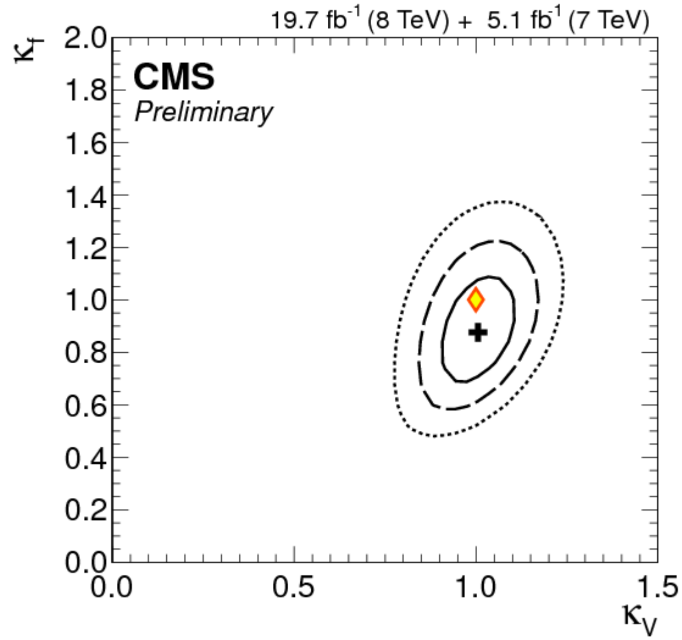
Decays of the SM-like Higgs boson in the Georgi-Machacek model

Heather Logan
Carleton University
Ottawa, Canada

LHC HXSWG, BRs subgroup
October 8, 2014

Based on K. Hartling, K. Kumar, H.E.L., 1404.2640 and work in preparation

Motivation for isospin ≥ 1



Consider the hWW coupling:

- SM: $i\frac{g^2 v}{2} g_{\mu\nu}$ ($v \simeq 246$ GeV)

- 2HDM: $i\frac{g^2 v}{2} g_{\mu\nu} \sin(\beta - \alpha)$

- SM + singlet: $i\frac{g^2 v}{2} g_{\mu\nu} \cos\alpha$ ($h = \phi \cos\alpha - s \sin\alpha$)

Extended Higgs sector with isospin doublets or singlets always have hVV couplings less than or equal to those in the SM.

- SM + some multiplet X: $i\frac{g^2 v_X}{2} g_{\mu\nu} \cdot 2\left[T(T+1) - \frac{Y^2}{4}\right]$ ($Q = T^3 + Y/2$)

The only way to enhance the hWW coupling above its SM value is through a scalar with isospin ≥ 1 that has a non-negligible vev and mixes into the observed Higgs h. $\Rightarrow$ triplets benchmark

Motivation for isospin ≥ 1

Enhancement of (all) the h couplings is also interesting because it can hide a non-SM contribution to the Higgs BRs.

LHC measures rates in particular final states:

$$\text{Rate} = \frac{\sigma_{\text{SM}} \Gamma_{\text{SM}}}{\Gamma_{\text{SM}}^{\text{tot}}} \to \frac{\kappa^2 \sigma_{\text{SM}} \cdot \kappa^2 \Gamma_{\text{SM}}}{\kappa^2 \Gamma_{\text{SM}}^{\text{tot}} + \Gamma_{\text{new}}}$$

Rates are identical to SM Higgs predictions if

$$\kappa^2 = \frac{1}{1 - \text{BR}_{\text{new}}}$$

Constraint on Γ^{tot} (equivalently on κ) from off-shell $gg\ (\to h^*) \to ZZ$ assumes no new resonances in s-channel: rather model-dependent.

To study this further, nice to have a concrete model $\Rightarrow$ e.g., can study effect of heavy H^0 resonance on off-shell $gg\ (\to h^*) \to ZZ$.

