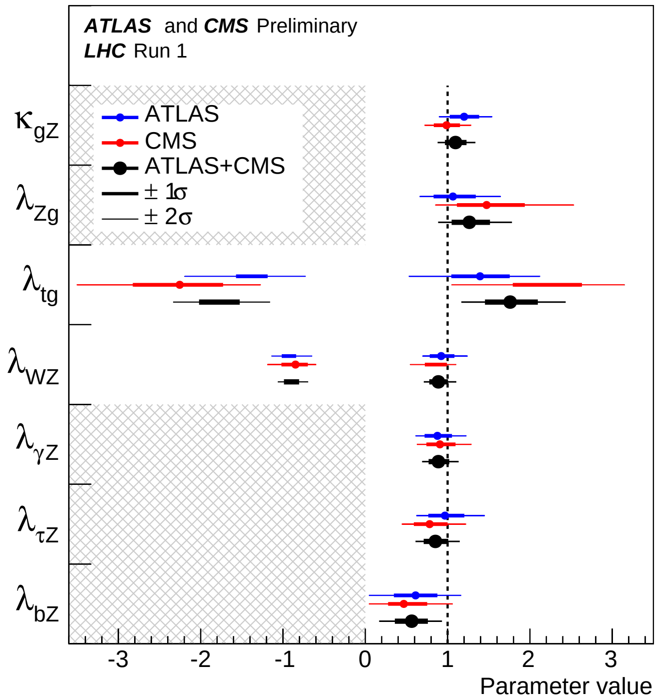
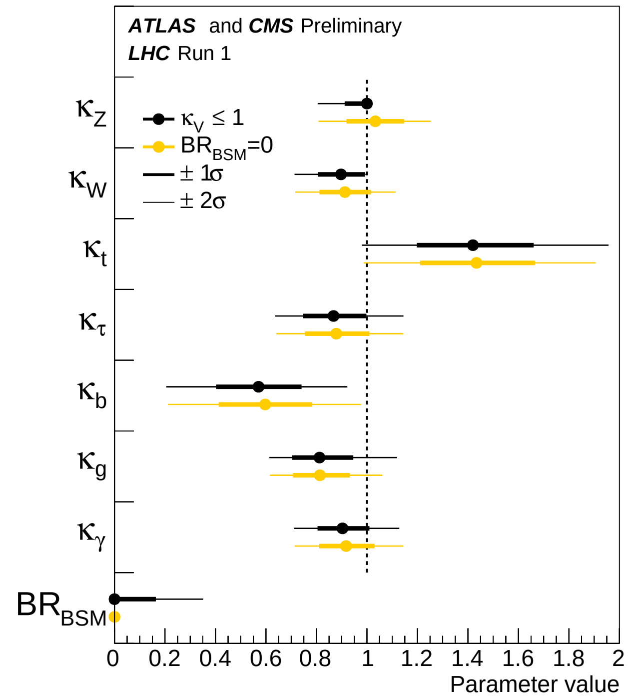
Higgs physics beyond the Standard Model

Heather Logan
Carleton University

ATLAS Canada meeting
Carleton University, May 2016

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?

$\rightarrow$ two-Higgs-doublet models

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

$\rightarrow$ 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 interesting search channels

Conclusions

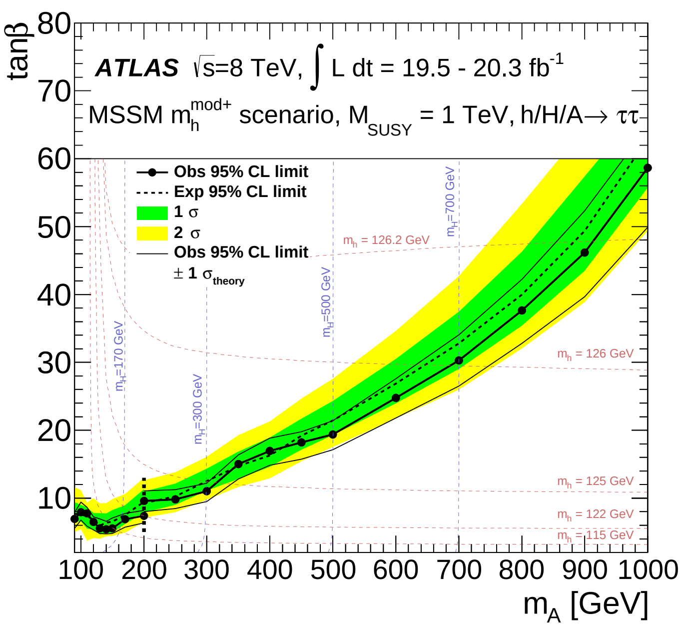
Additional sources of fermion masses?

