Custodial symmetry violation in the Georgi-Machacek model

Heather Logan
Carleton University
Ottawa, Canada

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Based on B. Keeshan, HEL & T. Pilkington, arXiv:1807.11511

Outline

Introduction

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Our implementation

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Introduction

Can we constrain the possibility that "exotic" Higgs fields (isospin $> 1/2$) contribute to electroweak symmetry breaking?

Generically this is very strongly constrained by the ρ parameter:

$$\rho \equiv \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M_Z^2}{g^2/M_W^2} = \frac{v_\phi^2 + a\langle X^0\rangle^2}{v_\phi^2 + b\langle X^0\rangle^2}$$

$$\begin{aligned} a &= 4\left[T(T+1) - Y^2\right] c \\ b &= 8Y^2 \end{aligned}$$

$Q = T^3 + Y$; SM doublet: $Y = 1/2$

Expt: $\rho = 1.00037 \pm 0.00023$ (2016 PDG)

Need to do some model-building; otherwise $v_{\text{exotic}} \ll v_{\text{doublet}}$.

There are only two known approaches:

1) Use the septet $(T, Y) = (3, 2)$: $\rho = 1$ by accident!

Doublet $\left(\frac{1}{2}, \frac{1}{2}\right)$ + septet $(3, 2)$: Scalar septet model

Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

2) Use global $SU(2)_L \times SU(2)_R$ imposed on the scalar potential

Global $SU(2)_L \times SU(2)_R \to$ custodial SU(2) ensures tree-level $\rho = 1$

Doublet + triplets $(1, 0) + (1, 1)$: Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

Doublet + quartets $\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)$:
Doublet + quintets $(2, 0) + (2, 1) + (2, 2)$:
Doublet + sextets $\left(\frac{5}{2}, \frac{1}{2}\right) + \left(\frac{5}{2}, \frac{3}{2}\right) + \left(\frac{5}{2}, \frac{5}{2}\right)$:

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

Larger than sextets $\to$ too many large multiplets, violates perturbativity

Can also have duplications, combinations $\to$ ignore that here.

Both approaches have theoretical "issues":

1) Can't give the septet a vev through spontaneous breaking without generating a physical massless Goldstone boson.

Have to couple it to the SM doublet through a dimension-7 $X\Phi^*\Phi^5$ term Hisano & Tsumura 2013

Need the UV completion to be nearby!

2) Global SU(2)$_L\times$SU(2)$_R$ is broken by gauging hypercharge.

Gunion, Vega & Wudka 1991

Special relations among params of *full* gauge-invariant scalar potential can only hold at one energy scale: violated by running due to hypercharge. Garcia-Pepin, Gori, Quiros, Vega, Vega-Morales, Yu 2014

Need the UV completion to be nearby!

This talk: quantify (2) in the Georgi-Machacek model.

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets $(1,0)+(1,1)$ in a bi-triplet:

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

Global SU(2)$_L\times$SU(2)$_R$ $\to$ custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_\chi$

Most general scalar potential invariant under SU(2)$_L\times$SU(2)$_R$:

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

9 parameters, 2 fixed by G_F and m_h $\to$ 7 free parameters. Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

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Global $SU(2)_L \times SU(2)_R \to$ custodial symmetry $\langle\chi^0\rangle = \langle\xi^0\rangle \equiv v_\chi$

Physical spectrum:

Bi-doublet: $2 \otimes 2 \to 1 \oplus 3$

Bi-triplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

- Two custodial singlets mix $\to h^0,\ H^0$ m_h, m_H, angle α
  Usually identify $h^0 = h(125)$

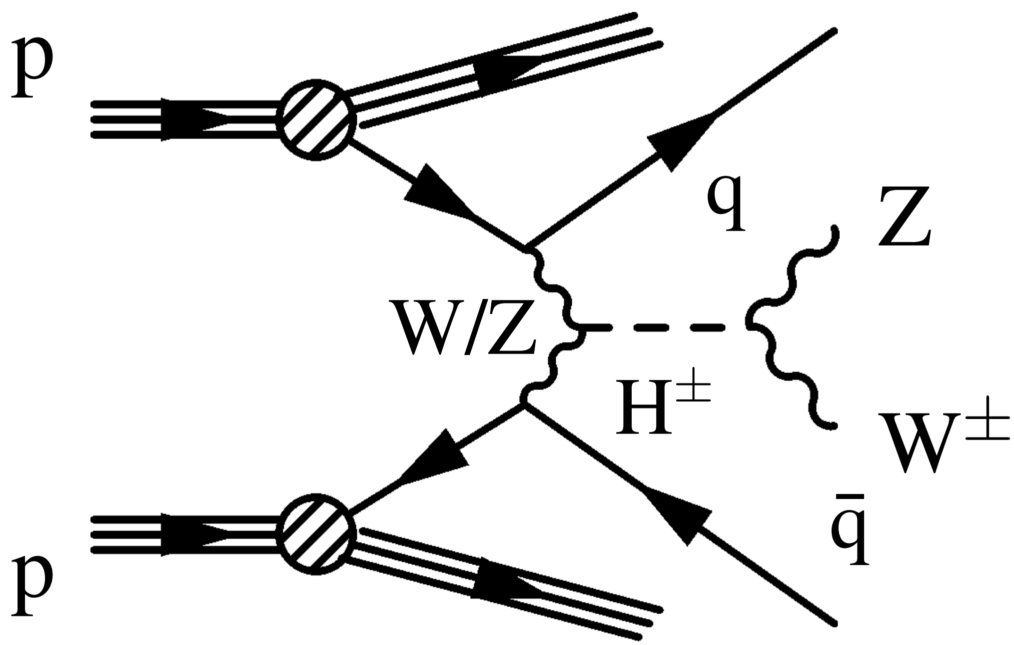
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ m_3 + Goldstones
  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan\beta \to \cot\theta_H$

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8}v_\chi/v_{SM}$
  $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

Smoking-gun processes:

VBF $\rightarrow H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ VBF + like-sign dileptons + MET

VBF $\rightarrow H_5^{\pm} \rightarrow W^\pm Z$ VBF + $qq\ell\ell$; VBF + 3ℓ + MET



Cross section $\propto s_H^2 \equiv$ fraction of M_W^2, M_Z^2 due to exotic scalars

