Extracting Higgs boson couplings from LHC data

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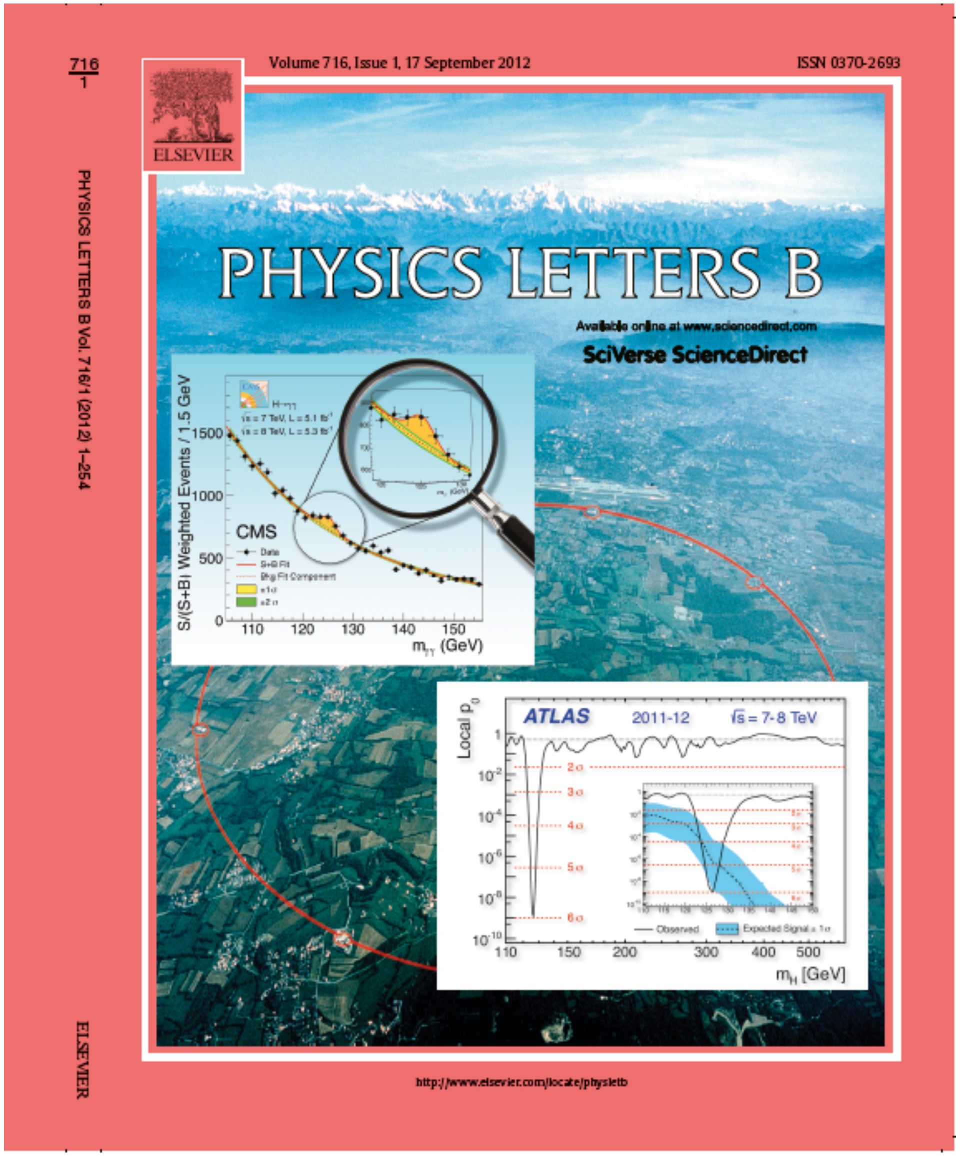
Duhrssen, Heinemeyer, H.E.L, Rainwater, Weiglein, & Zeppenfeld, hep-ph/0406323

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

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

Discovery of the Higgs boson (summer 2012)



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P. Higgs congratulating ATLAS spokesperson on Higgs boson discovery (or vice versa?)

Picture: Christian Science Monitor

Launches a new era of precision Higgs measurements

Outline

Introduction: the Higgs boson in the Standard Model

Higgs couplings at the Large Hadron Collider

Why Higgs couplings are interesting

Fitting the couplings: issues and ways forward

Conclusions

Introduction: the descriptive version

The Higgs field is a new kind of field that fills all space

Kind of like a magnetic field, but without a direction

It carries weak gauge charges (isospin and hypercharge):
the W and Z bosons interact with it and thereby become massive

It interacts with different fermions with different strengths:
thereby the quarks and leptons all acquire their different masses

(except probably for neutrinos: that's another story)

This is the description in the Standard Model: largely untested!

Introduction: the mathy version

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: the mathy version

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

W and Z:

$g_Z \equiv \sqrt{g^2 + g'^2}$, $v = 246$ 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:

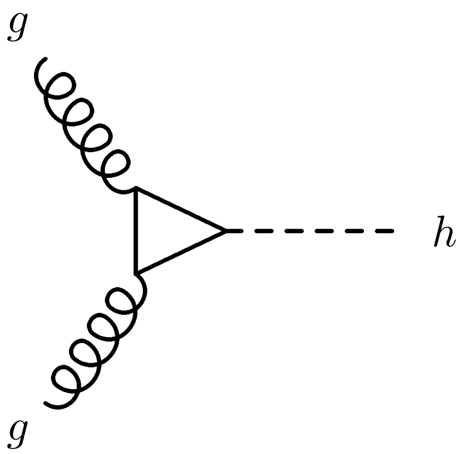
$$\mathcal{L} = -y_f \bar{f}_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$

$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f: \; i m_f/v$$

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

All predicted in the Standard Model, with no free parameters!

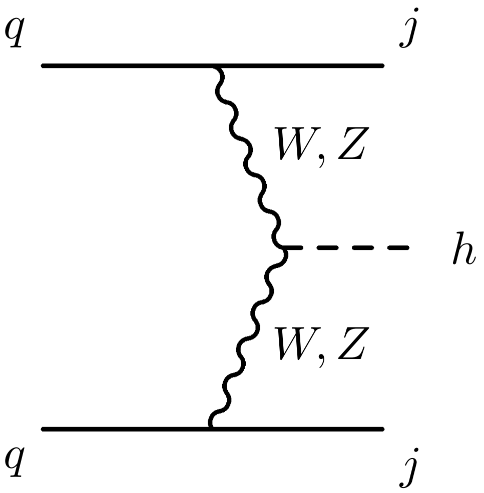
Higgs couplings at the LHC: top 4 (+1) production modes



1) Gluon fusion
(90% of Higgs production at LHC)

Top quark in the loop gives most important contribution (bottom quark few-%)

