BSM Higgs bosons above 1 TeV
(theory overview)

Heather Logan
Carleton University

for CMS Higgs group
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The naturalist: "Having one Higgs at 125 GeV and the rest above 1 TeV is fine-tuned. Why would you do that?"

The pragmatist: "We look for SUSY at multi TeV and that is fine-tuned too. If we have the reach, it's silly not to do the search. (Also, $\sim$2 TeV is not all that fine-tuned.)"

Outline

SM + singlet model

Two Higgs doublet model

SM + triplets model (Georgi-Machacek)

Summary: “rules of thumb”

SM + singlet model

Simplest possible extension (but not necessarily the most interesting!)

Two Higgs states:

$$h = \cos\alpha\,\phi^{0,r} - \sin\alpha\,S, \qquad H = \sin\alpha\,\phi^{0,r} + \cos\alpha\,S$$

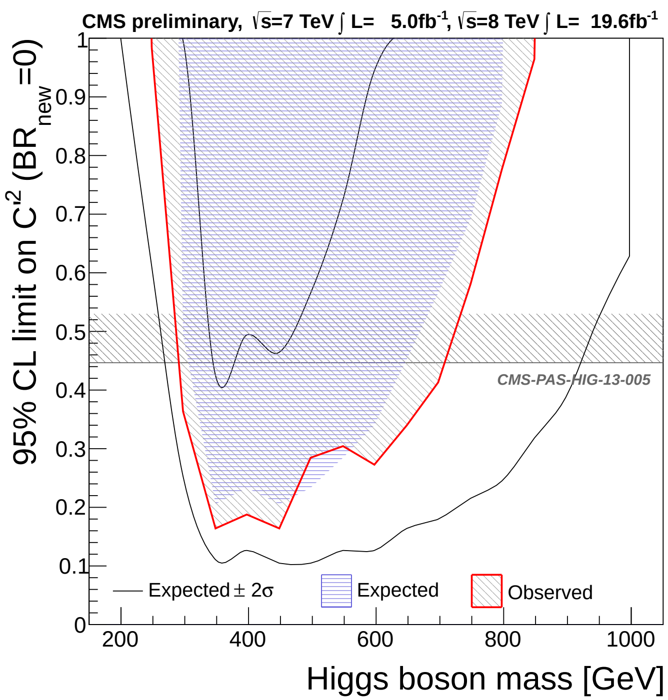
- Couplings of h universally suppressed by $\cos\alpha \equiv \kappa^h \equiv C$

- Couplings of H are complementary: $\sin\alpha \equiv \kappa^H \equiv C'$

Sum rule $(\kappa^h)^2 + (\kappa^H)^2 = 1$ is $\cos^2\alpha + \sin^2\alpha = 1$

Production xsec $= (\kappa^H)^2 \sigma(\text{SM})$ at H mass

- Can have new decay $H \to hh$ for $m_H > 2m_h \simeq 250$ GeV: BRnew



SM + singlet model

Cannot take H arbitrarily heavy at fixed κ^H!

Typically $\kappa^H \propto v/M_H$ in singlet model

Related to "decoupling limit" of $h(125)$ interactions.

2 ways to see this:

- Study scalar potential of the model

Write masses, mixing angles, etc in terms of Lagrangian parameters

Consider perturbativity constraints on dimensionless couplings

Constraints are very model-specific

- Study perturbative unitarity of $WW \to WW$ scattering

Model-independent constraints

(Sometimes model-specific constraints are tighter)

SM + singlet model: scalar potential e.g. Barger et al, 0706.4311

$$V = \frac{m^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \frac{M^2}{2}S^2 + \frac{\mu_1}{2}\Phi^\dagger\Phi S + \frac{\lambda'}{2}\Phi^\dagger\Phi S^2 + \left(\frac{\mu_1 m^2}{2\lambda}\right)S + \frac{\mu_2}{3}S^3 + \frac{\lambda''}{4}S^4$$

$m^2, M^2 \sim$ (mass)^2, $\mu_1, \mu_2 \sim$ (mass), $\lambda, \lambda', \lambda''$ dimensionless

Coefficient of S chosen so $\langle S \rangle = 0$ (no physical consequences)

EWSB $\rightarrow v = \sqrt{-2m^2/\lambda}$ or $m^2 = -\lambda v^2/2$

$\Rightarrow$ Eliminate m^2 in favour of $v \simeq 246$ GeV

The other dimensionful couplings M^2, μ_1, μ_2 can be large.

