Toward a calculator for the Georgi-Machacek model

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

Outline

Introduction: why triplets?

The Georgi-Machacek model

The decoupling limit

Indirect constraints

Outlook: toward a calculator

Introduction: why triplets?

Isospin-triplet scalars appear in models for a variety of reasons:

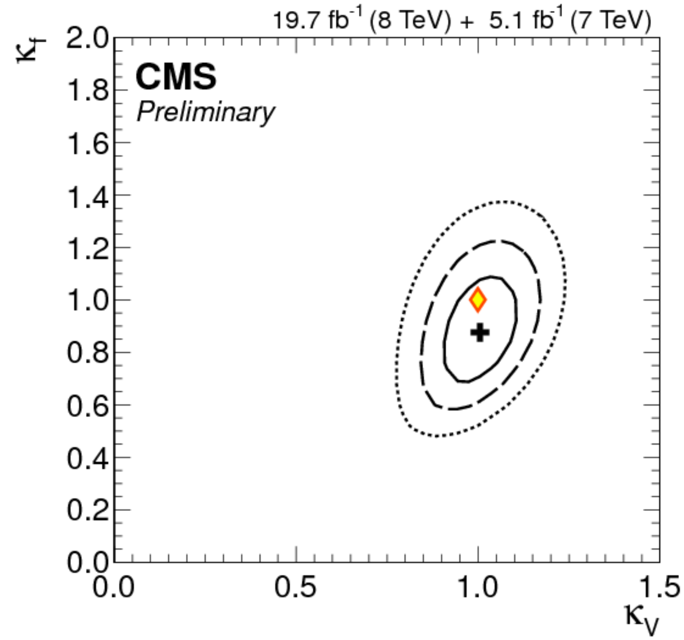
- to generate neutrino mass via $\bar{L}^c_L \Delta L_L$ operator (type-2 seesaw)

- to enhance the $h \to \gamma\gamma$ width (H^{++} in the loop)

- because they show up in some nice BSM models (3-3-1 models, some little Higgs models, left-right symmetric models)

- because they lead to an interesting benchmark model for properties measurements of the SM-like Higgs boson

Introduction: why triplets?



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

Introduction: why triplets?

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 $\Rightarrow$ can study effect of heavy H^0 resonance on off-shell gg $(\to h^*) \to ZZ$.

The Trouble with Triplets: 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; isospin septet with $Y = 4$

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

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 $\langle \phi^0 \rangle = v_\phi/\sqrt{2}$

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

Georgi-Machacek model

Georgi & Machacek, NPB262, 463 (1985)

Chanowitz & Golden, PLB165, 105 (1985)

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

Observation: the SM Higgs potential accidentally preserves a global SU(2)$_L\times$SU(2)$_R$ symmetry: bigger than the gauged SU(2)$_L$ $\times$U(1)$_Y$ symmetry.

Consequence: When SU(2)$_L\times$U(1)$_Y$ $\to$U(1)$_{EM}$, the global symmetry breaks via SU(2)$_L\times$SU(2)$_R$ $\to$SU(2)$_c$: "custodial symmetry". Ensures $\rho = 1$ at tree level; violated by hypercharge and $m_t \neq m_b$.

Idea: Construct by hand a scalar potential for the triplets that preserves SU(2)$_L\times$SU(2)$_R$

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 $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$:

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

Vevs: (preserves the diagonal $\mathrm{SU}(2)_c$ 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 $\mathrm{SU}(2)_R$: 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

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

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.

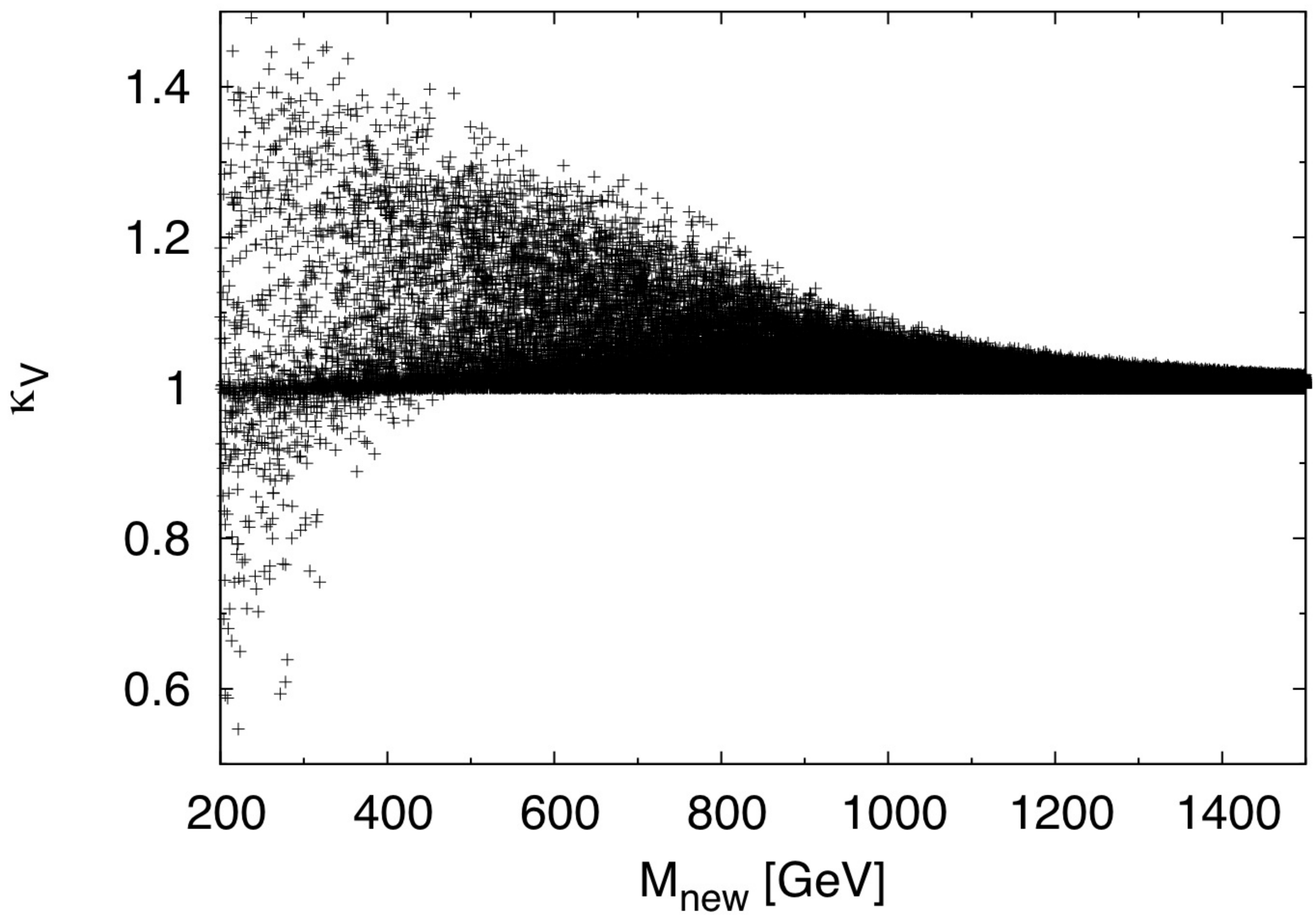
$\sin\theta_H \equiv \frac{2\sqrt{2}v_\chi}{v} \simeq \frac{M_1 v}{\sqrt{2}\mu_3^2}$ $\Rightarrow$ Triplet contribution to M_W, M_Z goes away as $\mu_3 \rightarrow$ large.

