Search for new Higgs bosons via same-sign top quark pair production + a jet at CMS, arXiv:2311.03261

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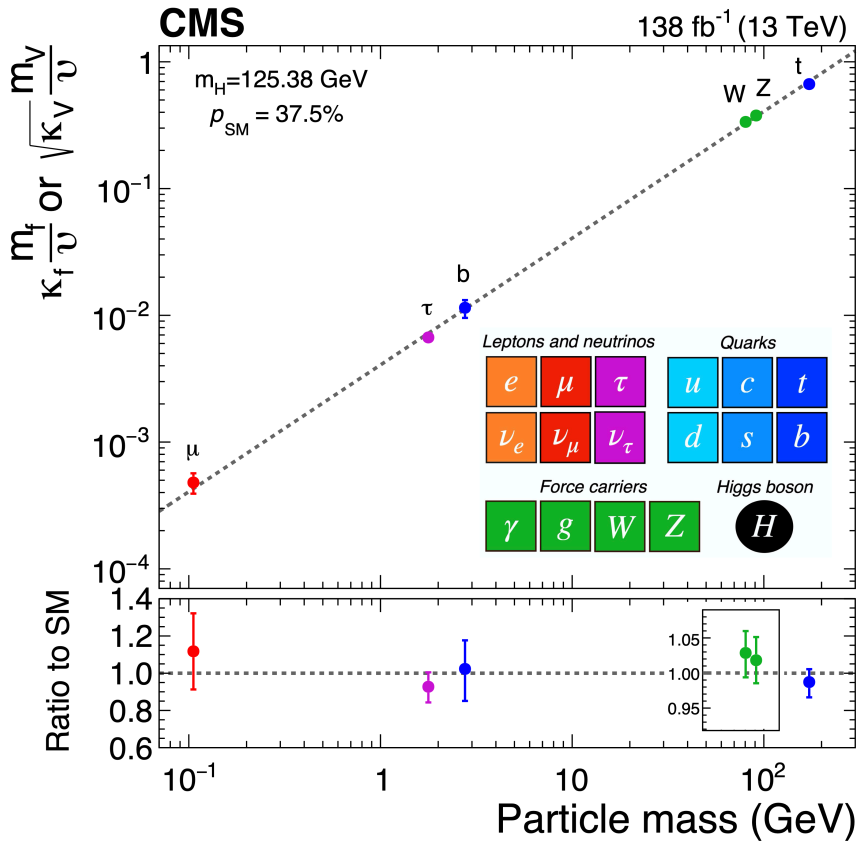
Introduction

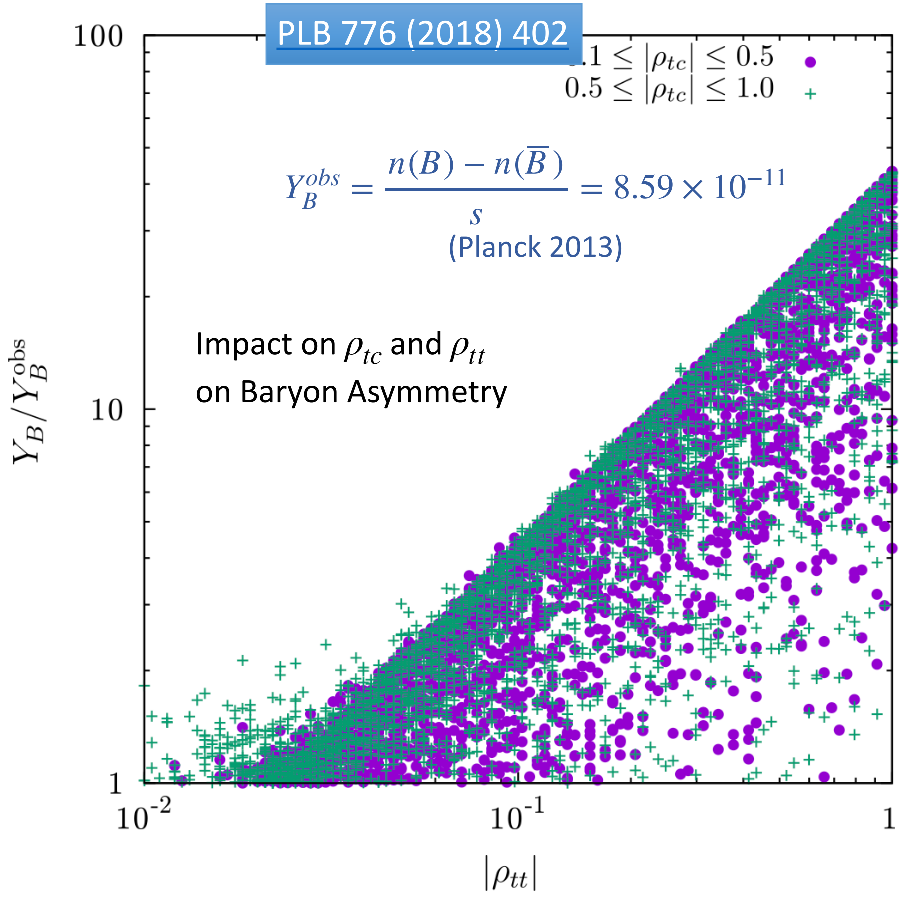
- In these « *dark times between experimental breakthroughs* »* we ask if there are additional scalar doublets.
- If N(doublets) ≥ 2, *baryon asymmetry of the Universe* may be explained.



* S. Weinberg

Introduction

- 2HDM introduces five scalar bosons: $H^{\pm}, H, h, A$
- When $\mathbb{Z}_2$ symmetry is dropped in 2HDM to allow flavor changing neutral currents (FCNC) —> generalized 2HDM (g2HDM)
  - Many parameters and extra processes arise.
  - Alignment emerges when no $\mathbb{Z}_2$ symmetry and all extra Higgs quartic couplings $\mathcal{O}(1)$ + extra top Yukawa couplings $\mathcal{O}(1)$—> Electroweak baryogenesis, lack of FCNC (e.g. $t \to ch_{125}/uh_{125}$ or $h_{125} \to \mu\tau/e\tau$), … *may* be explained.
  - sub-TeV $H^{\pm}, H, A$ bosons may still exist <—> New physics scale <10-20 TeV.



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

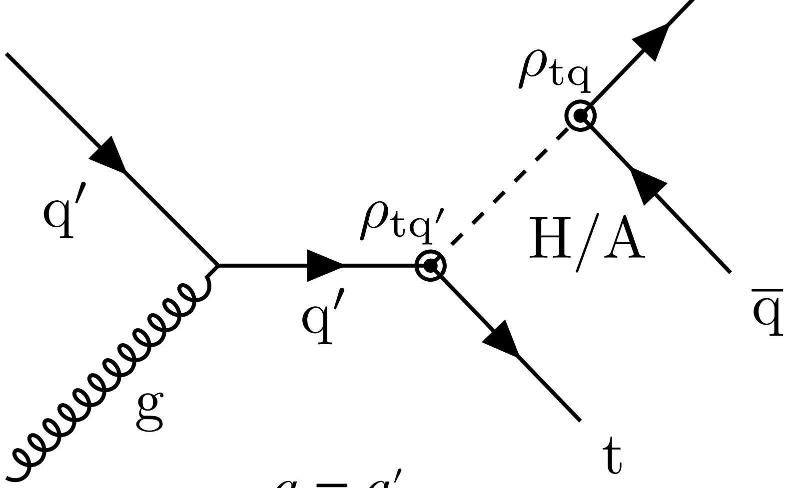
$q_i q_j h$ coupling (125 GeV Higgs) $\propto - y_{ij} \sin_\gamma + \rho_{ij} \cos_\gamma$

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

- Alignment limit: $\cos \gamma_{H-h} \approx 0$
  - h becomes h_{125}
  - No HVV, AVV interactions.
  - Suppresses FCNC interactions for h but allows for H and A.

