Vector-like Fermions and the Electroweak Phase Transition

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(Work with H. Davoudiasl & I. Lewis, 1211.3449)

Beyond the SM after the first LHC run, GGI

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A SM-like Higgs

Overall good agreement with SM expectations... but still room for interesting deviations.
Precise measurement of Higgs properties can illuminate nature of EW phase transition

\[ V(\phi) \]

In the SM, with \( m_H = 125 \text{ GeV} \): a smooth crossover \( (1^{st}-\text{order PT only for } m_H \lesssim 80 \text{ GeV}) \)

But deviations (due to new physics) might have potentially important implications

- Baryon Asymmetry of the Universe
- Gravitational wave signals
Finite temperature: thermal masses + new cubic term in $\phi$:

$$V(\phi, T) \sim m(T)^2 \phi^2 + E T \phi^3 + \lambda(T) \phi^4$$

- When positive: min. at origin
- "far away min.": $\phi \sim E T / \lambda$

$$\frac{\phi_c}{T_c} \sim \frac{E}{\lambda} \sim \frac{E \nu^2}{m_h^2}$$

Small $E$: $\phi_c / T_c \ll 1$

Should be $> 1$, for EW baryogenesis

(need non-perturbative methods to establish nature of phase transition)
New physics required if the EWPhT plays a role in generation of the BAU

``Lore’’: to strengthen the EWPhT, requires new *bosonic* degrees of freedom to either

- change the Higgs potential at tree-level (e.g. adding singlets)
- enhance the $E$-term at loop level

Both cases can be thought as relying on effective cubic terms

Typically, new fermions not thought to be particularly useful for this purpose...

... they do not induce a cubic term

In light of Higgs discovery:
Cohen, Morrissey & Pierce, 1203.2924
Carena, Nardini, Quirós & Wagner, 1207.6330
Fok, Kribs, Martin & Tsai, 1208.2784
Chung, Long & Wang, 1209.1819
Huan, Shu & Zhang, 1210.0906
Laine, Nardini & Rummikainen, 1211.7344
However, I know of one previous example where fermions can help the EWPhT:

- Use the fact that when their mass depends on the Higgs vev, it is different in the broken and unbroken phases.
- **Decoupling** from thermal bath in **broken phase** leads to reheating, delaying the phase transition: increase in $\phi_c/T_c$
Higgs Di-photon Rate

Loop-level processes prime suspects for deviations from SM

\[ R_{\gamma\gamma}^{\text{ATLAS}} = 1.80^{+0.42}_{-0.36} \]
\[ R_{\gamma\gamma}^{\text{CMS}} = 0.78^{+0.28}_{-0.26} \]

(7 TeV)

\[ R_{\gamma\gamma}^{\text{ATLAS}} = 1.65^{+0.34}_{-0.30} \]
\[ R_{\gamma\gamma}^{\text{CMS}} = 1.56 \pm 0.43 \]

(8 TeV)

(pre-Moriond 2013)

(post-Moriond 2013)

**Signal strength**

- Untagged 0
- Untagged 1
- Untagged 2
- Untagged 3
- Di-jet
- Di-jet loose
- Di-jet tight
- One-lepton
- Low-mass two-jet
- Loose high-mass two-jet

**Event Class**

- Combined
- MET
- Muon
- Electron

**8 TeV**

\( \mu = 7 \text{ TeV}, \ L = 19.6 \text{ fb}^{-1} \) (MVA)

\( \mu = 8 \text{ TeV}, \ L = 5.1 \text{ fb}^{-1} \) (MVA)

**Best Fit**

\( \sigma / \sigma_{\text{SM}} = 0.78 \pm 0.28 \pm 0.26 \)
Vector-like Systems

Higgs diphoton rate, normalized to SM

\[ R_{\gamma\gamma} \simeq \left| 1 - \frac{F_{1/2}(\tau_1) Q_1^2}{F_{SM}} \frac{\partial \ln m_1(v)}{\partial \ln v} \right|^2 \]

