The 9th China LHC Physics Workshop (CLHCP2023)

Search for extra Higgs bosons through same-sign top-quark production in association with an extra jet

2311.03261

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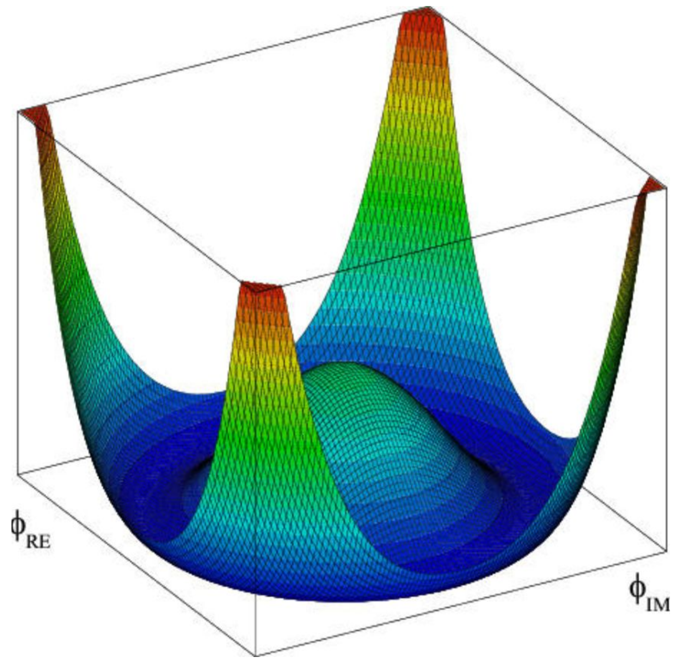
Introduction: 2HDM

- A simple doublet with nonzero vev is introduced to construct the SSB and let the gauge bosons to be massive, and we are lucky that we found the scalar – Higgs boson in 2012.

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

- SM is complete after Higgs boson discovery, but not the physics – we need more than the SM
  - Neutrino mass
  - μ g-2
  - Dark matter/energy
  - ...



- A straightforward expansion of SM is adding one more Higgs doublet

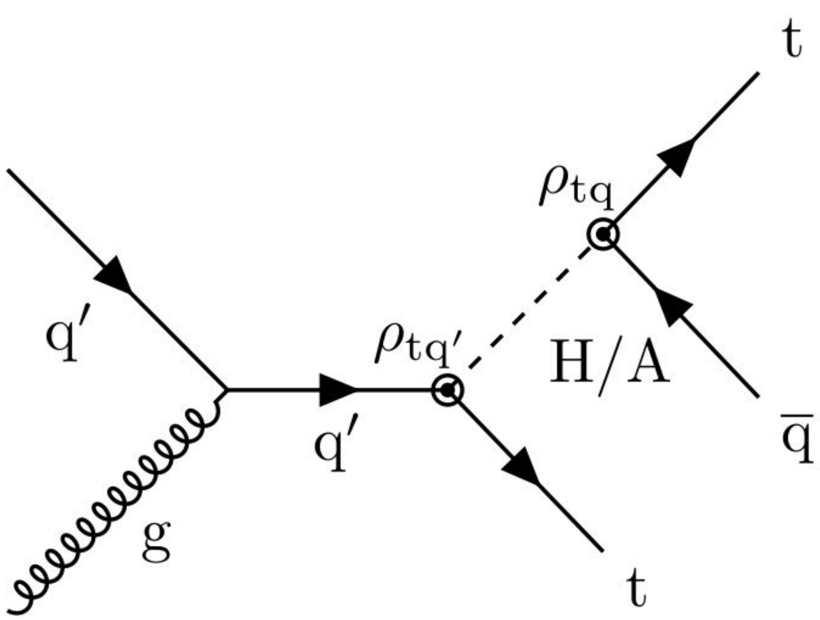
$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}.$$

$$\begin{aligned} \mathcal{V}_{2\Phi} &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right] \\ &+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\ &+ \left(\frac{1}{2}\lambda_5 \left(\Phi_1 \Phi_2 \right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \right] \left(\Phi_1^\dagger \Phi_2 \right) + \text{H.c.} \right). \end{aligned}$$

Massive W/Z bosons, and 5 physical Higgs bosons: two charged Higgs, two CP-even and one CP-odd Higgs

Introduction: 2HDM type-III

- Typical Feynman diagram we are investigating is on the right
- It's clear there is tree-level FCNC in the diagram, but we know tree-level FCNC is well constrained nowadays.
- Type-I/II 2HDM don't allow tree-level FCNC by introducing a Z2 symmetry between two doublets. However References (PLB 798 (2019) 134953, PLB 786 (2018) 212) claim that such tree-level FCNC can exist without Z2 symmetry due to the RunI Higgs alignment.



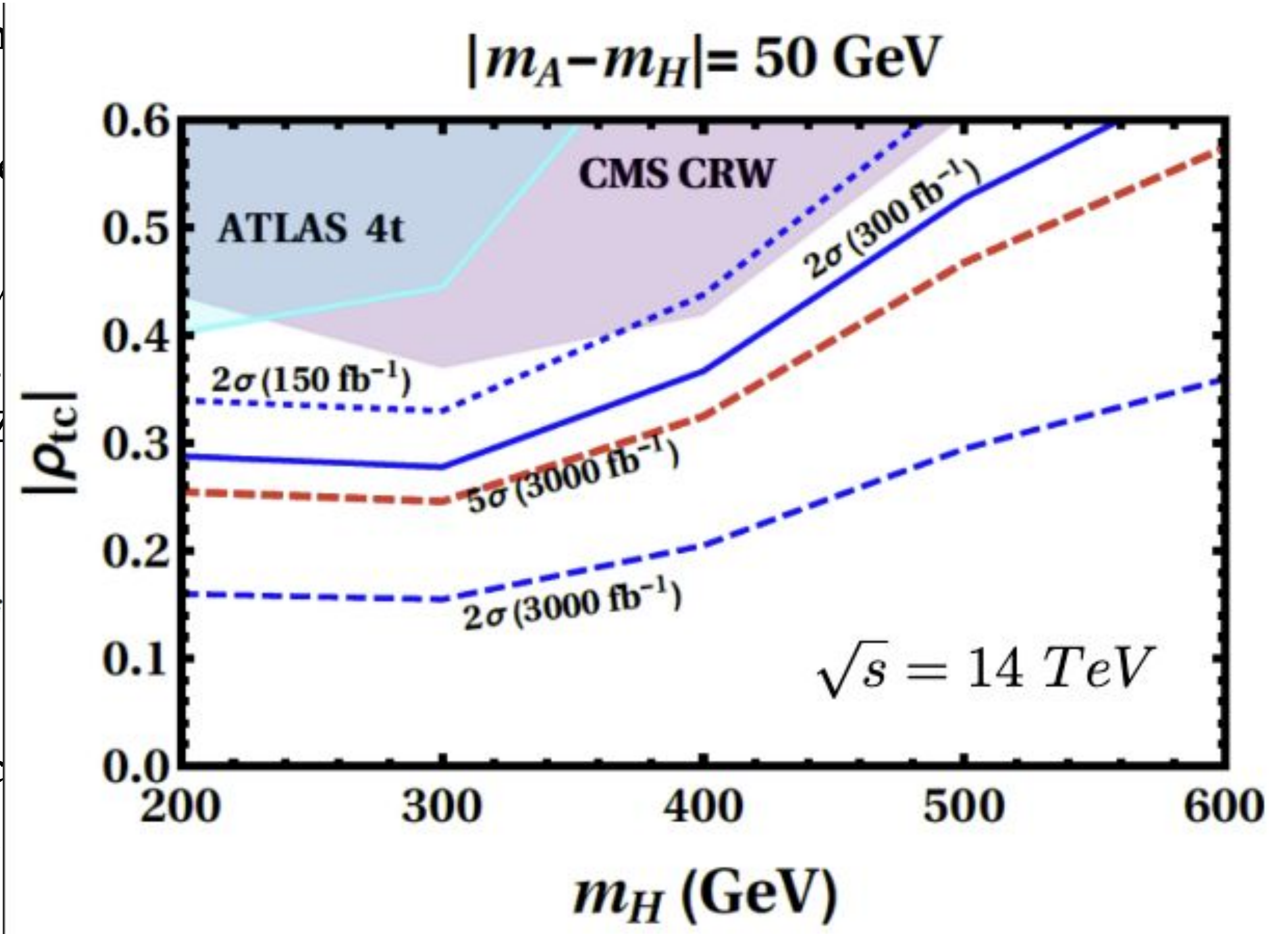
t→ ch(125) is searched right after the higgs(125) discovery, limits @95% CL from ATLAS,