The signal

$$\rho_{qq'} \propto \sqrt{m_q m_{q'}}$$



$q = q'$

$$qg \to tH \to tt\bar{q}$$
$$\to (\ell^+ b\nu)(\ell^+ b\nu)\bar{q}$$

- Probe extra Yukawa couplings with top quarks within g2HDM:
  - $0.1 < \rho_{tq} < 1.0$ with one coupling (ρ_{tu} or ρ_{tc}) at a time assuming all other extra Yukawa couplings are zero.
  - No H—A interference: Only A (or equivalently only H): $200 \le m_{A/H} \le 1000$ GeV
  - With H—A interference assuming $m_A - m_H = 50$ GeV: $250 \le m_A \le 1000$ GeV

σ(inter.) $\approx \sigma$(non- inter.) for $m_A - m_H \gtrsim 100$ GeV

$\sigma = 0$ for $m_A = m_H$

} $m_A - m_H = 50$ GeV retains some interference effect along with reasonably high cross sections

$\sigma(tt\bar{u}) \approx 1 \times 10^{-4}$ to $\approx 7 \times 10^{-1}$ pb

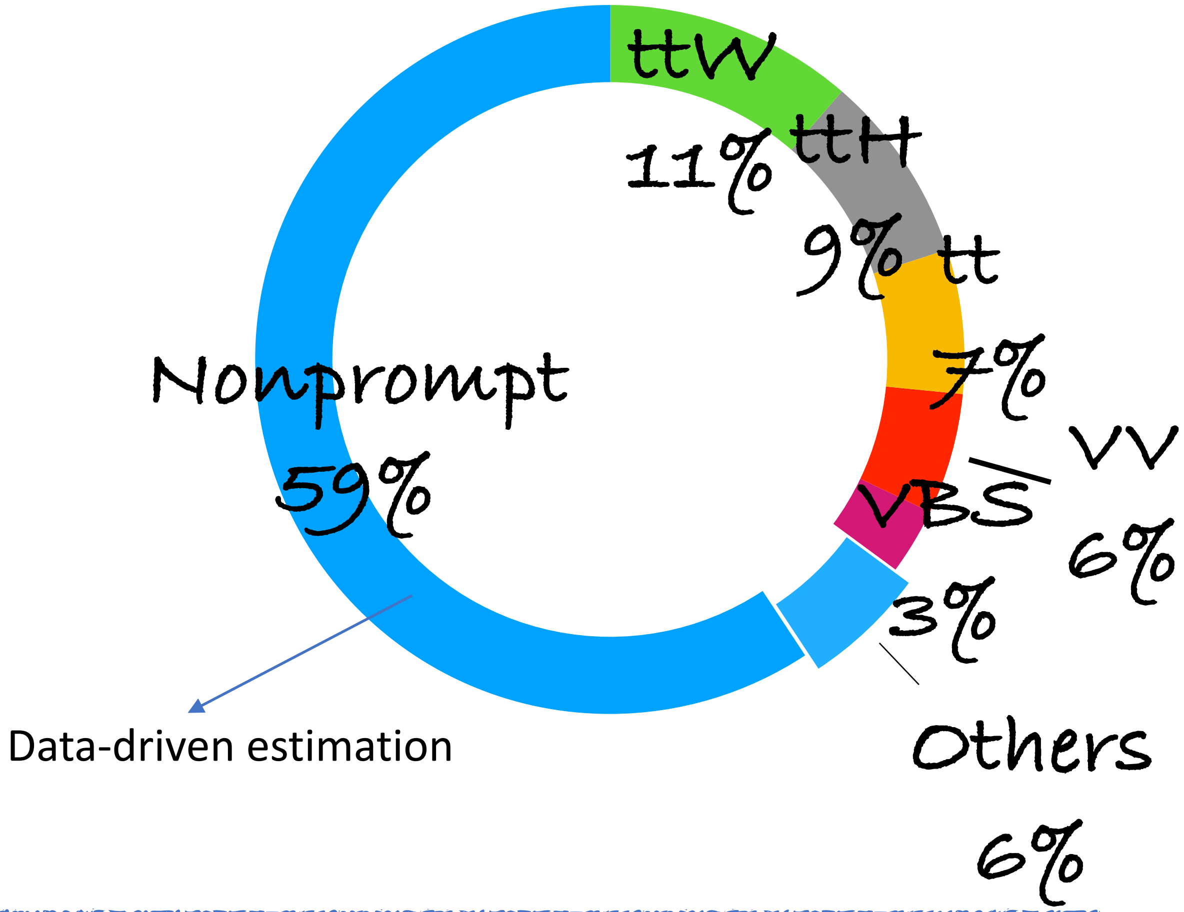
$\sigma(tt\bar{c}) \approx 5 \times 10^{-6}$ to $\approx 7 \times 10^{-2}$ pb

MG5_aMC + PYTHIA8 [MLM]

Event Selection and Background Composition

- Search performed in $e^{\pm}e^{\pm}, \mu^{\pm}\mu^{\pm}, e^{\pm}\mu^{\pm}$ categories
- $p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 20$ GeV; $|\eta(e)| < 2.5$, $|\eta(\mu)| < 2.4$
- Veto events with a third lepton with $p_T(\ell) > 10$ GeV
- $\Delta R(\ell_1, \ell_2) > 0.3$
- $m_{\ell\ell} > 20$ GeV
- Veto events with $60 < m(\ell_1, \ell_2) < 120$ GeV
- $p_T^{miss} > 30$ GeV
- At least three jets with $p_T(j) > 30$ GeV, $|eta(j)| < 2.4$, $\Delta R(j, \ell) > 0.4$
- BDT > -0.6 to have improved stability of the fit and its uncertainties.

Before the BDT cut



Data-driven estimation for charge misidentification in $e^{\pm}e^{\pm}$ channel

—> Applied to all MC events.

