# Search for new scalar in general 2HDM via $cg \to tS^0$

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Energy Frontier in Particle Physics: LHC and Future Colliders

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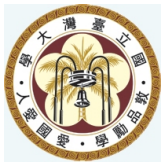

# Outline

- Introduction
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- Same-sign dilepton
- Triple top
- Summary

# Introduction

- A second Higgs doublet of 125 GeV boson is possible, replicating fermions generations in scalar sector.
- Possibly hidden due to alignment.
- Alignment without decoupling: No $Z_2$ symmetry + all quartic couplings of extra Higgs $\mathcal{O}(1)$ and $\mu_{22}^2/v^2 \sim \mathcal{O}(1)$. $\mu_{22}^2$ inertial mass of extra Higgs. [Hou and Kikuchi, arXiv:1706.07694]
- Allows extra scalar mass $\sim 500$ GeV.
- Required for first order Electroweak Phase Transition (EWPT).
- Diagonal $S^0tt$ ($S^0 = A, H$) and FCNH $S^0tc$ Yukawa: $\mathcal{O}(1)$ is possible.
- Large $S^0tt$: efficient Electroweak Baryogenesis EWBG. [K. Fuyuto, W-.S. Hou, E. Senaha, arXiv:1705.05034]
- If $|S^0tt|$ small: $S^0tc \sim \mathcal{O}(1)$ with near maximal phase for EWBG.
- Driven by alignment and EWBG, we study $cg \to tS^0$ process at 14 TeV LHC.

# Model framework

# Higgs potential

- CP conserving general Higgs potential without $Z_2$ symmetry:

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

- Higgs basis where $\Phi$ generates $v$, $\mu_{12}^2$ is identified as $\eta_6$ and $\mu_{22}^2$ is inertial mass of $\Phi'$.
- Mass matrix for CP even Higgs:

$$
M = \begin{pmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & \mu_{22}^2 + \frac{1}{2}(\eta_3+\eta_4+\eta_5)v^2 \end{pmatrix}
$$

# Mass Matrix

- Diagonalizing matrix:

$$R = \begin{pmatrix} \cos\gamma & -\sin\gamma \\ \sin\gamma & \cos\gamma \end{pmatrix}$$

$\cos\gamma = 0$ is analogous to $\cos(\beta-\alpha) = 0$ in Type-II 2HDM

- Masses of $H$ and $A$ :

$$m^2_{H^0}, m^2_{A^0} = \mu^2_{22} + \frac{1}{2}(\eta_3 + \eta_4 \pm \eta_5)v^2,$$

# Natural Alignment

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

- Alignment: Current data shows 125 GeV Scalar behaves like Standard Model Higgs. $\cos\gamma = 0$ and $\sin\gamma = -1$.
- Close to alignment: $\cos\gamma \simeq \frac{-\eta_6 v^2}{m_H^2 - m_h^2}$.
- Alignment without decoupling in Type-II 2HDM. [M. Carena et al. JHEP 1404]
- $\eta_6 << 1$. [Bechtle et al. Eur. Phys. J. C 2017].
- $|\eta_6| \lesssim \eta_{3,4,5} \sim \mathcal{O}(1) \lesssim \mu_{22}^2/v^2$. Can result in small $\cos\gamma$. Natural Alignment. [Hou et al. arXiv:1706.07694]
- Mass of the extra scalar: Sub-TeV, thanks to Natural Alignment.
- Such extra scalar can drive EWPT strongly 1st order, needed for EWBG. [More on Alignment: See talk by H. Haber]

