Custodial Symmetry Violation in the Georgi-Machacek model*

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Abstract

This poster examines the effects custodial symmetry (CS) violation in the GM model. We assume that CS is exact at some scale, Λ and use the 1st order RGEs (leading log approx.) to run down to the weak scale and calculate the effect on observables. We find that the typical scales of CS can be as high as $\mathcal{O}$(10-200 TeV) with a maximum of 10^6. Even with large amounts of running, the CS violating effects (on masses, couplings and decays) are tiny. Outside of special parts of parameter space (e.g. a degenerate spectrum) they are generically too small to be detected at the LHC although they may be large enough to detect at a future e^+e^- collider.

Georgi-Machacek Model (GM)

Adds real and complex triplet to SM doublet

Enforce $SU(2)_L \times SU(2)_R$ symmetry to fix $\rho = 1$ at tree-level:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix}, \qquad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

Most general scalar potential that preserves $SU(2)_L \times SU(2)_R$:

$$V(\Phi, X) = \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) - M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}$$

Georgi & Machacek 1985
Chanowitz & Golden 1985

GM Physical spectrum

Physical spectrum arranged according to $SU(2)_C$ representation:

Bidoublet gives: $2 \otimes 2 \to 3 \oplus 1$

Bitriplet gives: $3 \otimes 3 \to 5 \oplus 3 \oplus 1$

Have 3 parameters: $c_H = \frac{v_\phi}{v}, s_H = \frac{\sqrt{8}v_\chi}{v}$ (give fraction of doublet and triplet contribution to vector boson masses) and singlet mixing angle α

Singlets: H^0 and h^0 with mass m_H, $m_h = 125\,GeV$

Triplets: (H_3^+, H_3^0, H_3^-) with mass m_3 + Goldstones

- Pheno similar to type I 2HDM, $cot\theta_H \to tan\beta$

Fiveplet: $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ with mass m_5

- Fermionphobic, H_5VV couplings proportional to s_H^2
- Pheno benchmark for 'exotic' scalars generated by exotic isospin rep.

History of custodial violation in GM

Custodial violation in Georgi-Machacek model has had a vibrant history

Gunion, Vega & Wudka 1991: Standard T parameter calculation yields infinity as a result of uncontrolled UV divergence from hypercharge violating custodial symmetry. Need full gauge invariant potential for counterterm

Englert, Re & Spannowsky 1302.6505 applied S, T parameter constraints by subtracting a counterterm for T

Chiang, Kuo & Yagyu 1804.02633 used measured T parameter as input to fix custodial violating counterterm when calculating h couplings at 1 loop

Blasi, De Curtis & Yagyu 1704.08512 used RGEs to study custodial violation from running up from a custodial symmetric theory at the weak scale

Our approach assume custodial symmetry generated accidentally at some scale Λ in an unspecified UV completion (e.g. composite higgs) and use RGEs to run down to weak scale

Most general gauge potential and custodial symmetry violation

$$V(\phi,\chi,\xi) = \tilde{\mu}_2^2\phi^\dagger\phi + \tilde{\mu}_3'^2\chi^\dagger\chi + \frac{\tilde{\mu}_3^2}{2}\xi^\dagger\xi + \tilde{\lambda}_1(\phi^\dagger\phi)^2 + \tilde{\lambda}_2|\tilde{\chi}^\dagger\chi|^2 + \tilde{\lambda}_3(\phi^\dagger\tau^a\phi)(\chi^\dagger t^a\chi) + \left[\tilde{\lambda}_4(\tilde{\phi}^\dagger\tau^a\phi)(\chi^\dagger t^a\xi) + \mathrm{h.c.}\right] + \tilde{\lambda}_5(\phi^\dagger\phi)(\chi^\dagger\chi) + \tilde{\lambda}_6(\phi^\dagger\phi)(\xi^\dagger\xi) + \tilde{\lambda}_7(\chi^\dagger\chi)^2 + \tilde{\lambda}_8(\xi^\dagger\xi)^2 + \tilde{\lambda}_9|\chi^\dagger\xi|^2 + \tilde{\lambda}_{10}(\chi^\dagger\chi)(\xi^\dagger\xi) - \frac{1}{2}\left[\tilde{M}_1'\phi^\dagger\Delta_2\tilde{\phi} + \mathrm{h.c.}\right] + \frac{\tilde{M}_1}{\sqrt{2}}\phi^\dagger\Delta_0\phi - 6\tilde{M}_2\chi^\dagger\overline{\Delta}_0\chi.$$

where, $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, $\quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}$, $\quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ -\xi^{+*} \end{pmatrix}$

