Higgs physics beyond the Standard Model

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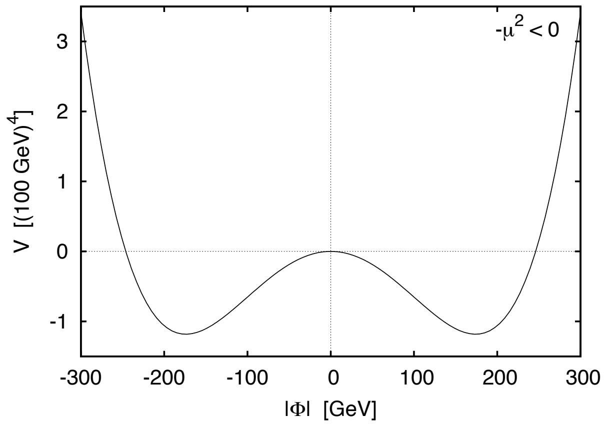
The Standard Model:
electroweak symmetry breaking from a scalar SU(2)$_L$ doublet

A one-line theory:

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

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

$-\mu^2$ term: vacuum condensate! EW symmetry spontaneously broken; Goldstone bosons gauged away, 1 physical particle h.



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

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

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

The Standard Model:
electroweak symmetry breaking from a scalar SU(2)$_L$ doublet

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

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

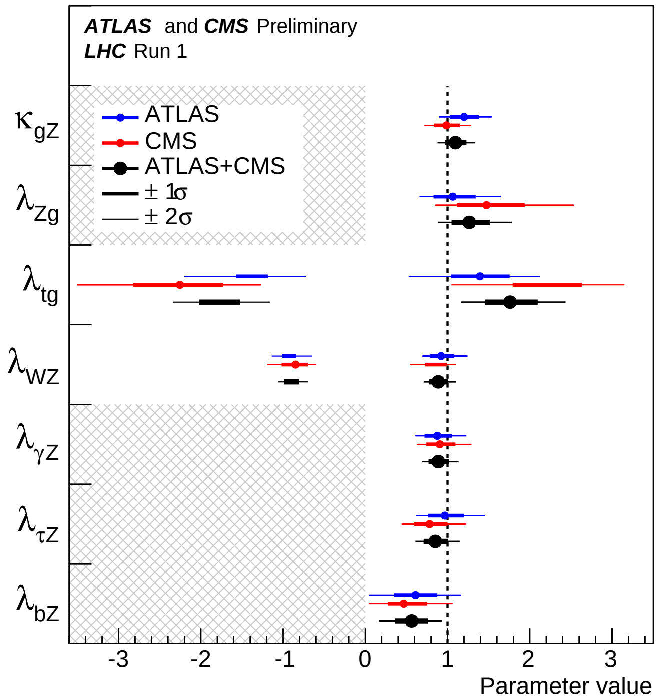
$$\mathcal{L} = |\mathcal{D}_\mu \Phi|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+W^- + (g_Z^2/8)(h+v)^2 ZZ$$
$$M_W^2 = g^2v^2/4 \qquad hWW:\; i(g^2v/2)g^{\mu\nu}$$
$$M_Z^2 = g_Z^2v^2/4 \qquad hZZ:\; i(g_Z^2v/2)g^{\mu\nu}$$

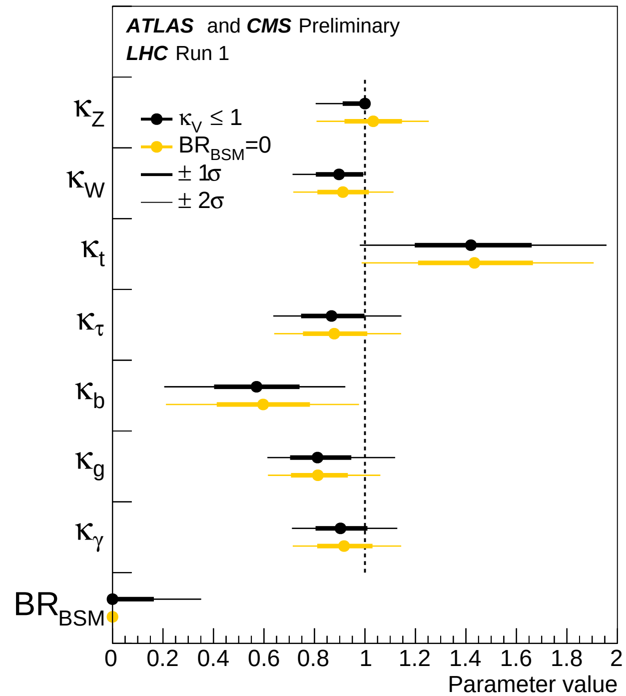
Fermions:

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

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

LHC measurements of 125 GeV Higgs boson properties are fully consistent with SM picture: ATLAS-CONF-2015-044





But there is still plenty of room for extensions of the Higgs sector.

This talk:

- What else could be condensed in the vacuum?
- How do we search for its excitations?

This talk: Outline

What else could be condensed in the vacuum?

(1) Additional source of fermion masses?

→ two-Higgs-doublet models

(2) Additional (non-doublet) source of electroweak breaking?

→ models with higher-isospin scalar multiplets

For each: How do we search for its excitations?

- Properties & signatures of extra Higgs bosons
- Patterns of couplings and spectra
- A few under-exploited search channels

Conclusions

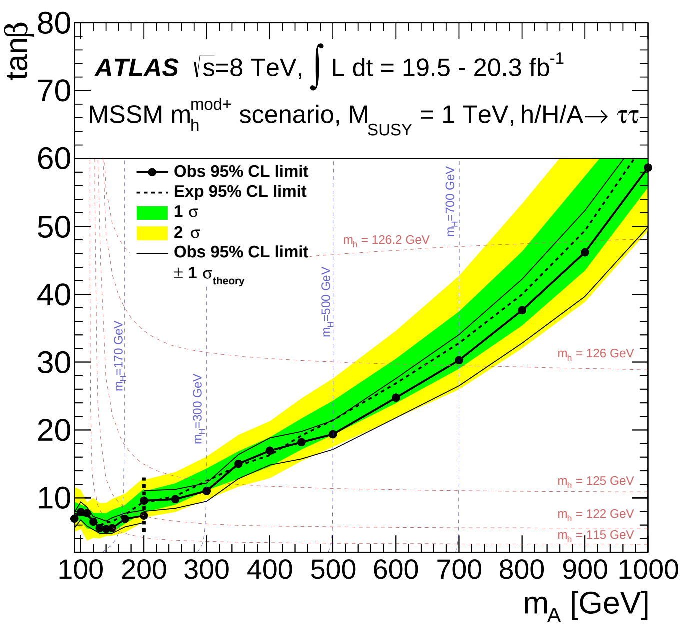
Additional sources of fermion masses?

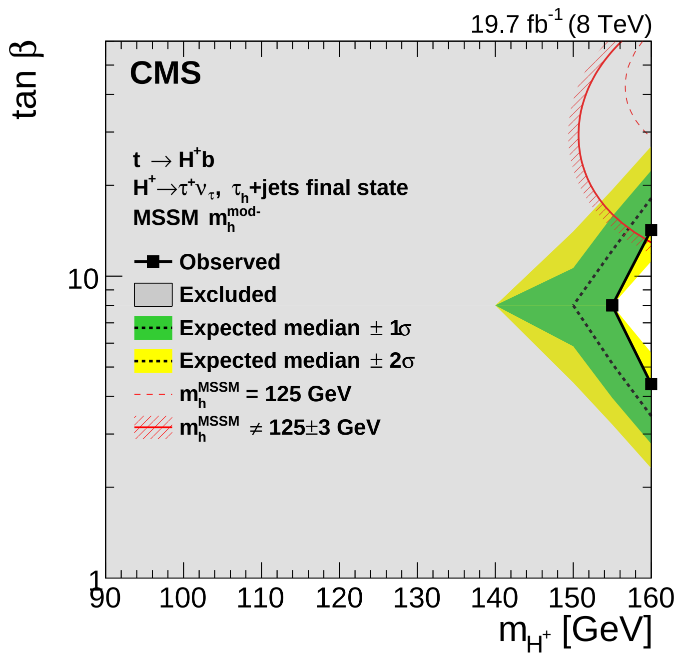
$\rightarrow$ Two-Higgs-Doublet Model

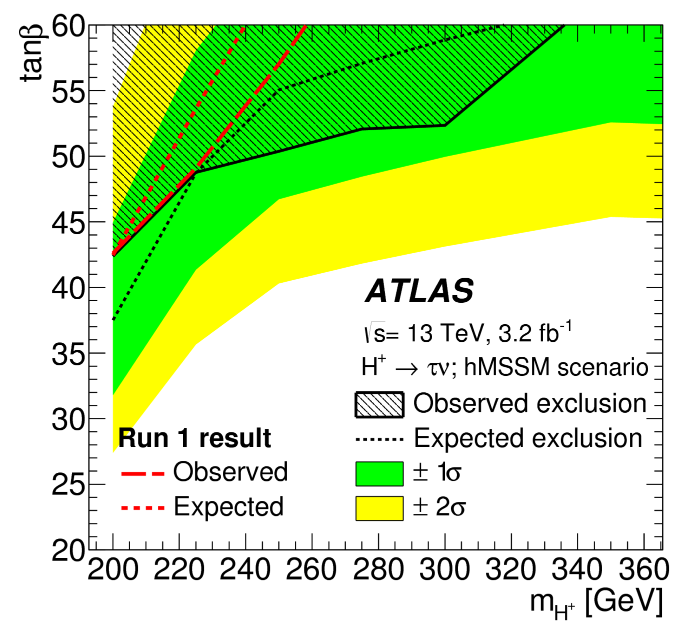
Two-Higgs-Doublet Model

"Type-II" model is the Higgs sector of the MSSM (at tree level)
Five Higgs states: h, H, A, $H^{\pm}$

Most-well-known searches:
$b\bar{b} \to H/A \to \tau\tau$; $t \to bH^{+}$ or $pp \to \bar{t}H^{+}$, $H^{+} \to \tau\nu$







Also $gg \to H \to WW, ZZ$; $pp \to H/A \to Z + A/H$

Two-Higgs-Doublet Model

Two doublets: Φ_1 and Φ_2, vevs $v_1^2 + v_2^2 = v_{\rm SM}^2$, $v_2/v_1 \equiv \tan\beta$
- Up-type quark masses from Φ_2: coupling strength m_u/v_2
- Down-type quark and lepton masses from Φ_2 (Type I) or Φ_1 (Type II): coupling strength $m_{d,\ell}/v_2$ (Type I) or $m_{d,\ell}/v_1$ (Type II)

Five Higgs states (counting H^+ and H^- as two):

$$h = \cos\alpha\,\phi_2^{0,r} - \sin\alpha\,\phi_1^{0,r} \qquad H = \sin\alpha\,\phi_2^{0,r} + \cos\alpha\,\phi_1^{0,r}$$
$$A = \cos\beta\,\phi_2^{0,i} - \sin\beta\,\phi_1^{0,i} \qquad H^\pm = \cos\beta\,\phi_2^\pm - \sin\beta\,\phi_1^\pm$$

First do a change of basis to the Higgs basis:

$$\Phi_h = \sin\beta\,\Phi_2 + \cos\beta\,\Phi_1 \qquad \Phi_0 = \cos\beta\,\Phi_2 - \sin\beta\,\Phi_1$$

Defined by vacuum expectation values:
Φ_h vev $= v_{\rm SM}$, Φ_0 vev $= 0$

Two-Higgs-Doublet Model: Higgs basis

Φ_h vev $= v_{\rm SM}$, Φ_0 vev $= 0$

Five Higgs states (counting H^+ and H^- as two):

$$h = \sin(\beta-\alpha)\,\phi_h^{0,r} - \cos(\beta-\alpha)\,\phi_0^{0,r}$$
$$H = \cos(\beta-\alpha)\,\phi_h^{0,r} + \sin(\beta-\alpha)\,\phi_0^{0,r}$$
$$A = \phi_0^{0,i} \qquad\qquad H^\pm = \phi_0^\pm$$

