Constraining Triple-Top Production via Four-Top and Top-Pair Studies

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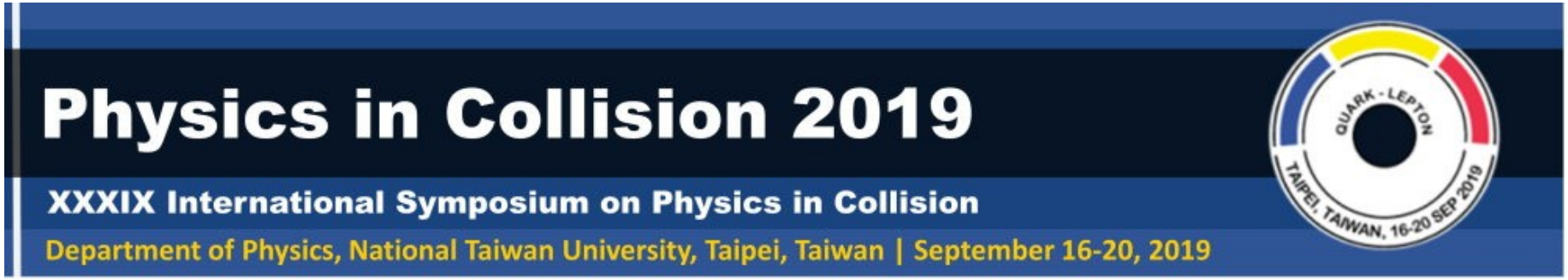
with W.-S.Hou and M. Kohda



Overview

- Multi top-quark production. Staple programs at the LHC.
- Both ATLAS and CMS covered: Top-pair, single-top, four-top.
- No study for triple-top production.
- In SM triple-top cross section is few fb. Excellent probe for New Physics.
- Triple-top cross section: at pb level in general 2HDM (G2HDM).

Extra Yukawas : $\rho_{tc},\ \rho_{tt}.$

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

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

Multi-top productions at LHC

SM Top-pair

$t\bar{t} : \sigma \approx 830$ pb @13 TeV (LHC cross sec. WG)

SM Single-top

t-channel single-top : $\sigma \approx 217$ pb

s-channel single-top : $\sigma \approx 10$ pb @13 TeV (LHC cross sec. WG)

$Wt : \sigma \approx 70$ pb

SM Four-top

$4t$: $\sigma \approx 10$ fb @13 TeV (J. Alwall et al. JHEP '14)

See also talk By Anna Lipniacka

SM triple-top

$\sigma \approx 2$ fb @14 TeV (Barger et al. PLB '10)

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

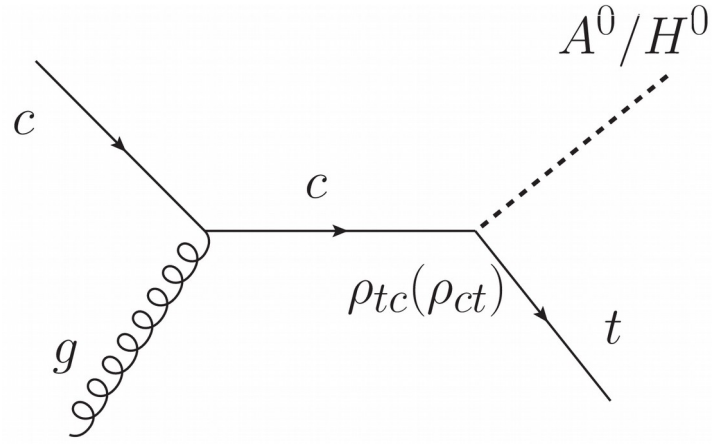
- **Triple-top (G2HDM):**

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

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

1. SM $3t$ at fb level.

2. Clean $3b$-jets, 3-lepton final state



- **Same-sign top:**

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

May emerge earlier than triple-top

(See also Hou, Lin, Ma, Yuan, PLB '97)

The 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.

$$-\frac{1}{\sqrt{2}}\sum_{F=U,D,L}\bar{F}_{iL}\Big[\big(-\lambda^F_{ij}s_\gamma+\rho^F_{ij}c_\gamma\big)h^0$$

$$+\big(\lambda^F_{ij}c_\gamma+\rho^F_{ij}s_\gamma\big)H^0-i\,\mathrm{sgn}(Q_F)\rho^F_{ij}A^0\Big]F_{jR}+\mathrm{h.c.}$$

