Taming the LHC flat direction in Higgs coupling measurements

Heather Logan

Carleton University

University of Toronto theory seminar

December 8, 2014

K. Hartling, K. Kumar & H.E.L., 1404.2640, 1410.5538, & work in progress

+ work in progress with M.-J. Harris, B. Keeshan, T. Pilkington, & V. Rentala

Outline

Introduction: what we learn from Higgs couplings

LHC Higgs coupling fit and the flat direction

Realizing the flat direction: enhanced hVV couplings

The Georgi-Machacek model
- Theoretical constraints
- Decoupling limit
- Indirect constraints
- Direct searches

How to tame the LHC flat direction

Conclusions

Introduction: Higgs couplings in the Standard Model

A one-line theory:

$$\mathcal{L}_{Higgs} = |\mathcal{D}_\mu H|^2 - [-\mu^2 H^\dagger H + \lambda (H^\dagger H)^2] - [y_f \bar{f}_R H^\dagger F_L + \text{h.c.}]$$

Most general, renormalizable, gauge-invariant theory involving a single spin-zero (scalar) field with isospin 1/2, hypercharge 1.

$-\mu^2$ term: electroweak symmetry spontaneously broken; Goldstone bosons can be gauged away leaving 1 physical particle h.

$$H = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix}$$

Mass and vacuum expectation value of h are fixed by minimizing the Higgs potential:

$$v^2 = \mu^2/\lambda \qquad\qquad M_h^2 = 2\lambda v^2 = 2\mu^2$$

Introduction: Higgs couplings in the Standard Model

SM Higgs couplings to SM particles are fixed by the mass-generation mechanism.

W and Z: $\qquad g_Z \equiv \sqrt{g^2 + g'^2}$, $v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$
$$M_W^2 = g^2 v^2/4 \qquad hWW:\; i(g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ:\; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

$$\mathcal{L} = -y_f \bar{f}_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$
$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f:\; i m_f/v$$

Gluon pairs and photon pairs:
induced at 1-loop by fermions, W-boson.

Introduction: Higgs couplings beyond the Standard Model

W and Z:

- EWSB can come from more than one Higgs doublet, which then mix to give h mass eigenstate. $v \equiv \sqrt{v_1^2 + v_2^2}$, $\phi_v = \frac{v_1}{v} h_1 + \frac{v_2}{v} h_2$

$$\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$$
$$M_W^2 = g^2 v^2/4 \qquad hWW: \; i\langle h|\phi_v\rangle (g^2 v/2) g^{\mu\nu} \equiv i\kappa_W (g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \; i\langle h|\phi_v\rangle (g_Z^2 v/2) g^{\mu\nu} \equiv i\kappa_Z (g^2 v/2) g^{\mu\nu}$$

Note $\kappa_W = \kappa_Z$. Also, $\kappa_{W,Z} = 1$ when $h = \phi_v$: "decoupling limit".

- Part of EWSB from larger representation of SU(2). $Q = T^3 + Y/2$

$$\mathcal{L} \supset |\mathcal{D}_\mu \Phi|^2 \;\rightarrow\; (g^2/4)[2T(T+1) - Y^2/2](\phi + v)^2 W^+ W^- + (g_Z^2/8) Y^2 (\phi + v)^2 ZZ$$

Can get $\kappa_W \neq \kappa_Z$ and/or $\kappa_{W,Z} > 1$ after mixing to form h.
Tightly constrained by ρ parameter, $\rho \equiv M_W^2 / M_Z^2 \cos^2\theta_W = 1$ in SM.

Introduction: Higgs couplings beyond the Standard Model

Fermions:

Masses of different fermions can come from different Higgs doublets, which then mix to give h mass eigenstate:

$$\mathcal{L} = -y_f \bar{f}_R \Phi_f^\dagger F_L + \text{(other fermions)} + \text{h.c.}$$

$$m_f = y_f v_f/\sqrt{2} \qquad h\bar{f}f: \; i\langle h|\phi_f\rangle(v/v_f)m_f/v \equiv i\kappa_f m_f/v$$

In general $\kappa_t \neq \kappa_b \neq \kappa_\tau$; e.g. MSSM with large $\tan\beta$ (Δ_b).

Note $\langle h|\phi_f\rangle(v/v_f) = \langle h|\phi_f\rangle/\langle\phi_v|\phi_f\rangle$

$\Rightarrow$ $\kappa_f = 1$ when $h = \phi_v$: "decoupling limit".

Introduction: Higgs couplings beyond the Standard Model

Gluon pairs and photon pairs:

- κ_t and κ_W change the normalization of top quark and W loops.

- New coloured or charged particles give new loop contributions.
  e.g. top squark, charginos, charged Higgs in MSSM

New particles in the loop can affect $h \leftrightarrow gg$ and $h \to \gamma\gamma$ even if h is otherwise SM-like.

$\Rightarrow$ Treat κ_g and κ_γ as add'l independent coupling parameters.

Coupling extraction at the LHC

Measure event rates at LHC: sensitive to production and decay couplings. Narrow width approximation:

$$\text{Rate}_{ij} = \sigma_i \, \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}}$$

Coupling dependence (at leading order):

$$\sigma_i = \kappa_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_j = \kappa_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum \kappa_k^2 \Gamma_k^{\text{SM}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

Coupling extraction at the LHC

Measure event rates at LHC: sensitive to production and decay couplings. Narrow width approximation:

$$\text{Rate}_{ij} = \sigma_i \, \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}}$$

Coupling dependence (at leading order):

$$\sigma_i = \kappa_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_j = \kappa_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \kappa_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

Non-SM decays could also be present:

- invisible final state (can look for this with dedicated searches)
- "unobserved" final state (e.g., $h \rightarrow$ jets)

Unobserved final states cause a "flat direction" in the fit

Allow an unobserved decay mode while simultaneously increasing all couplings to SM particles by a factor $\kappa_i \equiv \kappa$:

$$\text{Rate}_{ij} = \kappa^2 \sigma_i^{\text{SM}} \frac{\kappa^2 \Gamma_j^{\text{SM}}}{\kappa^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

All measured Higgs production and decay rates will be equal to their SM values if:

$$\kappa^2 = \frac{1}{1 - \text{BR}_{\text{new}}} \geq 1 \qquad \text{BR}_{\text{new}} \equiv \frac{\Gamma_{\text{new}}}{\kappa^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

Coupling enhancement hides presence of new decays!
New decays hide presence of coupling enhancement!

