Signatures of additional top and bottom Yukawa couplings at the LHC

Tanmoy Modak

National Taiwan University

Phys.Lett.B 776 379-384; Phys.Lett.B 786 212-216;
Phys.Rev.D98, 075007; Phys.Rev.D99, 055046;
Phys.Rev.D99, 115022; Phys.Rev.D100, 035018;
Phys.Lett.B798 134953; Phys.Lett.B800 135105;
Phys.Rev.D101, 035007; 1912.10613;
2005.09928 (Osaka U.)

@ Osaka U. Seminar

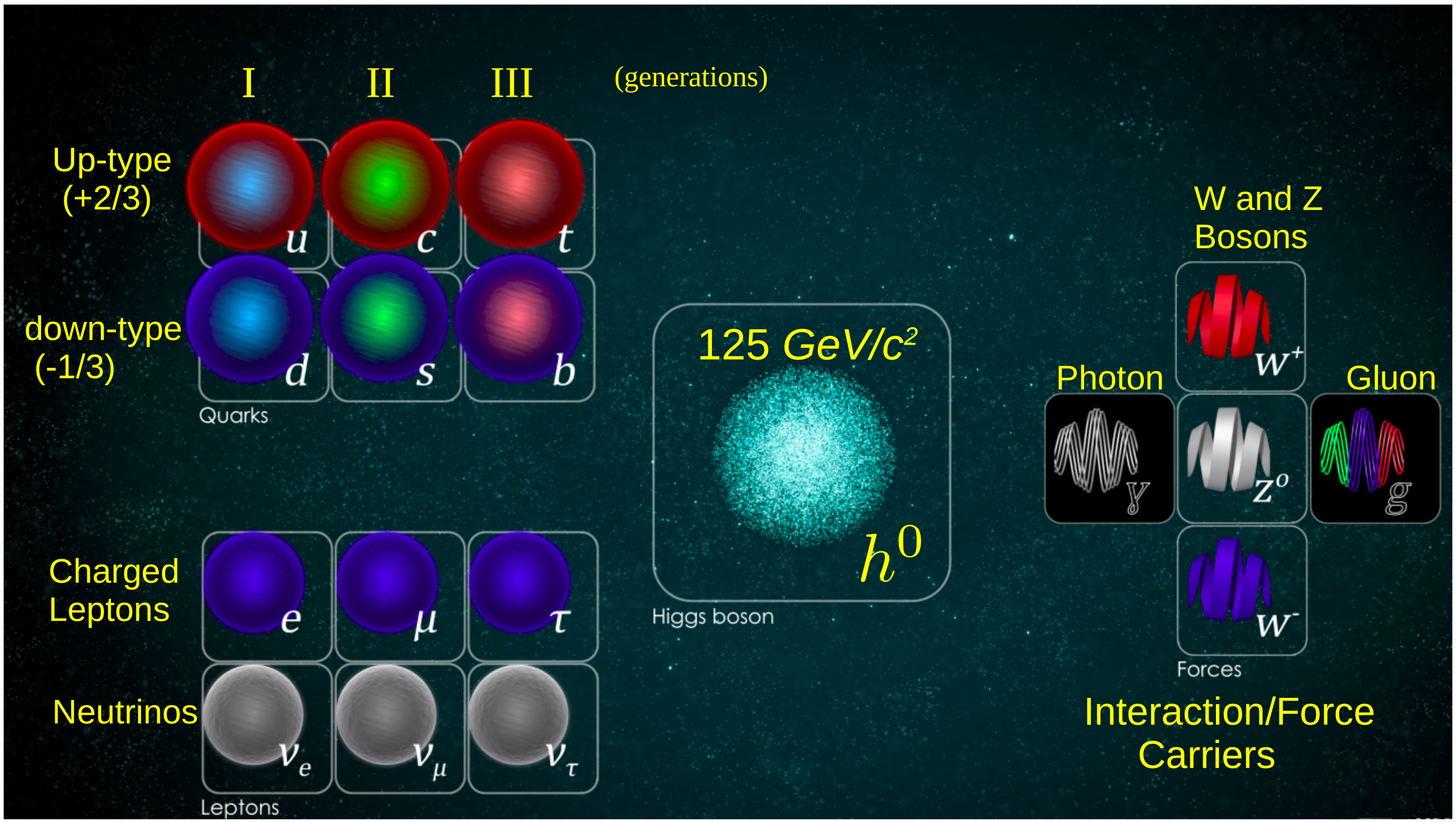
Outline

- Overview
- Formalism
- Signatures for extra top Yukawa couplings
- Signatures for extra bottom Yukawa couplings
- Summary

Overview

Standard Model

Standard Model (SM) of elementary particles:



(CERN website)

- Discovery of Higgs Boson in 2012 at the Large Hadron Collider: SM became complete in terms of particle content.

Higgs Mechanism

Brout-Englert-Higgs mechanism

The Higgs Potential in the SM:

$$V(\Phi) = \lambda(\Phi^\dagger\Phi)^2 + \mu^2(\Phi^\dagger\Phi)$$

$\lambda > 0$: avoid potential unbounded from below

Higgs field: SU(2)$_L$ doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

For: $\mu^2 < 0$: potential has a minimum at:

$$\langle \Phi^\dagger\Phi \rangle = \frac{-\mu^2}{2\lambda} = \frac{v^2}{2}$$

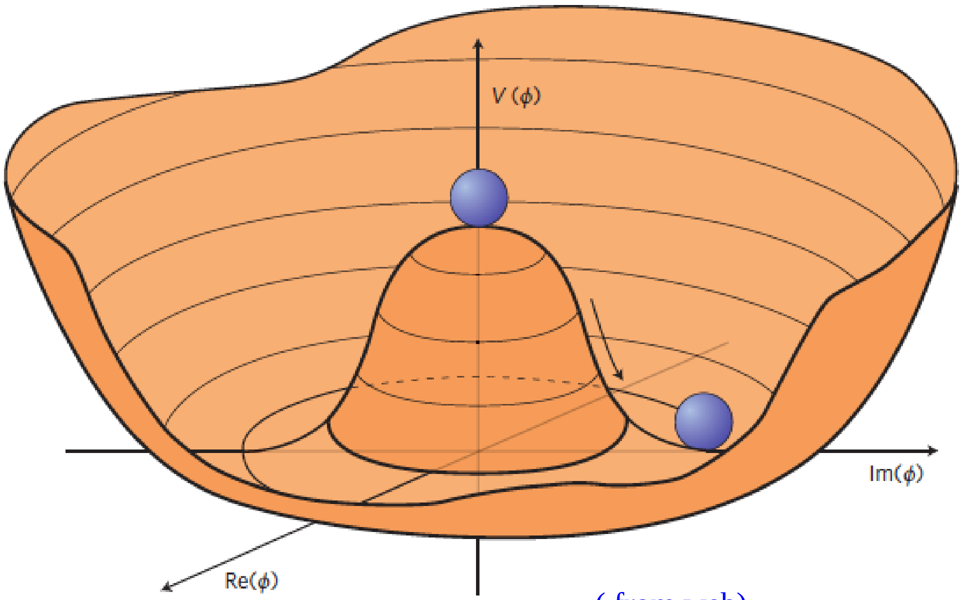
v: vacuum expection value

Spontaneous symmetry breaking

$$\Phi(x) = \begin{pmatrix} 0 \\ \frac{v+h^0(x)}{\sqrt{2}} \end{pmatrix}$$

$h^0(x)$: physical Higgs boson

$\Rightarrow$ $SU(2)_L \times U(1)_Y$ broken to $U(1)_{EM}$



(from web)

Masses:

$$m_{W^\pm} = \frac{1}{2}g''v$$

$$m_{Z^0} = \frac{1}{2}v\sqrt{g'^2 + g''^2}$$

g' and g'': gauge couplings of $U(1)_Y$ and $SU(2)_L$

$$m_{h^0} = \sqrt{2\lambda v^2}$$

$$m_f = \lambda_f v/\sqrt{2}$$

λ_fs: Yukawa couplings

Discovery of 125 GeV Higgs boson

2012
A good year

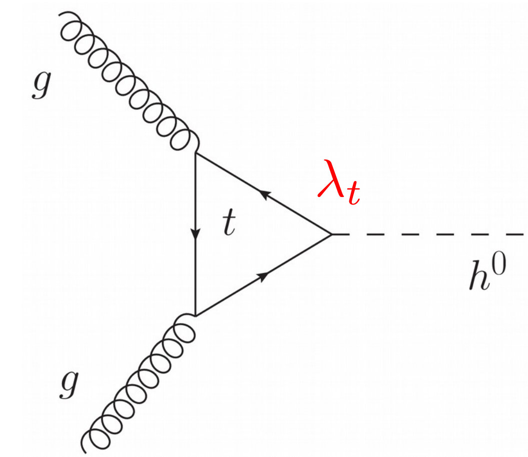
Discovered at the LHC by ATLAS and CMS collaborations.