(see e.g., Davidson, Haber PRD '05)

(see also discussion in Hou & Kikuchi, EPL'18)

$\cos\gamma = c_\gamma$:mixing angle bwtween $h^0(125)$ and H^0

$c_\gamma \sim 0.2$

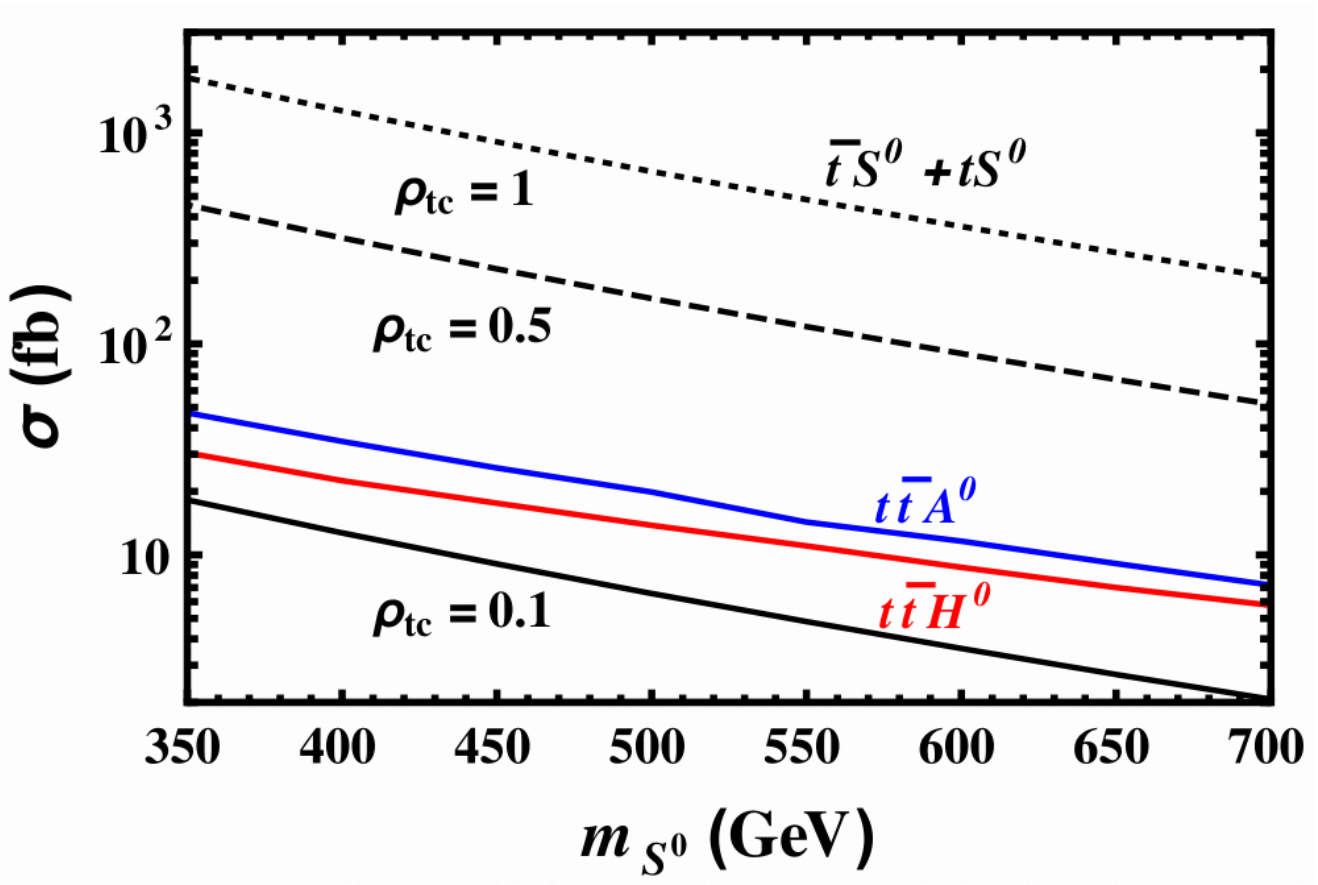
- Complex ρ_{tt} and ρ_{tc}: Electroweak Baryogenesis

(Fuyuto, Hou, Senaha PLB '18)

