$H \rightarrow hh$ in the Georgi-Machacek model

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Introduction: motivating the Georgi-Machacek model

Can we constrain the possibility that “exotic” Higgs fields (isospin $> 1/2$) contribute to electroweak symmetry breaking?

Generically this is very strongly constrained by the $\rho$ parameter:

$$\rho \equiv \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M_Z^2}{g^2/M_W^2} = \frac{v^2_\phi + a\langle X^0 \rangle^2}{v^2_\phi + b\langle X^0 \rangle^2}$$

\[ a = 4 \left[ T(T + 1) - Y^2 \right] c \quad Q = T^3 + Y; \text{ SM doublet: } Y = 1/2 \]

\[ b = 8Y^2 \]

Expt: $\rho = 1.00039 \pm 0.00019$ (2018 PDG)

Need to do some model-building; otherwise $v_{\text{exotic}} \ll v_{\text{doublet}}$. 

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There are only two known approaches:

1) Use the septet \((T, Y) = (3, 2)\): \(\rho = 1\) by accident!
   Doublet \(\left(\frac{1}{2}, \frac{1}{2}\right)\) + septet \((3, 2)\): Scalar septet model
   Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

2) Use global \(\text{SU}(2)_L \times \text{SU}(2)_R\) imposed on the scalar potential
   Global \(\text{SU}(2)_L \times \text{SU}(2)_R \rightarrow \) custodial \(\text{SU}(2)\) ensures tree-level \(\rho = 1\)
   Doublet + triplets \((1, 0) + (1, 1)\): Georgi-Machacek model
   Georgi & Machacek 1985; Chanowitz & Golden 1985
   Doublet + quartets \(\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)\): Generalized Georgi-
   Doublet + quintets \((2, 0) + (2, 1) + (2, 2)\): Machacek models
   Doublet + sextets \(\left(\frac{5}{2}, \frac{1}{2}\right) + \left(\frac{5}{2}, \frac{3}{2}\right) + \left(\frac{5}{2}, \frac{5}{2}\right)\):
   Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015
   Larger than sextets \(\rightarrow\) too many large multiplets, violates perturbativity

Can also have duplications, combinations \(\rightarrow\) ignore that here.
Georgi-Machacek model  
Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet $+$ triplets $(1,0) + (1,1)$ in a **bi-triplet:**

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

Global $SU(2)_L \times SU(2)_R \rightarrow$ custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_\chi$

**Physical spectrum:**

**Bi-doublet:** $2 \otimes 2 \rightarrow 1 \oplus 3$

**Bi-triplet:** $3 \otimes 3 \rightarrow 1 \oplus 3 \oplus 5$

- Two custodial singlets mix $\rightarrow h, H \ m_h, m_H$, angle $\alpha$
  
  Usually identify $h = h(125)$

- Two custodial triplets mix $\rightarrow (H^+_3, H^0_3, H^-_3) \ m_3 +$ Goldstones

  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan \beta \rightarrow \cot \theta_H$

- Custodial fiveplet $(H^{++}_5, H^+_5, H^0_5, H^-_5, H^{--}_5) \ m_5$

  Fermiophobic; $H_5VV$ couplings $\propto s_H \equiv \sqrt{8}v_\chi/v_{SM}$

  $s_H^2 \equiv$ exotic fraction of $M_W^2, M_Z^2$

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Usual LHC searches:

\[ VBF \rightarrow H_{5}^{\pm\pm} \rightarrow W^{\pm}W^{\pm} \]

\[ VBF \rightarrow H_{5}^{\pm} \rightarrow W^{\pm}Z \]

Cross section \( \propto s_{H}^{2} \equiv \text{fraction of } M_{W}^{2}, M_{Z}^{2} \text{ due to exotic scalars} \)
Most stringent constraint: CMS, arXiv:1709.05822

Table 3: Estimated signal and background yields after the selection. The statistical uncertainties are reported for all six channels, while the sums are reported with the statistical and systematic uncertainties added in quadrature. The processes contributing to less than 1% of the total background are not listed, but included in the total background yield.