(ILC gets around this using decay-mode-independent measurement of $e^+e^- \to Zh$ cross section from recoil-mass method.)

Ways to deal with this:

- assume no unobserved decays

  (ok for checking consistency with SM, but highly model-dependent)
- assume hWW and hZZ couplings are no larger than in SM

  (valid if only SU(2)-doublets/singlets are present)
- include direct measurement of Higgs width

  (only works for heavier Higgs so that $\Gamma_{\rm tot} >$ expt. resolution;

  $\Gamma_{\rm tot}^{\rm SM} \simeq 4$ MeV for 125 GeV Higgs)
- include indirect measurement of Higgs width in $gg\ (\to h^*) \to ZZ$

  (model dependent if new stuff runs in ggh loop

  or add'l light scalars are exchanged in s-channel)
- include indirect measurement of Higgs width in $m_{\gamma\gamma}$ peak shift

  (not enough sensitivity at LHC)

No known model-independent way around this at LHC.

$\Longrightarrow$ study particular explicit models to try to get some insight!

Realizing the flat direction: enhanced hVV couplings

Models with isospin doublets or singlets have hVV couplings smaller than or equal to those of the SM.

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

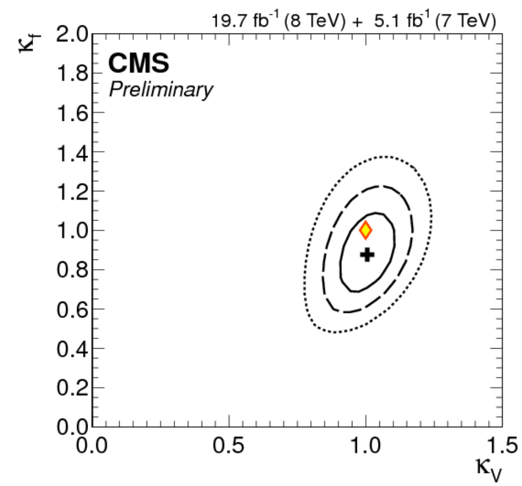
- 2HDM: $i\frac{g^2 v}{2} g_{\mu\nu} \sin(\beta - \alpha)$

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

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

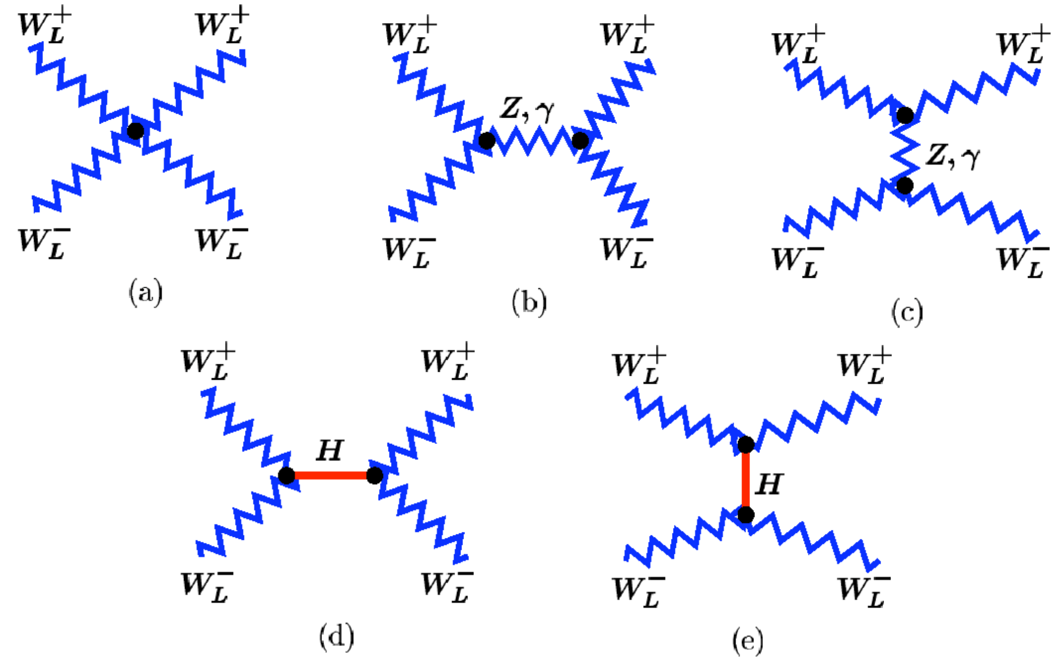
Enhanced hVV couplings require a scalar multiplet that:

- Has isospin ≥ 1
- Has a non-negligible vev
- Mixes with the doublet to make h



Another way to see this: unitarity of longitudinal VV scattering

SM: bad E^2/v^2 behaviour cancelled by h_{SM} exchange.