Parton level cross sections

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

Parton level cross sections at LO:



fixed $\rho_{tt} = 1$

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

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

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

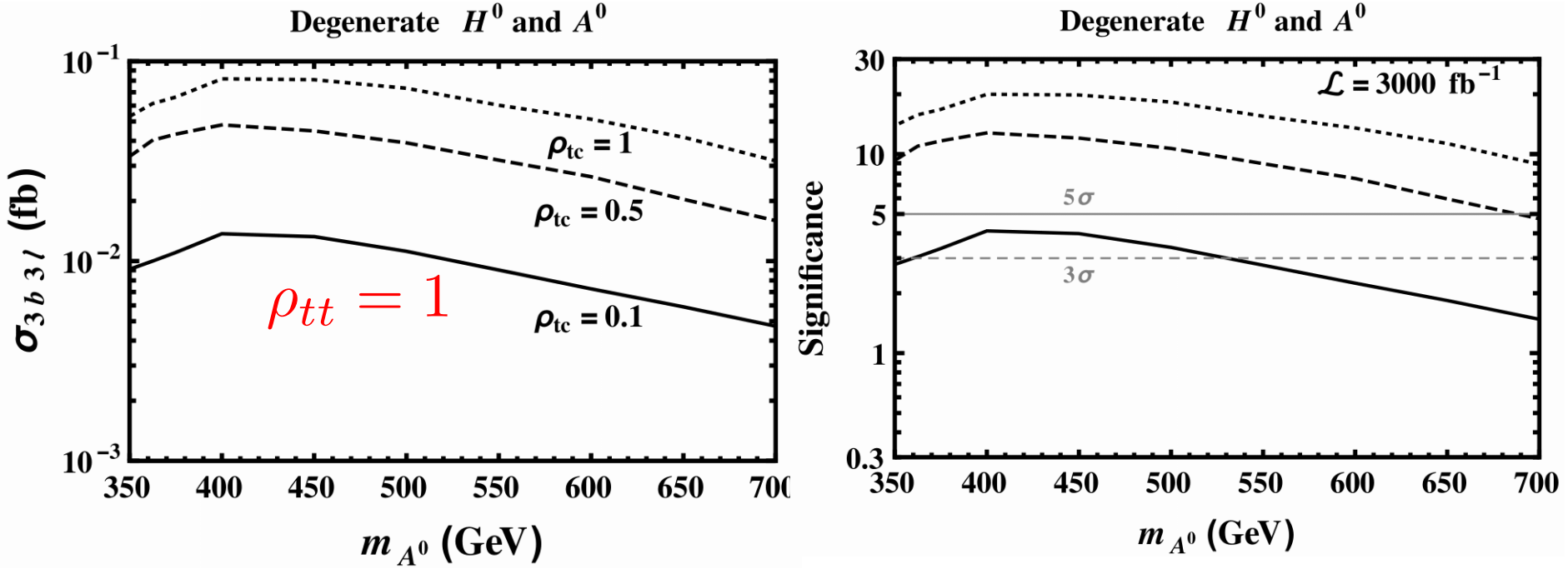
PDF set : NN23LO1

$\sqrt{s} = 14$ TeV

MadGraph5_aMC@NLO

Triple-top discovery

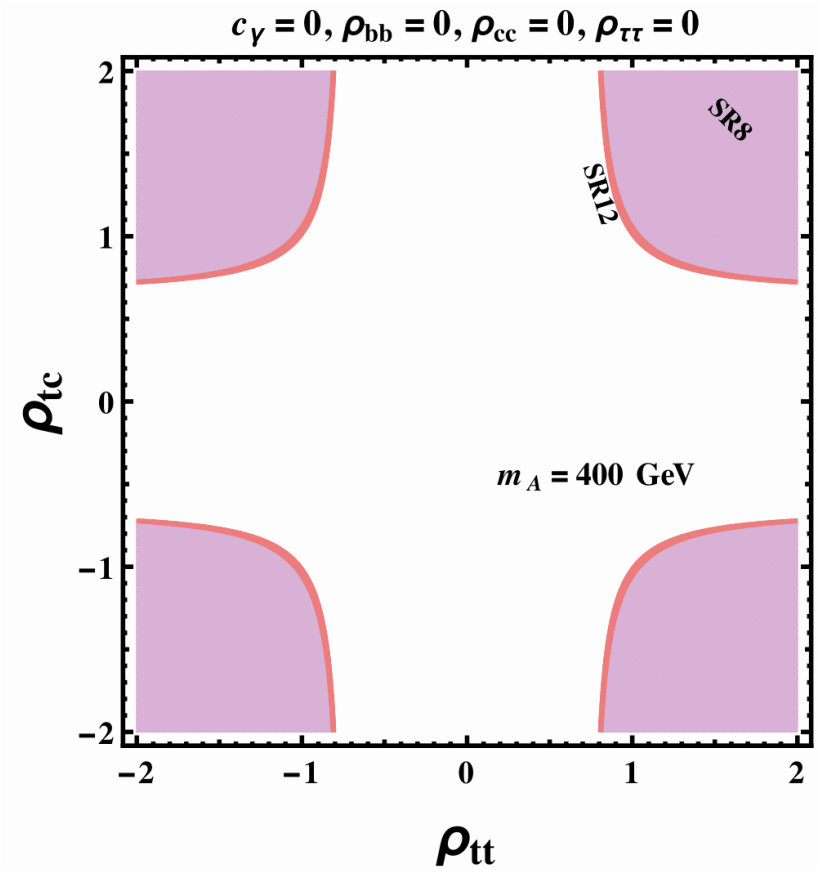
(W.-S Hou, M. Kohda, TM PLB '18)



@14 TeV with $3b3\ell$ signature

- 5σ for : e.g. if $\rho_{tc} = 0.5$, $\rho_{tt} = 1$ and $m_{S^0} \lesssim 680$ GeV.

Constraint on triple-top from 4t



