Extra Yukawas: Searching for New Scalars via Triple-Top Signature

Tanmoy Modak

National Taiwan University

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With: M. Kohda & W.-S. Hou

Overview

- 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 1706.07694v3)

- 2HDM without Z_2 ➡ *Extra Yukawas* : $\rho_{tc}, \ \rho_{tt}.$
- ***Sub-TeV Second Doublet*** + ***Extra Yukawas***:

  Novel Signatures at LHC: $cg \to tA^0/tH^0 \to tt\bar{t}.$

  Precursor: $cg \to tA^0/tH^0 \to tt\bar{c}.$

- Bonus: Discovery may shed light on *Baryon Asymmetry of the Universe*.

  (Fuyuto, Hou, Senaha PLB '18)

The Yukawa Sector

- E.g. in 2HDM-II: up- and down-type quarks get masses from different doublets.
  - Mass and Yukawa matrices are diagonalized simultaneously.
  - Realized by invoking Z_2 symmetry. NFC. *(Glashow, Weinberg PRD'77)*
- 2HDM without Z_2: Both doublets couple with up- and down-type fermions.
  - After diagonalization of fermion mass matrices: Two different Yukawas. κ_f and ρ_f with $\kappa_f = \frac{\sqrt{2}m_f}{v}$.
  - κ_f diagonal and real; ρ_f non-diagonal and in general complex.

In particular for up-type quark:

$$-\frac{1}{\sqrt{2}}\bar{u}(\kappa_u c_{\beta-\alpha} - \rho_u s_{\beta-\alpha})P_R u H^0 + \frac{i}{\sqrt{2}}\bar{u}\rho_u P_R u A^0 + \text{h.c.}$$

$$\begin{bmatrix} H^0 \\ h^0 \end{bmatrix} = \begin{bmatrix} c_{\beta-\alpha} & s_{\beta-\alpha} \\ -s_{\beta-\alpha} & c_{\beta-\alpha} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

- In alignment limit : $c_{\beta-\alpha} = 0$: for simplicity

$$\frac{\rho_{ij}}{\sqrt{2}}\,\bar{u}_{iL}(H^0 + i\,A^0)u_{jR} + \text{h.c.}$$

- ρ_{ij} : could share same flavor organization features as SM

⬇

Trickling down off-diagonal elements

(Cheng, Sher PRD'87, see also WS Hou PLB '92)

- $\rho_{bb} \sim \kappa_b, \rho_{\tau\tau} \sim \kappa_\tau$ and $\rho_{tt}, \rho_{tc} \sim \kappa_t \simeq 1.$

- Complex ρ_{tt} of $\mathcal{O}(1)$ strength can drive EWBG.
  For small $|\rho_{tt}|$, $\mathcal{O}(1)$ ρ_{tc} with maximal phase. (Fuyuto, Hou, Senaha PLB '18)

- B physics constraint: $\rho_{ct} \simeq 0.$ (Chen et al. PLB '13, Altunkaynak et al. PLB '15)

Signatures at LHC

- $gg \to A^0/H^0 \to t\bar{t}$: interference with $gg \to t\bar{t}$. (See e.g. Carena and Liu JHEP '16)

  Recent ATALS study: could be sensitive. (ATLAS PRL '18)

  ➡ study above $t\bar{t}$ threshold

- Other search modes:

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

  (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 et al. PLB '15)

  suffers from $t + j$ mass resolution.

  (CMS-PAS-B2G-16-025)

- **Triple-top:**

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

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

1. SM $3t$ at fb level.
2. Clean $3b$-jets, 3-lepton final state

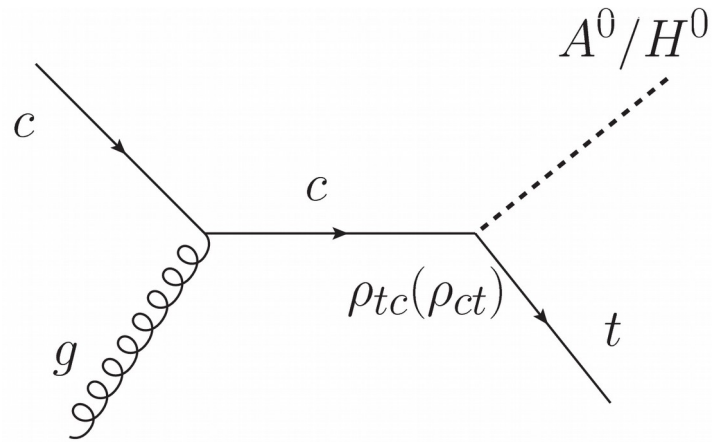
(Barger, Keung, Yencho, PLB '10)