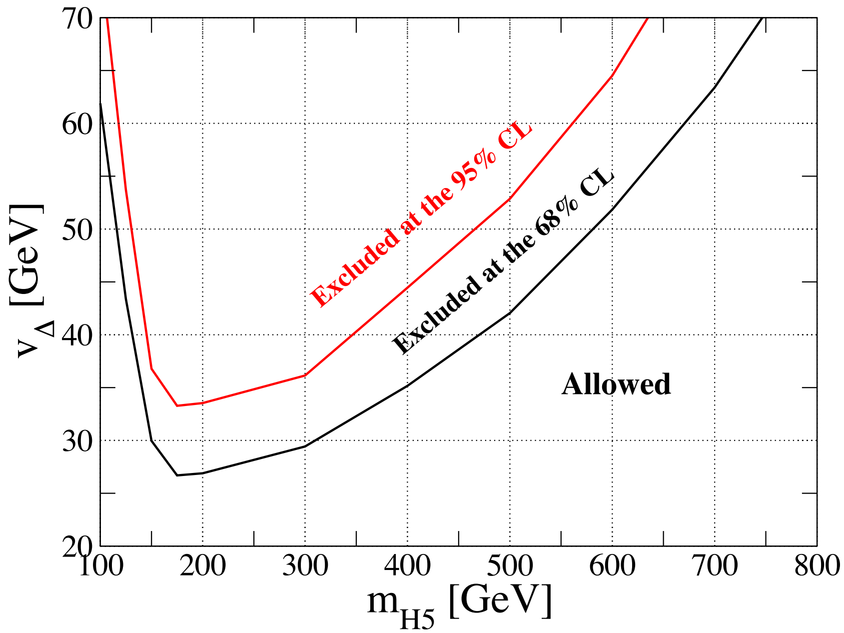
Searches

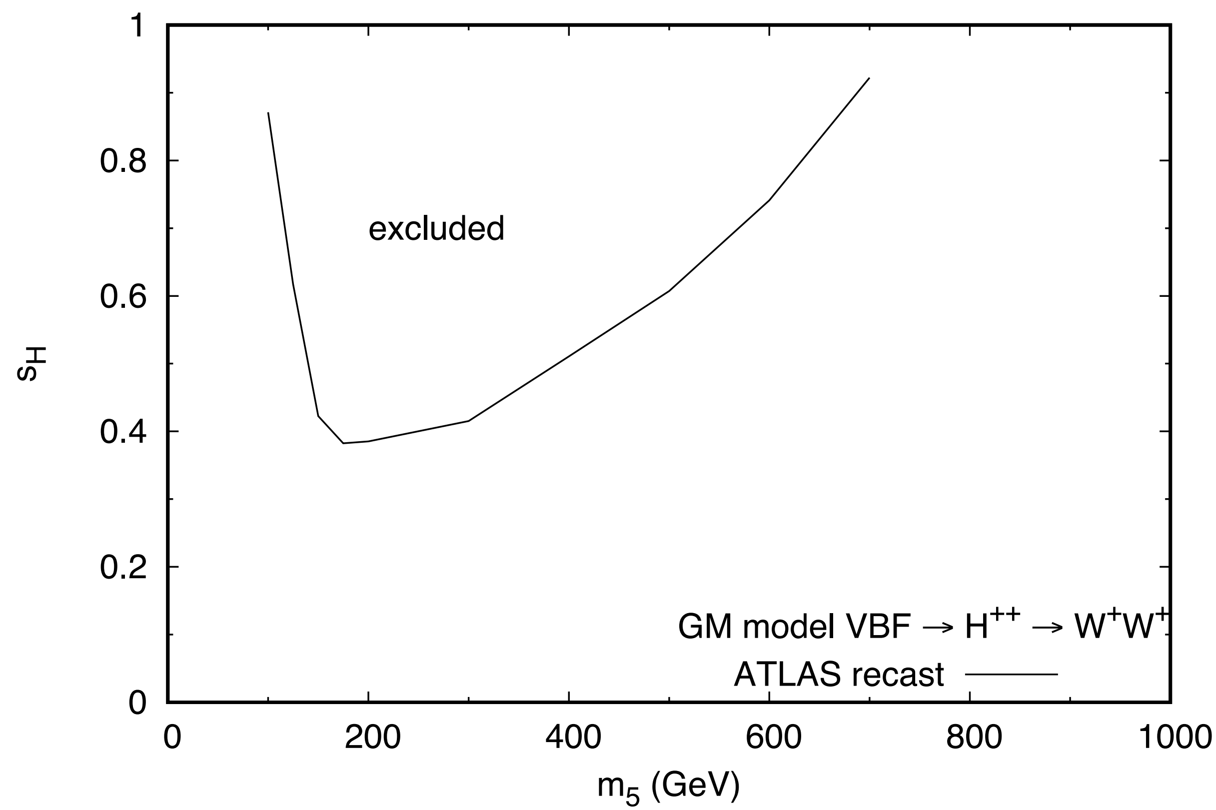
SM VBF $\to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET cross section measurement

ATLAS Run 1 1405.6241, PRL 2014

Recast to constrain VBF $\to H_5^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET

Chiang, Kanemura, Yagyu, 1407.5053

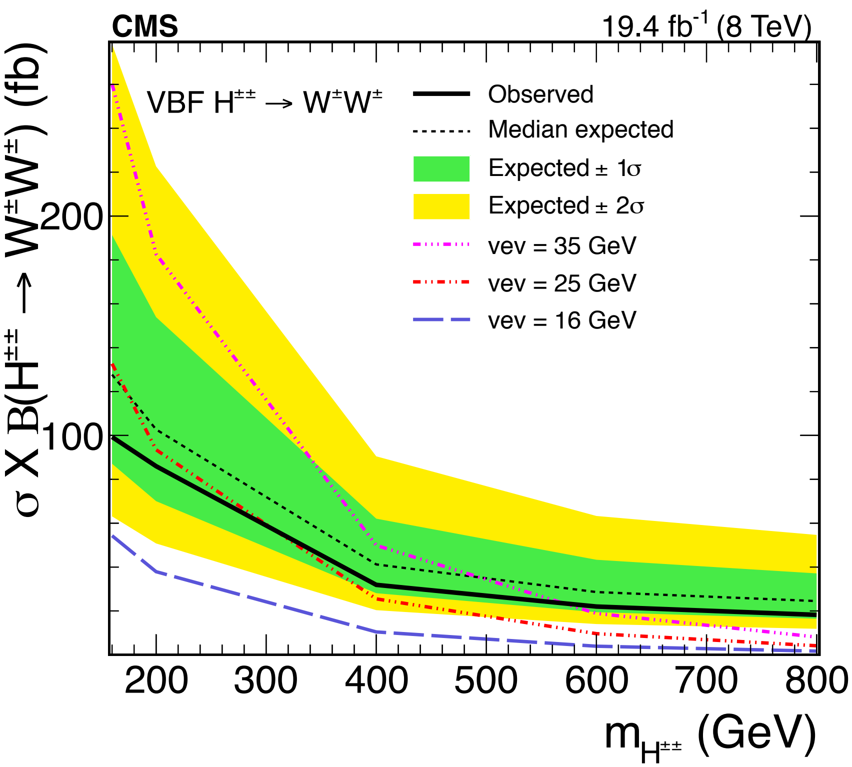


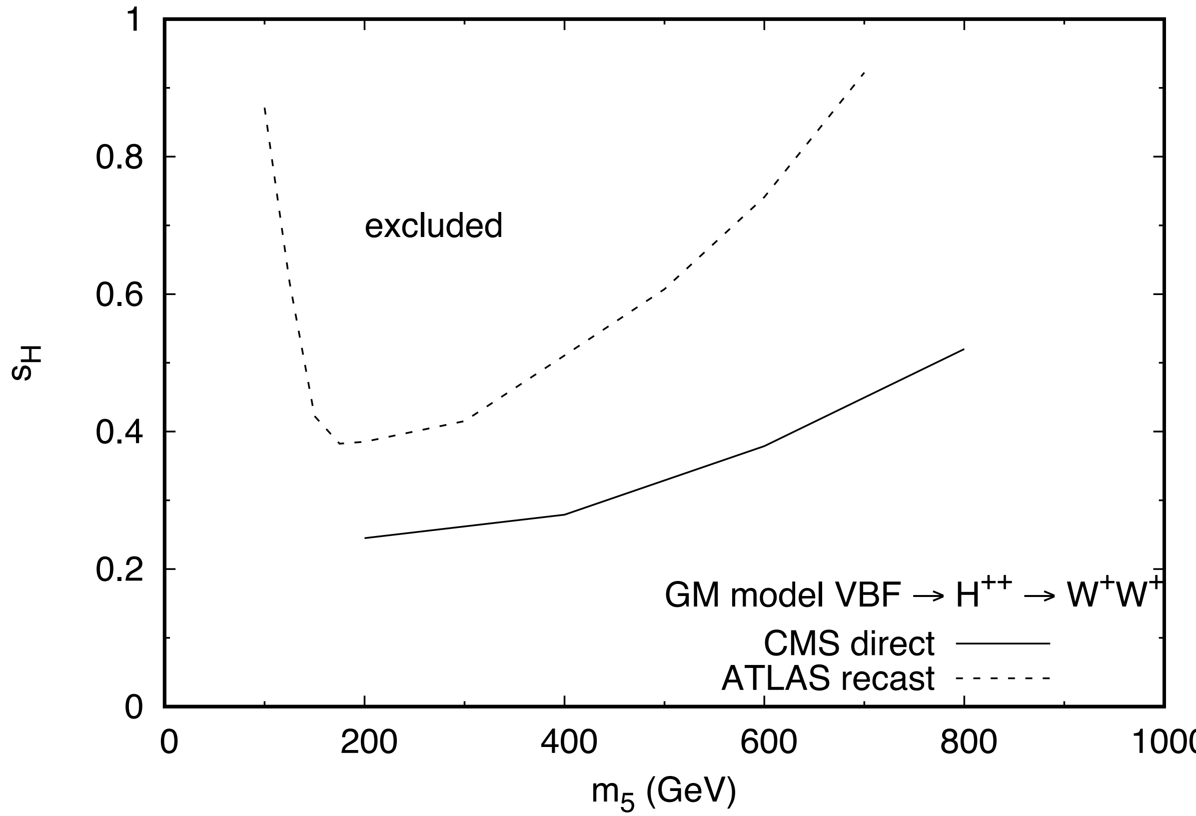


Searches

VBF $H_5^{\pm\pm} \to W^\pm W^\pm \to \ell^\pm \ell^\pm$ + MET (CMS Run 1)

CMS 1410.6315, PRL 2015

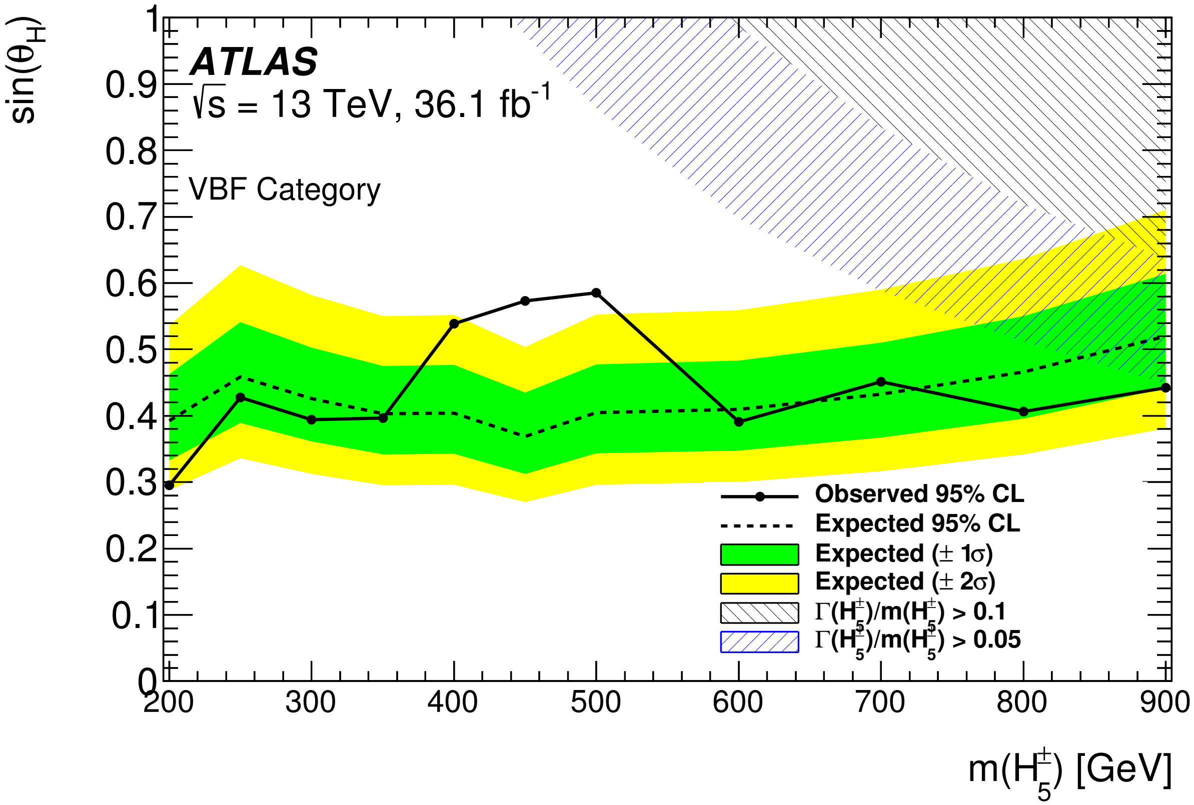




Translated using VBF $\to H^{\pm\pm}$ cross sections from LHCHXSWG-2015-001 (M. Zaro + HEL)

VBF $H_5^\pm \to W^\pm Z \to \ell^\pm \ell^+ \ell^- + \text{MET}$ (ATLAS Run 2)

