Higgs physics beyond the Standard Model

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ATLAS Canada meeting
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LHC measurements of 125 GeV Higgs boson properties are fully consistent with SM picture:

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?

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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 interesting search channels

Conclusions
Additional sources of fermion masses?

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

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Two-Higgs-Doublet Model

Two doublets: $\Phi_1$ and $\Phi_2$, vevs $v_1^2 + v_2^2 = v_{SM}^2$, $v_2/v_1 \equiv \tan \beta$
- Up-type quark masses from $\Phi_2$: coupling strength $m_u/v_2$
- Down-type quark and lepton masses from $\Phi_2$ (Type I) or $\Phi_1$ (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):

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

First do a change of basis to the Higgs basis:

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

Defined by vacuum expectation values:
$\Phi_h$ vev $= v_{SM}$, $\Phi_0$ vev $= 0$
Two-Higgs-Doublet Model: Higgs basis

\( \Phi \)

\[ \Phi_{h} \text{ vev} = v_{SM}, \, \Phi_{0} \text{ vev} = 0 \]

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

\[ h = \sin(\beta - \alpha) \phi_{h}^{0,r} - \cos(\beta - \alpha) \phi_{0}^{0,r} \]
\[ H = \cos(\beta - \alpha) \phi_{h}^{0,r} + \sin(\beta - \alpha) \phi_{0}^{0,r} \]
\[ A = \phi_{0}^{0,i} \]
\[ H^{\pm} = \phi_{0}^{\pm} \]

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 \( \sin(\beta - \alpha) \equiv \kappa_{h}^{V} \)
- Couplings of \( H \) to \( VV \) are complementary: \( \cos(\beta - \alpha) \equiv \kappa_{H}^{V} \)

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:

\[ \kappa_{V}^{h} \sim 1 \pm 0.2 \quad \Rightarrow \quad |\kappa_{V}^{H}| \lesssim 0.45 \]

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

- 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 $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$:

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

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

\[ \mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3 [H_1^\dagger H_2 + \text{h.c.}] + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1) (H_2^\dagger H_2) \]

\[ + Z_4 (H_1^\dagger H_2) (H_2^\dagger H_1) + \left\{ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + [Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\}, \]

(2)

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

Minimization of potential yields \( Y_1 = -Z_1 v^2/2, \quad Y_3 = -Z_6 v^2/2 \)

Only one dimensionful parameter \( Y_2 \equiv M^2 \), can be large \( \gg v^2 \)

Masses:

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

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

\[ m_h^2 \sim Z_1 v^2 \quad m_H^2 \sim M^2 \quad \cos(\beta - \alpha) \sim Z_6 v^2/M^2 \sim v^2/M^2 \]

\[ \Rightarrow \text{Fast decoupling!} \quad \text{Bad news for VBF} \rightarrow H \text{ and } H \rightarrow WW/ZZ \text{ at high } m_H \]

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

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Two-Higgs-Doublet Model: fermion couplings

Two doublets: $\Phi_1$ and $\Phi_2$, vevs $v_1^2 + v_2^2 = v_{SM}^2$, $v_2/v_1 \equiv \tan \beta$
- Up-type quark masses from $\Phi_2$: coupling strength $m_u/v_2$
- Down-type quark and lepton masses from $\Phi_2$ (Type I) or $\Phi_1$ (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: $\Phi_h$ vev = $v_{SM}$, $\Phi_0$ vev = 0

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

Physical Higgs states: $\cos(\beta - \alpha) \simeq Z_6 v_2^2/M^2 \sim v^2/M^2$

$$h = \sin(\beta - \alpha) \phi^{0,r}_h - \cos(\beta - \alpha) \phi^{0,r}_0$$
$$H = \cos(\beta - \alpha) \phi^{0,r}_h + \sin(\beta - \alpha) \phi^{0,r}_0$$
$$A = \phi^{0,i}_0 \quad H^\pm = \phi^\pm_0$$

So $A = \phi^{0,i}_0$, $H^\pm = \phi^\pm_0$, and for decoupling or alignment $H \simeq \phi^{0,r}_0$: the BSM Higgs bosons all live in the $\Phi_0$ doublet.

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Two-Higgs-Doublet Model: fermion couplings

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First do a change of basis to the Higgs basis: $\Phi_h$ vev = $v_{SM}$, $\Phi_0$ vev = 0

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

Coupling strengths of $\Phi_0$ 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

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Two-Higgs-Doublet Model: an under-exploited search channel: $gg \rightarrow H/A \rightarrow t\bar{t}$ at low $\tan \beta$

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

Type II: $\cot \beta \times m_u/v_{\text{SM}}$ (up-type)
Type II: $\tan \beta \times m_d,\ell/v_{\text{SM}}$ (down-type & leptons)

- Nontrivial interference with continuum $gg \rightarrow t\bar{t}$ background
- Expts need theory prediction including signal/background interference, lineshape, & QCD corrections
- Associated prod’n $pp \rightarrow b\bar{b}H/A$, $H/A \rightarrow t\bar{t}$ could help at moderate $\tan \beta$

Dicus, Stange, & Willenbrock, 1994

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Additional (non-doublet) sources of electroweak breaking?

