Search for new Higgs bosons via same-sign top quark pair production in association with a jet at CMS

在CMS上通过同号顶夸克+喷注寻找新的希格斯玻色子

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Phys. Lett. B 850 (2024) 138478

arXiv: 2311.03261

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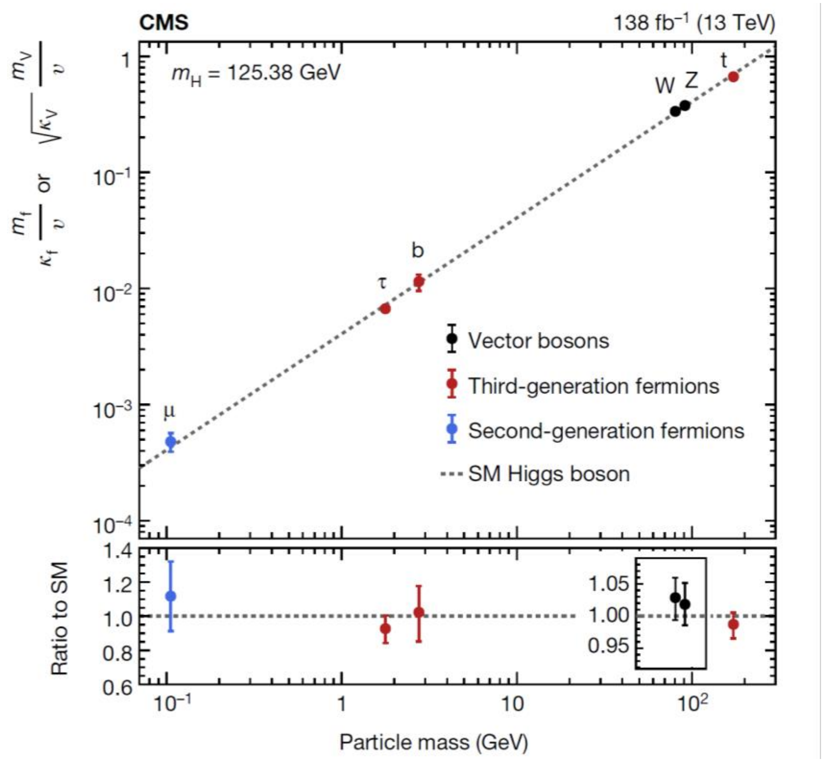
Introduction

- A Higgs boson with mass at 125 GeV/c^2 has been discovered in 2012
- Yukawa couplings of the Higgs boson to t & b, and τ & μ are consistent with SM
- Is the 125 GeV Higgs boson the only one?
- Two-Higgs-doublet model (2HDM)
  - CP-even neutral scalar bosons h and H with $m_H > m_h$
  - One CP-odd pseudoscalar boson A
  - Two charged Higgs bosons $H^{\pm}$ scalar boson

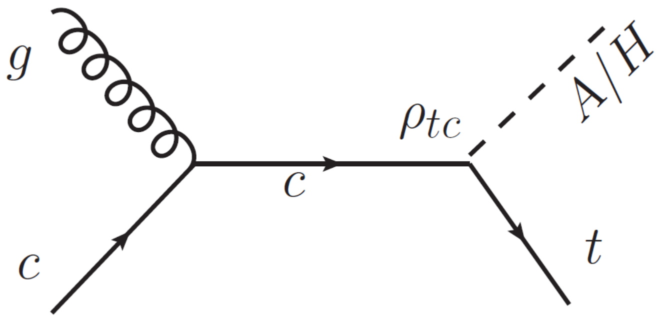
Nature **607** (2022) 52
Nature **607** (2022) 60

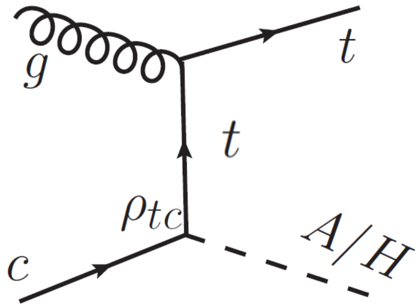


G.C. Branco, Phys. Rep. 516 1 (2012) 1
arXiv:1106.0034

2HDM

- These additional Higgs bosons at mass scales $\lesssim$1 TeV may still exist with additional Yukawa couplings hidden by fermion mass-mixing hierarchy
- Because of alignment they may have a negligible impact on the 125 GeV SM-like Higgs boson
- Alignment suppresses Flavor Changing Neutral Higgs (FCNH) interaction of h boson $t \to ch/uh, t \to \mu\tau/e\tau$, but allows them for the H and A bosons