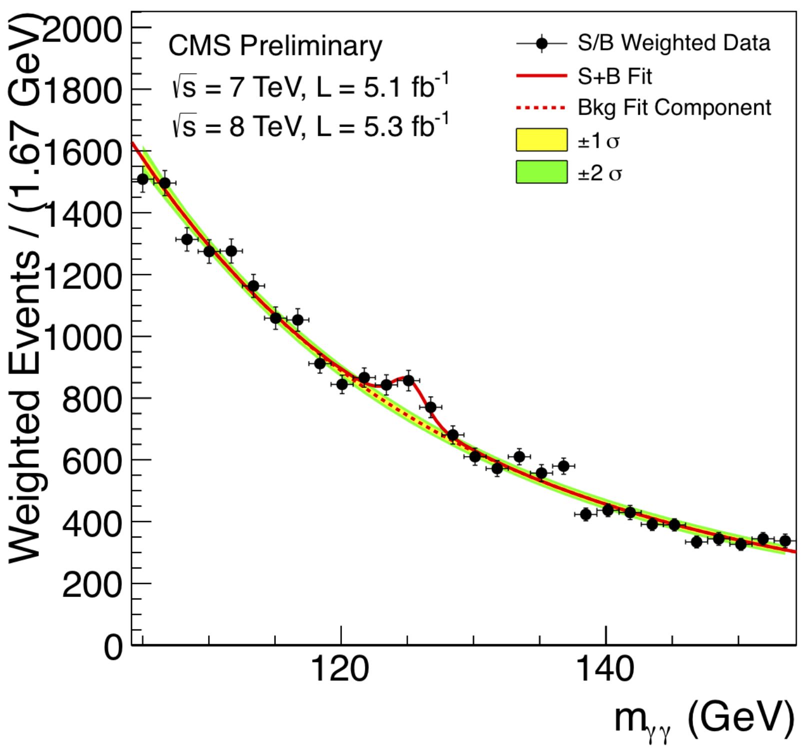
(ATLAS, PLB'12; CMS, PLB'12)

proton-proton (pp) collision with data from
7+8 TeV CM energy

Primary search modes:

$pp \to h^0 \to \gamma\gamma$
$pp \to h^0 \to ZZ^* \to 4$ leptons
$pp \to h^0 \to WW^* \to \ell\nu\ell\nu$





(CERN website)

Subsequently:

h^0 couplings to: τ lepton and, t and b quarks are discovered

Within error-bar all couplings found to be consistent with SM

- Matter Anti-matter asymmetry of the Universe. We see mostly matter.
- Neutrinos are massive (neutrino oscillations).
- Existence of Dark matter and its nature.
- Hierarchy Problem in SM. Needs fine tuning to get 125 GeV Higgs mass.

- No concrete evidence of New Physics so far from LHC, LHCb or Belle etc.
- Couplings of 125 GeV boson is SM like.
- Flavor anomalies: $R(K)$, $R(K^*)$, $R(D^*)$; Tension with SM is softening. Needs independent measurements from Belle-II.

Where is New Physics?

Could be heavy (> TeV scale)
Terrible LHC search

1) Light, weakly coupled Sub-TeV resonances.

2) Excellent signatures For LHC, LHCb and Other experiments

- Current data: 125 GeV scalar is SM-Higgs like. Indication of Alignment (approximate).
- Second doublet could be rather heavy. Alignment from Decoupling.
- Alignment without Decoupling: if happens, *sub-TeV second doublet*.

  (Carena et al. JHEP ’14, PRD ’15; Bechtle et al. EPJC ’17; See also Gunion et al. PRD ’03.)

- Approximate Alignment without Decoupling: Can be realized in 2HDM.

  (see e.g. Hou & Kikuchi, EPL’18)

- 2HDM without Z_2 ➡ *Extra Yukawas* : $\rho_{tc}, \ \rho_{tt}, \ \rho_{bb}.$
- ***Sub-TeV Second Doublet*** + ***Extra Yukawas***: Novel Signatures at LHC:
- Motivation: Discovery may shed light on *Baryon Asymmetry of the Universe*.

  (Fuyuto, Hou, Senaha PLB ’18, TM, Senaha PRD’19)

Formalism

Higgs Sector

general Two Higgs doublet model (*g2HDM*)

CP conserving Higgs sector without Z_2 :

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

(e.g. Davidson and Haber PRD'05, Hou and Kikuchi, EPL' 18)

✦ In Higgs Basis:

$\langle\Phi\rangle = (0, v/\sqrt{2})^T$ ⟶ $h^0,\ H^0,\ A^0,\ H^\pm$

$\langle\Phi'\rangle = (0,0)^T$

mixing angle between h^0 and H^0: $\cos\gamma = c_\gamma$

$c_\gamma \simeq \frac{-\eta_6 v^2}{m_{H^0}^2 - m_{h^0}^2}$; $\qquad c_\gamma \sim 0.2 - 0.1$

★ $m_{A^0},\ m_{H^\pm},\ m_{H^0} \sim 200\text{–}600$ GeV ⟶ Excellent scope for LHC

Yukawa Sector

- 2HDM without Z_2: Both doublets couple with up- and down-type fermions.
- After diagonalization of fermion mass matrices: Two different Yukawas. λ^F and ρ^F with $\lambda_f = \frac{\sqrt{2}m_f}{v}$.
- λ^F diagonal and real; ρ^F non-diagonal and in general complex.

$$\lambda^u \equiv \begin{pmatrix} \lambda_u & & \\ & \lambda_c & \\ & & \lambda_t \end{pmatrix}, \quad \lambda^d \equiv \begin{pmatrix} \lambda_d & & \\ & \lambda_s & \\ & & \lambda_b \end{pmatrix}, \quad \lambda^\ell \equiv \begin{pmatrix} \lambda_e & & \\ & \lambda_\mu & \\ & & \lambda_\tau \end{pmatrix}$$

(Davidson, Haber PRD '05)

$$\rho^u \equiv \begin{pmatrix} \rho_{uu} & \rho_{uc} & \rho_{ut} \\ \rho_{cu} & \rho_{cc} & \rho_{ct} \\ \rho_{tu} & \rho_{tc} & \rho_{tt} \end{pmatrix}, \quad \rho^d \equiv \begin{pmatrix} \rho_{dd} & \rho_{ds} & \rho_{db} \\ \rho_{sd} & \rho_{ss} & \rho_{sb} \\ \rho_{bd} & \rho_{bs} & \rho_{bb} \end{pmatrix}, \rho^\ell \equiv \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

It is likely: $\rho_{ii} \sim \lambda_i$

- complex ρ_{tt}, ρ_{tc} :
  (K. Fuyuto, W.-S Hou, E. Senaha; PLB '18)

  complex ρ_{bb} :
  (TM, E. Senaha; PRD '19)

  → Recipe for Electroweak Baryogenesis (EWBG)

- $h^0 f_i \bar{f}_j$: $-\lambda_{ij} s_\gamma + \rho_{ij} c_\gamma$

  $H^0 f_i \bar{f}_j$: $\lambda_{ij} c_\gamma + \rho_{ij} s_\gamma$

  $A^0 f_i \bar{f}_j$: $-i\ \mathrm{sgn}(Q_f) \rho_{ij}$

  Recipe for discovery

Signatures for extra top Yukawa couplings

Signatures at LHC

- $gg \to A^0/H^0 \to t\bar{t}:$ interference with $gg \to t\bar{t}$.