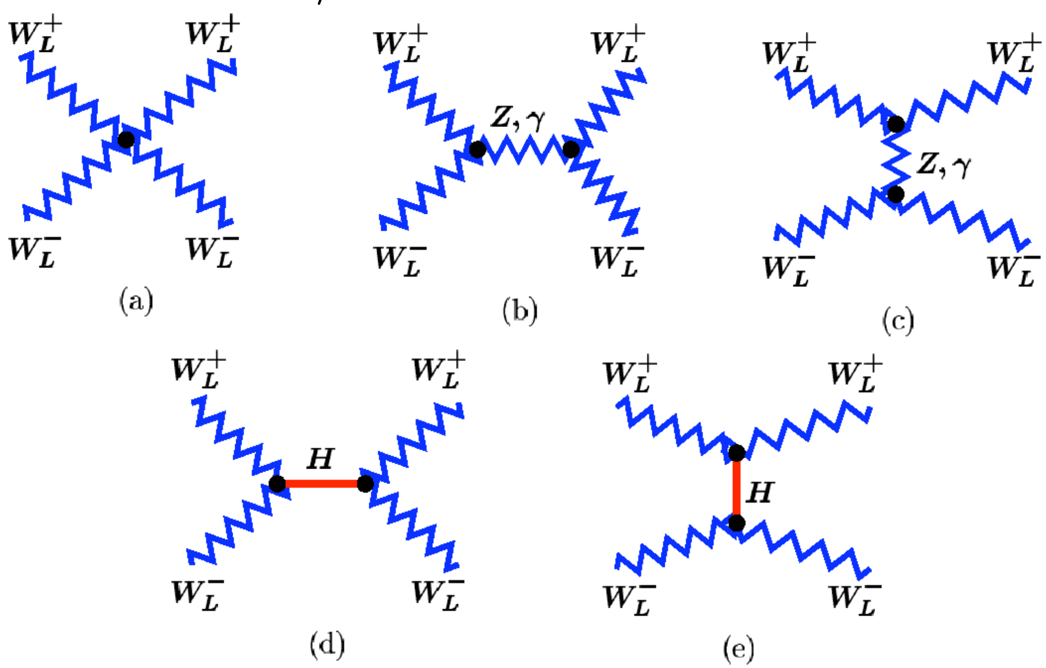
Lee, Quigg & Thacker 1977

(graphics: Chivukula, LHC4ILC 2007)

2HDM, SM+singlet: $h_{\text{SM}} \rightarrow h^0 + H^0$ $\quad\quad$ $\sin^2 + \cos^2 = 1$

Another way to see this: unitarity of longitudinal VV scattering

SM: bad E^2/v^2 behaviour cancelled by h_{SM} exchange.



Graphics: Chivukula, LHC4ILC 2007

When h^0VV coupling > SM, including H^0 only makes it worse!

$\Rightarrow$ Unitarization requires custodial 5-plet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$.
Need multiplet with isospin ≥ 1! and vev $\neq 0$ for H_5VV coupling!

$$H_5^{++}W^-W^- : \; ig_5 \frac{2M_W^2}{v} g_{\mu\nu}, \qquad (\kappa_V^{h,\max})^2 - \frac{5}{6} g_5^2 = 1$$

Falkowski, Rychkov & Urbano, 1202.1532

How big can scalar multiplets be?

Consider an electroweak scalar multiplet of isospin T and hypercharge Y:

$$\begin{array}{rcll} X & = & (\chi_T, \chi_{T-1}, \ldots, \chi_{-T})^T & \text{(complex)} \\ \Xi & = & (\xi^Q, \ldots, \xi^0, \ldots, \xi^{-Q})^T & \text{(real)} \end{array}$$

Large isospin $\to$ large weak charges: at some point perturbativity breaks down.

Compute $2 \to 2$ scattering amplitudes for scalars to *transverse* gauge bosons and impose $|\mathrm{Re}\, a_0| < 1/2$:

$$T \leq \begin{cases} 7/2 & \text{(complex)} \\ 4 & \text{(real)} \end{cases}$$

Hally, HEL & Pilkington, 1202.5073

Problems with larger scalar multiplets

The main phenomenological constraint on scalar multiplets with $T \geq 1$ comes from the ρ parameter:

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

($Q = T^3 + Y/2$, 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)

Global fits: $\rho = 1.000\,40 \pm 0.000\,24$ PDG 2014

But we want non-negligible vevs!
Only two approaches using symmetry: (could also tune ρ by hand, but ick)

- $\rho = 1$ "by accident" for isospin septet with $Y = 4$

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

- Preserve $\rho = 1$ using custodial symmetry: impose $SU(2)_L \times SU(2)_R$ global sym on scalar potential. Georgi & Machacek, NPB262, 463 (1985)

Detail:

SM + real triplet ξ: $\rho > 1$

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

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

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

To avoid this being fine-tuned, enforce $v_\xi = v_\chi$ using a symmetry.

$SU(2)_L \times SU(2)_R$ global symmetry on scalar potential:
- present by accident in SM Higgs sector
- breaks to diagonal subgroup $SU(2)_{\text{custodial}}$ upon EWSB

Georgi-Machacek model

Georgi & Machacek, NPB262, 463 (1985)

Chanowitz & Golden, PLB165, 105 (1985)

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

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

Vevs: (preserves the diagonal $SU(2)_c$ 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

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

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 sets 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

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

Free parameters: m_h, m_H, m_3, m_5, v_χ, α. (m_h or $m_H = 125$ GeV)

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 $|\mathrm{Re}\, a_0| < 1/2$ 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)

Decoupling limit

Fix μ_2^2 using W mass:
$\rightarrow$ Scalar potential has 3 dimensionful parameters: μ_3^2, M_1, M_2.

Decoupling limit is $\mu_3^2 \gg v^2$.

Perturbativity and absence of bad minima constrain $|M_1|/\sqrt{\mu_3^2} \lesssim 3.3$ and $|M_2|/\sqrt{\mu_3^2} \lesssim 1.2$.

$m_H \simeq m_3 \simeq m_5 \simeq \sqrt{\mu_3^2}$ up to relative $\mathcal{O}(v^2/\mu_3^2)$ corrections.