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

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

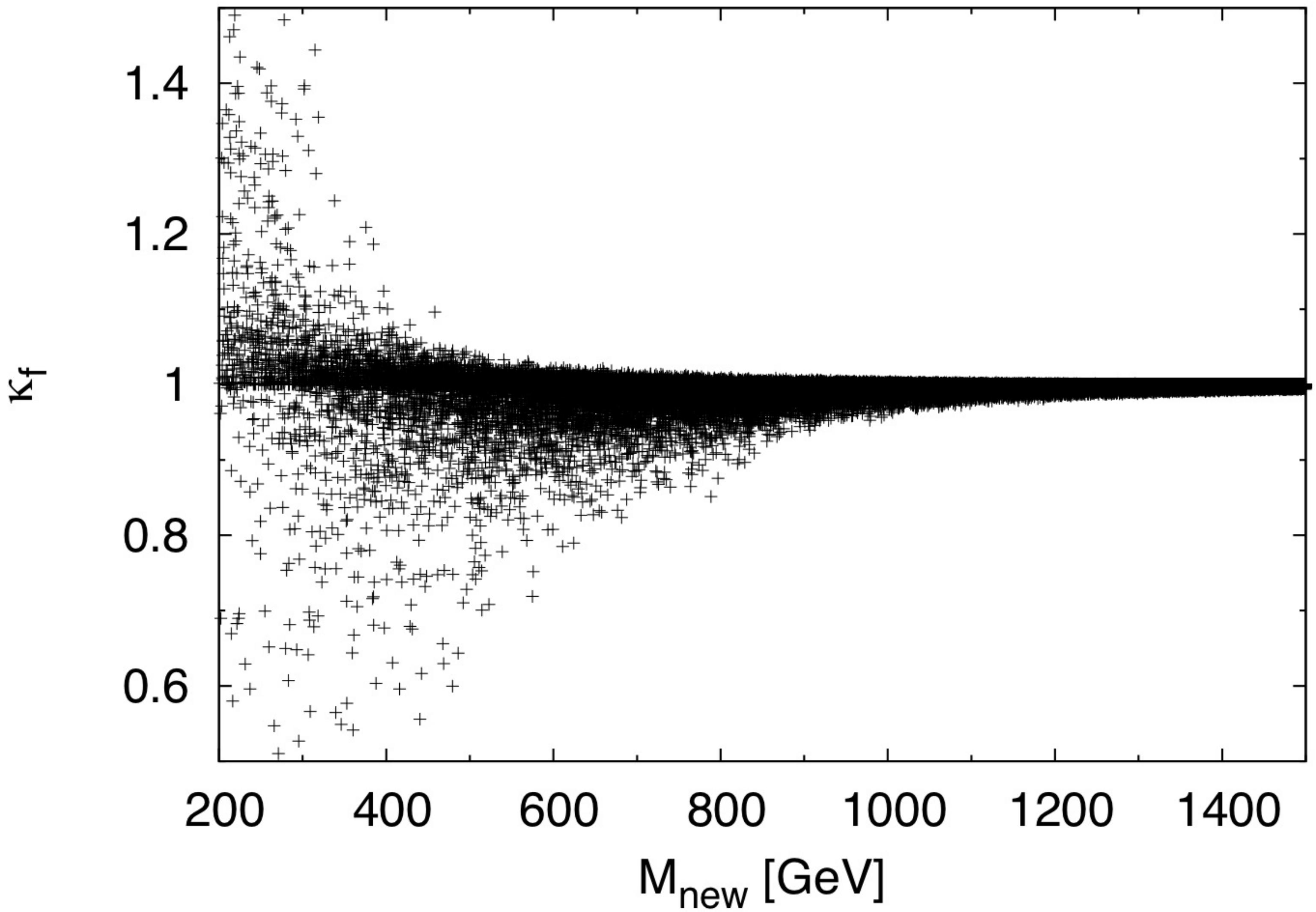
Numerical results: hVV coupling enhancement can be quite large!