Couplings to vector boson pairs:

$\phi_h^{0,r}VV$ couplings same as SM, while $\phi_0^{0,r}VV = 0$:

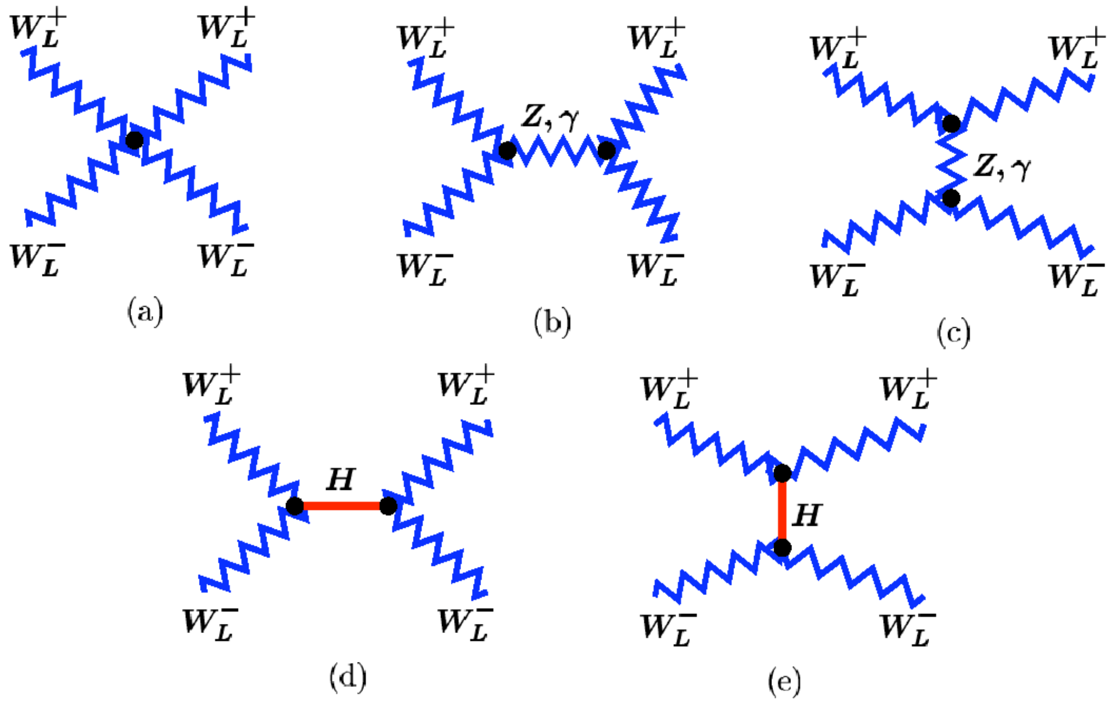
- Couplings of h to VV universally suppressed by $\sin(\beta-\alpha) \equiv \kappa_V^h$
- Couplings of H to VV are complementary: $\cos(\beta-\alpha) \equiv \kappa_V^H$

Sum rule: $(\kappa_V^h)^2 + (\kappa_V^H)^2 = \sin^2(\beta-\alpha) + \cos^2(\beta-\alpha) = 1$

Q: how big can $\kappa_V^H = \cos(\beta-\alpha)$ be? Controls $H \to WW, ZZ$ and VBF $\to H$

From h coupling measurements: $\kappa_V^h \sim 1 \pm 0.2 \quad \Rightarrow \quad |\kappa_V^H| \lesssim 0.45$

Perturbative unitarity of $WW \to WW$ scattering: E^0 term



Graphic: S. Chivukula

- SM: $m_h^2 < 16\pi v^2/5 \simeq (780\ \text{GeV})^2$ Lee, Quigg & Thacker 1977

- 2HDM: $(\kappa_V^h)^2 m_h^2 + (\kappa_V^H)^2 m_H^2 < 16\pi v^2/5$

- combine with sum rule $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$:

$$\cos^2(\beta - \alpha) \equiv (\kappa_V^H)^2 < \frac{16\pi v^2 - 5m_h^2}{5(m_H^2 - m_h^2)} \simeq \frac{16\pi v^2}{5m_H^2} \simeq \left(\frac{780\ \text{GeV}}{m_H}\right)^2$$

Two-Higgs-Doublet Model: Higgs basis Haber et al, 1507.00933

$$\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3[H_1^\dagger H_2 + \text{h.c.}] + \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 + \tfrac{1}{2}Z_2(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2)$$
$$+Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{\tfrac{1}{2}Z_5(H_1^\dagger H_2)^2 + \left[Z_6(H_1^\dagger H_1) + Z_7(H_2^\dagger H_2)\right]H_1^\dagger H_2 + \text{h.c.}\right\}, \quad (2)$$

$Y_1, Y_2, Y_3 \sim (\text{mass})^2$, $Z_1, \ldots Z_7$ dimensionless $H_1 \equiv \Phi_h$, $H_2 \equiv \Phi_0$

Minimization of potential yields $Y_1 = -Z_1 v^2/2$, $Y_3 = -Z_6 v^2/2$
Only one dimensionful parameter $Y_2 \equiv M^2$, can be large $\gg v^2$

Masses:

$$m_{H^\pm}^2 = Y_2 + Z_3 v^2/2 \qquad m_A^2 = m_{H^\pm}^2 + (Z_4 - Z_5)v^2/2$$

$$M_{h,H}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$$

$m_h^2 \simeq Z_1 v^2$ $\qquad$ $m_H^2 \simeq M^2$ $\qquad$ $\cos(\beta - \alpha) \simeq Z_6 v^2/M^2 \sim v^2/M^2$

$\Rightarrow$ Fast decoupling! Bad news for VBF $\to H$ and $H \to WW/ZZ$ at high m_H

$$\cos^2(\beta - \alpha) \equiv (\kappa_V^H)^2 \simeq Z_6^2 \frac{v^4}{m_H^4} = Z_6^2 \left(\frac{246 \text{ GeV}}{m_H}\right)^4$$

Two-Higgs-Doublet Model: fermion couplings

Two doublets: Φ_1 and Φ_2, vevs $v_1^2 + v_2^2 = v_{\rm SM}^2$, $v_2/v_1 \equiv \tan\beta$
- Up-type quark masses from Φ_2: coupling strength m_u/v_2
- Down-type quark and lepton masses from Φ_2 (Type I) or Φ_1 (Type II): coupling strength $m_{d,\ell}/v_2$ (Type I) or $m_{d,\ell}/v_1$ (Type II)

First do a change of basis to the Higgs basis: Φ_h vev $= v_{\rm SM}$, Φ_0 vev $= 0$

$$\Phi_h = \sin\beta\,\Phi_2 + \cos\beta\,\Phi_1 \qquad \Phi_0 = \cos\beta\,\Phi_2 - \sin\beta\,\Phi_1$$

Physical Higgs states: $\cos(\beta-\alpha) \simeq Z_6 v^2/M^2 \sim v^2/M^2$

$$h = \sin(\beta-\alpha)\,\phi_h^{0,r} - \cos(\beta-\alpha)\,\phi_0^{0,r}$$
$$H = \cos(\beta-\alpha)\,\phi_h^{0,r} + \sin(\beta-\alpha)\,\phi_0^{0,r}$$
$$A = \phi_0^{0,i} \qquad H^\pm = \phi_0^\pm$$

So $A = \phi_0^{0,i}$, $H^\pm = \phi_0^\pm$, and for decoupling or alignment $H \simeq \phi_0^{0,r}$: the BSM Higgs bosons all live in the Φ_0 doublet.

Two-Higgs-Doublet Model: fermion couplings

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First do a change of basis to the Higgs basis: Φ_h vev $= v_{SM}$, Φ_0 vev $= 0$

$$\Phi_h = \sin\beta\,\Phi_2 + \cos\beta\,\Phi_1 \qquad \Phi_0 = \cos\beta\,\Phi_2 - \sin\beta\,\Phi_1$$

Coupling strengths of Φ_0 to fermions:

Type I: $\cos\beta \times m_f/v_2 = \cot\beta \times m_f/v_{SM}$ (all quarks & leptons)

Type II: $\cos\beta \times m_u/v_2 = \cot\beta \times m_u/v_{SM}$ (up-type)
Type II: $\sin\beta \times m_{d,\ell}/v_1 = \tan\beta \times m_{d,\ell}/v_{SM}$ (down-type & leptons)

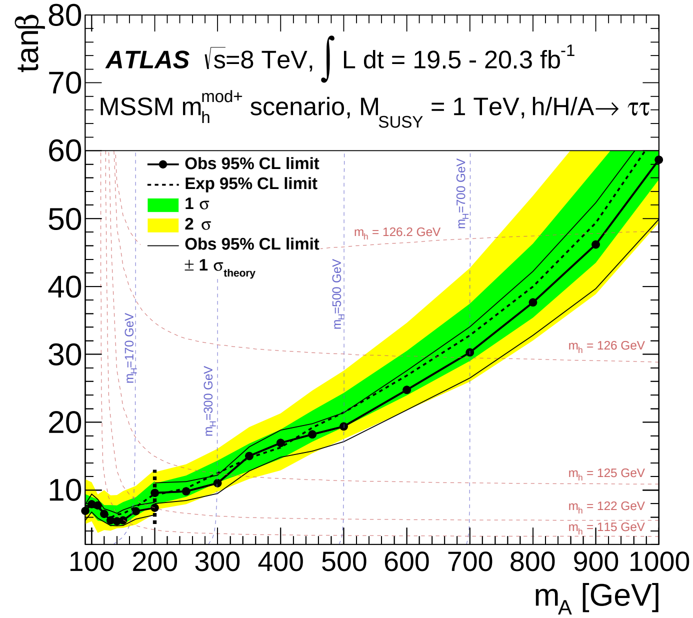
These are NOT suppressed when the BSM Higgses are heavy!
Good news for heavy Higgs production via gluon fusion, $b\bar{b}$-fusion

Two-Higgs-Doublet Model: under-exploited search channels I: $gg \to H/A \to t\bar{t}$ at low $\tan\beta$

Type I: $\cot\beta \times m_f/v_{\mathrm{SM}}$ (all quarks & leptons)

Type II: $\cot\beta \times m_u/v_{\mathrm{SM}}$ (up-type)

Type II: $\tan\beta \times m_{d,\ell}/v_{\mathrm{SM}}$ (down-type & leptons)