—> Rate increase with p_t and η and varies from $\approx 10^{-5}$ to $\approx 10^{-2}$

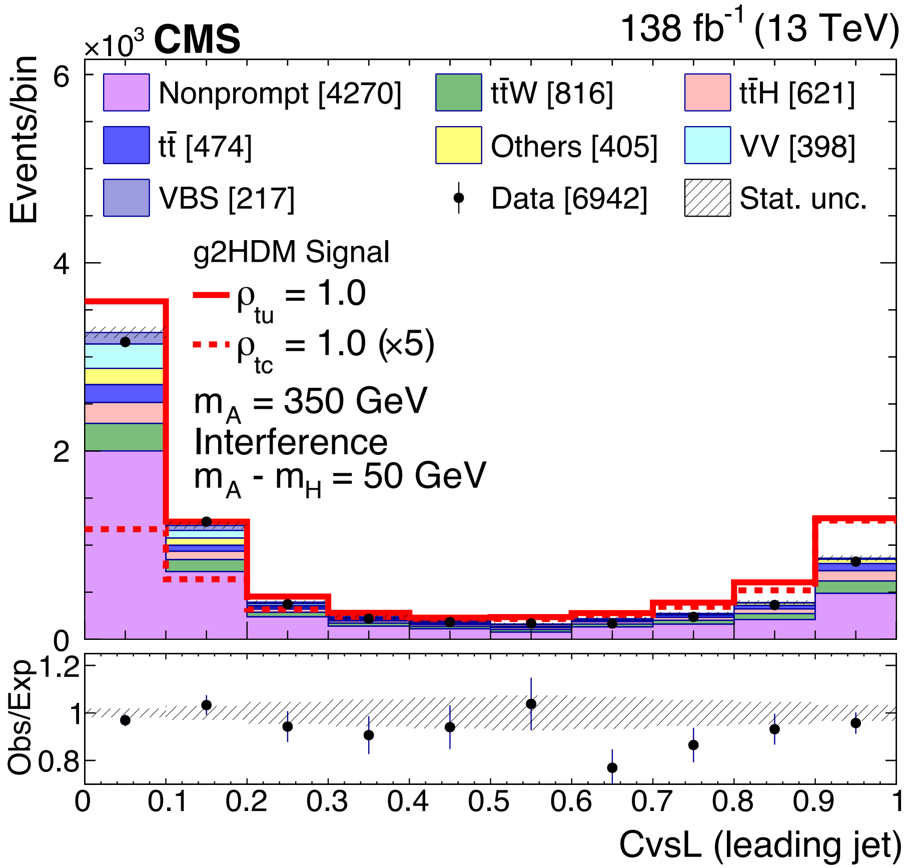
Inputs to the BDTs

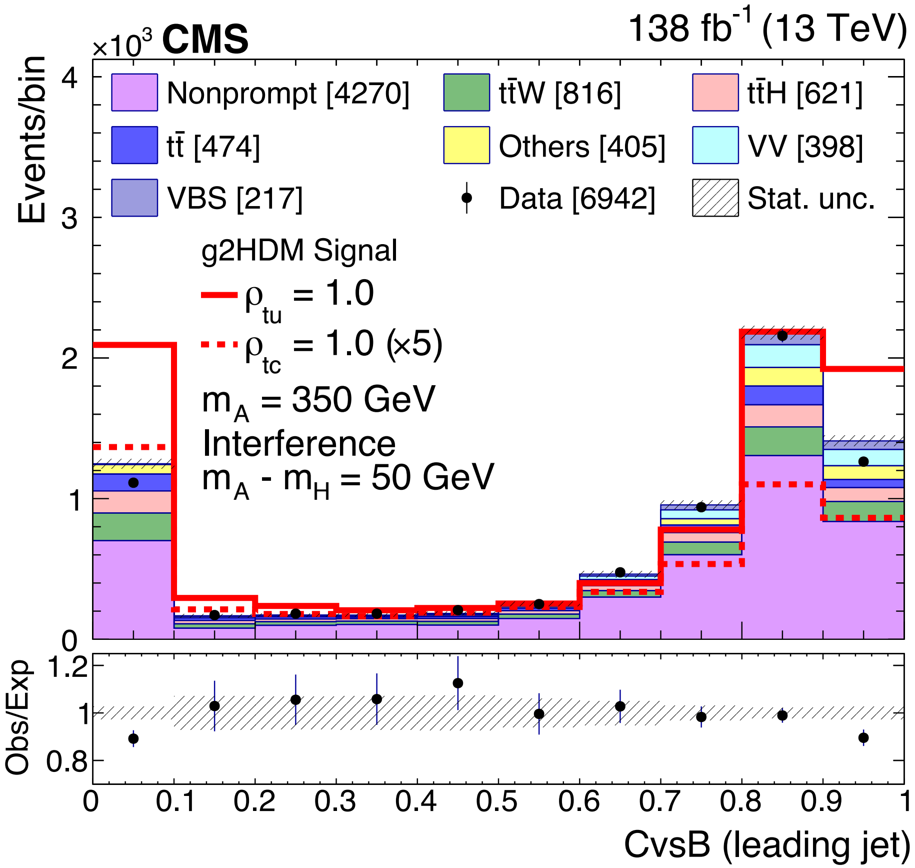
Table 1: Input variables of the BDT. Jets and leptons are ordered by p_T.

Input variables of the BDT		
$\mathrm{CvsL}(j_a)$	$a = 1,2,3$	Charm- vs light-quark jet identification variable
$\mathrm{CvsB}(j_a)$	$a = 1,2,3$	Charm- vs bottom-quark jet identification variable
$\Delta R(j_a, j_b)$	$1 \leq a < b \leq 3$	Angular separation between jets
$m(j_a, j_b)$	$1 \leq a < b \leq 3$	Invariant mass of jet pairs
$\Delta R(j_a, l_b)$	$a = 1,2,3; b = 1,2$	Angular separation between jet and lepton
$m(j_a, l_b)$	$a = 1,2,3; b = 1,2$	Invariant mass of jet-lepton pairs
$p_T(\ell_a)$	$a = 1,2$	Transverse momentum of leptons
$m(\ell_1, \ell_2, j_a)$	$a = 1,2,3$	Invariant mass of the two leptons plus the highest p_T jet
$m(\ell_1, \ell_2)$		Invariant mass of the two leptons
H_T		Scalar p_T sum of the jets
p_T^{miss}		Missing transverse momentum

- BDTs trained independently for 4 data-taking periods x [10 mass (w/o interference) + 9 mass (w interference)] x ($\rho_{tu} = 0.4$ and $\rho_{tc} = 0.4$) —> 152 BDTs in total.
- MC samples w/ $\rho_{tu}(\rho_{tc}) = 0.4$ to scale limits for other couplings for each mass.
- For $\rho_{tc} = 0.4$, for a signal eff. ~96%, background rejection rates:
  - 50% ($m_A = 200$ GeV)
  - 76% ($m_A = 1$ TeV).