W.S. Hou,
arXiv:2012.05735
arXiv:1706 .07694
Phys. Lett. B 296 (1992) 179

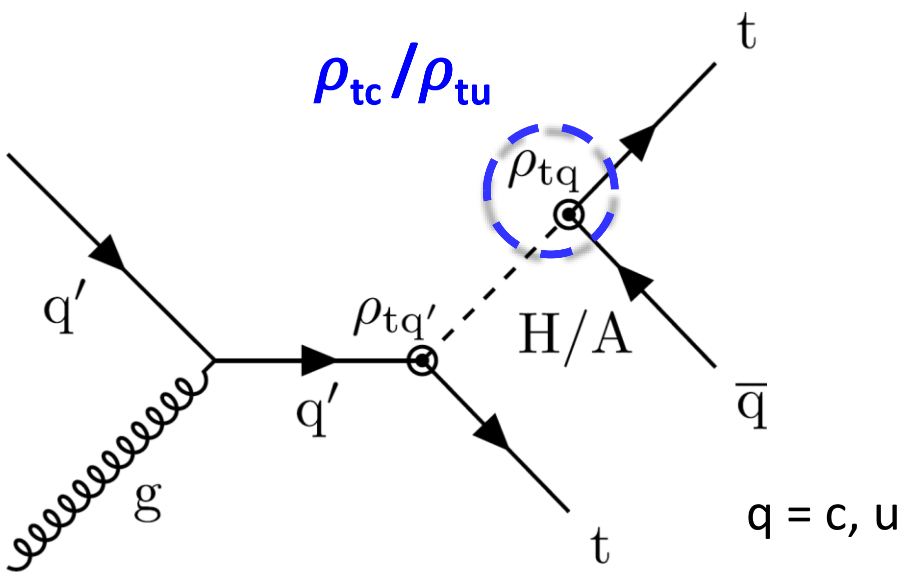
New Yukawa couplings

- The scenario can be studied in the generalized 2HDM (g2HDM)
- With new Yukawa couplings such as $\rho_{\tau\mu}$, ρ_{tu}, ρ_{tc}, ρ_{tt} that may assume significantly large values
  - May also explain the electroweak baryogenesis, and therefore the disappearance of antimatter soon after the Big Bang
  - The new top Yukawa coupling ρ_{tc} with a similar strength to $\rho_{\tau\mu}$ may be compatible with the observed data depending on the $H^{\pm}$ mass, which may also explain a possible muon g−2 anomaly

T.D. Lee, Phys. Rev. D 8 (1973) 1226
G.C. Branco, arXiv:1106.0034
K. Fuyuto, arXiv:1705.05034
K. Fuyuto, arXiv:1910.12404
ATLAS, arXiv:2307.14759
D.P. Aguillard, arXiv:2308.06230

Search for extra Yukawa couplings

- Such Higgs bosons (H or A) are within the reach of the LHC and may be searched for in different channels
- Here we focus on search for the existence of these couplings, ρ_{tu} and ρ_{tc}, through $pp \rightarrow tH/A \rightarrow tt\bar{q}\ (q = u, c)$
  - ρ_{tc} (let ρ_{tu}=0)
  - ρ_{tu} (let ρ_{tc}=0)



- For each coupling, consider with and w/o interference between A and H

Data analysis

Letter

Search for new Higgs bosons via same-sign top quark pair production in association with a jet in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration *

- PP collision at $\sqrt{s}$=13 TeV
- Run 2 data collected by CMS (2016- 2018, 138 fb^{-1})
- Signal and backgrounds simulated with MadGraph5_aMC@NLO 2.6.5
- Parton showering, fragmentation, and hadronization with PYTHIA v8.240
- Mass in 200 ~ 1000 GeV assumed for A (H), and a mass too high to be of reach is assumed for H (A)
- Similar work has also been studied in ATLAS

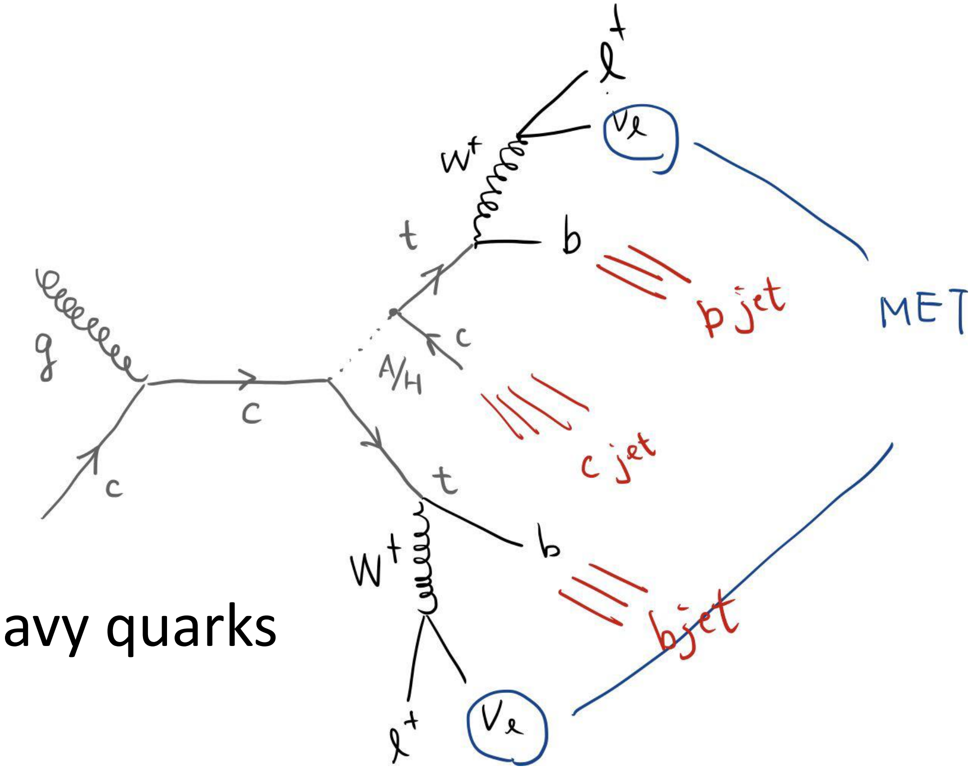
Search for heavy Higgs bosons with flavour-violating couplings in multi-lepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector

ATLAS Collaboration

ATLAS, JHEP 12 (2023) 081
arXiv:2307.14759

Analysis strategy

- The final-state signature for the signal $tt\bar{q}$
  - Two same-sign (SS) leptons with at least three jets
  - Two jest identified as b jets and one compatible with originating from u or c
  - Missing transverse momentum (MET) by ν_l
- Main background
  - Electrons from photon conversions
  - Jets misidentified as leptons
  - Hadrons misidentified as leptons
  - Non-prompt leptons from leptonic decays of heavy quarks