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

Hartling, Kumar & HEL, 1404.2640

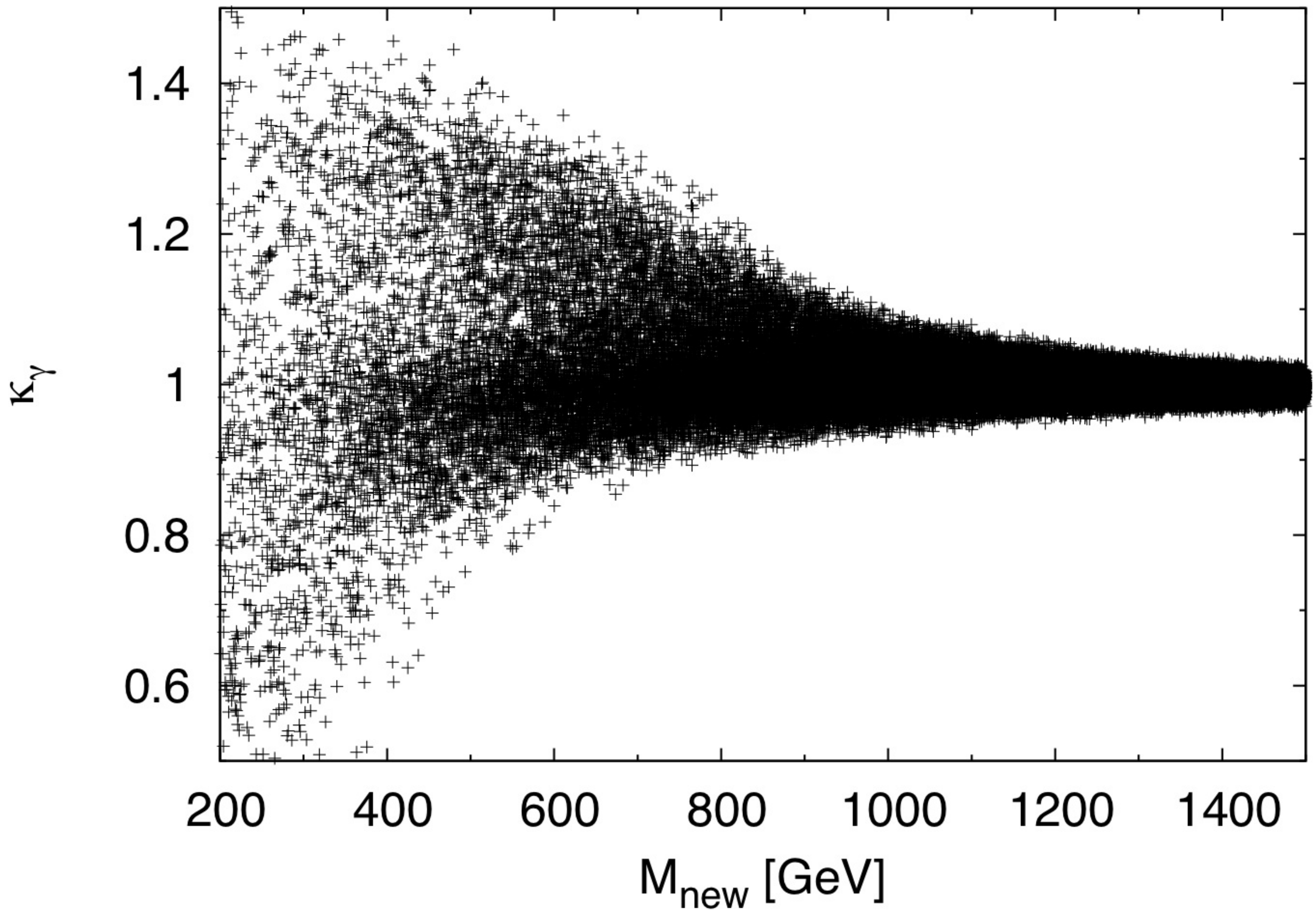
Numerical results: hff coupling typically < 1; $\kappa_f > 1$ possible at low $M_{\rm new}$



