

Flavor changing neutral Higgs couplings: A road map for discovery at LHC

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Outline

- Overview
- Framework
- Same-sign top and triple-top
- Top-assisted di-Higgs
- Summary

Overview

Overview

- Current data : 125 GeV (h^0) 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 is plausible*.
Can be realized in 2HDM.

(see W.-S Hou's talk for details)

- 2HDM without Z_2  *Extra Yukawas : ρ_{tc}, ρ_{tt} .*
Baryon Asymmetry of the Universe.

(See talk by E. Senaha)

- ***Sub-TeV Second Doublet + Extra Yukawas***: Novel Signatures at LHC:

Triple-top: $cg \rightarrow tA^0/tH^0 \rightarrow tt\bar{t}$.

Same-sign top: $cg \rightarrow tA^0/tH^0 \rightarrow tt\bar{c}$.

Top-assisted di-Higgs: $cg \rightarrow tH^0 \rightarrow thh$.

Framework

The Higgs sector

CP conserving 2HDM without Z_2 :

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

★ Near Alignment (In Higgs Basis):

$$c_\gamma \simeq \frac{-\eta_6 v^2}{m_H^2 - m_h^2}; \quad \langle \Phi \rangle = (0, v/\sqrt{2})^T \\ \langle \Phi' \rangle = (0, 0)^T$$

$$\cos(\beta - \alpha) \simeq \frac{-Z_6 v^2}{m_H^2 - m_h^2} \\ \tan \beta = \frac{v_2}{v_1}$$

(Bechtle et al. EPJC '17)

★ Alignment without decoupling:

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

CP-even mass matrix:

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

(Hou and Kikuchi, 1706.07694v3)

Excellent scope
for LHC search

(See talk by W.-S Hou)

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 emerge: 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.

$$-\frac{1}{\sqrt{2}} \sum_{F=U,D,L} \bar{F}_{iL} \left[(-\lambda_{ij}^F s_\gamma + \rho_{ij}^F c_\gamma) h^0 + (\lambda_{ij}^F c_\gamma + \rho_{ij}^F s_\gamma) H^0 - i \operatorname{sgn}(Q_F) \rho_{ij}^F A^0 \right] F_{jR} + \text{h.c.}$$

(Davidson, Haber PRD '05)

It is likely that $\rho_f \sim \lambda_f$

Signatures at LHC

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

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

→ study above $t\bar{t}$ threshold

- $gg \rightarrow A^0/H^0 \rightarrow t\bar{c}$: Could be discovered. (Altunkaynak PLB '15)

suffers from $t + j$ mass resolution. (CMS-PAS-B2G-16-025)

(See K.-F Chen's talk)

- Other search modes:

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

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

● **Triple-top:**

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

where, $S^0 \equiv A^0 \text{ or } H^0$

- 1. SM $3t$ at fb level.
(Barger, Keung, Yencho, PLB '10)
- 2. Clean $3b$ -jets,
 3 -lepton final state

● **Same-sign top:**

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

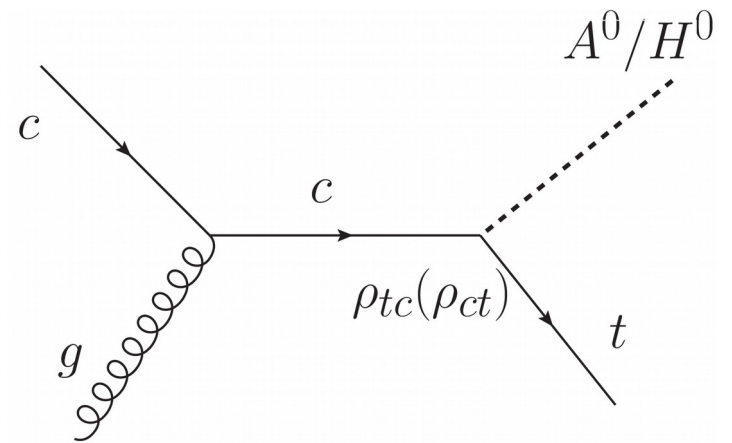
May emerge earlier than triple-top

(See also Hou et al. PLB '97)

● **Top-assisted di-Higgs:**

$$cg \rightarrow tH^0 \rightarrow th^0h^0$$

$5b + 1\ell + E_T^{\text{miss}}$



Assumed nearly degenerate heavy scalars to forbid:

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

(Phys.Lett. B776 379-384;
Phys.Lett. B786 212-216;
W.-S Hou, M. Kohda, TM)

(Phys.Rev. D99, 055046; W.-S Hou, M. Kohda, TM)