→ models with higher-isospin scalar multiplets
Part of electroweak breaking from a higher-isospin scalar field?

Fermion masses can arise only from SU(2)\textsubscript{L} doublet(s)

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

\[ m_f = y_f v_\phi \left/ \sqrt{2} \right. \]

\[ \phi^0, r \bar{f} f : iy_f / \sqrt{2} = im_f / v_\phi \]

\( F_L \) is doublet, \( f_R \) is singlet, need \( \Phi \) 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

\[ \Phi = \left( \begin{array}{c} \phi^+ \\ (v_\phi + \phi^0, r + i\phi^0, i) / \sqrt{2} \end{array} \right) \]

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

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

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

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

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

$(Q = T^3 + Y/2$, 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 $\rightarrow (v_\phi/v_{SM})^2 > (0.287)^2 = 0.082$

$\Rightarrow$ At least 8.2% of $M^2_{W,Z}$ comes from doublet.

Lots of room for higher-isospin scalar contributions!

Can we constrain this exotic possibility?

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Problem with higher-isospin scalar fields

\[ \rho \equiv \text{ratio of strengths of charged and neutral weak currents} \]

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

\( (Q = T^3 + Y/2, \text{vevs defined as } \langle \phi_k^0 \rangle = v_k/\sqrt{2} \text{ for complex reps and } \langle \phi_k^0 \rangle = v_k \text{ for real reps}) \)

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 \( \rho \) by hand, but icky)

1) Impose global SU(2)_L×SU(2)_R symmetry on scalar sector \( \implies \) 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

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The models

1) Models with global $\text{SU}(2)_L \times \text{SU}(2)_R$ 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:

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

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

Generic experimental probe is diboson resonance search in VBF.

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Georgi-Machacek model  
Georgi & Machacek 1985; Chanowitz & Golden 1985

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

\[ \Phi = \begin{pmatrix} \phi^0 & \phi^+ \\ -\phi^{++} & \phi^0 \end{pmatrix} \quad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{++*} & \xi^0 & \chi^+ \\ \chi^{+++} & -\xi^{++*} & \chi^0 \end{pmatrix} \]

Physical spectrum: Custodial symmetry fixes almost everything!

Bidoublet: 2 \times 2 \rightarrow 3 + 1  
Bitriplet: 3 \times 3 \rightarrow 5 + 3 + 1

- Two custodial singlets mix \rightarrow h^0, H^0

- Two custodial triplets mix \rightarrow (H_3^+, H_3^0, H_3^-) + Goldstones

- Custodial fiveplet \((H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})\) unitarizes \(VV \rightarrow VV\)
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 \( \Rightarrow \) “GGM$_n$”

Bidoublet: \( 2 \times 2 \rightarrow 3 + 1 \)
Bitriplet: \( 3 \times 3 \rightarrow 5 + 3 + 1 \)
Biquartet: \( 4 \times 4 \rightarrow 7 + 5 + 3 + 1 \)
Bipentet: \( 5 \times 5 \rightarrow 9 + 7 + 5 + 3 + 1 \)
Bisextet: \( 6 \times 6 \rightarrow 11 + 9 + 7 + 5 + 3 + 1 \)

Larger bi-$n$-plets forbidden by perturbative unitarity of weak charges!
Hally, HEL, & Pilkington 1202.5073

- Two custodial singlets mix \( \rightarrow h^0, H^0 \)
- Two custodial triplets mix \( \rightarrow (H^+_3, H^0_3, H^-_3) + \) Goldstones
- Custodial fiveplet \( (H^{++}_5, H^+_5, H^0_5, H^-_5, H^{--}_5) \) unitarizes \( VV \rightarrow VV \)
- Additional states

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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! 

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

$H_5VV$ couplings are nonzero: very different from 2HDM!

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

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

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

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

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!

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Constraint from VBF $H^\pm_5 \to W^\pm W^\pm \to$ same-sign dileptons

Theorist-recasting of ATLAS $W^\pm W^\pm jj$ cross-section measurement \[ \text{ATLAS, 1405.6241} \]

⇒ put limit on VBF $\to H^\pm_5$ 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

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What about higher $H_5$ masses?

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

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

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

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

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

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

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\begin{align*}
  g_5^{GM} &= \sqrt{2}s_H, &
  g_5^{GGM4} &= \sqrt{\frac{24}{5}}s_H, &
  g_5^{GGM5} &= \sqrt{\frac{42}{5}}s_H, &
  g_5^{GGM6} &= \frac{8}{\sqrt{5}}s_H
\end{align*}

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

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Constraint from VBF $H^\pm_5 \to W^\pm Z \to qq\ell^+\ell^-$

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

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

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

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

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

$$
\Rightarrow m_5 \gtrsim 76 \text{ GeV}, \\
\text{independent of } g_5
$$

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

HEL & Rentala, 1502.01275

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What about lower $H_5$ masses?

Scalar pair prod’n $q\bar{q'} \rightarrow W^* \rightarrow H_5^0H_5^\pm$: 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 loop contributions to $H_5^0 \rightarrow \gamma\gamma$
(but a full model scan is now feasible)

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

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

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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?
   → two-Higgs-doublet models

2. Additional (non-doublet) source of electroweak breaking?
   → models with higher-isospin scalar multiplets

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