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

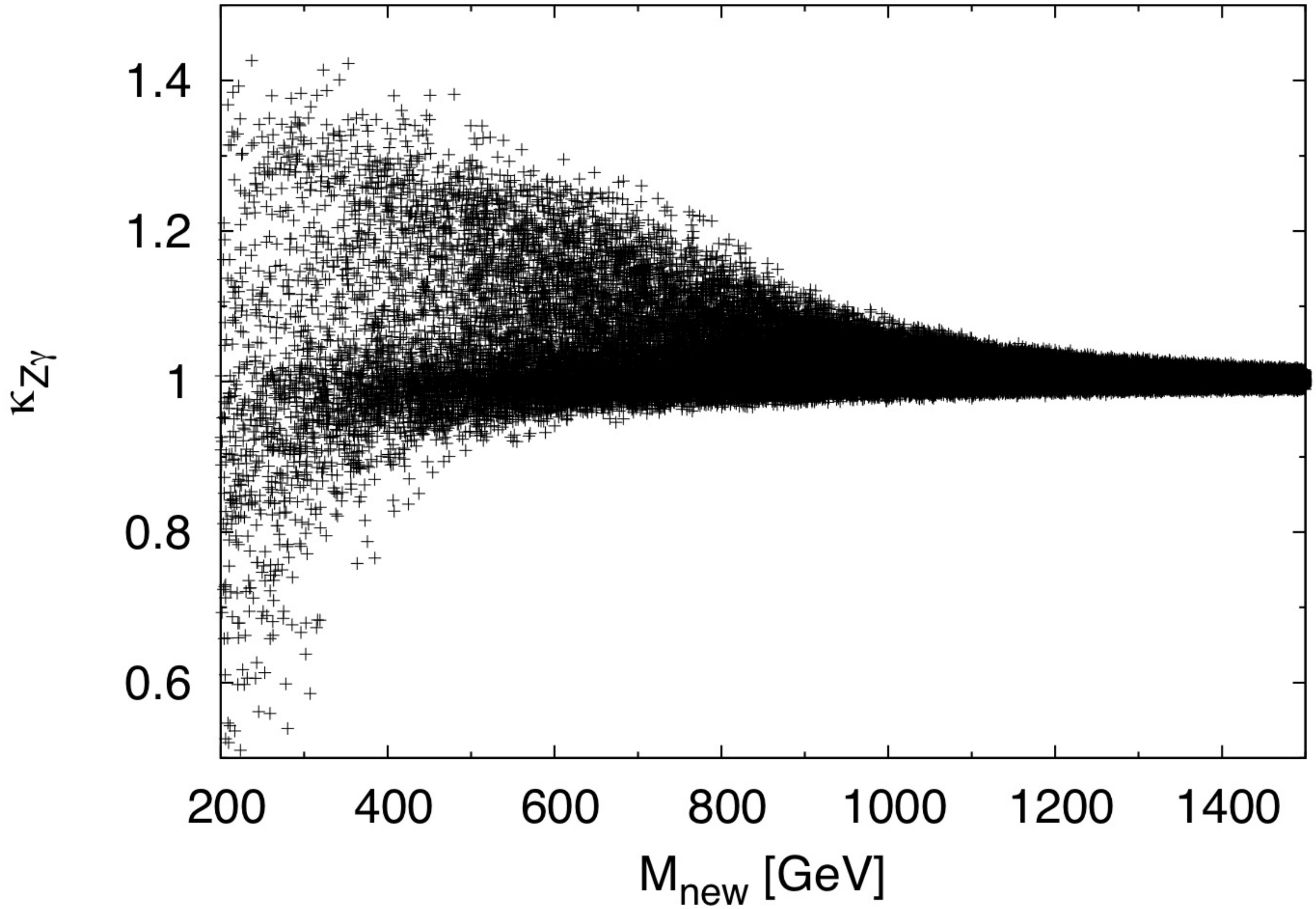
Hartling, Kumar & HEL, 1404.2640

Numerical results: $h\gamma\gamma$ coupling contributions from charged scalars in loop



$M_{\text{new}} \equiv$ mass of *lightest* new state. Hartling, Kumar & HEL, 1404.2640

Numerical results: $hZ\gamma$ coupling contributions from charged scalars in loop



$M_{\text{new}} \equiv$ mass of *lightest* new state. Hartling, Kumar & HEL, 1404.2640

Decoupling limit: the bottom line

All h^0 coupling deviations decouple like $M_1^2 v^2/\mu_3^4$.

- Slow decoupling $\sim v^2/M_{\rm new}^2$ if $M_1 \sim \sqrt{\mu_3^2}$.

- Fast decoupling $\sim v^4/M_{\rm new}^4$ if $M_1 \sim v$.

Compare 2HDM:

$\kappa_V \sim 1 + \mathcal{O}(v^4/M_{\rm new}^4)$, $\kappa_f \sim 1 + \mathcal{O}(v^2/M_{\rm new}^2)$ at tree level. Gunion & Haber, hep-ph/0207010

1-loop 2HDM corrections $\rightarrow \delta\kappa_V \sim (loop\ factor) \cdot \mathcal{O}(v^2/M_{\rm new}^2)$. M. Kikuchi, talk on Tuesday

- Relationship in decoupling limit: $\kappa_V \simeq 1 + 3\epsilon$, $\kappa_f \simeq 1 - \epsilon$.

$\epsilon = M_1^2 v^2/8\mu_3^4$

Indirect constraints

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

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

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

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

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

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

(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)

$B_s \to \mu^+\mu^-$: adapted from new calculation for Aligned 2HDM by Li, Lu & Pich, 1404.5865

Only relevant contribution comes from the Z penguin:

$$\frac{\bar{B}(B_s^0 \to \mu^+\mu^-)}{\bar{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}}} = \left| \frac{C_{10}^{\text{SM}} + C_{10}^{\text{GM}}}{C_{10}^{\text{SM}}} \right|^2$$

$$C_{10}^{\text{GM}} = \frac{1}{8} \tan^2\theta_H \frac{m_t^2}{M_W^2} \left[\frac{R}{1-R} + \frac{R \log R}{(1-R)^2} \right], \qquad R = \frac{m_t^2}{m_3^2}$$