- Nontrivial interference with continuum $gg \to t\bar{t}$ background

Dicus, Stange, & Willenbrock, 1994

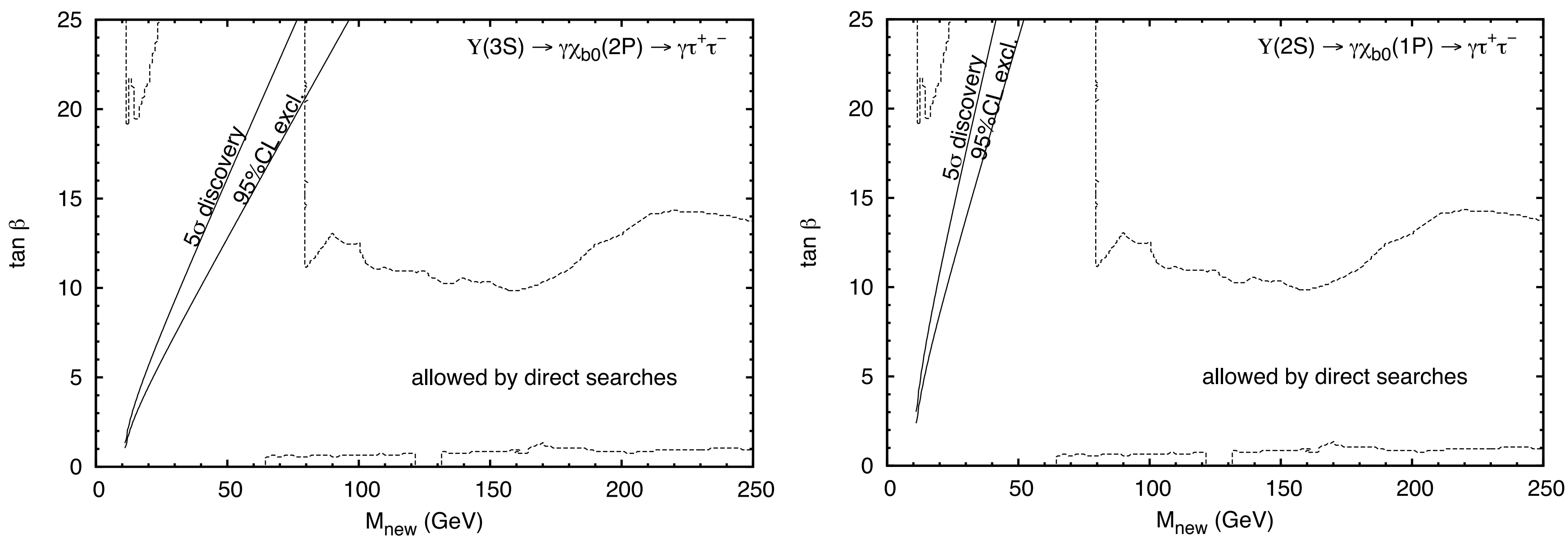
- Expts need theory prediction including signal/background interference, lineshape, & QCD corrections

- Associated prod'n $pp \to b\bar{b}H/A$, $H/A \to t\bar{t}$ could help at moderate $\tan\beta$

Two-Higgs-Doublet Model: under-exploited search channels II: indirect probe of light h from scalar bottomonium χ_{b0} decay

Similar to charged Higgs in $B^+ \to \tau\nu$, pseudoscalar in $\eta_b \to \tau\tau$

Type-II 2HDM, H is 125 GeV SM-like Higgs, lighter $h \subset \Phi_0$
$\Upsilon \to \gamma\chi_{b0}$, $\chi_{b0} \to \tau\tau$ via off-shell h: rate $\propto \tan^4\beta/m_h^4$



250 fb^{-1} on $\Upsilon(3S/2S)$ at Belle-II S. Godfrey & HEL, 1510.04659

- CMS $pp \to \phi \to \tau\tau$ search goes down to 80 GeV HiggsBounds 4.2.0
- Continuum $e^+e^- \to \gamma\tau\tau$ background: ∼4k events under photon peak with no selection cut optimization → room for improvement

Additional (non-doublet) sources of electroweak breaking?

$\rightarrow$ models with higher-isospin scalar multiplets

Part of electroweak breaking from a higher-isospin scalar field?

Fermion masses can arise only from SU(2)$_L$ doublet(s)

$$\mathcal{L} = -y_f \bar{f}_R \Phi^\dagger F_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(\phi^{0,r} + v_\phi)\bar{f}_R f_L + \text{h.c.}$$

$$m_f = y_f v_\phi/\sqrt{2} \qquad \phi^{0,r}\bar{f}f : \; i y_f/\sqrt{2} = i m_f/v_\phi$$

F_L is doublet, f_R is singlet, need Φ doublet for gauge invariance

Top quark Yukawa perturbativity $\Rightarrow$ lower bound on doublet vev:
define $\cos\theta_H \equiv v_\phi/v_{\text{SM}}$, then $\tan\theta_H < 10/3$ (or $\cos\theta_H > 0.287$)

Scalar couplings to fermions come from their doublet content

$$\Phi = \begin{pmatrix} \phi^+ \\ (v_\phi + \phi^{0,r} + i\phi^{0,i})/\sqrt{2} \end{pmatrix}$$

With other scalar fields in play, Goldstone bosons are linear combinations of different fields.

Part of electroweak breaking from a higher-isospin scalar field?

W and Z masses arise from anything carrying SU(2)$_L \times$U(1)$_Y$

$$M_W^2 = \frac{g^2}{4} \sum_k 2 \left[T_k(T_k+1) - \frac{Y_k^2}{4} \right] v_k^2 = \frac{g^2}{4} v_{\rm SM}^2$$

$$M_Z^2 = \frac{g^2}{4\cos^2\theta_W} \sum_k Y_k^2 v_k^2 = \frac{g^2}{4\cos^2\theta_W} v_{\rm SM}^2$$

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

Used $Q = 0$ for component carrying the vev to simplify expressions

Top Yukawa perturbativity $\to$ $(v_\phi / v_{\rm SM})^2 > (0.287)^2 = 0.082$
$\Rightarrow$ At least 8.2% of $M_{W,Z}^2$ comes from doublet.

Lots of room for higher-isospin scalar contributions!

Can we constrain this exotic possibility?

Problem with higher-isospin scalar fields

$\rho \equiv$ 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: $\rho = 1.000\,40 \pm 0.000\,24$

We can still have higher-isospin scalars with non-negligible vevs;
only two approaches using symmetry: (could also tune ρ by hand, but icky)

1) 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

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

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

Larger solutions forbidden by perturbative unitarity of weak charges.

Hally, HEL, & Pilkington 1202.5073

The models

1) Models with global SU(2)$_L \times$SU(2)$_R$ symmetry:

a) Georgi-Machacek model

b) Generalizations to higher isospin

2) Model with a scalar septet (in progress)

All these models share a key common feature:

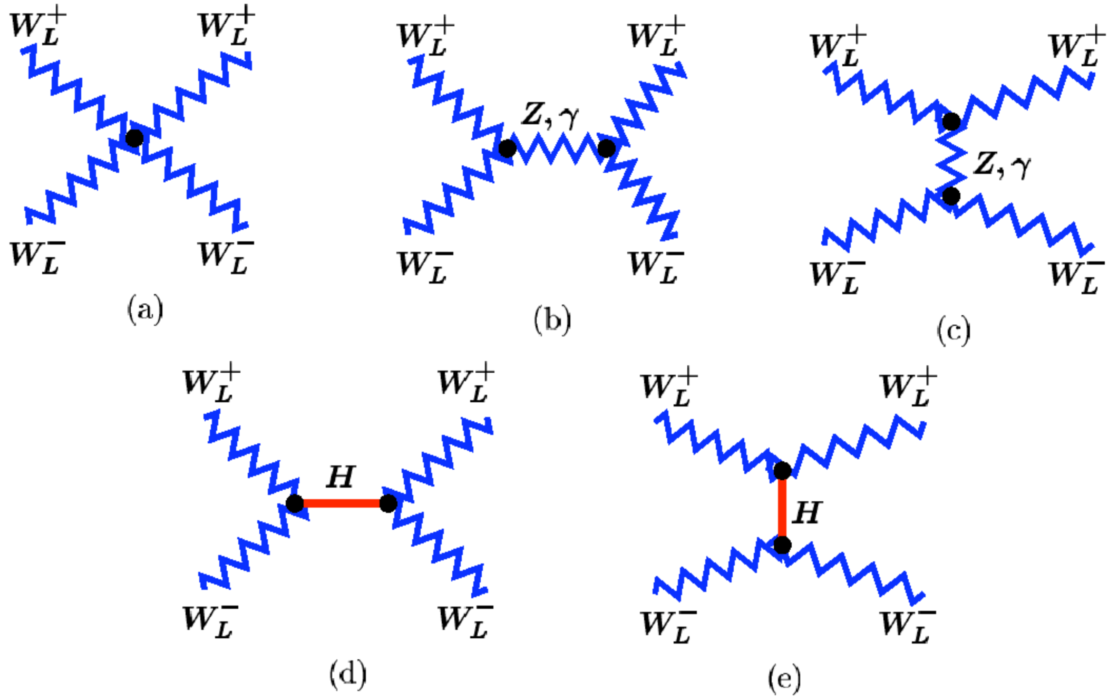
$H^{\pm\pm} \leftrightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \leftrightarrow W^{\pm}Z$

with couplings controlled by vev of higher-isospin scalar(s)

Generic experimental probe is diboson resonance search in VBF.

Theoretical origin of common feature:

Unitarization of $WW \to WW$, $WW \to ZZ$ scattering amplitudes



Graphic: S. Chivukula

- SM: Higgs exchange cancels E^2/v^2 term in amplitude.
- 2HDM: cancellation $\to$ sum rule $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$
- Higher-isospin scalars: $(\kappa_V^h)^2 + (\kappa_V^H)^2 > 1$, need $H^{\pm\pm}$ and $H^{\pm}$ in new u-channel diagrams: couplings inter-related

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

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 $VV \to VV$

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 m_h, m_H $\leftarrow$ (very similar
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ m_3 $\leftarrow$ to 2HDM)
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5 $\leftarrow$ new!

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!

Hally, HEL, & Pilkington 1202.5073

- 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: custodial fiveplet $H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}$

Custodial-fiveplet comes only from higher-isospin scalars:
no couplings to fermions!

$s_H^2 \equiv$ fraction of M_W^2, M_Z^2 from higher-isospin scalar

H_5VV couplings are nonzero: very different from 2HDM!

$$H_5^0 W_\mu^+ W_\nu^- : \quad -i\frac{2M_W^2}{v_{\text{SM}}}\frac{g_5}{\sqrt{6}} g_{\mu\nu},$$

$$H_5^0 Z_\mu Z_\nu : \quad i\frac{2M_Z^2}{v_{\text{SM}}}\sqrt{\frac{2}{3}} g_5 g_{\mu\nu},$$

$$H_5^+ W_\mu^- Z_\nu : \quad -i\frac{2M_W M_Z}{v_{\text{SM}}}\frac{g_5}{\sqrt{2}} g_{\mu\nu},$$

$$H_5^{++} W_\mu^- W_\nu^- : \quad i\frac{2M_W^2}{v_{\text{SM}}} g_5 g_{\mu\nu},$$

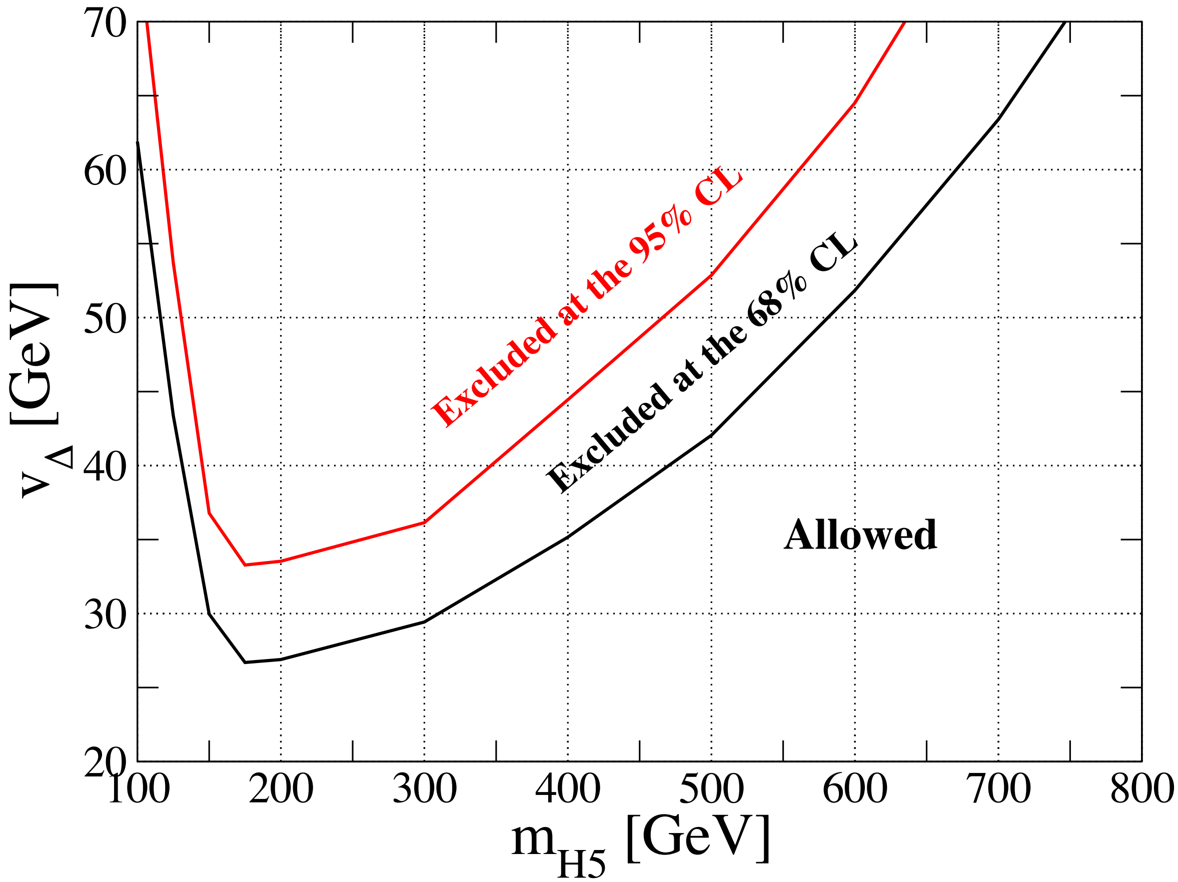
Coupling strength depends on the isospins of the scalars involved:

$$g_5^{\text{GM}} = \sqrt{2} s_H, \quad g_5^{\text{GGM4}} = \sqrt{\frac{24}{5}} s_H, \quad g_5^{\text{GGM5}} = \sqrt{\frac{42}{5}} s_H, \quad g_5^{\text{GGM6}} = \frac{8}{\sqrt{5}} s_H$$

Direct probe of higher-isospin vacuum condensate!

Constraint from VBF $H_5^{\pm\pm} \to W^\pm W^\pm \to$ same-sign dileptons

Theorist-recasting of ATLAS $W^\pm W^\pm jj$ cross-section measurement ATLAS, 1405.6241
$\Rightarrow$ put limit on VBF $\to H_5^{\pm\pm}$ cross section, directly constrain g_5



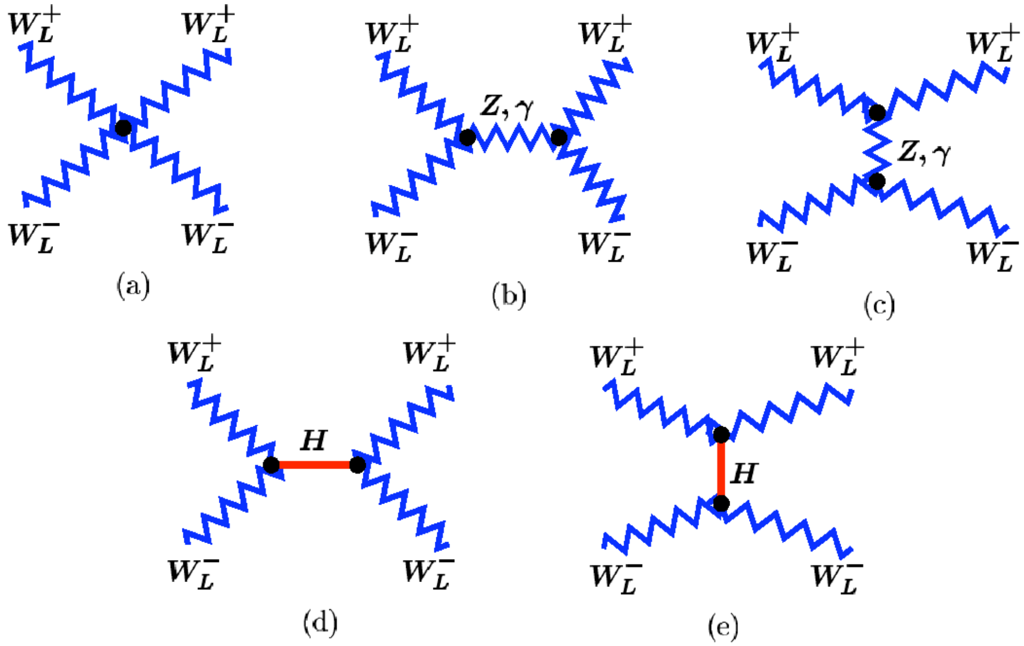
$g_5 = \sqrt{2} s_H$ in GM model

$v_\Delta \equiv v_\chi = s_H v_{SM}/\sqrt{8}$

Chiang, Kanemura & Yagyu, 1407.5053

What about higher H_5 masses?

Perturbative unitarity of $WW \to WW$ scattering: E^0 term



Graphic: S. Chivukula

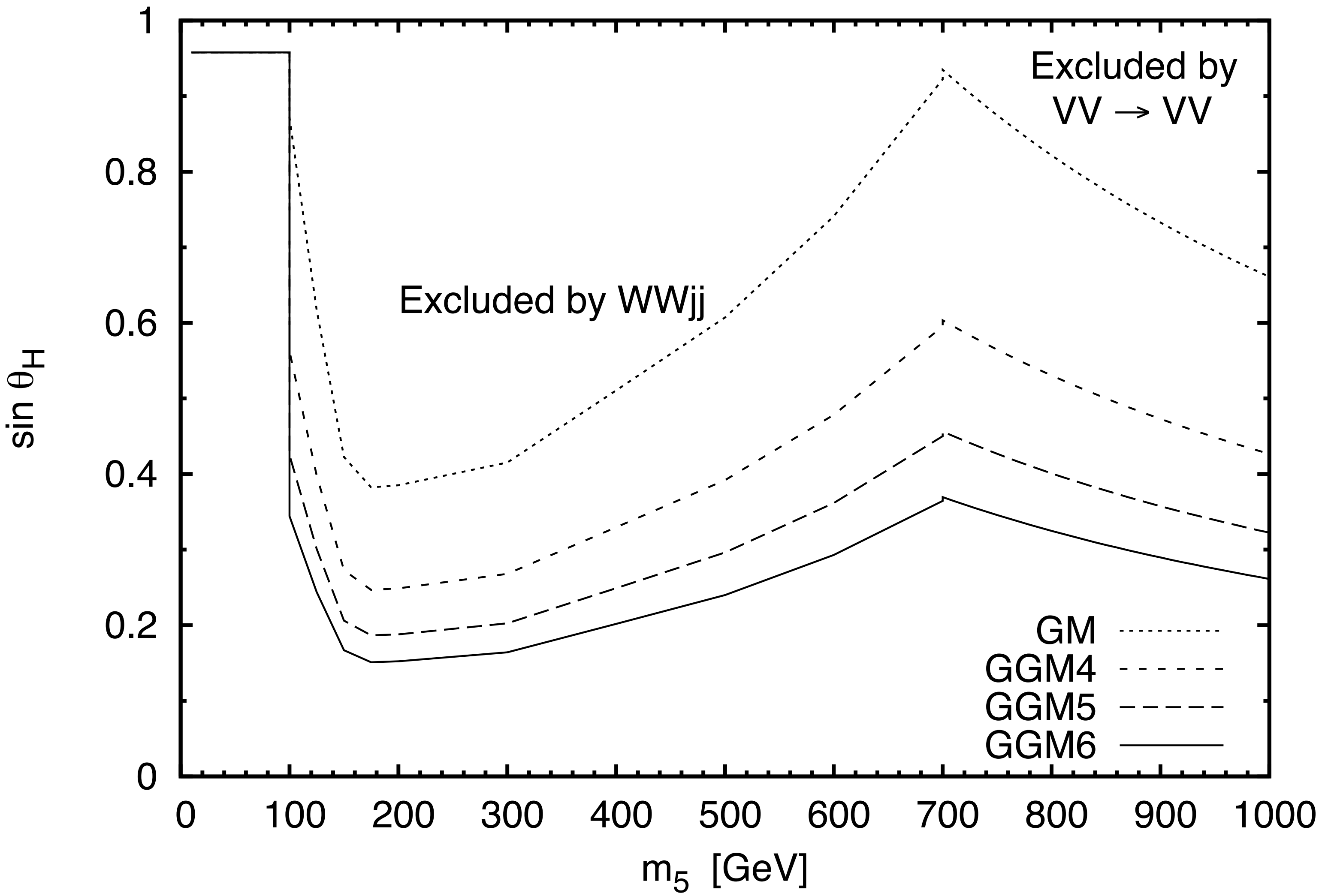
- SM: $m_h^2 < 16\pi v_{\rm SM}^2/5 \simeq (780 \text{ GeV})^2$ Lee, Quigg & Thacker 1977

- GM model: $\left[(\kappa_V^h)^2 m_h^2 + (\kappa_V^H)^2 m_H^2 + \frac{2}{3} g_5^2 m_5^2\right] < 16\pi v_{\rm SM}^2/5$

- combine with sum rule $(\kappa_V^h)^2 + (\kappa_V^H)^2 - \frac{5}{6} g_5^2 = 1$:

$$g_5^2 < \frac{6}{5} \frac{(16\pi v_{\rm SM}^2 - 5m_h^2)}{(4m_5^2 + 5m_h^2)} \simeq \frac{24\pi v_{\rm SM}^2}{5m_5^2} \simeq \left(\frac{955 \text{ GeV}}{m_5}\right)^2$$

Good news for VBF production (compared to 2HDM $(\kappa_V^H)^2 \sim v^4/m_H^4$)