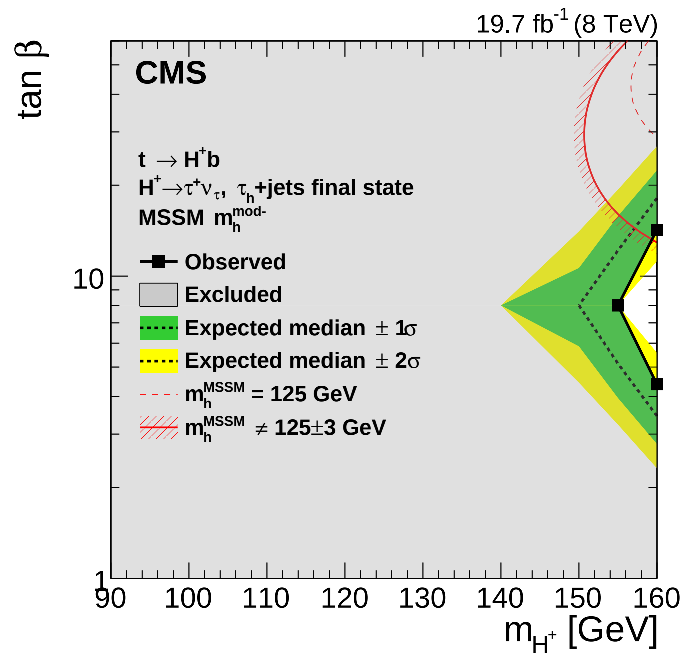
$\rightarrow$ Two-Higgs-Doublet Model

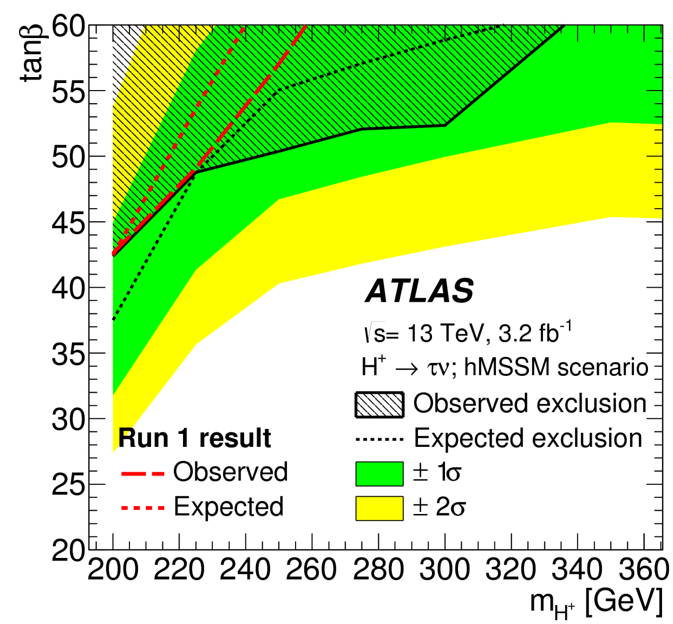
Two-Higgs-Doublet Model

"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 $\phi_0^{0,r} VV = 0$:

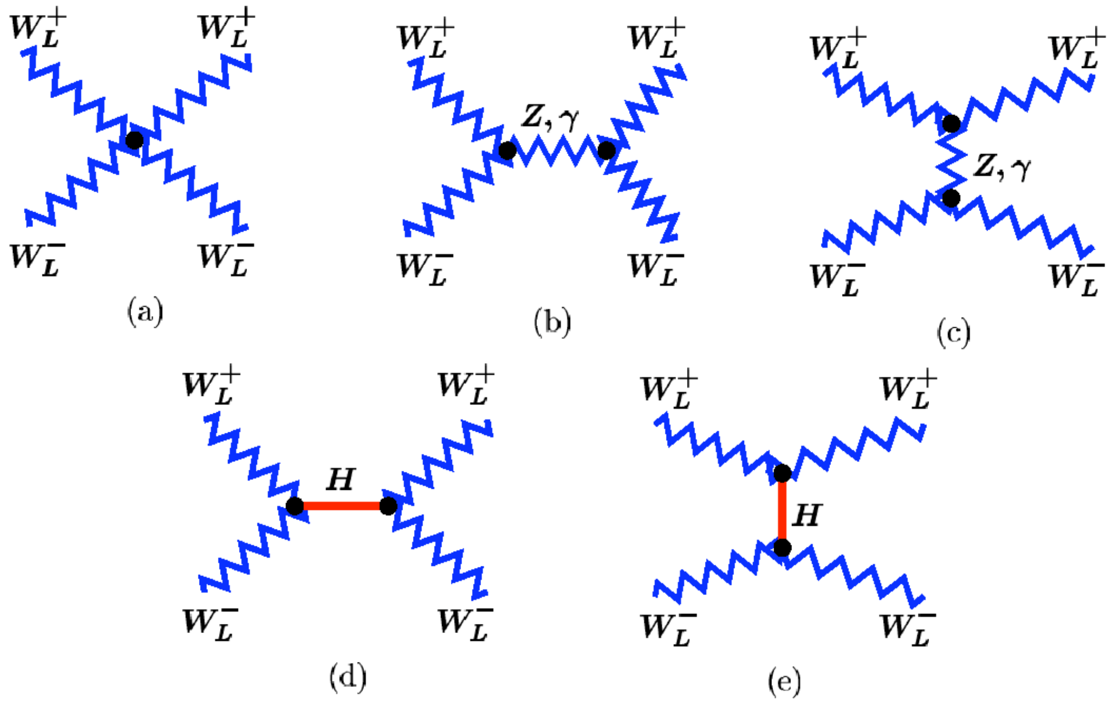
- Couplings of h to VV universally suppressed by $\sin(\beta - \alpha) \equiv \kappa_V^h$
- Couplings of H to VV are complementary: $\cos(\beta - \alpha) \equiv \kappa_V^H$

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 $= v_{\rm SM}$, Φ_0 vev $= 0$

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

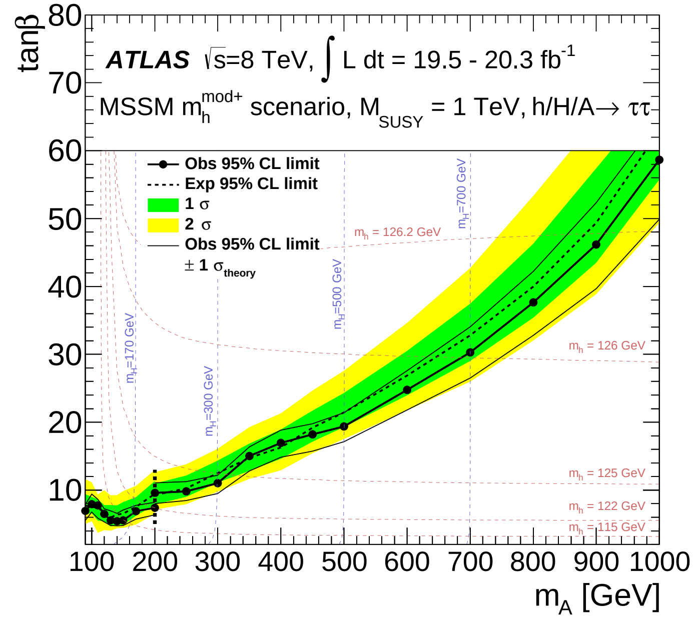
Coupling strengths of Φ_0 to fermions:

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 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: an under-exploited search channel: $gg \to H/A \to t\bar{t}$ at low $\tan\beta$



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

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

Type II: $\tan\beta \times m_{d,\ell}/v_{\rm SM}$ (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 $\tan\beta$

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 $\rightarrow$ $(v_\phi/v_{\rm SM})^2 > (0.287)^2 = 0.082$
$\Rightarrow$ 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 $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ 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.

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!

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!

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

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

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

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

Coupling strength depends on the isospins of the scalars involved:

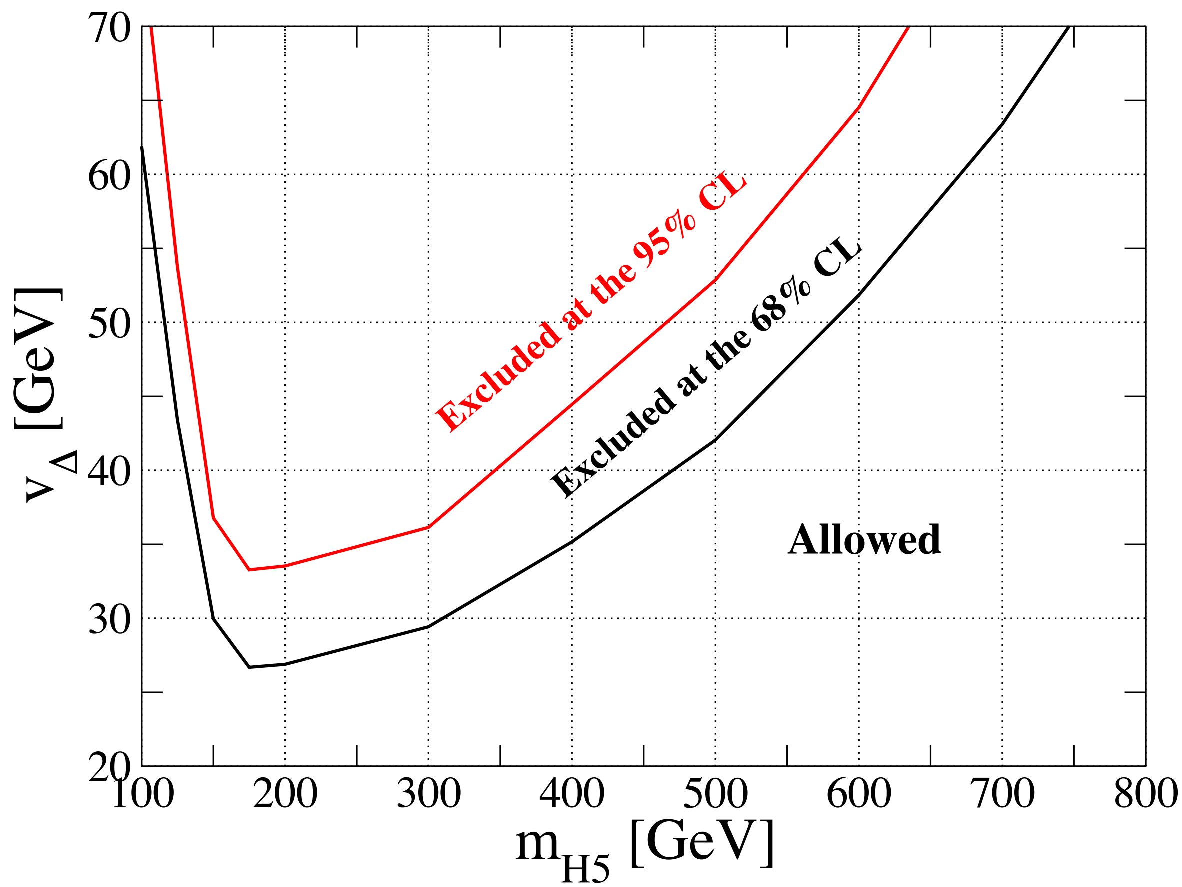
$$g_5^{\rm GM} = \sqrt{2}s_H, \quad g_5^{\rm GGM4} = \sqrt{\frac{24}{5}}s_H, \quad g_5^{\rm GGM5} = \sqrt{\frac{42}{5}}s_H, \quad g_5^{\rm GGM6} = \frac{8}{\sqrt{5}}s_H$$