Dimensionless couplings $\lambda, \lambda', \lambda''$ are bounded by requiring all $2 \rightarrow 2$ scalar scattering amplitudes satisfy perturbative unitarity.

SM + singlet model: scalar potential using Barger et al, 0706.4311

$$V = \frac{m^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \frac{M^2}{2}S^2 + \frac{\mu_1}{2}\Phi^\dagger\Phi S + \frac{\lambda'}{2}\Phi^\dagger\Phi S^2 + \left(\frac{\mu_1 m^2}{2\lambda}\right)S + \frac{\mu_2}{3}S^3 + \frac{\lambda''}{4}S^4$$

Mass^2 matrix for h and H in the $(\phi^{0,r}, S)$ basis:

$$M^2_{h,H} = \begin{pmatrix} \lambda v^2/2 & \mu_1 v/2 \\ \mu_1 v/2 & M^2 + \lambda' v^2/2 \end{pmatrix}$$

Consider $M \gg v$, with $\mu_1 \sim M$:

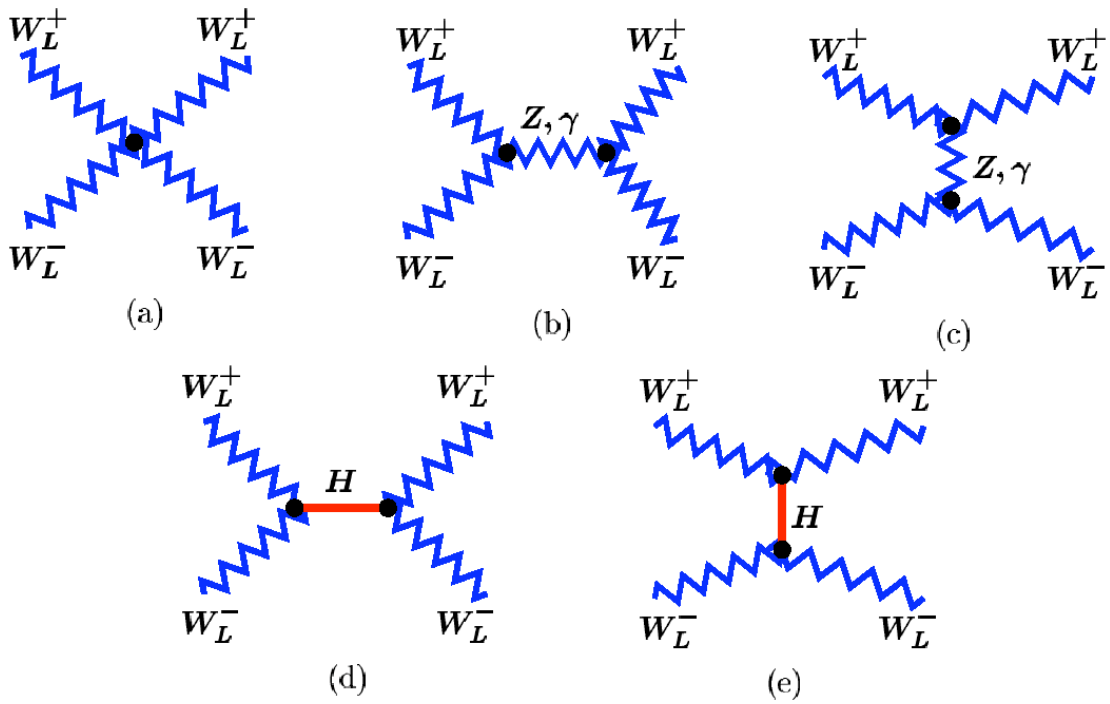
$\mu_1 \lesssim \mathcal{O}(M)$ or cubic term leads to bad alternative minimum of potential

$m_h^2 \simeq \lambda v^2/2$ $\qquad m_H^2 \simeq M^2$ $\qquad C' \equiv \sin\alpha \simeq \mu_1 v/2M^2 \sim v/M$

