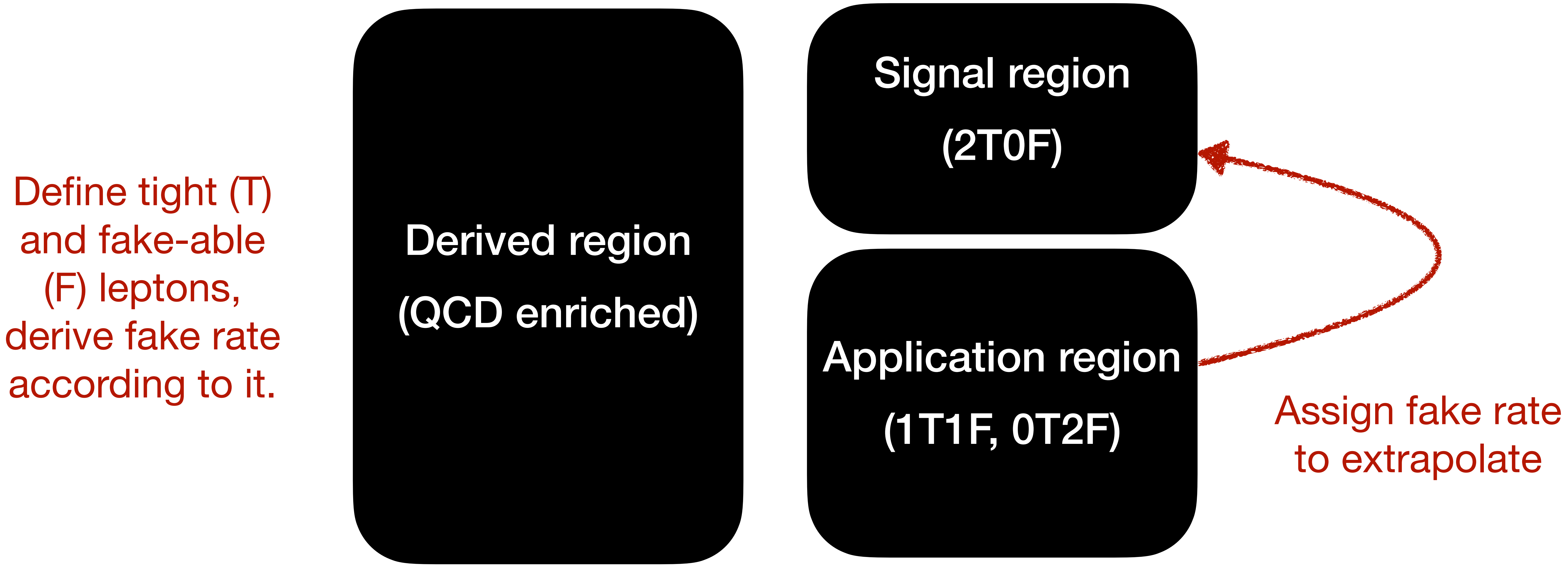


Non-prompt background

Background Contribution
(Before BDT cut)



- The main background is comprised of events with nonprompt leptons originating from leptonic decays of heavy quarks, hadrons misidentified as leptons, electrons from photon conversions, or jets misidentified as leptons.
- We utilize so called “tight-to-loose” method to estimate the lepton fake rate and then extrapolate the events in application region into signal region according to it.



Background Category

Category	Samples
TT	TTTo2L
VV	WW(OS) WZ(QCD)
VBS	WpWpJJ(EWK+QCD) WLLjj ZZJJTo4L
ttH	ttH
ttW	ttWtoLnu ttWtoQQ

Category	Samples
Others	tW & tbarW DY ttZZ ttWW ttWZ ttWH ttZH ttZ(ll + qq) tZq tttj tttW tttt ZZZ WZZ WWZ WWW