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



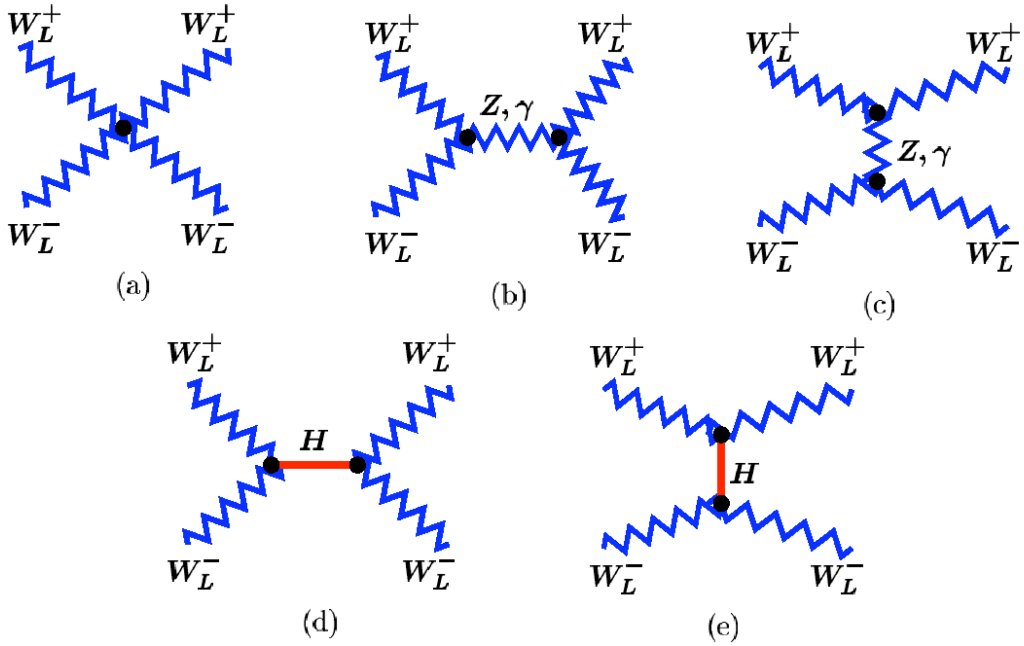
$g_5 = \sqrt{2} s_H$ in GM model

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

Chiang, Kanemura & Yagyu, 1407.5053

What about higher H_5 masses?