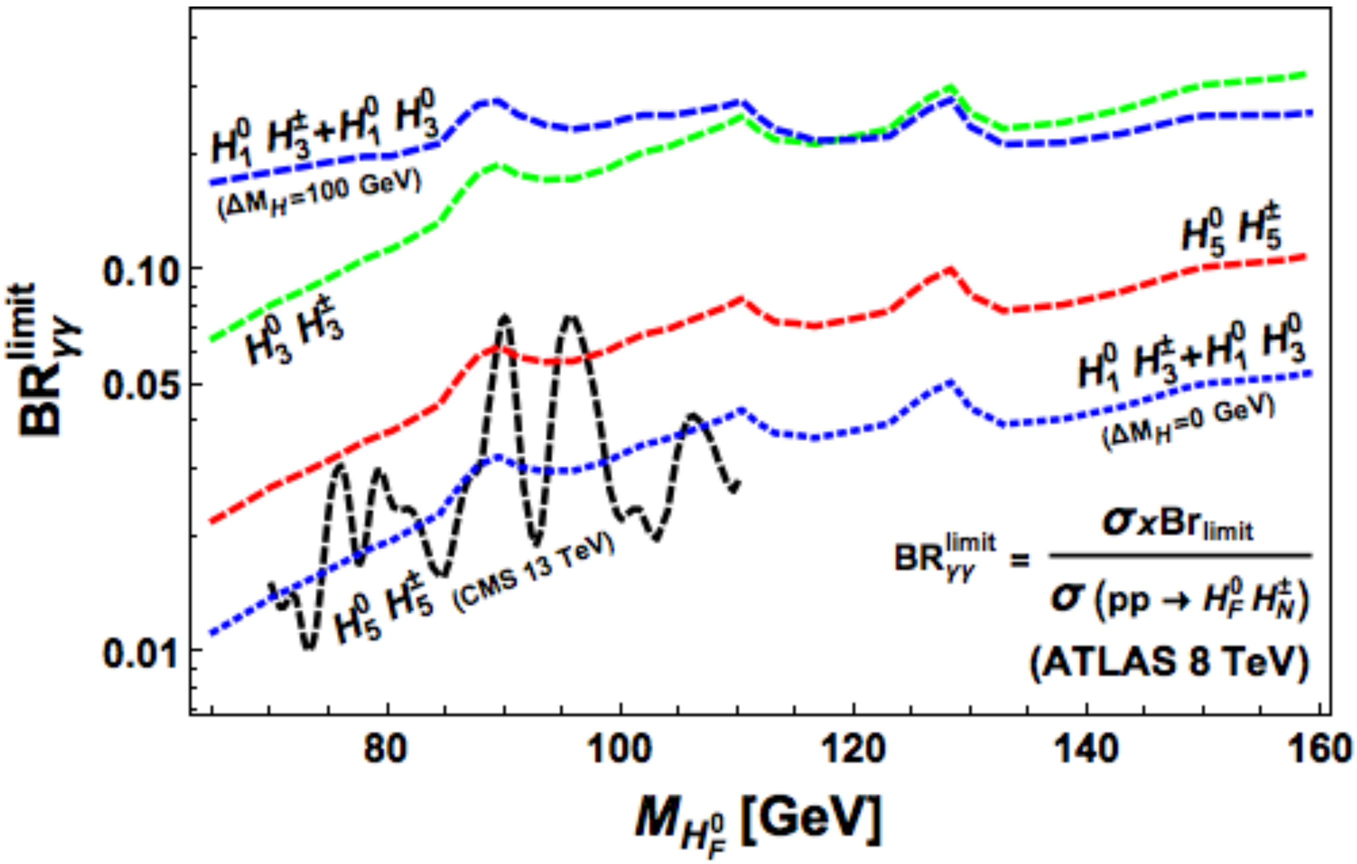
ATLAS 1806.01532



Stronger upper bound on s_H for $m_5 \in (700, 900)$ GeV compared to $H_5^{\pm\pm}$

Searches: $H_5^0 \to \gamma\gamma$ at low mass

Drell-Yan $pp \to H_5^0 H_5^\pm$ depends only on m_5 and gauge couplings!



Vega, Vega-Morales & Xie, 1805.01970

If W loop contribution dominates $H_5^0 \to \gamma\gamma, Z\gamma$, tree and loop decays scale the same way with s_H and $m_5 \lesssim 110$ GeV is excluded.

Custodial symmetry violation in the GM model: a long history

Gunion, Vega & Wudka 1991 showed that computing the T parameter in the GM model yields infinity due to an uncancelled UV divergence caused by hypercharge violating the custodial symmetry at 1-loop. Full gauge-invariant but SU(2)$_L\times$SU(2)$_R$-violating scalar potential yields the needed counterterm.

Englert, Re & Spannowsky 1302.6505 applied S, T parameter constraints by subtracting a counterterm for T (just the divergent part? not clear)

Chiang, Kuo & Yagyu 1804.02633 calculated 1-loop renormalized predictions for h couplings in GM model and used measured T parameter as input to fix the relevant custodial-symmetry-violating counterterm

Blasi, De Curtis & Yagyu 1704.08512 computed the RGEs and studied custodial violation from running up from custodial-symmetric theory at the weak scale (RGEs independently checked by us)

Full gauge-invariant potential:

$$
\begin{aligned}
V(\phi,\chi,\xi) &= \tilde\mu_2^2\phi^\dagger\phi + \tilde\mu_3'^2\chi^\dagger\chi + \frac{\tilde\mu_3^2}{2}\xi^\dagger\xi \\
&+\tilde\lambda_1(\phi^\dagger\phi)^2 + \tilde\lambda_2|\tilde\chi^\dagger\chi|^2 + \tilde\lambda_3(\phi^\dagger\tau^a\phi)(\chi^\dagger t^a\chi) \\
&+\left[\tilde\lambda_4(\tilde\phi^\dagger\tau^a\phi)(\chi^\dagger t^a\xi) + \text{h.c.}\right] + \tilde\lambda_5(\phi^\dagger\phi)(\chi^\dagger\chi) \\
&+\tilde\lambda_6(\phi^\dagger\phi)(\xi^\dagger\xi) + \tilde\lambda_7(\chi^\dagger\chi)^2 + \tilde\lambda_8(\xi^\dagger\xi)^2 \\
&+\tilde\lambda_9|\chi^\dagger\xi|^2 + \tilde\lambda_{10}(\chi^\dagger\chi)(\xi^\dagger\xi) \\
&-\frac{1}{2}\left[\tilde M_1'\phi^\dagger\Delta_2\tilde\phi + \text{h.c.}\right] + \frac{\tilde M_1}{\sqrt2}\phi^\dagger\Delta_0\phi - 6\tilde M_2\chi^\dagger\overline{\Delta}_0\chi
\end{aligned}
$$

where

$$
\begin{aligned}
\Delta_2 &\equiv \sqrt2\tau^a U_{ai}\chi_i = \begin{pmatrix} \chi^+/\sqrt2 & -\chi^{++} \\ \chi^0 & -\chi^+/\sqrt2 \end{pmatrix}, \\
\Delta_0 &\equiv \sqrt2\tau^a U_{ai}\xi_i = \begin{pmatrix} \xi^0/\sqrt2 & -\xi^+ \\ -\xi^{+*} & -\xi^0/\sqrt2 \end{pmatrix}, \\
\overline{\Delta}_0 &\equiv -t^a U_{ai}\xi_i = \begin{pmatrix} -\xi^0 & \xi^+ & 0 \\ \xi^{+*} & 0 & \xi^+ \\ 0 & \xi^{+*} & \xi^0 \end{pmatrix}.
\end{aligned}
$$

Minimize potential, compute mass matrices, etc.