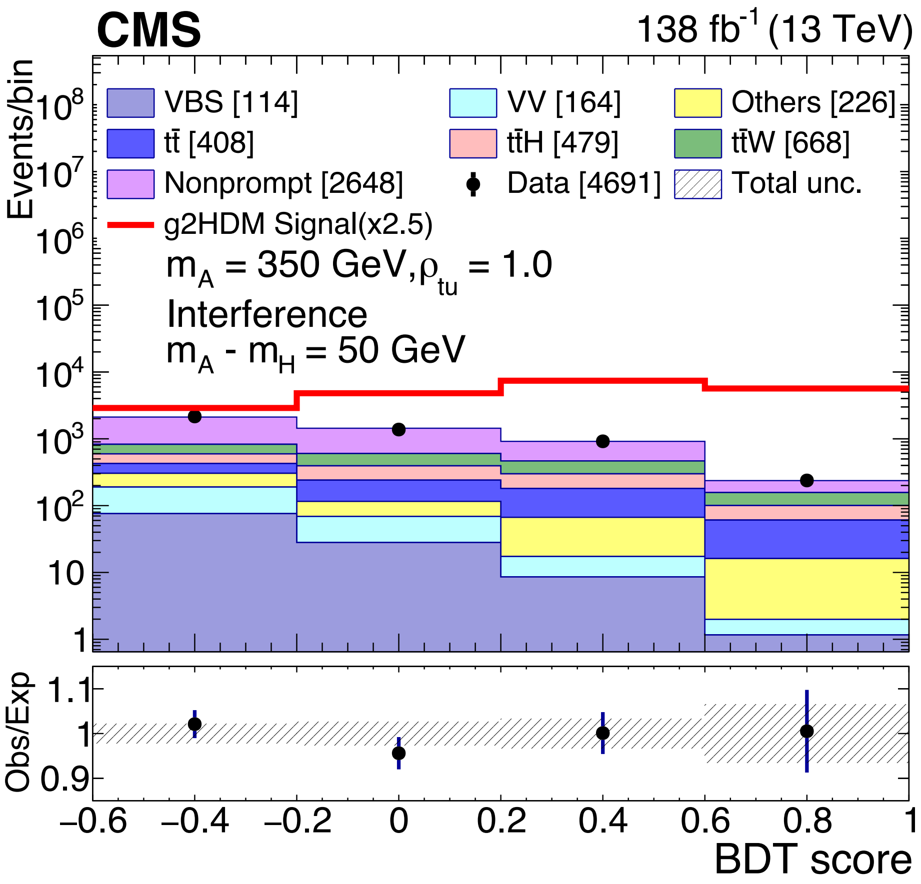
Jet Flavor Identification

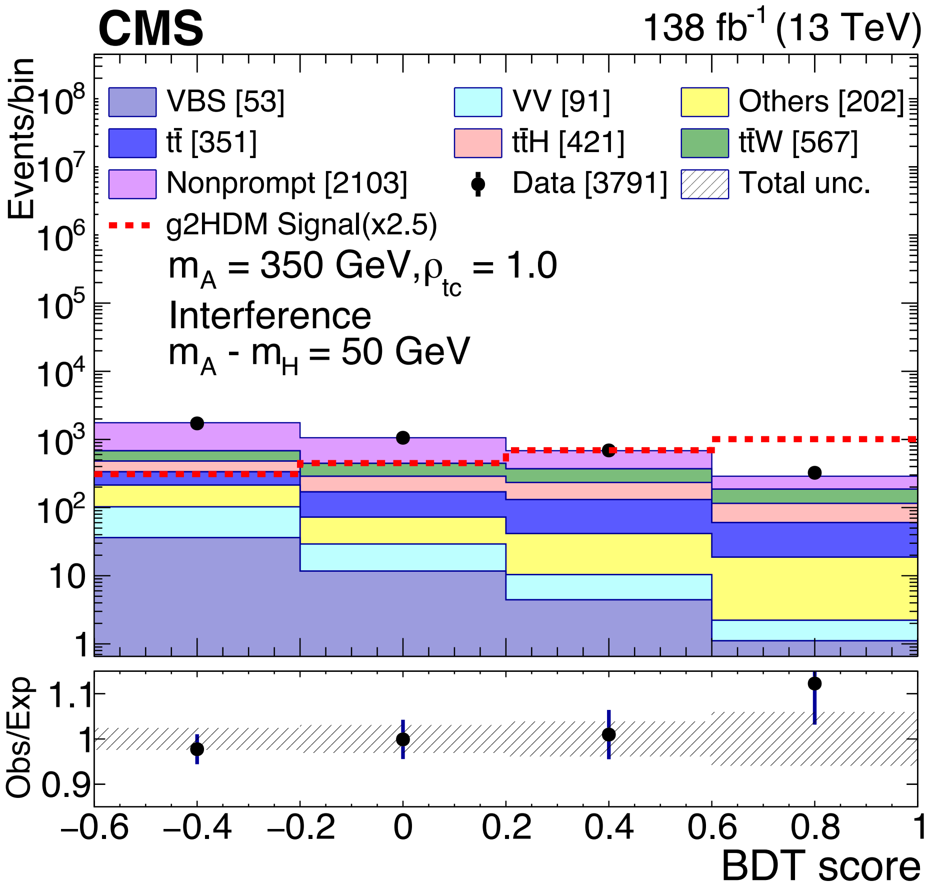




- DeepJet algorithm: Flavor identification using global variables, charged/neutral particle and secondary vertex kinematics in the jets. JINST 15 (2020) P12012

BDT Distributions for Signal Extraction





- 4 bins of BDT score in each decay mode simultaneously fit to extract limits for each signal mass-coupling hypothesis.

% Effect of Nuisances on Pre-fit Expected Event Yields

Uncertainty source	Shape	Category $e^{\pm}e^{\pm}$	Category $\mu^{\pm}\mu^{\pm}$	Category $e^{\pm}\mu^{\pm}$	Correlated across Years	Correlated across Categories
Experimental						
Luminosity	—	1.2–2.5	1.2–2.5	1.2–2.5	✓	✓
Pileup	✓	<0.1–2.8	<0.1–1.8	<0.1–2.3	✓	✓
Trigger efficiency	✓	0.4–2.6	0.2–1.1	0.3–1.2	—	—
L1 trigger inefficiency	✓	0.1–0.8	0.1–0.3	0.1–0.4	✓	✓
Lepton identification	✓	0.1–1.7	<0.1–0.4	<0.1–0.6	—	✓
Lepton energy scale	✓	—	<0.1–0.2	<0.1–0.2	—	✓
Charge misid.	✓	1.2–13.1	—	—	—	—
Jet energy scale	✓	<0.1–4.5	<0.1–1.7	<0.1–1.5	✓	✓
Jet energy resolution	✓	<0.1–2.6	<0.1–1.8	<0.1–1.6	—	✓
Unclustered energy	✓	<0.1–2.6	<0.1–0.5	<0.1–0.8	—	✓
Jet flavor identification	✓	<0.1–12.1	<0.1–8.8	<0.1–11.6	✓	✓
Nonprompt lepton BG statistical component	✓	<0.1–27.2	1.9–16.2	3.0–13.2	—	✓
Nonprompt lepton BG	—	27,15,11,10	27,15,11,10	27,15,11,10	—	✓
Theoretical						
Signal QCD scales	✓	10.3–10.5	10.0–10.2	9.9–10.0	✓	✓
Signal PDF	✓	0.7	0.6–0.7	0.5–0.6	✓	✓
Signal parton shower	✓	3.6–4.3	4.0–4.3	6.3–7.3	✓	✓
$t\bar{t}$	—	6.1	6.1	6.1	✓	✓
VV	—	4.5	4.5	4.5	✓	✓
VBS	—	10.4	10.4	10.4	✓	✓
$t\bar{t}H$	—	7.8	7.8	7.8	✓	✓
$t\bar{t}W$	—	10.7	10.7	10.7	✓	✓
Other backgrounds	—	5.4	5.4	5.4	✓	✓