H production xsecs $\propto (\kappa^H)^2 \sim v^2/M^2$ (h couplings $C = 1 - \mathcal{O}(v^2/M^2)$)

Complicated but no show-stoppers
Theorists can calculate all this and give you model-specific scans

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

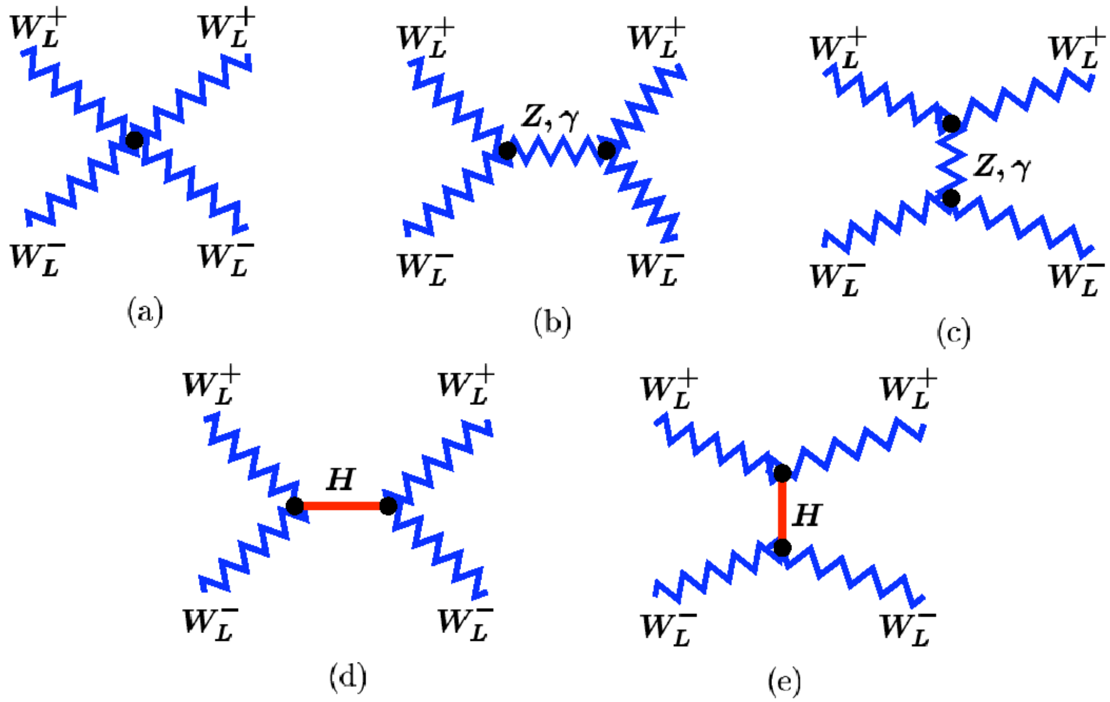


Graphic: S. Chivukula

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

- SM+singlet: To preserve cancellation at $E \gg m_H$, need a sum rule: $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$ (equivalent to $C^2 + C'^2 = \cos^2\alpha + \sin^2\alpha = 1$)