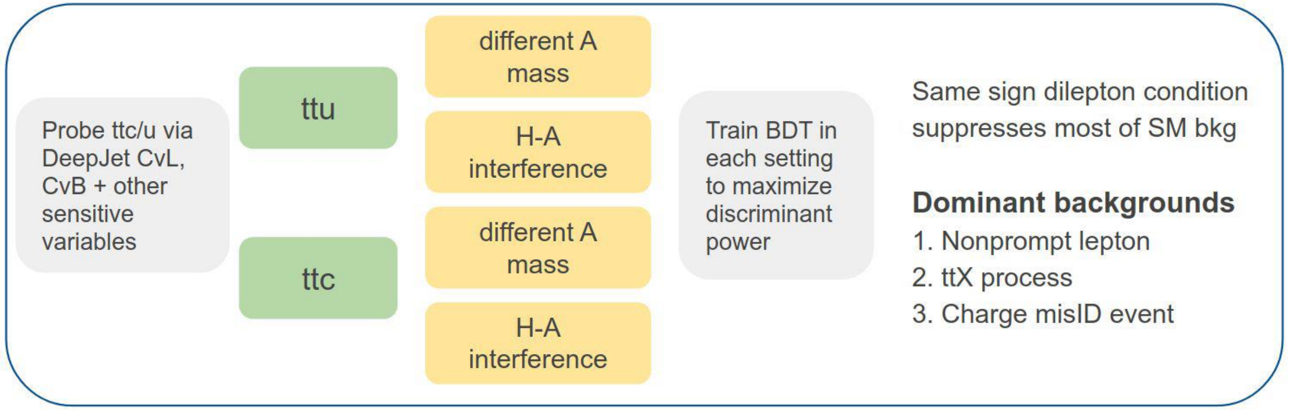
Event selection

- Signal region definition
  - Only two “Tight” leptons with SS, veto events if a third “Loose” lepton
  - Leading lepton pT > 30 GeV
  - Sub-leading lepton pT > 20 GeV
  - $\Delta R(l_1, l_2) > 0.3$
  - $m(l_1, l_2) > 20$ GeV
  - Veto events with $m(l_+, l_-) \in (60,120)$ GeV in ee channel
  - MET > 30 GeV
  - At least three tight jet (no tagger here)

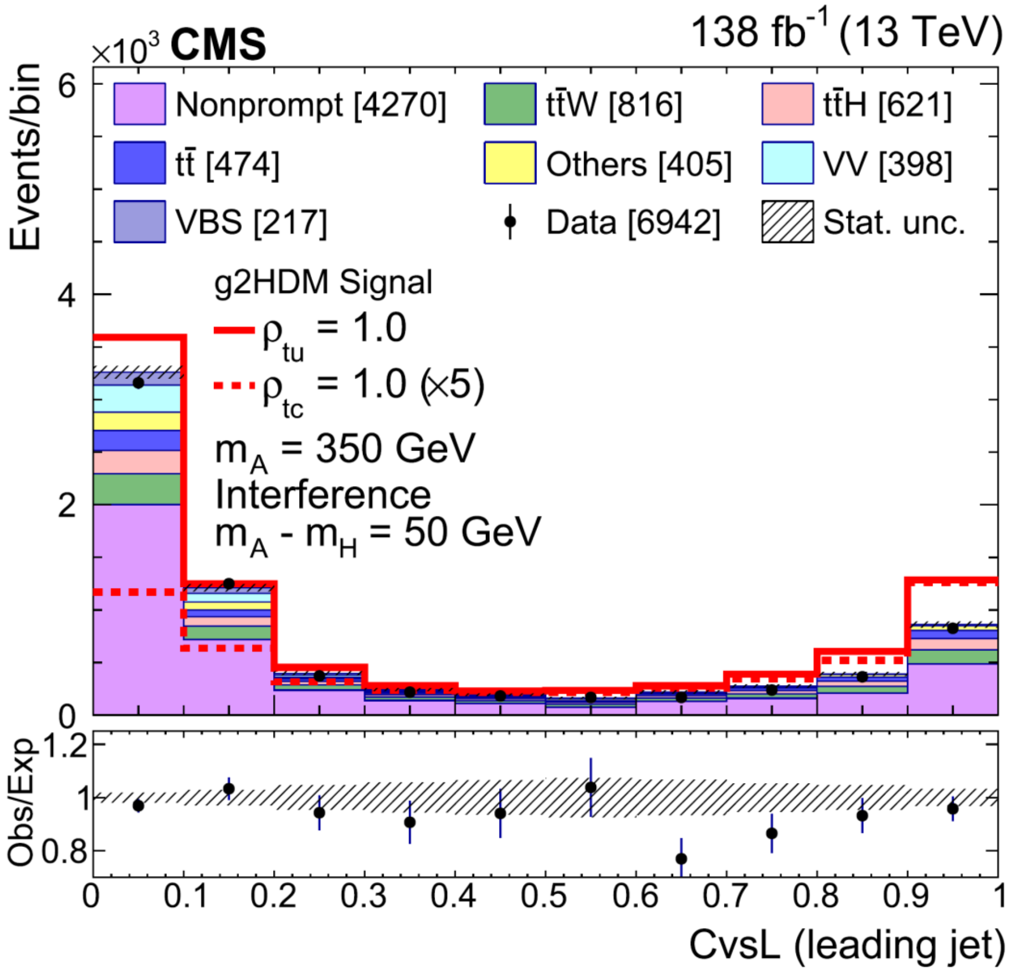
Table 1
Input variables of the BDT. Jets and leptons are ordered by p_T.