Problem with isospin ≥ 1: the ρ parameter

$\rho \equiv$ ratio of strengths of charged and neutral weak currents $\simeq 1$ to high precision.

$$\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W} = \frac{\sum_k 2[T_k(T_k+1) - Y_k^2/4]v_k^2}{\sum_k Y_k^2 v_k^2}$$

($Q = T^3 + Y/2$, vevs defined as $\langle \phi_k^0 \rangle = v_k/\sqrt{2}$ for complex reps and $\langle \phi_k^0 \rangle = v_k$ for real reps)

$\rho = 1$ "by accident" for SM doublet. also for isospin septet with $Y = 4$

(septet: Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303)

SM + real triplet ξ ($Y=0$): $\rho > 1$

SM + complex triplet χ ($Y=2$): $\rho < 1$

Combine them both: $\langle \chi^0 \rangle = v_\chi$, $\langle \xi^0 \rangle = v_\xi$; doublet $\langle \phi^0 \rangle = v_\phi/\sqrt{2}$

$$\rho = \frac{v_\phi^2 + 4v_\xi^2 + 4v_\chi^2}{v_\phi^2 + 8v_\chi^2} = 1 \text{ when } v_\xi = v_\chi$$

Georgi-Machacek model

Georgi & Machacek, NPB262, 463 (1985)

Chanowitz & Golden, PLB165, 105 (1985)

Enforce $v_\xi = v_\chi$ using a symmetry.

Assemble the real + complex triplets into a bitriplet (analogous to the SM Higgs bidoublet) under global SU(2)$_L\times$SU(2)$_R$:

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

Vevs: (preserves the diagonal SU(2)$_c$ "custodial" subgroup)

$$\langle\Phi\rangle = \frac{v_\phi}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \langle X\rangle = v_\chi \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

W and Z boson masses constrain the combination of vevs:

$$v_\phi^2 + 8v_\chi^2 \equiv v^2 \simeq (246\ \text{GeV})^2$$

Gauging hypercharge breaks the SU(2)$_R$: divergent radiative correction to ρ at 1-loop (need a relatively low cutoff scale) Gunion, Vega & Wudka, PRD43, 2322 (1991)

Physical spectrum: Custodial symmetry fixes almost everything!

Bidoublet: $2 \times 2 \to 3 + 1$ Bitriplet: $3 \times 3 \to 5 + 3 + 1$

Custodial 5-plet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$, common mass m_5

$H_5^{++} = \chi^{++}$, $H_5^{+} = (\chi^{+} - \xi^{+})/\sqrt{2}$, $H_5^0 = \sqrt{2/3}\,\xi^0 - \sqrt{1/3}\,\chi^{0,r}$

Custodial triplet $(H_3^{+}, H_3^{0}, H_3^{-})$, common mass m_3

$H_3^{+} = -\sin\theta_H \phi^{+} + \cos\theta_H (\chi^{+} + \xi^{+})/\sqrt{2}$, $H_3^0 = -\sin\theta_H \phi^{0,i} + \cos\theta_H \chi^{0,i}$; $\tan\theta_H = 2\sqrt{2} v_\chi / v_\phi$

(orthogonal triplet is the Goldstones)

Two custodial singlets h^0, H^0, masses m_h, m_H, mixing angle α

$$h^0 = \cos\alpha\,\phi^{0,r} - \sin\alpha(\sqrt{1/3}\,\xi^0 + \sqrt{2/3}\,\chi^{0,r})$$
$$H^0 = \sin\alpha\,\phi^{0,r} + \cos\alpha(\sqrt{1/3}\,\xi^0 + \sqrt{2/3}\,\chi^{0,r})$$

Most general scalar potential:

Aoki & Kanemura, 0712.4053

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

Hartling, Kumar & HEL, 1404.2640

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

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

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

Theory constraints

Perturbative unitarity: impose $|\text{Re}\, a_0| < 1/2$ on eigenvalues of coupled-channel matrix of $2 \to 2$ scalar scattering processes. Constrain ranges of λ_{1-5}.

