Extracting Higgs boson couplings from LHC data

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TRIUMF Colloquium
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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; H.E.L. & V. Rentala, 1502.01275
+ work in progress with K. Hartling, A. Peterson, M. Zaro, C. Degrande, M.-J. Harris, B. Keeshan, T. Pilkington, S. Godfrey, R. Campbell, & A. Poulin

Outline

Introduction: the Higgs boson in the Standard Model

Higgs couplings at the Large Hadron Collider

Why Higgs couplings are interesting ... but tricky to measure

Some explicit models and their phenomenology

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:
only just starting to be tested!

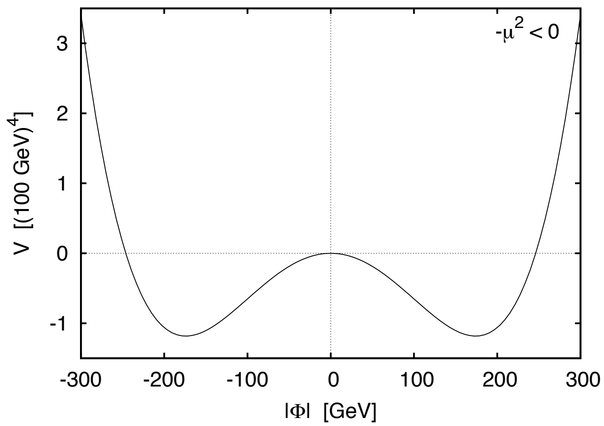
Introduction: the mathy version

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:

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

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

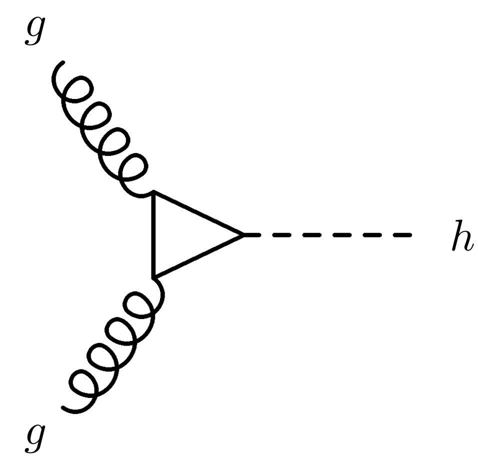
All predicted in the Standard Model, with no free parameters!

Higgs couplings at the LHC: top 4 production modes

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

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

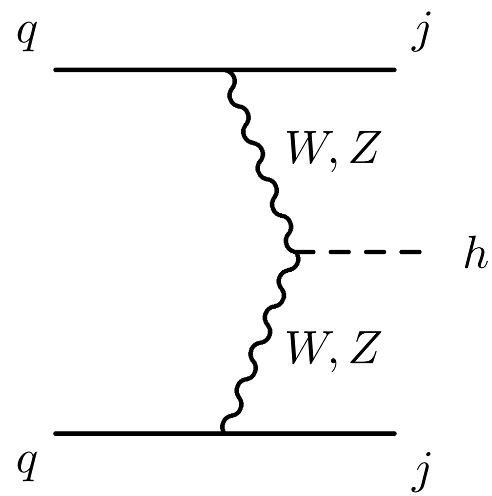
Just Higgs produced: need distinctive decays: $\gamma\gamma$, $ZZ \to 4\ell$



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

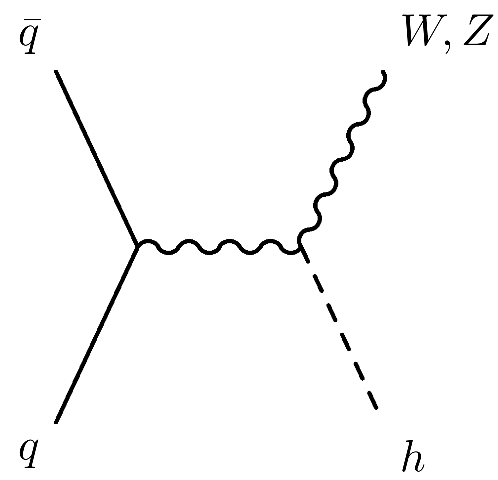


Higgs couplings at the LHC: top 4 production modes

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

Higgs couples to WW or ZZ

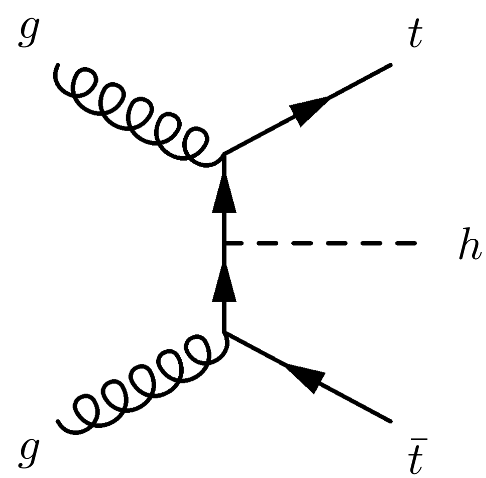
$W \to \ell\nu$ or $Z \to \ell^+\ell^-$ provide distinctive tags: essential if Higgs decay is similar to backgrounds!