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



Graphic: S. Chivukula

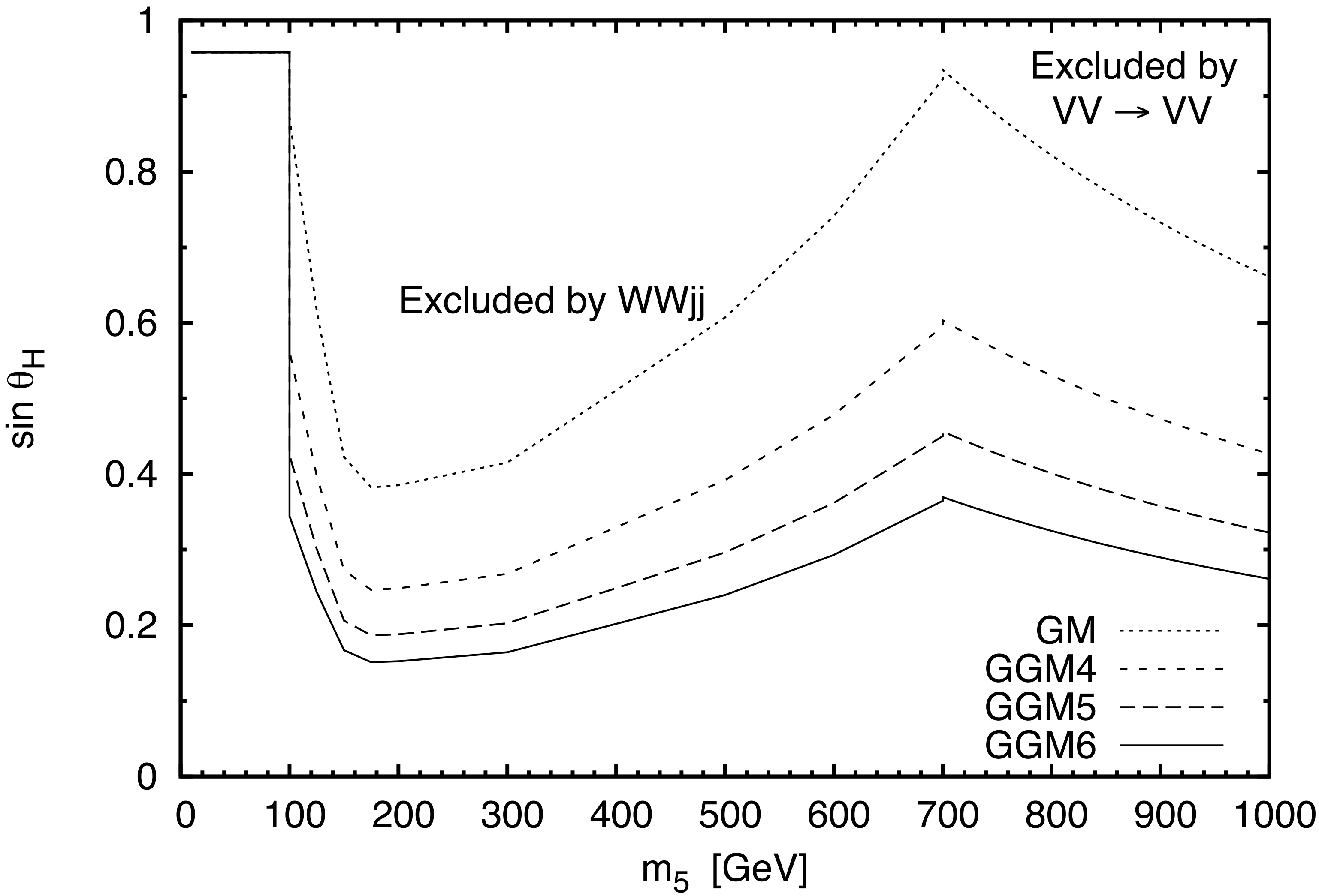
- SM: $m_h^2 < 16\pi v_{\rm SM}^2/5 \simeq (780~\text{GeV})^2$ Lee, Quigg & Thacker 1977

- 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 $(\kappa_V^H)^2 \sim v^4/m_H^4$)