Recent interest in **vector-like systems**: appeal to ``level repulsion’’:

\[ M = \begin{pmatrix} m_\psi & \frac{1}{\sqrt{2}} y v \\ \frac{1}{\sqrt{2}} y c v & m_\chi \end{pmatrix} \]

- **Enhancement**
- **Suppression**

CMQW mechanism: if BSM states electromagnetically charged → Higgs diphoton rate suppressed

But there is a **different mechanism**, that can be consistent with a diphoton enhancement, and more intimately connected to fermionic nature of new physics

(Davoudiasl, Lewis & EP, 1211.3449)
A Simple Model

Minimal extension (for illustration):

$$(\psi, \psi^c) \sim (1, 2)_{\pm 1/2} \quad (\chi, \chi^c) \sim (1, 1)_{\mp 1}$$

(“vector-like leptons”)

Mass and Yukawa terms:

$$-\mathcal{L}_m = -m_\psi \psi\psi^c + m_\chi \chi\chi^c + yH\psi\chi + y_c H^\dagger \psi^c \chi^c + \text{h.c.}$$

Interesting region for EWPhT when fermion masses hierarchical. Assume $m_\psi \gg m_\chi$

EFT analysis with $\psi$ integrated out: may be more general than simple model
For $m_\psi \gg v, m_\chi$, integrate out "ψ" and obtain EFT for (SM + "χ"):

\[ \Delta \mathcal{L} = 2G_m H^\dagger H \chi \chi^c \]

where 
\[ G_m = \frac{y^2}{2(m_\psi - m_\chi)} > 0 \]

Light vector-like fermion mass is 
\[ m_1 = m_\chi - G_m v^2 \]

Interactions of light state with physical Higgs (after EWSB):

\[ \mathcal{L}_{\text{Yuk}} = y_{\text{eff}} h \chi \chi^c + \text{h.c.} \]

\[ y_{\text{eff}} = -2G_m v < 0 \]

Interesting diphoton enhanc. when

\[ y_{\text{eff}} \sim \mathcal{O}(1) \quad \text{and} \]

\[ m_1 \sim 100 - 200 \text{ GeV} \]
T = 0 Potential in EFT

1-loop effective potential (T = 0)

\[ \Delta V_{\text{Eff}} = -\frac{4}{64\pi^2} m_1(\phi)^4 \left[ \ln \frac{m_1(\phi)^2}{\mu^2} - \frac{3}{2} \right] + \text{counterterms} \]

(in $\overline{MS}$ scheme)

Noting that $\phi^6$ and $\phi^8$ terms are divergent:

\[ \text{“}V_{\text{Tree}}\text{”} = -\frac{1}{2} \bar{\mu}^2 \phi^2 + \frac{1}{4} \bar{\lambda} \phi^4 + \frac{1}{6} \bar{\gamma} \phi^6 + \frac{1}{8} \bar{\delta} \phi^8 \]

However, within the UV model, they are determined...

\[ \bar{\gamma} \text{ and } \bar{\delta} \]

arbitrary within EFT

(Davoudiasl, Lewis & EP, 1211.3449)
Matching and Running

However, within the UV model, they are determined...

\[ \tilde{\gamma} = \tilde{\gamma}_{\text{th}} + \tilde{\gamma}_{\text{RG}} \]
\[ \tilde{\delta} = \tilde{\delta}_{\text{th}} + \tilde{\delta}_{\text{RG}} \]

with threshold contributions

\[ \tilde{\gamma}_{\text{th}} = \frac{Z_{\gamma} y^6}{16\pi^2} \frac{m_\psi(m_\psi^2 + 7m_\chi m_\psi - 2m_\chi^2)}{(m_\psi - m_\chi)^5} \sim \frac{y^6}{16\pi^2} \frac{1}{m_\psi} \]
\[ \tilde{\delta}_{\text{th}} = -\frac{Z_{\delta} y^8}{48\pi^2} \frac{7m_\psi^3 + 27m_\chi m_\psi^2 - 4m_\chi^3}{(m_\psi - m_\chi)^7} \sim -\frac{7y^8}{48\pi^2} \frac{1}{m_\psi^4} \]

and running contributions

\[ \tilde{\gamma}_{\text{RG}} \approx -\frac{3G_m^3 m_\chi}{2\pi^2} \ln \left( \frac{m_\psi^2}{\mu^2} \right) \]
\[ \tilde{\delta}_{\text{RG}} \approx \frac{G_m^4}{2\pi^2} \ln \left( \frac{m_\psi^2}{\mu^2} \right) \]

- Determined by EFT only
- This is the only difference with naive CW potential in UV model (actually, just the sign)
Quartic Instabilities?