Aoki & Kanemura, 0712.4053

Bounded-from-belowness of the scalar potential: consider all combinations of fields nonzero. Further constraints on λ_{1-5}.

Hartling, Kumar & HEL, 1404.2640

Absence of deeper custodial SU(2)-breaking minima: numerical check that desired minimum is the deepest (1-dim scan over finite parameter range). Constraints involve all 9 parameters.

Hartling, Kumar & HEL, 1404.2640

(we do not consider situations in which the desired vacuum is metastable)

Indirect constraints: R_b, $b \to s\gamma$, etc.

Key observations: ($\tan\theta_H = 2\sqrt{2}v_\chi/v_\phi$)

1) Fermion masses generated by a *single* SU(2)$_L$ Higgs doublet.

$$h\bar{f}f: \quad -i\frac{m_f}{v}\frac{\cos\alpha}{\cos\theta_H}, \qquad H\bar{f}f: \quad -i\frac{m_f}{v}\frac{\sin\alpha}{\cos\theta_H},$$

$$H_3^0\bar{u}u: \quad \frac{m_u}{v}\tan\theta_H\gamma_5, \qquad H_3^0\bar{d}d: \quad -\frac{m_d}{v}\tan\theta_H\gamma_5,$$

$$H_3^+\bar{u}d: \quad -i\frac{\sqrt{2}}{v}V_{ud}\tan\theta_H\left(m_uP_L - m_dP_R\right),$$

$$H_3^+\bar{\nu}\ell: \quad i\frac{\sqrt{2}}{v}\tan\theta_H m_\ell P_R \qquad \text{(all } H_5f\bar{f} \text{ couplings } = 0)$$

(b, τ Yukawas *not* enhanced: nonoblique/b-phys effects involve couplings $\sim m_t\tan\theta_H$)

2) $H_3^+H_3^-Z$ coupling is identical to H^+H^-Z coupling in 2HDMs due to custodial symmetry.

$\Rightarrow$ Leading nonoblique Z-pole and b-physics constraints are the same as those in the Type-I 2HDM, with $\cot\beta \to \tan\theta_H$ and $m_{H^+} \to m_3$! These constrain the m_3–v_χ plane.

Indirect constraints: R_b, $b \to s\gamma$, etc.

R_b: known a long time in GM model; same form as Type-I 2HDM

HEL & Haber, hep-ph/9909335; Chiang & Yagyu, 0902.4665; Type-I: Grant, hep-ph/9410267

B_s–$\bar{B}_s$ mixing: adapted from Type-I 2HDM

Mahmoudi & Stal, 0907.1791

$B_s \to \mu^+\mu^-$: adapted from new calculation for Aligned 2HDM

Li, Lu & Pich, 1404.5865

$b \to s\gamma$: adapted from Type-I 2HDM, using SuperIso

Barger, Hewett & Phillips, PRD41, 3421 (1990); SuperIso v3.3 (Mahmoudi)

Strongest constraint is from $b \to s\gamma$.
We'll show two versions:
- "tight" constraint, 2σ from expt central value
- "loose" constraint, 2σ from SM limit (already 1.6σ from expt)

Indirect constraints: S parameter

We also implement the S-parameter constraint, marginalizing over the T-parameter.