16 Lagrangian parameters compared to 9 in original GM model: Matching gauge-invariant potential to original GM model yields

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

RGEs with $g' = 0$ preserve these relations.

Keeping $g' \neq 0$ violates these relations and introduces custodial symmetry violation through the RGE running.

Our implementation

Basic idea:

- Assume custodial symmetry at some high scale Λ

(accidental $SU(2)_L \times SU(2)_R$ coming from UV completion e.g. composite Higgs)

- Run down to weak scale ⇒ custodial violation generated

(1-loop RGEs, tree-level matching ≡ leading log approximation)

Measured value of ρ will put an upper bound on scale Λ

- Subject to ρ constraint (and perturbativity at Λ), quantify maximum allowed custodial symmetry violation and its phenomenological consequences

Our implementation

Details:

- Start with a benchmark scenario at the weak scale* (for concreteness, and to get G_F, m_h close to their correct values)
* "weak scale" $= m_5$

H5plane benchmark (introduced by HXSWG for H_5 LHC searches)

Fixed Parameters	Variable Parameters	Dependent Parameters
$G_F = 1.1663787 \times 10^{-5}$ GeV^{-2}	$m_5 \in [200, 3000]$ GeV	$\lambda_2 = 0.4 m_5/(1000$ GeV$)$
$m_h = 125$ GeV	$s_H \in (0, 1)$	$M_1 = \sqrt{2} s_H (m_5^2 + v^2)/v$
$\lambda_3 = -0.1$		$M_2 = M_1/6$
$\lambda_4 = 0.2$		

- Run up with $g' = 0$ (custodial symmetric!) to some scale Λ; check perturbativity of quartic couplings (avoid Landau pole)
$\Rightarrow$ upper bound on Λ to avoid perturbativity violation

Our implementation

Details (continued):

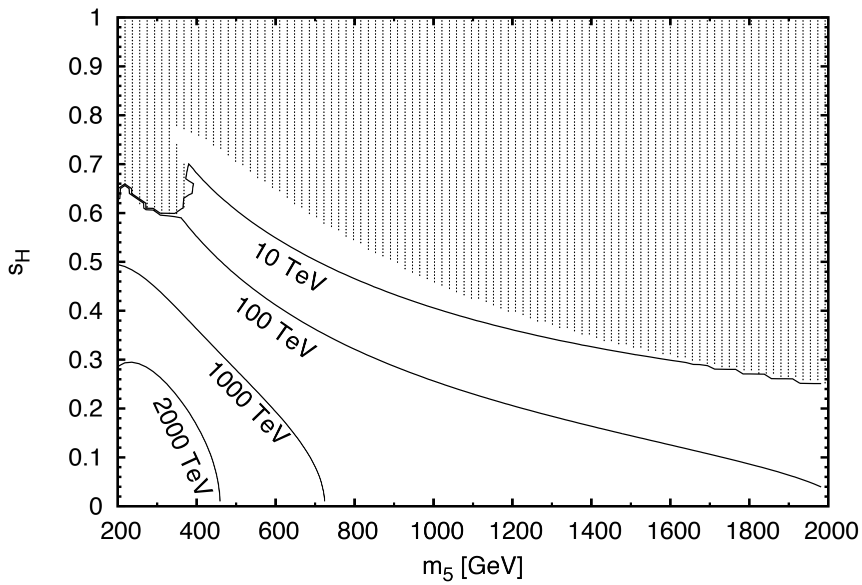
- Run back down with $g' \neq 0$ to get the custodial-violating Lagrangian parameters at the weak scale

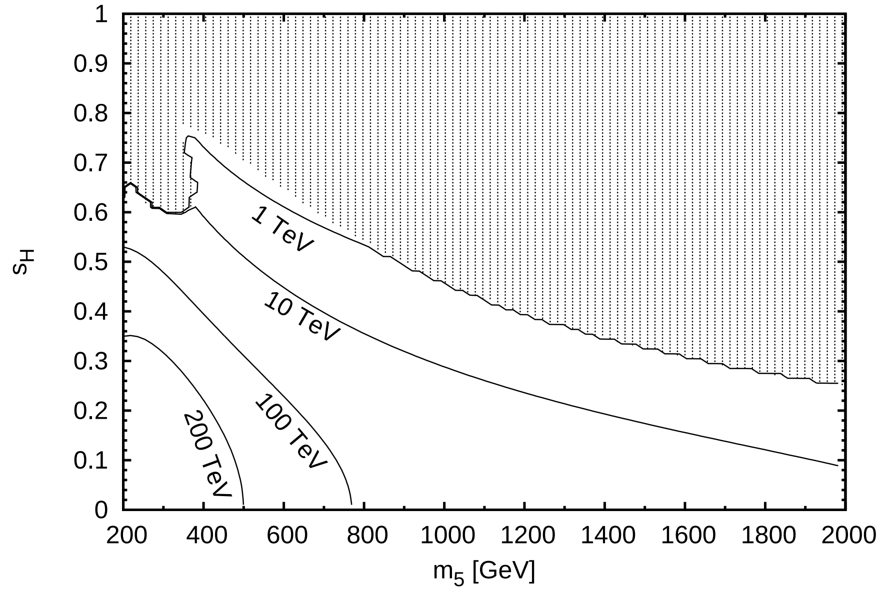
- Compute vevs $\rightarrow G_F$ and mass matrices $\rightarrow m_h$; adjust original weak-scale inputs and iterate until these match experiment in custodial violating theory

- Compute ρ; adjust upper bound on Λ if necessary
$\rho = 1.00037 \pm 0.00023$ (2016 PDG) [require within $\pm 2\sigma$]

- Compute weak-scale predictions for custodial-violating observables (λ^h_{WZ}, mass splittings, mixings)