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

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

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

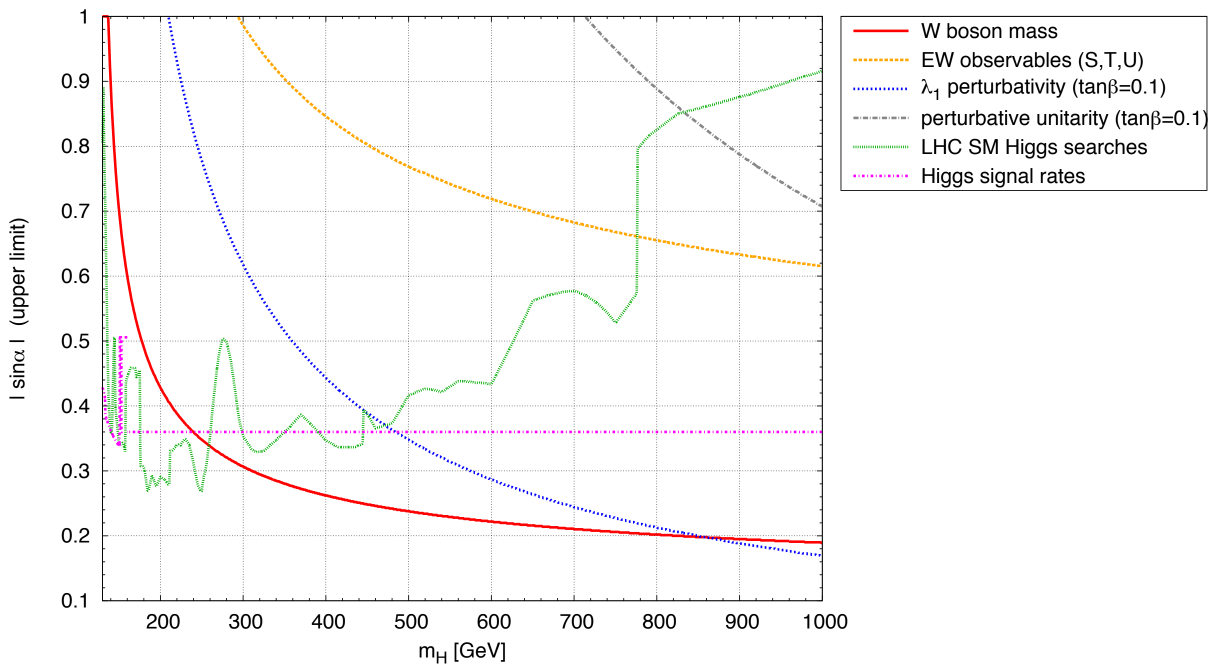
$$C'^2 \equiv (\kappa_V^H)^2 < \frac{16\pi v^2 - 5m_h^2}{5(m_H^2 - m_h^2)} \simeq \frac{16\pi v^2}{5m_H^2} \simeq \left(\frac{780 \text{ GeV}}{m_H}\right)^2$$

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

#1. Heavy Higgs couplings to WW/ZZ generically fall like $1/M_H$

SM + singlet model: electroweak precision constraints

T parameter (yellow) and W boson mass (red) are more constraining until very high masses ($WW \to WW$ unitarity takes over eventually)



Robens & Stefaniak, 1601.07880

SM + singlet: $\kappa_f^H = \kappa_V^H = \sin\alpha$: all possible production cross sections are rather suppressed, but the model is still viable.

$\sim\sim$ 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

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):

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

In this language the high-mass behaviour of $H, A, H^\pm$ is not very transparent.

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

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

Two Higgs Doublet Model: Higgs basis

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

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

$\phi_h^{0,r}VV$ 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 $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$ is $\sin^2(\beta-\alpha) + \cos^2(\beta-\alpha) = 1$

VBF production xsec = $(\kappa_V^H)^2\sigma(\text{SM})$ at H mass

$WW \to WW$ perturbative unitarity constrains

$$\cos^2(\beta-\alpha) \equiv (\kappa_V^H)^2 \lesssim \left(\frac{780\ \text{GeV}}{m_H}\right)^2$$

same as singlet... But for 2HDM the constraint from the scalar potential is much more stringent!

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:

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

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

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

Compare singlet $m_h^2 \simeq \lambda v^2/2$ $m_H^2 \simeq M^2$ $C' \equiv \sin\alpha \simeq \mu_1 v/2M^2 \sim v/M$

Fast decoupling $\cos^2(\beta - \alpha) \equiv (\kappa_V^H)^2 \simeq Z_6^2 v^4/m_H^4$!

Makes VBF very suppressed! But precision EW constraints are looser than SM+singlet.

$\sim\sim$ 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)

Two Higgs Doublet Model: fermion couplings

Two doublets: Φ_1 and Φ_2, vevs $v_1^2 + v_2^2 = v_{\rm SM}^2$, $v_2/v_1 \equiv \tan\beta$
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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 at high mass $H \simeq \phi_0^{0,r}$, $A = \phi_0^{0,i}$, $H^\pm = \phi_0^\pm$: the entire doublet becomes heavy.