# Yukawa couplings

- In Alignment limit, Yukawa couplings for up-type quarks,

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

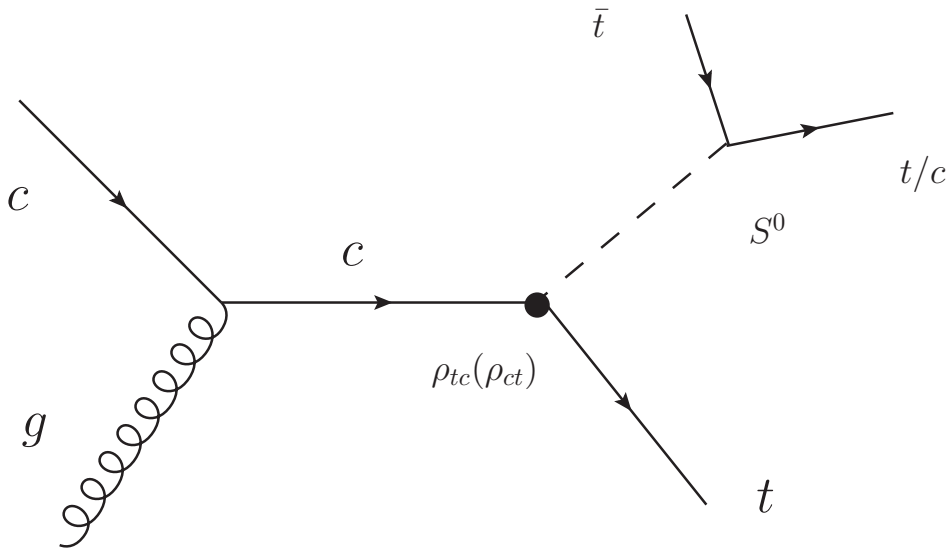
- $\rho_{ij}$ in general non-diagonal.
- $\rho_{tt}$ and $\rho_{tc}$ to be $\mathcal{O}(y_t)$ where $y_t \cong 1$.
- $\rho_{bb}$ and $\rho_{\tau\tau}$ (and $\rho_{\tau\mu}$) should not be larger than the $y_b$ and $y_\tau$.
- $B$ Physics: $\rho_{ct} \simeq 0$. [Chen et al. Phys. Lett. B (2013), Altunkaynak et al. Phys. Lett. B (2015)]
- Large $\rho_{tt}$ (with phase): Driver of EWBG.
- If $|\rho_{tt}|$ is small, $\rho_{tc}$ with large phase can also drive EWBG.

# Searches at LHC

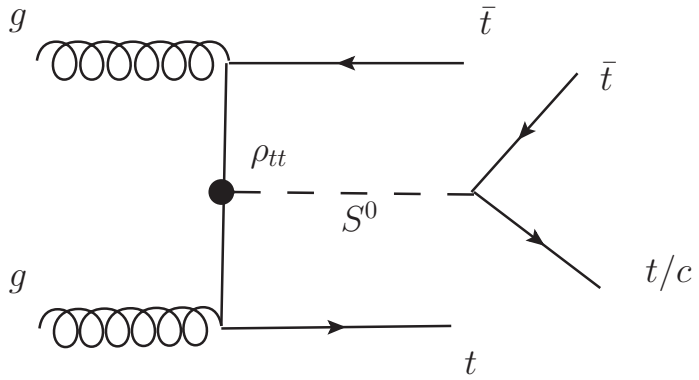
- Masses: $\sim 500$ GeV, large $\rho_{tt}$ and large $\rho_{tc}$.
- $gg \to S^0 \to t\bar{t}$: Interference with QCD $t\bar{t}$ background. Could be sensitive. [ATLAS-CONF-2016-073]
- $gg \to S^0 \to \bar{t}c + \bar{c}t$: suffers from mass resolution of $(t+j)$.
- Large $\rho_{tt}$ may drive $gg \to t\bar{t}S^0$. [Kanemura et al. Nucl. Phys. B (2015), N. Craig et al. JHEP 1506, JHEP 1701]
- $cg \to tS^0 + \bar{t}S^0, S^0 \to t\bar{t}$: Excellent S/B ratio, clean final state topology.
- $cg \to tS^0 + \bar{t}S^0$, $gg \to t\bar{t}S^0$: Same-sign dilepton may emerge first.