- 1. Tiny di-Higgs in SM
- 2. Resonant di-Higgs
- 3. Probe for Higgs potential

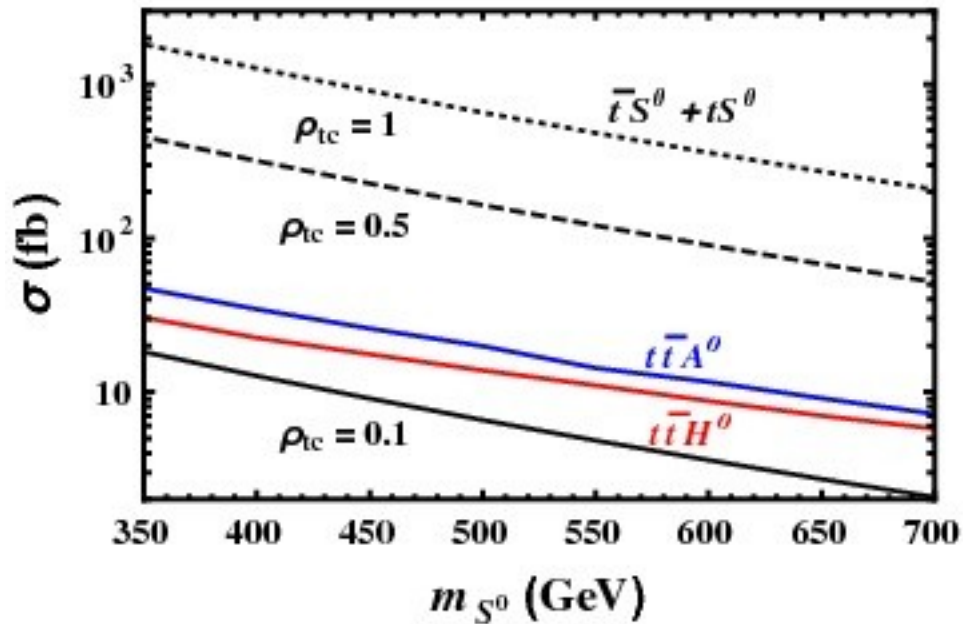
(see Spencer Chang's,
Kingman Cheung's and S.
Paganis' talk)

Same-sign top and triple-top

Parton level cross sections

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

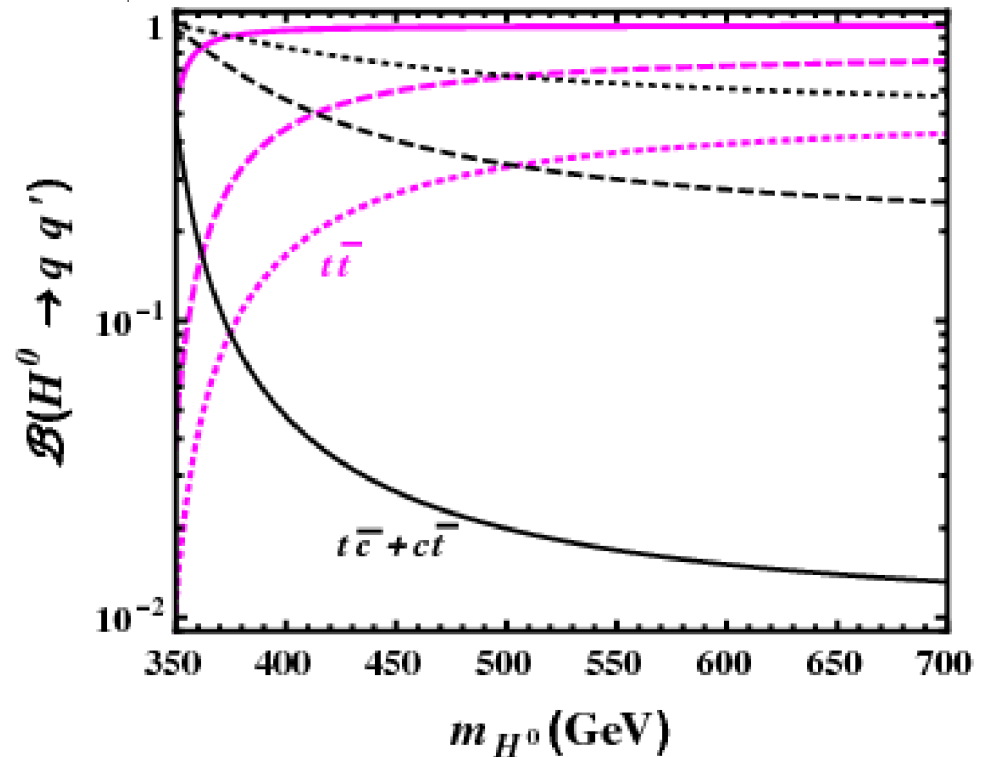
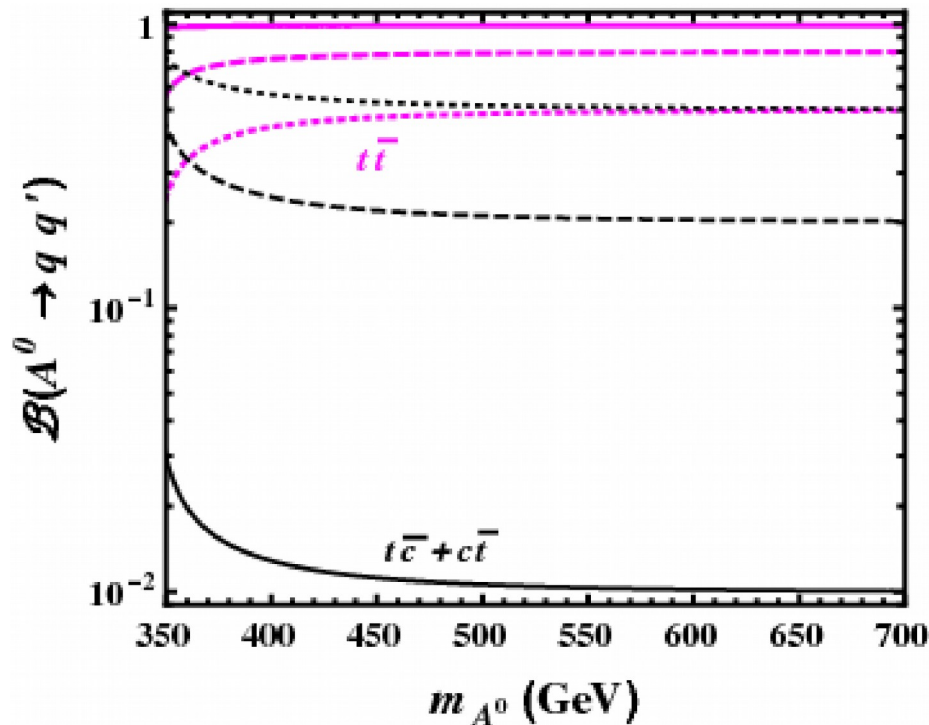
Parton level cross sections at LO:



$\sigma(pp \rightarrow tS^0)$
 $\sigma(pp \rightarrow t\bar{t}A^0)$
 $\sigma(pp \rightarrow t\bar{t}H^0)$

$\sqrt{s} = 14$ TeV
 fixed $\rho_{tt} = 1$
 PDF set : NN23LO1
 MadGraph5_aMC@NLO

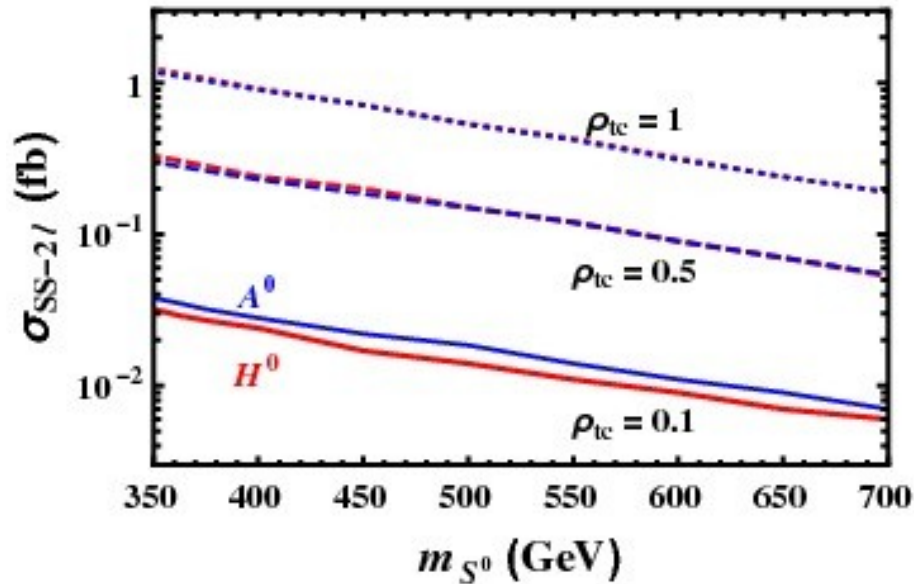
For $\Gamma_{H^0} = \Gamma_{A^0}$ and $m_{A^0} = m_{H^0}$,
 $pp \rightarrow tA^0 \rightarrow t\bar{t}c$ and $pp \rightarrow tH^0 \rightarrow t\bar{t}c$
 cancels each other exactly.