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

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

Coupling strengths of Φ_0 to fermions:

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

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

These are independent of the heavy-Higgs mass scale!
Good news for heavy Higgs production via gluon fusion, $b\bar{b}$-fusion

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#2. Heavy Higgs couplings to fermions are not 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

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)

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except in SM+singlet where fermion couplings are tied to VV couplings

#3. Heavy Higgs states become more degenerate at high mass

generic for the members of an SU(2) multiplet: $\Delta m \sim \lambda v^2/M$

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs + two isospin-triplets in a bitriplet:

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

Two custodial singlets h, H, masses m_h, m_H, mixing angle α

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

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)

Custodial 5-plet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$, common mass m_5

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

Georgi-Machacek model: scalar potential

Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

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

$\mu_2^2, \mu_3^2 \sim (\text{mass})^2$, $M_1, M_2 \sim (\text{mass})$, $\lambda_1, \ldots \lambda_5$ dimensionless

As in 2HDM, eliminate 2 dimensionful params in favour of vevs

Heavy BSM Higgs bosons: $\mu_3^2 \equiv M^2 \gg v^2$; need $M_1, M_2 \lesssim M$:

Mass matrices $\Rightarrow m_H^2, m_3^2, m_5^2 \simeq M^2$: all states become heavy
Mixing angle $\sin\alpha \sim M_1 v/\mu_3^2 \sim v/M$: $\kappa_V^H \sim v/M$ like singlet
H_3 fermion couplings $\sim \tan\theta_H m_f/v$, $\sin\theta_H \sim M_1 v/\mu_3^2 \sim v/M$

$\sin\theta_H \equiv 2\sqrt{2} v_\chi/v$

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in Type-II 2HDM can even be enhanced $\sim \tan\beta$ (down-type & leptons)

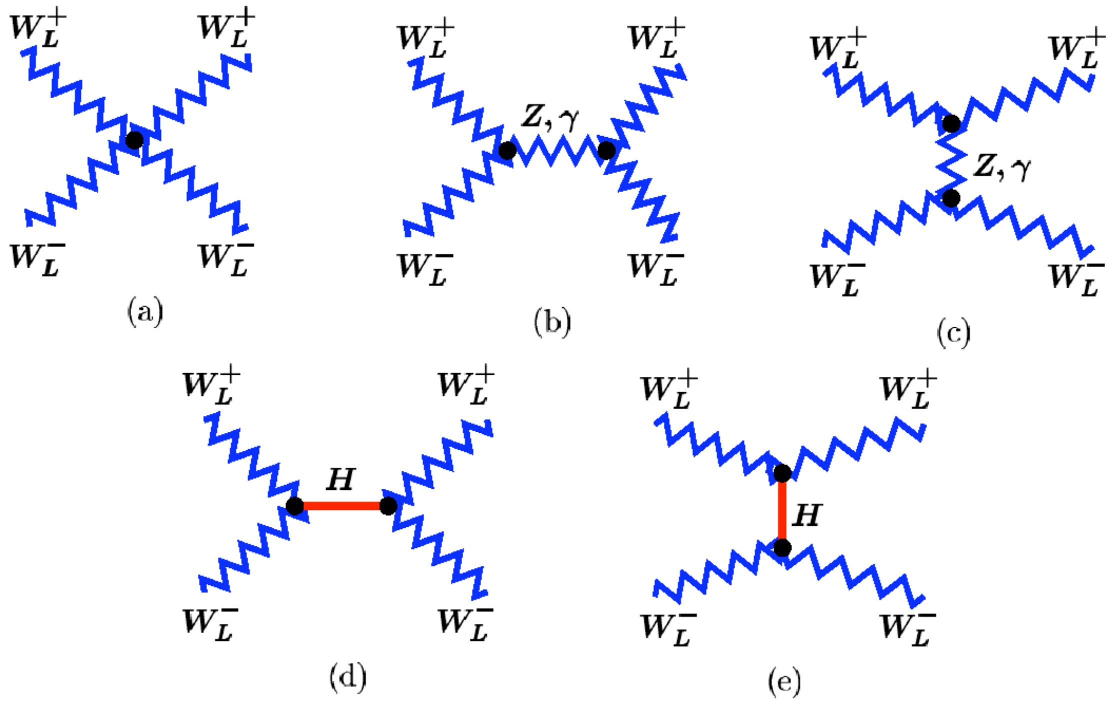
except in SM+singlet where fermion couplings are tied to VV couplings

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: $\Delta m \sim \lambda v^2/M$