  ➡ study above $t\bar{t}$ threshold

  (ATLAS PRL'18, CMS 1908.01115)

  (See e.g. Carena and Liu JHEP '16)

- $gg \to t\bar{t}A^0/H^0 \to t\bar{t}t\bar{t}, tt\bar{t}c$

  (Craig, et al., JHEP '15, '17; Kanemura et al. NPB '15; Gori et al. PRD '16)

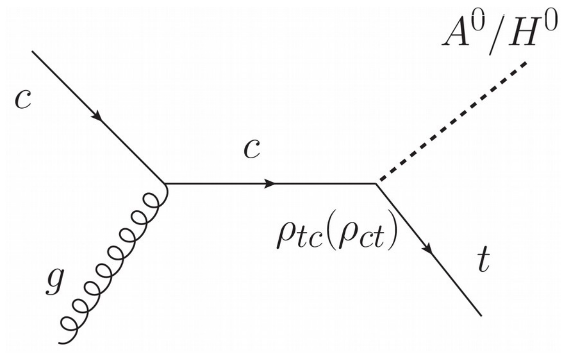
- $gg \to A^0/H^0 \to t\bar{c}:$ Could be discovered. (Altunkaynak PLB '15)
  suffers from $t+j$ mass resolution. (CMS-PAS-B2G-16-025)

- **Triple-top:**

$$cg \to tS^0 \to tt\bar{t}$$

where, $S^0 \equiv A^0 or H^0$

SM 3t at fb level
(Barger, Keung, Yencho, PLB '10);
Clean 3b jets-3lepton signature



- **Same-sign top:**

$$cg \to tS^0 \to tt\bar{c}$$

(See also Hou, Lin, Ma, Yuan, PLB '97, S. Iguro, K. Tobe NPB'17)

<u>May emerge earlier than triple-top</u>

(W.-S. Hou, M. Kohda, TM, PLB'19)

- **Some other modes**

$$cg \to tH^0 \to th^0h^0$$ → Top-assisted di-Higgs, Probe for Higgs potential

(W.-S. Hou, M. Kohda, TM, PRD'19)

$$cg \to tA^0 \to tZH^0$$ → Favored by strongly First order EWPT (Dorsch et al.PRL'14)

(W.-S. Hou, TM, PRD'20)

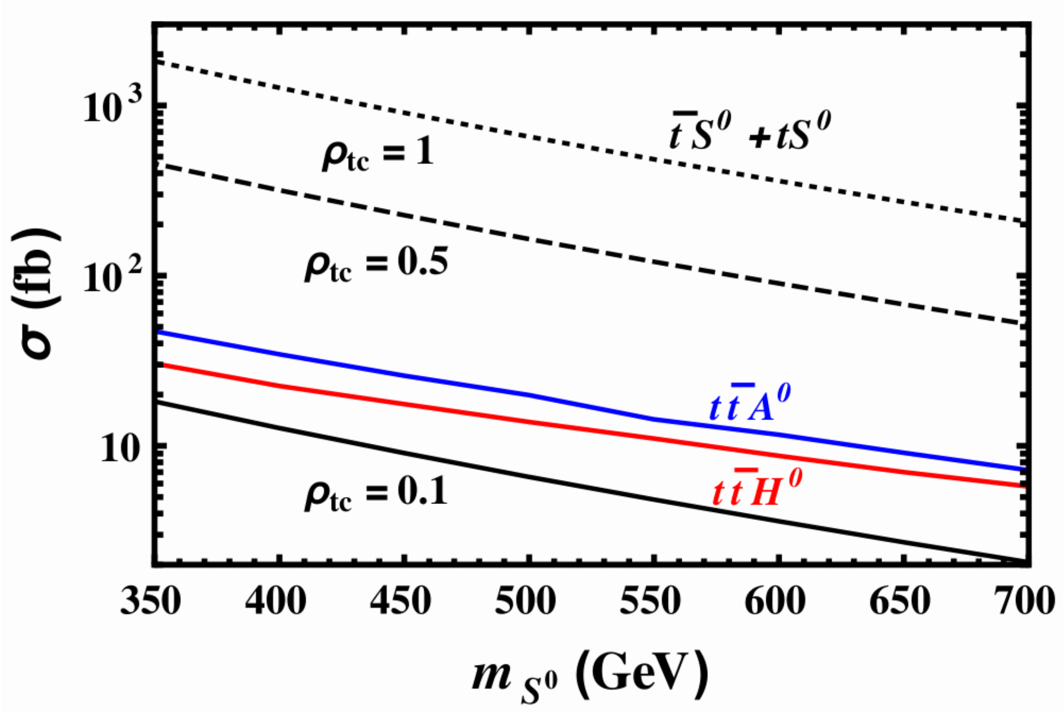
$$cg \to bH^+ \to bt\bar{b}$$

(D.K. Ghosh,W.-S. Hou, TM, 1912.10613)

Parton level cross sections

(W.-S Hou, M. Kohda, TM PLB '18)

Parton level cross sections at LO:



fixed $\rho_{tt} = 1$

$\sigma(pp \to tS^0)$

$\sigma(pp \to t\bar{t}A^0)$

$\sigma(pp \to t\bar{t}H^0)$

PDF set : NN23LO1

$\sqrt{s} = 14$ TeV

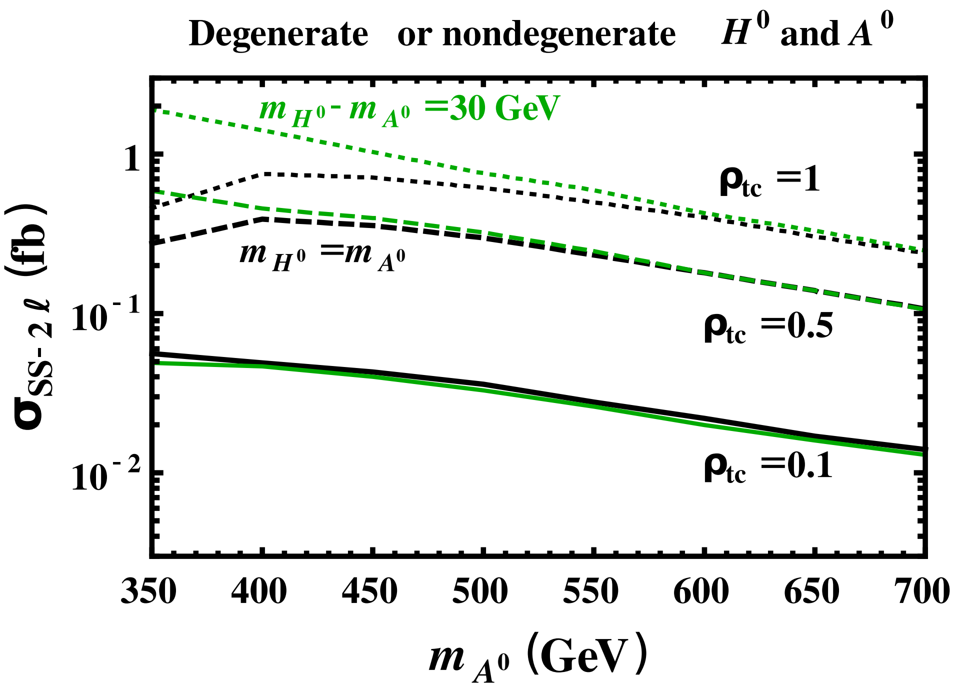
MadGraph5_aMC@NLO

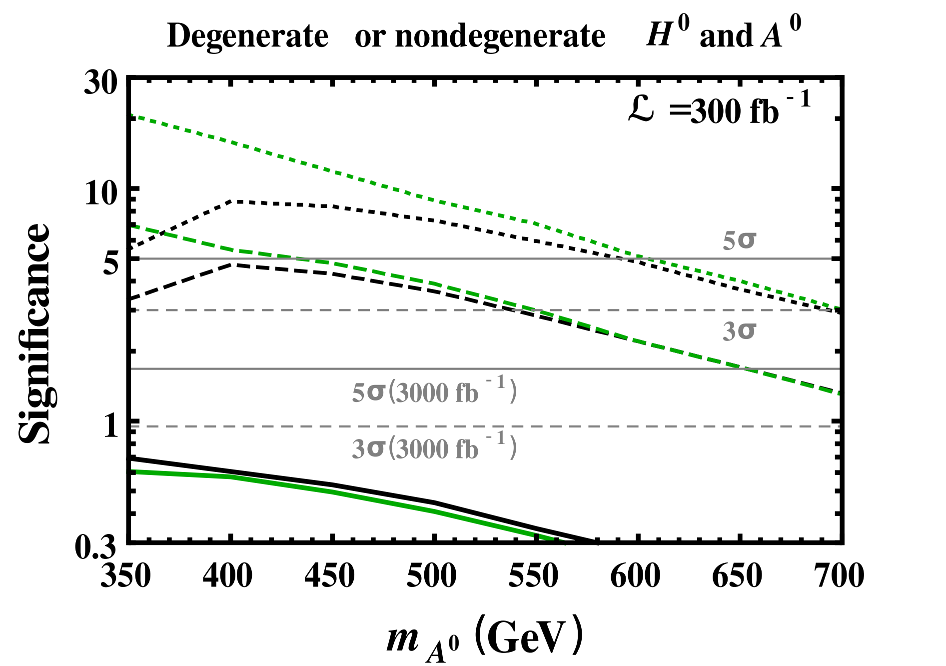
Same-sign top

MadGraph5_aMC + Pythia + Delphes

Event selection: 2 same-sign leptons (e, μ) $+ \geq 3$jets with $2b$-tagged

denoted as $(SS\text{-}2\ell)$

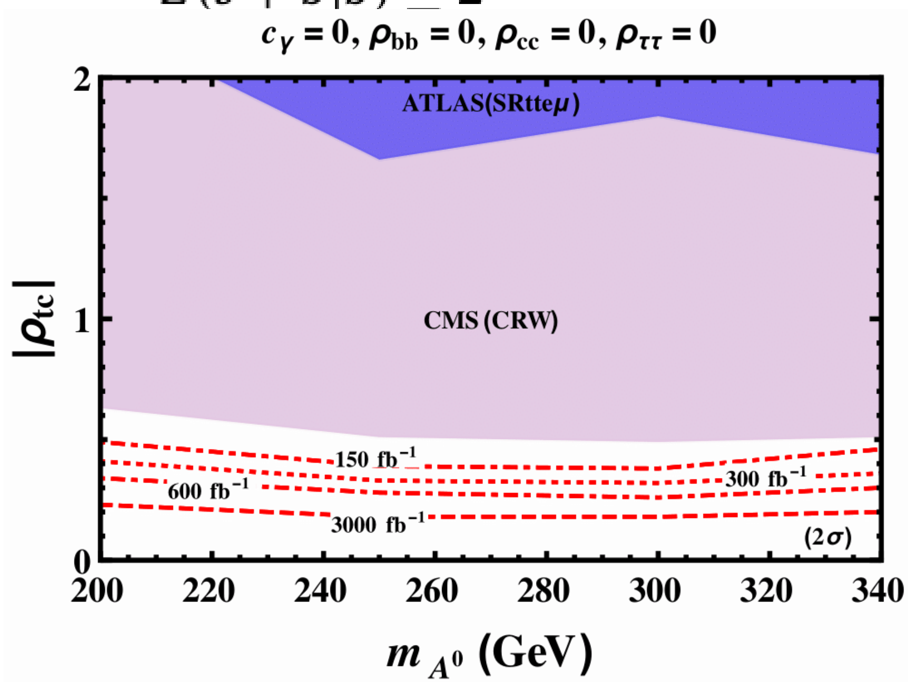




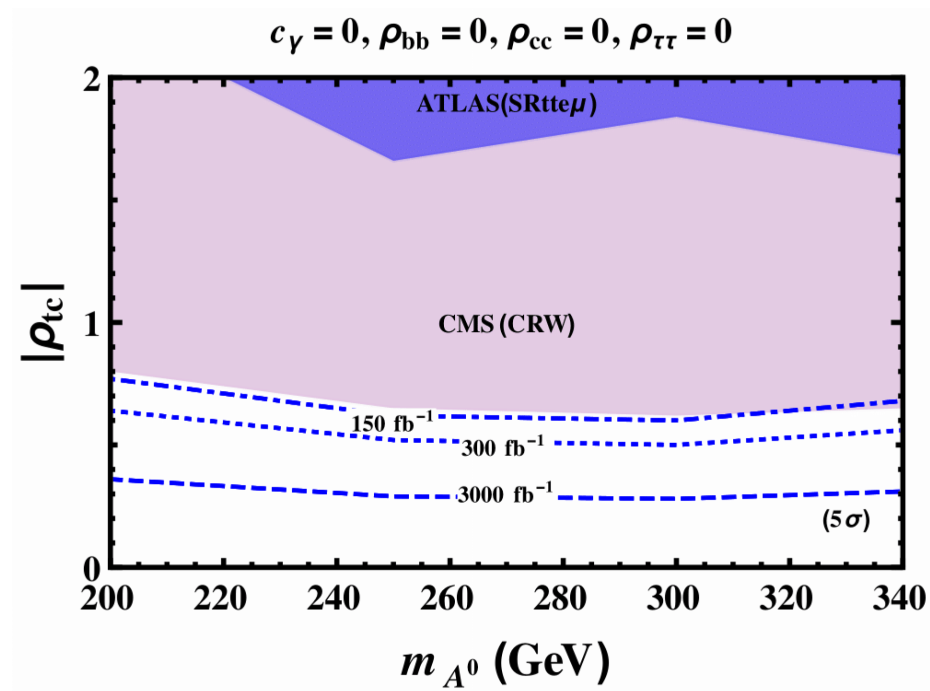
Signal at LO. Backgrounds with QCD corrections included.