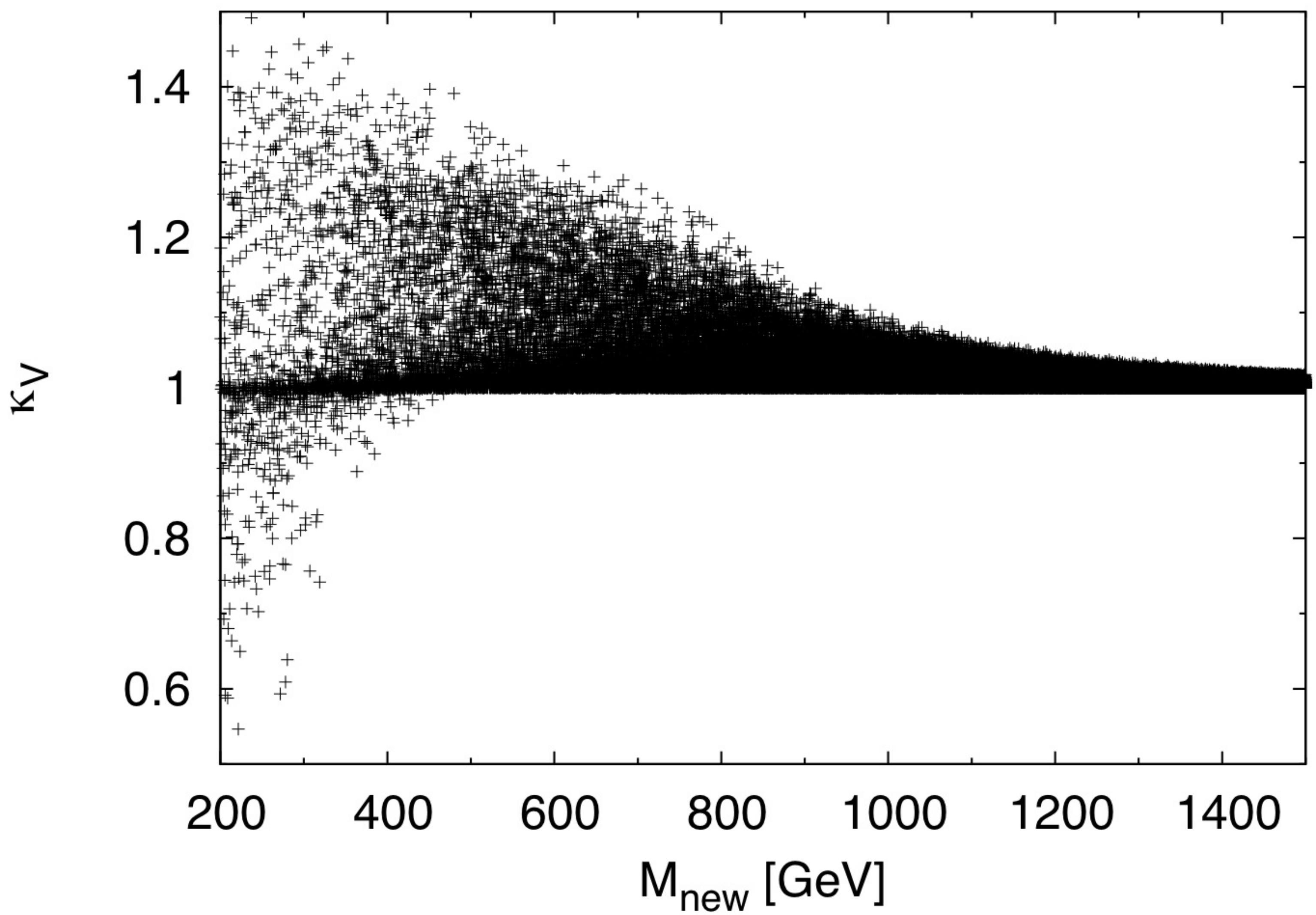
$\sin\theta_H \equiv \frac{2\sqrt{2}v_\chi}{v} \simeq \frac{M_1 v}{\sqrt{2}\mu_3^2}$ $\Rightarrow$ Triplet contribution to M_W, M_Z goes away as $\mu_3 \rightarrow$ large.

$\sin\alpha \simeq -\frac{\sqrt{3}M_1 v}{2\mu_3^2}$ $\Rightarrow$ Triplet admixture in h^0 goes away as $\mu_3 \rightarrow$ large.

hVV coupling: $\kappa_V = \cos\alpha\frac{v_\phi}{v} - \frac{8}{\sqrt{3}}\sin\alpha\frac{v_\chi}{v} \simeq 1 + \frac{3}{8}\frac{M_1^2 v^2}{\mu_3^4} \geq 1!$

hff coupling: $\kappa_f = \cos\alpha\frac{v}{v_\phi} \simeq 1 - \frac{1}{8}\frac{M_1^2 v^2}{\mu_3^4}$ deviation related to κ_V!

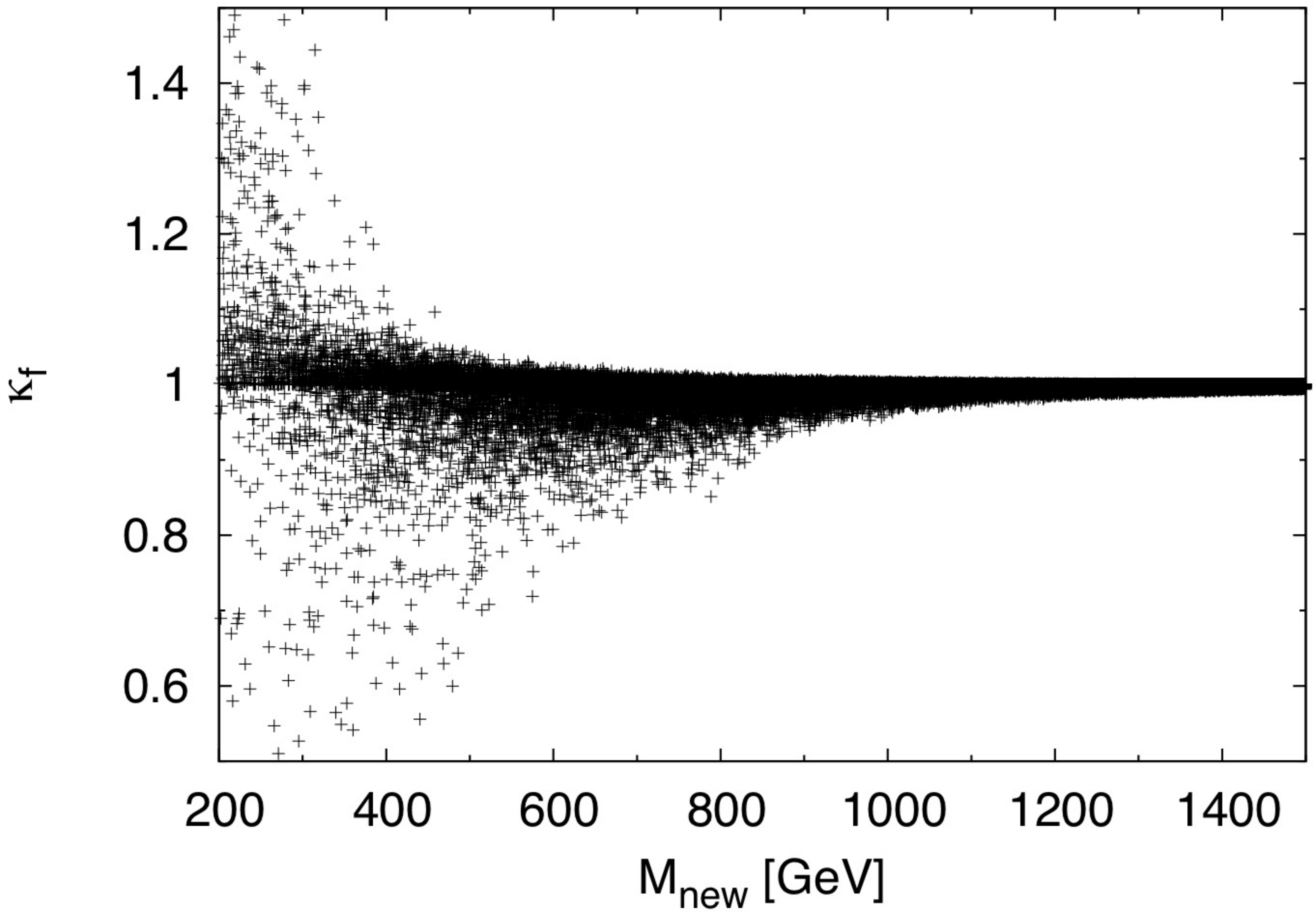
Numerical results: hVV coupling enhancement can be quite large!