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



Graphic: S. Chivukula

- Georgi-Machacek model: sum rule involves h, H, and $H_5^{0,\pm\pm}$

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

H_5 couplings to WW/ZZ $\propto \sin\theta_H$ in GM model

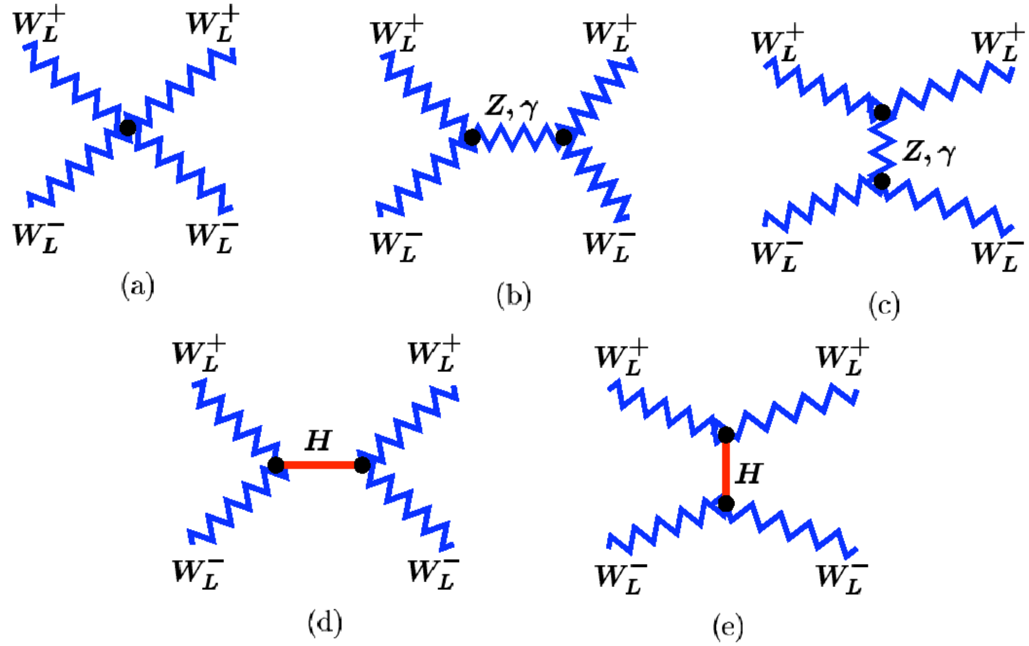
$$
\begin{aligned}
H_5^0 W_\mu^+ W_\nu^- : &\qquad -i\frac{2M_W^2}{v}\frac{\sin\theta_H}{\sqrt{3}} g_{\mu\nu}, \\
H_5^0 Z_\mu Z_\nu : &\qquad i\frac{2M_Z^2}{v}\frac{2\sin\theta_H}{\sqrt{3}} g_{\mu\nu}, \\
H_5^+ W_\mu^- Z_\nu : &\qquad -i\frac{2M_W M_Z}{v}\sin\theta_H g_{\mu\nu}, \\
H_5^{++} W_\mu^- W_\nu^- : &\qquad i\frac{2M_W^2}{v}\sqrt{2}\sin\theta_H g_{\mu\nu},
\end{aligned}
$$

$VV \to VV$ unitarization sum rule:

$$(\kappa_V^h)^2 + (\kappa_V^H)^2 - \frac{5}{3}\sin^2\theta_H = 1$$

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

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

- GM model: $\left[(\kappa_V^h)^2 m_h^2 + (\kappa_V^H)^2 m_H^2 + \frac{4}{3}\sin^2\theta_H m_5^2\right] < 16\pi v^2/5$

- combine with sum rule $(\kappa_V^h)^2 + (\kappa_V^H)^2 - \frac{5}{3}\sin^2\theta_H = 1$:

$$\sin^2\theta_H < \frac{3}{5}\frac{(16\pi v^2 - 5m_h^2)}{(4m_5^2 + 5m_h^2)} \simeq \frac{12\pi v^2}{5m_5^2} \simeq \left(\frac{675 \text{ GeV}}{m_5}\right)^2$$

Good news for VBF production (compared to 2HDM coup $\sim v^2/M^2$)

$\sim\sim$ 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).