- **Same-sign top:**

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

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

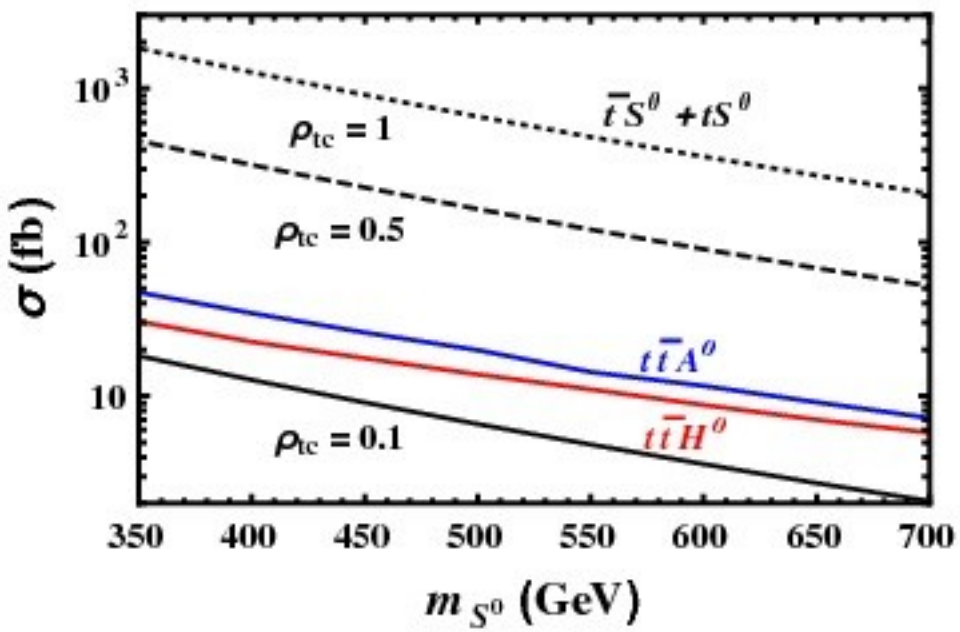
(See also Hou et al. PLB '97)



- Assumed nearly degenerate heavy scalars to forbid:

$$H^0 \to A^0 Z, H^\pm W^\mp \text{ or reverse.}$$

Parton level cross sections



Parton level cross sections at LO:

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

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

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

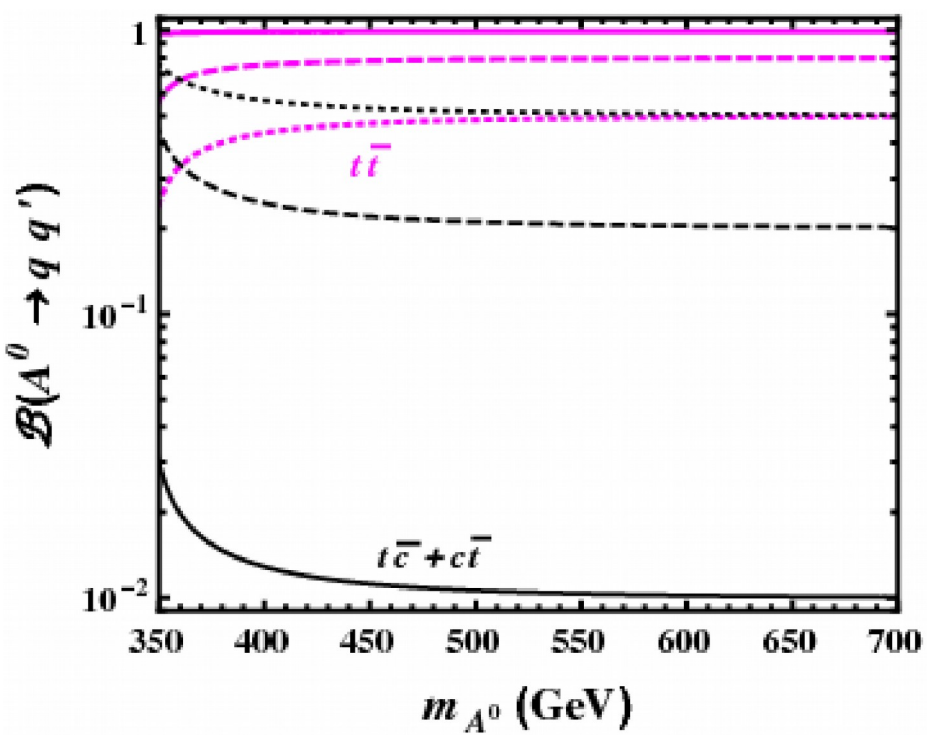
$\sqrt{s} = 14$ TeV

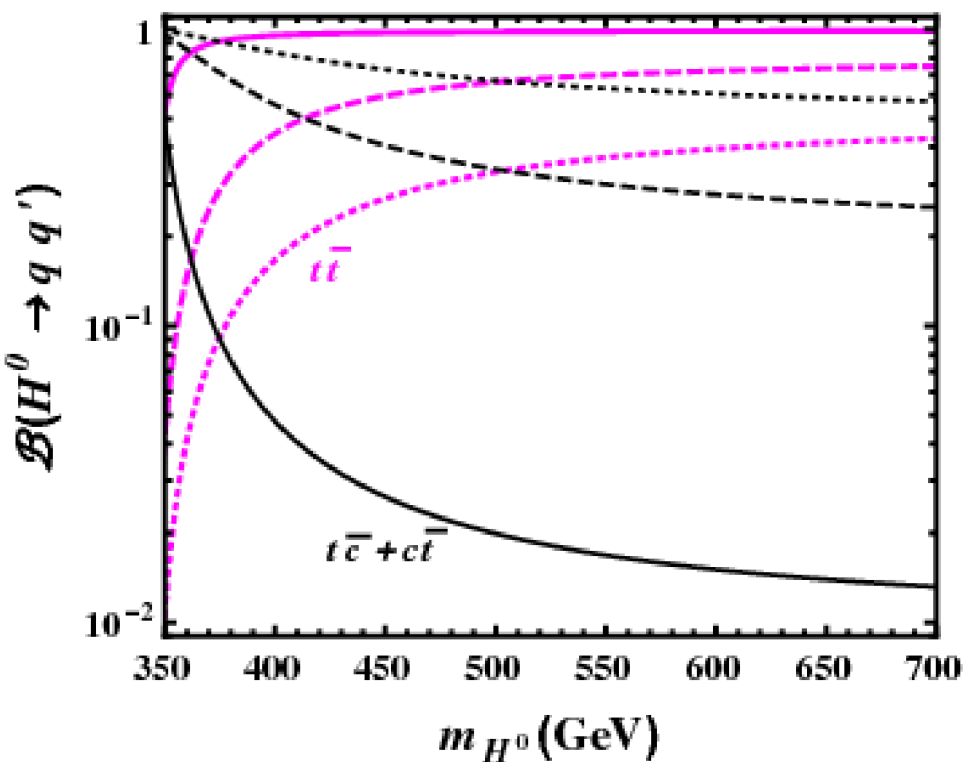
fixed $\rho_{tt} = 1$

PDF set : NN23LO1

MadGraph5_aMC@NLO

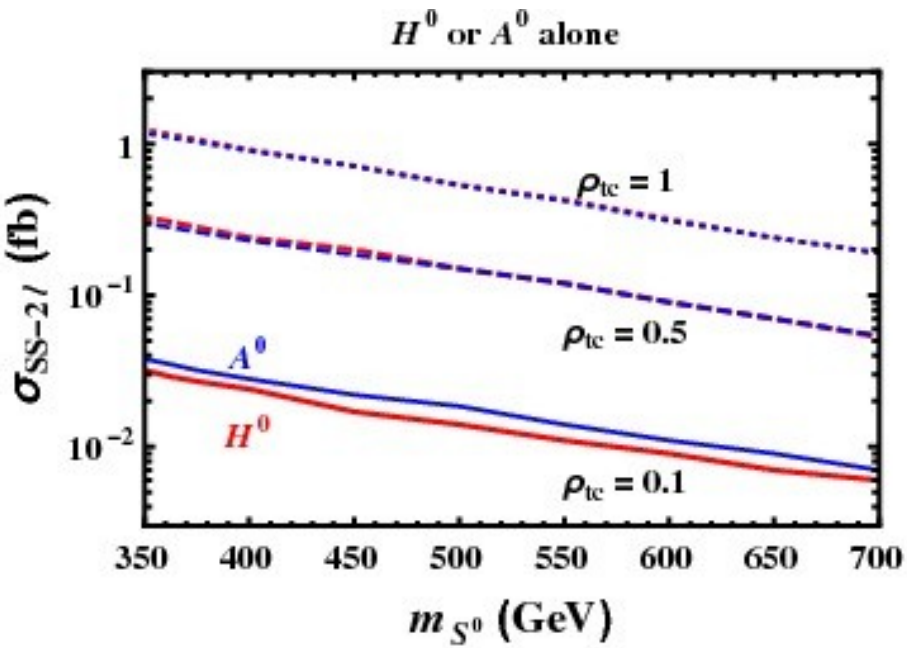