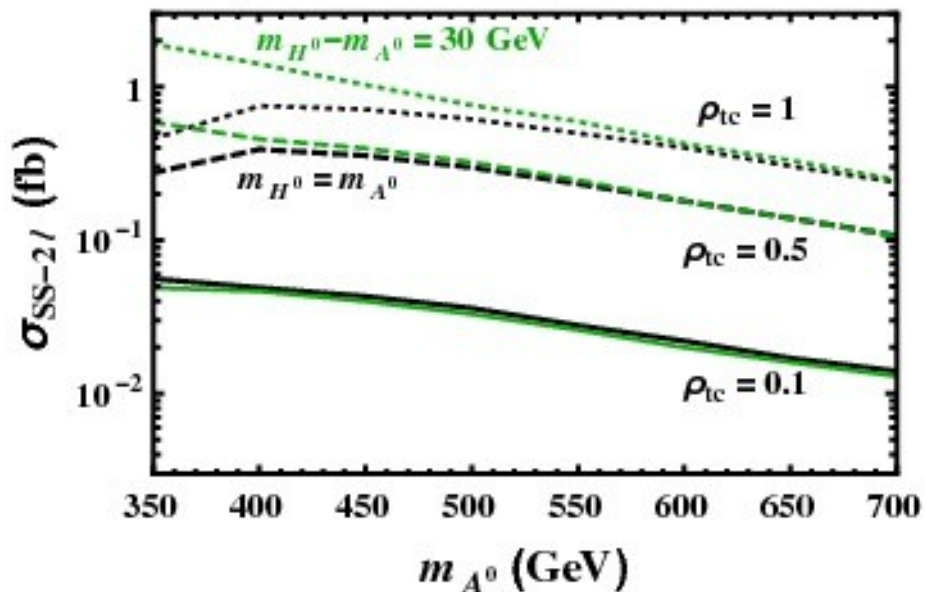
Same-sign top

MadGraph5_aMC + Pythia 6.4 + Delphes-3.4.0

H^0 or A^0 alone



Degenerate or nondegenerate H^0 and A^0



Process:

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

Event selection:

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

denoted as ($SS-2\ell$)

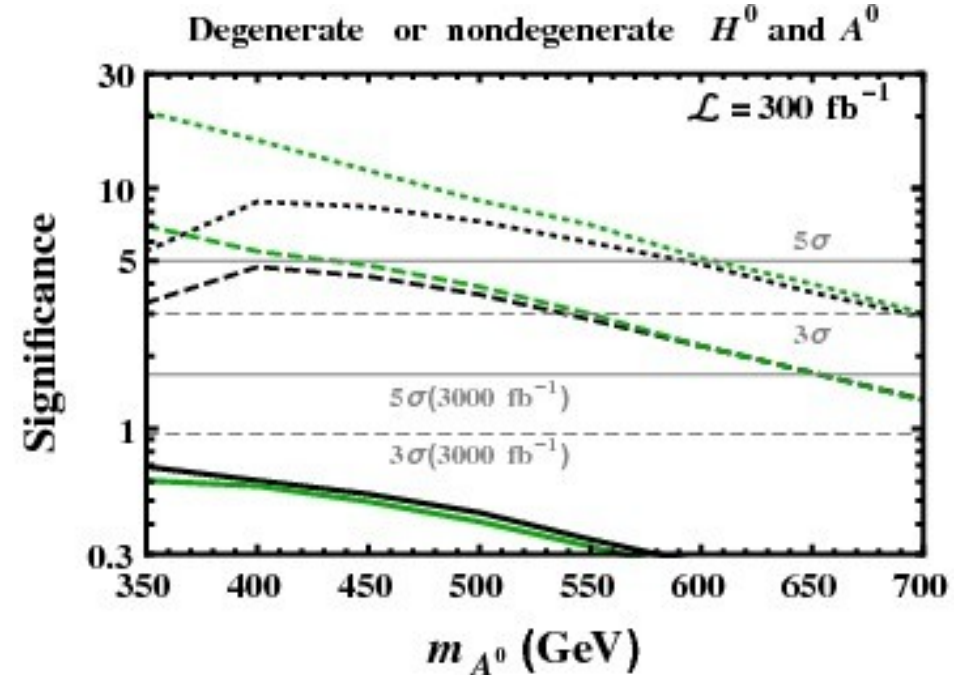
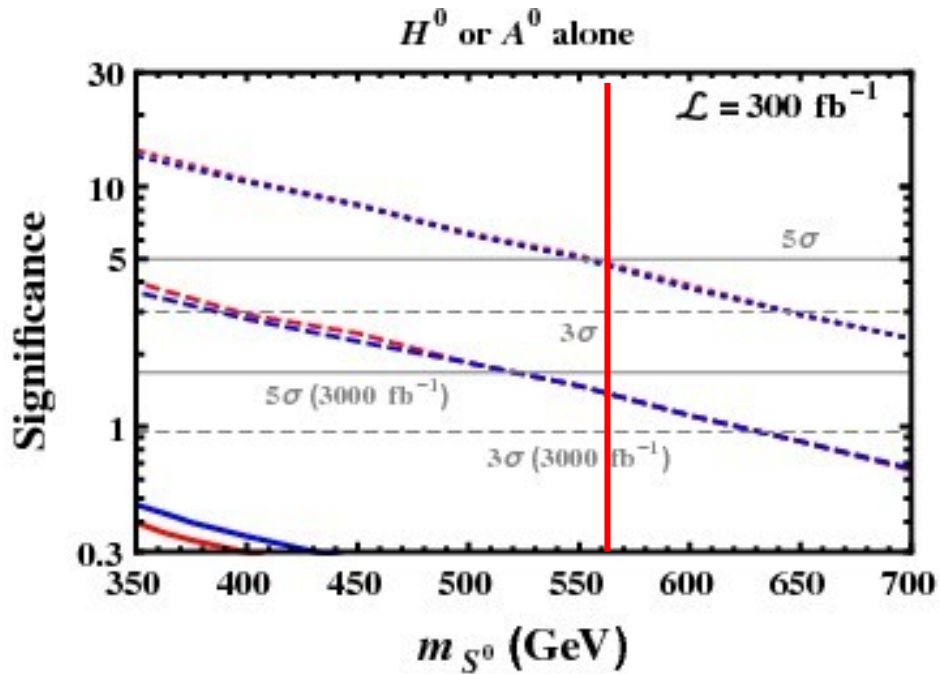
Backgrounds	Cross section (fb)
$t\bar{t}Z$	0.04
$t\bar{t}W$	0.72
tZ +jets	0.001
$3t + j$	0.0002
$3t + W$	0.0004
$t\bar{t}h$	0.024
$4t$	0.04
Q -flip	0.04