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

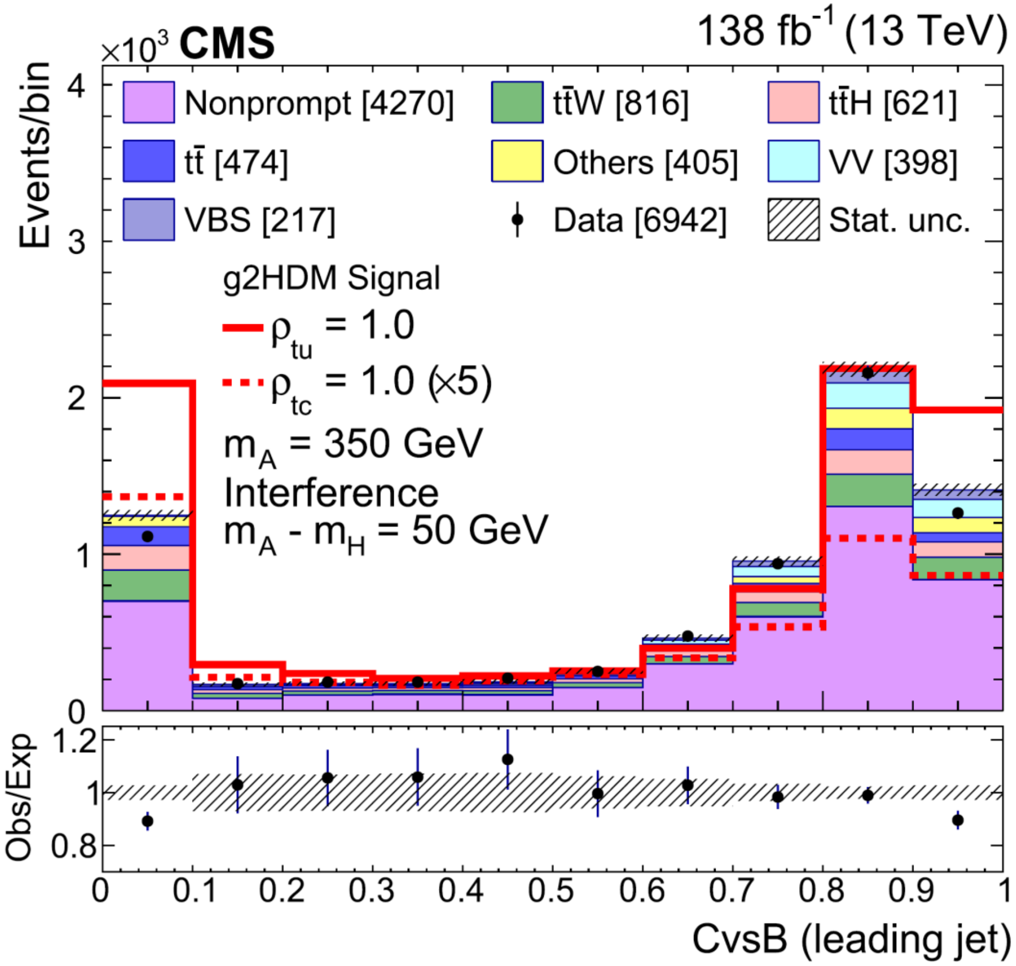
Signal Extraction with BDT



Distinguish Jets



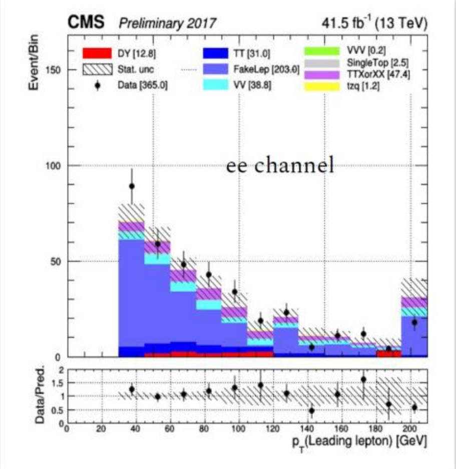
Charm vs Light quark

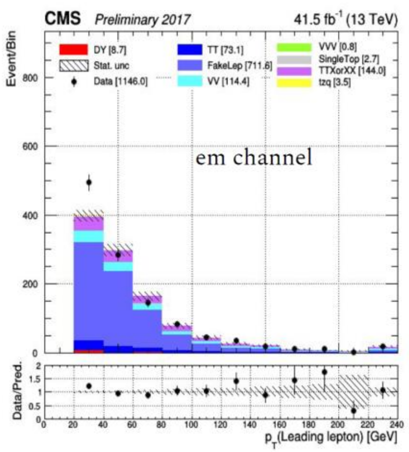


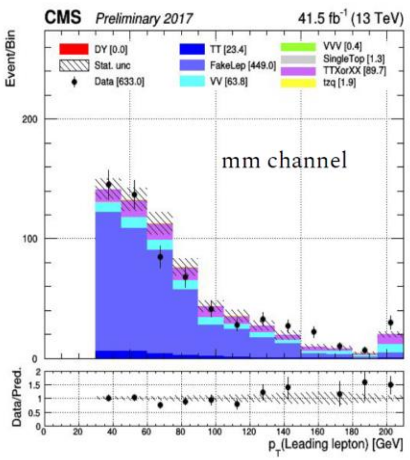
Charm vs Bottom quark

Background estimation and systematic uncertainties

- Search performed in three SS dilepton categories: $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$
- Fake rates applied on the fakeable events constructed from data