4) Associated production of $h+t\bar{t}$
(rare: only 1% of total Higgs rate at 13 TeV)

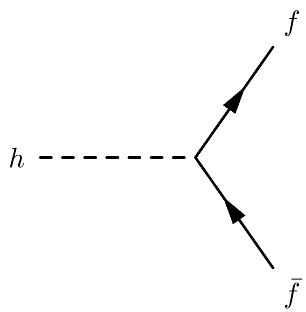
Higgs couples to $t\bar{t}$: cleaner probe of $ht\bar{t}$ coupling than gluon fusion

Two top quarks provide distinctive tags

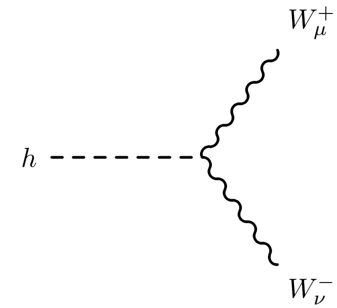


Higgs couplings at the LHC: decays

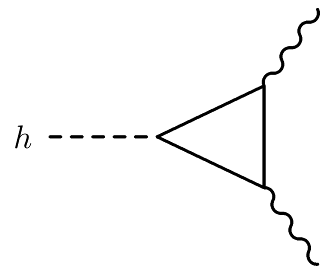
2 fermions:
$b\bar{b}$, $\tau\tau$, $c\bar{c}$



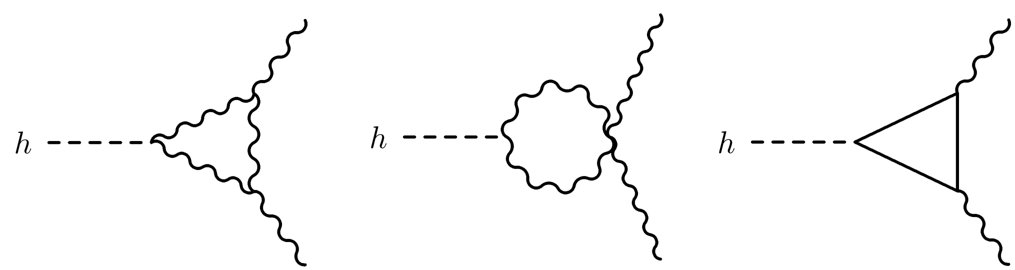
$WW \to \ell\nu\ell\nu$
or $ZZ \to 4\ell$, $2\ell 2\nu$



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



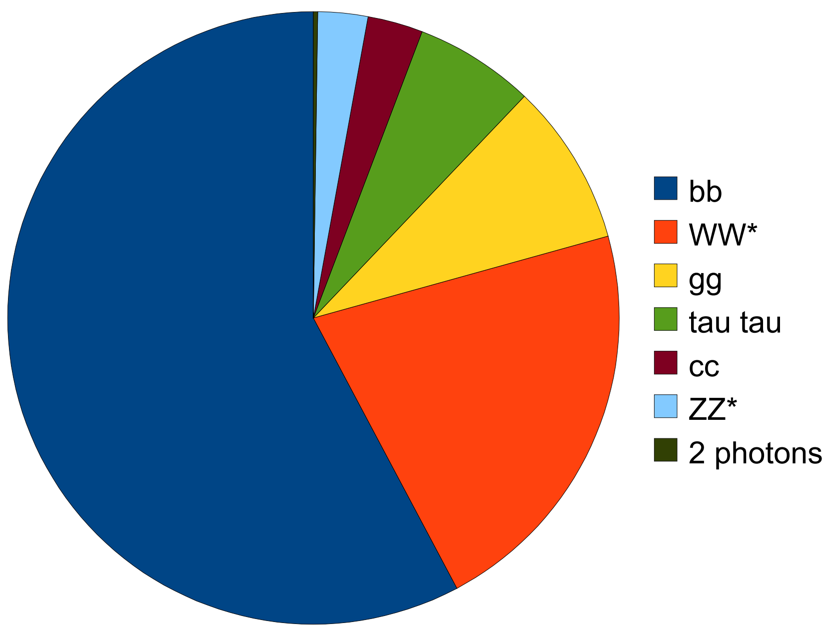
Higgs couplings at the LHC: decays

Predict the decay rate Γ_i into each final state i.

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

Fraction of Higgs decays into a particular final state is

$$\mathrm{BR}_i \equiv \frac{\Gamma_i}{\Gamma_{\rm tot}}$$ "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

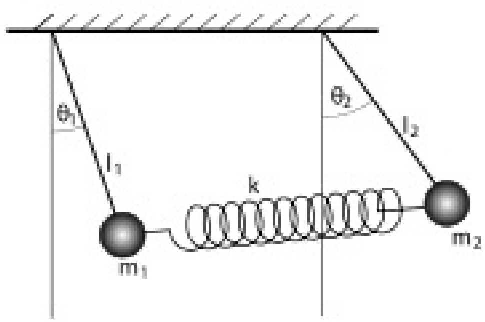
Problems from theory:

- 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

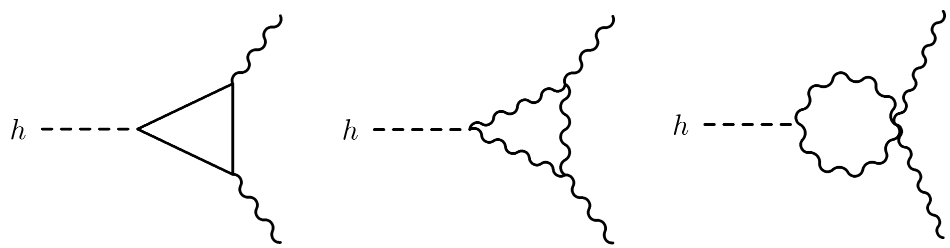
Each one has excitations, in general they are coupled together:
→ there are more Higgs states (including electrically-charged!)
→ physical particles are mixtures



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.
$\rightarrow$ Dark matter?