Just Higgs produced: need distinctive decays:
$\gamma\gamma$, $ZZ \to 4\ell$



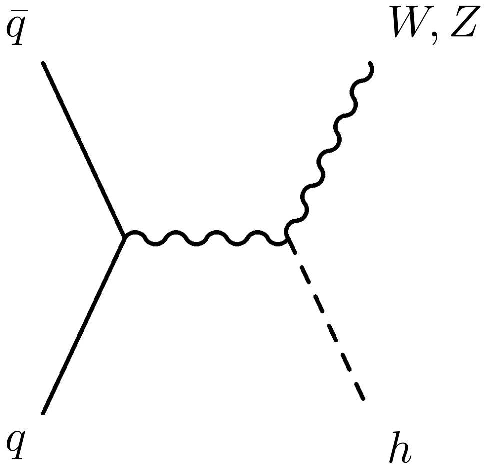
2) Weak boson fusion
($\sim$10% of Higgs production at LHC)

Higgs couples to WW or ZZ

Two energetic “tagging jets” produced:
distinctive production signature

Higgs couplings at the LHC: top 4 (+1) production modes

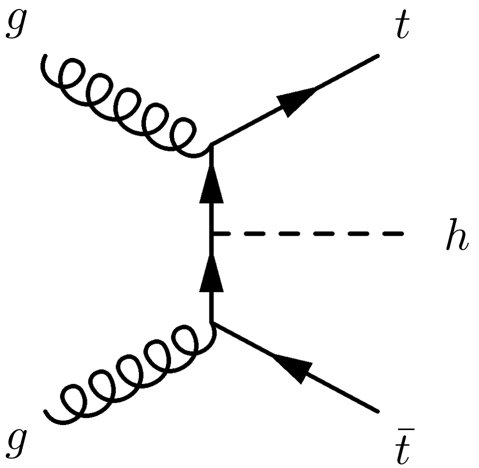
3) Associated production of $h + W$, $h + Z$
(a couple percent of total Higgs rate)



Higgs couples to WW or ZZ

$W \to \ell\nu$ or $Z \to \ell^+\ell^-$ provide distinctive tags: essential if Higgs decay is similar to backgrounds!

4) Associated production of $h + t\bar{t}$
(rare: only 1% of total Higgs rate at 14 TeV)



Higgs couples to $t\bar{t}$: cleaner probe of $ht\bar{t}$ coupling than gluon fusion

Two top quarks provide distinctive tags

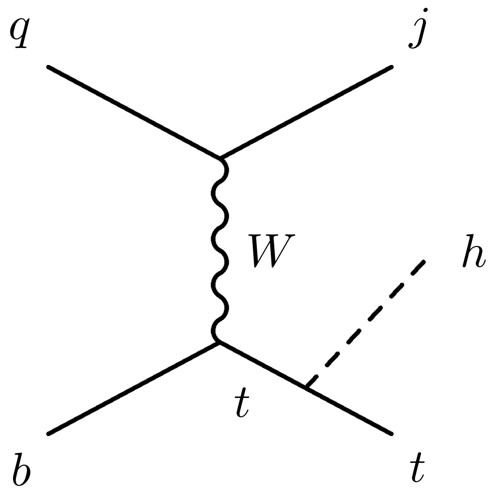
Higgs couplings at the LHC: top 4 (+1) production modes

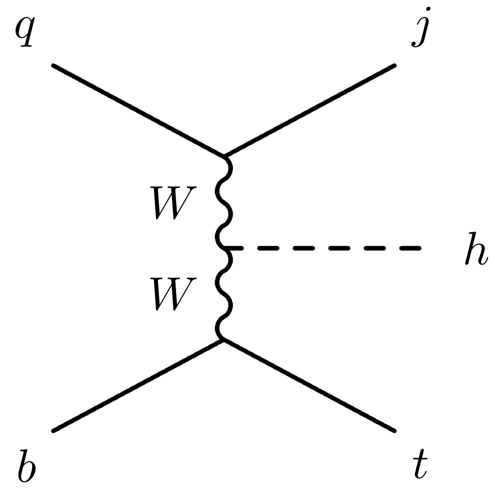
+1) Higgs + single top associated prod’n (extremely rare!)

Interesting because of interference between two diagrams involving Higgs couplings to top quark and W boson

SM: strong destructive interference (∼90% cancellation)

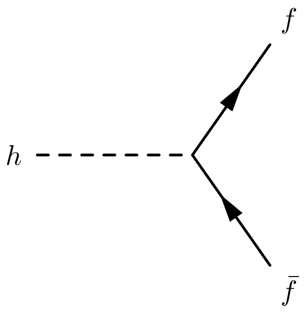
Lets us test the relative sign between the hWW and $ht\bar{t}$ couplings (flip a sign → constructive interference → 10x larger rate)



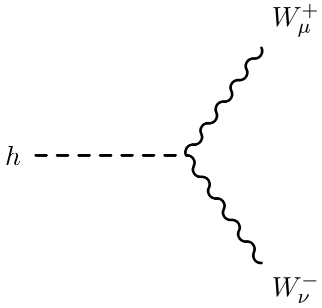


Higgs couplings at the LHC: decays

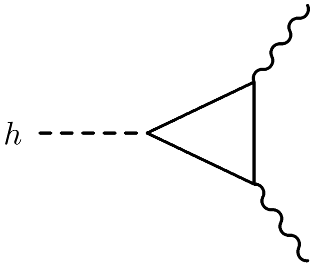
2 fermions:
$b\bar{b}$, $\tau\tau$, $c\bar{c}$



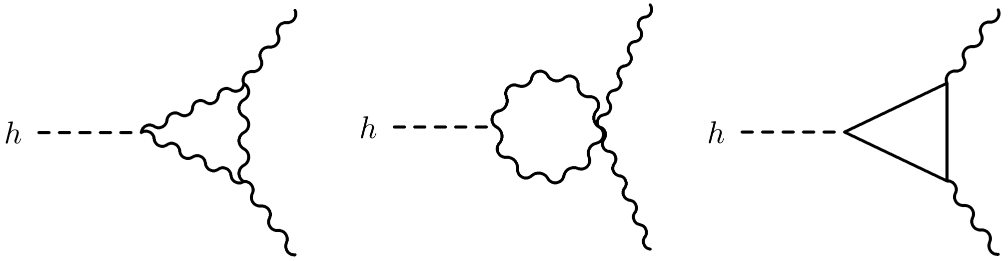
$WW \to \ell\nu\ell\nu$
or $ZZ \to 4\ell$, $2\ell 2\nu$



2 gluons, mainly through a top quark loop (bottom loop a few percent)



2 photons, mainly through a W boson loop; top quark loop interferes destructively (-30%), small contribution from bottom loop