Results (within H5plane benchmark): cutoff scale



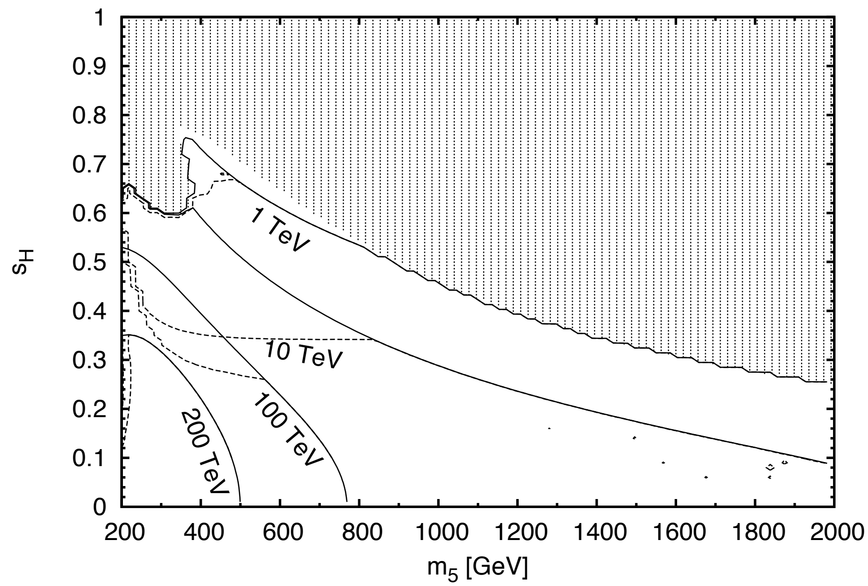


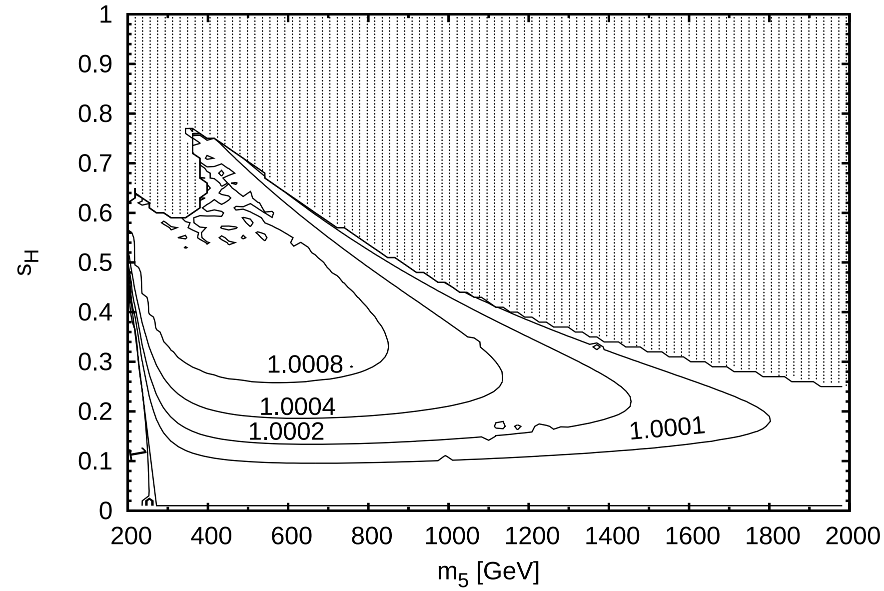
Left: Scale of Landau pole

Right: Highest scale at which perturbative unitarity constraints on custodial-symmetric λ_i remain satisfied

UV completion must appear below 10s to 100s of TeV

Results (within H5plane benchmark): ρ parameter





Left: Maximum cutoff scale including ρ parameter constraint (dashed) + perturbative unitarity (solid)

Right: Weak-scale value of ρ, for Λ as large as possible

ρ samples full 2σ allowed range

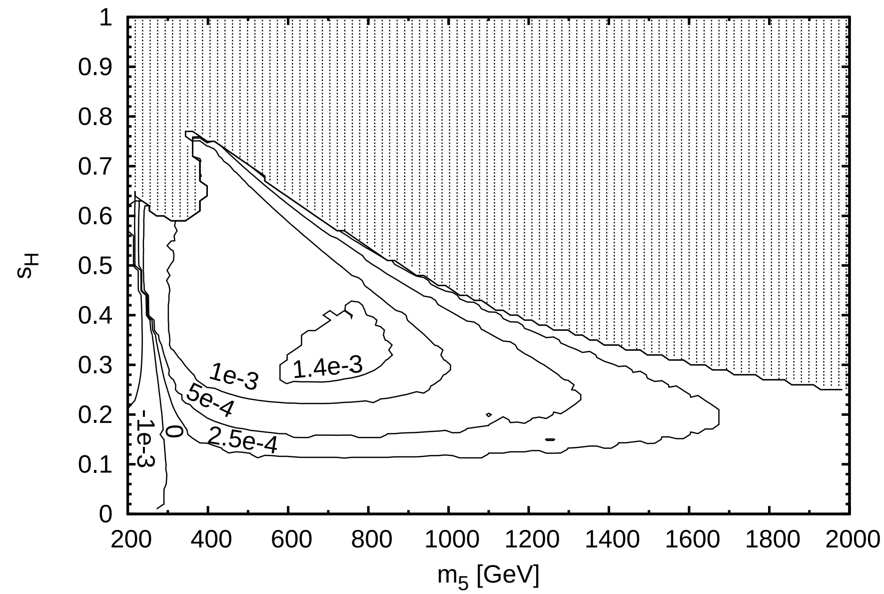
$\Delta\rho$ is positive in most of H5plane benchmark parameter space

Results (within H5plane benchmark): hWW/hZZ

Test of custodial symmetry violation in h_{125} couplings:

$$\lambda^h_{WZ} \equiv \frac{\kappa^h_W}{\kappa^h_Z}$$

Plot: $\delta\lambda^h_{WZ} \equiv \lambda^h_{WZ} - 1$
for Λ as large as possible



Deviation from SM prediction ($\lambda^h_{WZ} = 1$) at most half a percent

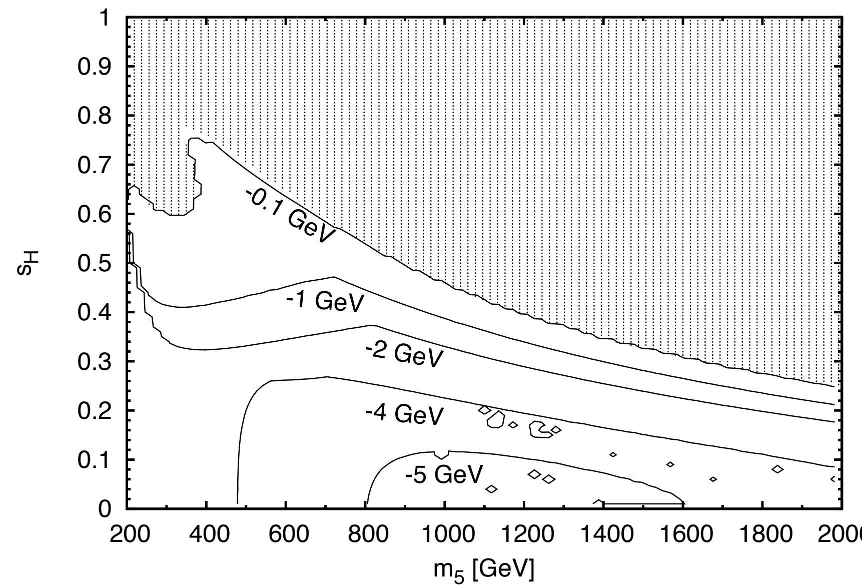
Current LHC precision: $\lambda^h_{WZ} = 0.88^{+0.10}_{-0.09}$ ATLAS + CMS Run 1, 1606.02266