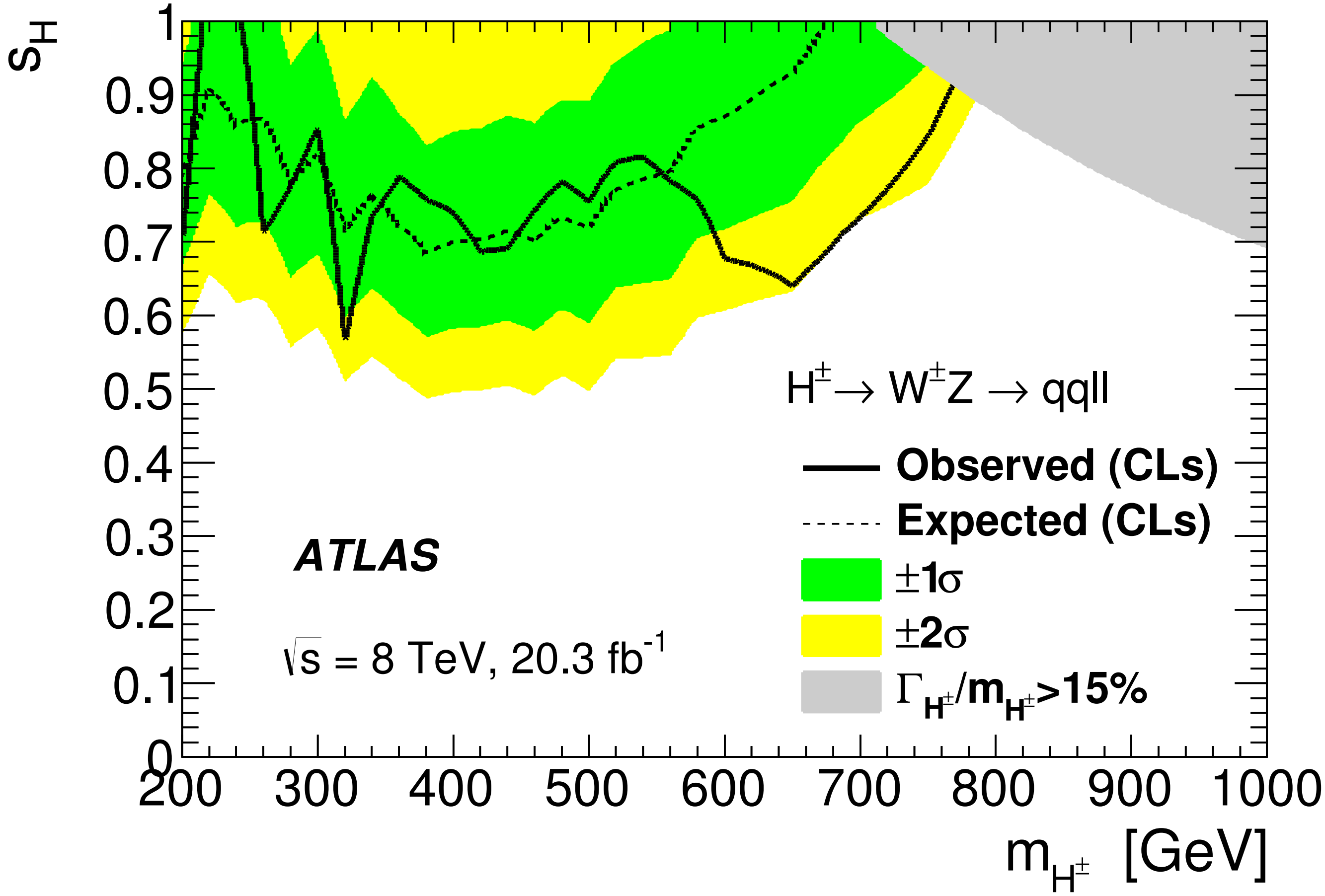
HEL & Rentala, 1502.01275

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

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 $m_5 \gg M_W$

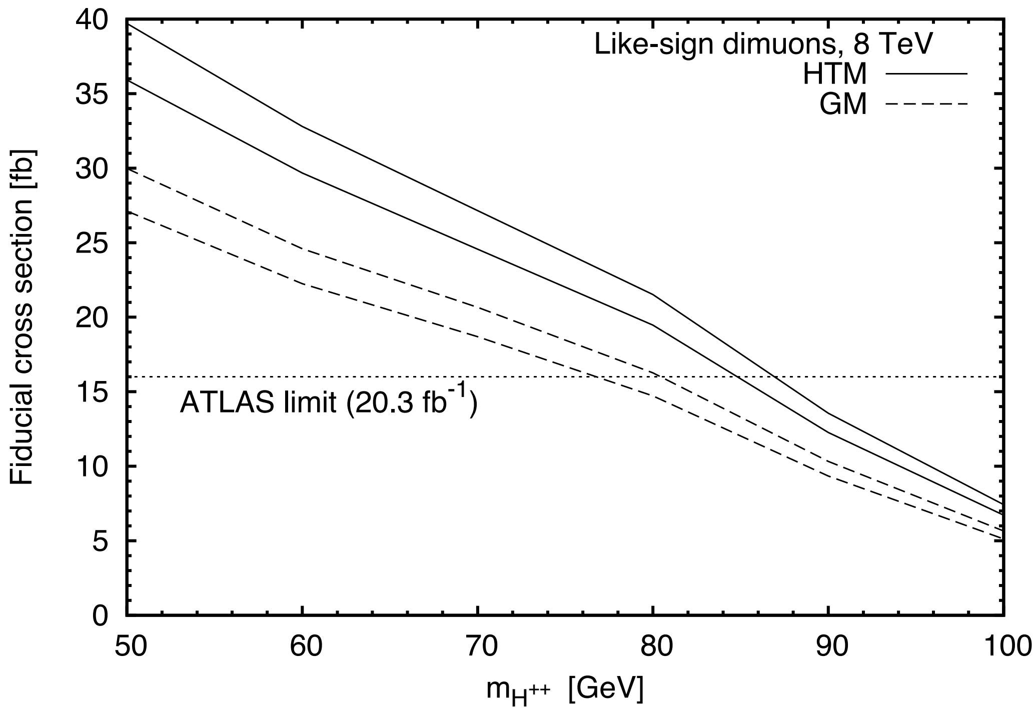
What about lower H_5 masses? pair production, $H_5^{++} \to W^+W^+$