$\rho_{tc} = 0.4$, $m_A = 350$ GeV, $m_A - m_H = 50$ GeV

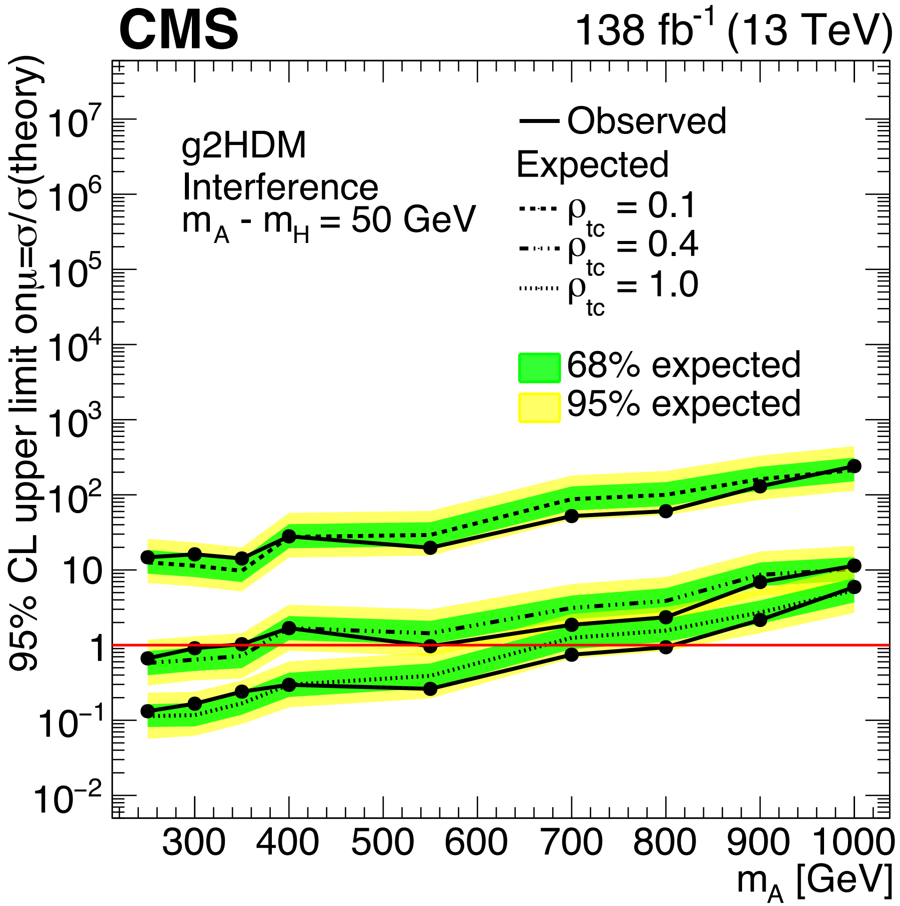
- Dominant systematic uncertainties
  - Flavor tagging
  - Nonprompt lepton background estimation
  - $t\bar{t}W$ cross section
  - Statistical

Results

- Results consistent with SM predictions

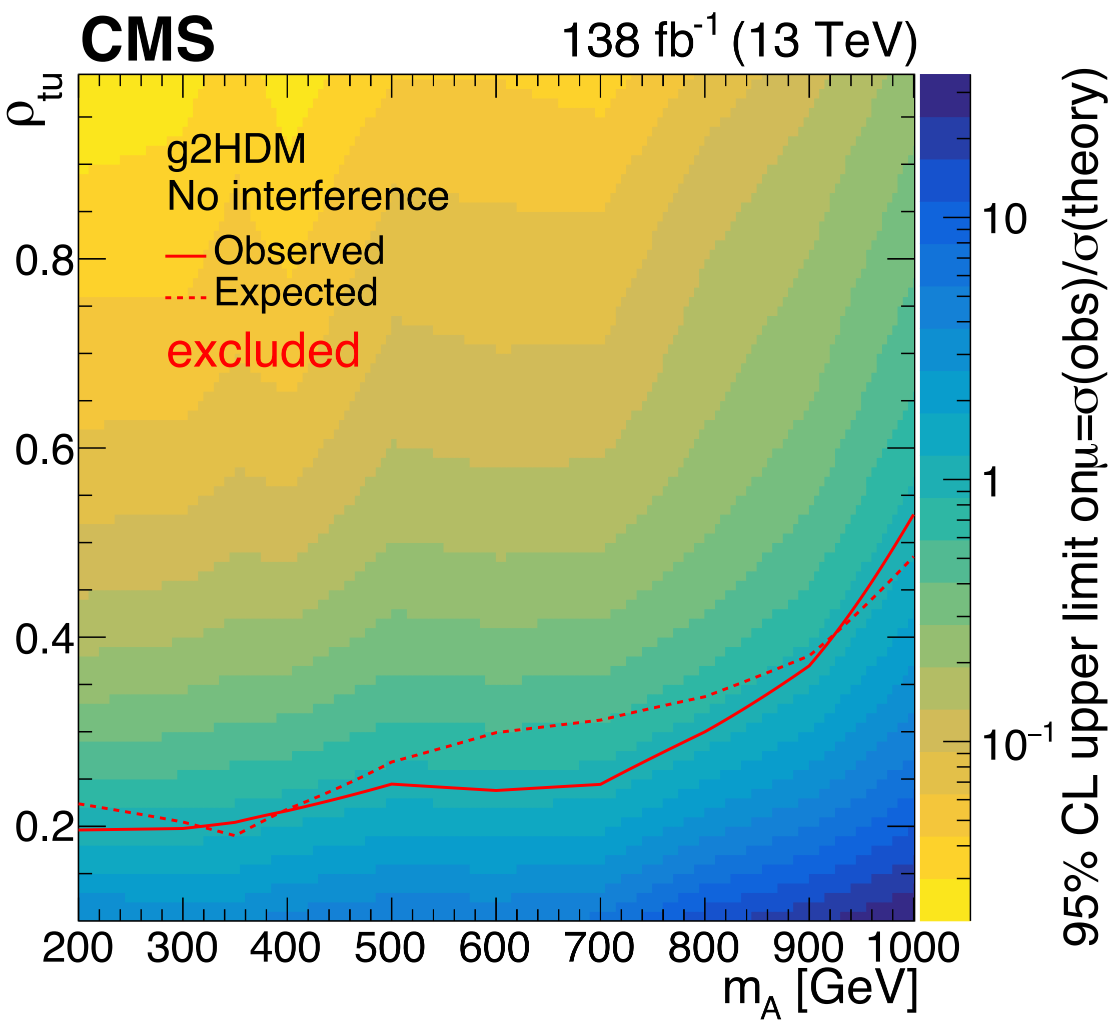
Observed (expected) mass limit [GeV]

