Vector-like Fermions and the Electroweak Phase Transition

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

Fermilab Theory Seminar

May 14, 2013

ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

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A CONFESSION

I still have *faith* that there is physics BSM... at the ``TeV scale"

EWSB may be well-described by the SM Higgs sector...

... but hard to believe it is more than a
`*phenomenological description*'

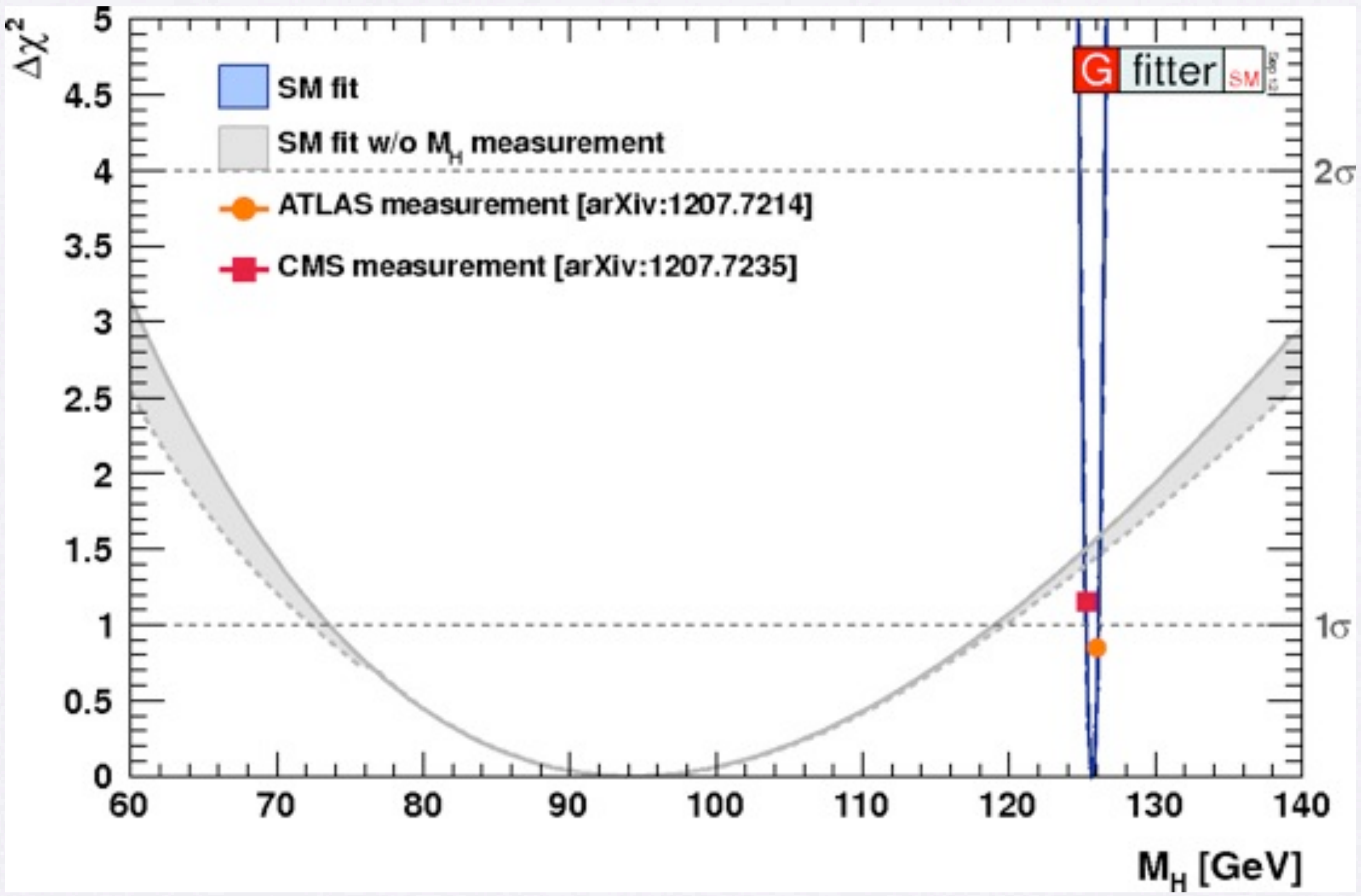
What is the (dynamical) mechanism leading to EWSB?