(W.-S Hou, M. Kohda, TM, arXiv:1906.09703)

CMS search for SM 4-top: SR8

13 TeV 36 fb^{-1} (CMS, EPJC '16)

at least $3\ell(\ell = e, \mu)+$
at least 4 jets with 3 b-tagged

expctd. events: 2.62±0.54

observed events: 2

SR12

(CMS, arXiv:1908.06463)

13 TeV 137 fb^{-1}

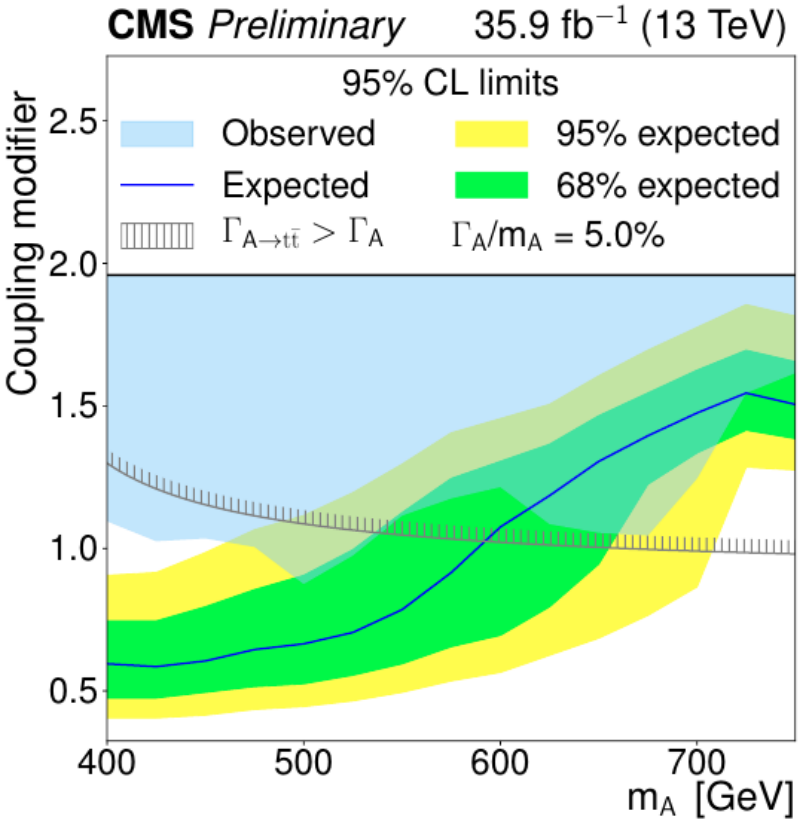
event selection: same as SR8
but no. of jets restricted to 4

expctd. events: 2.1±0.6

observed events: 2

Excess from CMS

See also talk
By
Stefania Spagnolo



(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, 1906.09703)

Outlook

- NFC may be overkill.
  2HDM without Z_2. Extra Yukawas: ρ_{tt}, and FCNH: ρ_{tc}.