Higgs couplings at the LHC: decays

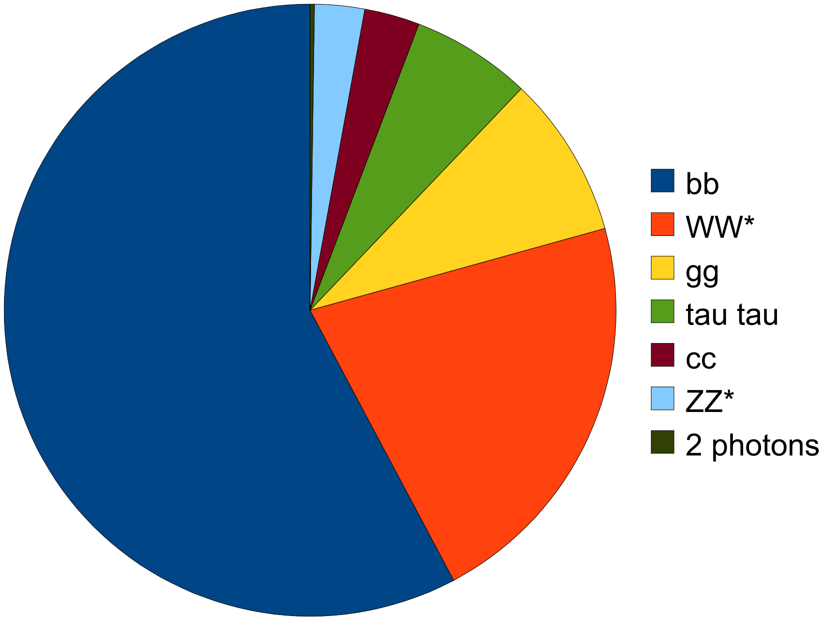
Predict the decay rate Γ_i into each final state i.

Total decay rate is $\Gamma_{\text{tot}} \equiv \sum_i \Gamma_i$.

Fraction of Higgs decays into a particular final state is

$$\text{BR}_i \equiv \frac{\Gamma_i}{\Gamma_{\text{tot}}}$$

"branching ratio"



Why Higgs couplings are interesting: search for new physics!

We know that the Standard Model cannot be the whole story.

Problems from data:

- Dark matter (and dark energy?!?)
  - Higgs portal; $h \to$ invisible
- Matter-antimatter asymmetry
  - Electroweak baryogenesis, need modified Higgs potential

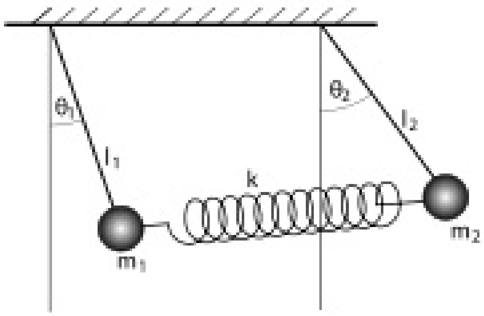
Problems from theory:

- Hierarchy problem
  - SUSY; composite Higgs/Randall-Sundrum; little Higgs; fine tuning??
- Neutrino masses (why so very tiny?)
  - Type-2 seesaw scalar triplet; neutrino-coupled doublet
- Flavour (origin of quark and lepton masses, mixing, CP violation?)
  - Clues from fermion couplings to Higgs?

Three general possibilities:

1) More than one Higgs field in the vacuum

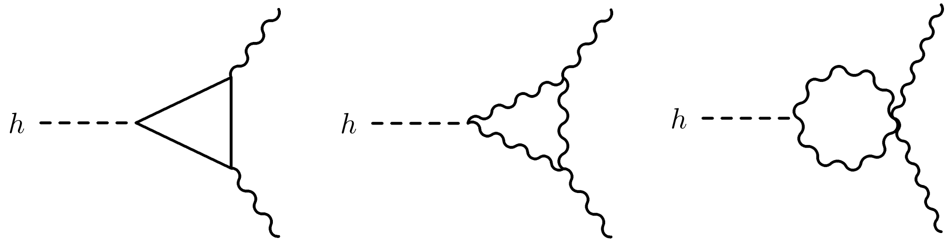
Each one has excitations, in general they are coupled together:
→ there are more Higgs states (including electrically-charged!)
→ physical particles are mixtures



Couplings of physical Higgs h are modified due to mixing:
parameterize by multiplicative factors κ_i

Three general possibilities:

2) New particles that interact with the Higgs



Like top squarks, charginos in Supersymmetry:
They run in the loops that cause ggh and $h\gamma\gamma$ couplings

Modified loop-induced couplings: probe for new physics through its virtual effects!

Three general possibilities:

3) New particles that the Higgs can decay into

The Higgs can interact with new particles that don't interact via the strong, weak, or electromagnetic interactions.
→ Dark matter?

Can also interact with light new particles that have so far evaded direct searches.
→ New light particles that decay to non-distinctive final states, like QCD jets

The Higgs could be our window to new physics!

New decays add to $\Gamma_{\rm tot}$: affect the "visible" Higgs branching ratios via

$$\mathrm{BR}_i \equiv \frac{\Gamma_i}{\Gamma_{\rm tot}} = \frac{\Gamma_i}{\Gamma_{\rm SM} + \Gamma_{\rm new}}$$

Extracting Higgs couplings from LHC data

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. → correlations

Extracting Higgs couplings from LHC data

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

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

Coupling dependence (at leading order):

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

Each rate depends on multiple couplings. → correlations

Non-SM decays could also be present:

- invisible final state (can look for this with dedicated searches)
- “unobserved” final state (e.g., $h \to$ 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:

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

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

(e^+e^- Higgs factories like ILC get 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 $\Gamma_{\text{tot}} >$ expt. resolution;
  $\Gamma^{\text{SM}}_{\text{tot}} \simeq 4$ 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!

Models that realize the flat direction are “exotic”

Have to generate hWW and hZZ couplings larger than in SM with simultaneous enhancement of $hf\bar{f}$ couplings

Need new Higgs bosons in isospin-1 representation or larger

⇒ Implies existence of doubly-charged Higgs boson H^{++} that decays to W^+W^+!

Study explicit models:

- Georgi-Machacek model

    w/ K. Hartling & K. Kunal; + B. Keeshan & T. Pilkington

- Generalizations of Georgi-Machacek model to higher isospin

    w/ V. Rentala

- SM Higgs mixing with a scalar septet

    w/ M.-J. Harris

Georgi-Machacek model

Georgi & Machacek, NPB262, 463 (1985)

Chanowitz & Golden, PLB165, 105 (1985)

SM scalar doublet ϕ + complex triplet χ + real triplet ξ:

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

Matrix form preserves a global symmetry that prevents problems with electroweak ρ parameter

Physical states:

- Two singlets h^0 (mass m_h), H^0 (mass m_H)

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

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

- Triplet (H_3^+, H_3^0, H_3^-), mass m_3 (orthogonal triplet is the Goldstones)

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

- Five-plet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$, mass m_5

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

For a full analysis of the model:

Most general scalar potential consistent with symmetries

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

Apply theory constraints Hartling, Kumar & HEL, 1404.2640

- perturbative unitarity of quartic couplings
- scalar potential bounded from below
- global minimum is the desired electroweak-breaking one