Indirect constraints

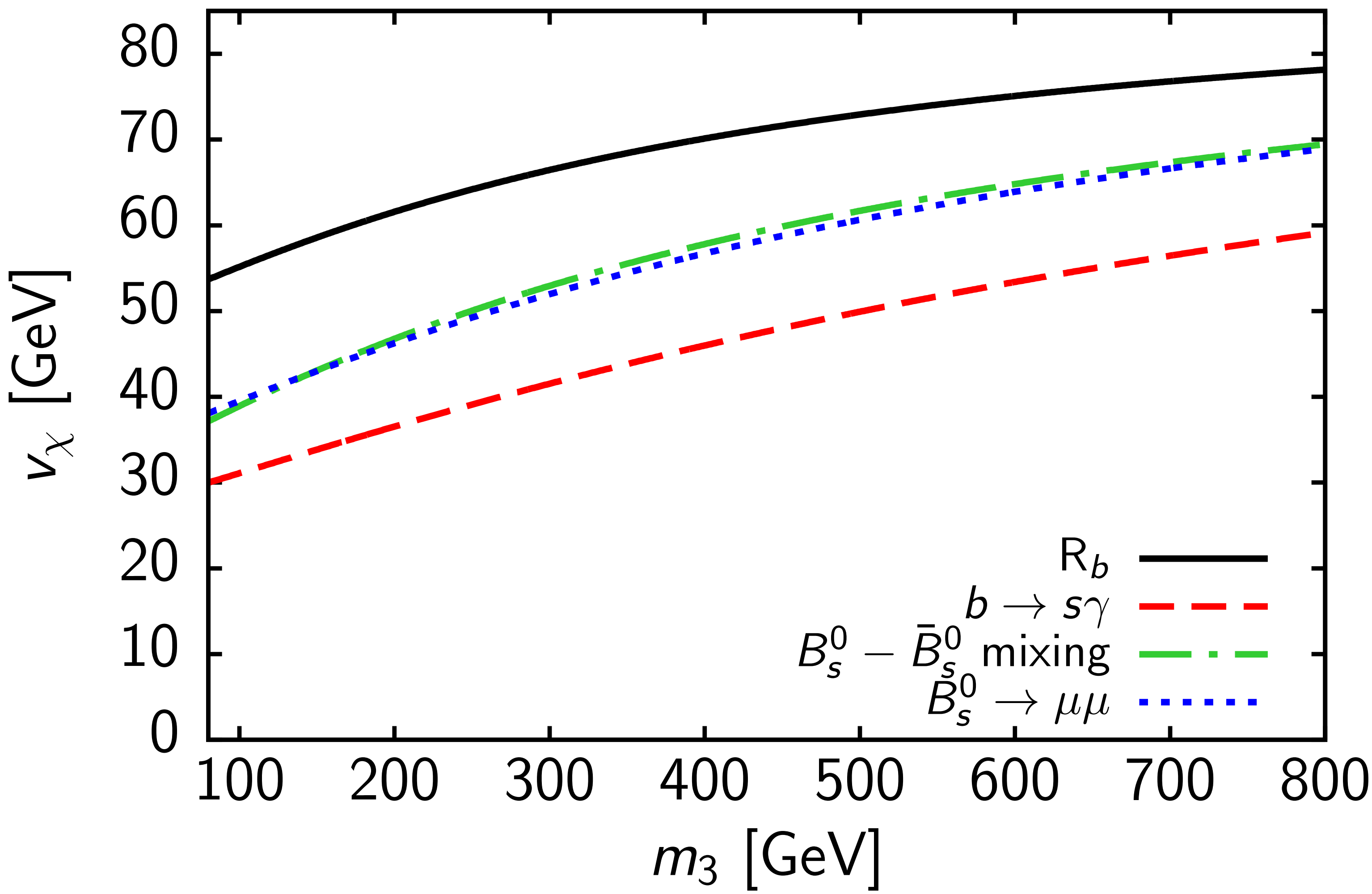
We also implement the S-parameter constraint, marginalizing over the T-parameter.

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.

Comparison of nonoblique & b-physics constraints



VERY PRELIMINARY!

Hartling, Kumar & HEL, work in progress

(Li, Lu & Pich 1404.5865 identify $B_s \to \mu\mu$ constraint as stronger than others, incl. $b \to s\gamma$)

Aside on numerical results:

$b \to s\gamma$: we used [Not yet cross-checked]

- SM calculation from Misiak et al, hep-ph/0609232:

$$\text{BR}(\bar{B} \to X_s\gamma)_{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4} \text{ for } E_\gamma > 1.6 \text{ GeV}$$

- current preliminary HFAG combined experimental result:

$$\text{BR}(\bar{B} \to X_s\gamma)_{\text{expt}} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4} \text{ for } E_\gamma > 1.6 \text{ GeV}$$

$B_s \to \mu\mu$: we used [Cross-checked]

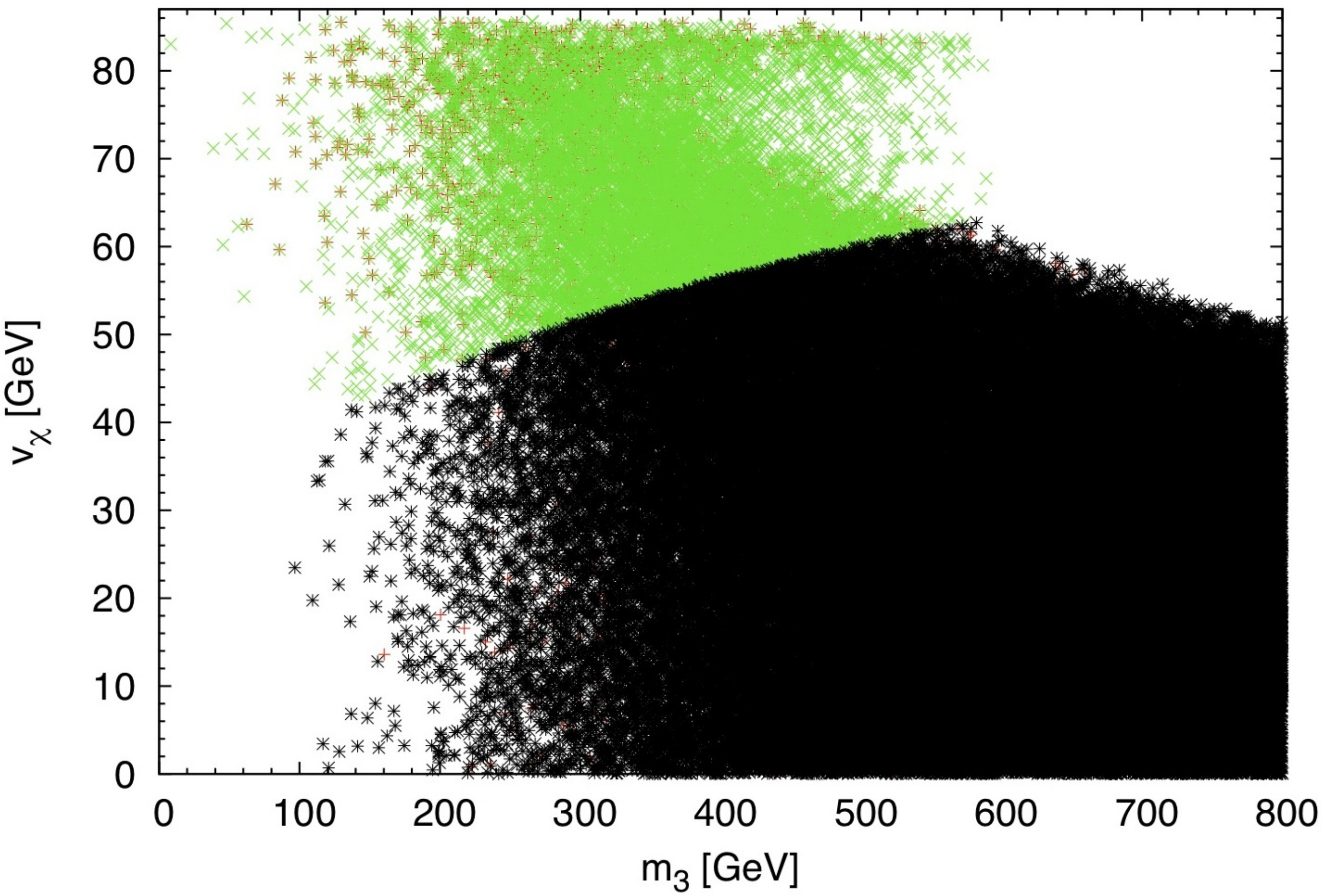
- SM calculation from Bobeth et al, 1311.0903, updated in Li, Lu & Pich 1404.5865 with slightly different m_t:

$$\overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.67 \pm 0.25) \times 10^{-9}$$

- current combined CMS and LHCb measurement,

$$\overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{expt}} = (2.9 \pm 0.7) \times 10^{-9}$$

$B_s \to \mu\mu$ constraint: interplay with decoupling (green points are excluded)



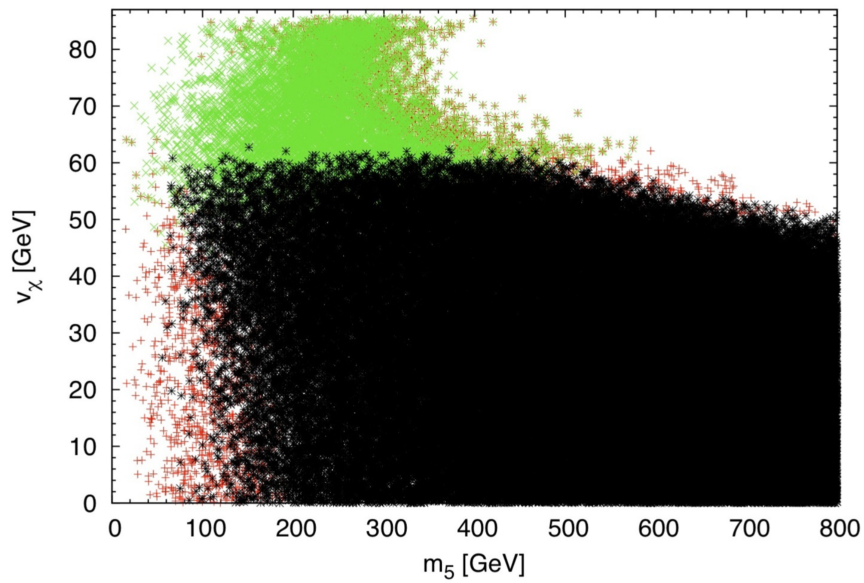
PRELIMINARY-ish

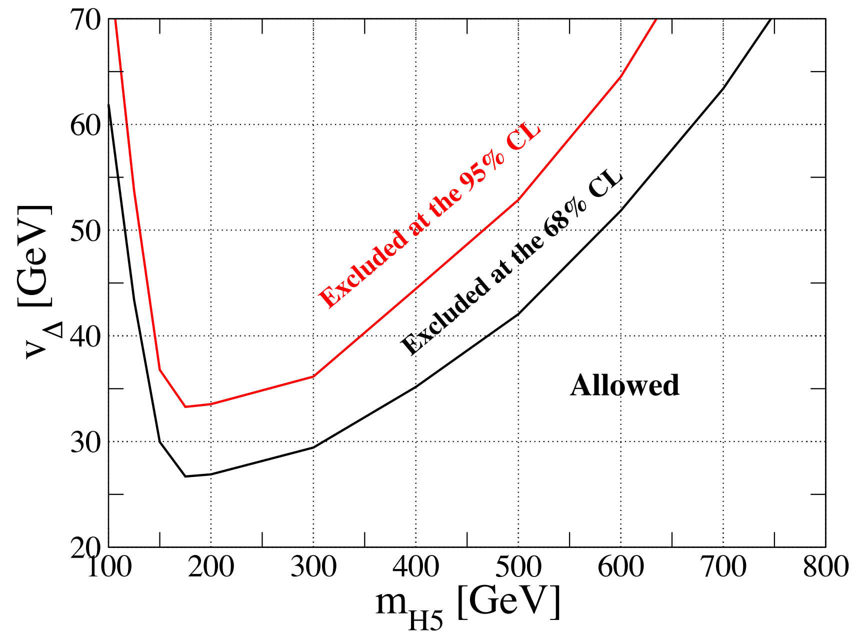
Hartling, Kumar & HEL, work in progress

(Still working on implementing the $b \to s\gamma$ constraint in our numerical-scan code: bound on v_χ will be about 10 GeV lower.)

Effect of $B_s \to \mu\mu$ constraint on m_5: compare direct search!