RG running of Higgs quartic (below $m_\psi$):

$$16\pi^2 \frac{d\lambda}{dt} = \lambda \left( 6\lambda - 9g_2^2 - 3g_1^2 + 12y_t^2 \right) - 6y_t^4 + \frac{3}{8} \left[ 2g_2^2 + (g_2^2 + g_1^2)^2 \right] - 48G_m^2 m_X^2$$

from new light fermion

fermionic terms induce "instability"

Quartic coupling from effective potential at low and high temperatures:

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• Effective Potential in EFT shows instability at
  \( \sim 600 \text{ GeV} \gg \text{EW scale} \)
The Shape of the Eff. Pot.

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(Davoudiasl, Lewis & EP, 1211.3449)
The Shape of the Eff. Pot.

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- At \( T = 0 \) and \( \phi \sim \text{EW} : m^2 < 0, \lambda > 0 \)

- At \( T \sim \text{EW} : m^2 > 0, \lambda < 0 \)
  \( \text{stabilization by higher-dim operators} \)

(Davoudiasl, Lewis & EP, 1211.3449)
EFT with $\psi$ integrated out: match $\phi$ correlators and run from $m_\psi$ to $m_\chi \sim v$

- captures "small $\phi$" behavior, but not large
  (finite radius of convergence of Taylor expansion of effective potential)

- Coleman-Weinberg potential in full UV model suggests instability delayed to multi-TeV scale ($\sim m_\psi$)

- Thus, in non-renormalizable theories one should be careful in interpreting the familiar quartic instability
The Mechanism

Keep it simple by dropping non-crucial terms, e.g. cubic:

\[ V(\phi, T) \sim \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4 + \frac{1}{6} \gamma \phi^6 \]

When \( \mu^2 > 0, \lambda < 0, \gamma > 0 \)

``far away min.``: \( \phi \sim \sqrt{-\lambda/\gamma} \)

Degenerate with min. at origin when \( \lambda^2 \sim 6\gamma \mu^2 \ll 1 \) (determines critical temp.)

Also estimate

\[ \phi_c \sim \sqrt[4]{\mu/\gamma} \]

\( \Rightarrow \)

may get sizeable \( \phi_c/T_c \) !

Similar to proposal by Grojean, Servant & Wells. Here, \( \lambda < 0 \) from fermions and finite Temp.

(hep-ph/0407019)

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EFT Agnostic Analysis

- Strength of the phase transition ($\phi_c/T_c$) in

$$-y_{\text{eff}} = 2G_m v$$

(coupling of light fermion to Higgs)

versus

$$\bar{\gamma}(\mu = m_\chi)$$

(dim-6 stabilizing operator)

Observations:

- Need sizeable underlying $y, y_c \sim \text{few}$
- Sensitivity to UV completion through stabilizing higher-dim. operators
- Consistent with important Higgs diphoton rate enhancement

Star is a benchmark in UV model with:

<table>
<thead>
<tr>
<th>$m_\psi$ (TeV)</th>
<th>$m_\chi$ (GeV)</th>
<th>$y = y_c$</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>300</td>
<td>4</td>
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Green regions: effect of 10% (1%) higher-loop corrections at the matching scale
In the heavy doublet limit: \( m_\psi \gg m_\chi, v \), leading contribution to \( T \) from

\[
\Delta T \sim \frac{1}{16\pi s_W^2 c_W^2} \frac{y^2 y_c^2 v^4}{M_Z^2 m_\psi^2}
\]

(may be sizeable...)