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

Signal at LO. Backgrounds with QCD corrections included.

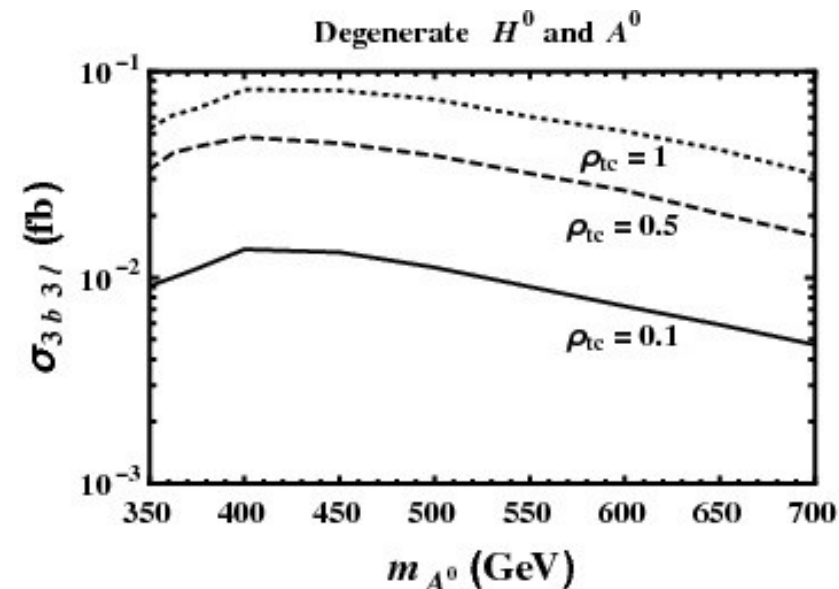
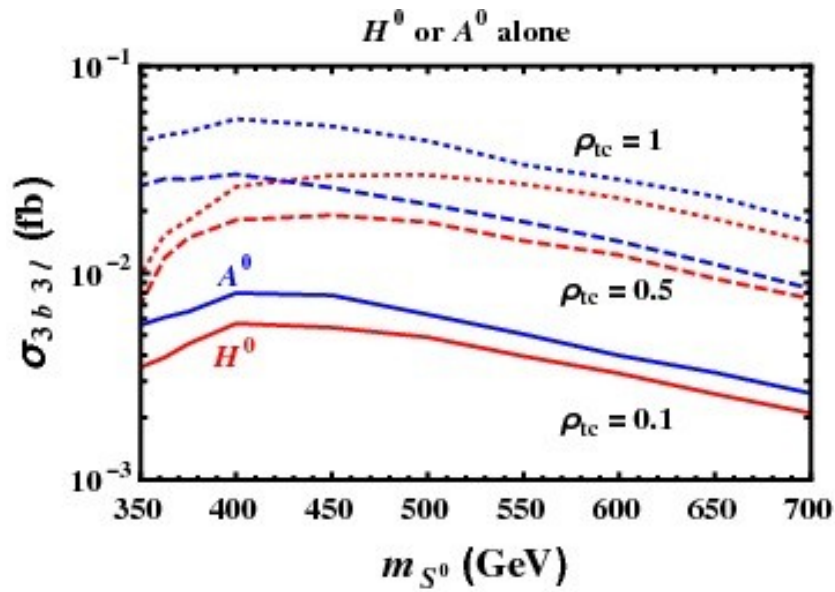
Discovery potential:

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



- 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:

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

Event selection:

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

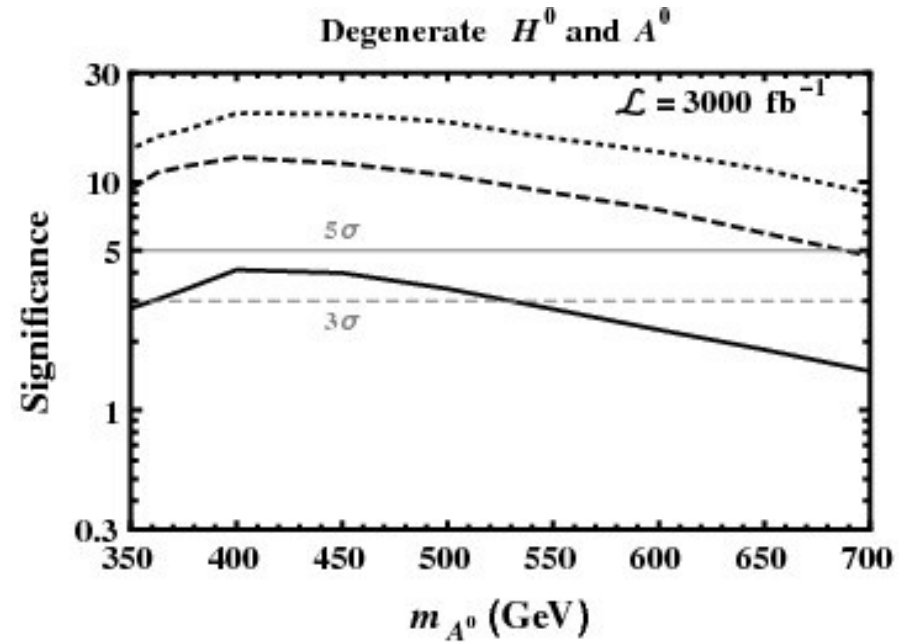
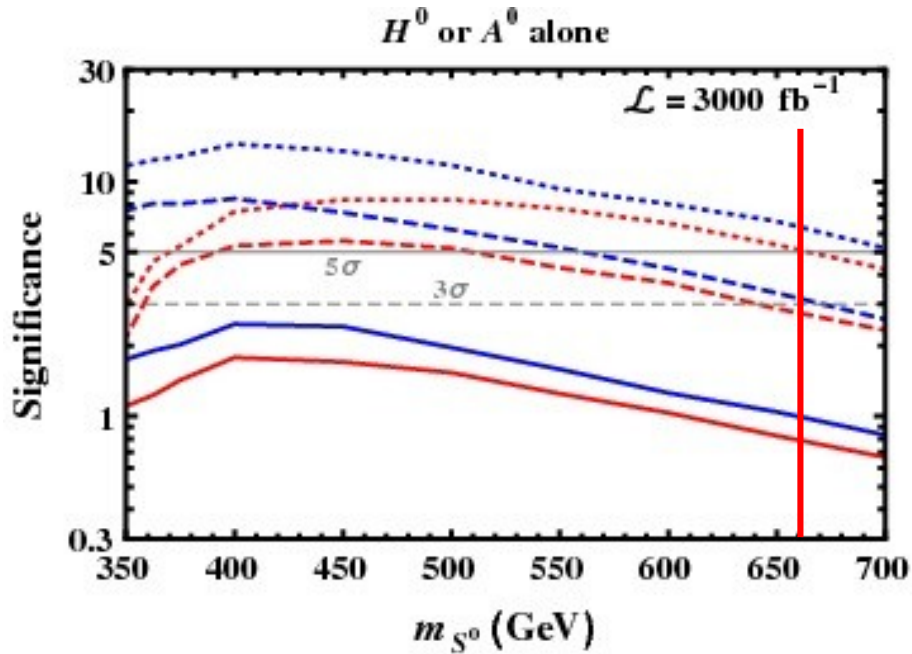
denoted as (3b3 ℓ)

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:



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

A light scalar ?