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

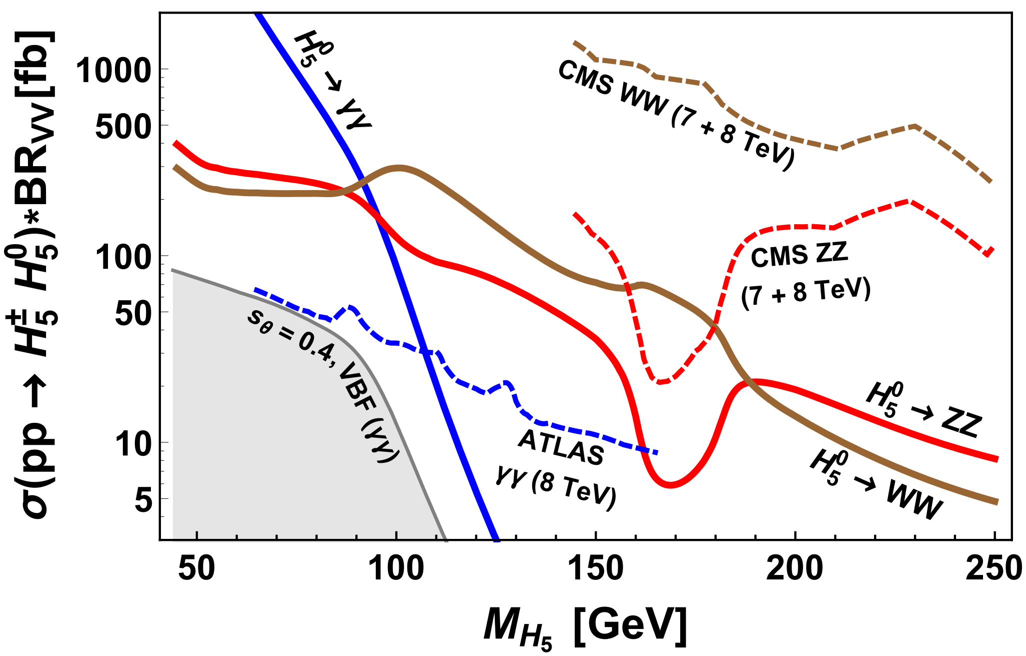
Takes advantage of mass-degeneracy of H_5^{++} and H_5^{+}

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 $H_5^0 \to \gamma\gamma$
(but a full model scan is now 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.