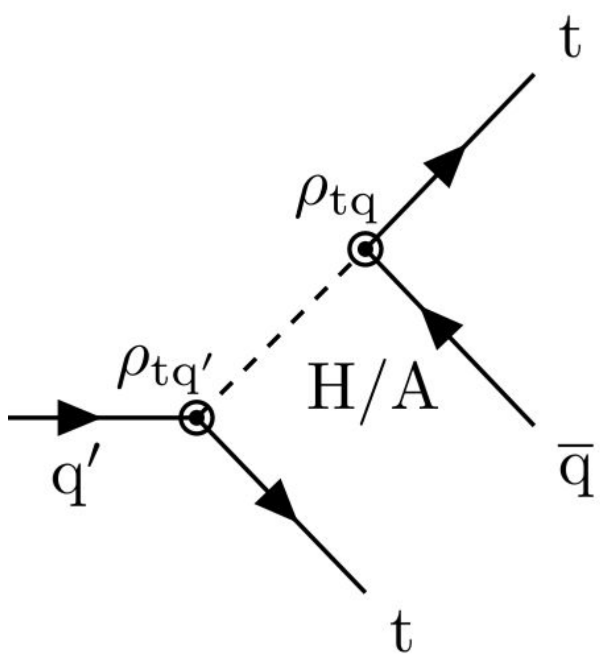
$$\mathcal{B}(t \to ch) < 1.1 \times 10^{-3}, \qquad (\text{ATLAS } 36\ \text{fb}^{-1},\ 2019)$$

$$-\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[\big(-\lambda_i^f \delta_{ij} s_\gamma + \rho_{ij}^f c_\gamma \big) h + \big(\lambda_i^f \delta_{ij} c_\gamma + \rho_{ij}^f s_\gamma \big) H - i\, \mathrm{sgn}(Q_f) \rho_{ij}^f A \Big] R\, f_j$$
$$-\bar{u}_i \left[(V \rho^d)_{ij} R - (\rho^{u\dagger} V)_{ij} L \right] d_j H^+ - \bar{\nu}_i \rho_{ij}^\ell R\, \ell_j H^+ + h.c., \qquad (5)$$

- From formula above, it's possible that t->ch is difficult to search is not due to the small coupling rho_ij but the small alignment cγ
- For A/H, the coupling is not hidden behind the cγ, so we move to the A/H search

- Typical Feynm
- It's clear there
  well constrain
- Type-I/II 2HD
  symmetry betv
  (2019) 134953, PL
  exist without Z





$$-\frac{1}{\sqrt{2}} \quad \ldots \quad {}^{f}_{ij} A \Big] R\, f_j \qquad (5)$$

t→ ch(125) is searc ... 95%
CL is from ATLA

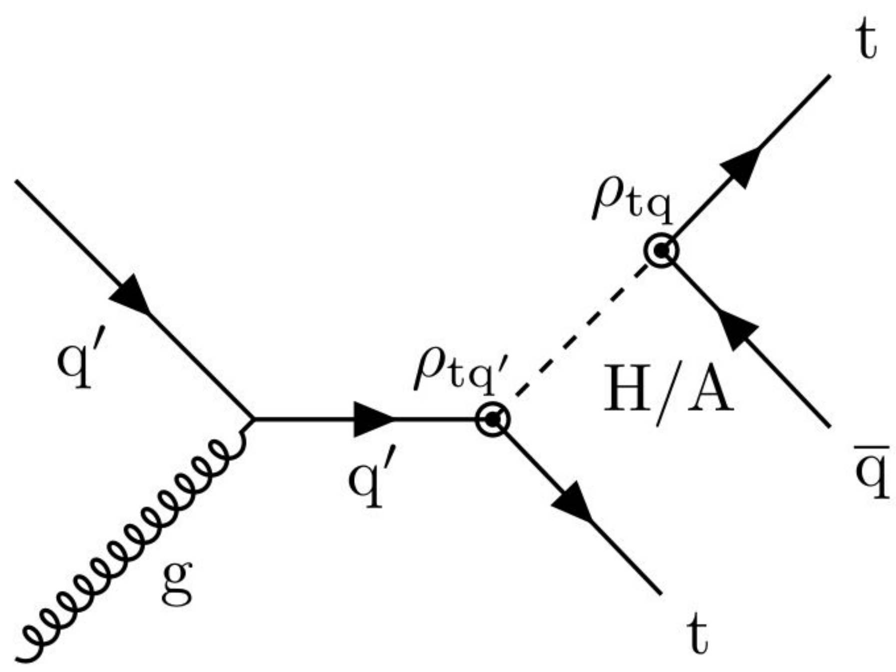
- From formula. ... small coupling
  rho_ij but the small alignment cγ

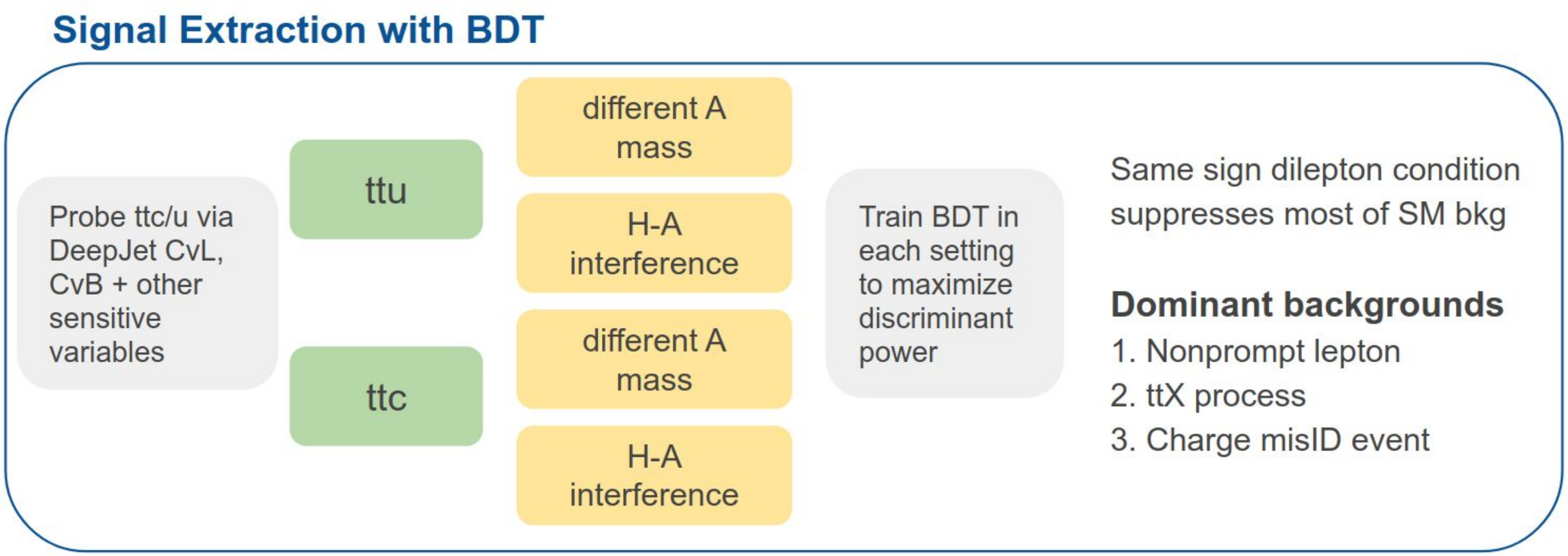
Low mass (< ~700 GeV) extra higgs bosons may exist.