Can also interact with light new particles that have so far evaded direct searches.
$\rightarrow$ 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. $\rightarrow$ correlations

Extracting Higgs couplings from LHC data

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

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$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \kappa_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

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:

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

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 $\Gamma_{\rm tot} >$ 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 1412.7577)
- 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

$\Rightarrow$ Implies existence of doubly-charged Higgs boson H^{++} that decays to W^+W^+! (more on next slide)

Study explicit models:

- Georgi-Machacek model

  w/ K. Hartling & K. Kunal;

  + A. Peterson, M. Zaro & C. Degrande, + B. Keeshan & T. Pilkington (in prog)

  extension with singlet w/ S. Godfrey, R. Campbell & A. Poulin (in prog)

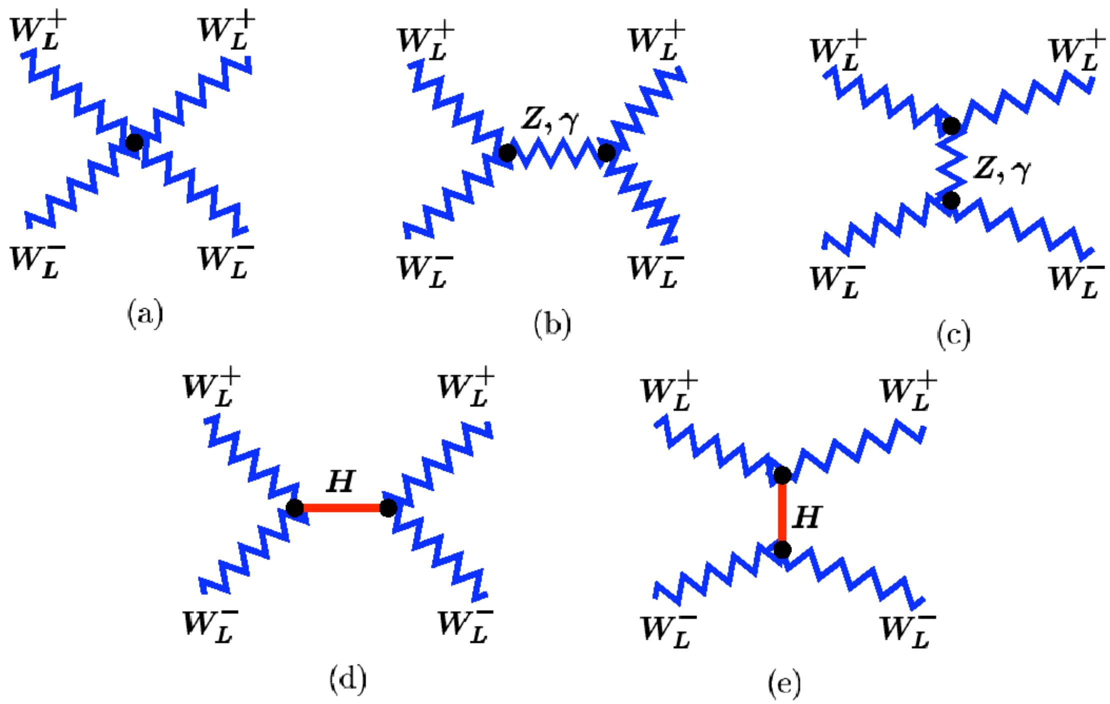
- Generalizations of Georgi-Machacek model to higher isospin

  w/ V. Rentala

- SM Higgs mixing with a scalar septet

  w/ M.-J. Harris (in prog)

Implications of $\kappa_V^h > 1$



Graphic: S. Chivukula

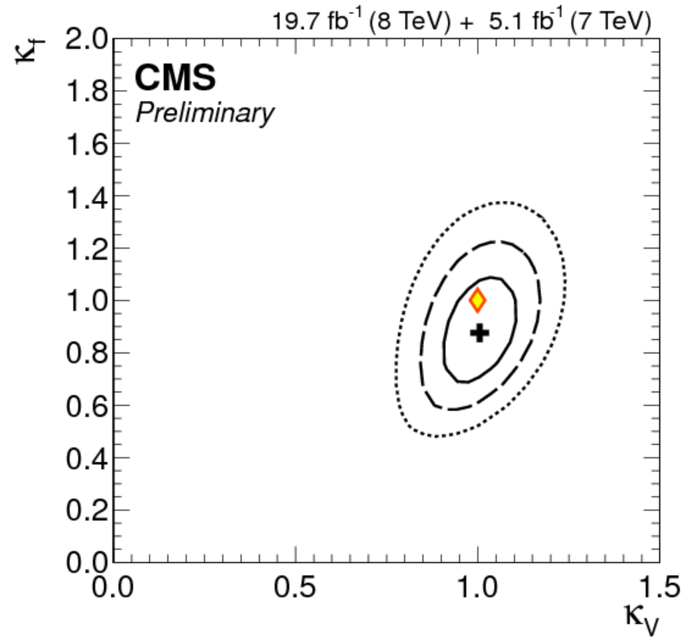
SM: Higgs exchange cancels remaining E^2/v^2 term in amplitude.

2HDM/SM+singlet: cancellation $\Rightarrow$ sum rule $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$.

$\kappa_V^h > 1$: need doubly-charged scalar exchanged in u-channel!
Implies presence of larger isospin representation(s).

Falkowski, Rychkov & Urbano, 1202.1532 (see also Higgs Hunter's Guide)

Implementation of $\kappa_V^h > 1$



hVV coupling always suppressed in models with doublets/singlets:

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

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

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

hWW coup can be enhanced in models with triplets (or larger):

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

- scalar with isospin ≥ 1
- must have a non-negligible vev
- must mix into the observed Higgs h

How large can the isospin be?

Hally, HEL, & Pilkington 1202.5073

Consider $2 \to 2$ scattering amplitudes for $V_T V_T \to \phi\phi$:
transverse $\mathrm{SU}(2)_L$ gauge bosons

- no growth with E^2; a_0 depends on weak charges & multiplicity of ϕ's

General result for complex scalar multiplet with $n = 2T + 1$:

$$a_{0,c}^{\mathrm{max,SU(2)}}(T) = \frac{g^2}{16\pi}\frac{(n^2-1)\sqrt{n}}{2\sqrt{3}}$$

- Real scalar multiplet: divide by $\sqrt{2}$ to account for smaller multiplicity
- More than one multiplet: add a_0's in quadrature

Require largest eigenvalue a_0^{max} satisfies $|\mathrm{Re}\, a_0| < 1/2$:

- Complex multiplet $\Rightarrow T \leq 7/2$ (8-plet)
- Real multiplet $\Rightarrow T \leq 4$ (9-plet)
- Constraints tighter if multiple large multiplets are present

Essentially a requirement that the weak charges not be too large.