[Recent BSM Higgs result: Talk by S. Paganis]

# Feynman Diagrams




$(a)tS^0 Process$




$(b)t\bar{t}S^0 Process$

# Cross sections

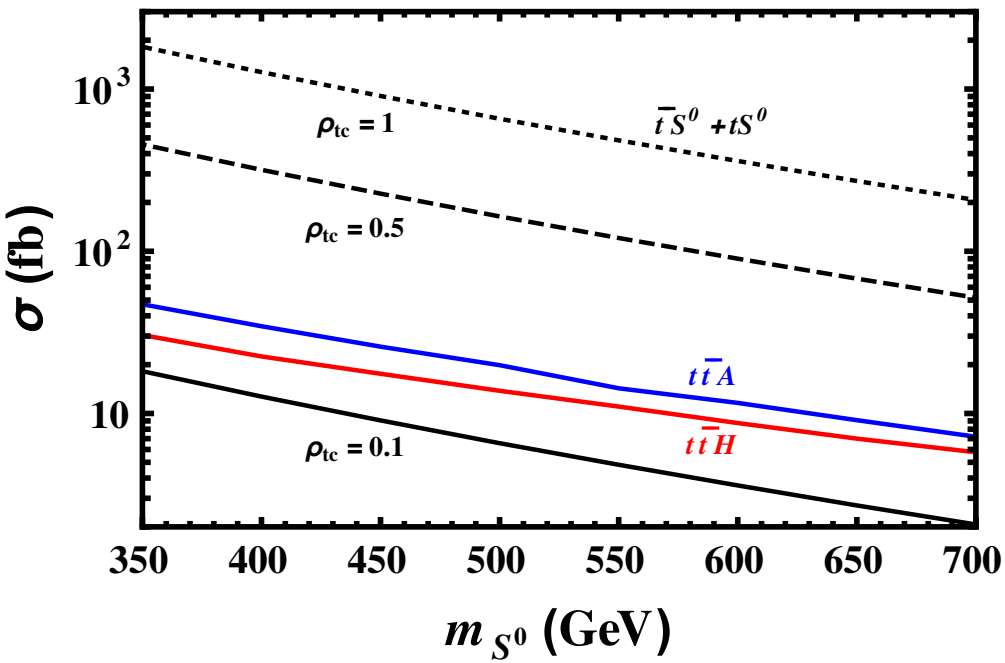



Figure: Cross sections for $H$ and $A$.

MadGraph5_aMC@NLO, PDFset: NN23LO1 PDF
SM $t\bar{t}t \sim$ fb.