Reduces to GM potential if impose special conditions which will be violated by hypercharge loops

Can only be exact at 1 energy scale, away from scale RGE running will violate relations

Relation to GM potential

Now have 16 parameters which reduce to the CS 9 when they obey:

$\tilde{\mu}_2^2 = \mu_2^2$	$\tilde{\lambda}_2 = 2\lambda_3$	$\tilde{\lambda}_6 = 2\lambda_2$	$\tilde{\lambda}_{10} = 4\lambda_4$
$\tilde{\mu}_3'^2 = \mu_3^2$	$\tilde{\lambda}_3 = -2\lambda_5$	$\tilde{\lambda}_7 = 2\lambda_3 + 4\lambda_4$	$\tilde{M}_1' = M_1$
$\tilde{\mu}_3^2 = \mu_3^2$	$\tilde{\lambda}_4 = -\sqrt{2}\lambda_5$	$\tilde{\lambda}_8 = \lambda_3 + \lambda_4$	$\tilde{M}_1 = M_1$
$\tilde{\lambda}_1 = 4\lambda_1$	$\tilde{\lambda}_5 = 4\lambda_2$	$\tilde{\lambda}_9 = 4\lambda_3$	$\tilde{M}_2 = M_2$

Running RGEs with $g' = 0$ will respect these relations

Running $g' \neq 0$ will violate these relations

Treat violation as perturbation of CS GM spectrum- express new mass eigenstates in terms of GM eigenstates

Our method

-Choose a set of parameters at the weak scale (parameterized by m_5) from the custodial symmetric GM model and solve for spectrum

-Choose a scale of custodial symmetry (subject to constraint from perturbative unitarity of λ_i at said scale) and run up to CS scale using RGEs with $g' = 0$

-Use CS relations to set all 16 general parameters at high scale

-Run back down to the weak scale using full RGEs

-Calculate vevs, GF, and m_h; adjust inputs λ_1 and μ_2^2 iteratively until match measurements in custodial violating theory

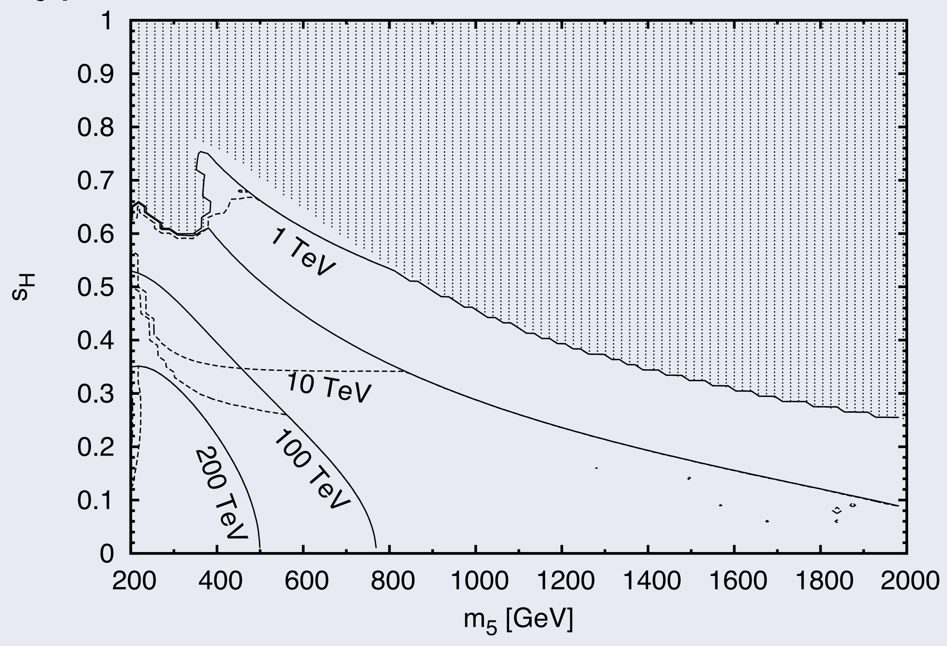
-Compute ρ and use $\pm 2\sigma$ region of $\rho = 1.00037 \pm 0.00023$ to place second constraint on scale