- Extra Yukawas: leading to novel triple-top (and same-sign top) signature at LHC.

- 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

The Higgs sector

CP conserving 2HDM without Z_2 :

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

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

✦ Near Alignment (In Higgs Basis:):

$\langle\Phi\rangle = (0, v/\sqrt{2})^T$
$\langle\Phi'\rangle = (0,0)^T$ ➡ $h^0,\ H^0,\ A^0,\ H^\pm$

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

✦ Alignment without decoupling:

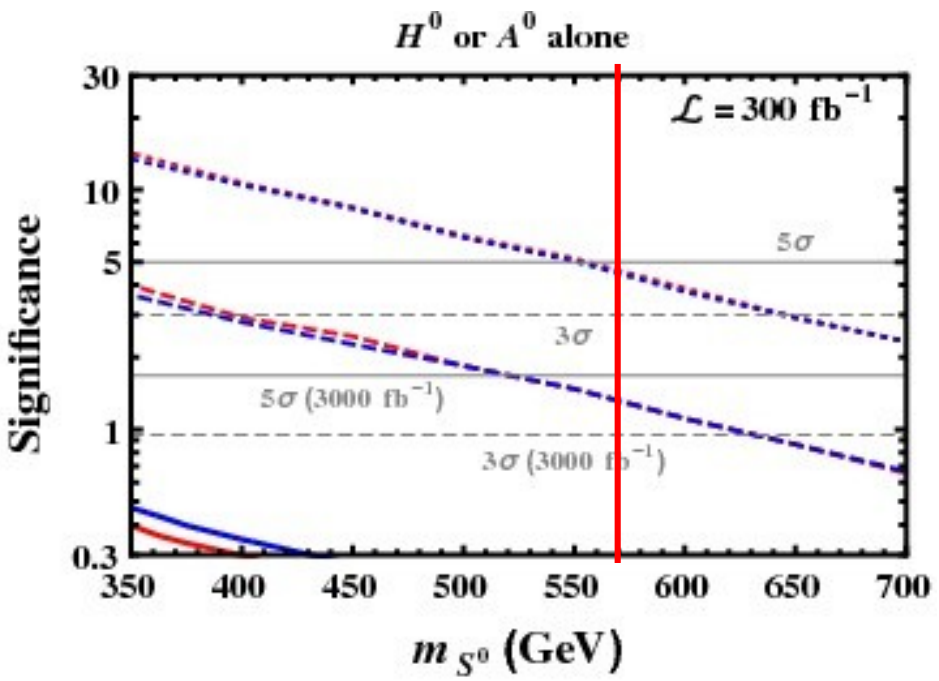
$$c_\gamma \simeq \frac{-\eta_6 v^2}{m_{H^0}^2 - m_{h^0}^2};$$

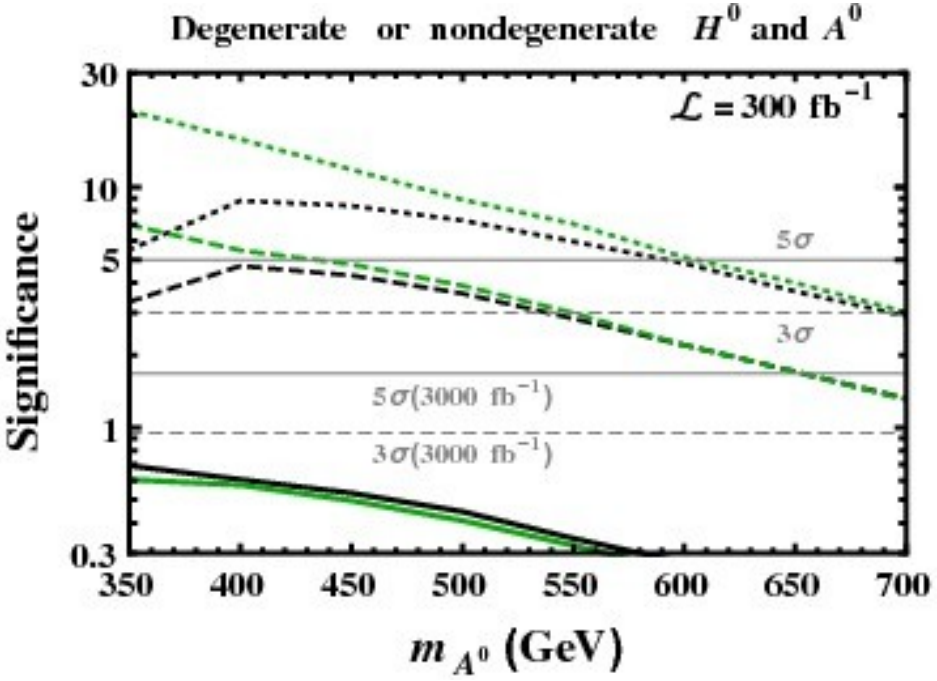
c_γ ~0.2–0.3 even for $m_{H^0} \sim$ 200–300 GeV ➡ Excellent scope for LHC search