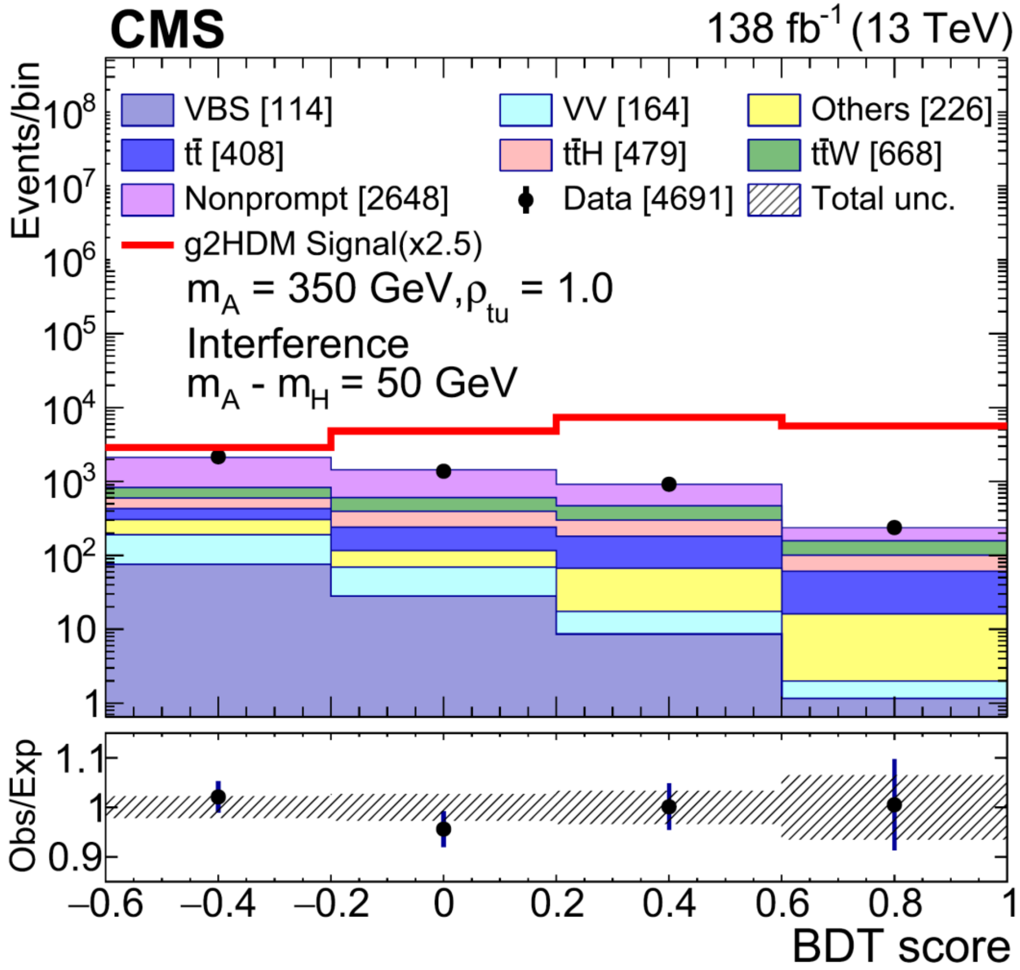




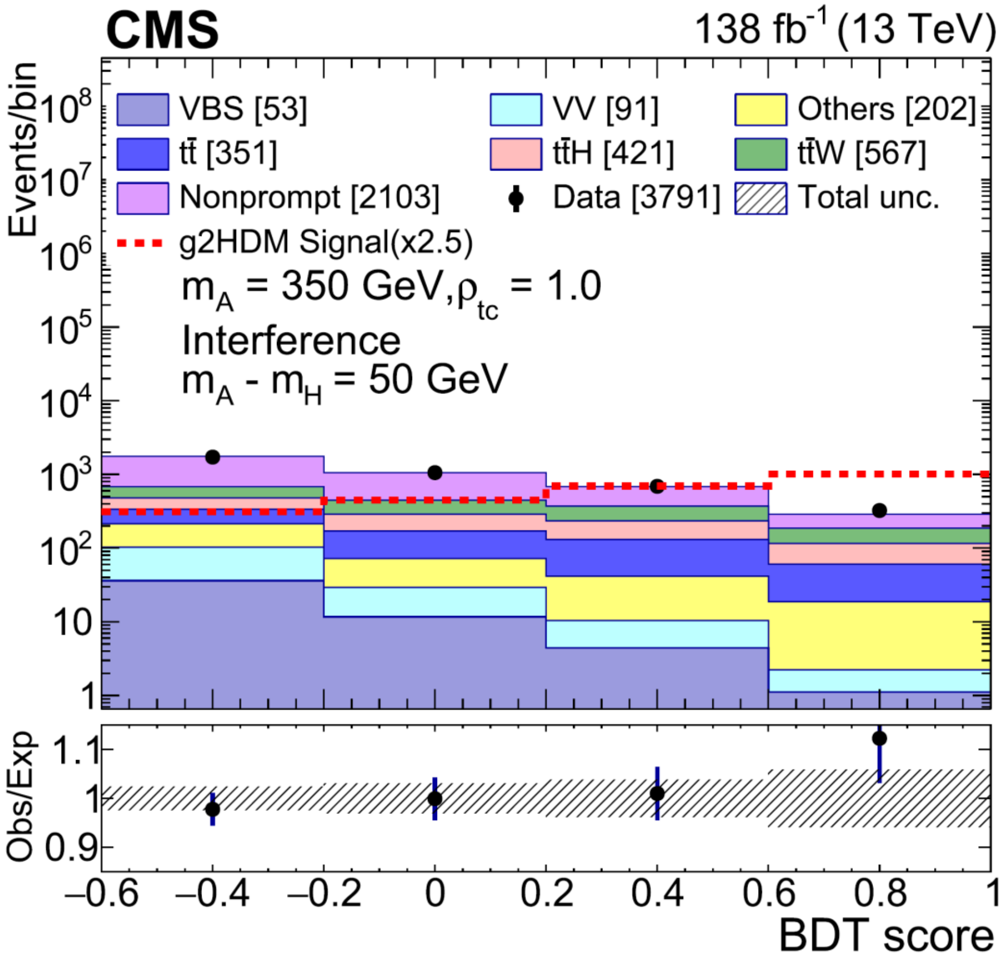


Uncertainty source	Shape	Category			Correlated across	
		$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	Years	Categories
Experimental						
Luminosity	—	1.2–2.5	1.2–2.5	1.2–2.5	✓	✓
Pileup	✓	<0.1–2.8	<0.1–1.8	<0.1–2.3	✓	✓
Trigger efficiency	✓	0.4–2.6	0.2–1.1	0.3–1.2	—	—
L1 trigger inefficiency	✓	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	✓	✓