<table>
<thead>
<tr>
<th>Process</th>
<th>Data</th>
<th>Signal + total bkg.</th>
<th>Signal</th>
<th>Total bkg.</th>
<th>Nonprompt</th>
<th>WZ</th>
<th>QCD WW</th>
<th>(W_g)</th>
<th>Triboson</th>
<th>Wrong sign</th>
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<td></td>
<td>14</td>
<td>19.0 ± 1.9</td>
<td>6.2 ± 0.2</td>
<td>12.8 ± 1.9</td>
<td>5.6 ± 1.7</td>
<td>3.0 ± 0.2</td>
<td>0.6 ± 0.1</td>
<td>1.4 ± 0.5</td>
<td>0.8 ± 0.2</td>
<td>1.5 ± 0.6</td>
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<td>63</td>
<td>67.6 ± 3.8</td>
<td>24.7 ± 0.4</td>
<td>42.9 ± 3.8</td>
<td>24.9 ± 3.6</td>
<td>8.5 ± 0.3</td>
<td>1.7 ± 0.1</td>
<td>3.6 ± 0.9</td>
<td>2.2 ± 0.4</td>
<td>1.4 ± 0.6</td>
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<td>40</td>
<td>44.1 ± 3.4</td>
<td>18.3 ± 0.4</td>
<td>25.7 ± 3.4</td>
<td>18.4 ± 3.3</td>
<td>4.4 ± 0.2</td>
<td>1.3 ± 0.1</td>
<td>0.2 ± 0.2</td>
<td>1.2 ± 0.4</td>
<td>1.1 ± 0.6</td>
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<td>10</td>
<td>11.8 ± 1.8</td>
<td>2.5 ± 0.1</td>
<td>9.4 ± 3.4</td>
<td>5.0 ± 1.6</td>
<td>1.9 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>0.8 ± 0.4</td>
<td>0.6 ± 0.3</td>
<td>0.8 ± 0.6</td>
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<td>48</td>
<td>38.9 ± 3.3</td>
<td>8.7 ± 0.2</td>
<td>30.2 ± 3.3</td>
<td>19.9 ± 3.2</td>
<td>5.2 ± 0.3</td>
<td>0.6 ± 0.1</td>
<td>2.3 ± 0.7</td>
<td>0.5 ± 0.3</td>
<td>0.9 ± 0.6</td>
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<td>26</td>
<td>23.9 ± 2.8</td>
<td>6.5 ± 0.2</td>
<td>17.4 ± 3.3</td>
<td>14.2 ± 2.8</td>
<td>2.2 ± 0.2</td>
<td>0.4 ± 0.1</td>
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<td>0.5 ± 0.4</td>
<td>0.8 ± 0.6</td>
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<tr>
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<td>201</td>
<td>205 ± 13</td>
<td>66.9 ± 2.4</td>
<td>138 ± 13</td>
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<td>25.1 ± 1.1</td>
<td>1.1 ± 0.4</td>
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</tbody>
</table>

Searches for \(\text{VBF} \rightarrow H_{5}^{\pm} \rightarrow W^\pm Z\): not quite as constraining

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WG3 Extended Scalars  
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Can GM model provide a benchmark for $H \rightarrow hh$?

- Custodial singlet $H$ couples to fermion pairs
  $\rightarrow$ production via gluon fusion

- $Hhh$ coupling can be substantial

- $h$ BRs are generally SM-like in allowed parameter regions

$H f \bar{f}$ and $Hhh$ couplings both go to zero in $s_H \rightarrow 0$ limit, but direct-search constraints are still far away from this limit.
Cross section constrained so far: ATLAS, arXiv:1804.06174
Full parameter scan in GM model: (Preliminary)

GMCALC 1.4.1, 13 TeV LHC
excluded by H^{++} searches
allowed
ATLAS limit, 1804.06174

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Dependence on $s_H$: (Preliminary)

- GMCALC 1.4.1, 13 TeV LHC excluded by $H^{++}$ searches
- Allowed, $s_H = 0.1$
- $0.2$
- $0.3$
- $0.4$
- ATLAS limit, 1804.06174

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Summary:

Georgi-Machacek model can provide an interesting benchmark for $gg \to H \to hh$ searches.

Current $H \to hh$ sensitivity ($\lesssim 36 \text{ fb}^{-1}$, 13 TeV) probes otherwise-unexcluded model points up to $m_H \sim 1 \text{ TeV}$!

Feedback wanted: how best to provide this model interpretation to the experiments?
BACKUP SLIDES
The H5plane benchmark is not so interesting for $H \rightarrow hh$ searches:

H5plane benchmark designed for VBF $\rightarrow H_{5}^{\pm\pm}$, $H_{5}^{\pm}$ searches; two free parameters are $m_{5}$ and $s_{H}$, other parameters fixed
Georgi-Machacek model  

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets \((1, 0) + (1, 1)\) in a bi-triplet:

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

Global \(SU(2)_L \times SU(2)_R \rightarrow\) custodial symmetry \(\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_X\)

Most general scalar potential invariant under \(SU(2)_L \times SU(2)_R\):

\[
V(\Phi, X) = \frac{\mu_2^2}{2} \text{Tr}(\Phi^\dagger \Phi) + \frac{\mu_3^2}{2} \text{Tr}(X^\dagger X) + \lambda_1 [\text{Tr}(\Phi^\dagger \Phi)]^2 + \lambda_2 \text{Tr}(\Phi^\dagger \Phi) \text{Tr}(X^\dagger X) + \lambda_3 \text{Tr}(X^\dagger XX^\dagger X)
\]

\[
+ \lambda_4 [\text{Tr}(X^\dagger X)]^2 - \lambda_5 \text{Tr}(\Phi^\dagger \tau^a \Phi \tau^b) \text{Tr}(X^\dagger t^a X t^b)
\]

\[
- M_1 \text{Tr}(\Phi^\dagger \tau^a \Phi \tau^b) (UXU^\dagger)_{ab} - M_2 \text{Tr}(X^\dagger t^a X t^b) (UXU^\dagger)_{ab}
\]

9 parameters, 2 fixed by \(G_F\) and \(m_h\) → 7 free parameters.  

Aoki & Kanemura, 0712.4053  
Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526  
Hartling, Kumar & HEL, 1404.2640
Both approaches have theoretical “issues”:

1) Can’t give the septet a vev through spontaneous breaking without generating a physical massless Goldstone boson.

   Have to couple it to the SM doublet through a dimension-7 $X \Phi^* \Phi^5$ term [Hisano & Tsumura 2013]

   Need the UV completion to be nearby!

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

   Special relations among params of full gauge-invariant scalar potential can only hold at one energy scale: violated by running due to hypercharge. [Garcia-Pepin, Gori, Quiros, Vega, Vega-Morales, Yu 2014]

   Need the UV completion to be nearby!

This talk: quantify (2) in the Georgi-Machacek model.