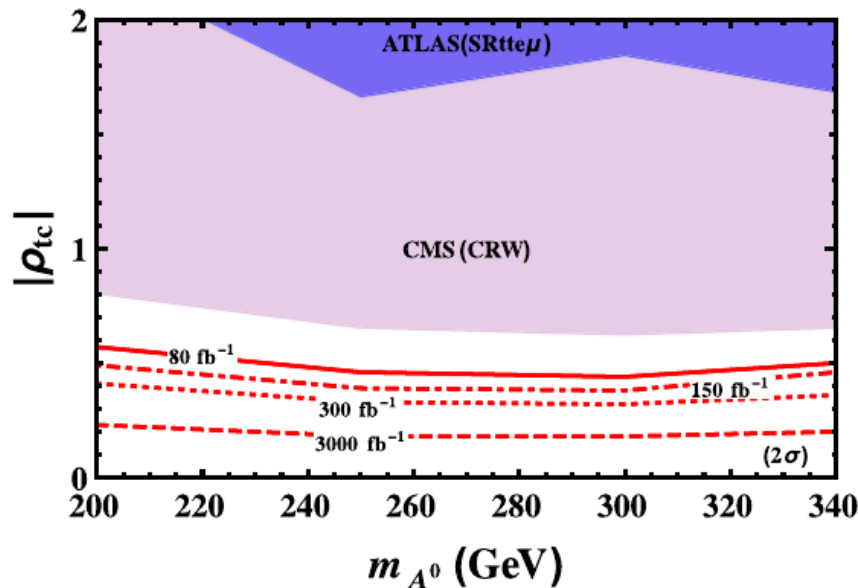
(W.-S Hou, M. Kohda, TM)

- Light (~ 200 GeV) A^0/H^0 . Can they still emerge?
- Small ρ_{tt} and c_γ
- A^0 considerably lighter than H^0 and H^\pm

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

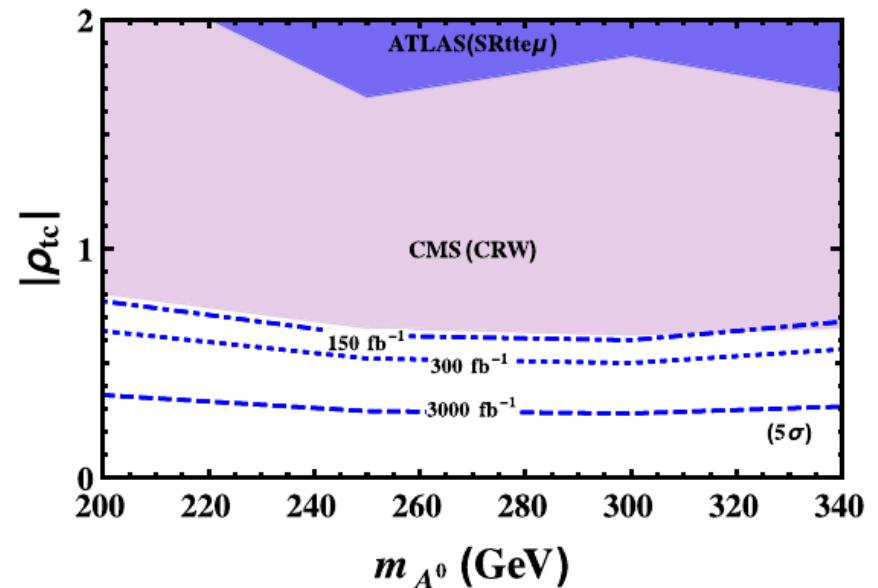
$$Z(s + b|b) \geq 2$$

$$c_\gamma = 0, \rho_{bb} = 0, \rho_{cc} = 0, \rho_{\tau\tau} = 0$$



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

$$c_\gamma = 0, \rho_{bb} = 0, \rho_{cc} = 0, \rho_{\tau\tau} = 0$$



- **ATLAS** same-sign top search (Run-1 data) ([JHEP '15](#)). $SRtte\mu$
- **CMS 4 top** search (2016 data) ([EPJC '18](#)). CRW region.

Top-assisted di-Higgs

Resonant di-Higgs

$$cg \rightarrow tH \rightarrow thh$$

The Hhh coupling

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

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

- For small c_γ :