Post-fit BDT for signal extraction

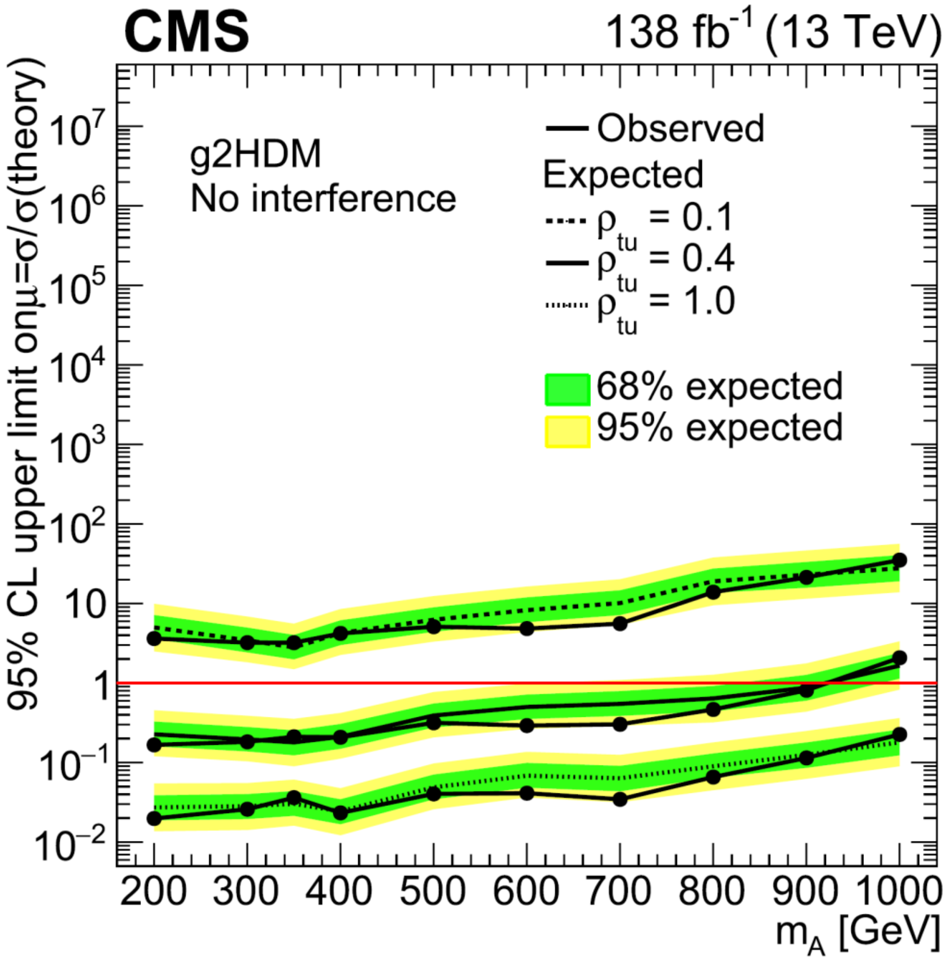


Assuming signal ρ_{tu}=1.0

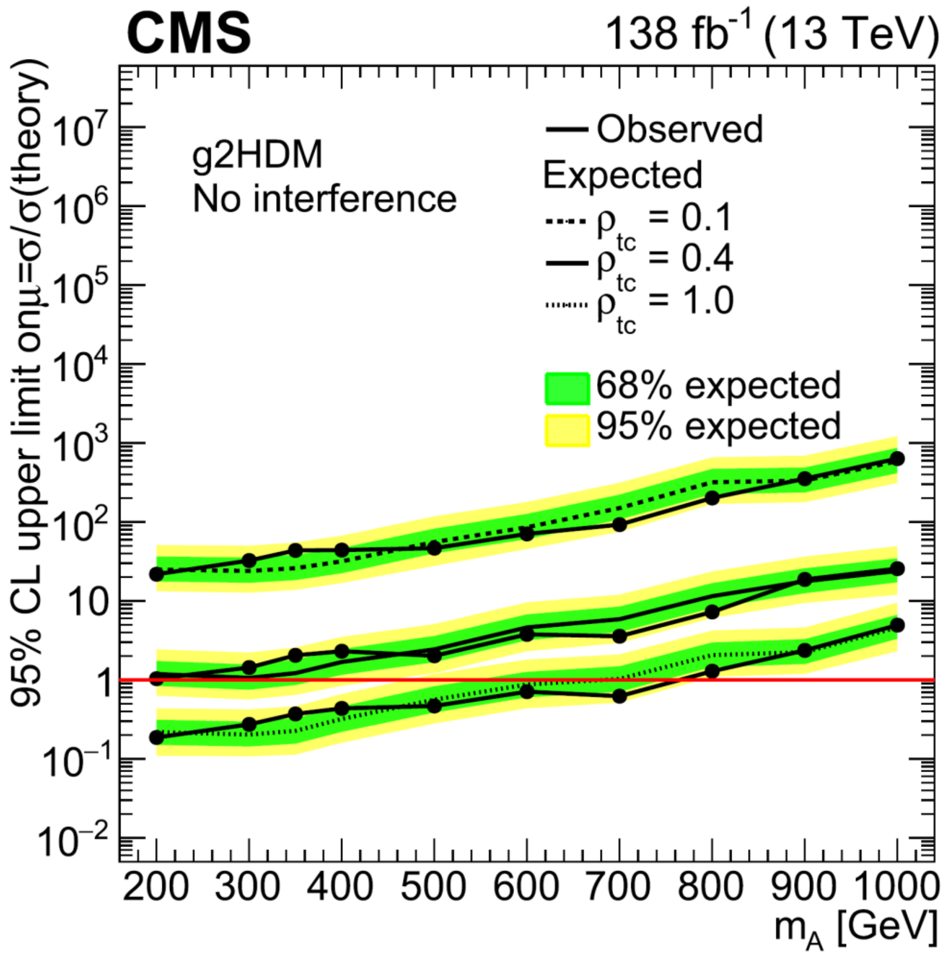


Assuming signal ρ_{tc}=1.0

Upper limits on signal strength