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

Hartling, Kumar & HEL, 1404.2640

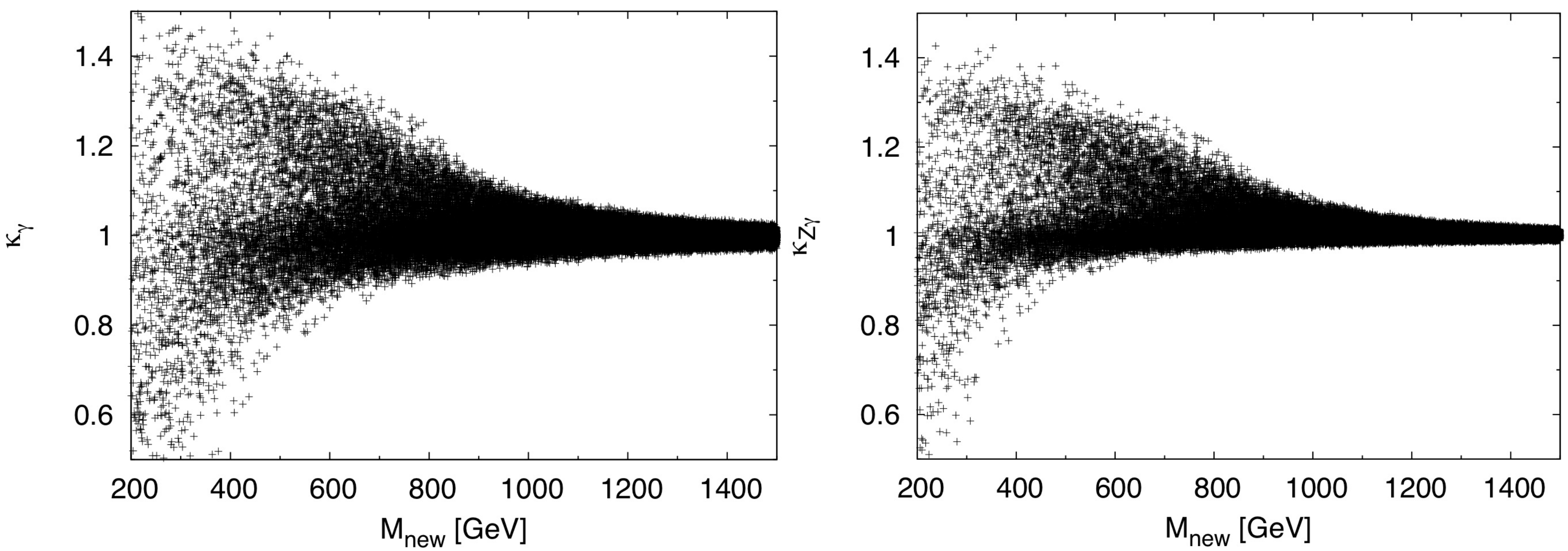
Numerical results: hff coupling typically < 1; $\kappa_f > 1$ possible at low $M_{\rm new}$



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

Hartling, Kumar & HEL, 1404.2640

Numerical results: $h\gamma\gamma$ & $hZ\gamma$ couplings incl charged scalars in loop



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

Hartling, Kumar & HEL, 1404.2640

Indirect constraints

Hartling, Kumar & HEL, 1410.5538

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 $m_{H^+} \to m_3$!

Indirect constraints

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

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

Barger, Hewett & Phillips, PRD41, 3421 (1990)

F. Mahmoudi, SuperIso

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

Li, Lu & Pich, 1404.5865

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 value (already 1.3σ from expt)

Indirect constraints

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

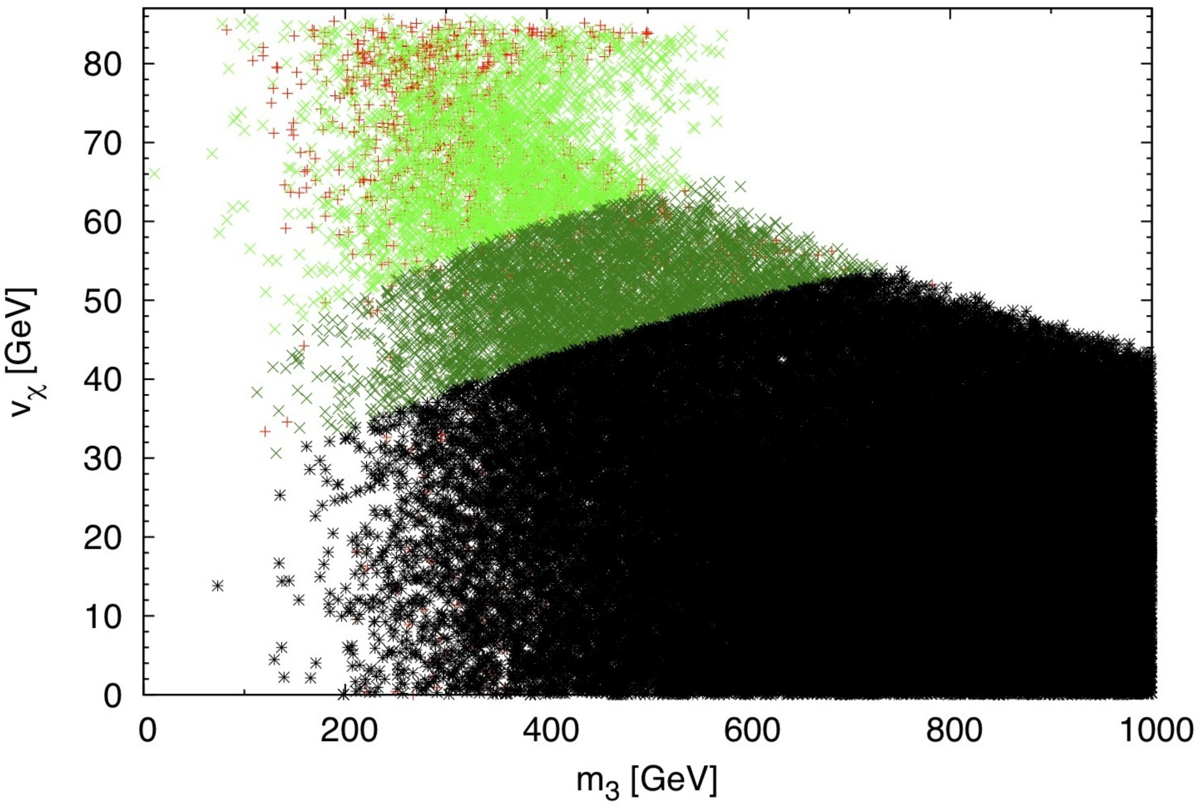
Rationale:

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, 1410.5538

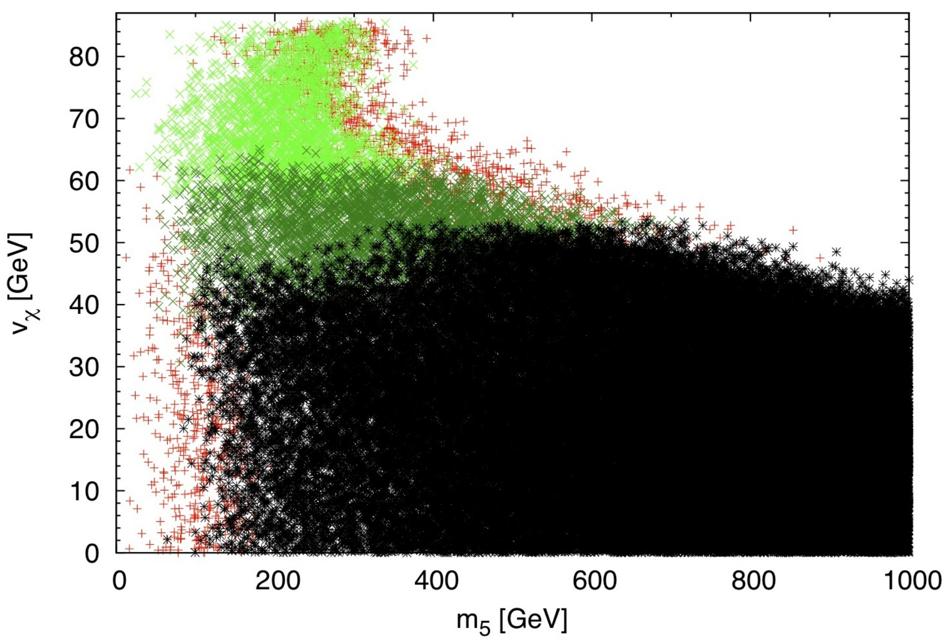
light green: excluded by $b \to s\gamma$

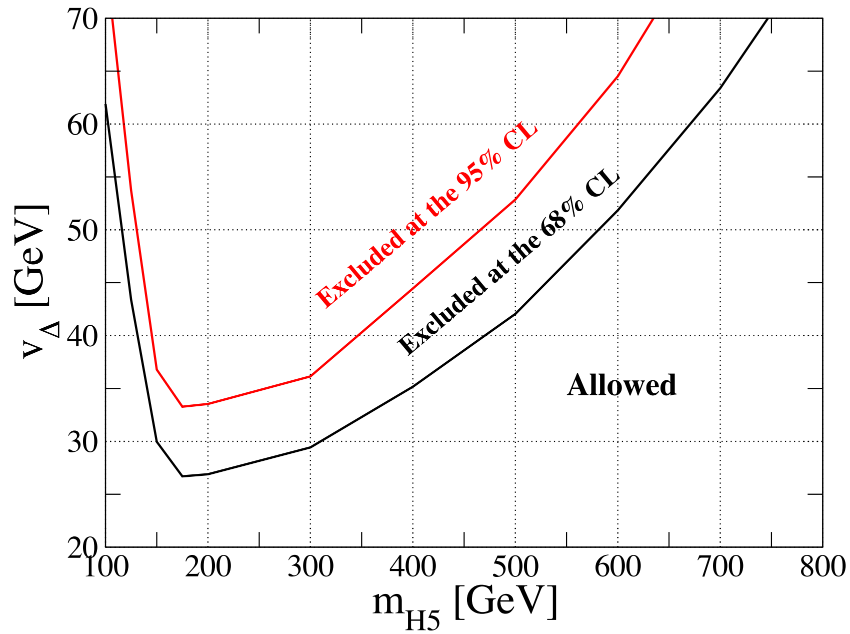
dark green: "loose" constraint, $<2\sigma$ from SM limit (already 1.3σ from expt)