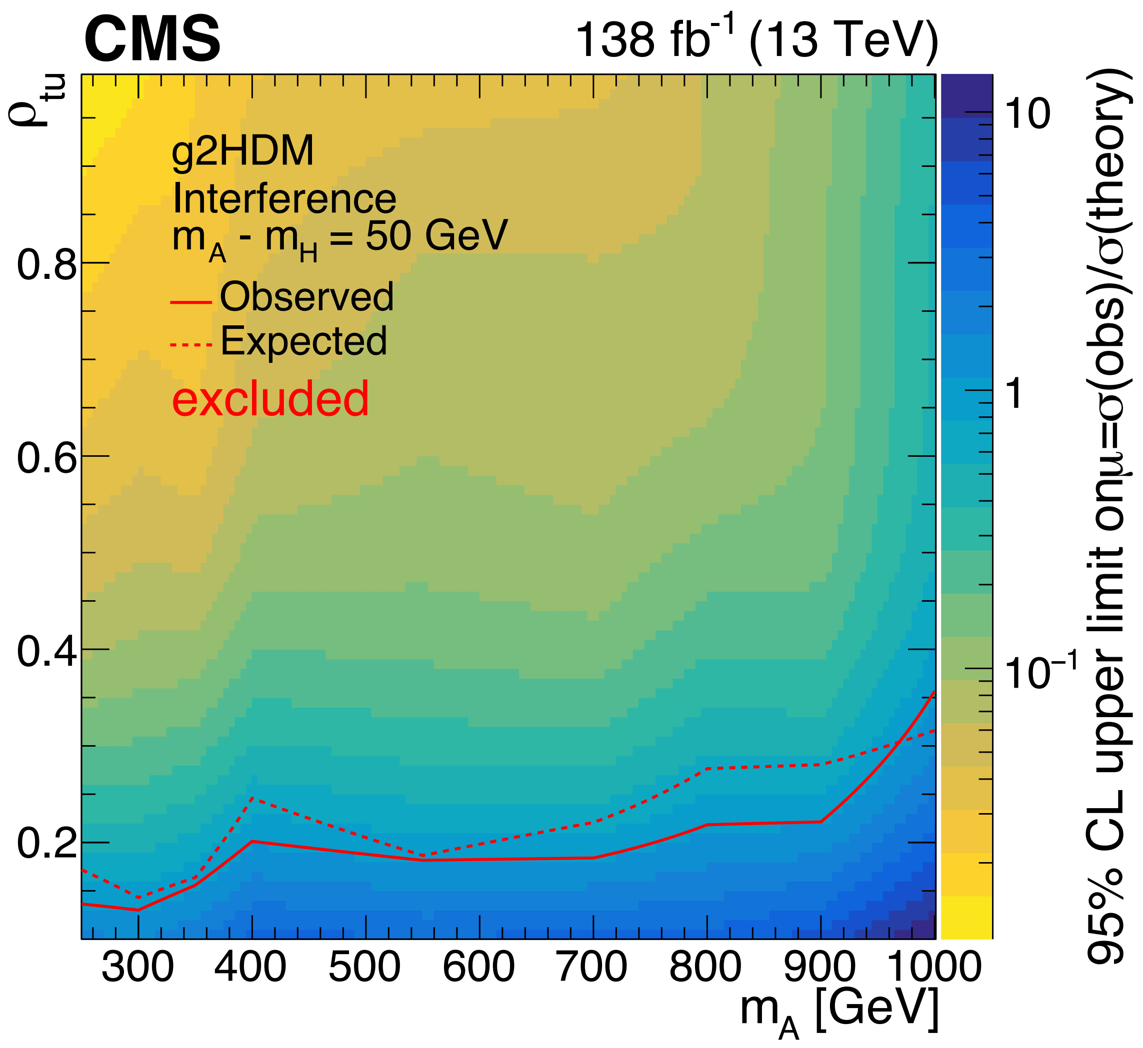
	without interference	with interference	with interference
	m_A or m_H	m_A	m_H
ρ_{tu}			
0.4	920 (920)	1000 (1000)	950 (950)
1.0	1000 (1000)	1000 (1000)	950 (950)
ρ_{tc}			
0.4	no limit	340 (370)	290 (320)
1.0	770 (680)	810 (670)	760 (620)



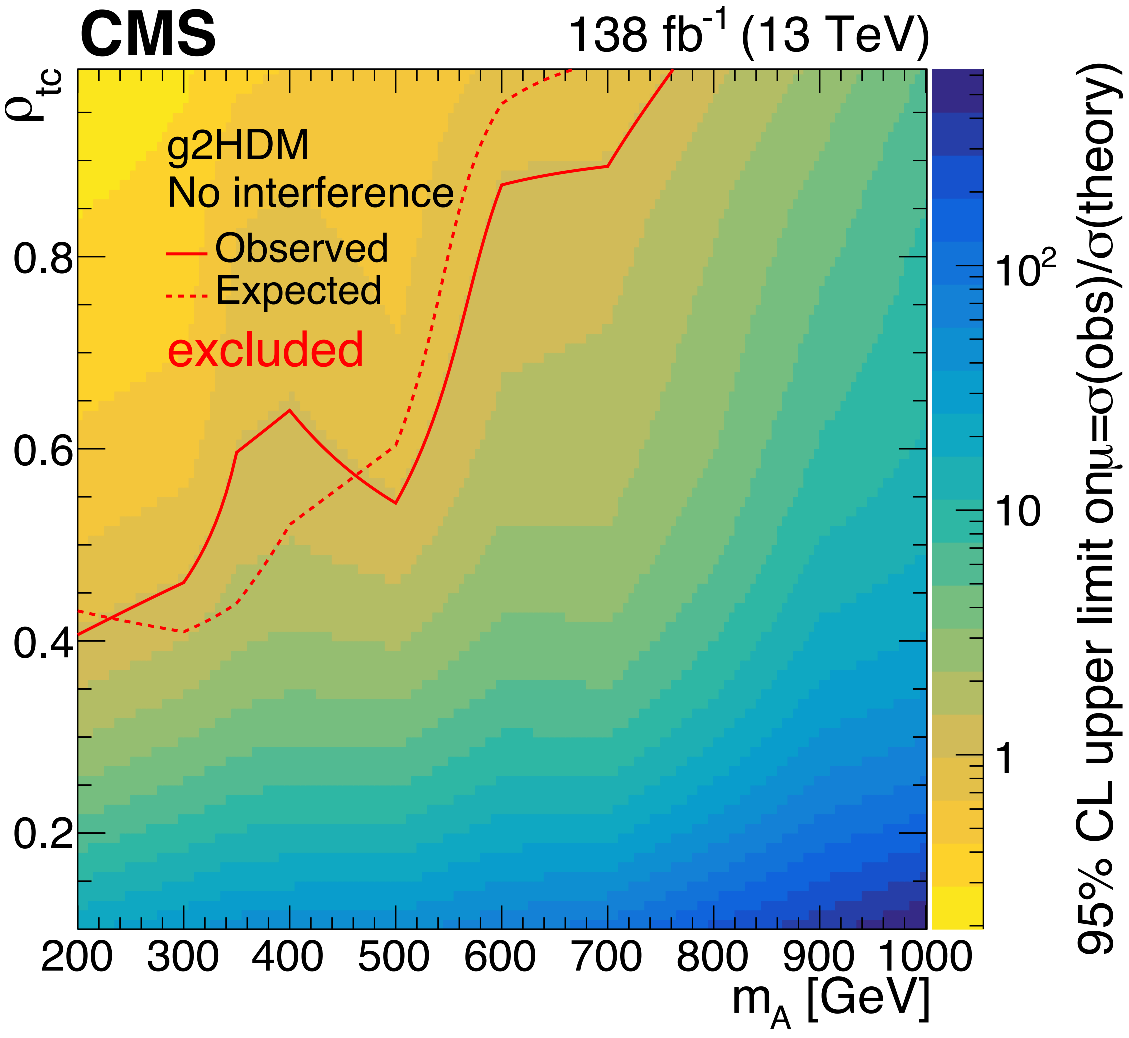
- Stricter limits for
  - ρ_{tu} higher signal cross section <— PDF effect.
  - interference higher signal cross section <— having A & H simultaneously.