The \( S \)-parameter is less constraining in the same limit:

\[
\Delta S \sim \frac{2y^2 v^2}{9\pi m_\psi^2} [6 \ln(m_\psi/m_\chi) - 7]
\]
A Custodial Extension

Two important shortcomings so far:

- In spite of large $m_\psi$, sizeable $T$ parameter suggests imposing custodial symmetry
- Lightest charged state must decay (so far stable)

Both can be addressed by adding a vector-like ``RH neutrino'', $(n, n^c)$

$$-\Delta \mathcal{L}_m = m_n nn^c + \tilde{y} H^\dagger \psi n + \tilde{y}_c H \psi^c \chi^c + \text{h.c.}$$

When $y = \tilde{y}$, $y_c = \tilde{y}_c$ and $m_n = -m_\chi$, can rewrite as $SU(2)_L \times SU(2)_R$ invariant:

$$-\mathcal{L}_{\text{Yuk}} = y \psi \Phi \xi + y_c \psi^c \Phi \xi^c + \text{h.c}$$

with $\xi^{(e)} \equiv \begin{pmatrix} n^{(e)} \\ -\chi^{(e)} \end{pmatrix}$, $\Phi \equiv \begin{pmatrix} H^0^* \\ -H^- \\ H^0 \end{pmatrix}$

In this limit $T = 0$. Need to ensure neutral lightest state, which breaks custodial softly.
## A Detailed Example

### Input parameters:

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<tbody>
<tr>
<td>$m_\psi$</td>
<td>4 TeV</td>
<td>$m_\chi$</td>
<td>300 GeV</td>
<td>$m_n$</td>
<td>$-250$ GeV</td>
<td>$y$</td>
<td>$\tilde{y}$</td>
<td>4</td>
<td>$y_c$</td>
<td>3.5</td>
<td>$\tilde{y}_c$</td>
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### Vector-like spectrum:

#### At $T = 0$

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<tr>
<td>Charged</td>
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<td>Neutral</td>
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<tr>
<td>$m_2^\pm$</td>
<td>4.11 TeV</td>
<td>$m_2^0$</td>
<td>4.11 TeV</td>
<td>$m_1^\pm$</td>
<td>189 GeV</td>
<td>$m_1^0$</td>
<td>140 GeV</td>
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#### At $T = T_c$

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<tr>
<td>$m_2^\pm$</td>
<td>4.06 TeV</td>
<td>$m_2^0$</td>
<td>4.06 TeV</td>
<td>$m_1^\pm$</td>
<td>240 GeV</td>
<td>$m_1^0$</td>
<td>191 GeV</td>
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### Phase transition:

- $\phi_c = 179.3$ GeV
- $T_c = 158.4$ GeV
- $\phi_c/T_c = 1.13$

Bubbles nucleate slightly below $T_c$

### EWPT and diphoton enhancement:

- $\Delta T \sim 10^{-4}$
- $\Delta S \approx 0.04$
- $\Delta U \sim 10^{-6}$
- $R_{\gamma\gamma} \approx 1.5$

### Consistent at 95% CL with current PDG ellipse

Look forward to further developments!

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Conclusions & Outlook

• We illustrated in a simple model the potentially far-reaching consequences of deviations from the SM Higgs properties in answering long-standing questions:

  - The nature of the EWPhT itself
  - The relevance of EW scale physics in the generation of the BAU (details to be worked out)

• Within the model:

  \[ V'''(v) = 3m_H^2/v + 8\gamma v^3 \]

  \[ \mathcal{O}(1) \text{ correction} \]

  \[ \rightarrow \] expect 40-60% suppression in \( gg \rightarrow HH \)

  \[ \rightarrow \] measurement of stabilizing effect (a crucial ingredient in underlying mechanism)

  - Measurement of lightest charged fermion mass + diphoton rate: \( (m_\chi, G_mv) \)

• **Main ingredients:**
  - a fermion state in the few TeV scale
  - a parametrically lighter fermion state
  - Underlying Yukawa interactions with \( y \sim 3 - 4 \)

  \{ \text{Rather familiar from (warped) extra-dimensional constructions!} \}