$$Z(x|n) = \sqrt{-2\ln\frac{L(x|n)}{L(n|n)}}$$

$Z(s+b|b) \geq 2$



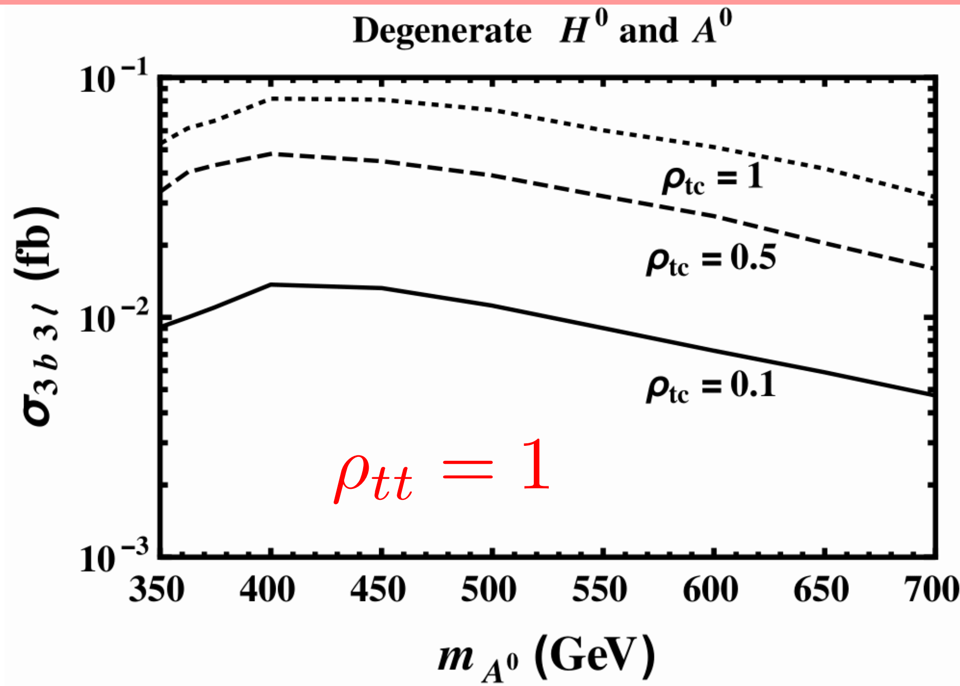
$Z(b|s+b) \geq 5$

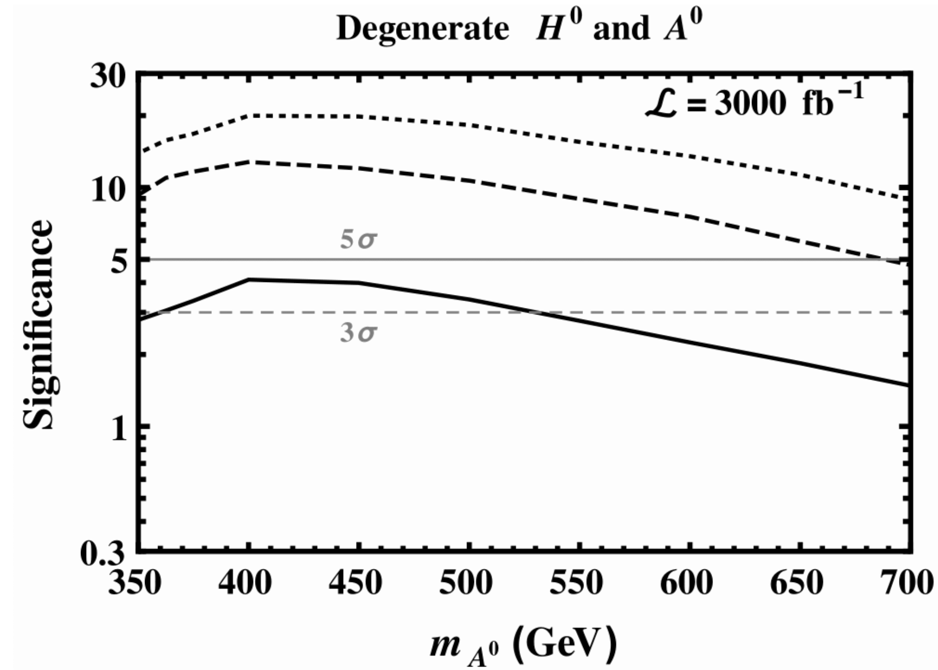


(W.-S Hou, M. Kohda, TM PLB ’18)

Triple-top discovery

(W.-S Hou, M. Kohda, TM PLB '18)





@14 TeV with $3b3\ell$ signature

$$pp \to tS^0 + X \to tt\bar{t} + X$$

The top assisted di-Higgs

(W.-S Hou, M. Kohda, TM, PRD '19)

$$c_\gamma^2 = \frac{\eta_1 v^2 - m_h^2}{m_H^2 - m_h^2}, \qquad \sin 2\gamma = \frac{2\eta_6 v^2}{m_H^2 - m_h^2}$$

$$\eta_1 = \frac{m_h^2 s_\gamma^2 + m_H^2 c_\gamma^2}{v^2},$$

$$\eta_3 = \frac{2(m_{H^\pm}^2 - \mu_{22}^2)}{v^2},$$

$$\eta_4 = \frac{m_h^2 c_\gamma^2 + m_H^2 s_\gamma^2 - 2m_{H^\pm}^2 + m_A^2}{v^2},$$

$$\eta_5 = \frac{m_H^2 s_\gamma^2 + m_h^2 c_\gamma^2 - m_A^2}{v^2},$$

$$\eta_6 = \frac{(m_h^2 - m_H^2)(-s_\gamma)c_\gamma}{v^2},$$

Here we dropped the "0" from ***h^0, H^0, A^0***

The *Hhh* coupling

- Hhh coupling: coefficient of $\lambda_{Hhh} H h^2$

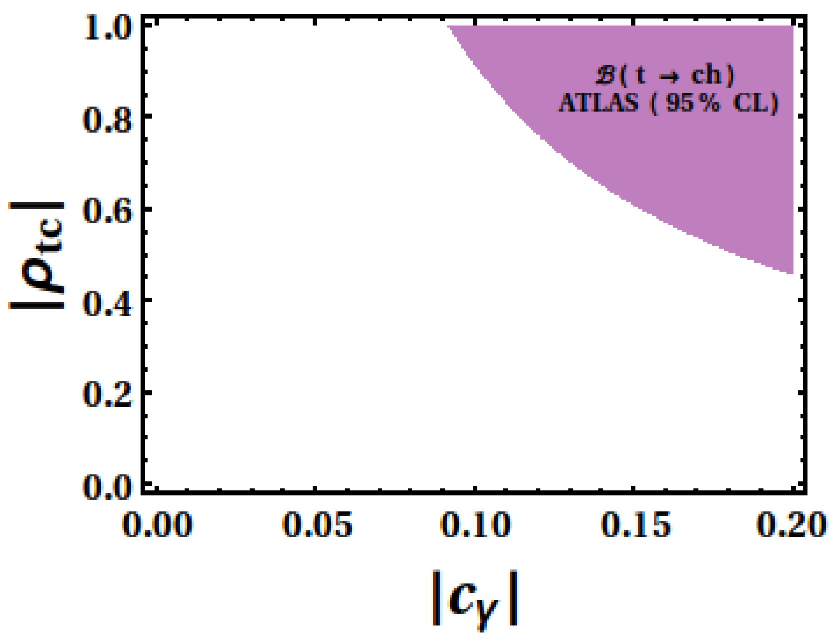
$$\lambda_{Hhh} = \frac{v}{2}\Big[3c_\gamma s_\gamma^2 \eta_1 + c_\gamma(3c_\gamma^2 - 2)\eta_{345} + 3s_\gamma(1 - 3c_\gamma^2)\eta_6 + 3s_\gamma c_\gamma^2 \eta_7\Big]$$

- For small c_γ :

$$\lambda_{Hhh} \simeq \frac{c_\gamma}{2} v \left[3\frac{m_H^2}{v^2} - 2\eta_{345} + 3\mathrm{sgn}(s_\gamma)c_\gamma \eta_7 + \mathcal{O}(c_\gamma^2)\right]$$

Unitarity, Perturbativity:
2HDMC: Higgs basis
+
T-parameter

Additionally all $|\eta_i| < 3$



- $cg \to tH^0 \to th^0h^0$
- $5b + 1\ell + E_T^{\rm miss}$
- Finite b-tagging efficiency

Signature:

$5j(4b) + 1\ell + E_T^{\rm miss}$

BP	ρ_{tc}	tc	hh	WW	ZZ
1	0.54	0.698	0.232	0.049	0.021
2	0.54	0.688	0.238	0.051	0.023
3	0.54	0.677	0.235	0.06	0.027
a	0.54	0.700	0.229	0.049	0.021
b	0.54	0.686	0.240	0.051	0.023
c	0.54	0.674	0.238	0.059	0.027

BP	Signal (fb)	Total Bkg. (fb)	Significance 600 (3000) fb^{-1}
1	0.396	9.002	3.2 (7.2)
2	0.38	9.86	2.9 (6.6)
3	0.288	10.915	2.1 (4.8)
a	0.39	8.906	3.2 (7.1)
b	0.368	9.948	2.8 (6.4)
c	0.295	10.898	2.2 (4.9)

$m_H \sim 300$ GeV

tZH production

$A \to ZH$ decay

Favored by Strongly 1^{st} order EWPT

(Dorsch et. al, PRL'14)

$cg \to tA \to tZH$ (W.-S. Hou, TM, PRD'20)