Apply indirect experimental constraints Hartling, Kumar & HEL, 1410.5538

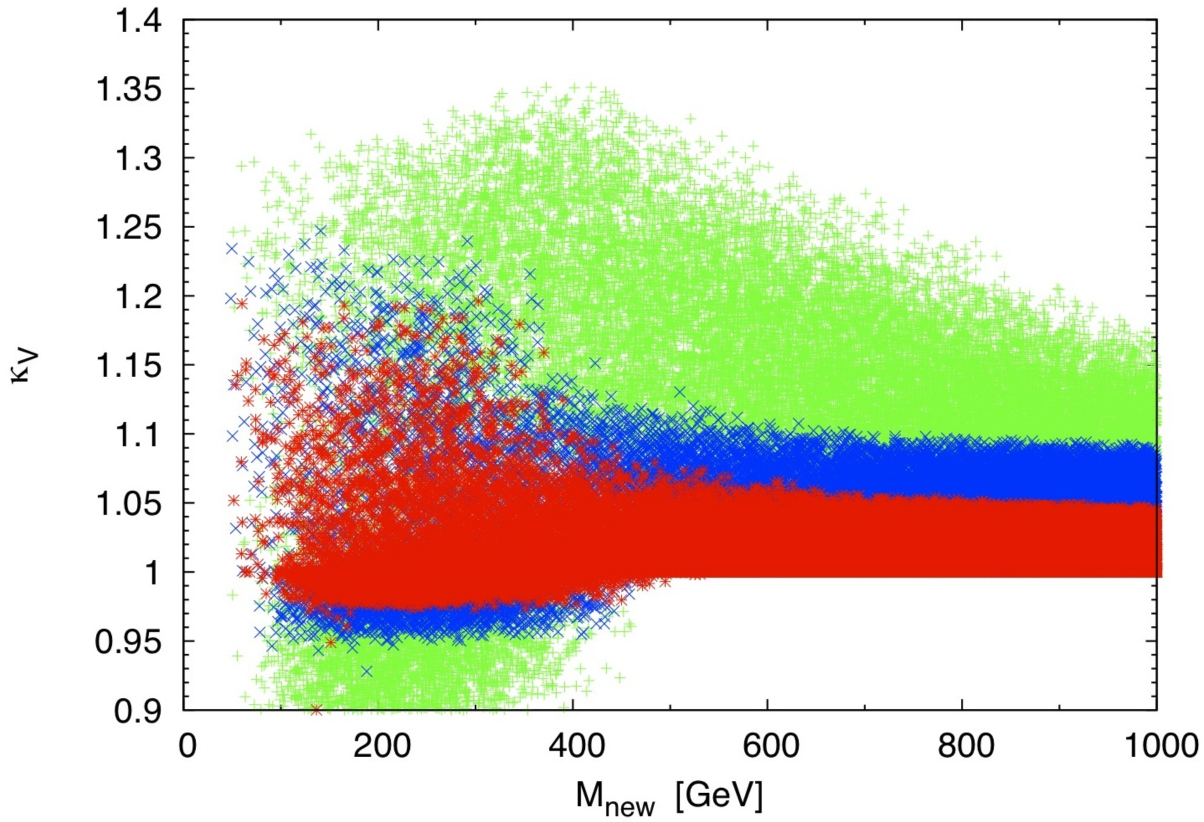
- $b \to s\gamma$
- also R_b, B_s–$\overline{B}_s$ mixing, $B_s \to \mu^+\mu^-$, S parameter

Apply constraints from direct experimental searches (yet to come)

Main result:

Simultaneous enhancement of hVV and $hf\bar{f}$ couplings

$\Rightarrow$ new scalars must be relatively light!



All points are allowed by theoretical & indirect experimental constraints.

Colours: $hf\bar{f}$ coupling within 10% or 5% of hVV coupling

Hartling, Kumar & HEL, 1410.5538

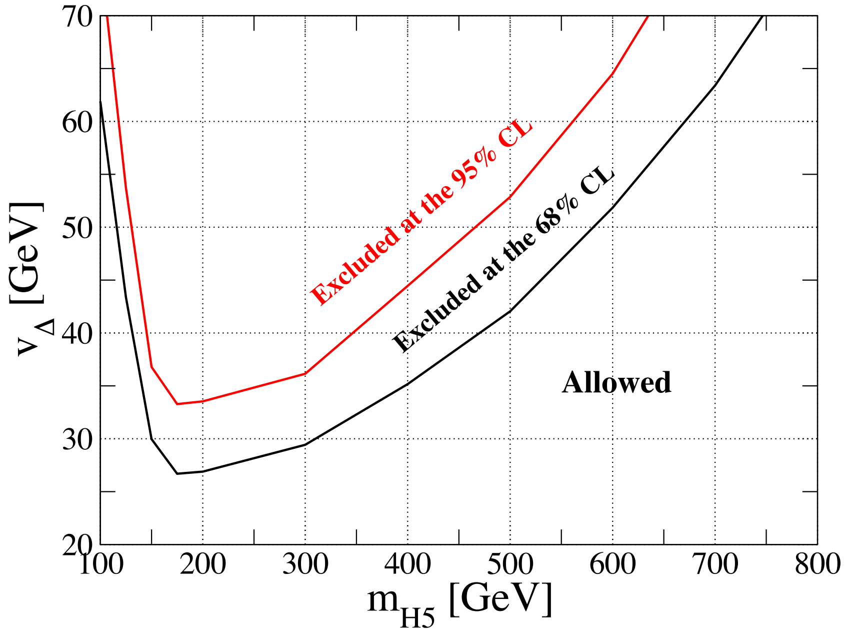
$M_{\text{new}} \equiv$ mass of *lightest* new state.

Significant enhancement of $hf\bar{f}$ and hVV couplings at the same time (required to realize flat direction) implies $M_{\text{new}} \lesssim$ 400 GeV.

In progress: fold in *direct* searches for new scalars

Particularly interesting: $H^{++} \to W^+W^+$

ATLAS measurement of like-sign $W^\pm W^\pm jj$ cross section
$\to$ reinterpret as upper bound on vector boson fusion production
of $H^{\pm\pm} \to W^\pm W^\pm$ Chiang, Kanemura & Yagyu, 1407.5053



Indirectly constrains hVV coupling as a function of H^{++} mass

Sum rule:

$$(hVV \text{ coup})^2 \leq 1 + \frac{40}{3}\frac{v_\chi^2}{v^2}$$

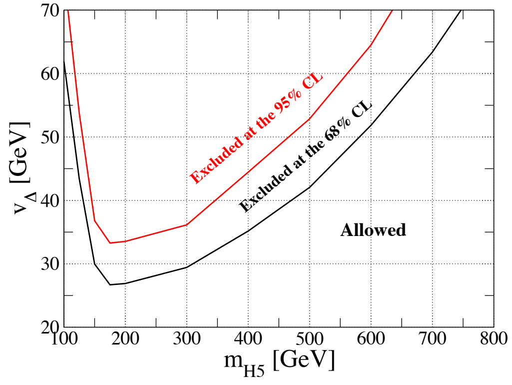
How to tame the LHC flat direction

Realizing the flat direction implies that new scalars are light.

- $M_{\rm new} \lesssim 400$ GeV in Georgi-Machacek model

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

- needed for theoretical consistency
- search in VBF $H^{++} \to W^+W^+$
- direct relationship between $H^{++}W^-W^-$ and max hVV coupling



Chiang, Kanemura & Yagyu, 1407.5053

Similar relationship holds in septet model and higher-isospin generalizations of Georgi-Machacek model.