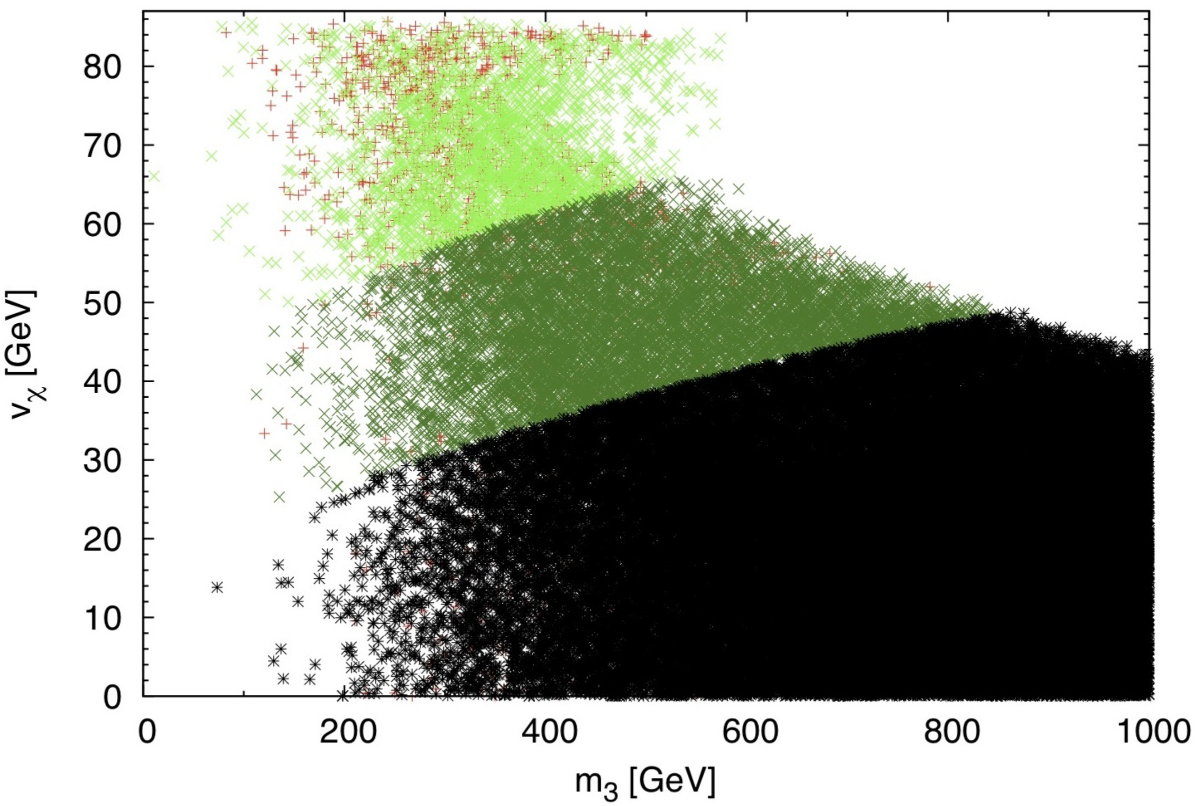
Rationale:

T-parameter is (notoriously) divergent at 1-loop in GM model; to cancel the divergence one must introduce a global-SU(2)$_R$–violating counterterm. Gunion, Vega & Wudka, PRD43, 2322 (1991)

Introduces a small tree-level breaking of custodial SU(2)
$\rightarrow$ small tree-level contribution to ρ parameter
$\rightarrow$ use to cancel a finite piece of the 1-loop contribution to T.

$b \to s\gamma$ constraint: interplay with theory constraints

Together they give an upper bound on v_χ



Hartling, Kumar & HEL, in preparation

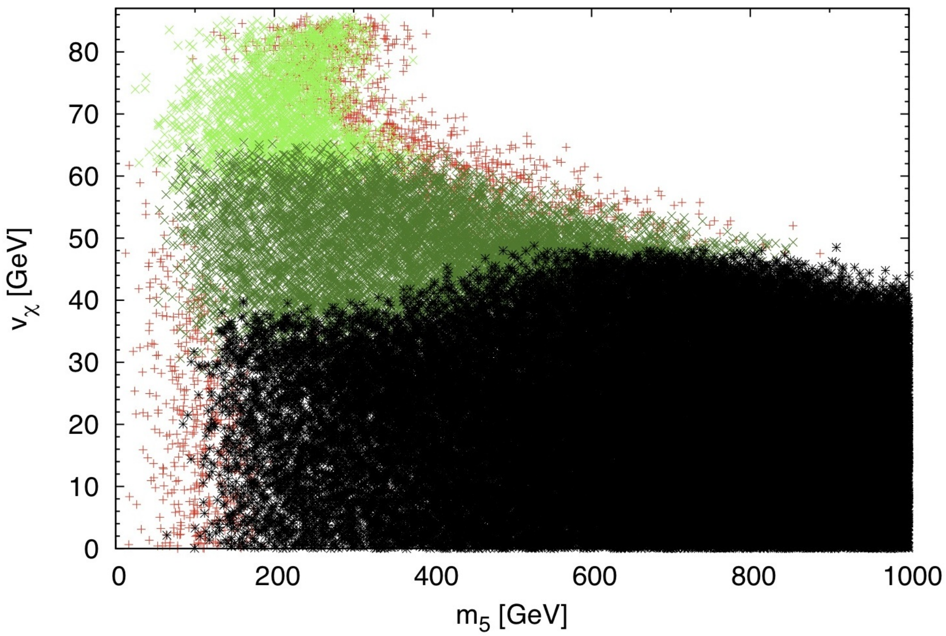
light green: excluded by $b \to s\gamma$