Results


CMS
138 fb-1 (13 TeV)
ρtu
g2HDM
No interference
Observed
Expected
excluded
0.8
0.6
0.4
0.2
200
300
400
500
600
700
800
900
1000
mA [GeV]
10
1
10−1
95% CL upper limit on μ=σ(obs)/σ(theory)


CMS
138 fb-1 (13 TeV)
ρtu
g2HDM
Interference
mA - mH = 50 GeV
Observed
Expected
excluded
0.8
0.6
0.4
0.2
300
400
500
600
700
800
900
1000
mA [GeV]
10
1
10−1
95% CL upper limit on μ=σ(obs)/σ(theory)

Results


CMS
138 fb-1 (13 TeV)
ρtc
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No interference
Observed
Expected
excluded
0.2
0.4
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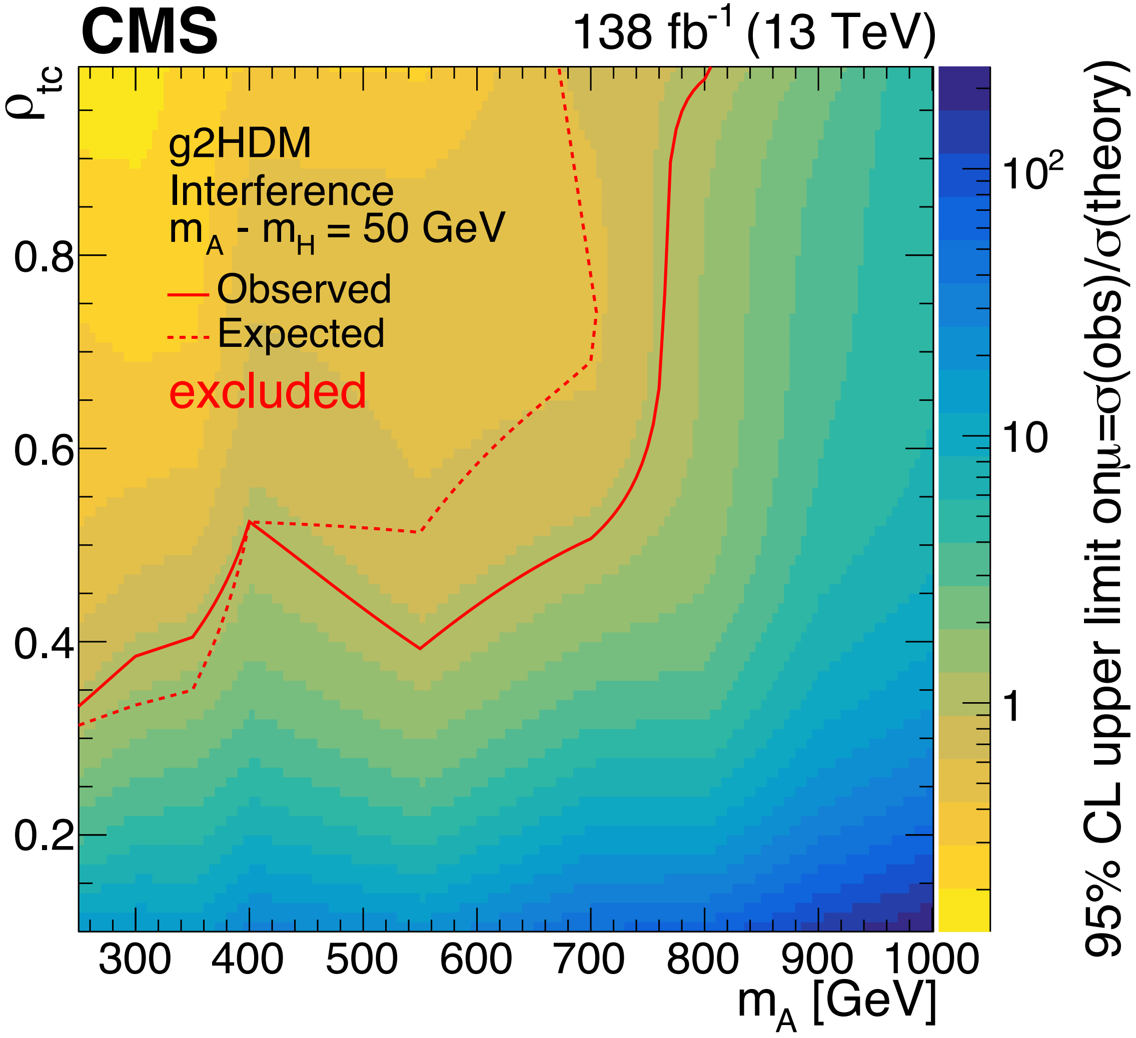
0.8
200 300 400 500 600 700 800 900 1000
mA [GeV]
1
10
10²
95% CL upper limit on μ=σ(obs)/σ(theory)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300 400 500 600 700 800 900 1000
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10²
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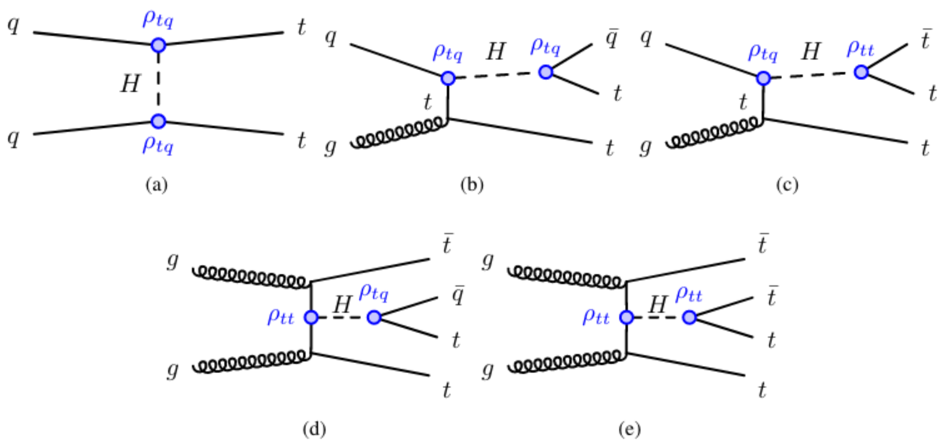
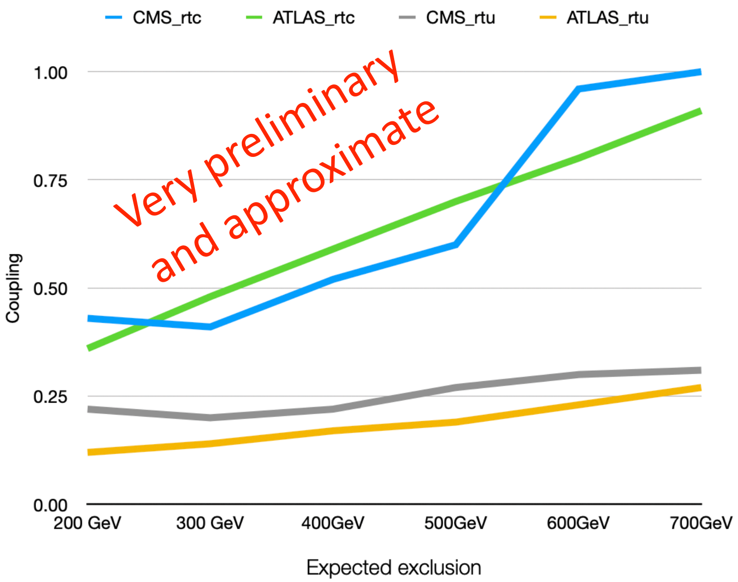
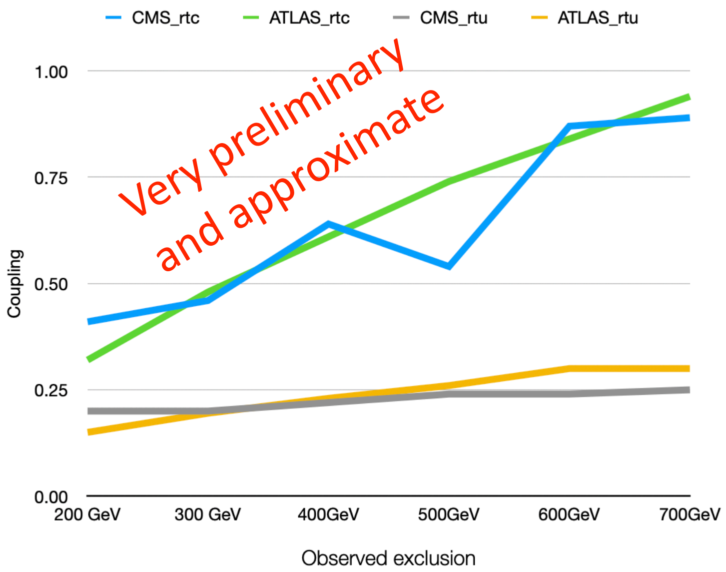
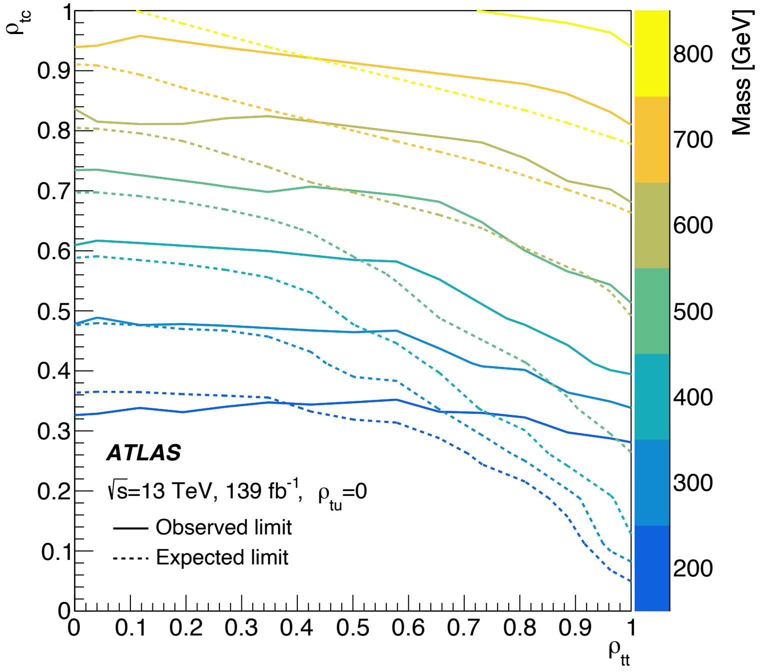
ATLAS Analysis arXiv:2307.14759