-Use constraints to place upper bound on scale, Λ

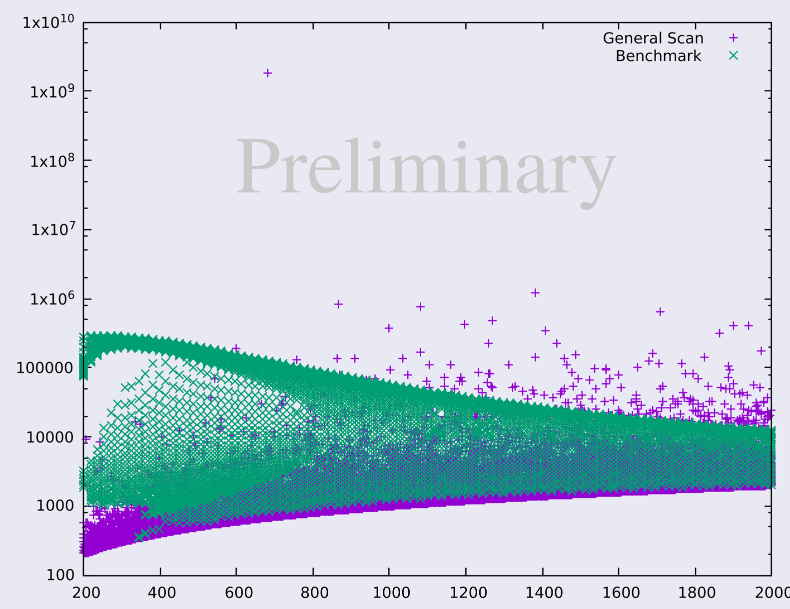
-Calculate weak scale custodial violating observables using upper bound

Results-Upper bound on Λ

Typical scales in the order of 10-100 TeV but can be as high as 10^6 TeV



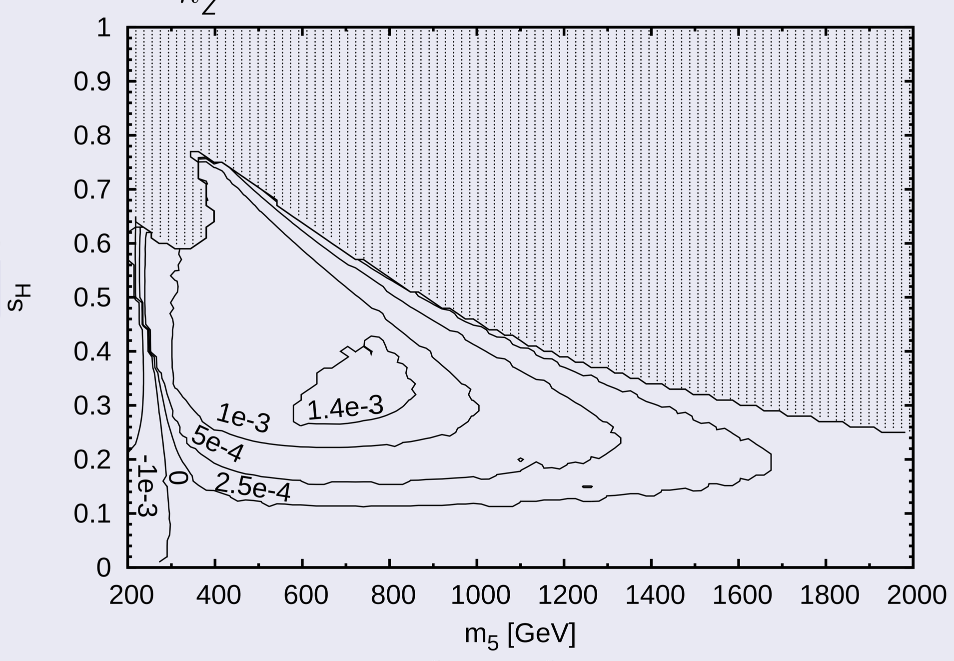
Left: Scale of the maximum cutoff versus m_5 in benchmark