Future precision based on hWW and hZZ projections:
HL-LHC: a few percent
ILC: about half a percent
FCC-ee: about 0.2 percent

Results (within H5plane benchmark): mass splittings

Plot: $m_{H_3^\pm} - m_{H_3^0}$
for Λ as large as possible

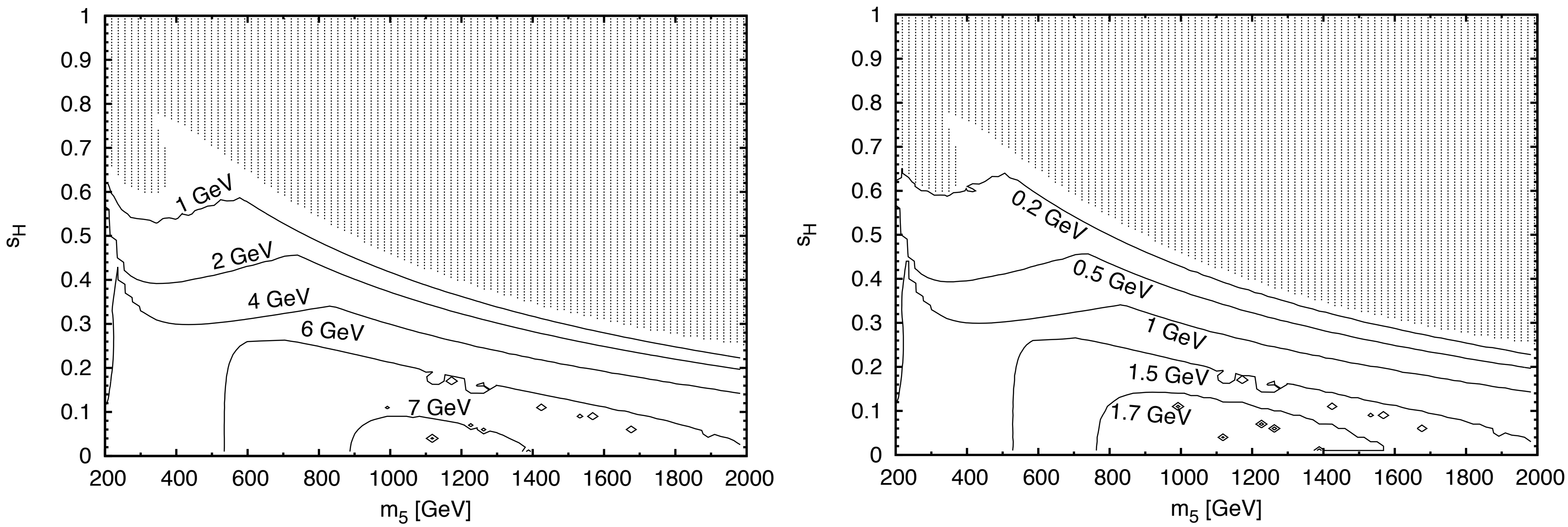
(negative values: $H_3^\pm$ is lighter)



Custodial-violating mass splitting of $H_3^{0,\pm}$ is at most 5.3 GeV.
$m_{H_3^0} > m_{H_3^\pm}$ everywhere in H5plane benchmark.

Measurement prospects: $H_3^0 \to b\bar{b}, t\bar{t}$; $H_3^+ \to t\bar{b}$
Couplings as in Type-I 2HDM: down-type decays not enhanced
Mass splitting too small to detect at LHC

Results (within H5plane benchmark): mass splittings



Left: $m_{H_5^{\pm\pm}} - m_{H_5^0}$
for Λ as large as possible

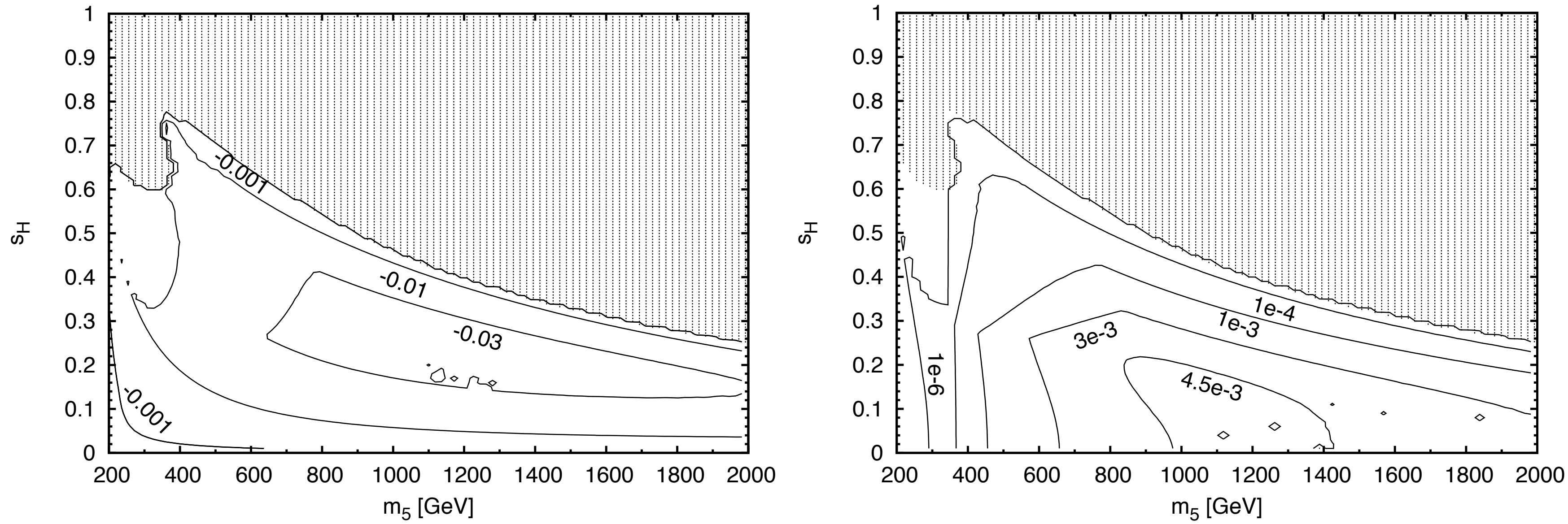
Right: $m_{H_5^{\pm}} - m_{H_5^0}$

Custodial-violating mass splitting of $H_5^{0,\pm,\pm\pm}$ is at most 7.2 GeV.
$m_{H_5^{\pm\pm}} > m_{H_5^{\pm}} > m_{H_5^0}$ everywhere in H5plane benchmark.

Decays are to VV – similar challenges to detect small mass splittings at LHC.