Problem with isospin ≥ 1: the ρ parameter

$\rho \equiv$ ratio of strengths of charged and neutral weak currents

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

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

PDG 2014: $\rho = 1.00040 \pm 0.00024$

Two approaches:

1) $\rho = 1$ "by accident" for $(T, Y) = (\frac{1}{2}, 1)$ SM doublet, $(3, 4)$ septet

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

Larger solutions forbidden by perturbative unitarity of weak charges!

2) Impose global SU(2)$_L \times$SU(2)$_R$ symmetry on scalar sector
$\Longrightarrow$ breaks to custodial SU(2) upon EWSB; $\rho = 1$ at tree level

Georgi & Machacek 1985; Chanowitz & Golden 1985

Both 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 $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ 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: focus on (2): Georgi-Machacek model and its generalizations to higher isospin

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs bidoublet + two isospin-triplets in a bitriplet:

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

Physical spectrum: Custodial symmetry fixes almost everything!

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

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

- Two custodial singlets mix $\to h^0,\ H^0$
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ + Goldstones
- Custodial fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$ unitarizes $VV \to VV$

Generalized Georgi-Machacek models

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

Replace the bitriplet with a bi-n-plet $\Longrightarrow$ "GGMn"

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

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

Biquartet: $4 \times 4 \to 7 + 5 + 3 + 1$

Bipentet: $5 \times 5 \to 9 + 7 + 5 + 3 + 1$

Bisextet: $6 \times 6 \to 11 + 9 + 7 + 5 + 3 + 1$

Larger bi-n-plets forbidden by perturbative unitarity of weak charges!

- Two custodial singlets mix $\to h^0$, H^0
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ + Goldstones
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ unitarizes $VV \to VV$
- Additional states

Phenomenology I: construct in parallel to original GM model

Vevs: $\langle \Phi \rangle = (v_\phi/\sqrt{2}) I_{2\times 2}$, $\langle X_n \rangle = v_n I_{n\times n} \Longrightarrow$ define $c_H = v_\phi / v$

Two custodial-singlet states are mixtures of $\phi^{0,r}$ and custodial singlet from X:

$$h = c_\alpha \phi^{0,r} - s_\alpha H_1^{\prime 0}, \qquad H = s_\alpha \phi^{0,r} + c_\alpha H_1^{\prime 0}$$

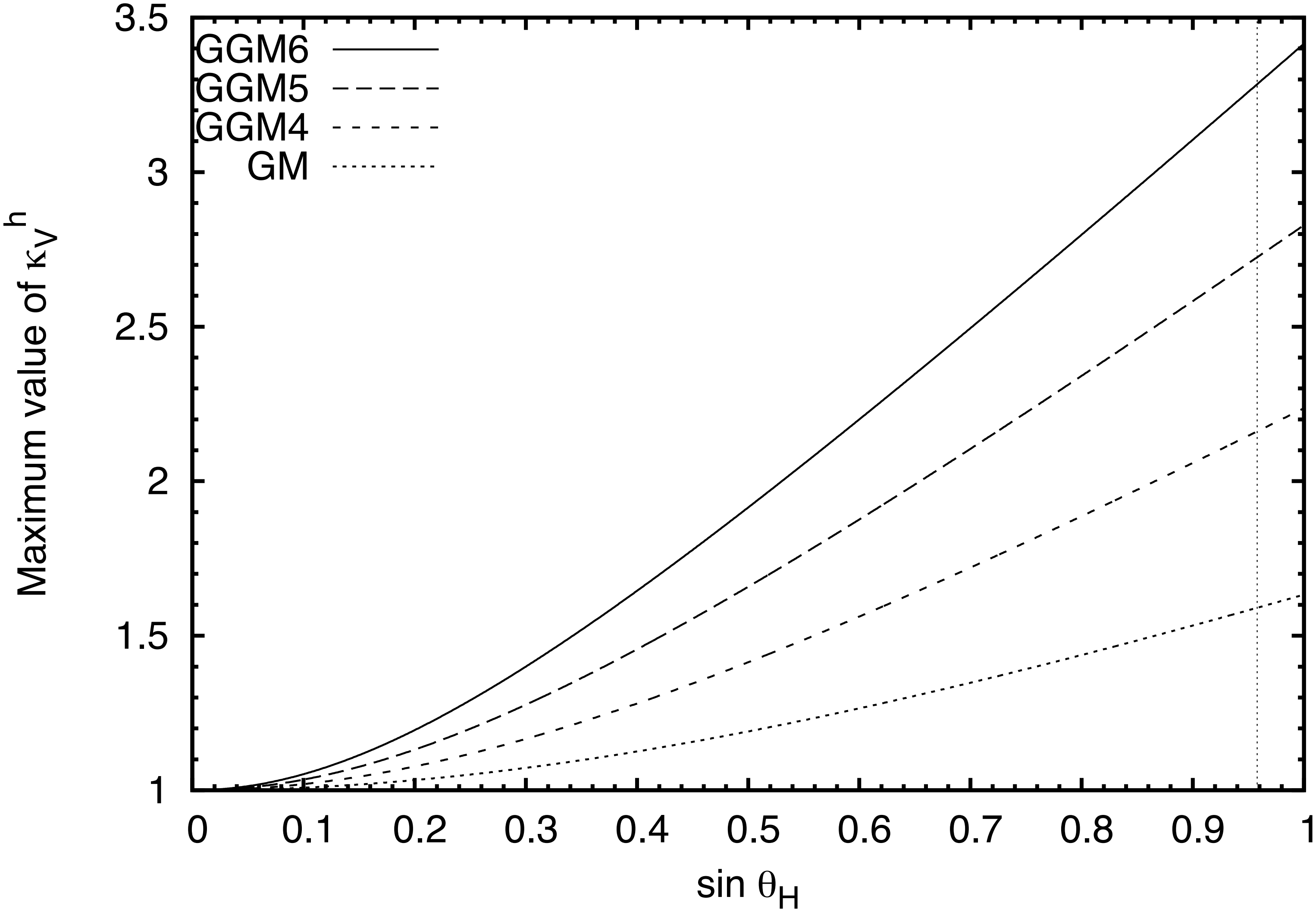
Couplings:

$$\kappa_V^h = c_\alpha c_H - \sqrt{A} s_\alpha s_H \qquad \kappa_f^h = c_\alpha / c_H$$
$$\kappa_V^H = s_\alpha c_H + \sqrt{A} c_\alpha s_H \qquad \kappa_f^H = s_\alpha / c_H$$