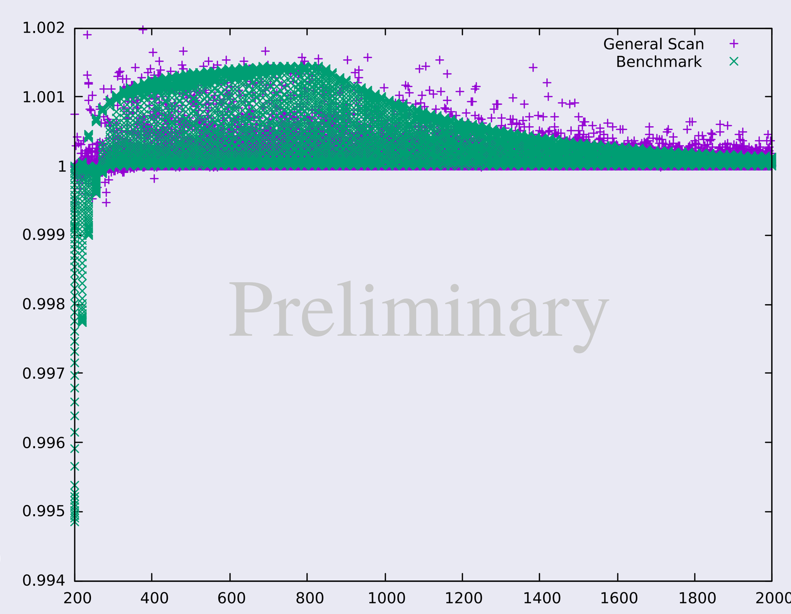
Right: Scale of the maximum cutoff versus m_5 in a general scan

Results- $\lambda_{WZ}^{\tilde{h}}$; Test of custodial symmetry violation in sm-like higgs couplings

$\lambda_{WZ}^{\tilde{h}} \equiv \frac{\kappa_W^{\tilde{h}}}{\kappa_Z^{\tilde{h}}}$ is a measure of CS violation (= 1 if scale of CS is the weak scale)



Left: Contours of $\delta\lambda_{WZ}^{\tilde{h}} = \lambda_{WZ}^{\tilde{h}} - 1$ at maximum cutoff scale in benchmark



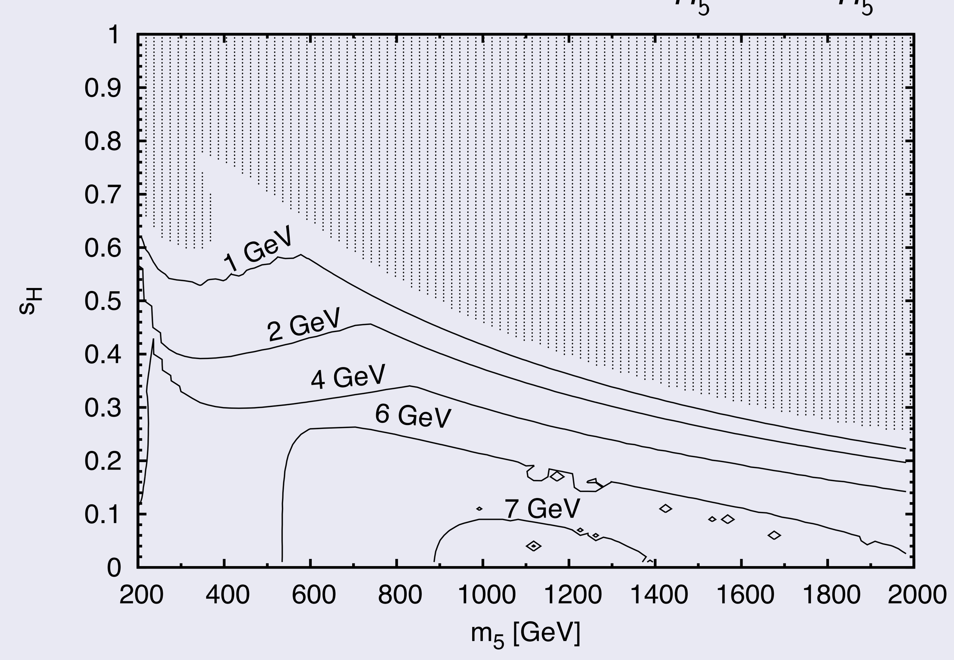
Right: $\lambda_{WZ}^{\tilde{h}}$ at maximum cutoff versus m_5 in a general scan