BP	η_1	η_2	η_3	η_4	η_5	η_{345}	η_6	η_7	$m_{H^\pm}$ (GeV)	m_A (GeV)	m_H (GeV)	$\frac{\mu_{22}^2}{v^2}$
a	0.258	2.133	2.87	-0.569	-1.194	1.107	0	-0.791	310	339	207	0.15
b	0.258	1.366	2.718	-0.733	-1.97	0.015	0	-0.252	354	404	208	0.71
c	0.258	2.432	2.67	-0.652	-2.21	-0.192	0	0.091	393	449	260	1.21

BP	Signal (fb)	Significance ($\mathcal{Z}$) 600 (3000) fb^{-1}
a	0.055	1.5 (3.4)
b	0.115	2.7 (6.0)
c	0.092	2.1 (4.8)

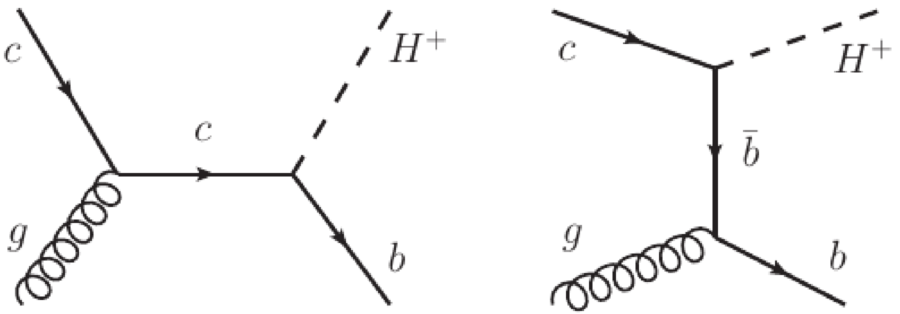
$cg \to tA \to tZh$: Not promising

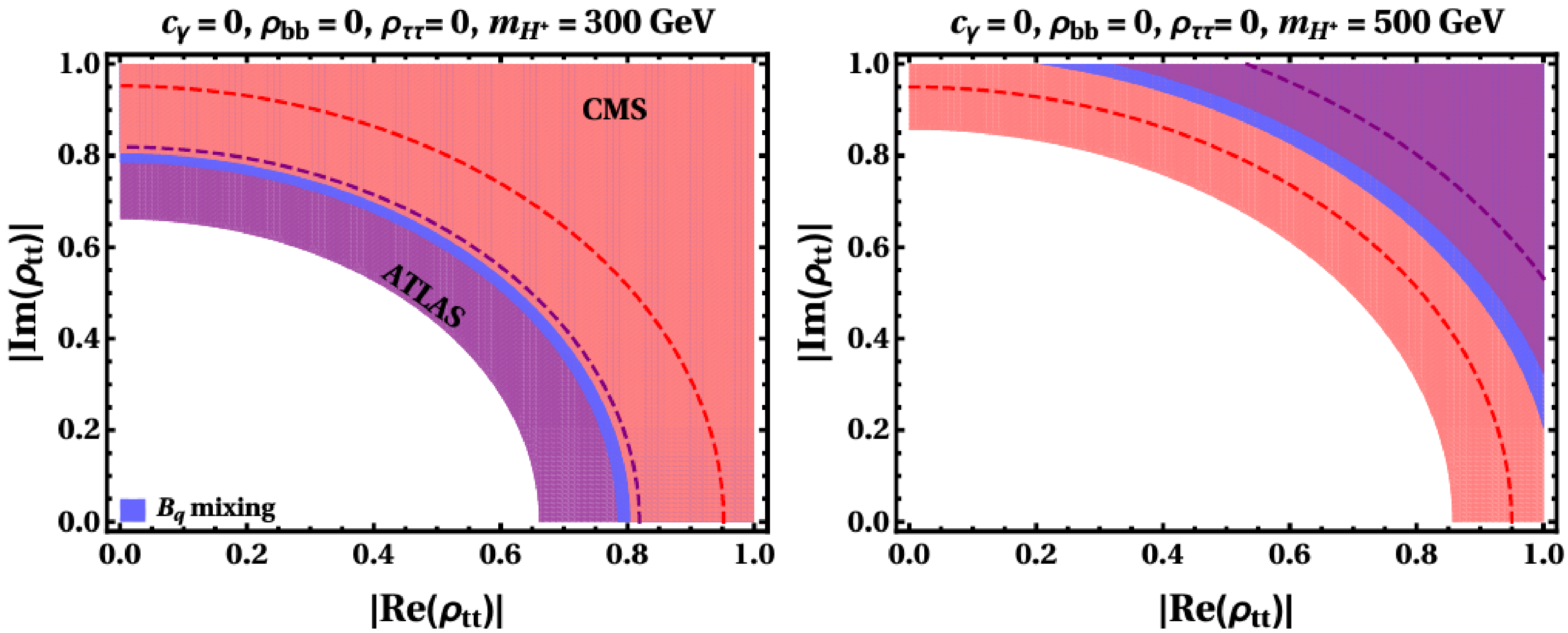
bH^+ production

(D.K. Ghosh, W.-S. Hou, TM, 1912.10613)

$$cg \to bH^+ \to bt\bar{b}$$

$$\rho_{tt}, \rho_{tc}$$





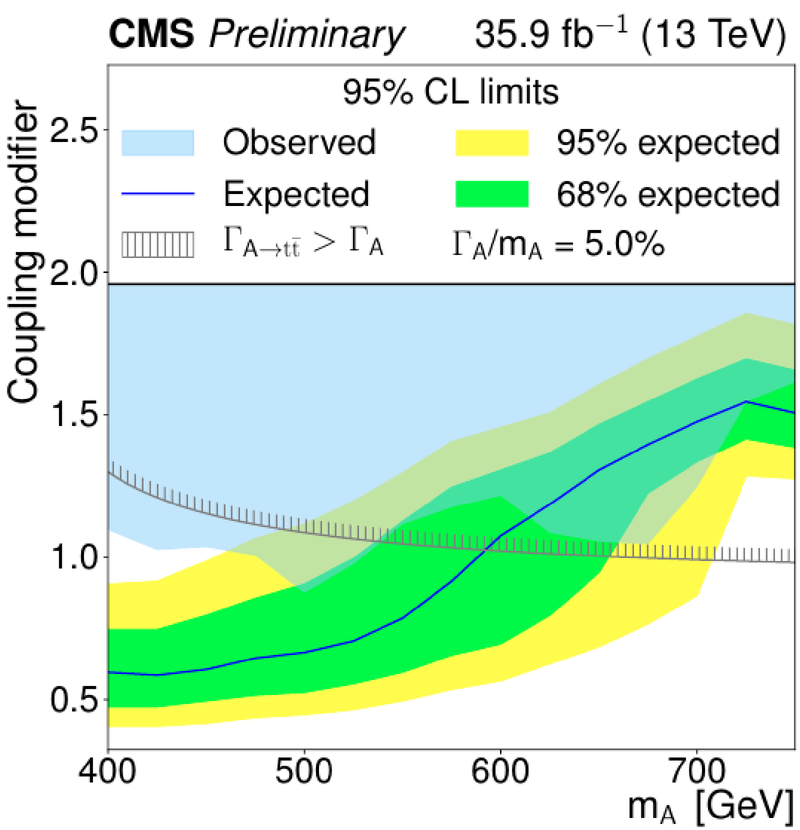
$$|\rho_{tc}| = 0.4, \; |\text{and } \rho_{tt}| = 0.6$$

	η_2	η_3	η_4	η_5	η_7	$\frac{\mu_{22}^2}{v^2}$	m_{H^+}	m_A	m_H
BP1	1.40	0.62	0.53	1.06	−0.79	1.18	300	272	372
BP2	0.71	0.69	1.52	−0.93	0.24	3.78	500	569	517

	$t\bar{t}j$s	tj	Wtjs	$t\bar{t}h$	$t\bar{t}Z$	other	$\mathrm{B_{tot}}$	Sig
BP1	1546	42	27	4.2	1.5	3.1	1627	11.4
BP2	1000	27	16	2.9	1.2	1.9	1049	9.3

The discovery potential with ~ 137 , 300 and 600 fb^{-1} datasets $\sim 3.3\sigma$, 4.9σ, 6.9σ for BP1, and $\sim 3.4\sigma$, 5.0σ, 7.1σ for BP2.