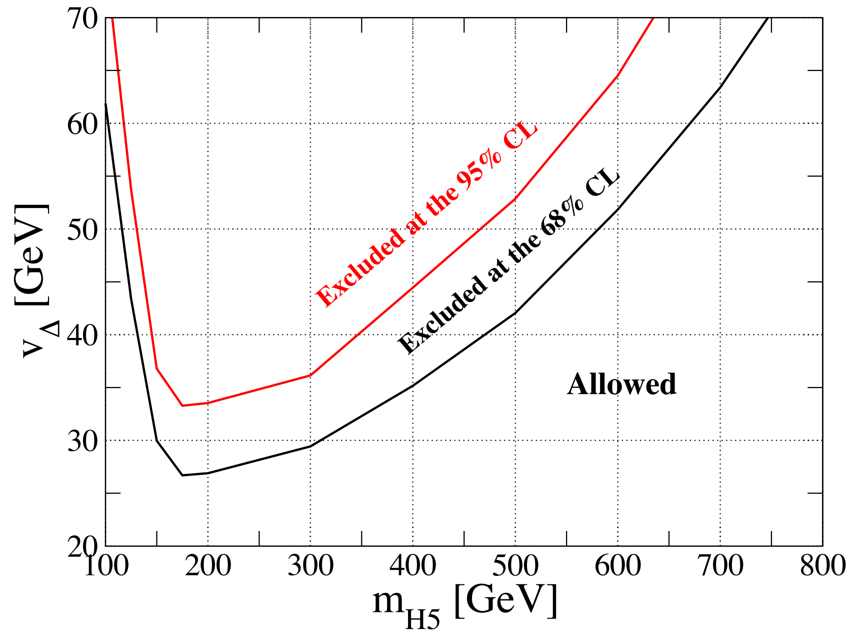
dark green: "loose" constraint, $<2\sigma$ from SM limit (already 1.6σ from expt)

black: "tight" constraint, $<2\sigma$ from expt central value

Comparison to direct search for $H^{++} \to W^+W^+$:

Theorists' recasting of ATLAS measurement of like-sign $W^\pm W^\pm jj$ cross section to constrain VBF $H^{\pm\pm} \to W^\pm W^\pm$:





Hartling, Kumar & HEL, in preparation

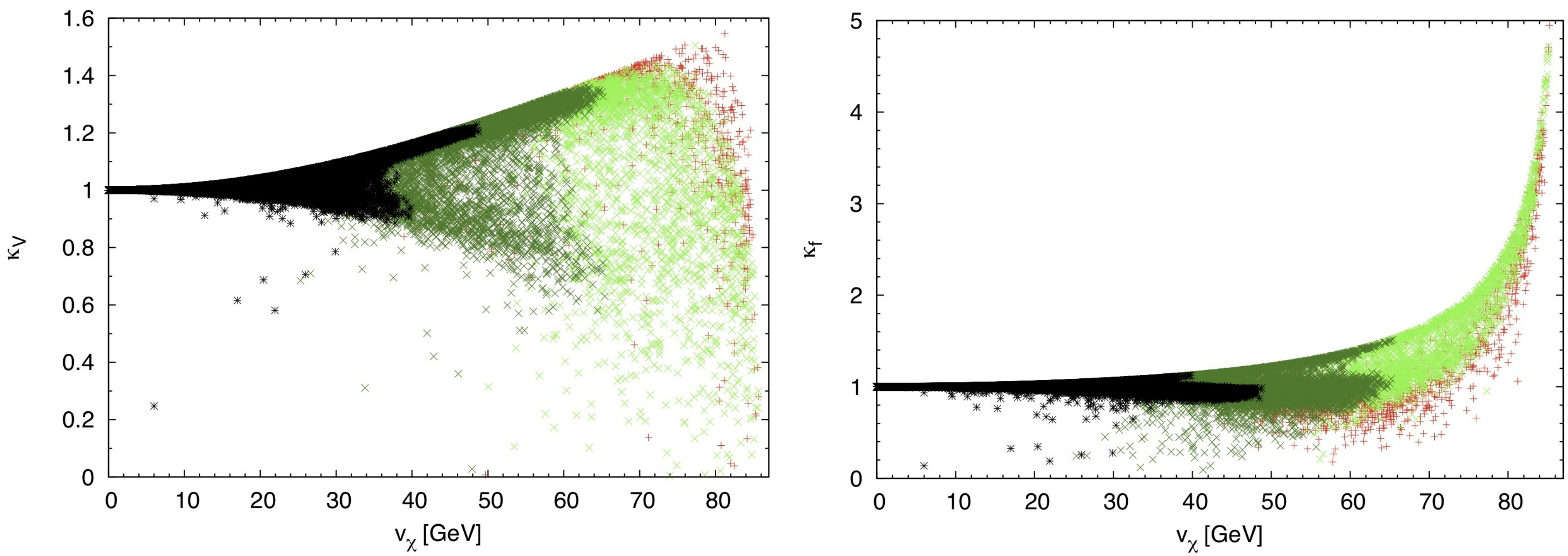
(red points are excluded by S parameter)

Chiang, Kanemura & Yagyu, 1407.5053

Like-sign $WWjj$ will eliminate a large fraction of the dark green points allowed by the "loose" $b \to s\gamma$ constraint.

VBF $H_5^\pm \to W^\pm Z$ constrains the same m_5–v_χ parameter plane.