c.f. current measurement: $\lambda_{WZ}^{\tilde{h}} = 0.88^{+0.10}_{-0.09}$ and expected precision at HL-LHC (1-2 %) and ILC (0.5%)

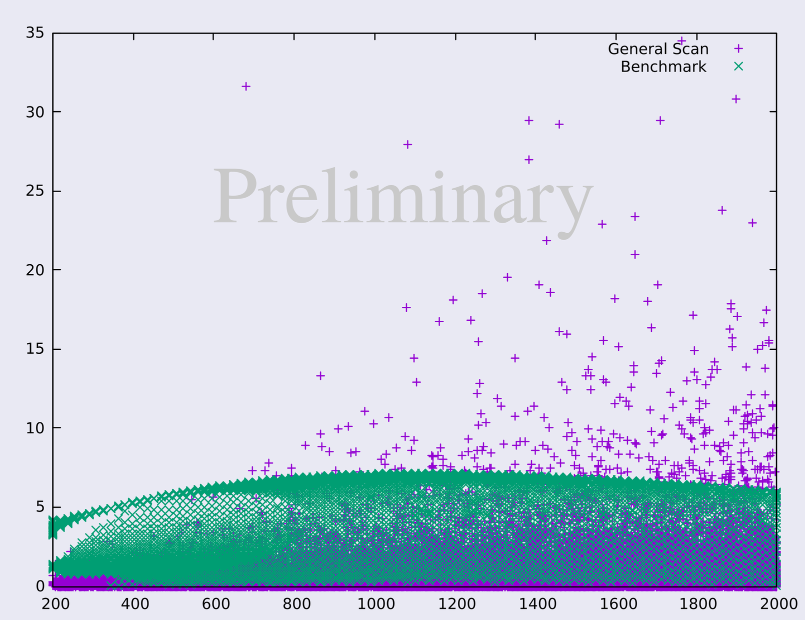
Results- Mass splittings within custodial 5-plet

In benchmark plane mass splittings of 5-plet obey hierarchy: $m_{\tilde{H}_5^{++}} > m_{\tilde{H}_5^+} > m_{\tilde{H}_5^0}$

In general scan some points have $m_{\tilde{H}_5^+} < m_{\tilde{H}_5^0}$ but with splittings of no more than 1.5 GeV



Left: Contours of $m_{\tilde{H}_5^{++}} - m_{\tilde{H}_5^0}$ at maximum cutoff scale in benchmark