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

Here we dropped the “0” from h^0, H^0, A^0

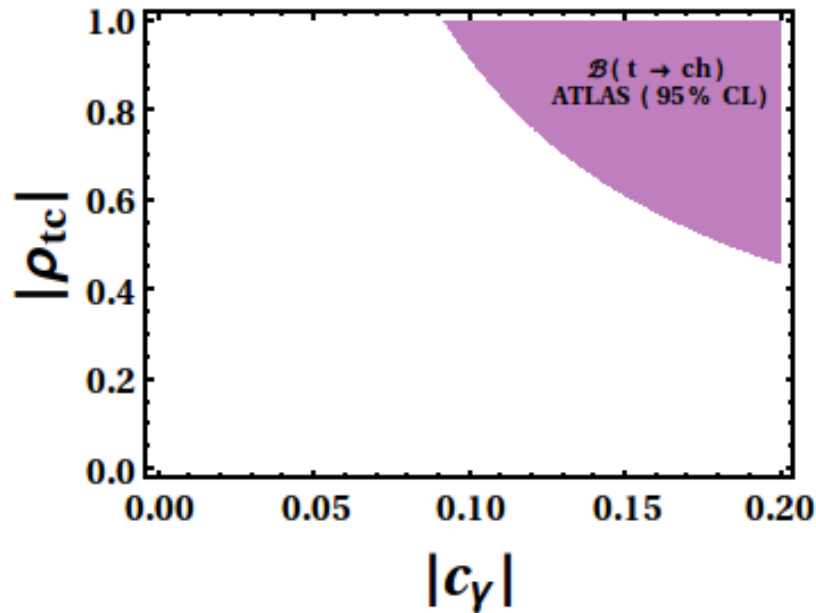
$$c_\gamma^2 = \frac{\eta_1 v^2 - m_h^2}{m_H^2 - m_h^2}, \quad \sin 2\gamma = \frac{2\eta_6 v^2}{m_H^2 - m_h^2}$$

Unitarity, Perturbativity,
positivity:

by 2HDMC: Higgs basis
+
T-parameter

Additionally all $|\eta_i| < 3$

The Hhh coupling



- $cg \rightarrow tH$: Depends on $|\rho_{tc}|$
- $\mathcal{B}(H \rightarrow hh)$ depends on c_γ
- Trade-off between $|\rho_{tc}|$ and c_γ



Optimized choices

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)	c_γ	s_γ	$ \lambda_{Hhh} $ (GeV)	$\frac{\mu_{22}^2}{v^2}$
1	0.287	2.996	-0.188	2.039	-2.555	-0.704	-0.172	0.557	303.27	480.96	279.49	0.169	-0.986	96.80	1.61
2	0.294	2.781	0.269	2.095	-2.945	-0.581	-0.21	0.633	340.18	518.26	303.48	0.169	-0.986	104.32	1.77
3	0.309	2.984	-0.017	2.416	-2.727	-0.328	-0.301	0.881	362.90	536.38	354.15	0.169	-0.986	123.03	2.18
a	0.286	2.97	1.508	-2.189	-0.02	-0.701	-0.169	0.525	377.31	276.72	277.71	0.169	-0.986	96.07	1.59
b	0.294	2.973	1.42	-1.976	-0.037	-0.593	-0.211	0.631	388.90	304.0	303.92	0.169	-0.986	105.06	1.78
c	0.309	2.976	0.294	-0.62	-0.045	-0.371	-0.301	0.932	377.17	353.3	353.89	0.169	-0.986	124.00	2.2

BP1, BP2 and BP3: $m_H < m_{H^\pm}, m_A$

BPa, BPb and BPc: $|m_A - m_H| < 5 \text{ GeV}$ and $m_H < m_{H^\pm}$

$\mathcal{B}(H \rightarrow hh) \sim 20\%$ for $\rho_{tc} \sim 0.5$

The discovery

- $t \rightarrow b\ell\nu$ helps from QCD multi-jets

BP	$t\bar{t}$ (fb)	Single top (fb)	$t\bar{t}h$ (fb)	$4t$ (fb)	$t\bar{t}W$ (fb)	$t\bar{t}Z$ (fb)	Others (fb)
1	6.701	1.014	1.008	0.016	0.022	0.234	0.007
2	7.418	1.014	1.117	0.019	0.022	0.262	0.008
3	7.939	1.521	1.135	0.024	0.02	0.268	0.008
<i>a</i>	6.616	1.014	1.0	0.016	0.022	0.231	0.007
<i>b</i>	7.425	1.014	1.118	0.019	0.022	0.262	0.008
<i>c</i>	7.923	1.52	1.135	0.024	0.02	0.268	0.008

- $5b + 1\ell + E_T^{\text{miss}}$
- Finite b -tagging efficiency

Signature:

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

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)
<i>a</i>	0.39	8.906	3.2 (7.1)
<i>b</i>	0.368	9.948	2.8 (6.4)
<i>c</i>	0.295	10.898	2.2 (4.9)

Signal at LO. Backgrounds with QCD corrections included.

Summary

- 2HDM without Z_2 : **Extra Yukawas**: ρ_{tt} and FCNH: ρ_{tc} .
- **NFC** may be **overkill**.
- **Extra Yukawas**: leading to **novel signatures** at LHC.



- Light scalars are possible.
- **Triple-top** may require **HL-LHC**, however **Same-sign top** may emerge with **300 fb⁻¹** data.
- **Top-assisted di-Higgs** may emerge in the HL-LHC.
- Discovery may help understand the **Matter-Antimatter asymmetry** of the Universe.

Thank You

Back ups