$h(125)$ couplings: predictions for κ_V and κ_f



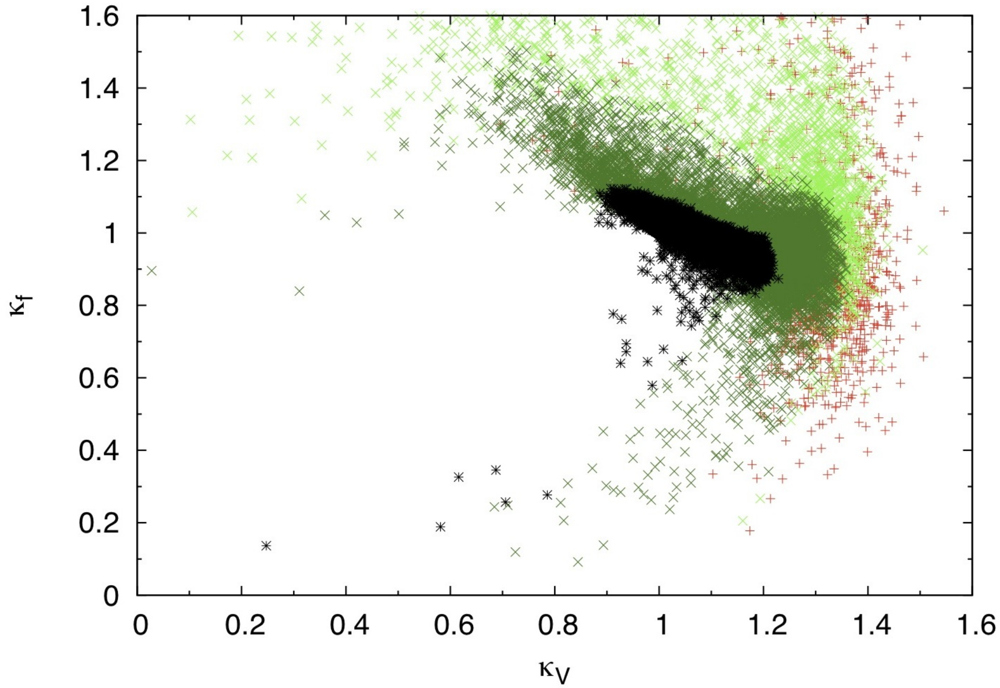
Hartling, Kumar & HEL, in preparation

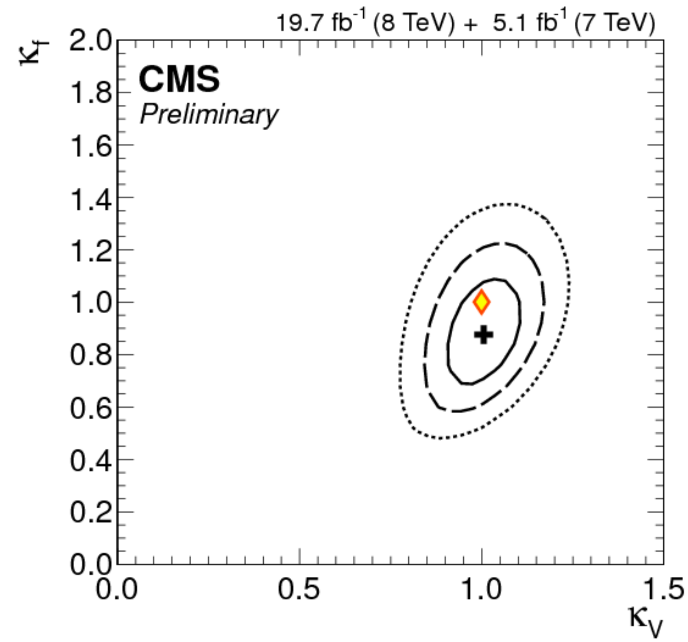
$$\kappa_V = \cos\alpha \frac{v_\phi}{v} - \frac{8}{\sqrt{3}} \sin\alpha \frac{v_\chi}{v} \qquad \kappa_f = \cos\alpha \frac{v}{v_\phi}$$

Upper bound on v_χ imposed by $b \to s\gamma$ constrains $\kappa_V \lesssim 1.36$ and $\kappa_f \lesssim 1.51$. ("loose" constraint)

Direct search for H^{++} in like-sign $WWjj$ will tighten this.