PRELIMINARY-ish ↓





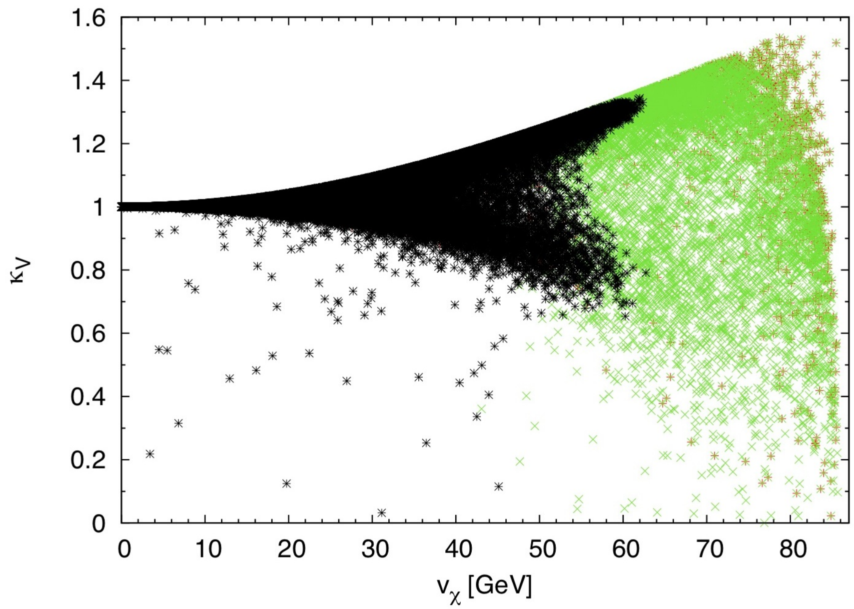
Hartling, Kumar & HEL, work in progress

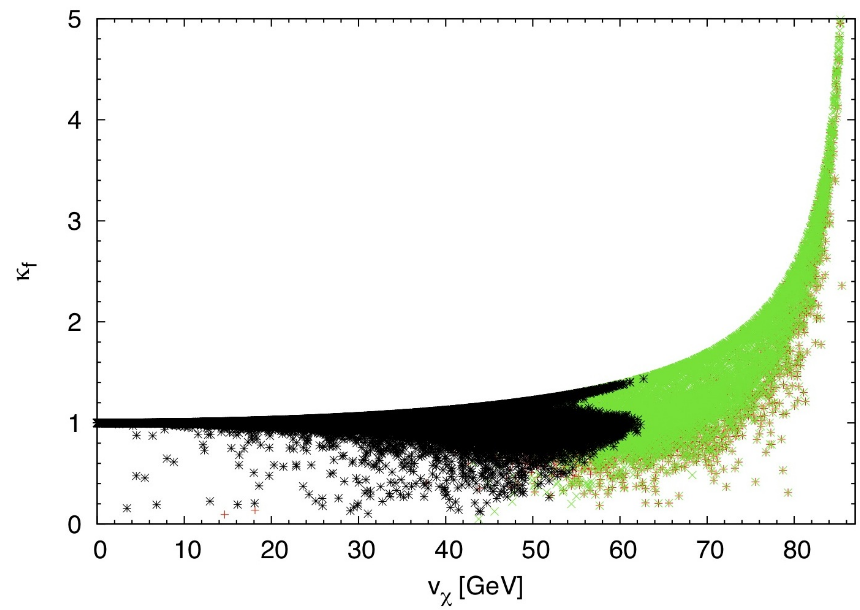
Chiang, Kanemura & Yagyu, 1407.5053

(red points are excluded by S parameter)

Recasting of ATLAS measurement of like-sign $W^{\pm}W^{\pm}jj$ cross section to constrain VBF $W^{\pm}W^{\pm} \to H^{\pm\pm} \to W^{\pm}W^{\pm}$.

Effect of $B_s \to \mu\mu$ constraint on κ_V and κ_f (green points are excluded)