Excess from CMS



(Fig. from CMS PAS HIG-17-027)

- $gg \to A \to t\bar{t}$

(CMS PAS HIG-17 027, arXiv:1908.01115)

$$\mathcal{L}_{\text{Yukawa, H}} = -g_{\text{Ht}\bar{\text{t}}}\frac{m_{\text{t}}}{v}\bar{\text{t}}\text{tH}, \qquad \mathcal{L}_{\text{Yukawa, A}} = ig_{\text{At}\bar{\text{t}}}\frac{m_{\text{t}}}{v}\bar{\text{t}}\gamma_5\text{tA}$$

$g_{At\bar{t}}/g_{Ht\bar{t}} \equiv$ Coupling modifier

- 3.5σ excess around $m_A = 400$ GeV

  $\Gamma_A/m_A \sim 4\%$

1. $|m_H - \text{m}_A|$ should not be large.
2. $gg \to t\bar{t}A \to t\bar{t}t\bar{t}$ limit should be respected
3. $g_{At\bar{t}}/g_{Ht\bar{t}}$ in general complex

- Can be accommodated in G2HDM

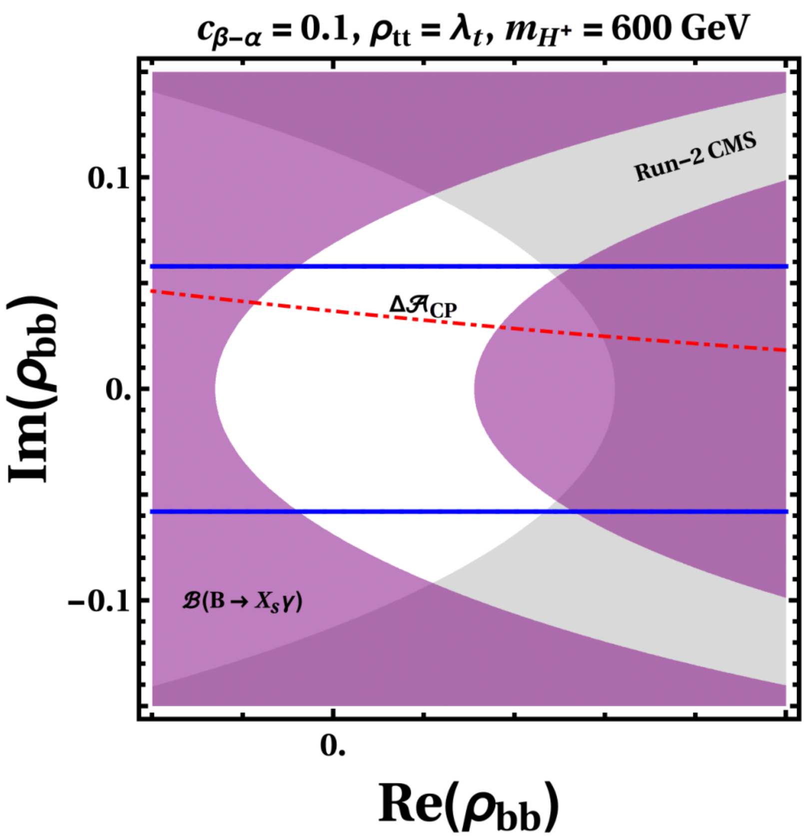
  $\rho_{tt} \sim 1.1, \ \rho_{tc} \sim 0.9$

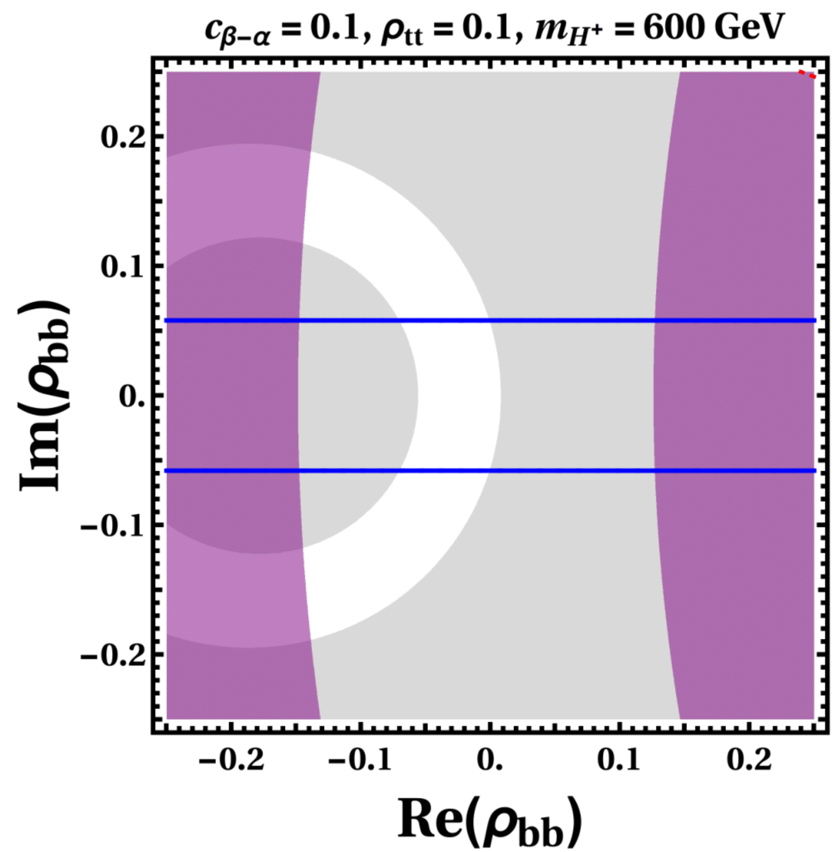
  (W.-S.Hou, M. Kohda, TM, PLB'19)

Signatures for extra bottom Yukawa couplings

Extra bottom Yukawa

EWBG via extra bottom Yukawa: $\mathrm{Im}(\rho_{bb}) \gtrsim 0.058.$ (TM, E. Senaha PRD '19)