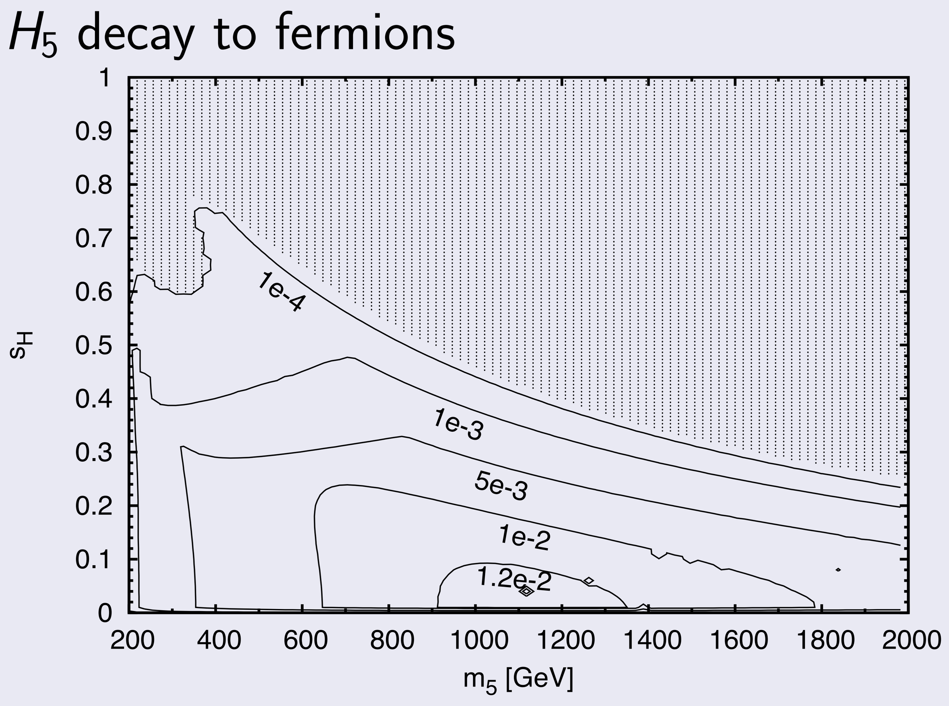


Right: $m_{\tilde{H}_5^{++}} - m_{\tilde{H}_5^0}$ at maximum cutoff versus m_5 in a general scan

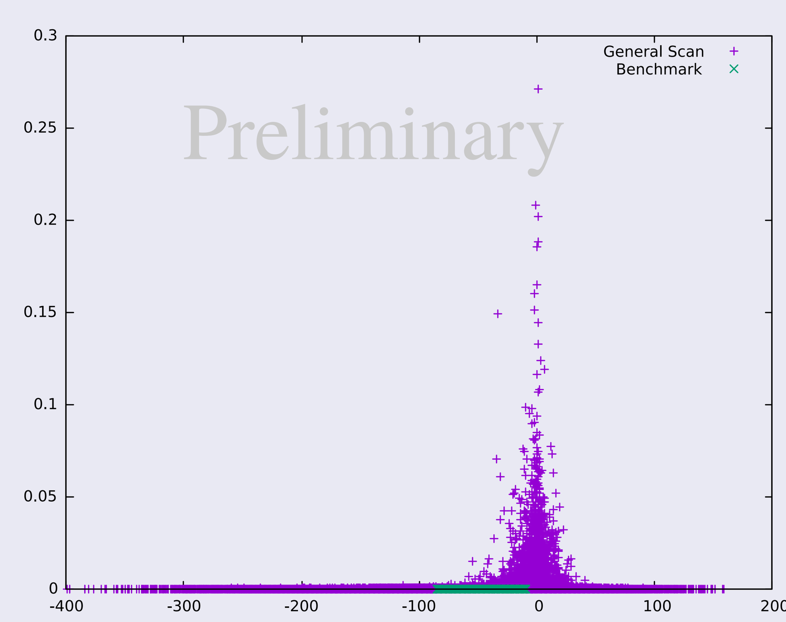
c.f. Chiang & Yagyu 1211.2658 and Chiang, Kanemura & Yagyu 1510.06297

Results- Induced BR of $\tilde{H}_5^+$ to fermions

CS violation induces mixing between CS states. H_5 states mixing with doublet induces H_5 decay to fermions



Left: Contours of BR of $\tilde{H}_5^+ -> tb$ at maximum cutoff scale in benchmark



Right: BR of $\tilde{H}_5^+ -> tb$ at maximum cutoff scale versus $m_{\tilde{H}_5^+} - m_{\tilde{H}_3^+}$ in a general scan

Branching ratio only significant when mixing with doublet enhanced by mass degeneracy (otherwise max of about 1.5%)

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