For $\Gamma_{H^0} = \Gamma_{A^0}$ and $m_{A^0} = m_{H^0}$, $pp \to tA^0 \to tt\bar{c}$ and $pp \to tH^0 \to tt\bar{c}$ cancels each other exactly.

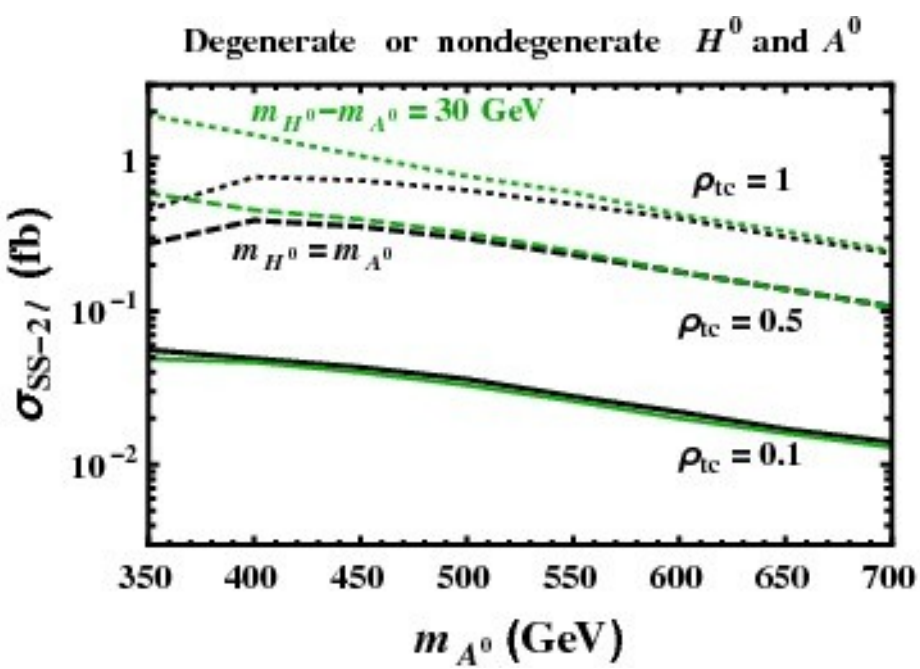




Same-sign top

MadGraph5_aMC + Pythia 6.4 + Delphes-3.4.0





Process:

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

Event selection:

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

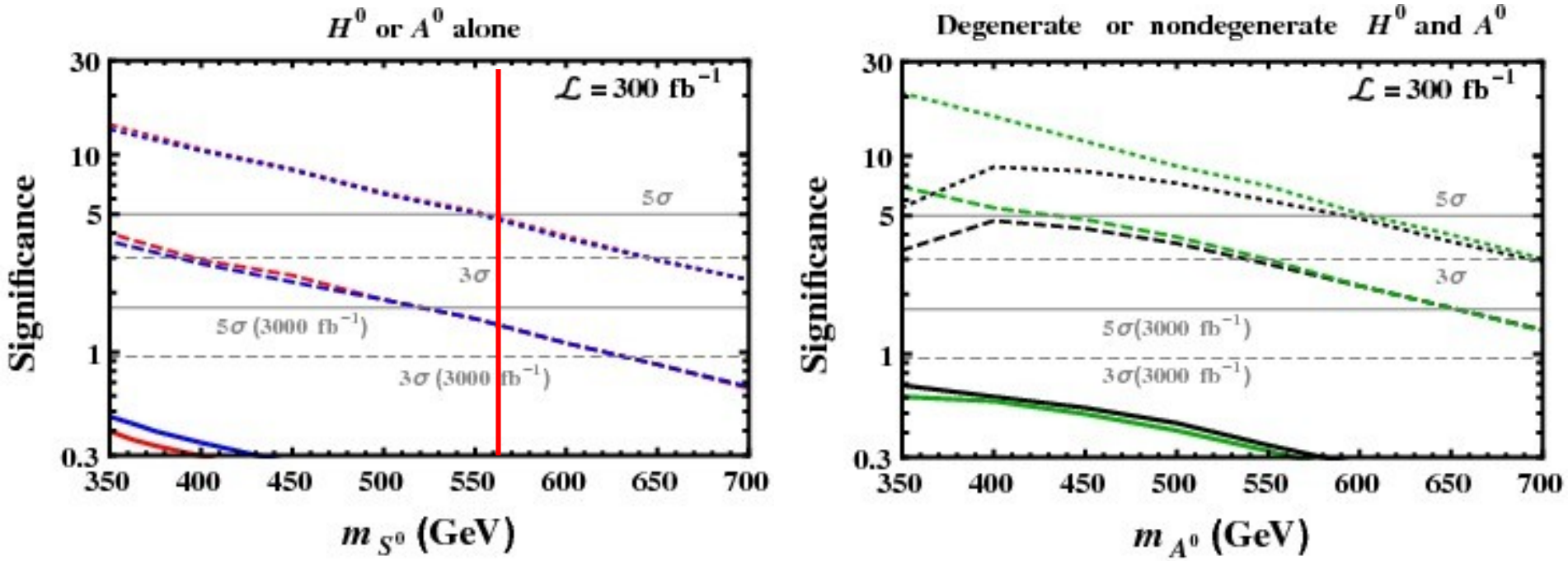
denoted as $(SS\text{-}2\ell)$

Backgrounds	Cross section (fb)
$t\bar{t}Z$	0.04
$t\bar{t}W$	0.72
tZ+jets	0.001
$3t + j$	0.0002
$3t + W$	0.0004
$t\bar{t}h$	0.024
$4t$	0.04
Q-flip	0.04

$+$Non-prompt $\sim 1.5 \times t\bar{t}W$ (CMS EPJC '17)

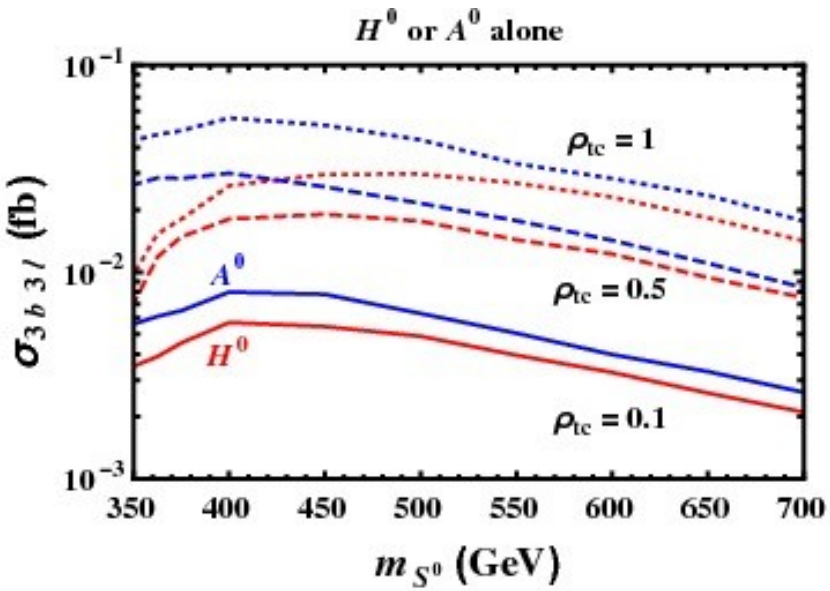
Signal at LO. Backgrounds with QCD corrections included.