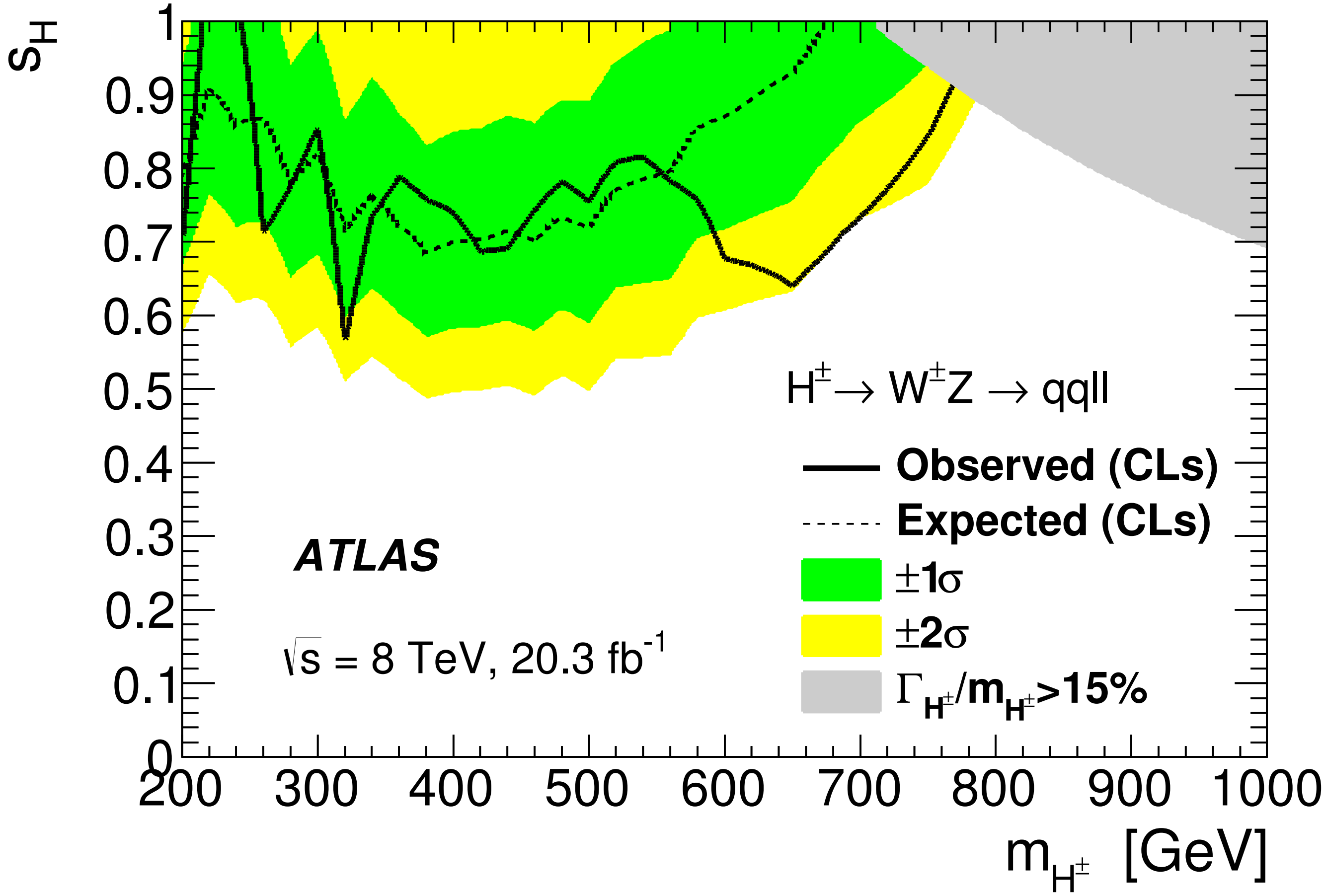
HEL & Rentala, 1502.01275

$$g_5^{\rm GM} = \sqrt{2} s_H, \quad g_5^{\rm GGM4} = \sqrt{\frac{24}{5}} s_H, \quad g_5^{\rm GGM5} = \sqrt{\frac{42}{5}} s_H, \quad g_5^{\rm GGM6} = \frac{8}{\sqrt{5}} s_H$$

Note: $s_H^2 \equiv$ exotic fraction of $M_{W,Z}^2$ is *least* constrained in original Georgi-Machacek model.

Constraint from VBF $H_5^{\pm} \to W^{\pm} Z \to qq\ell^+\ell^-$

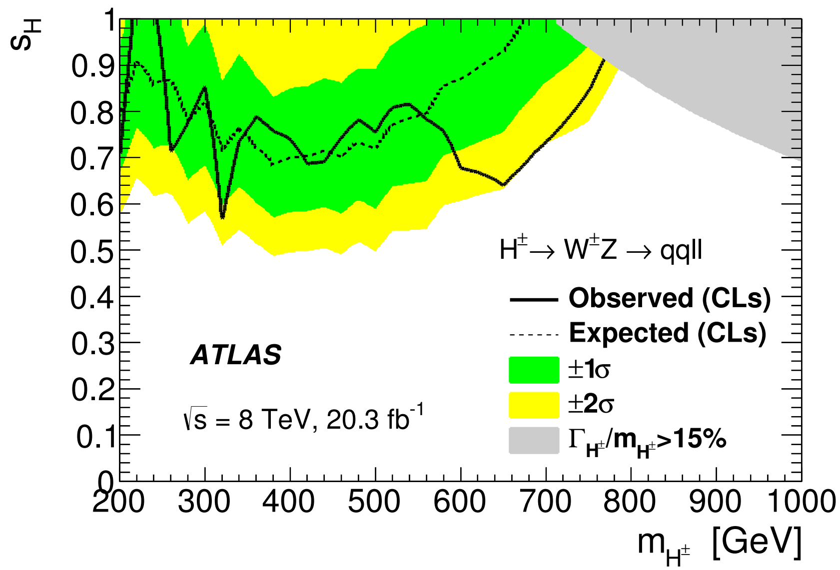
Dedicated ATLAS search for singly-charged resonance in VBF, using Georgi-Machacek model as benchmark

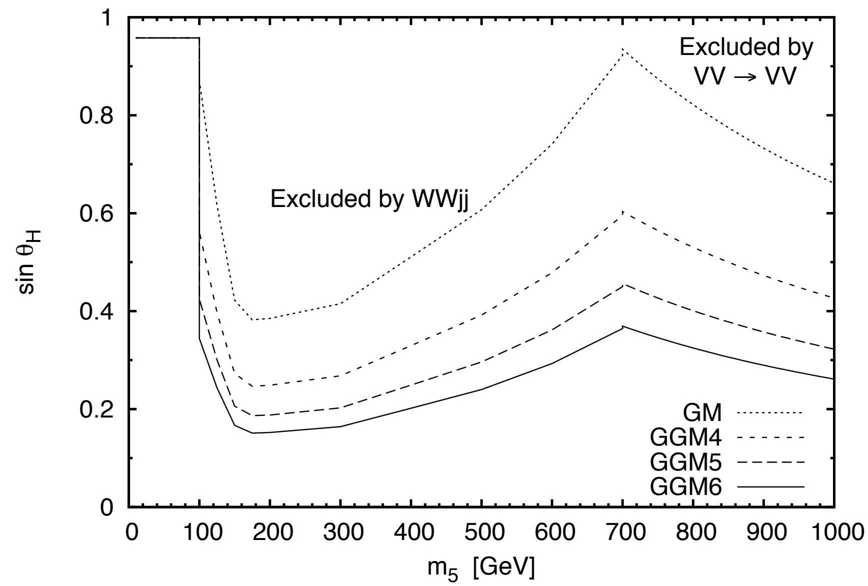


ATLAS 1503.04233

$g_5^2 \lesssim (955\ \text{GeV}/m_5)^2 \quad \Rightarrow \quad \Gamma_{H^+}/m_5 \lesssim 15\%$ for $m_5 \gg M_W$

$H_5^\pm \to W^\pm Z$ exclusion not quite as strong as $H_5^{\pm\pm} \to W^\pm W^\pm$, but more data is coming.





ATLAS 1503.04233

HEL & Rentala, 1502.01275,
after Chiang, Kanemura & Yagyu, 1407.5053,
after ATLAS, 1405.6241

Straightforward to translate constraint from Georgi-Machacek model onto its higher-isospin generalizations.

What about lower H_5 masses?

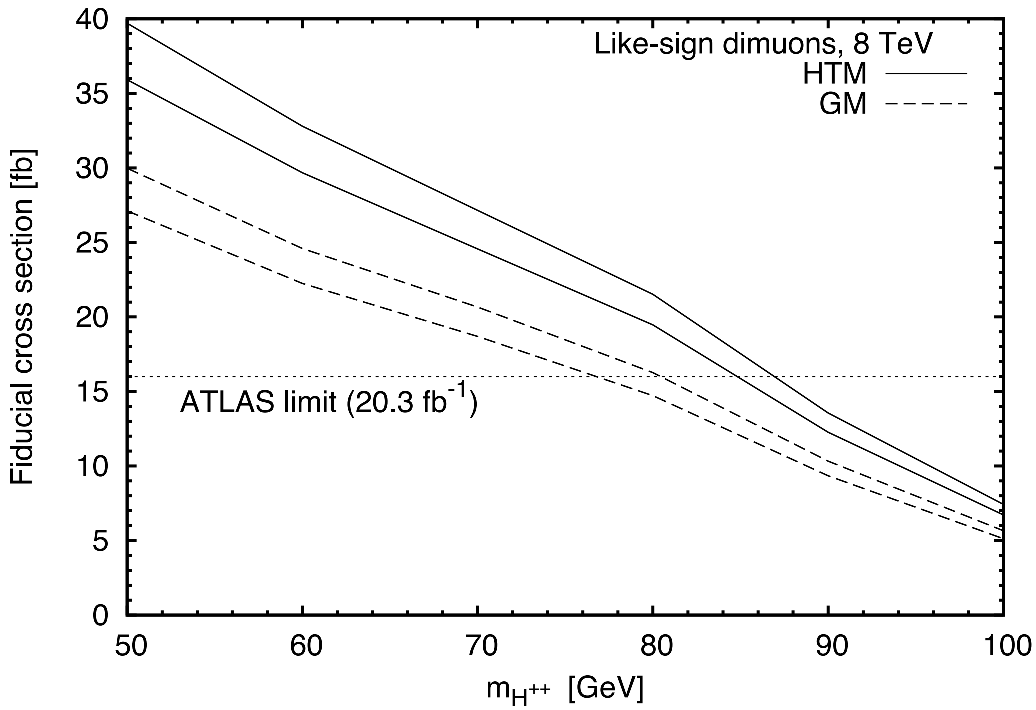
pair production, $H_5^{++} \to W^+W^+$

Constraint on $H^{\pm\pm}H^{\mp\mp} + H^{\pm\pm}H^{\mp}$ in Higgs Triplet Model from recasting ATLAS like-sign dimuons search ATLAS, 1412.0237

Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

Adapt to generalized Georgi-Machacek models using

$$\sigma_{\text{tot}}^{\text{NLO}}(pp \to H_5^{++}H_5^{--})_{\text{GM}} = \sigma_{\text{tot}}^{\text{NLO}}(pp \to H^{++}H^{--})_{\text{HTM}},$$
$$\sigma_{\text{tot}}^{\text{NLO}}(pp \to H_5^{\pm\pm}H_5^{\mp})_{\text{GM}} = \frac{1}{2}\sigma_{\text{tot}}^{\text{NLO}}(pp \to H^{\pm\pm}H^{\mp})_{\text{HTM}}.$$



HEL & Rentala, 1502.01275

$\Rightarrow$ $m_5 \gtrsim 76$ GeV, independent of g_5

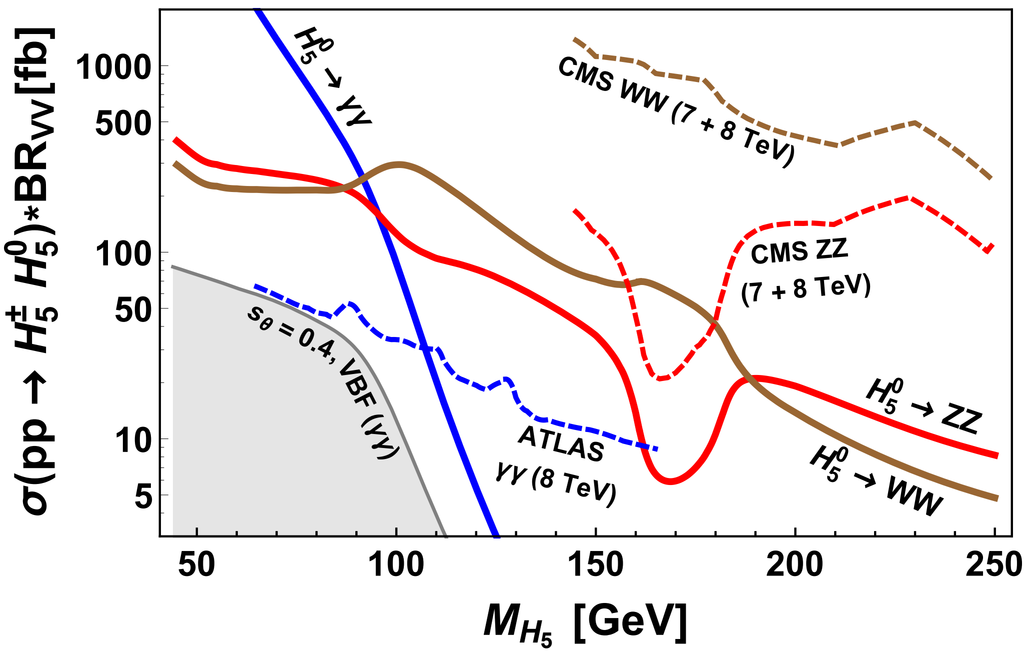
Takes advantage of mass-degeneracy of H_5^{++} and H_5^{+}

What about lower H_5 masses?

pair production, $H_5^0 \to \gamma\gamma$

Scalar pair prod'n $q\bar{q}' \to W^* \to H_5^0 H_5^\pm$: large xsec at low mass
Fermiophobic H_5^0: decays to $\gamma\gamma$ dominate at low mass

Take advantage of 8 TeV LHC diphoton cross-section limits!