Results (within H5plane benchmark): mixing

Custodial sym violation mixes doublet into fermiophobic H_5



Left: induced κ_f for H_5^0 for Λ as large as possible

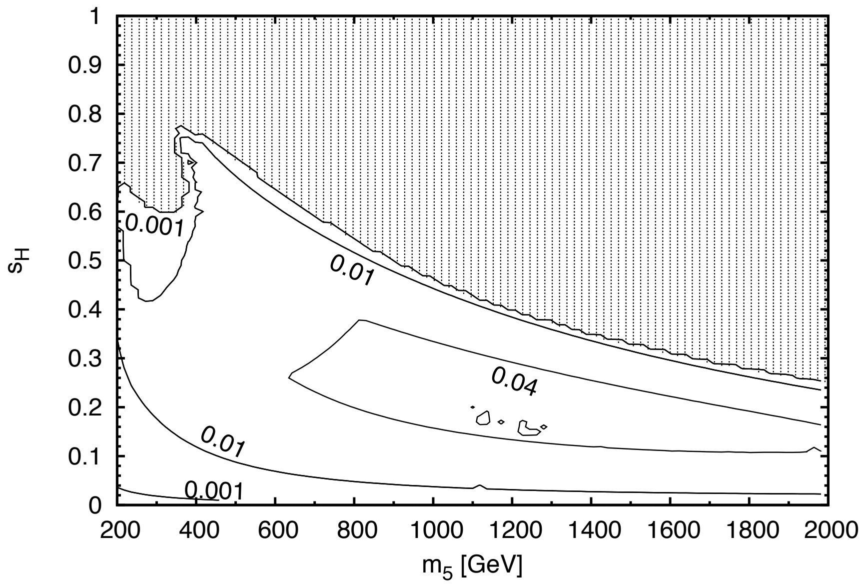
Right: BR($H_5^0 \to f\bar{f}$)

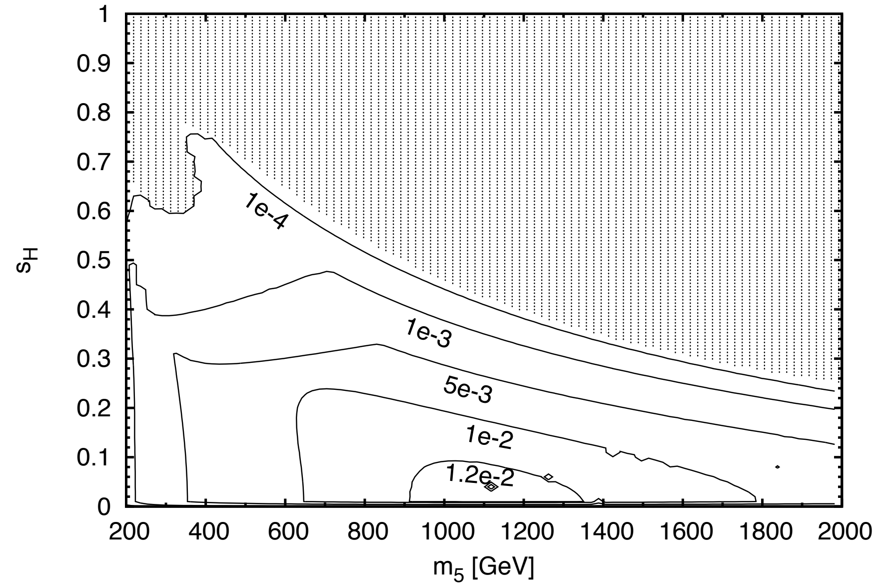
Custodial-violation-induced BR of H_5^0 to fermions ($t\bar{t}$) reaches almost half a percent in H5plane benchmark ($m_5 > 200$ GeV).

Effect at low mass $< 2M_W$ may be much more interesting: competition with powerful $H_5^0 \to \gamma\gamma$ channel $\Rightarrow$ future work

Results (within H5plane benchmark): mixing

Custodial sym violation mixes doublet into fermiophobic H_5





Left: induced κ_f for $H_5^{\pm}$ for Λ as large as possible

Right: BR($H_5^+ \to f\bar{f}$)

Custodial-violation-induced BR of H_5^+ to fermions ($t\bar{b}$) reaches 1.2% in H5plane benchmark ($m_5 > 200$ GeV).

At low mass $< M_W + M_Z$ this can compete with $W\gamma$ decay.

Conclusions and outlook

Hypercharge interactions violate custodial symmetry in the GM model beyond tree level.

We studied the impact of this assuming a custodial-symmetric theory at some high scale Λ and running down to the weak scale.

For this first pass we used the H5plane benchmark ($m_5 > 200$ GeV)

Main results:

- UV completion must lie below 10s to 100s of TeV
  forced by perturbative unitarity + measured ρ parameter
- Custodial-violating effects are small! (too small to see at LHC)
  assumption of custodial-symmetric GM is good for LHC searches

Custodial-violation-induced fermion couplings of otherwise fermiophobic H_5 may become important for masses below $2M_W$, where tree-level decays go offshell and loop decays become important.
Competition with powerful $H_5^0 \to \gamma\gamma$ channel? $\Rightarrow$ future work

BACKUP SLIDES

Most general SU(2)$_L\times$SU(2)$_R$-invariant scalar potential: Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

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

9 parameters, 2 fixed by M_W and m_h $\rightarrow$ free parameters are m_H, m_3, m_5, v_χ, α plus two triple-scalar couplings.

Dimension-3 terms usually omitted by imposing Z_2 sym. on X.

These dim-3 terms are essential for the model to possess a decoupling limit!

$(UXU^\dagger)_{ab}$ is just the matrix X in the Cartesian basis of SU(2), found using

$$U = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ -\frac{i}{\sqrt{2}} & 0 & -\frac{i}{\sqrt{2}} \\ 0 & 1 & 0 \end{pmatrix}$$

Fields and vevs for full gauge-invariant potential:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ -\xi^{+*} \end{pmatrix}, \tag{1}$$

$$\begin{aligned} \tilde{\phi} &\equiv C_2 \phi^* = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^* = \begin{pmatrix} \phi^{0*} \\ -\phi^{+*} \end{pmatrix} \\ \tilde{\chi} &\equiv C_3 \chi^* = \begin{pmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \chi^* = \begin{pmatrix} \chi^{0*} \\ -\chi^{+*} \\ \chi^{++*} \end{pmatrix}. \end{aligned} \tag{2}$$

$$\phi^0 \to \frac{\tilde{v}_\phi}{\sqrt{2}} + \frac{\phi^{0,r} + i\phi^{0,i}}{\sqrt{2}}, \qquad \chi^0 \to \tilde{v}_\chi + \frac{\chi^{0,r} + i\chi^{0,i}}{\sqrt{2}}, \qquad \xi^0 \to \tilde{v}_\xi + \xi^{0,r}. \tag{3}$$

$$\rho = \frac{\tilde{v}_\phi^2 + 4\tilde{v}_\chi^2 + 4\tilde{v}_\xi^2}{\tilde{v}_\phi^2 + 8\tilde{v}_\chi^2} = \frac{v^2}{v^2 + 4(\tilde{v}_\chi^2 - \tilde{v}_\xi^2)}. \tag{4}$$