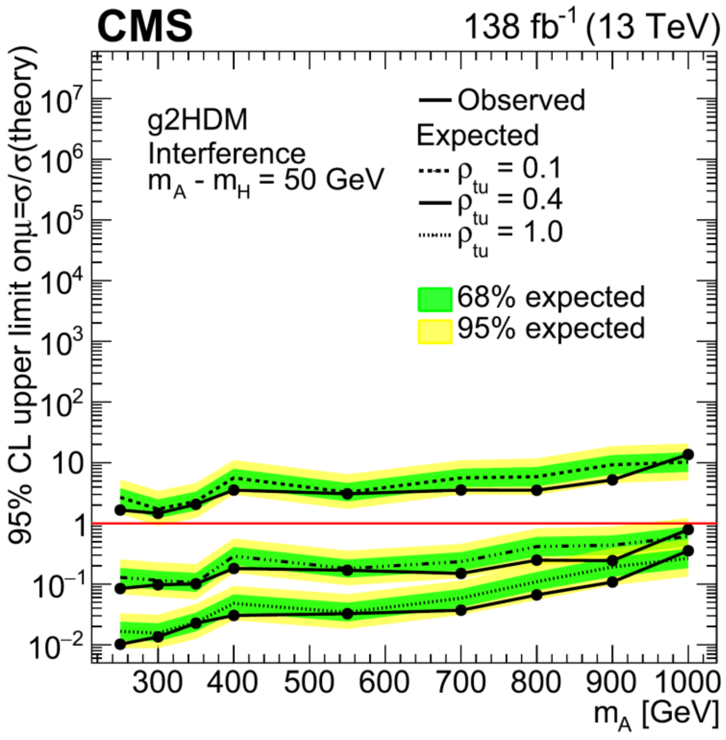


Signal strength with different ρ_{tu}

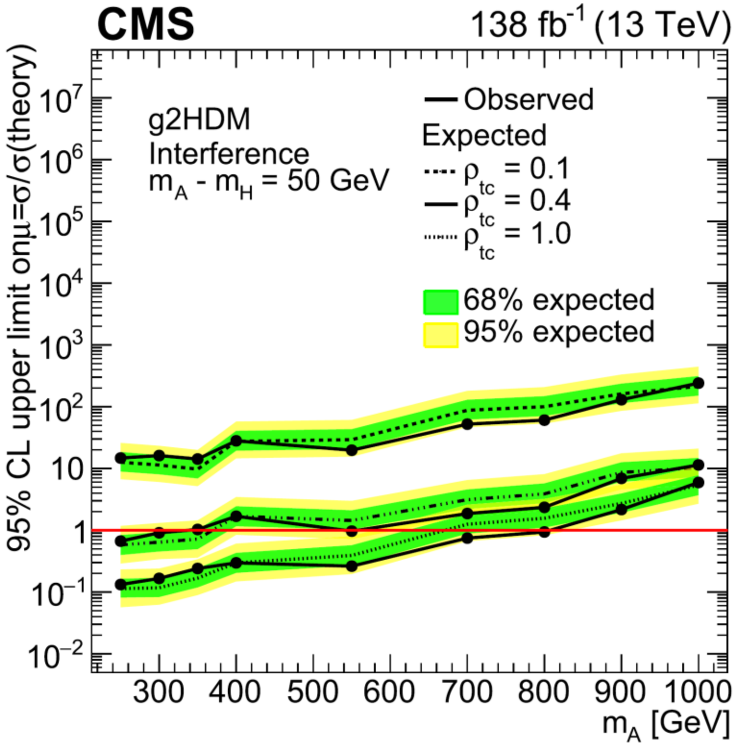


Signal strength with different ρ_{tc}

Upper limits on signal strength (interference)