Same-sign top discovery

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

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

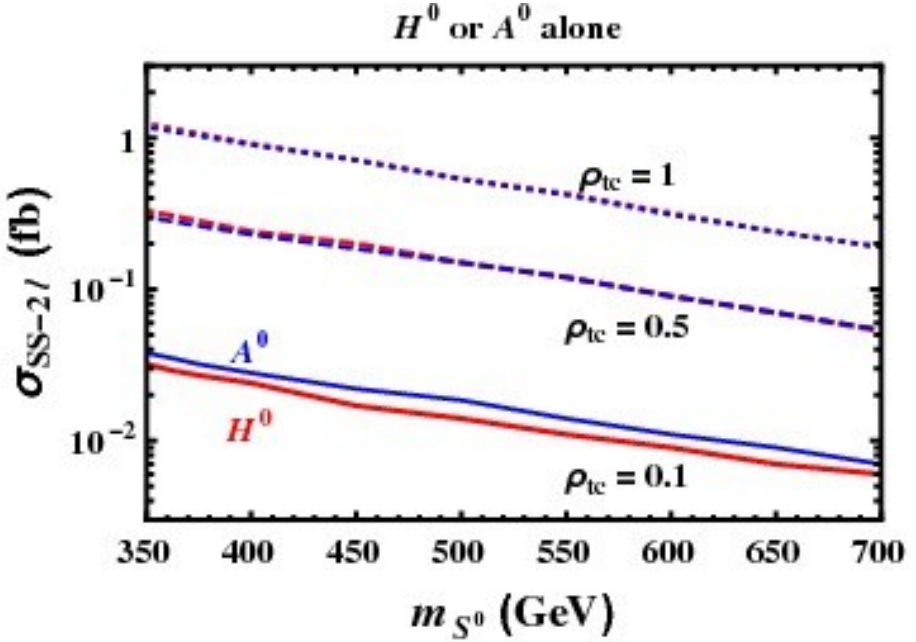


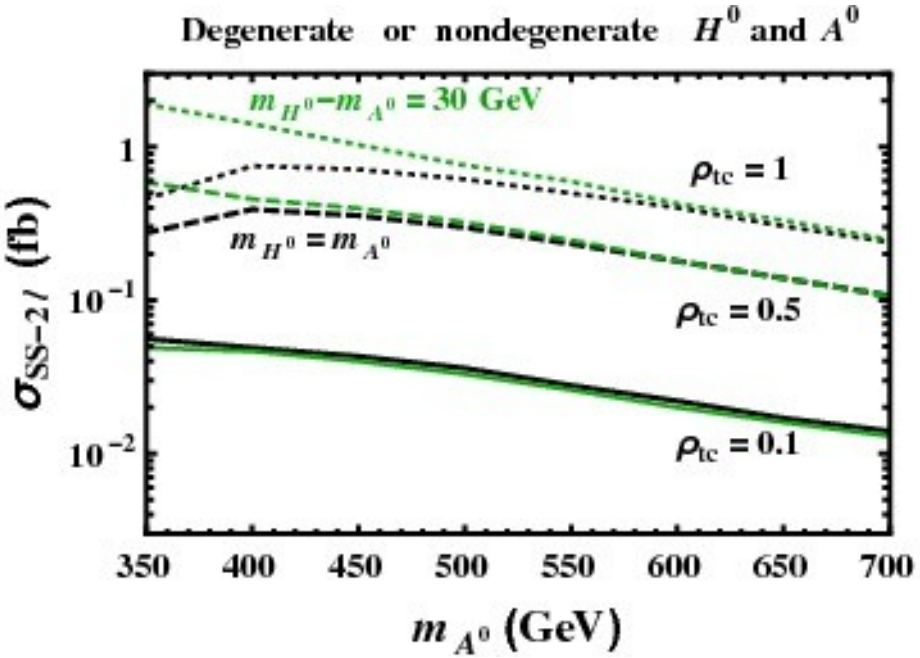


- H^0 or A^0 alone : 5σ for $\rho_{tc} = 1$ and $m_{S^0} \lesssim 550$ GeV.
- Discovery: easier for small H^0 - A^0 mass splitting case.
- Discovery could indicate ρ_{tc} driven BAU.