- For H, the coupling is not hidden behind the cγ, so we move to the A/H search

Analysis strategy

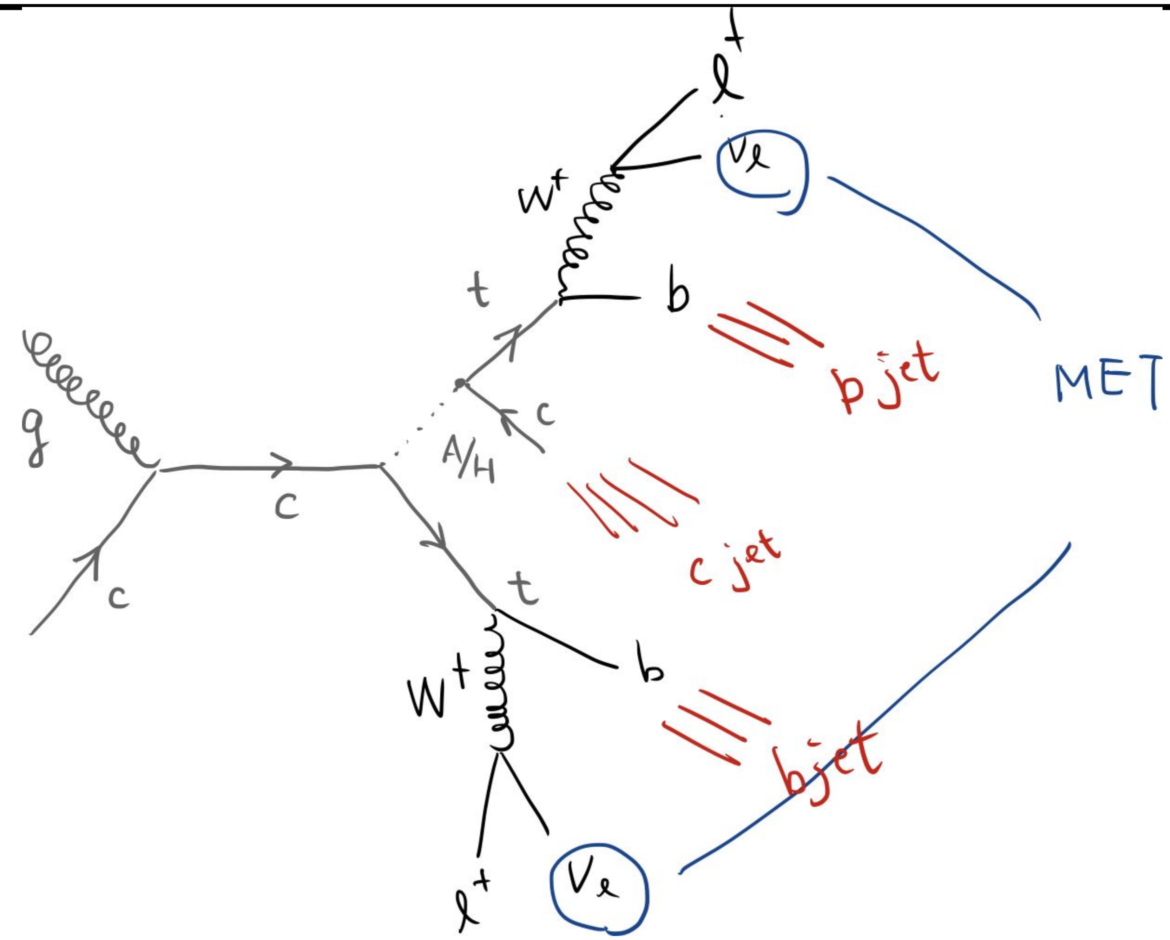
- Two couplings are considered
  - ρtc (let ρtu=0)
  - ρtu (let ρtc=0)
- For each coupling, consider with and without interference between CP-odd A and CP-even H





Objects selection

Leptons
- Three types of leptons in analysis:
  - Tight → Prompt lepton
  - Fakeable → nonprompt background estimation
  - Loose → Additional lepton veto
- Mva ID:
  - Good separation between prompt lepton and fake lepton to efficiently suppress the nonprompt bkg



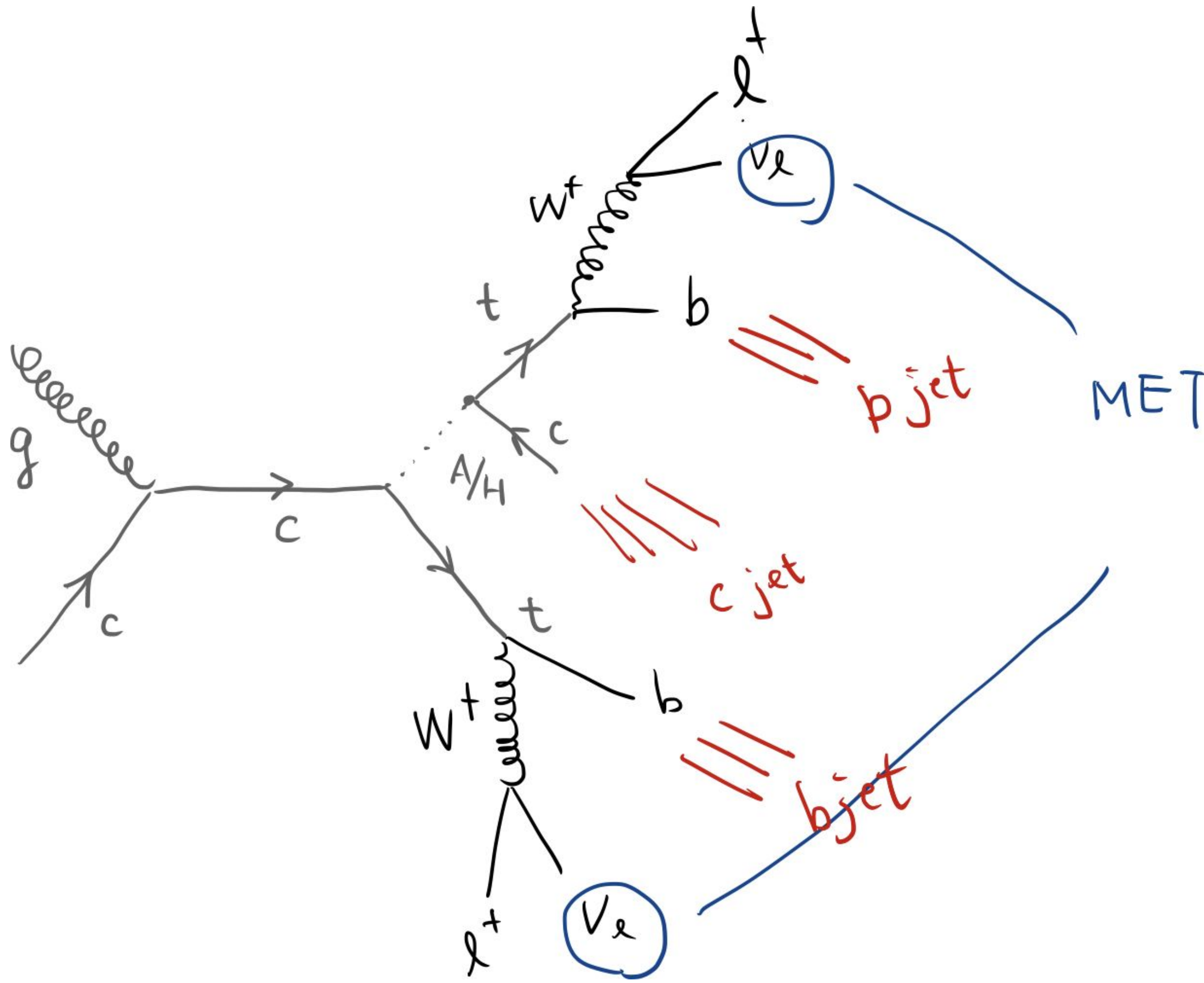
Tight/Fakeable Muon (Ele):
- Pt > 20 GeV
- |eta| < 2.4 (2.5)

Loose Muon (Ele):
- Pt > 10 GeV
- |eta| < 2.4 (2.5)

- Jet
  - $|\eta| < 2.4$
  - pT > 30 GeV
  - $\Delta R(j,l) > 0.4$
  - Jet energy correction applied
- MET
  - Pt > 30 GeV

Event selection

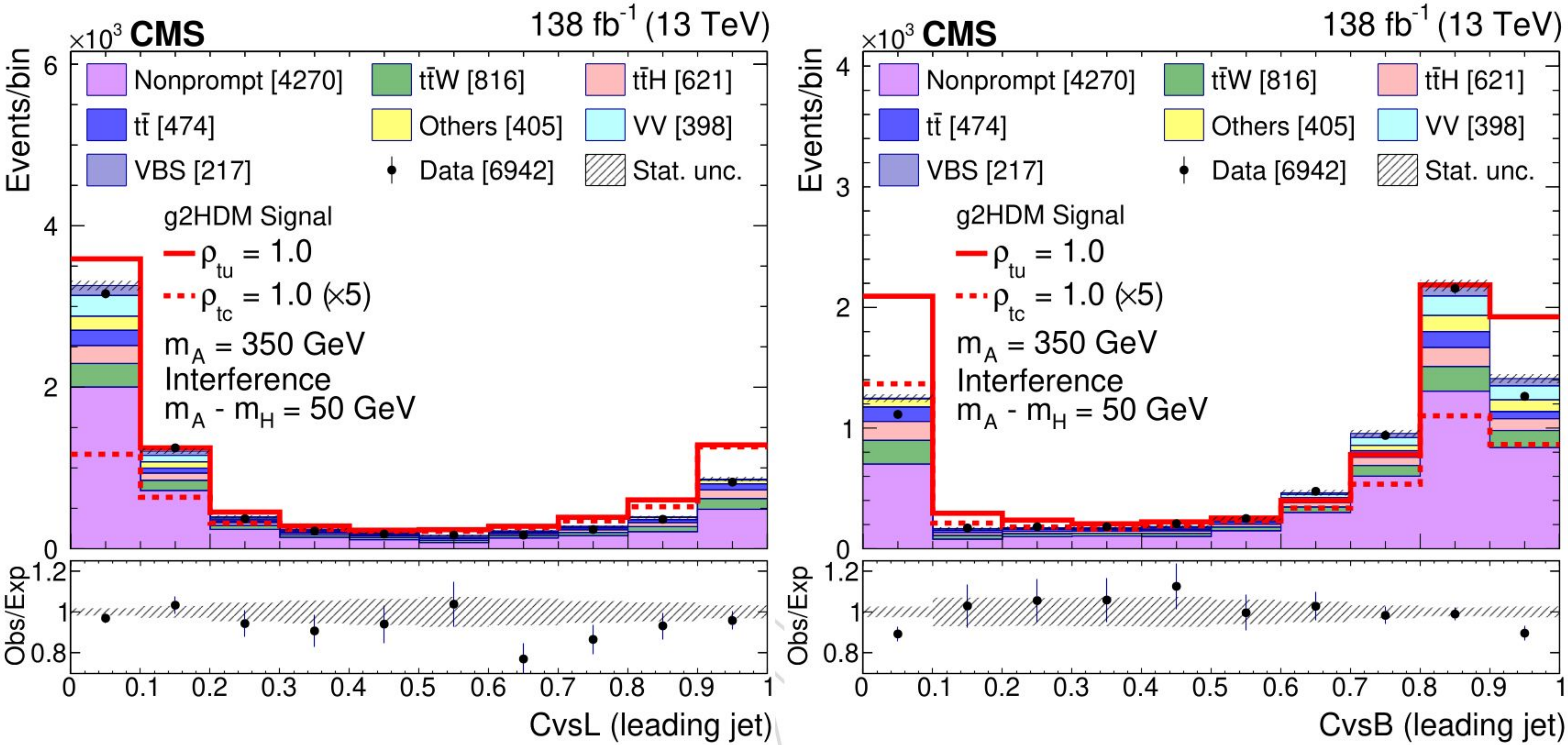
- **DY region** is used to check the validity of the analysis framework, and some of the SFs are derived in the DY region.
- The **ttbar region** is used to check the modeling of top quark events.
- **Signal region**: 2 same-sign leptons, at least three jets (two bjets and one cjet) and MET. In this analysis we will use flavor discriminator shape of jets for final signal extraction, i.e., no “tagger” is used.