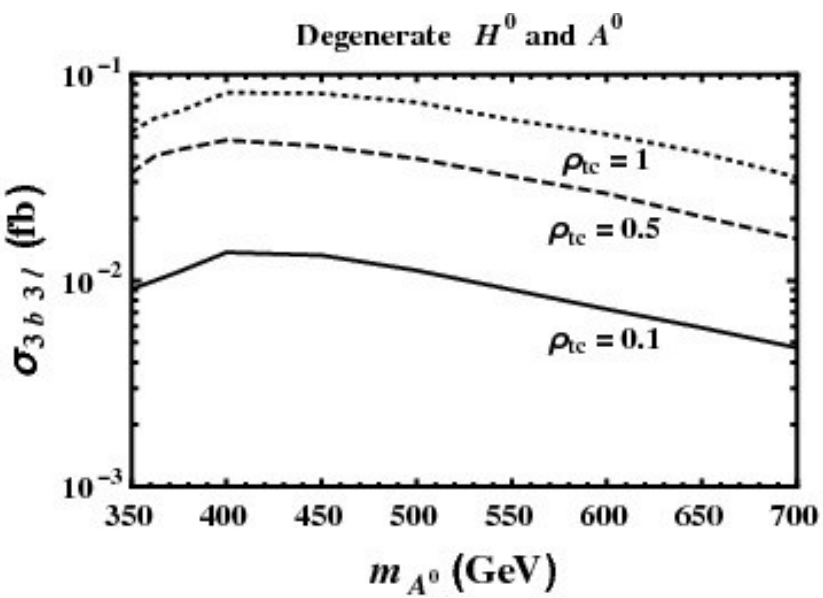
Discovery potential:



- H^0 or A^0 alone : 5σ for $\rho_{tc} = 1$ and $m_{S^0} \lesssim 550$ GeV.
- Discovery: easier for small H^0 - A^0 mass splitting case.
- Discovery could indicate ρ_{tc} driven BAU.

Triple-top





Process:

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

Event selection:

at least 3 leptons, $E_T^{\rm miss}$
$\geq$ 3jets with $\geq 3b$ *tagged*

denoted as $(3b3\ell)$

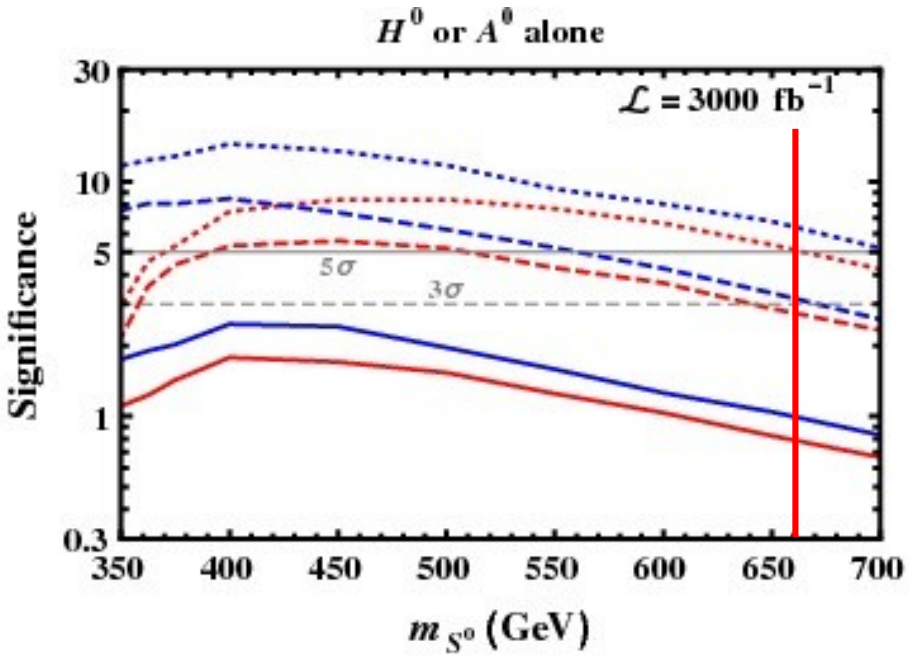
Backgrounds	Cross section (fb)	
$t\bar{t}Z$+jets	0.0205	(0.0026)
$t\bar{t}Wb$	0.0017	(0.0015)
$tZjb$	0.0002	(−)
$3t + j$	0.0001	(0.0001)
$3t + W$	0.0004	(0.0003)
$t\bar{t}h$	0.0015	(0.0013)
$4t$	0.0232	(0.0209)
$t\bar{t}$+jets (fake)	0.0026	(0.0025)

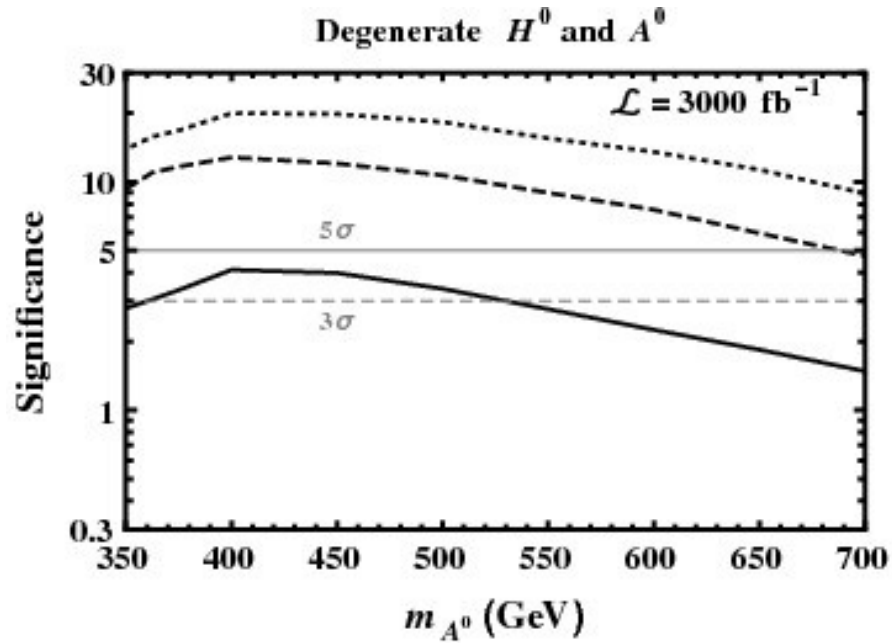
parenthesis: impact of Z-pole veto

Signal at LO. Backgrounds with QCD corrections included.

Discovery potential:

$$\mathcal{Z} = \sqrt{2[(S+B)\ln(1+S/B) - S]}$$





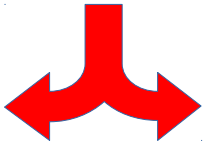
- 5σ for H^0 or A^0 only case : e.g. if $\rho_{tc} = 1,\ \rho_{tt} = 1$ and $m_{S^0} \lesssim 650$ GeV.
- For H^0 and A^0 degenerate case: significances are boosted by the addition of H^0 and A^0 contributions.

Summary

- 2HDM without Z_2 : Extra Yukawa ρ_{tt} and FCNH: ρ_{tc}.

- Extra Yukawas: leading to novel signatures at LHC.

Triple-top



Same-sign top

- Triple-top may require HL-LHC, however Same-sign top may emerge with 300 fb^{-1} data.

- Discovery may help understand the Matter-Antimatter asymmetry of the Universe.