- can get a lot of traction using only sum rules from theoretical consistency.
- but, need detailed studies of explicit models to understand relationship between hVV enhancement and range of H^{++} mass.

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
- generalizations of Georgi-Machacek to higher isospin
- SM Higgs mixing with a scalar septet

→ design searches for the additional light scalars
→ 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.

BACKUP SLIDES

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)

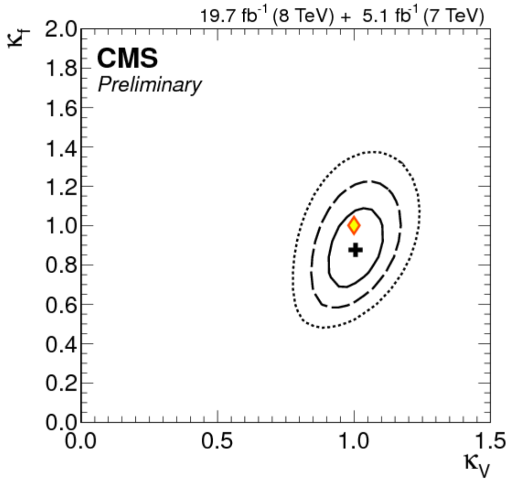
- 2HDM: $i\frac{g^2 v}{2} g_{\mu\nu} \sin(\beta - \alpha)$

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

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

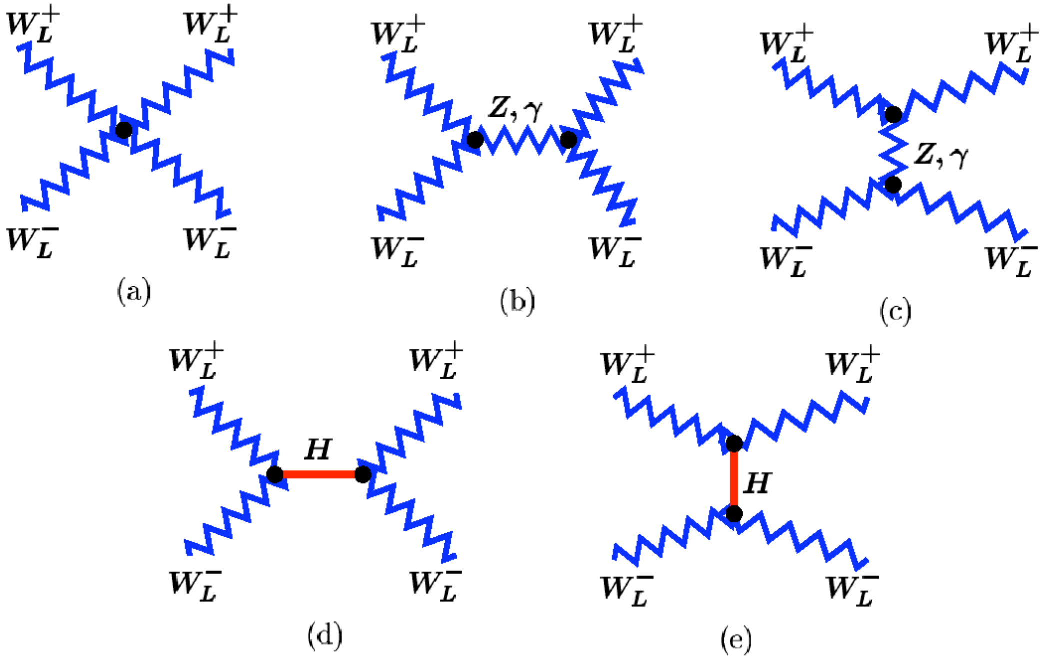
Enhanced hVV couplings require a scalar multiplet that:

- 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.



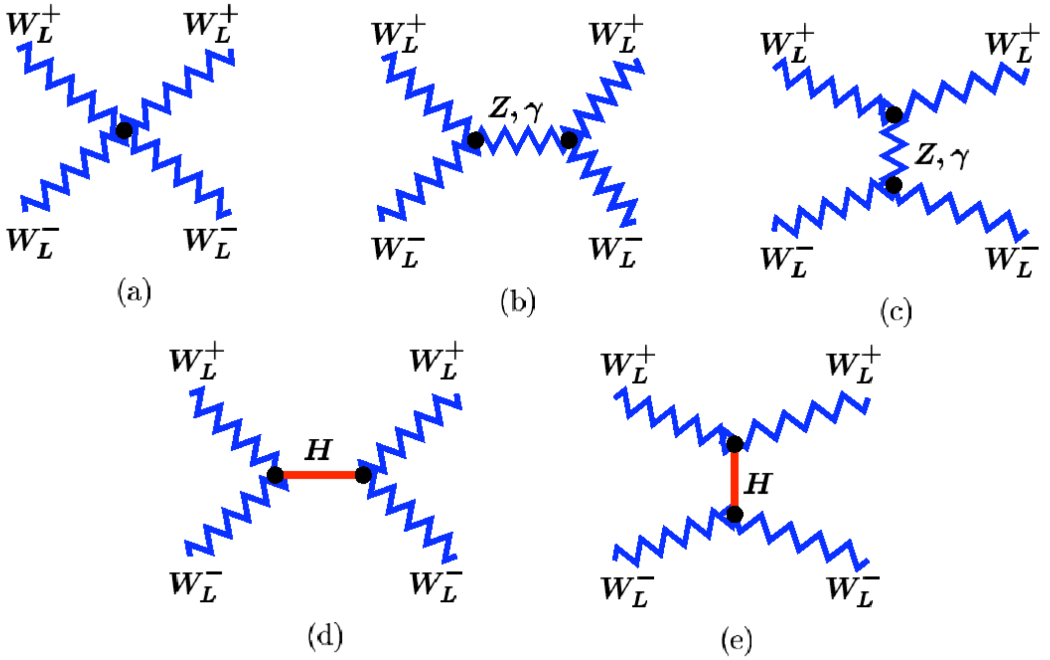
Lee, Quigg & Thacker 1977

(graphics: Chivukula, LHC4ILC 2007)

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

Another way to see this: unitarity of longitudinal VV scattering

SM: bad E^2/v^2 behaviour cancelled by $h_{\rm SM}$ 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!

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

Falkowski, Rychkov & Urbano, 1202.1532

How big can scalar multiplets be?

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

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

Large isospin → large weak charges: at some point perturbativity breaks down.