Backgrounds estimation

- **The most dominant bkg is the contribution of nonprompt lepton** which originates from heavy-flavor hadron decays, misidentified hadrons, decay products of muons from light-mesons, or photon conversions in jets. 'Tight-to-loose ratio' method is used to estimate the fake contribution, which calculate the probability of nonprompt lepton pass the signal lepton selection in a QCD-enriched region.
- **charge flipped correction** in di-ele channel: the probability of charge misidentification, apply on all the MC bkgs events with opposite charged electrons
- The contributions of all the other bkgs are estimated using simulation

Comparison between Data and prediction

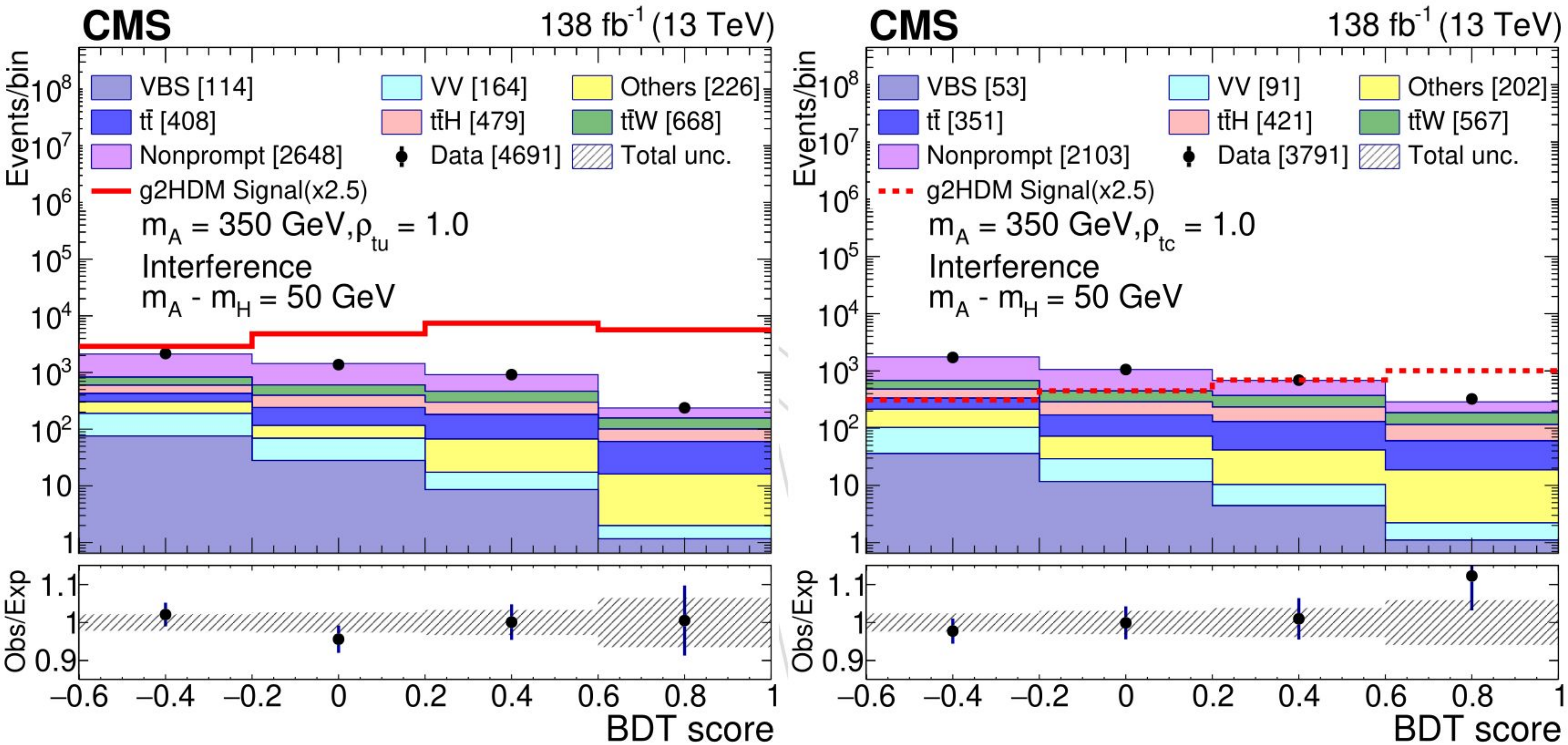


Reasonable agreements on the flavor information of jet between data and prediction after bkg estimation and also recommended flavor score correction

Signal extraction: BDT

- Inputs:
  - flavCvsB and flavCvsL of three jets
  - pt of two leptons
  - HT, MET
  - mll, mllj1, mllj2, mllj3
  - dleta_R among three jets