Thank You

Backups:

CP conserving 2HDM without Z_2 :

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

CP-even mass matrix:

$$R_\gamma = \begin{bmatrix} c_\gamma & -s_\gamma \\ s_\gamma & c_\gamma \end{bmatrix}$$

(Hou and Kikuchi, 1706.07694v3)

- Near Alignment:

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

In Higgs Basis:

$$\cos(\beta-\alpha) \simeq \frac{-Z_6 v^2}{m_H^2 - m_h^2}$$

(Bechtle et al. EPJC '17)

Exact alignment: c_γ *or* $\cos(\beta-\alpha) = 0.$
Current limit : $|c_\gamma| \sim 0.3$

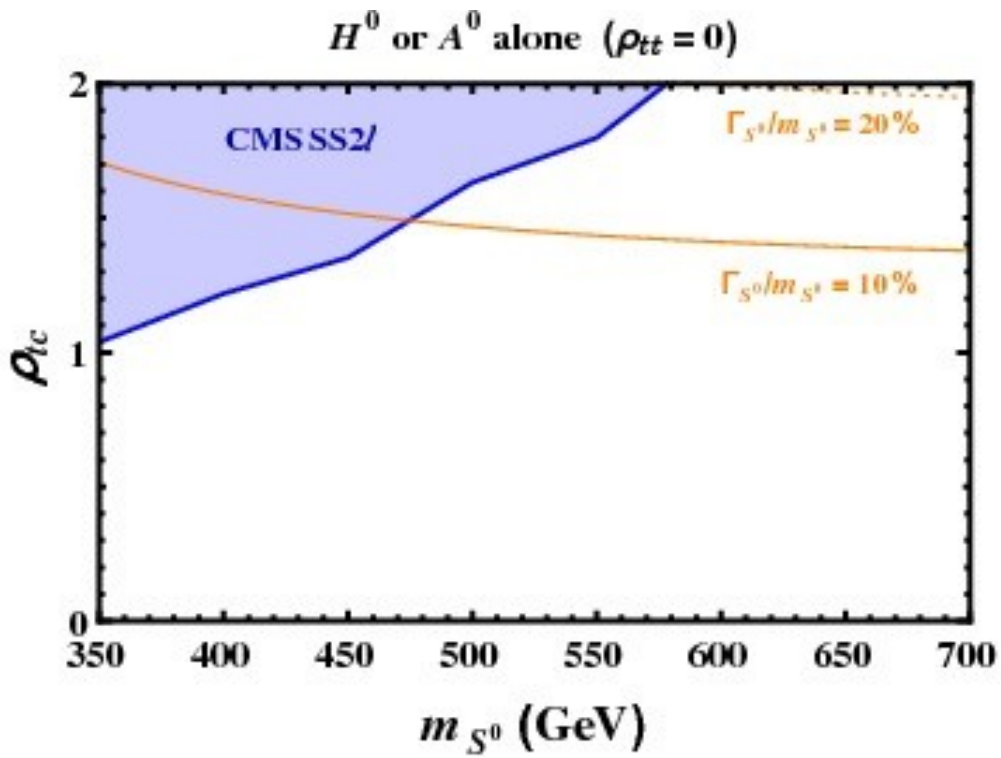
- Alignment without decoupling:

$|c_\gamma| \simeq 0.1$ even with $|\eta_6|$ or $|Z_6| \sim \mathcal{O}(1)$
and $m_H \lesssim 1\ TeV$

(Barnon et al. PRD '15,
Hou and Kikuchi, 1706.07694v3)

Excellent scope for LHC search

- All dimensionless parameters in Higgs potential could be $\mathcal{O}(1)$ → Strong 1st order EWPT



- ATLAS same-sign top search (Run-1 data) (JHEP '15). no Run-2 update.
  $cc \to tt$ via $t-$channel A^0/H^0
- ATLAS RPV SUSY search (2016 data) (JHEP '17). Could be most relevant but no Run-2 update.
- CMS search 2 SS2l, b-jets+MET (2016 data) (EPJC '17). We utilize Exclusive SR5
- CMS 4 top search (2016 data) (EPJC '18). Could be most relevant.