Compute 2 → 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 $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ global sym on scalar potential. Georgi & Machacek, NPB262, 463 (1985)

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 $SU(2)_L \times SU(2)_R$:

$$\Phi = \left(\begin{array}{cc} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{array} \right) \qquad X = \left(\begin{array}{ccc} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{array} \right)$$

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

$$\langle \Phi \rangle = \frac{v_\phi}{\sqrt{2}} \left(\begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array} \right) \qquad \langle X \rangle = v_\chi \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right)$$

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

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

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 → 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

Hartling, Kumar & HEL, 1410.5538

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

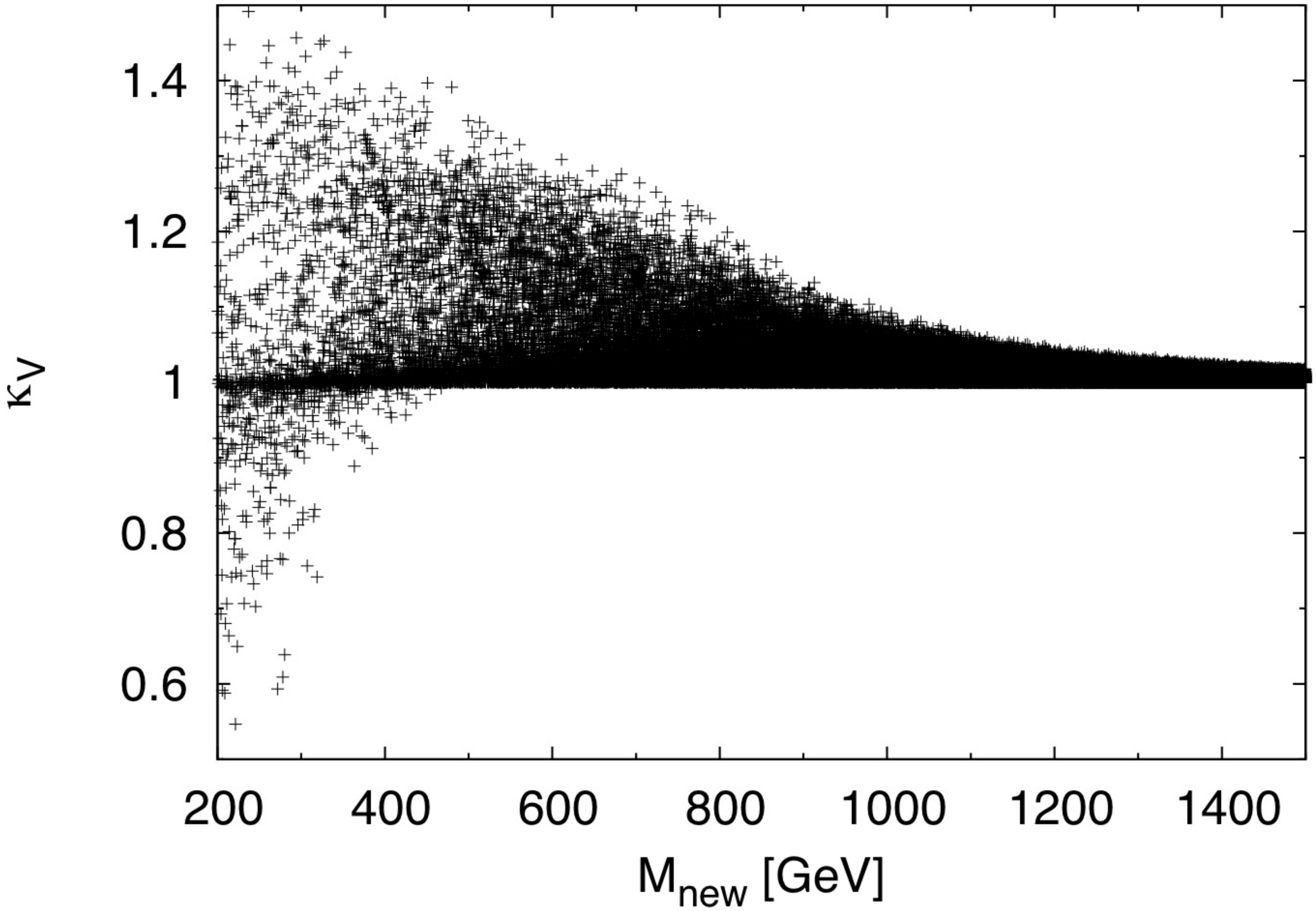
$B_s \to \mu^+\mu^-$: adapted from new calculation for Aligned 2HDM

Li, Lu & Pich, 1404.5865

S parameter: marginalize over T Gunion, Vega & Wudka, PRD43, 2322 (1991)

* strongest

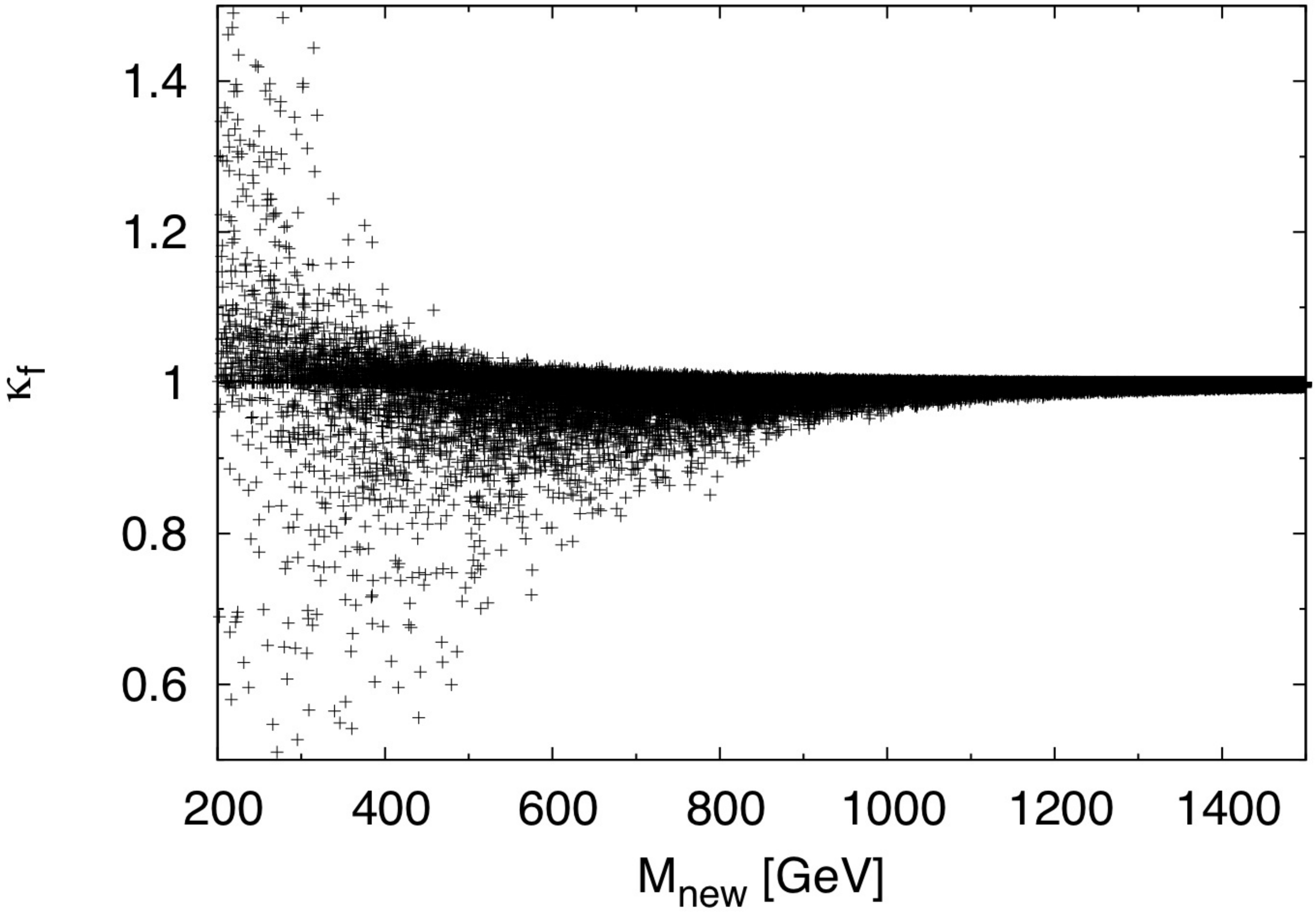
Numerical results: hVV coupling enhancement can be quite large!