Different BDTs are trained for different signals at different mass



Result

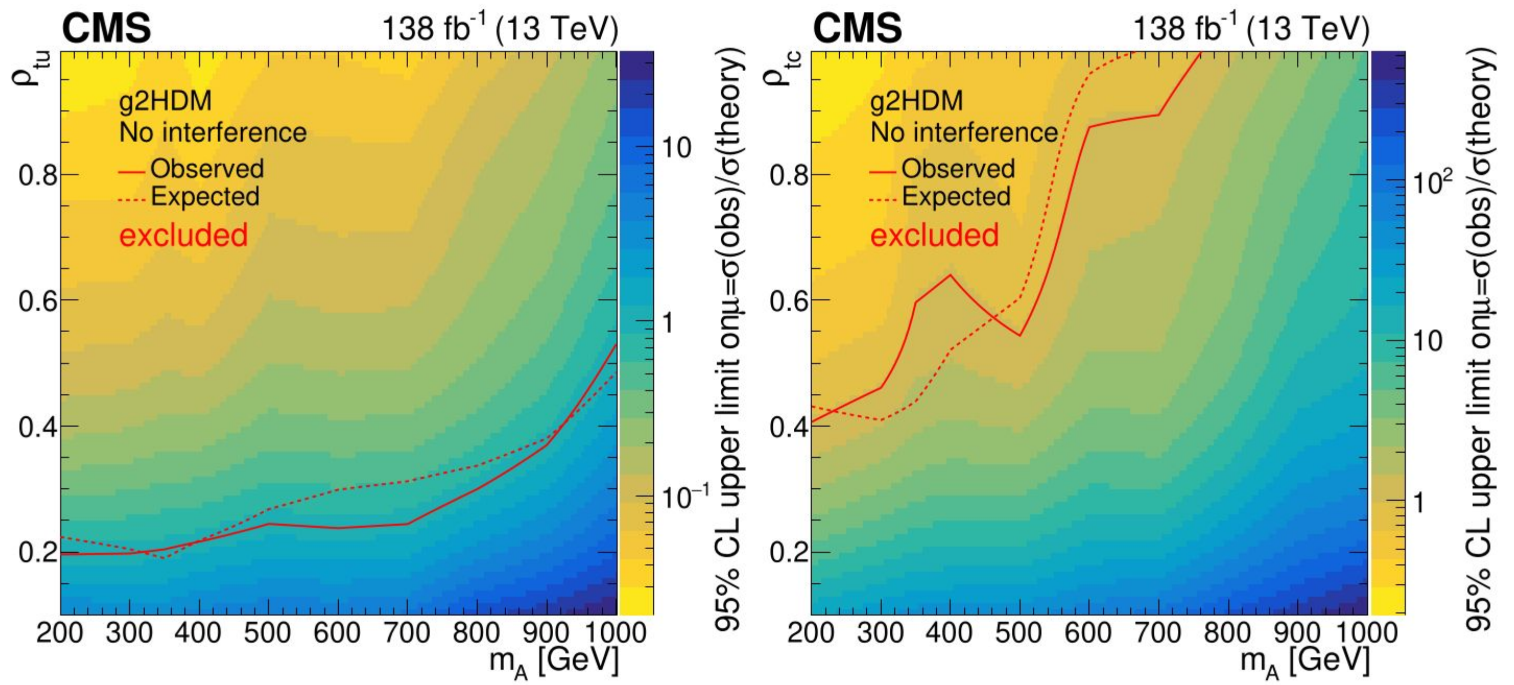


Figure 6: Observed 95% CL upper limit on the signal strength as a function of m_A and ρ_{tu} (left) and ρ_{tc} (right) for g2HDM without the A-H interference, for the combination of the $e^\pm e^\pm$, $\mu^\pm\mu^\pm$, and $e^\pm\mu^\pm$ categories. The color axis represents the observed upper limit on the signal strength. Expected (dashed lines) and observed (solid lines) exclusion contours are also shown.

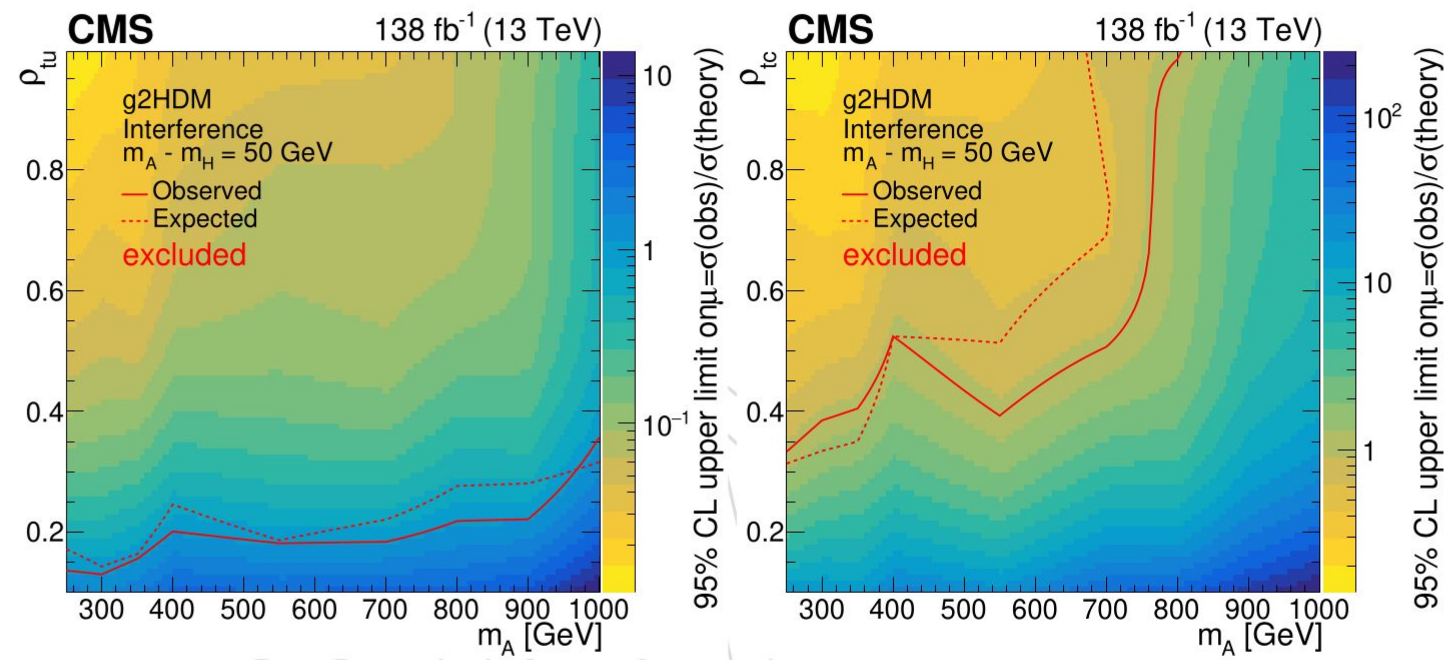


Figure 7: Observed 95% CL upper limit on the signal strength as a function of m_A and ρ_{tu} (left) and ρ_{tc} (right) for g2HDM signal model with the A-H interference, for the combination of the $e^\pm e^\pm$, $\mu^\pm\mu^\pm$, and $e^\pm\mu^\pm$ categories. The color axis represents the observed upper limit on the signal strength. Expected (dashed lines) and observed (solid lines) exclusion contours are also shown.

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)

ATLAS results, turn on all couplings. 2307.14759

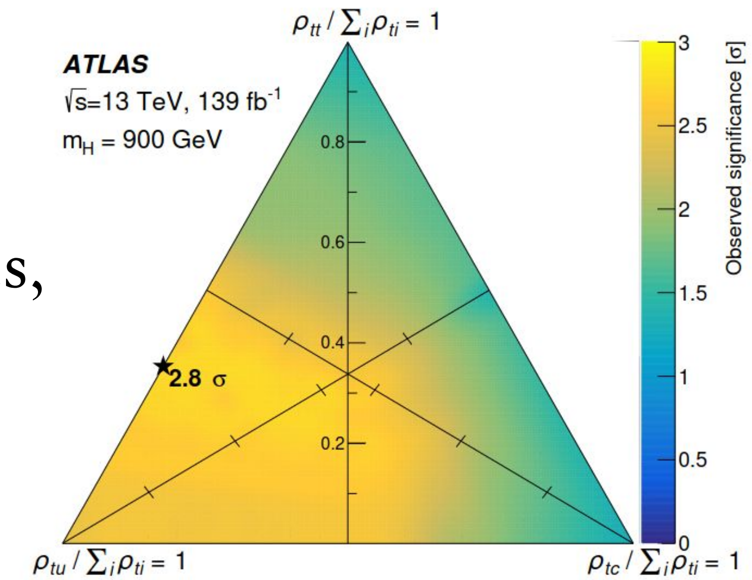


Figure 10: Observed significance for a heavy scalar with a mass of 900 GeV as a function of the three couplings normalised to the sum of the couplings. This normalisation eliminates one degree of freedom related to the total normalisation of the signal, which is not relevant for the computation of the significance. A residual dependency on the actual value of the coupling remains as the normalization of the sstt process scales as the fourth power of the couplings, while the rest of the processes scale as a function of the couplings squared. The star indicates the coupling configuration leading to the highest observed significance of 2.8 standard deviations.

Summary

- A search for extra Higgs bosons in ttq (q=u,c) bar final states is performed. 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 (type-III) considering ρtu and ρtc extra Yukawa couplings independently, and also first to consider mA–mH interference at the LHC
- Paper submitted to PLB

Thanks!

Additional slides

Event selection: DY

DY region is used to check the validity of the analysis framework, and some of the SFs are derived in the DY region.

DY region definition:

- Only two “Tight” leptons, veto events if there is a third “Loose” lepton.
- Leading lepton pT > 30 GeV
- Subleading lepton pT > 20 GeV
- m(l1,l2) $\in$(60,120)
- ΔR(l1,l2) > 0.3
- No hadronically decayed tau