Note that $\kappa_V^h \leq \left[1 + (A-1) s_H^2\right]^{1/2}$, saturated when $\kappa_V^H = 0$.
$\sqrt{A}$ factor comes from the generators: $A = 4T(T+1)/3$

$A_{\text{GM}} = 8/3$, $A_{\text{GGM4}} = 15/3$, $A_{\text{GGM5}} = 24/3$, $A_{\text{GGM6}} = 35/3$

Large enhancements of κ_V^h possible for large s_H (up to about 3.3)



Vertical line: y_t perturbativity $\rightarrow \tan\theta_H < 10/3$ HEL & Rentala, 1502.01275

Phenomenology II: entirely the same as original GM model

Two custodial-triplets are mixtures of $(\phi^+, \phi^{0,i})$ and custodial triplet from X:

$$G^{0,\pm} = c_H \Phi_3^{0,\pm} + s_H H_3'^{0,\pm} \qquad H_3^{0,\pm} = -s_H \Phi_3^{0,\pm} + c_H H_3'^{0,\pm}$$

Couplings to fermions are completely analogous to Type-I 2HDM:

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

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

$$H_3^+ \bar{\nu} \ell : \quad i\frac{\sqrt{2}}{v} \tan\theta_H m_\ell P_R.$$

$Z H_3^+ H_3^-$ also same as in 2HDM: constraints from $b \to s\gamma$, $B_s \to \mu\mu$, R_b, etc translate directly.

Vector-phobic: no $H_3 VV$ couplings

To do: better understand mapping onto 2HDM in order to translate LHC constraints.

Phenomenology III: again in parallel to original GM model

Custodial-fiveplet comes only from X: no couplings to fermions.

$H_5 VV$ couplings are nonzero: very different from 2HDM!

$$H_5^0 W_\mu^+ W_\nu^- : \qquad -i\frac{2M_W^2}{v}\frac{g_5}{\sqrt{6}} g_{\mu\nu},$$

$$H_5^0 Z_\mu Z_\nu : \qquad i\frac{2M_Z^2}{v}\sqrt{\frac{2}{3}} g_5 g_{\mu\nu},$$

$$H_5^+ W_\mu^- Z_\nu : \qquad -i\frac{2M_W M_Z}{v}\frac{g_5}{\sqrt{2}} g_{\mu\nu},$$

$$H_5^{++} W_\mu^- W_\nu^- : \qquad i\frac{2M_W^2}{v} g_5 g_{\mu\nu},$$

g_5 fixed by $VV \to VV$ unitarization sum rule:

$$(\kappa_V^h)^2 + (\kappa_V^H)^2 - \frac{5}{6}(g_5)^2 = 1$$

Falkowski, Rychkov & Urbano, 1202.1532 (see also Higgs Hunter's Guide)

(relies on custodial symmetry in scalar sector; same in *all* GGM models)

Constraints I & II:

Focus on constraining $(H_5^{\pm\pm}, H_5^{\pm}, H_5^0)$: sum rule guarantees

$$(\kappa_V^h)^2 \leq 1 + \frac{5}{6}(g_5)^2$$

(1) Direct-search constraint on VBF $H_5^{++} \to W^+W^+$ from re-casting ATLAS W^+W^+jj cross-section measurement.

Chiang, Kanemura & Yagyu, 1407.5053

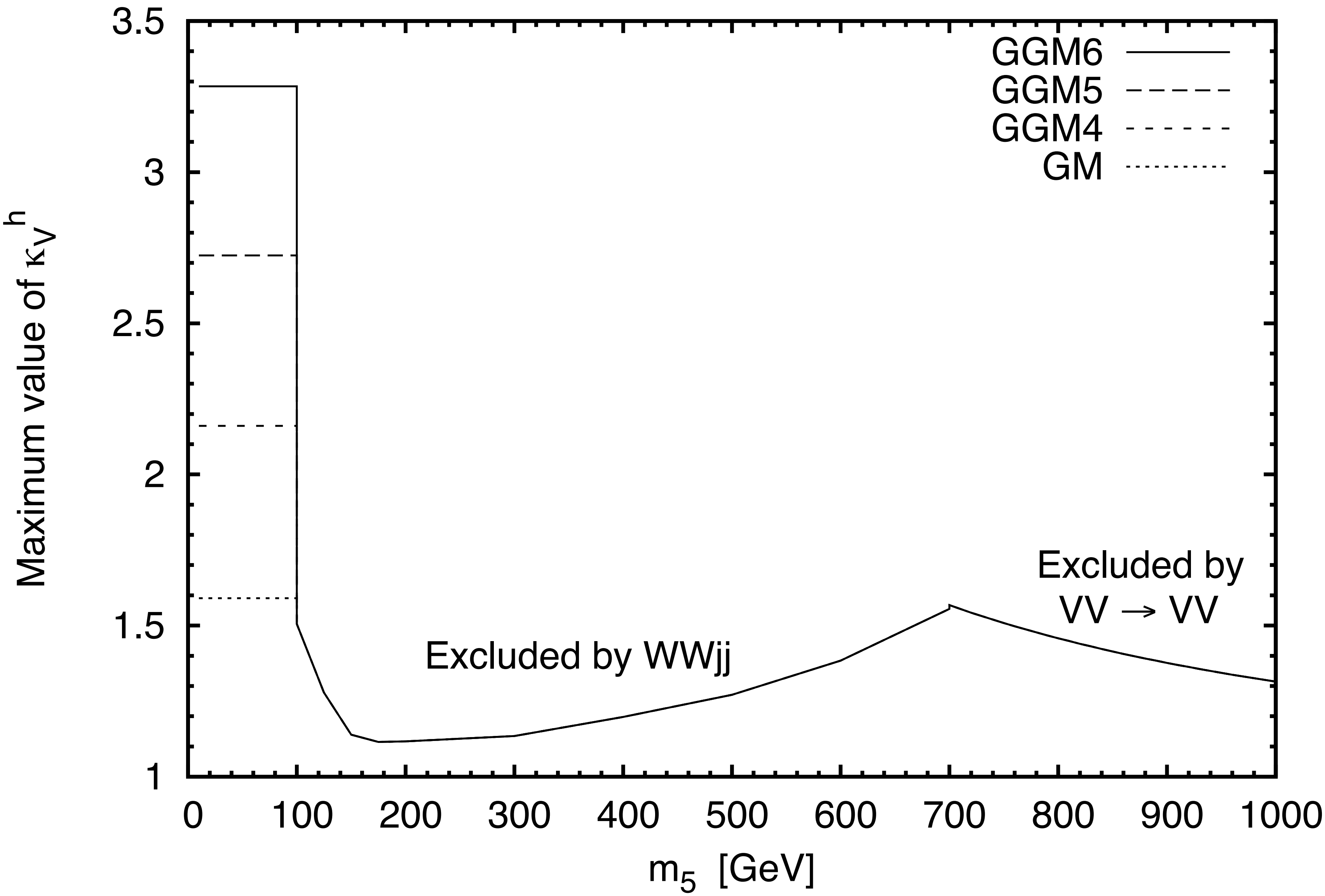
(2) Perturbative unitarity bound from finite part of $VV \leftrightarrow VV$.