PRELIMINARY-ish

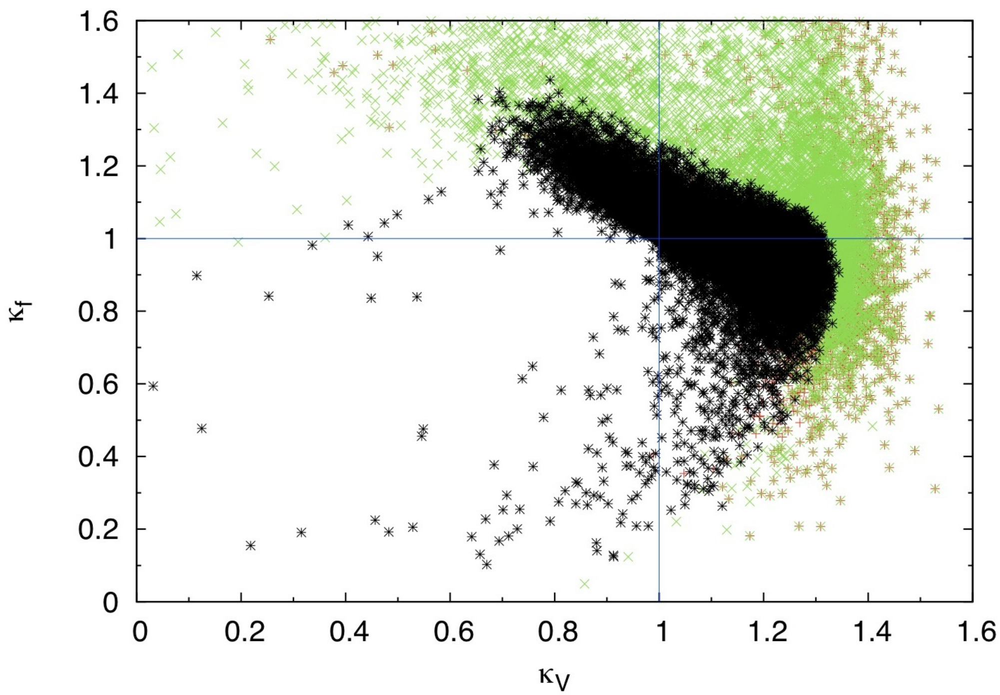
Hartling, Kumar & HEL, work in progress

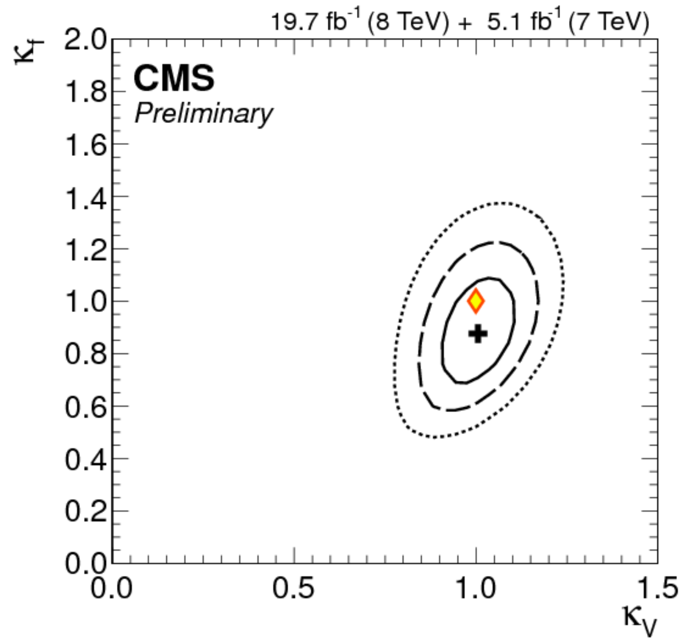
$$\kappa_V = \cos\alpha \frac{v_\phi}{v} - \frac{8}{\sqrt{3}} \sin\alpha \frac{v_\chi}{v} \qquad \kappa_f = \cos\alpha \frac{v}{v_\phi}$$

The upper bound on v_χ imposed by $B_s \to \mu\mu$ constrains $\kappa_V \lesssim 1.35$ and $\kappa_f \lesssim 1.45$.

- $b \to s\gamma$ constraint will tighten this a little.
- Direct search in like-sign $W^\pm W^\pm jj$ will tighten it a little more.

Effect of $B_s \to \mu\mu$ constraint on κ_V and κ_f (green points are excluded)



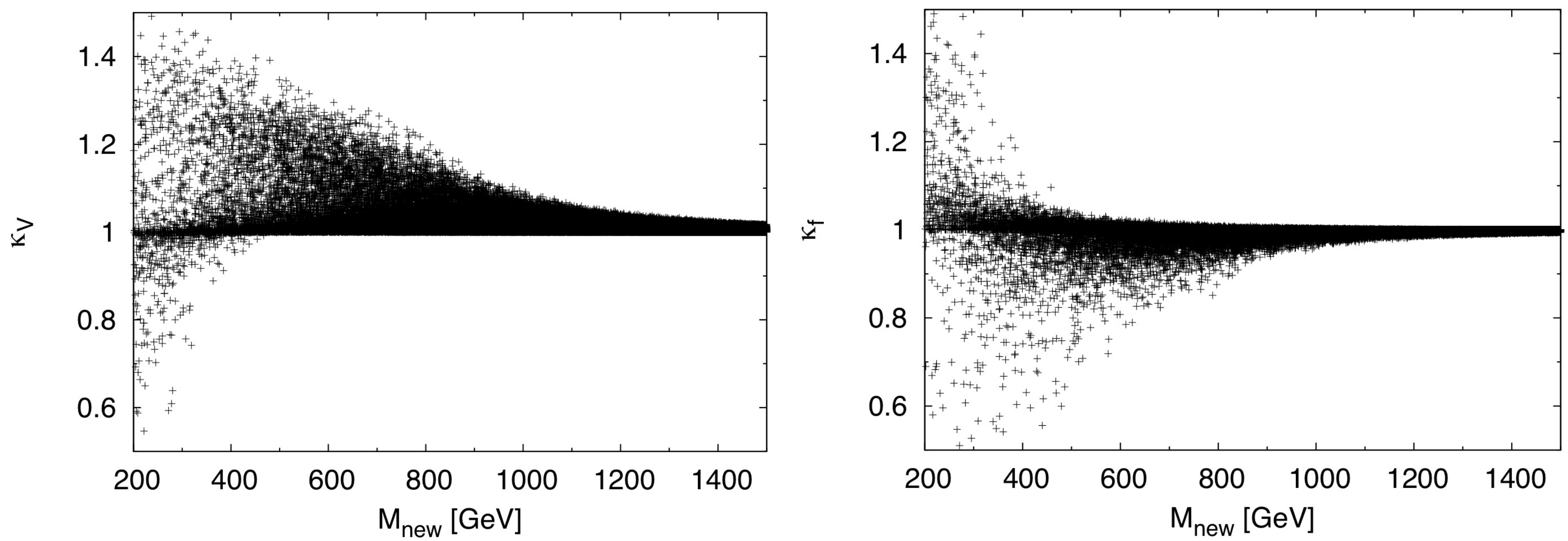


PRELIMINARY-ish Hartling, Kumar & HEL, work in progress

Along the line $\kappa_V = \kappa_f$, the $B_s \to \mu\mu$ measurement constrains $\kappa_V = \kappa_f \lesssim 1.15$. ($b \to s\gamma$, like-sign $WWjj$ will tighten this a little)

All LHC Higgs cross sections can be simultaneously enhanced by up to ∼30% ⇔ enhancement can be hidden by an unobserved non-SM Higgs decay BR_{new} up to ∼25%. (LHC flat direction!)

“Flat direction” region of $\kappa_V \simeq \kappa_f > 1$ is NOT near decoupling.



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

Hartling, Kumar & HEL, 1404.2640

κ_f is suppressed near decoupling limit: significant enhancement requires $M_{\text{new}} \lesssim$ 400–500 GeV.

There are relatively light states to search for in this scenario!

Illustrates the value of a full model implementation.

Outlook: toward a calculator for the Georgi-Machacek model

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

- model parameter input set includes m_h
- computes spectrum, h^0–H^0 mixing angle, v_χ
- implements theory checks (unitarity, bounded-from-below, no alt minima)
- implements S parameter, $B_s \to \mu\mu$ constraints; adding $b \to s\gamma$

- outputs spectrum, decay tables
- currently working on implementing QCD and offshell corrections to decay partial widths
- working on suitable format to output production couplings