Event selection: Top pair region

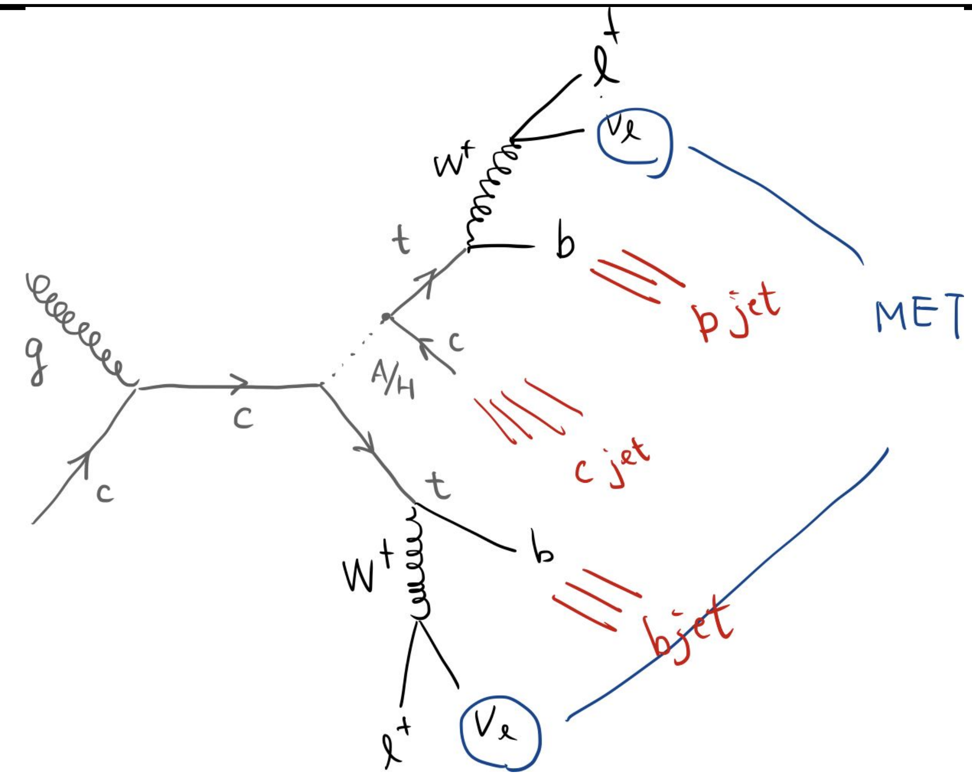
The ttbar region is used to check the modeling of top quark events, especially leptonically decayed and semi-leptonically decayed ttbar process.

Top pair region definition:

- Only two “Tight” leptons, veto events if there is a third “Loose” lepton.
- Leading lepton pT > 30 GeV
- Subleading lepton pT > 20 GeV
- m(l1,l2) > 20 GeV
- But veto m(l1,l2) $\in$(60,120) in ee channel
- ΔR(l1,l2) > 0.3
- No hadronically decayed tau
- At least one tight jet
- At least one b-tagged jet, which is “medium” WP of “DeepFlavour” tagging method

Event selection: signal region

The topology of signal event: 2 same-sign leptons, at least three jets (two bjets and one cjet) and MET. In this analysis we will use shape kinematics of jets for final signal extraction, i.e., no "tagger" is used.



Signal region definition:

- Only two "Tight" leptons with same-sign charge, veto events if a presence of a third "Loose" lepton.
- Leading lepton pT > 30(GeV)
- Subleading lepton pT > 20 GeV
- ΔR(l1,l2) > 0.3
- m(l1,l2) > 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)

Backgrounds estimation

For both electron and muon, we define "fakeable ID" and "tight ID", the fakerate of lepton is **calculated in a QCD-enriched region** defined as below:

- Event passes the prescaled single muon (electron) trigger path with very loose lepton selections
- Exactly one muon (electron) that passes the tight selection or the fakeable object selection
- No additional muons or electrons that pass the loose selection
- Only one jet with $p_T^j > 30$ GeV, $|\eta^j| < 2.4$, and $\Delta R(l,j) > 0.3$
- $p_T^{miss} < 30$ GeV, $m_T < 30$ GeV

Extra yukawa coupling: Introduction

link

- In 2HDM, 5 Higgs boson, 2 CP-even, 1 CP-odd, 2 charged. Without Z2 symmetry,

$$V(\Phi,\,\Phi') = \mu_{11}^2\Phi^2 + \mu_{22}^2\Phi'^2 - \left(\mu_{12}^2\Phi^\dagger\Phi' + \text{h.c.}\right) + \frac{\eta_1}{2}\Phi^4 + \frac{\eta_2}{2}\Phi'^4$$
$$+ \eta_3\Phi^2\Phi'^2 + \eta_4\Phi^\dagger\Phi'^2 + \left\{\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2 + \left[\eta_6\Phi^2 + \eta_7\Phi'^2\right]\Phi^\dagger\Phi' + \text{h.c.}\right\}.$$

Mass of two charge Higgs and CP-odd:

$$m_{H^\pm}^2 = \mu_{22}^2 + \frac{1}{2}\eta_3 v^2,$$
$$m_A^2 = \mu_{22}^2 + \frac{1}{2}(\eta_3 + \eta_4 - \eta_5)v^2.$$

Extra yukawa coupling: Introduction

With linear transformation to Higgs basis:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi' \end{pmatrix}$$

$$\mathrm{V}(\Phi,\Phi') \rightarrow \mathrm{V}(\mathrm{H}_1,\mathrm{H}_2)$$

Under Higgs basis, mass matrix of two CP-even

$$M^2_{\text{even}} = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & m_A^2 + \eta_5 v^2 \end{bmatrix},$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = (T) \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

$$R_\gamma^T M^2_{\text{even}} R_\gamma = \begin{bmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{bmatrix}, \quad R_\gamma = \begin{bmatrix} c_\gamma & -s_\gamma \\ s_\gamma & c_\gamma \end{bmatrix},$$

link

RunI alignment: the 125 GeV boson resemble rather SM higgs -> very small mixing angle between H1-H2, if let 125 GeV Higgs boson to be h, then

$$c_\gamma \cong \frac{\eta_6 v^2}{m_H^2 - m_h^2},$$

(if let 125 GeV Higgs boson to be H, then c_γ ~ 1)

~ 0

Extra yukawa coupling: coupling

Yukawa coupling of 2HDM without Z2 symmetry:

Phys. Rev. D 72, 035004 (2005), Phys. Lett. B 751,135 (2015), Phys. Lett. B 725, 378 (2013)

$$-\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[\big(-\lambda_i^f \delta_{ij} s_\gamma + \rho_{ij}^f c_\gamma \big) h + \big(\lambda_i^f \delta_{ij} c_\gamma + \rho_{ij}^f s_\gamma \big) H - i\,\mathrm{sgn}(Q_f) \rho_{ij}^f A \Big] R\, f_j$$
$$-\bar{u}_i \left[(V\rho^d)_{ij} R - (\rho^{u\dagger} V)_{ij} L \right] d_j H^+ - \bar{\nu}_i \rho_{ij}^\ell R\, \ell_j H^+ + h.c., \qquad (5)$$

t→ ch(125) is searched right after the higgs(125) discovery, currently best limits @95% CL is from ATLAS,

$$\mathcal{B}(t \to ch) < 1.1 \times 10^{-3}, \qquad (\text{ATLAS } 36\ \text{fb}^{-1},\ 2019)$$

From formula.5, it's possible that t->ch is difficult to search is not due to the small coupling rho_ij but the small alignment c_γ

For H, the coupling is not hidden behind the c_γ, so we move to the A/H search

Systematics

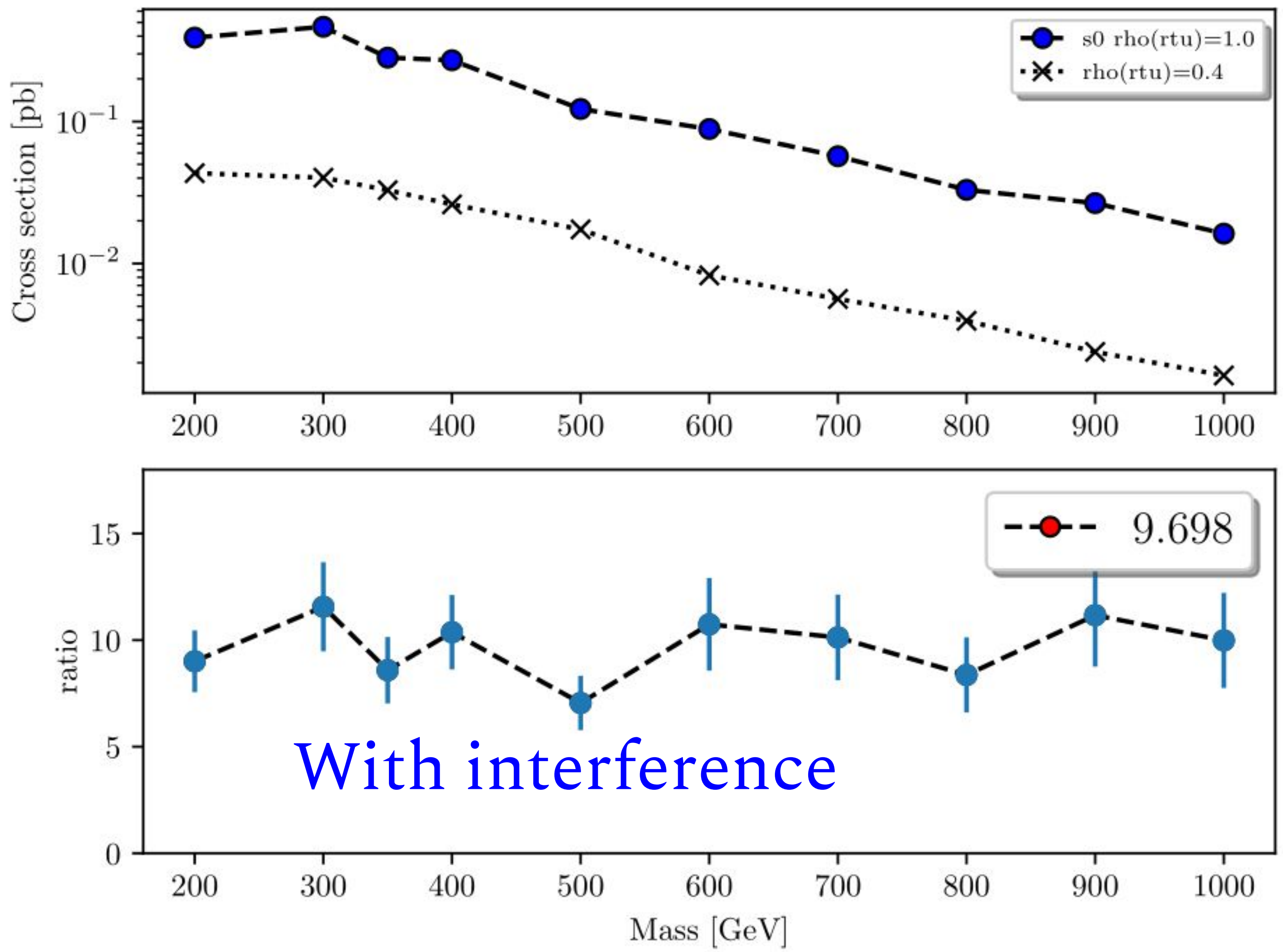
Uncertainty source	Shape	Category $e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	Correlated across Years	Categories
Experimental						
Luminosity	–	1.2–2.5	1.2–2.5	1.2–2.5	✓	✓
Pileup	✓	<0.1–2.8	<0.1–1.8	<0.1–2.3	✓	✓
Trigger efficiency	✓	0.4–2.6	0.2–1.1	0.3–1.2	–	–
L1 trigger inefficiency	✓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