- SM: $m^2_{h\text{SM}} < 16\pi v^2/5$ Lee, Quigg & Thacker 1977
- Custodial-symmetric models:

$$\left[(\kappa_V^h)^2 m_h^2 + (\kappa_V^H)^2 m_H^2 + \frac{2}{3} g_5^2 m_5^2\right] < \frac{16\pi v^2}{5}$$

- Combine with sum rule: HEL & Rentala, 1502.01275

$$(\kappa_V^h)^2 < 1 + \frac{(16\pi v^2 - 5m_h^2)}{(4m_5^2 + 5m_h^2)}$$



$\Rightarrow\ \kappa_V^h \lesssim 1.57$ for $m_5 > 100$ GeV

HEL & Rentala, 1502.01275

Constraints III:

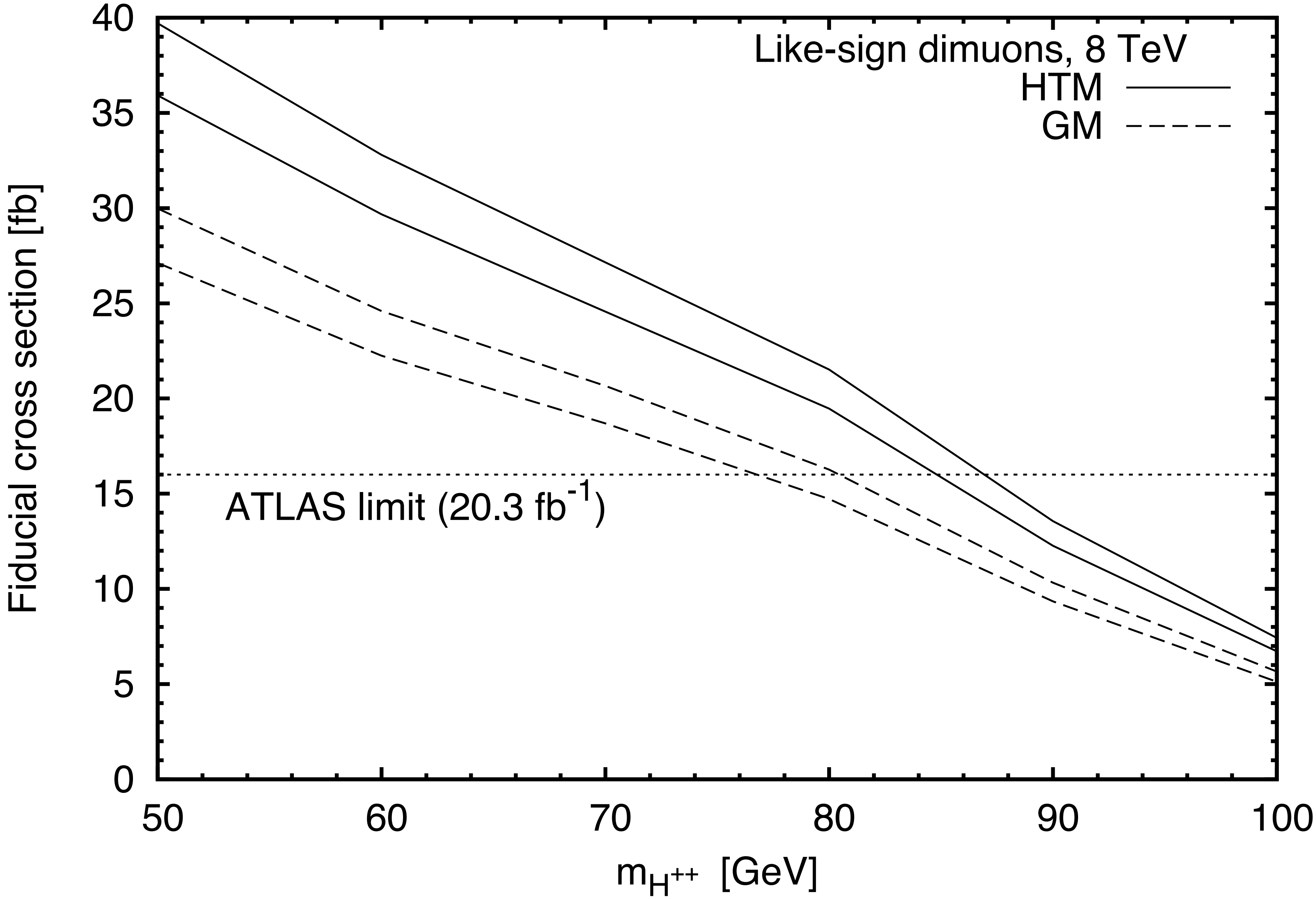
(3) Direct-search constraint on $H^{\pm\pm}H^{\mp\mp} + H^{\pm\pm}H^{\mp}$ in Higgs Triplet Model from recasting ATLAS like-sign dimuons meas.

Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

Adapt to generalized GM models using

$$\begin{aligned}
\sigma^{\rm NLO}_{\rm tot}(pp \to H_5^{++}H_5^{--})_{\rm GM} &= \sigma^{\rm NLO}_{\rm tot}(pp \to H^{++}H^{--})_{\rm HTM}, \\
\sigma^{\rm NLO}_{\rm tot}(pp \to H_5^{\pm\pm}H_5^{\mp})_{\rm GM} &= \frac{1}{2}\sigma^{\rm NLO}_{\rm tot}(pp \to H^{\pm\pm}H^{\mp})_{\rm HTM}.
\end{aligned}$$

Take advantage of mass degeneracy of all H_5 states.

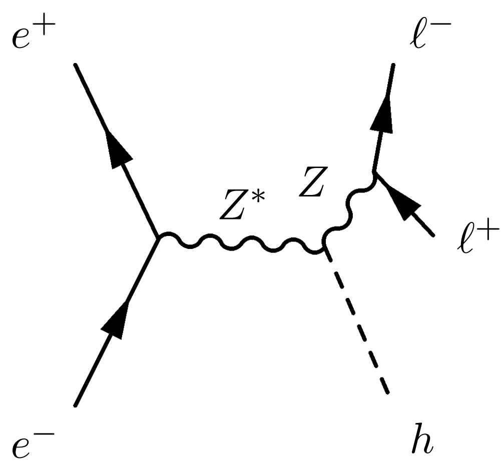


$\Rightarrow$ $m_5 \gtrsim 76$ GeV, no g_5 dependence HEL & Rentala, 1502.01275

Bands: $\pm 5\%$ theory uncertainty on cross section

Constraints IV:

(4) OPAL search for $Z+S^0$ production independent of S^0 decay modes: used recoil-mass method! Data from HiggsBounds



Recoil-mass method:

$p_h^\mu = p_{e^+}^\mu + p_{e^-}^\mu - p_{\ell^+}^\mu - p_{\ell^-}^\mu$ (4-momentum conservation)

Measure all quantities on right-hand side

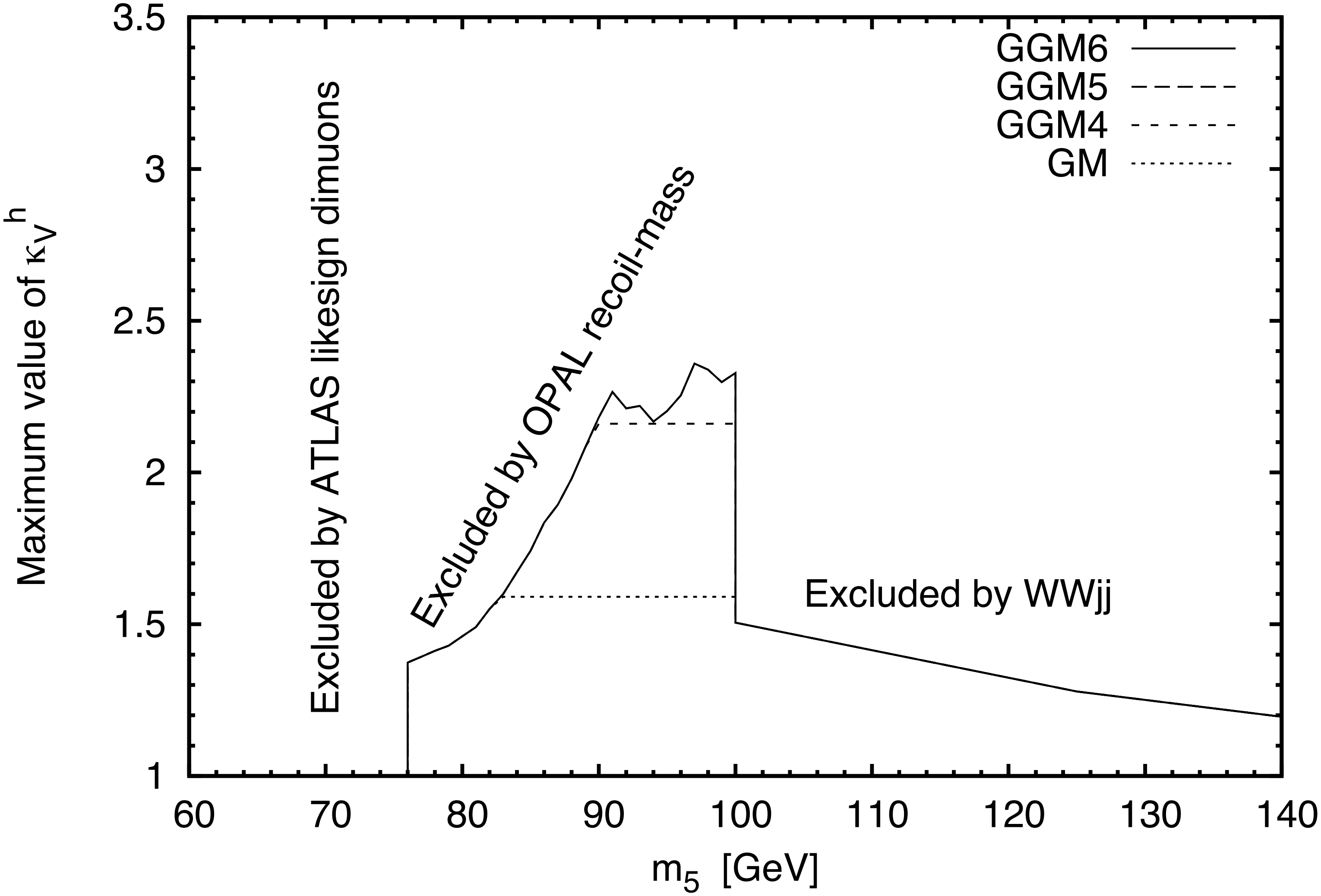
$p_h^2 = (p_{e^+} + p_{e^-} - p_{\ell^+} - p_{\ell^-})^2 = m_h^2$ for on-shell Higgs