Signal strength with different ρ_{tu}



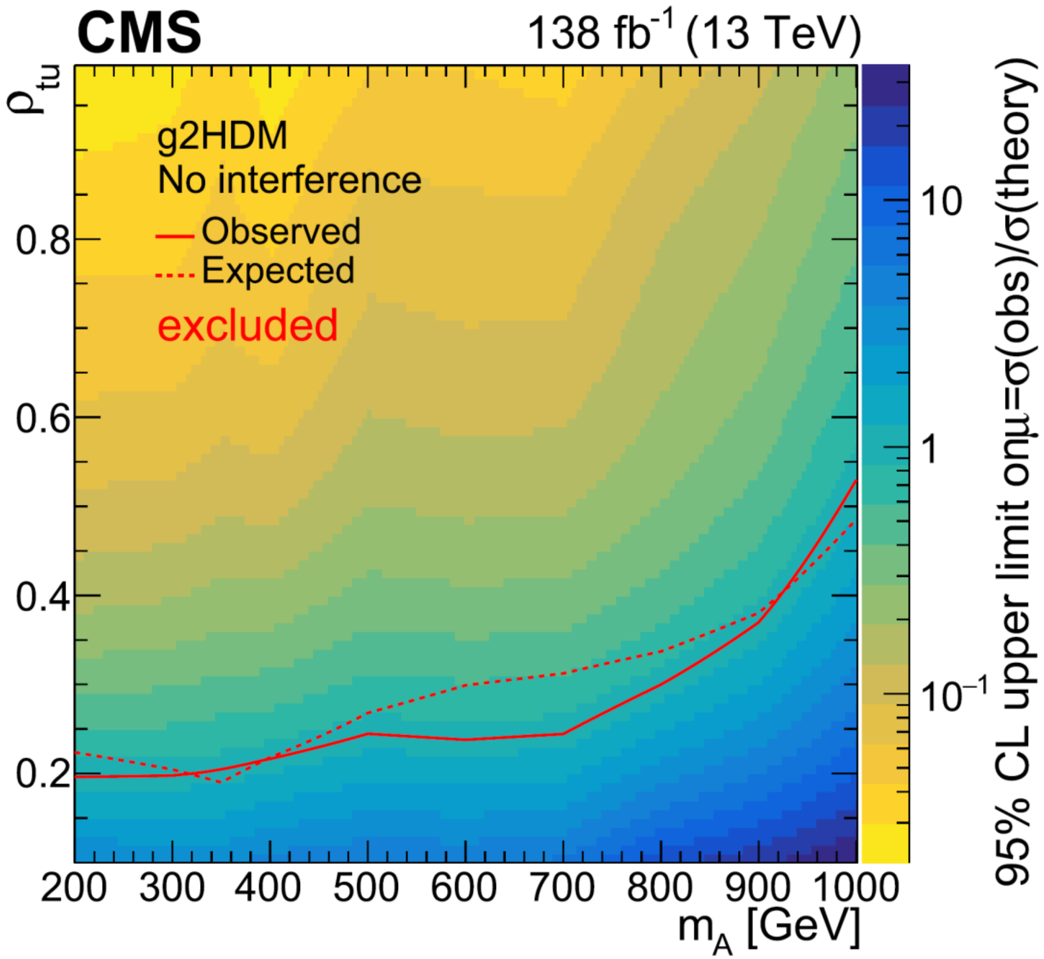
Signal strength with different ρ_{tc}

Table 3

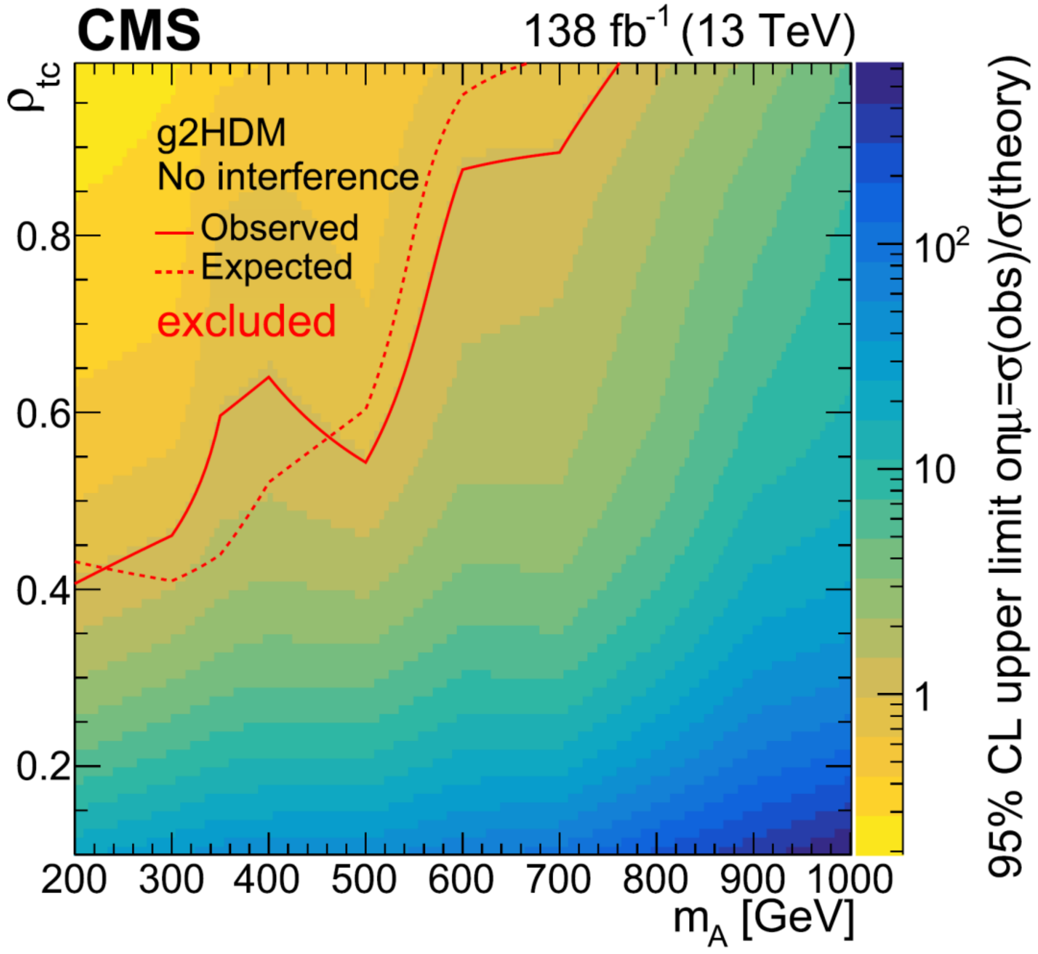
Observed (expected) lower limits on m_A at 95% CL. For the scenario without interference, the limits on m_H and m_A are the same.

	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)

Coupling strength vs m_A exclusion upper limit



ρ_{tu} excluded at different m_A



ρ_{tc} excluded at different m_A

Summary

- A search for extra Higgs bosons in $tt\bar{q}\ (q = u, c)$ final states is performed with CMS Run2 data
- No significant excess above the background prediction is observed
- Exclude almost all the phase space for $\rho_{tu} \geq 0.4$ and a significant portion for $\rho_{tc}{\sim}1.0$ (with the interference case having stronger limits)
- The results represent the first search based on g2HDM considering ρ_{tu} and ρ_{tc} extra Yukawa couplings independently, and also first to consider m_A–m_H interference at the LHC.

Thank you!