Excludes $m_5 \lesssim 110$ GeV independent of exotic vev

For illustration: plot neglects charged scalar loop contributions to $H_5^0 \to \gamma\gamma$
(full model scan is feasible)

Delgado, Garcia-Pepin, Quirós, Santiago, & Vega-Morales, 1603.00962

$H_5^+ \to W^+\gamma$ also interesting: BR implementation in progress

Conclusions

LHC Higgs measurements are (so far) consistent with the SM

But there is still room for New Physics in the electroweak-symmetry-breaking sector: additional scalar fields condensed in the vacuum!

(1) Additional source of fermion masses?

$\rightarrow$ two-Higgs-doublet models

(2) Additional (non-doublet) source of electroweak breaking?

$\rightarrow$ models with higher-isospin scalar multiplets

The more these contribute to EW breaking/fermion masses, the harder they are to hide from experiments.

- $H/A \to t\bar{t}$: probe low-$\tan\beta$ window of 2HDM
- VBF $H_5^{\pm\pm} \to W^\pm W^\pm$, $H_5^\pm \to W^\pm Z$: probe higher-isospin vev
- Fermiophobic scalar pair production at low mass: $\gamma\gamma$ and $W\gamma$

BACKUP

Septet model (work in progress)

Two CP-even neutral scalars:

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

One CP-odd neutral scalar: ($c_H \equiv v_\phi / v_{\rm SM}$ as usual)

$$A^0 = -s_H \phi^{0,i} + c_H \chi^{0,i}$$

Two charged scalars:
(one fermiophilic and one vectorphilic, but they mix in general)

$$\begin{aligned} H_f^+ &= -s_H \phi^+ + c_H \left(\sqrt{\frac{5}{8}} \chi^{+1} - \sqrt{\frac{3}{3}} (\chi^{-1})^* \right), \\ H_V^+ &= \sqrt{\frac{3}{8}} \chi^{+1} + \sqrt{\frac{5}{8}} (\chi^{-1})^* \end{aligned}$$

A doubly-charged scalar, that couples to W^+W^+:

$$H^{++} = \chi^{+2}$$

Some higher-charged states:

$$\chi^{+3}, \qquad \chi^{+4}, \qquad \chi^{+5}$$

- No H_5^0; would-be H_5^+ can mix with fermiophilic state
- Rely on H^{++} to constrain higher-isospin vacuum condensate

Septet model (work in progress)

$$H^{++}W^-_\mu W^-_\nu : \quad i\frac{2M_W^2}{v_{\rm SM}}(\sqrt{15}s_H)g_{\mu\nu}$$

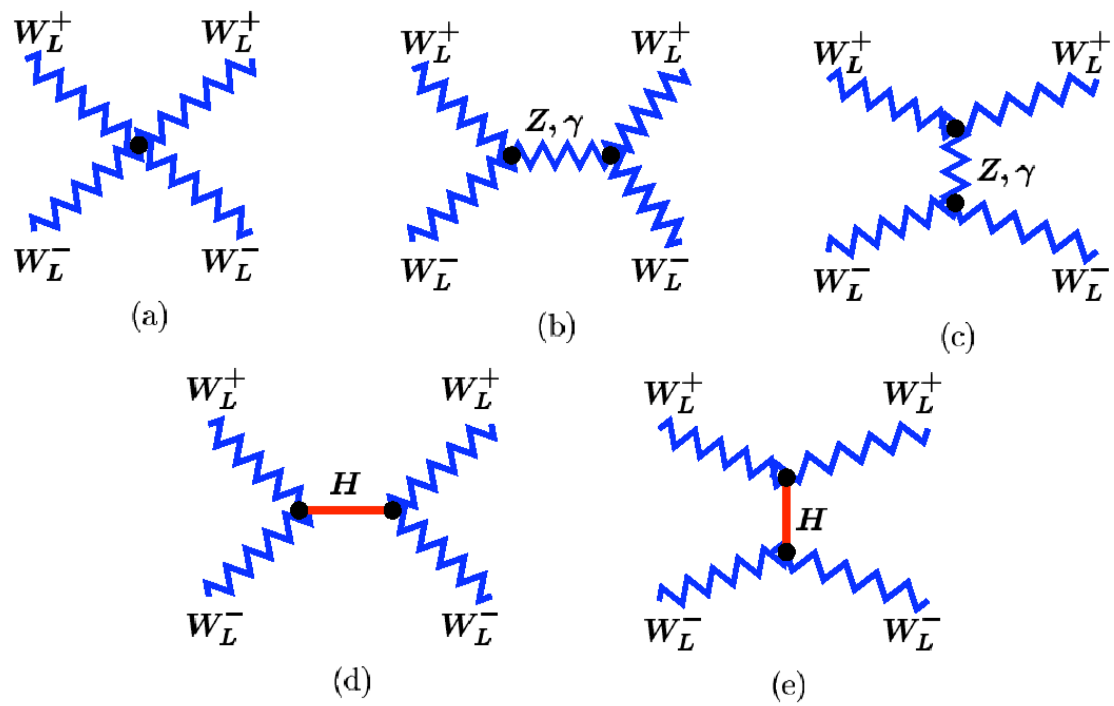
VBF $H^{\pm\pm} \to W^\pm W^\pm$ is as good as ever! $\to$ VBF likesign dileptons

VBF $H^\pm \to W^\pm Z$ loses its clean interpretation:
$H^+ \to \bar f f$ competes with W^+Z; $m_{H^+} \neq m_{H^{++}}$ in general

No custodial symmetry: unitarity bound on s_H at high $m_{H^{++}}$ is modified, but still remains useful.

Analysis of LHC constraints on septet-state pair production (trileptons; like-sign dileptons) excludes low masses $\to M_{\rm septet} \gtrsim 400$ GeV
Alvarado, Lehman & Ostdiek, 1404.3208

Perturbative unitarity of $WW \to WW$ scattering: E^2 term



Graphic: S. Chivukula

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

- 2HDM: To preserve cancellation at $E \gg m_H$, need a sum rule: $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$

Two-Higgs-Doublet Model: mass splittings

At high mass $H \simeq \phi_0^{0,r}$, $A = \phi_0^{0,i}$, $H^\pm = \phi_0^\pm$: the BSM Higgses all live (mostly) in a single doublet.

Mass splittings within an SU(2) multiplet come only from EWSB:

$$m_{H^\pm}^2 = Y_2 + Z_3 v^2/2 \qquad m_A^2 = m_{H^\pm}^2 + (Z_4 - Z_5) v^2/2$$

$$M_{h,H}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$$

$\Delta m^2 \sim \lambda v^2$ and $m^2 \sim M^2 \quad \Rightarrow \quad \Delta m \sim \lambda v^2/M$

Mass splittings $\Delta m \sim \lambda v \times v/M$

Heavy states become increasingly degenerate at high mass

Compare fermionic decay widths $\propto M$ at fixed coupling
(bosonic decay widths $\propto (v^4/M^4) \times M^3 \sim 1/M$ due to coupling suppression)

Both have theoretical "issues":

1) Global $SU(2)_L \times SU(2)_R$ is broken by gauging hypercharge.

Gunion, Vega & Wudka 1991

Special relations among param's 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!

2) 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!

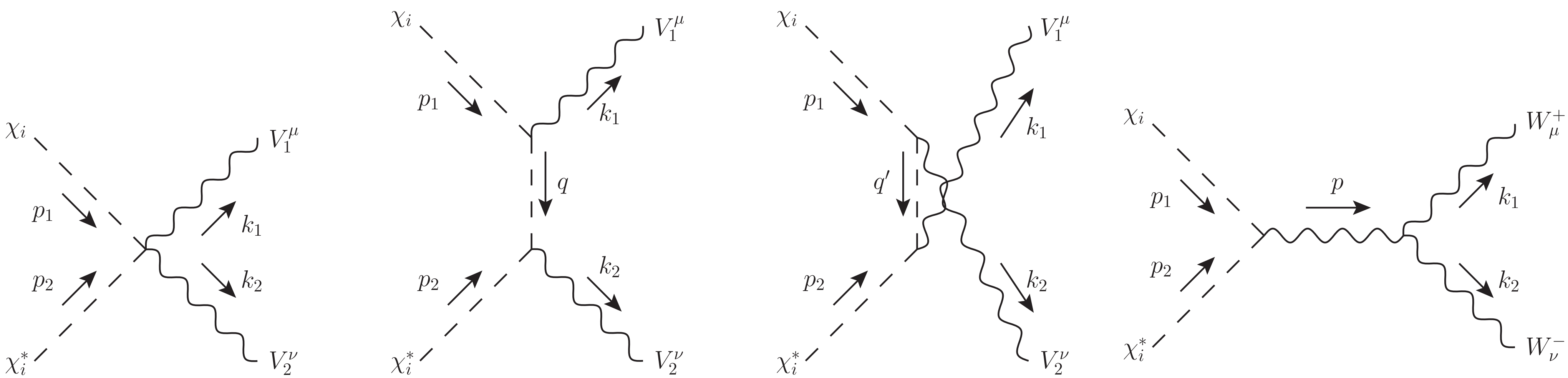
But we need a nearby UV completion to solve the hierarchy problem anyway.

How large can the isospin be?

Hally, HEL, & Pilkington 1202.5073

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

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



How large can the isospin be?

Hally, HEL, & Pilkington 1202.5073

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

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

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

$$a_0^{\text{max}} = \frac{g^2}{16\pi} \frac{(n^2 - 1)\sqrt{n}}{2\sqrt{3}}$$

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

Unitarity: require largest amplitude 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 more than one large multiplet is present

(generally required in $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$-symmetric models)

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

Phenomenology: custodial fiveplet $H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$

Custodial-fiveplet comes only from higher-isospin scalars:
no couplings to fermions!

$s_H^2 \equiv$ fraction of M_W^2, M_Z^2 from higher-isospin scalar

H_5VV couplings are nonzero: very different from 2HDM!

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

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

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

$$H_5^{++} W_\mu^- W_\nu^- : \quad i\frac{2M_W^2}{v_{SM}}g_5 g_{\mu\nu},$$

But g_5 is also 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)

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

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

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

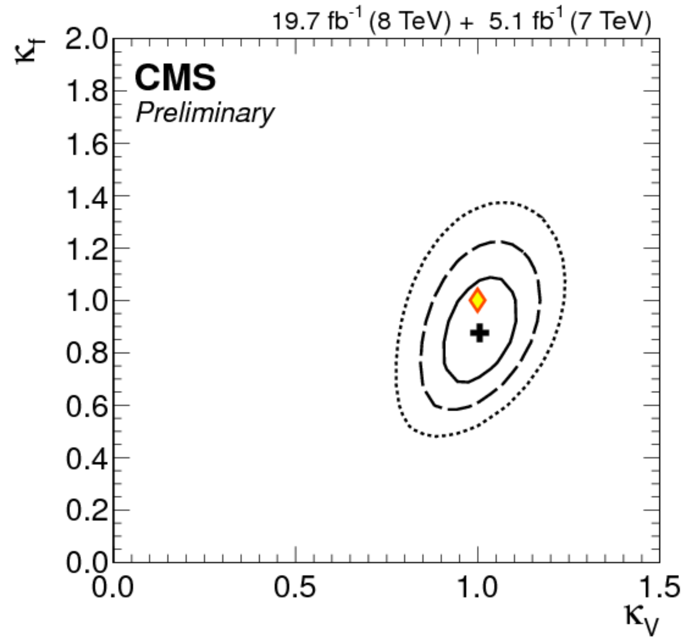
Implementation of $\kappa_V^h > 1$

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

Motivation for enhanced hVV couplings

Simultaneous enhancement of all the h couplings can hide a non-SM contribution to the Higgs width.