$h(125)$ couplings: correlation of κ_V and κ_f



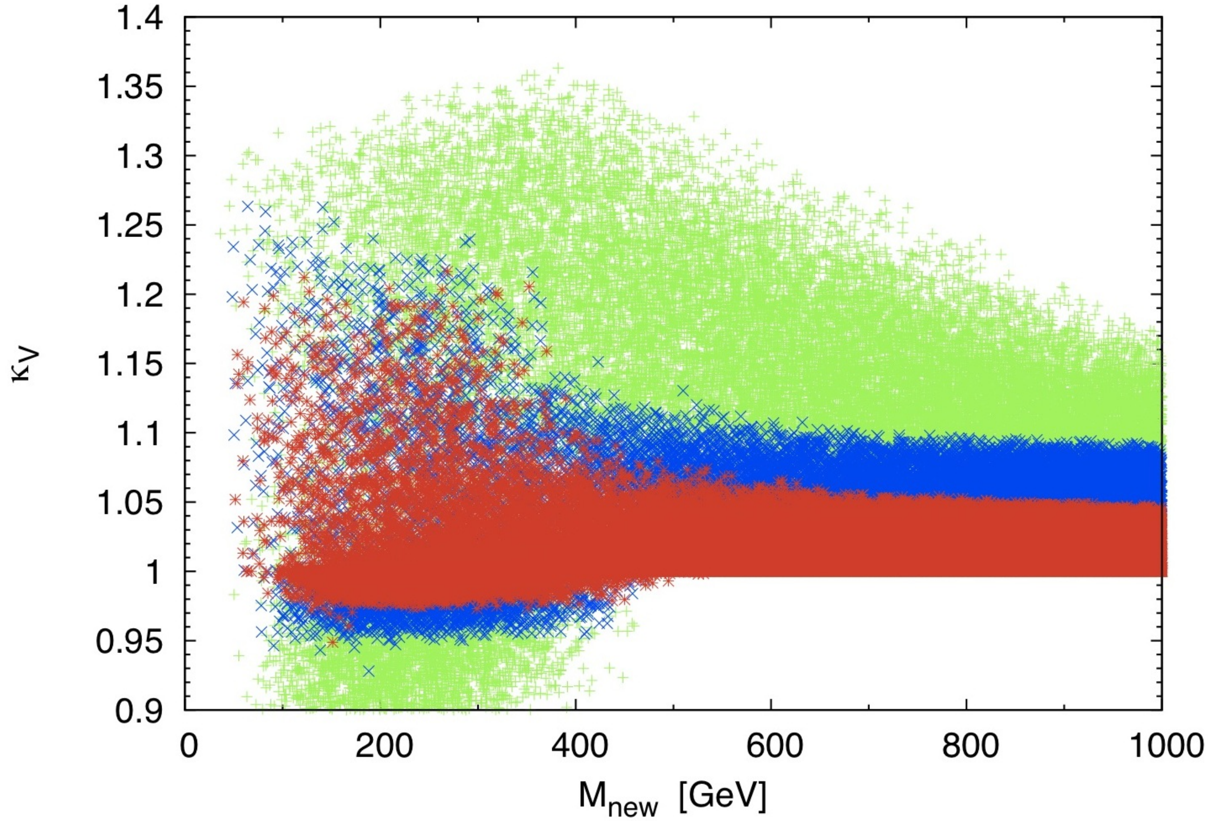


Hartling, Kumar & HEL, in preparation

Along the line $\kappa_V = \kappa_f$, the "loose" $b \to s\gamma$ measurement constrains $\kappa_V = \kappa_f \lesssim 1.20$. (like-sign $WWjj$ will tighten this)

All LHC Higgs cross sections can be simultaneously enhanced by up to $\sim$44% $\Leftrightarrow$ enhancement can be hidden by an unobserved non-SM Higgs decay BR_{new} up to $\sim$30%. (LHC flat direction!)

Simultaneous enhancement of κ_V and $\kappa_f \Rightarrow$ light new particles!



"loose" $b \to s\gamma$ constraint imposed

κ_f within 10% or 5% of κ_V

(rest of allowed points in green)

Hartling, Kumar & HEL, in preparation

$M_{\text{new}} \equiv$ mass of *lightest* new state.

$\kappa_f \lesssim 1$ when new particles are heavy: significant enhancement to match κ_V requires $M_{\text{new}} \lesssim 400$ GeV.

Outlook: toward a calculator for the Georgi-Machacek model

`GMCALC` code: Hartling, Kumar & HEL, work in progress

- Fortran code, hoping to release this fall
- parameter inputs include m_h; can do param scans
- computes spectrum, h^0–H^0 mixing angle, v_χ
- implements theory checks (unitarity, bounded-from-below, no alt minima)
- implements constraints from S parameter, $b \to s\gamma$, $B_s \to \mu\mu$
- computes decay BRs, production couplings for all scalars

- working on implementing QCD and offshell corrections to decay partial widths
- planning interface to HiggsBounds/HiggsSignals

contact logan@physics.carleton.ca