# Branching ratios of A and H (Simplified)

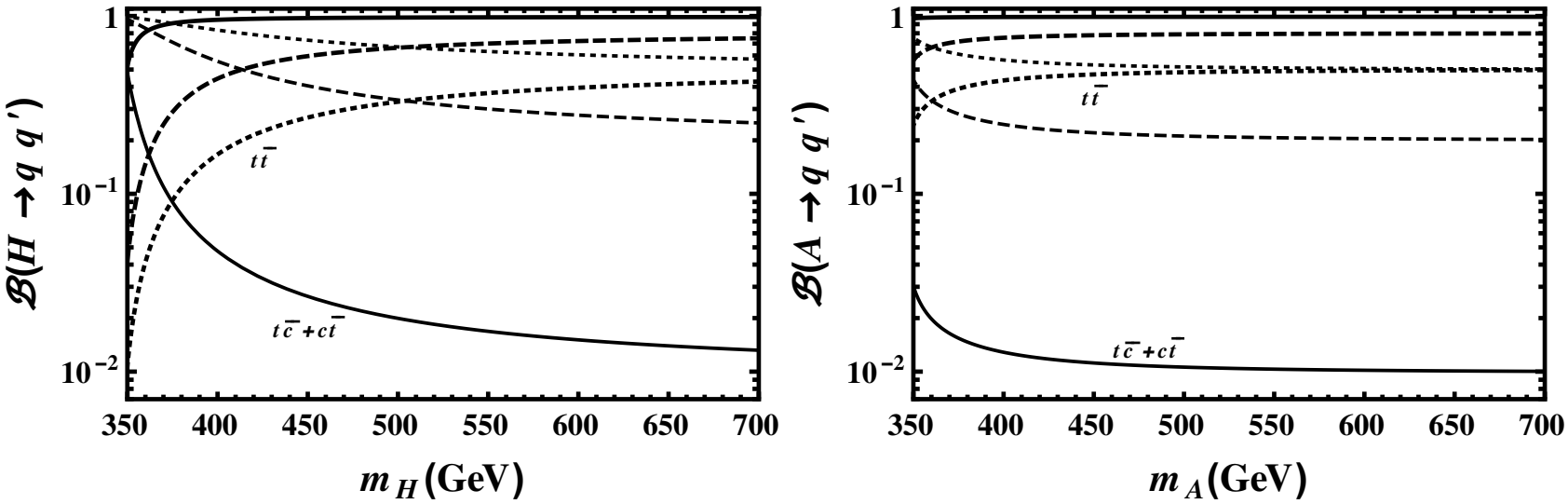



Figure: Branching ratios of $H^0$ [left] and $A^0$ [right]

# Same-sign Dilepton

# Processes and Selection criterion

- Processes:
  1) $cg \to tS^0 \to t\bar{t}t/tt\bar{c}$ (with conjugate process);
  2) $gg \to t\bar{t}S^0 \to t\bar{t}t\bar{t}/t\bar{t}c\bar{t}$(with conjugate process), (with at least two $t$ ($\bar{t}$) decay $t \to b\ell^+\nu_\ell$ ($\bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell$)). .
- Selection criteria: 2 same-sign dilepton (SS-$\ell\ell$), at least three jets out of which two are $b$-jets and missing energy $E_T^{\text{miss}}$.
- $p_T^{\ell_1} > 25$ GeV, $p_T^{\ell_2} > 20$ GeV; $\Delta R_{\ell\ell} > 0.4$, $|\eta^\ell| < 2.5$;
  $p_T^{b_1} > 30$ GeV, $p_T^{b_2} > 20$ GeV; $\Delta R_{bb/bj/jj/j\ell} > 0.4$, $|\eta^{j/b}| < 2.5$;
  $E_T^{\text{miss}} > 30$ GeV
- Sum of the transverse momenta of the two leading leptons and three leading jets $H_T > 300$ GeV.

Madgraph, Pythia 6.4, Delphes 3.4.0

# Backgrounds

| 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 |
| $4t$ | 0.04 |
| $Q$-flip | 0.04 |

Table: Backgrounds for same-sign dilepton at 14 TeV.

SM non-prompt background $\sim 1.5$ of $t\bar{t}W$ [CMS,Eur. Phys. J.C 77, 578 (2017)]