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

Hartling, Kumar & HEL, 1404.2640

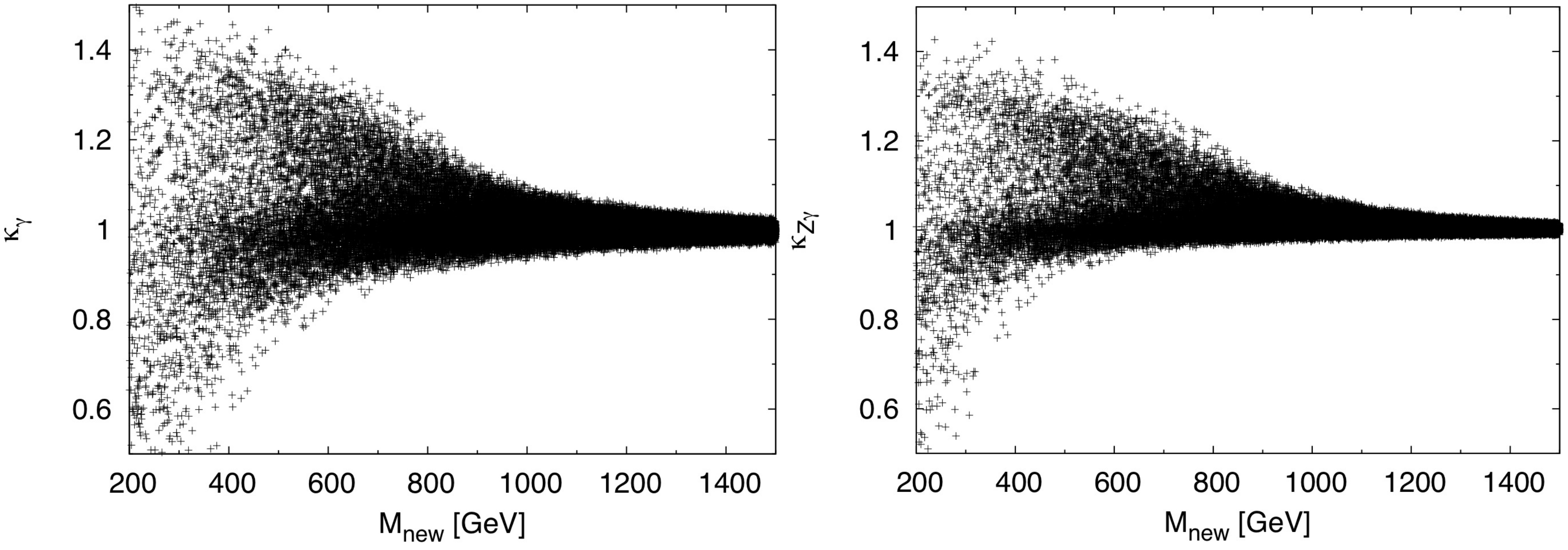
Numerical results: hff coupling typically < 1; $\kappa_f > 1$ possible at low $M_{\rm new}$



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

Hartling, Kumar & HEL, 1404.2640

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

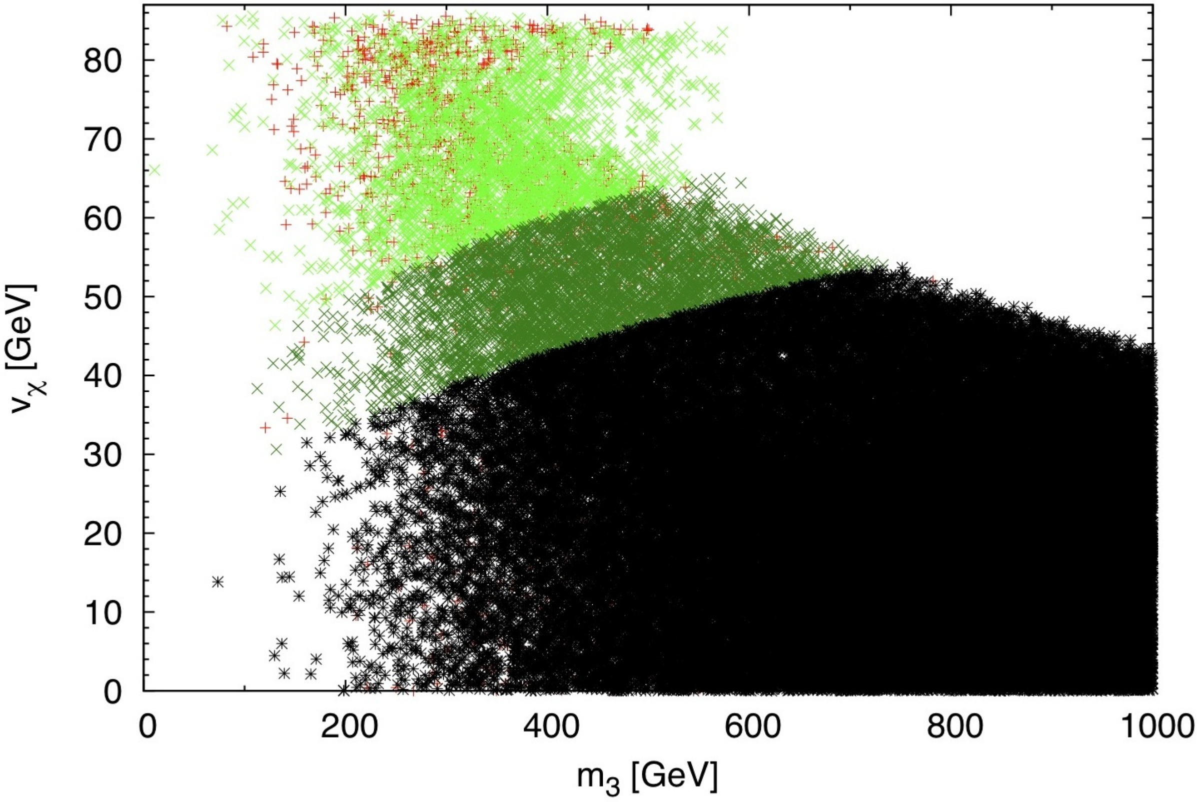


$M_{\text{new}} \equiv$ mass of *lightest* new state.