DRAFT

XSs

Category Correlated across

PID	Mass [GeV]	ρ_{tu}	ρ_{tc}	ρ_{tt}	$\sigma_{tt\bar{q}}$ [pb]	$\delta(\sigma_{tt\bar{q}})$ [pb]
A	800	0.1	0.0	0.0	1.921e-04	3.121e-05
A	800	0.4	0.0	0.0	4.547e-03	5.907e-04
A	800	0.8	0.0	0.0	1.983e-02	2.797e-03
A	800	1.0	0.0	0.0	3.965e-02	5.327e-03
A	800	0.0	0.1	0.0	1.102e-05	2.025e-06
A	800	0.0	0.4	0.0	2.332e-04	3.508e-05
A	800	0.0	0.8	0.0	9.572e-04	1.473e-04
A	800	0.0	1.0	0.0	1.661e-03	2.439e-04
A	900	0.1	0.0	0.0	1.411e-04	2.239e-05
A	900	0.4	0.0	0.0	2.915e-03	4.220e-04
A	900	0.8	0.0	0.0	1.519e-02	2.051e-03
A	900	1.0	0.0	0.0	2.588e-02	3.643e-03
A	900	0.0	0.1	0.0	9.145e-06	1.407e-06
A	900	0.0	0.4	0.0	1.344e-04	2.169e-05
A	900	0.0	0.8	0.0	7.142e-04	1.004e-04
A	900	0.0	1.0	0.0	1.335e-03	1.685e-04
A	1000	0.1	0.0	0.0	1.112e-04	1.610e-05
A	1000	0.4	0.0	0.0	1.452e-03	2.535e-04
A	1000	0.8	0.0	0.0	1.026e-02	1.507e-03
A	1000	1.0	0.0	0.0	1.733e-02	2.552e-03
A	1000	0.0	0.1	0.0	4.872e-06	8.489e-07
A	1000	0.0	0.4	0.0	9.192e-05	1.484e-05
A	1000	0.0	0.8	0.0	3.727e-04	6.023e-05
A	1000	0.0	1.0	0.0	6.182e-04	9.980e-05



7 0.6–0.7 0.5–0.6 ✓ ✓
-4.3 4.0–4.3 6.3–7.3 ✓ ✓

interference between A and H. Signal samples are also generated for the case where both A and H coexist and interfere assuming a mass difference $m_A - m_H = 50$ GeV, following Ref. [36]. The amplitudes for the processes $qg \to tA \to tt\bar{q}$ and $qg \to tH \to tt\bar{q}$ cancel when A and H are mass degenerate. The signal cross section is not significantly modified with respect to the noninterference case when the mass differences are larger than ≈100 GeV. Therefore, the inves-

Results

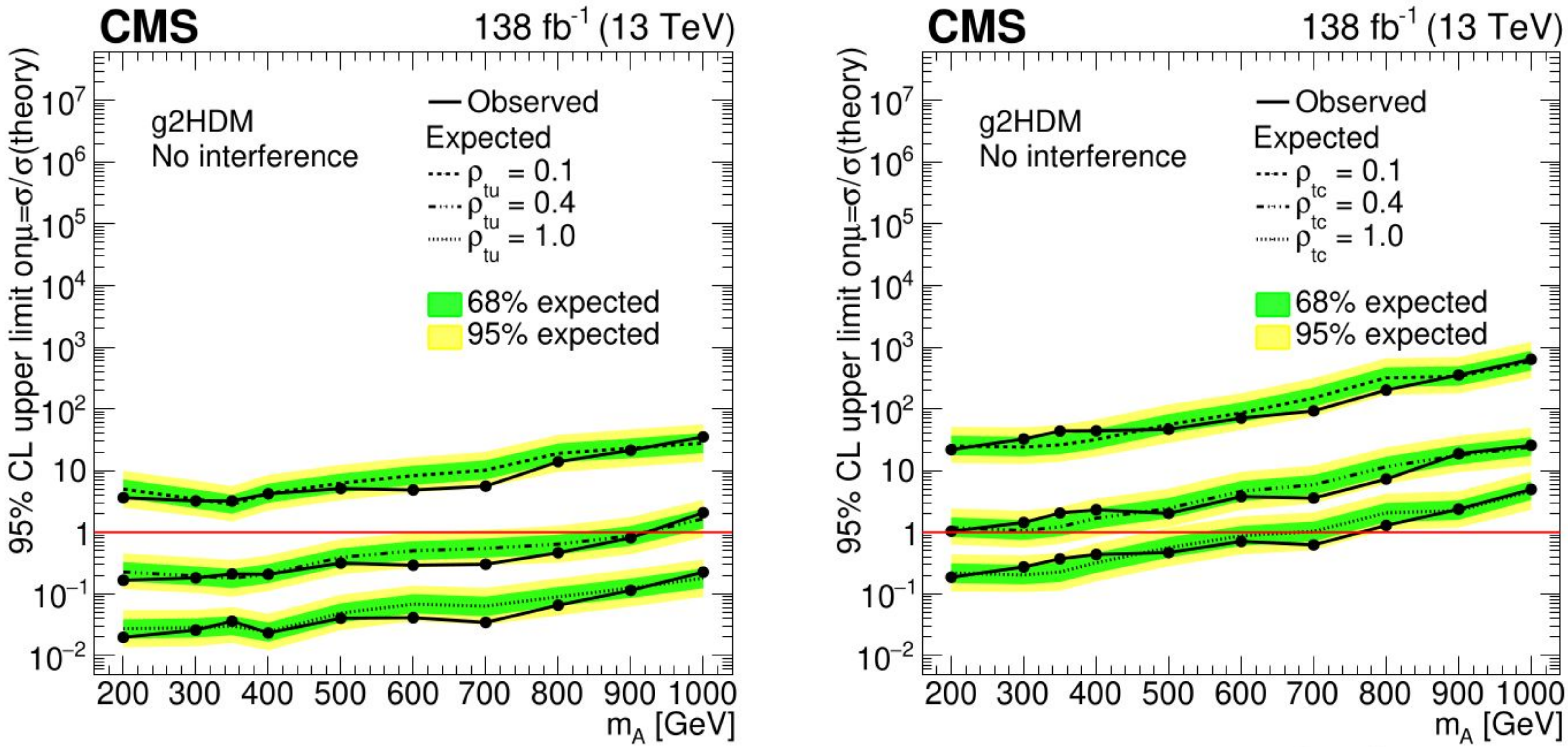


Figure 4: Observed and expected 95% CL upper limits on the signal strength as functions of m_A for g2HDM using different coupling assumptions: ρ_{tu} = 0.1, 0.4, 1.0 (left) and ρ_{tc} = 0.1, 0.4, 1.0 (right) without interference, for the combination of the $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, and $e^{\pm}\mu^{\pm}$ categories. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