# Cross section and significance

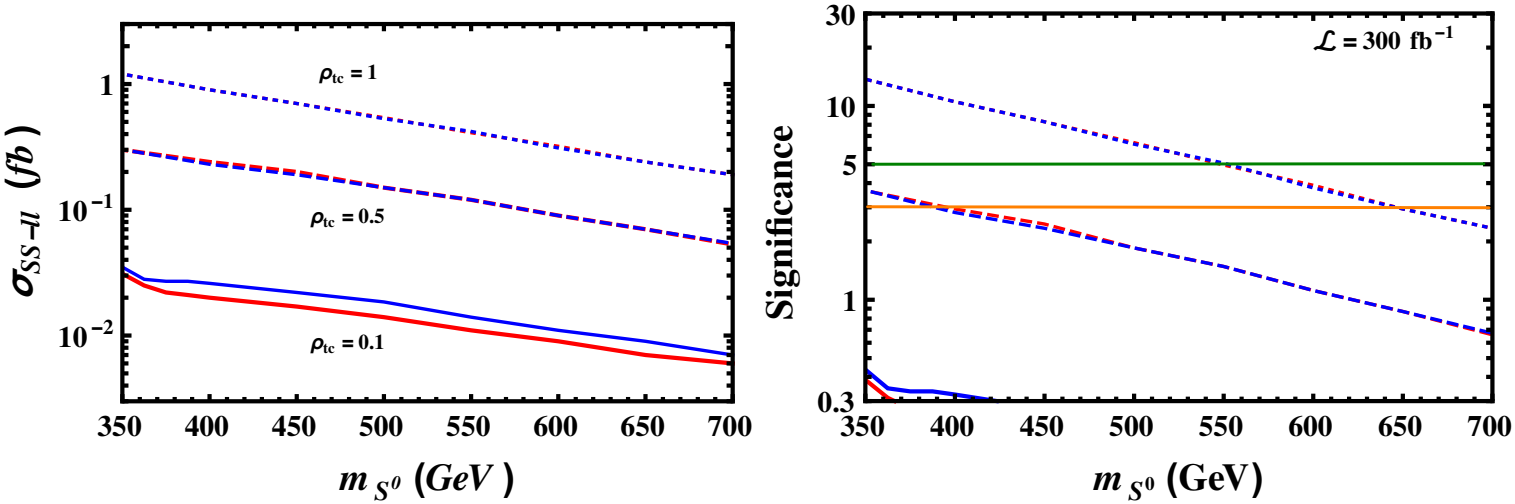



Figure: [left] Cross sections (fb), and [right] significance [right], $\sqrt{s} = 14$ TeV.

# Triple top

# Processes and Selection criteria

- Processes:
  1) $cg \to tS^0 \to t\bar{t}t$ (with conjugate process);
  2) $gg \to t\bar{t}S^0 \to t\bar{t}t\bar{t}/t\bar{t}c\bar{t}$ (with conjugate process).
- Selection criteria: at least three leptons, at least three $b$-jets and missing energy $E_T^{\text{miss}}$.
- $p_T^{\ell} > 30$ GeV, $p_T^{b} > 20$ GeV and $E_T^{\text{miss}} > 30$ GeV.
- $\Delta R$ and $|\eta|$ cuts : Same as SS-$\ell\ell$
- Sum of the transverse momenta of the three leading leptons and three leading $b$-jets $H_T > 300$ GeV.
- Use $76 < m_{\ell\ell} < 95$ $Z$ boson veto on events.

# Backgrounds

| 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) |
| $4t$ | 0.0232 (0.0209) |
| $t\bar{t}$+jets (fake) | 0.0026 (0.0025) |

Table: Backgrounds at 14 TeV for $3\ell 3b$.

Do not consider non-prompt background.