LHC measures rates in particular final states:

$$\text{Rate}_{ij} = \frac{\sigma_i \Gamma_j}{\Gamma_{\text{tot}}} = \frac{\kappa_i^2 \sigma_i^{\text{SM}} \cdot \kappa_j^2 \Gamma_j^{\text{SM}}}{\sum_k \kappa_k^2 \Gamma_k^{\text{SM}} + \Gamma_{\text{new}}}$$

All rates will be identical to SM Higgs if all $\kappa_i \equiv \kappa \geq 1$ and

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

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

Constraint on Γ^{tot} (equivalently on κ) from off-shell $gg\ (\to h^*) \to ZZ$ assumes no new resonances in s-channel: a light H can cancel effect of modified h couplings. 1412.7577

Study concrete models in which $\kappa > 1$ to gain insight.

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

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

Phenomenology I: custodial singlets h^0, H^0

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

Recall $c_H^2 =$ fraction of $M_{W,Z}^2$ coming from doublet vev

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

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

Couplings to W^+W^-/ZZ and $\bar{f}f$:

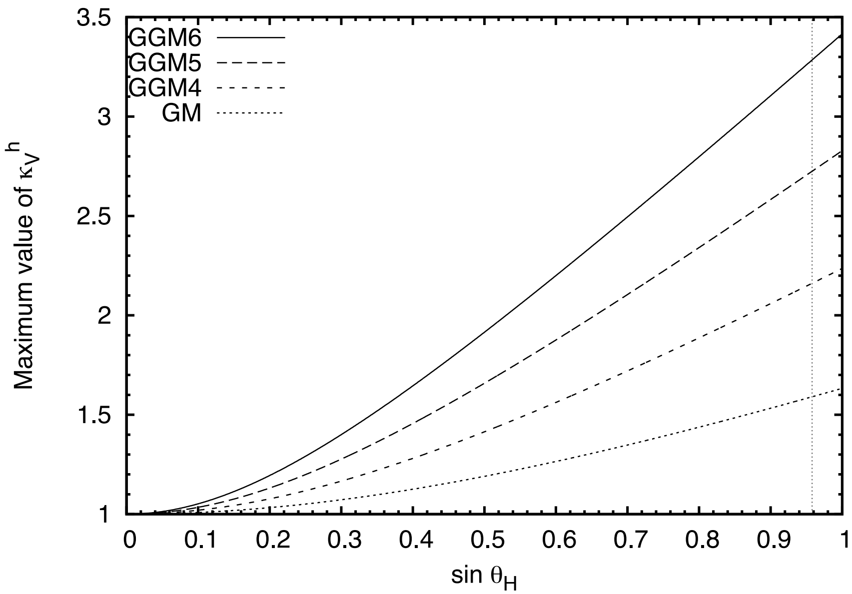
$$\kappa_V^h = c_\alpha c_H - \sqrt{A} s_\alpha s_H \qquad \kappa_f^h = c_\alpha / c_H$$
$$\kappa_V^H = s_\alpha c_H + \sqrt{A} c_\alpha s_H \qquad \kappa_f^H = s_\alpha / c_H$$

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: $A = 4T(T+1)/3$

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

(Septet model: $A_7 = 16$)

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



Vertical line:

y_t perturbativity $\to$ $\tan\theta_H < 10/3$

HEL & Rentala, 1502.01275

Impossible to have $\kappa_V^h, \kappa_f^h = 1$ without $s_H \to 0$:

High-precision measurements of Higgs couplings will constrain higher-isospin vacuum condensate.

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

Phenomenology II: custodial triplet H_3^+, H_3^0, H_3^-

Couplings to fermions are the same as $H^\pm, A^0$ in Type-I 2HDM:

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

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

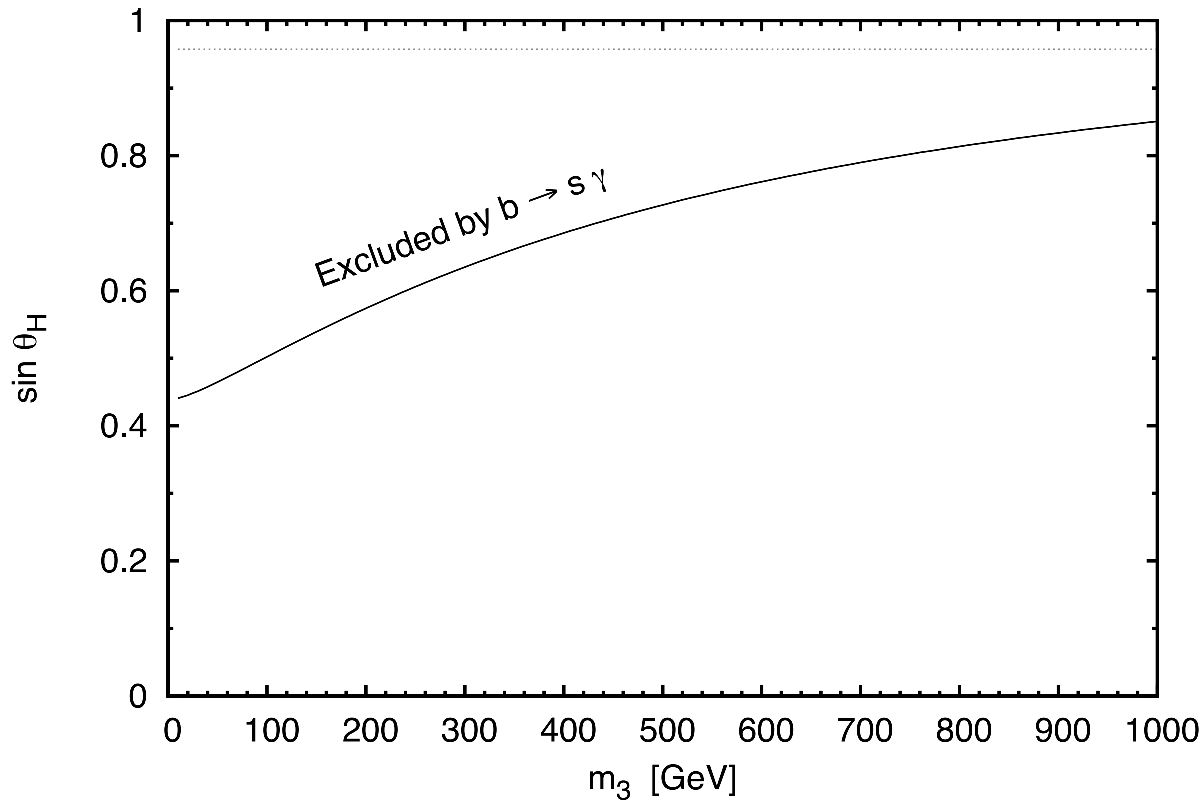
$$H_3^+ \bar \nu \ell: \quad i\frac{\sqrt{2}}{v} \tan\theta_H m_\ell P_R.$$

$Z H_3^+ H_3^-$ also the 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 at tree level.

Constraint from $b \to s\gamma$

H_3^+ in the loop: measurement constrains m_3 and $\sin\theta_H$
- Holds for all generalizations of Georgi-Machacek model
- Also constrains septet model, but not identical



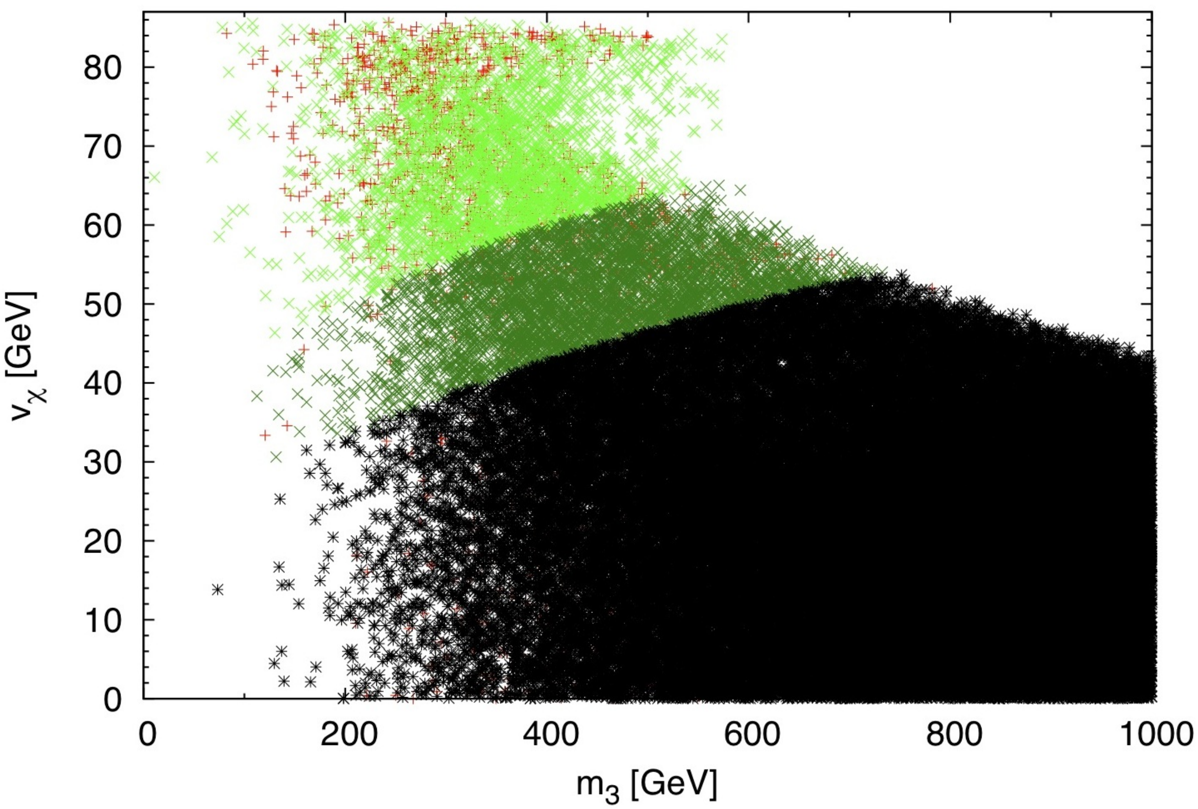
Hartling, Kumar & HEL, 1410.5538

Constraint from $b \to s\gamma$ in original Georgi-Machacek model:

Apply to original Georgi-Machacek model: $s_H^2 < 0.56$

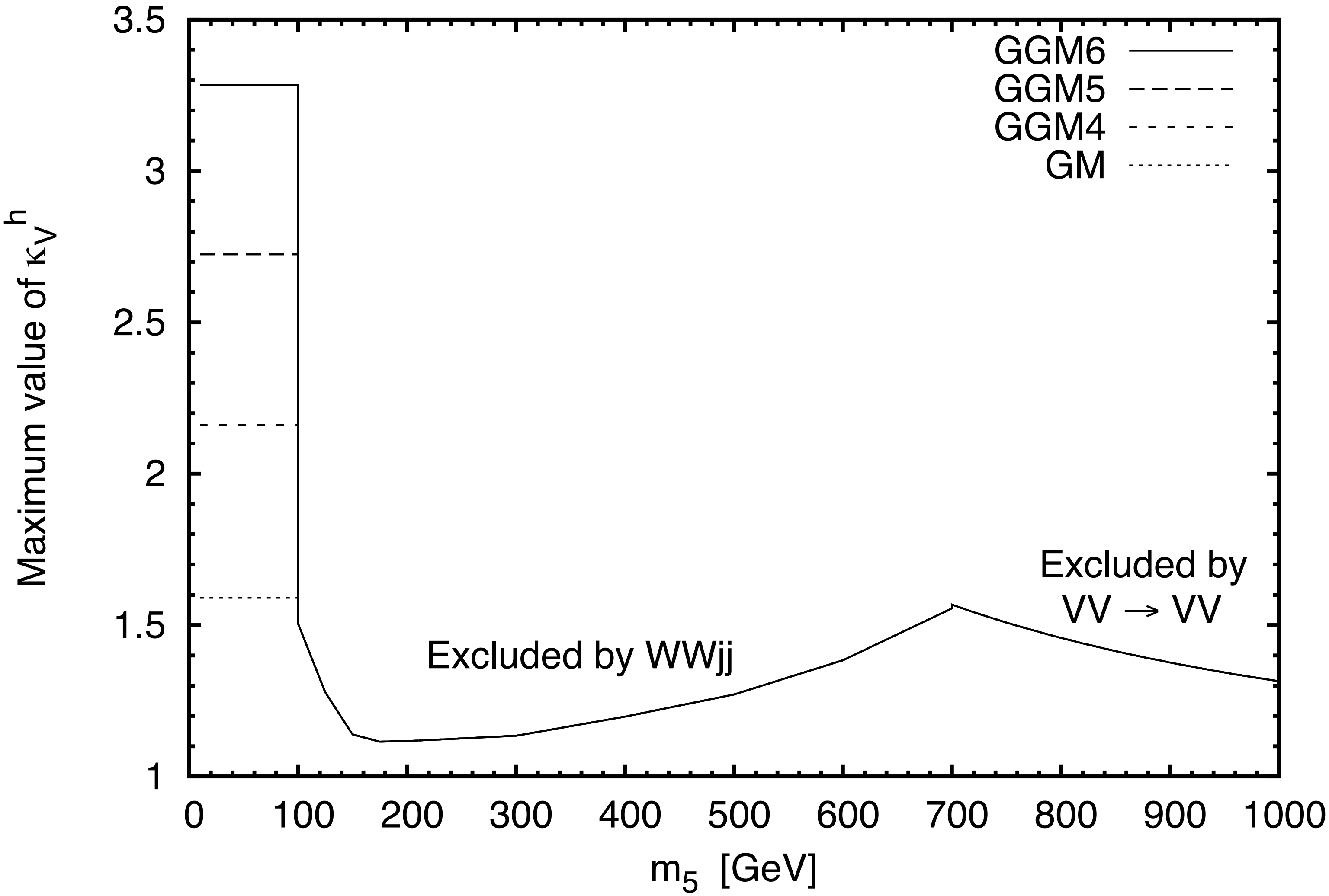
Can constrain because high s_H at high m_3 is theoretically inaccessible.

$\Rightarrow$ at least 44% of $M_{W,Z}^2$ is due to doublet vev (Model-dependent bound)



Hartling, Kumar & HEL, 1410.5538 (Light green points excluded by $b \to s\gamma$)

All the $SU(2)_L \times SU(2)_R$ models are the same when expressed in terms of g_5: use sum rule, $(\kappa_V^h)^2 \leq 1 + 5g_5^2/6$

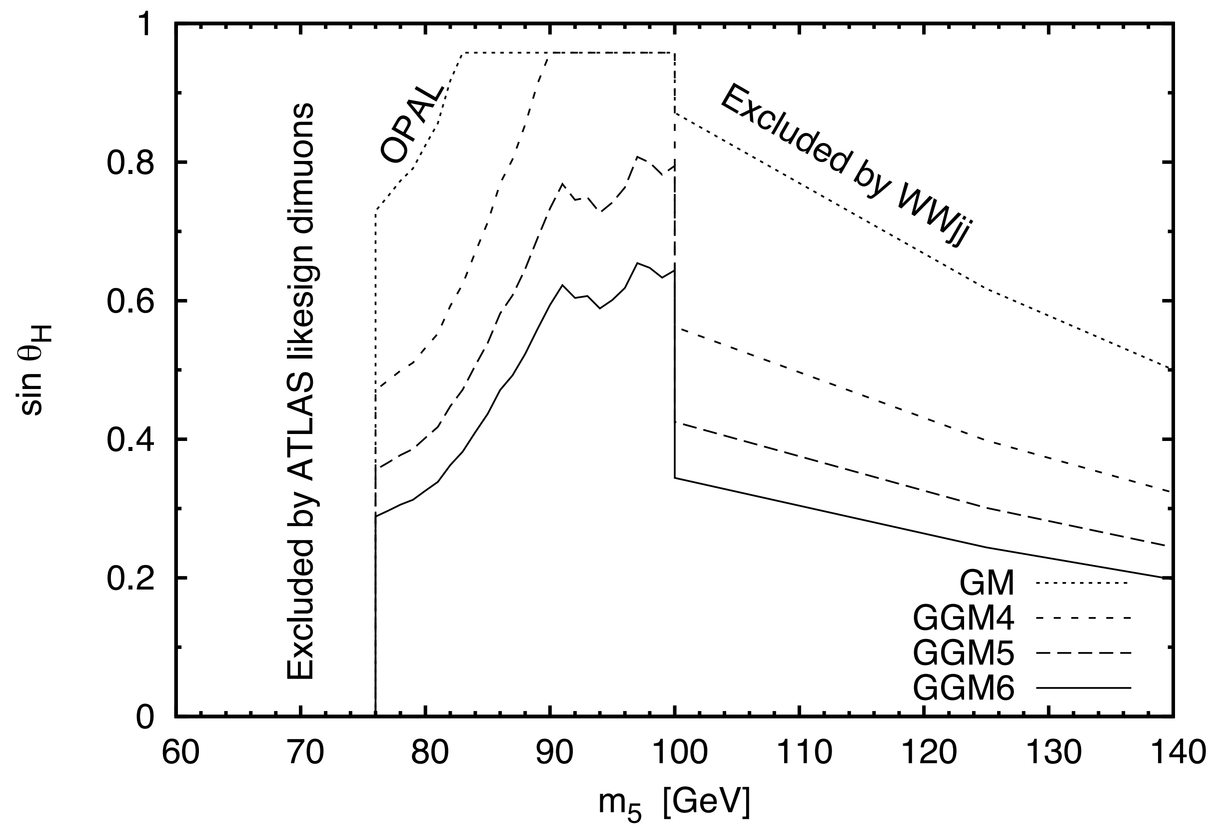


$\Rightarrow \ \kappa_V^h \lesssim 1.57$ for $m_5 > 100$ GeV

HEL & Rentala, 1502.01275

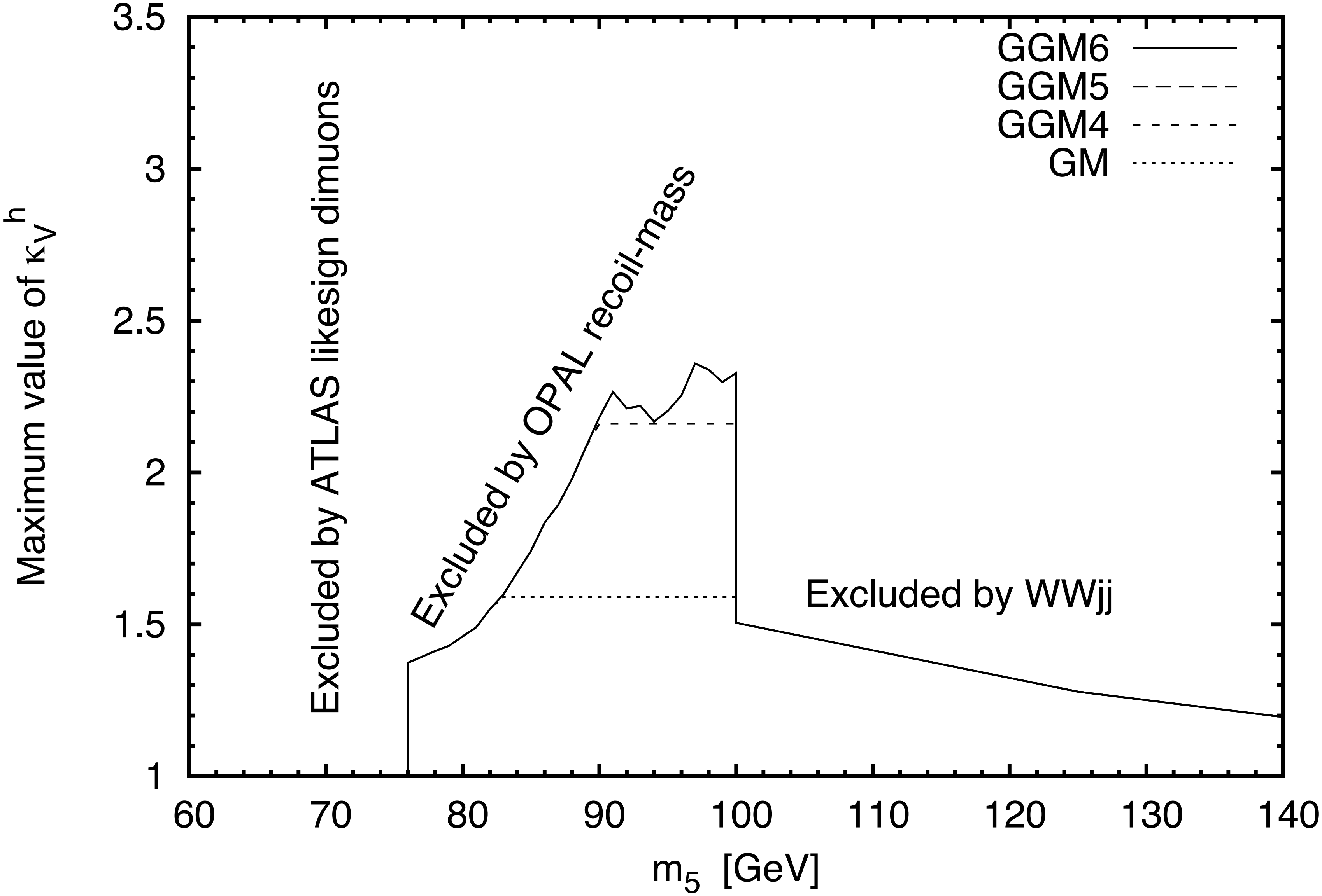
What about lower H_5 masses?

Decay-mode-independent OPAL search for $Z + S^0$ production: constrain $H_5^0 ZZ$ coupling $\propto g_5$ OPAL, hep-ex/0206022



HEL & Rentala, 1502.01275; used HiggsBounds 4.2.0 for OPAL exclusion contour

Takes advantage of mass degeneracy H_5^0 and H_5^{++}



$\Rightarrow\ \kappa_V^h \lesssim 2.36$ for all m_5! HEL & Rentala, 1502.01275

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

$\sim\sim$ Heavy BSM Higgs Rules of Thumb $\sim\sim$

#1. Heavy Higgs couplings to WW/ZZ generically fall like $1/M_H$
except sometimes there are tighter indirect constraints
except in 2HDM they fall like $1/M_H^2$ (reason: no cubic terms in V)
SM+triplets model $H_5^{0,\pm,\pm\pm}$ couplings to VV fall like $1/M$

#2. Heavy Higgs couplings to fermions need not be suppressed
in Type-II 2HDM can even be enhanced $\sim \tan\beta$ (down-type & leptons)
except in SM+singlet where fermion couplings are tied to VV couplings
except in SM+triplets where fermion coups due to doublet mixing $\sim v/M$

#3. Heavy Higgs states become more degenerate at high mass
generic for the members of an SU(2) multiplet: $\Delta m \sim \lambda v^2/M$

Spectrum separates into light SM-like Higgs doublet and heavy complete SU(2)$_L$ multiplet(s). Keys are (1) degree of mixing and/or vev carried by heavy multiplet; (2) heavy multiplet coupling to fermions (doublets only).