Results

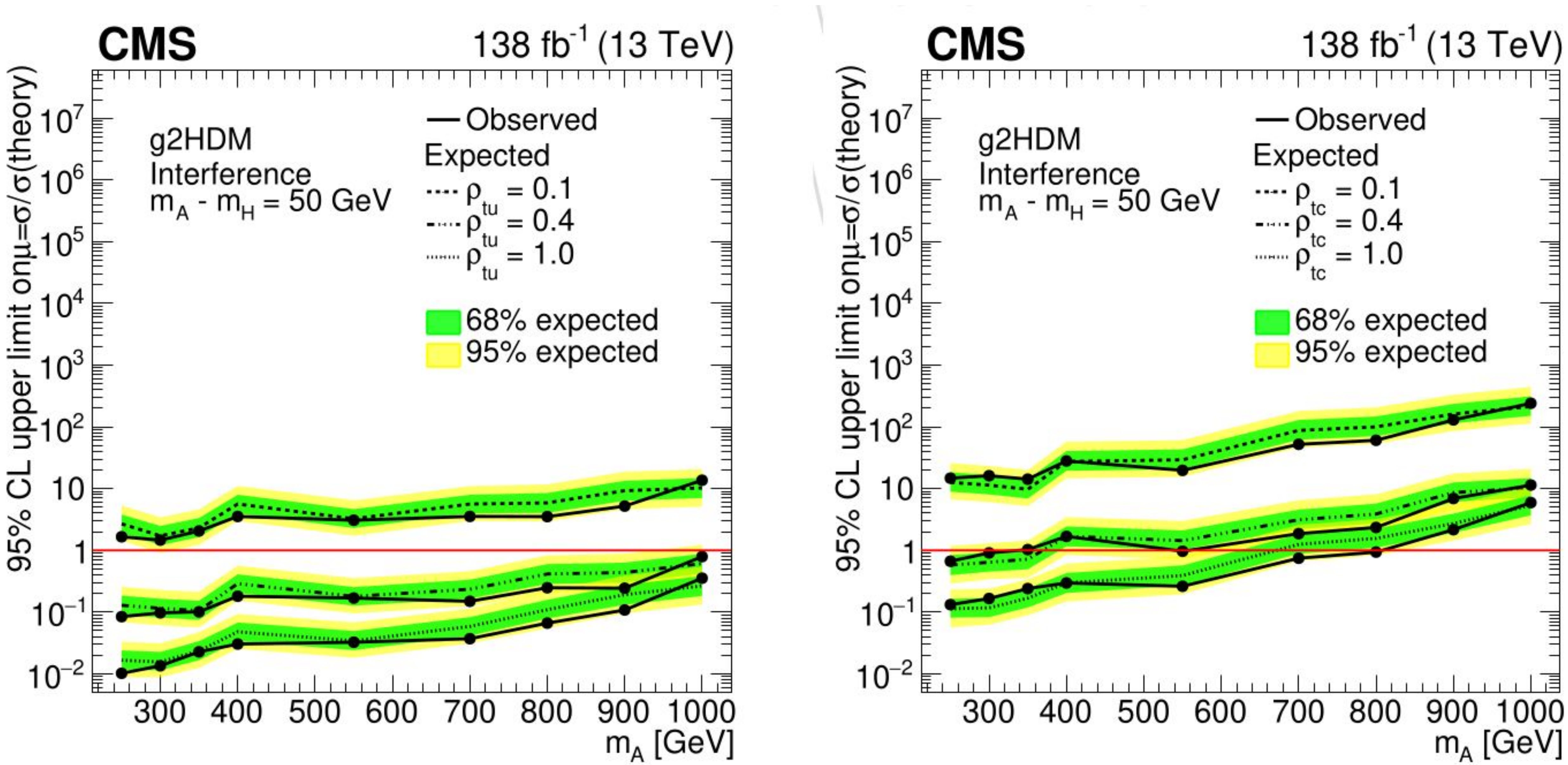


Figure 5: Observed and expected 95% CL upper limits on the signal strength as functions of m_A for g2HDM using different coupling assumptions: $\rho_{tu} = 0.1, 0.4, 1.0$ (left) and $\rho_{tc} = 0.1, 0.4, 1.0$ (right) with A-H interference assuming $m_A - m_H = 50\,\text{GeV}$, for the combination of the $e^\pm e^\pm$, $\mu^\pm\mu^\pm$, and $e^\pm\mu^\pm$ categories. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

ATLAS Results

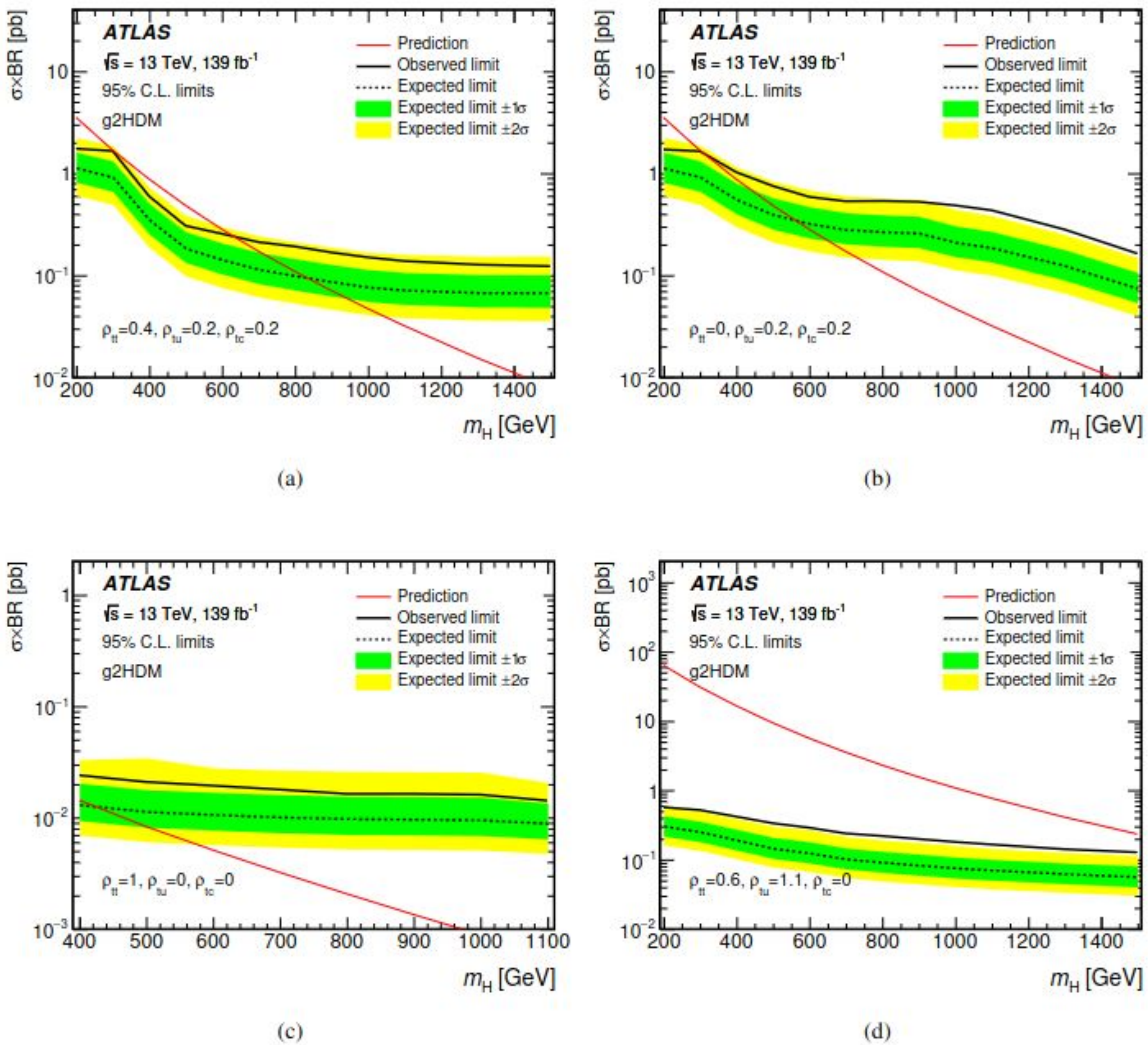


Figure 14: Observed and expected exclusion limits at 95% confidence level on the heavy Higgs boson mass for the g2HDM signal model for different couplings choices: (a) $\rho_{tt} = 0.4$, $\rho_{tc} = 0.2$, $\rho_{tu} = 0.2$, (b) $\rho_{tt} = 0$, $\rho_{tc} = 0.2$, $\rho_{tu} = 0.2$, (c) $\rho_{tt} = 1$, $\rho_{tc} = 0$, $\rho_{tu} = 0$, and (d) $\rho_{tt} = 0.6$, $\rho_{tc} = 0$, $\rho_{tu} = 1.1$, the latter corresponding to the couplings yielding the most significant excess. The yellow and green contours of the band around the expected limit are the $\pm1\sigma$ and $\pm2\sigma$ variations including all uncertainties, respectively. The theoretical prediction for the signal production cross section is also shown as a red line. The production cross section is the sum of the five production modes considered in the search.