Count events in the Higgs mass peak,

subtract background using sidebands

Get upper bound on $H_5^0 ZZ$ coupling $\propto g_5$ as function of m_5.

Take advantage of mass degeneracy of all H_5 states and custodial-symmetry relationship among couplings.



$\Rightarrow \;\; \kappa_V^h \lesssim 2.36$ for all m_5!

HEL & Rentala, 1502.01275

compare $\kappa_V^h \lesssim 3.3$ in unconstrained GGM6

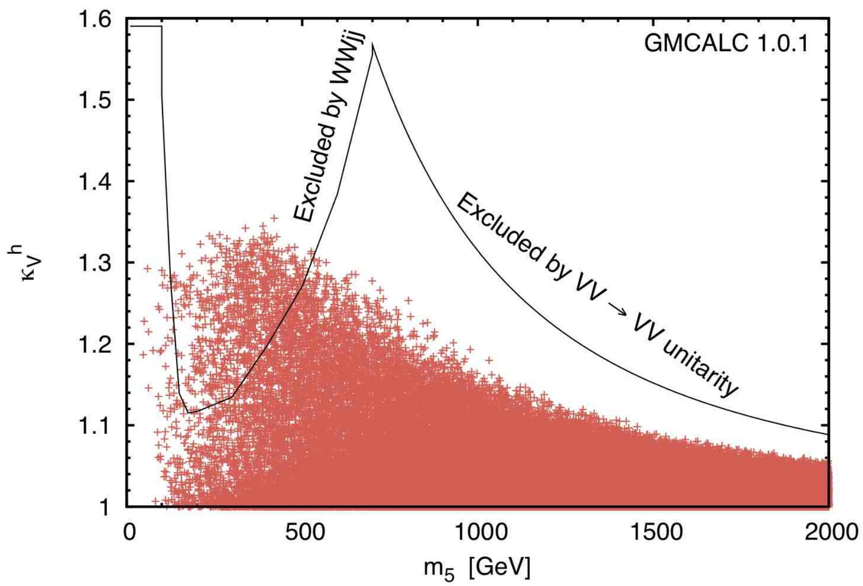
N.B.: Sum rules are different in septet model: no H_5^0 state, no custodial sym. $\Longrightarrow$ in prog.

Going further: full model implementations

Custodial symmetry + unitarity sum rules are extremely powerful!

But they are not the end of the story:

E.g., high-mass $VV \to VV$ unitarity constraint is not saturated by full theory-constrained Georgi-Machacek model!



- perturb. unitarity of quartic couplings
- scalar potential bounded from below
- no deeper custodial-violating minima
- $b \to s\gamma$ constraint

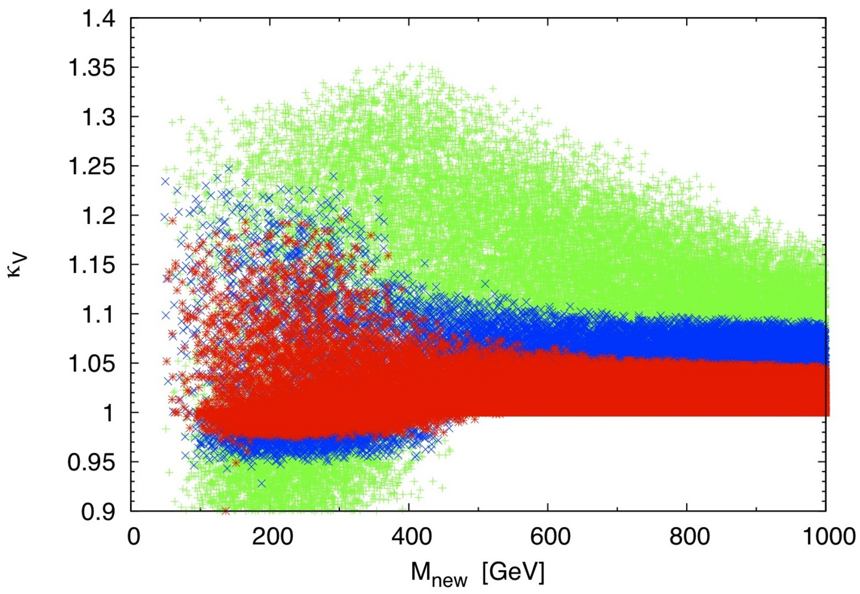
Explicit scalar potentials for Generalized GM models now available: analogous full study feasible (but tedious)

Going further: full model implementations

Custodial symmetry + unitarity sum rules are extremely powerful!

But they are not the end of the story:

E.g., *simultaneous* enhancement of κ_V and κ_f in full theory-constrained Georgi-Machacek model only when $M_{\rm new} \lesssim 400$ GeV!



All points are allowed by theoretical & indirect experimental constraints.

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

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

Hartling, Kumar & HEL, 1410.5538

Explicit scalar potentials for Generalized GM models now available: analogous full study feasible (but tedious)

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

$\rightarrow$ 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.

BACKUP SLIDES

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)$_L$×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

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

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

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

9 parameters, 2 fixed by M_W and m_h → 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)

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