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

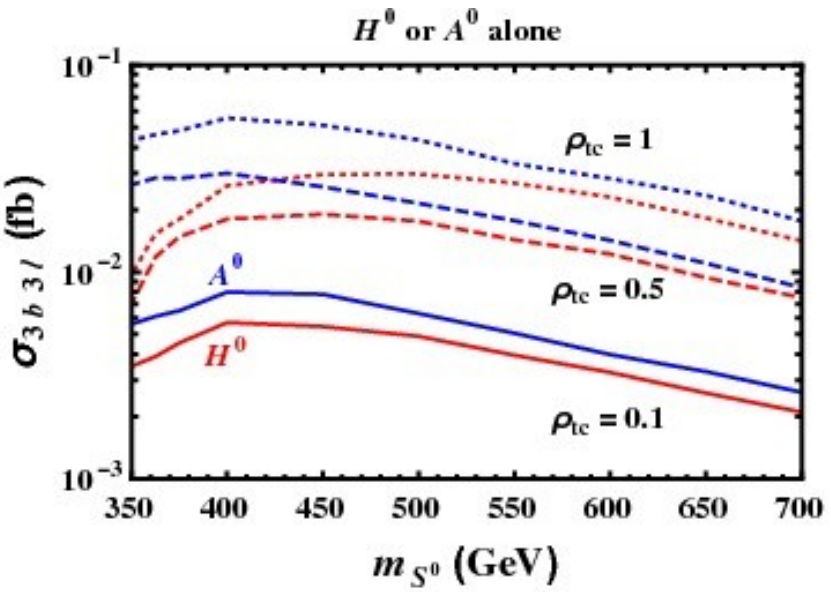
denoted as $(SS\text{-}2\ell)$

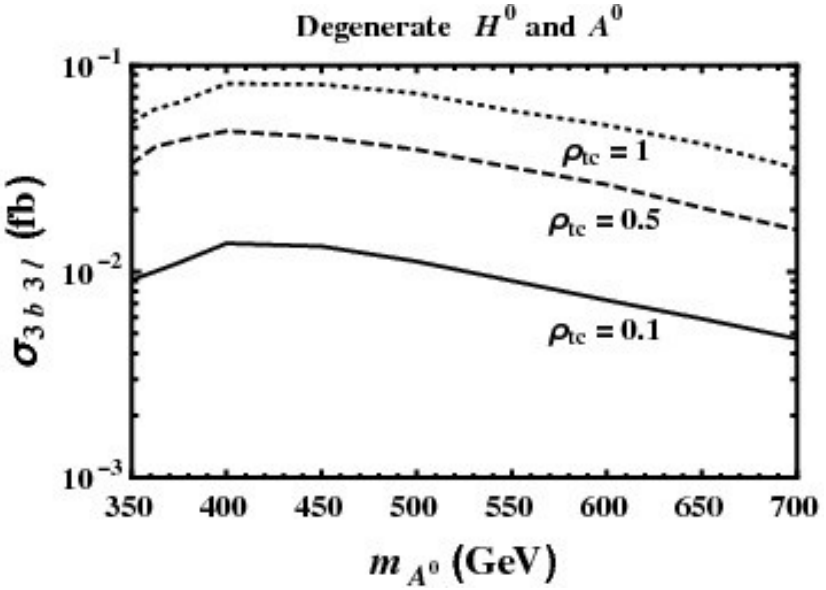
Backgrounds	Cross section (fb)
$t\bar{t}Z$	0.04
$t\bar{t}W$	0.72
tZ+jets	0.001
$3t + j$	0.0002
$3t + W$	0.0004
$t\bar{t}h$	0.024
$4t$	0.04
Q-flip	0.04

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

Signal at LO. Backgrounds with QCD corrections included.

Triple-top





Process:

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

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.