Hartling, Kumar & HEL, 1404.2640

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

Together they give an upper bound on v_χ



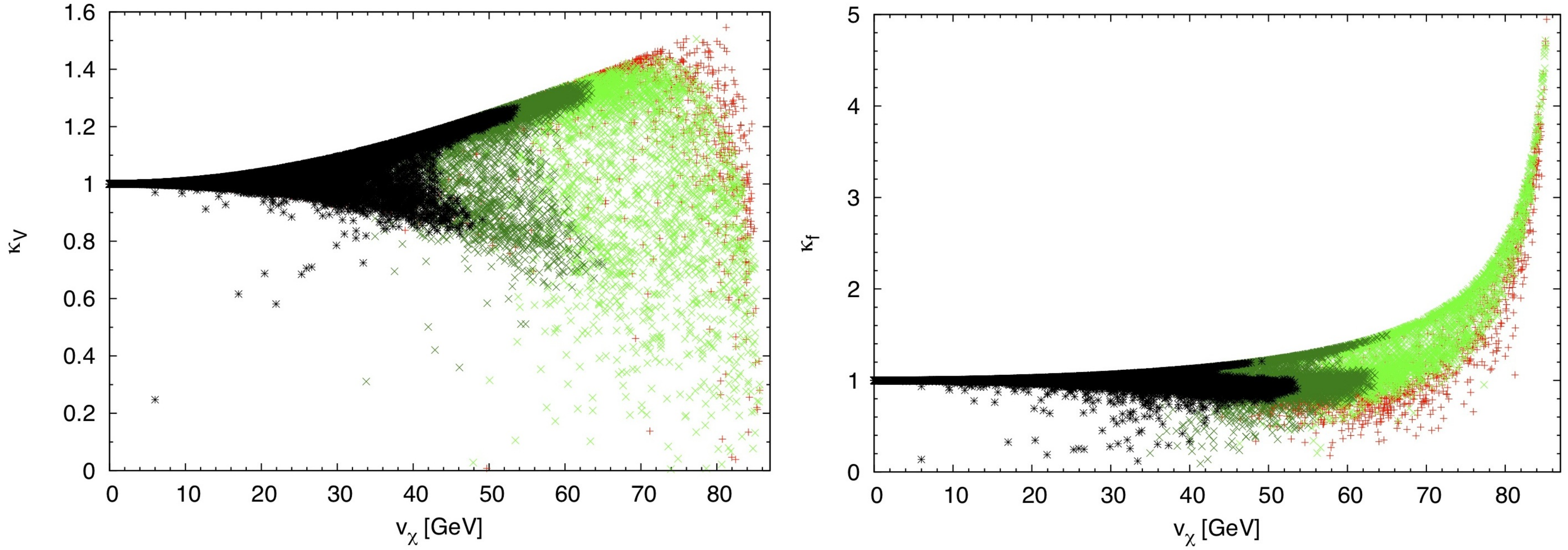
Hartling, Kumar & HEL, 1410.5538

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

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

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

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



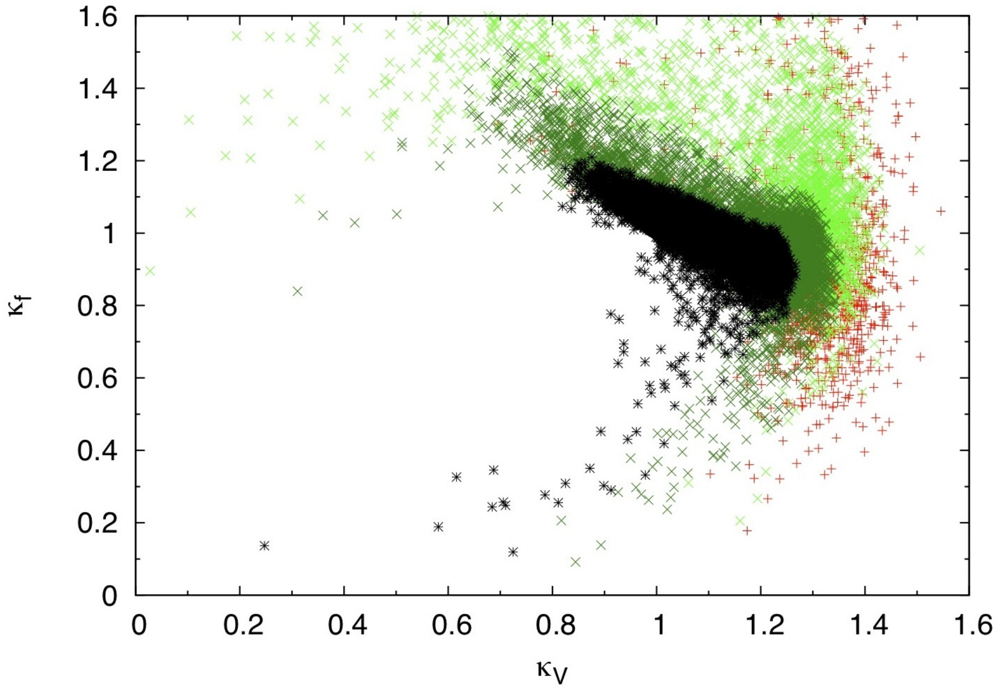
Hartling, Kumar & HEL, 1410.5538

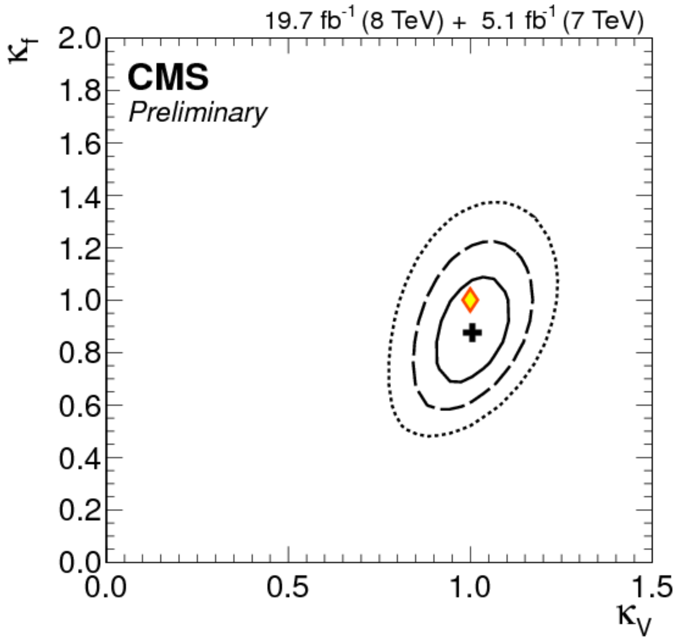
$$\kappa_V = \cos\alpha\frac{v_\phi}{v} - \frac{8}{\sqrt{3}}\sin\alpha\frac{v_\chi}{v} \qquad\qquad \kappa_f = \cos\alpha\frac{v}{v_\phi}$$

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, 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!)