- Considered ρ_{tu}/ρ_{tc}-induced same-sign top quark and ρ_{tt}-induced triple-top quark in the same umbrella w/ a general multi-lepton signature.
- No A-H interference or charm tagging
- Final limits not too different.
- ρ_{tt} not easy.
  - No limit on ρ_{tt} when ρ_{tc} (or ρ_{tu})=0
  - But e.g. ρ_{tt}=0.4, $\rho_{tc} = \rho_{tu} = 0.2, m_H = 200 - 620$ GeV excluded



Summary

- A search for $pp \to tH/A \to tt\bar{c}$ and $pp \to tH/A \to tt\bar{u}$ presented
- No significant excess above the background observed.
- ρ_{tu} largely excluded, but still a large portion of the phase space not constrained for ρ_{tc}.
- When no A-H interference
  - m_A < 920 GeV ($\rho_{tu} = 0.4$) and 1000 GeV ($\rho_{tu} = 1.0$) excluded.
  - m_A < 770 GeV ($\rho_{tc} = 1.0$) excluded.
- When A and H interfere with $m_A - m_H = 50$ GeV
  - m_A < 1000 GeV ($\rho_{tu} > 0.4$).
  - m_A < 340 GeV ($\rho_{tc} = 0.4$) and m_A < 810 GeV ($\rho_{tc} = 1.0$).

Additional Slides

Background Categories

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

Previous CMS Results

- Many searches performed for extra Higgs bosons but FCNC in extended Higgs sector still remains to be studied in detail.

$H/A \rightarrow tt$: EPJ C 77 (2017) 578

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

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

$H/A \rightarrow \mu\mu$: PLB 798 (2019) 134992

$A \rightarrow Zh \rightarrow (ll, \nu\nu)bb$: EPJC 79 (2019) 564

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

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

$X \rightarrow YH \rightarrow b\bar{b}b\bar{b}$: PLB 842 (2023) 137392

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

$H \rightarrow AA \rightarrow 4\gamma$: PRL 131 (2023) 101801

$H \rightarrow e\mu$: PRD 108 (2023) 072004

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

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

$H^{\pm} \rightarrow \tau_h\nu$: JHEP 07 (2019) 142

$H^{\pm} \rightarrow Wa$: PRL 123 (2019) 131802

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

$H^{\pm} \rightarrow cs, cb$: PRD 102 (2020) 072001

$H^{\pm} \rightarrow H(\tau\tau)W$: JHEP 09 (2023) 032

$H \rightarrow Za\gamma\gamma\ell\ell$: Submitted to PLB

$X \rightarrow HH/Y \rightarrow \gamma\gamma b\bar{b}$: Submitted to JHEP