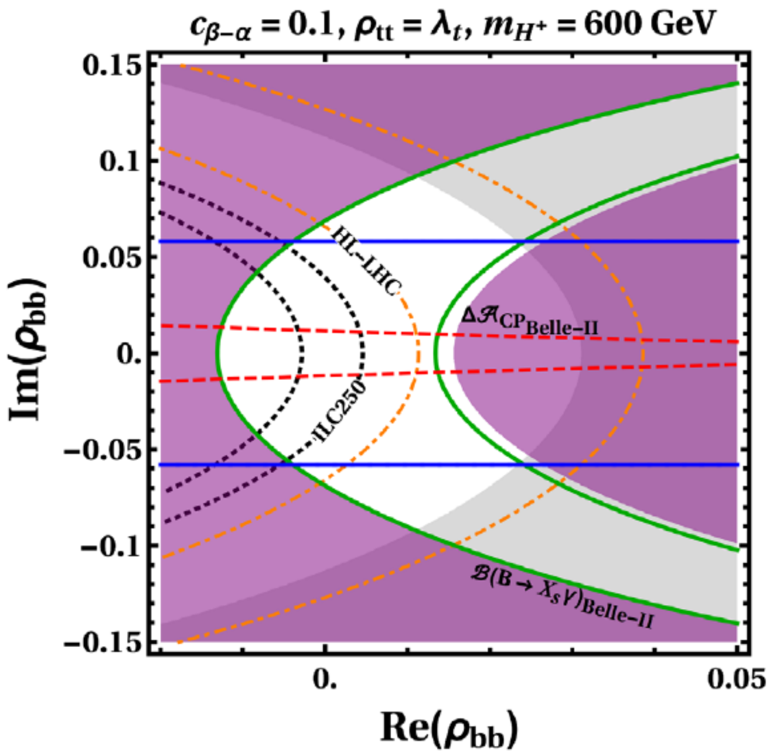


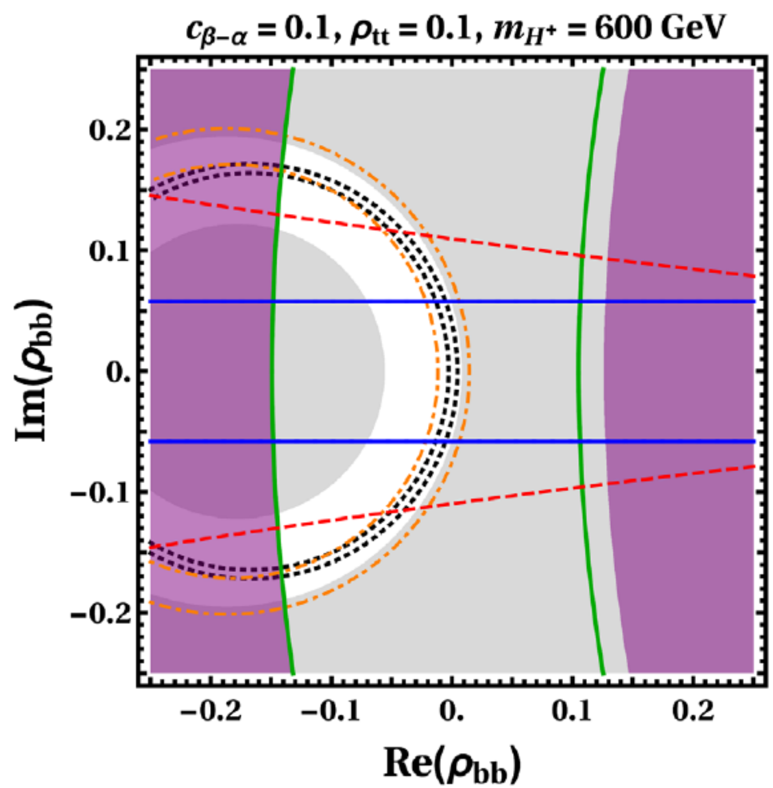
Asymmetry of CP asymmetr of $B \to X_s\gamma$: $\Delta\mathcal{A}_{\rm CP}$

$|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$ (ACME 2018)

Alleviated if: $0.06 \lesssim \mathrm{Im}\rho_{ee}/(\lambda_e\lambda_b) \lesssim 0.3$

In Future





Other signatures:

$bg \to bA \to bZH$ (TM, PRD '19)

Discovery (300 fb^{-1}): $m_A \sim 300 - 400$ GeV
HL-LHC: up to 600-700 GeV

$bg \to bA \to b\bar{t}t$ (TM, E. Senaha, 2005.09928)

ILC-250: *hbb*
Belle-II: $\mathcal{B}(B \to X_s\gamma)$, $\Delta\mathcal{A}_{CP}$

Summary

- 2HDM without Z_2 : Extra Yukawas.
- NFC may be overkill.
- Extra Yukawas: Electroweak Baryogenesis. ρ_{tt}, ρ_{bb} and FCNH: ρ_{tc}.
- Extra Yukawas: leading to novel signatures at LHC.
- ILC, LHC, Belle-II offer exquisite probes as well.
- Discovery may help understand the Matter-Antimatter asymmetry of the Universe.

Thank You

Back ups

Baryon Asymmetry of the Universe

Universe is matter dominated: Baryon Asymmetry or Matter-anti Matter Asymmetry

$$Y_B^{obs} = \frac{n_B - n_{\bar{B}}}{s} \approx 8.6 \times 10^{-11}$$ (Planck, Astron. Astrophys. 571, A16 (2014))

no. density of Baryon: n_B

Entropy density: $s = g^* T^3 (2\pi^2/45)$

Conditions for Baryogenesis: (Sakharov' Zh. Eksp. Teor. Fiz. Pis'ma 5 (1967) 32)

1. Baryon number violations:

Start with Baryon symmetric Universe: $\Delta B = 0$; Evolve to Baryon Asymmetric Universe: $\Delta B \neq 0$

2. C and CP violation:

If C and CP are conserved:
Rate of processes involving Baryons = Rate of C and CP conjugate process ⇨ No Baryon Asymmetry

3. Departure from thermal equilibrium:

In chemical equilibrium: no asymmetries in quantum numbers that are not conserved such as B

CPT invariance: Prevents of Baryon excess

All three Sakharov's conditions can be met at the Electroweak Phase Transition ⇨ Electroweak Baryogenesis

(V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, PLB'85, PLB'87;
A.G. Cohen, D.B. Kaplan and A.E. Nelson, Annu. Rev. Nucl. Part. Sci.'93)

Electroweak Baryogenesis

How about SM?

1. Baryon number is violation is due to the triangle anomaly (chiral anomaly).

The rate at zero temperature: $e^{-4\pi/\alpha_W}$ → Too tiny (Gerard't Hooft,PRL'76)

unsuppressed at finite temp. (V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, PLB'85, PLB'87;)

2. Weak interaction violates C maximally and violates CP by CKM

CP violation parametrized by Jarlskog invariant: in SM: $\sim 10^{-20}$

and, no kinematic enhancement factors in the thermal bath

} Too small for observed BAU

3. Departure from thermal equilibrium: by the electroweak phase transition but strongly first order

B-violating interactions are out of equilibrium in the bubble wall → A net Baryon Asymmetry inside the bubble wall

$m_h = 125$ GeV → Not strongly first order

g2HDM

$$\text{complex } \rho_{tt},\ \rho_{tc}: \quad \text{complex } \rho_{bb}:$$

} → Additional source of CP violation

$$\text{e.g. } S_{\rm CPV} = C_{\rm BAU}\,{\rm Im}[(Y_1)_{bs}(Y_2)^*_{bs}]$$

(TM, E. Senaha; PRD '19)

$$\mathrm{Im}\rho_{\rm bb} = -\frac{1}{\lambda_{\rm b}}\mathrm{Im}[(\mathrm{Y}_1)_{\rm bs}(\mathrm{Y}_2)^*_{\rm bs}]$$

Additional-bosonic degrees of freedom: $m_H,\ m_A,\ m_{H^\pm}$ → Strongly first order EWPT

$$\mathrm{Im}(\rho_{bb}) = -\frac{1}{\lambda_b}\mathrm{Im}[(Y_1)_{bs}(Y_2)^*_{bs}]$$

$$S_{\mathrm{CPV}} = C_{\mathrm{BAU}}\mathrm{Im}[(Y_1)_{bs}(Y_2)^*_{bs}]$$

total left-handed number density (in wall rest frame)

$$n_L(\bar{z}) \simeq \frac{r_2 v_w^2}{\Gamma_{ss}\bar{D}}\left(1 - \frac{D_q}{\bar{D}}\right) H(\bar{z}) + \mathcal{O}(1/\Gamma_Y)$$

$$H(\bar{z}) \simeq e^{v_w \bar{z}/\bar{D}} k_H L_w S_{b_L} \sqrt{a} / \sqrt{(\Gamma^-_{M_t} + \Gamma_H)(k_H(a+b)\bar{D})}$$

$\Gamma_{Y_t},\ \Gamma^-_{M_t},\ \Gamma_H \text{ and } \Gamma_{ss}$: rates by top-Higgs interactions, top-bubble wall interactions, Higgs number-violating interactions and strong sphaleron

Solving a diffusion equation for the baryon number density

$$n_B = \frac{-3\Gamma_B^{(\mathrm{sym})}}{2D_q\lambda_+}\int_{-\infty}^{0} dz'\ n_L(z')e^{-\lambda_- z'}$$

with $\lambda_\pm = [v_w \pm \sqrt{v_w^2 + 4\mathcal{R}D_q}]/2D_q$ and $\mathcal{R} = 15\Gamma_B^{(\mathrm{sym})}/4$

B changing rate in symm. phase via sphaleron: $\Gamma_B^{(\mathrm{sym})} = 5.4 \times 10^{-6} T$

Bubble Wall velocity: $v_w = 0.4$

Strong sphaleron rate: $\Gamma_{ss} = 3.2 \times 10^{-3} T$

Diffusion const.: $D_q = 8.9/T$