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, 1410.5538

Chiang, Kanemura & Yagyu, 1407.5053

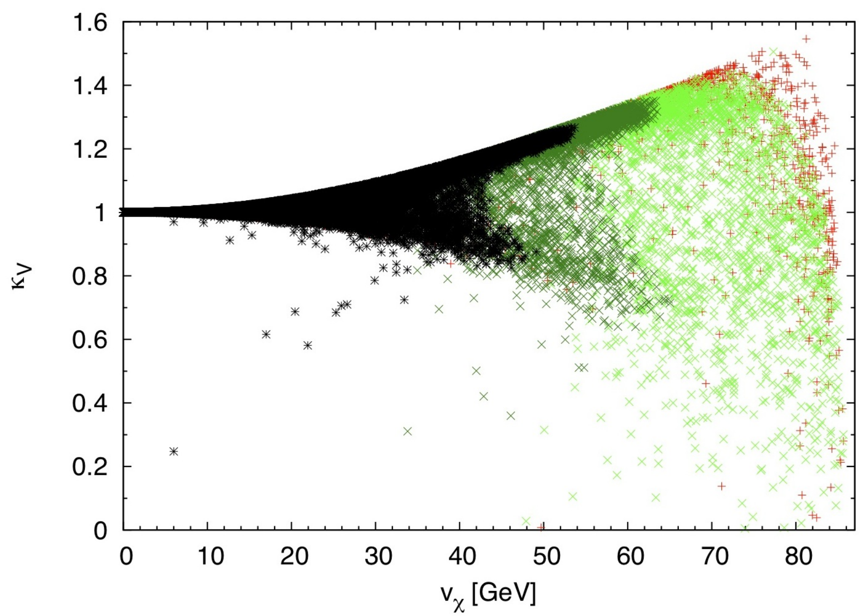
(red points are excluded by S parameter)

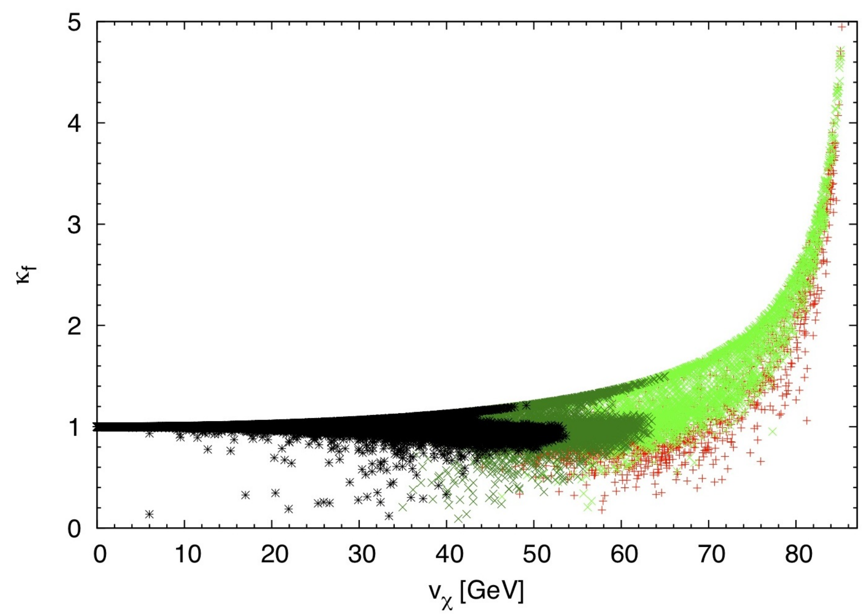
Like-sign $WWjj$ will eliminate a large fraction of the dark green points allowed by the "loose" $b \to s\gamma$ constraint.