# Cross sections and Discovery potential

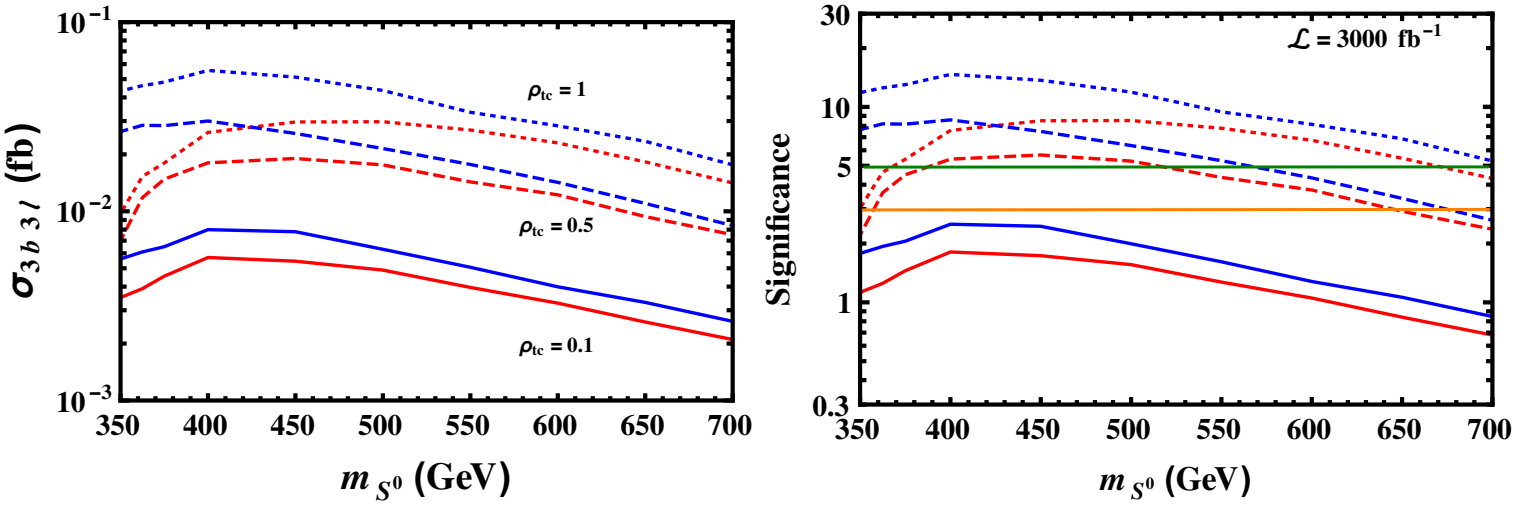
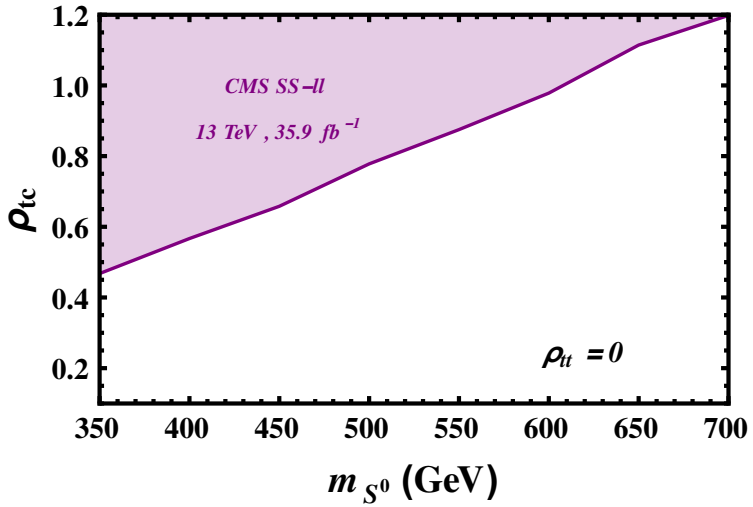



Figure: [left] Cross sections (fb), and [right] significance [right], $\sqrt{s} = 14$ TeV).

# Current constraint on $\rho_{tc}$ and $\rho_{tt}$ from Run-2 data

- SS-$\ell\ell$ search by CMS (13 TeV 35.9 fb$^{-1}$ data, [arXiv:1704.07323]) constrains $\rho_{tc}$ and $\rho_{tt}$.
- Several signal regions are defined.
- SR: At least two jets with two are $b$-tagged+ missing energy. High-High selection for same-sign dilepton i.e. $p_T > 25$ GeV.
- Assuming $\rho_{tt} = 0$, constraint on $\rho_{tc}$:




- Can probe/rule out $\rho_{tc}$ as driver.

# Summary

- Motivated by EWBG and alignment, we search FCNH initiated $cg \to tS^0$ process at LHC.
- We find SS-$\ell\ell$ will emerge first. Run-2 data already sensitive.
- The triple top would act as confirmation.
- If $\rho_{tt} \sim 1$ and $\rho_{tc} \gtrsim 0.5$: triple top could discover $S^0$ up to 700 GeV in HL-LHC.
- If both processes are seen: Might confirm EWBG via $\rho_{tt}$.
- If $\rho_{tt}$ is small triple top may not emerge. SS-$\ell\ell$ would still emerge driven by $\rho_{tc}$.
- This may confirm EWBG via $\rho_{tc}$.

# Thank You