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

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

$$\kappa_f = \cos\alpha \frac{v}{v_\phi}$$



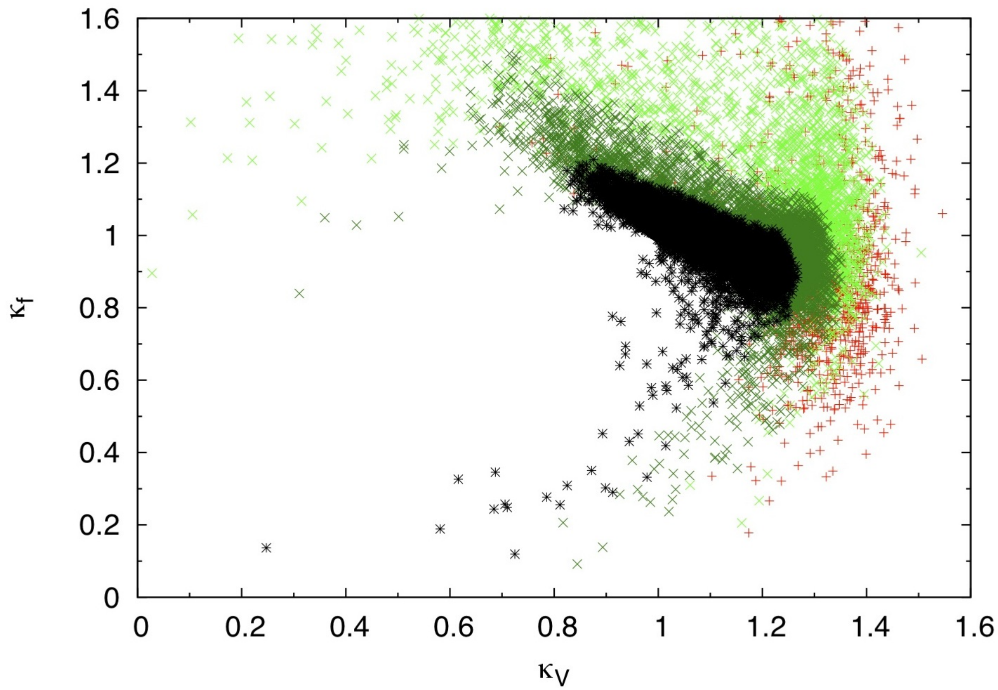


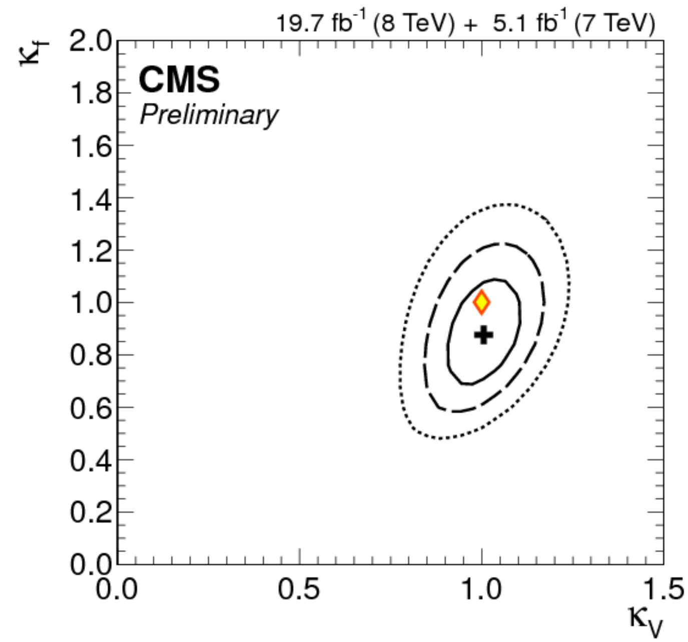
Hartling, Kumar & HEL, 1410.5538

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



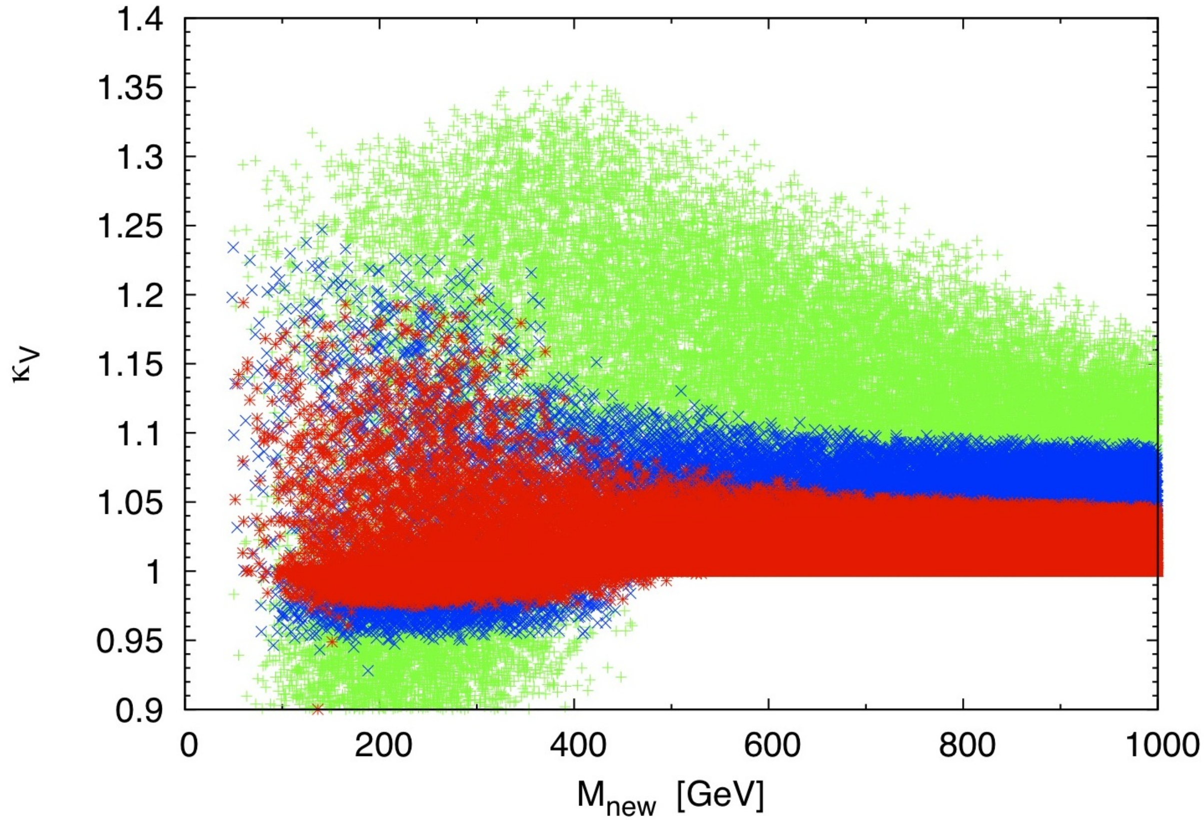


Hartling, Kumar & HEL, 1410.5538

Along the line $\kappa_V = \kappa_f$, the "loose" $b \to s\gamma$ measurement constrains $\kappa_V = \kappa_f \lesssim 1.18$. (like-sign $WWjj$ will tighten this)

All LHC Higgs cross sections can be simultaneously enhanced by up to ∼39% ⇔ enhancement can be hidden by an unobserved non-SM Higgs decay BR_{new} up to ∼28%. (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, 1410.5538

$M_{\text{new}} \equiv$ 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.

How to tame the LHC flat direction

Realizing the flat direction implies that new scalars are light.

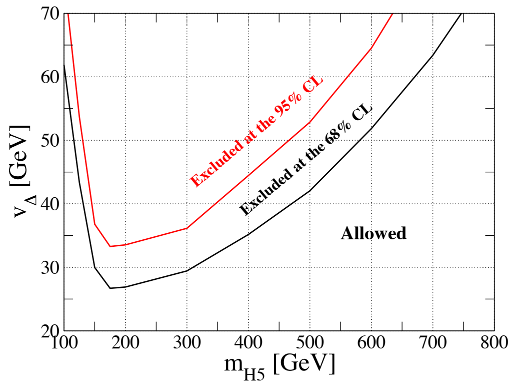
- non-decoupled scenario; $M_{\text{new}} \lesssim 400$ GeV in Georgi-Machacek model

Enhanced hVV coups require an H^{++} with couplings to W^+W^+.

- needed to unitarize $VV \to VV$
- search in VBF $H^{++} \to W^+W^+$
- direct relationship between $H^{++}W^-W^-$ coupling and κ_V^h:

  $(\kappa_V^{h,\text{max}})^2 - \frac{5}{6}g_5^2 = 1$ in general

  $(\kappa_V^{h,\text{max}})^2 = 1 + \frac{40}{3}v_\chi^2/v^2$ in GM



Chiang, Kanemura & Yagyu, 1407.5053

Same conclusion applies to septet model and higher-isospin generalizations of Georgi-Machacek model.

- can get a lot of traction using only $VV \to VV$ unitarity sum rules.
- but, need detailed studies of explicit models to understand correlations.

Conclusions

Flat direction is an annoying loophole in LHC Higgs coupling fits.
- ILC is immune to this problem!

To make progress: study explicit models where enhanced hVV couplings are realized.
- Georgi-Machacek model with scalar triplets
- SM + septet
- generalizations of Georgi-Machacek to higher isospin rep'ns

Nontrivial relationships among params due to theory constraints:
$\rightarrow$ design searches for the additional light scalars
$\rightarrow$ interpret search results to constrain the flat-direction scenario

This is still model-dependent, but we start to learn about the universal features of models that realize the LHC flat direction.