(Landau-Ginzburg vs BCS theory of superconductivity)

And of course: neutrino masses, DM, BAU

Electroweak Precision Tests

Agreement with light, weakly coupled Higgs: **an impressive triumph!**



$$\chi^2_{\rm min}/DOF = 21.8/14$$

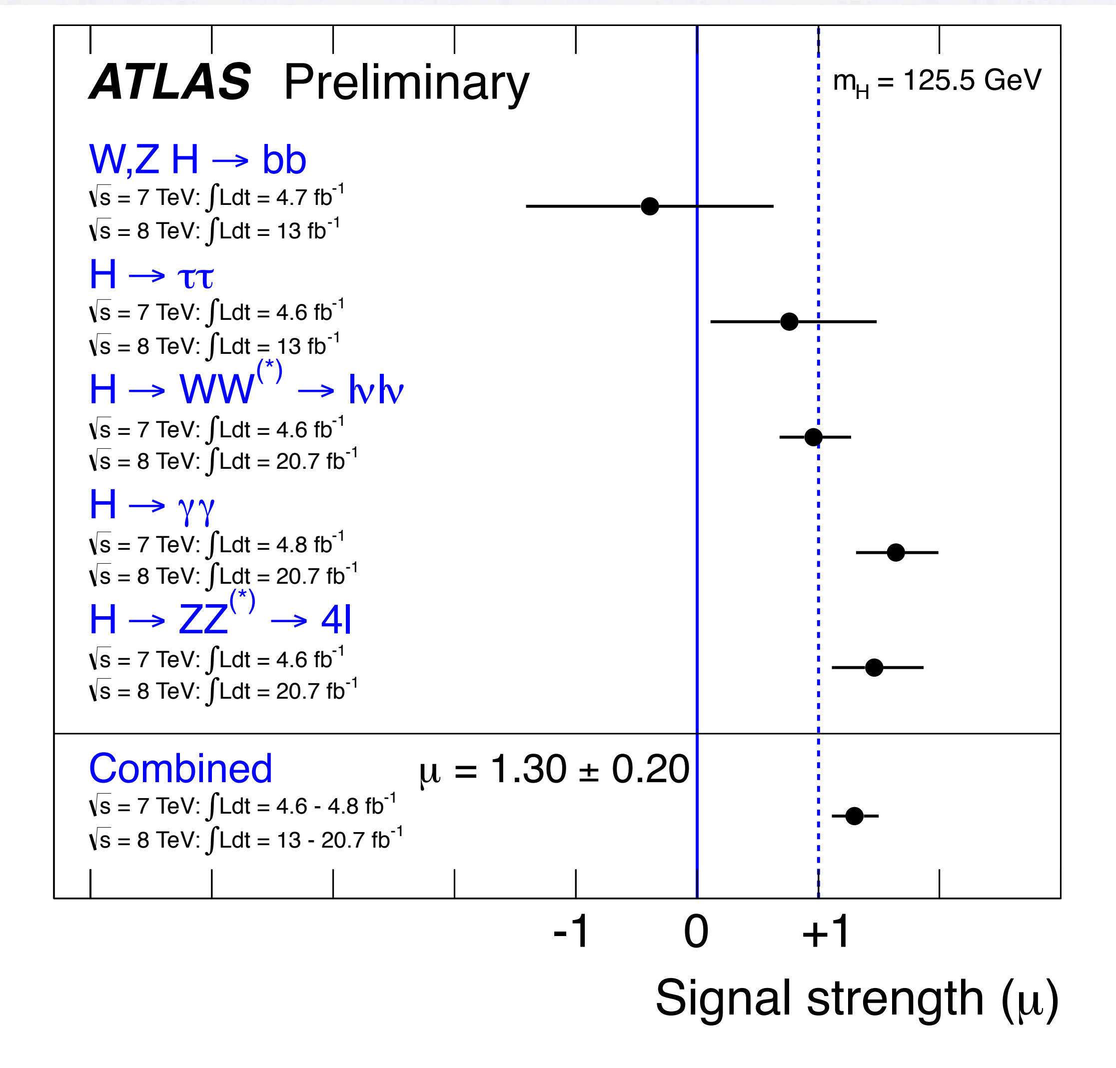
$$\text{p-value} = 0.08$$

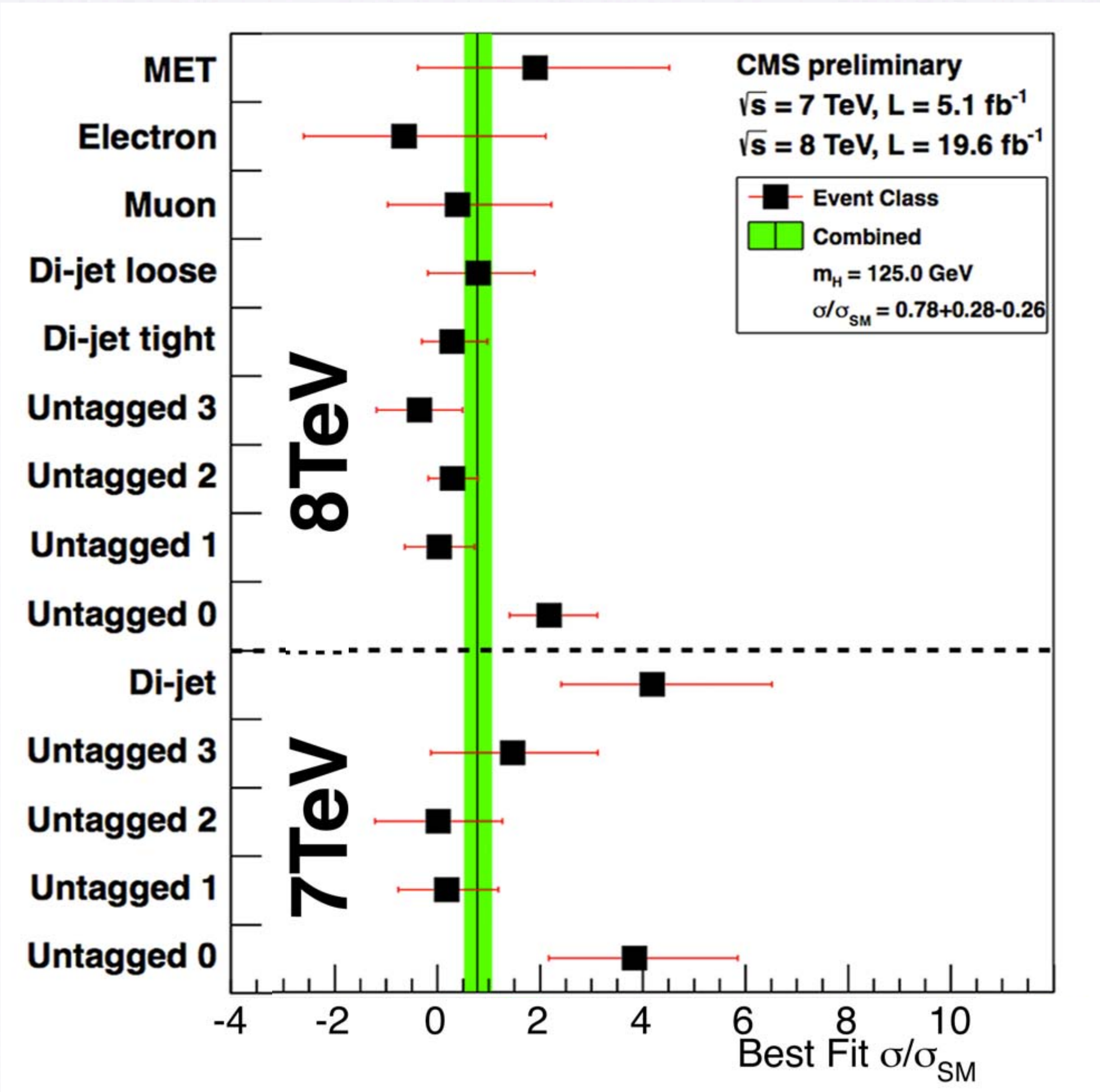
BSM physics should not get mass solely from EWSB (e.g. SUSY, XDim, etc.)

$\longrightarrow$ **Decoupling** (4th generation now strongly disfavored)

Higgs Signal Strengths

Good agreement with SM prediction (and seems to be converging with more data)





CERN Council 2012 ⟶ Winter 2013

Diphoton: ICHEP 2012 ⟶ Winter 2013

Higgs Di-photon Rate

Focus on Higgs: loop-level processes prime suspects for deviations from SM

$$R_{\gamma\gamma}^{\rm ATLAS} = 1.80^{+0.42}_{-0.36} \qquad R_{\gamma\gamma}^{\rm CMS} = 1.56 \pm 0.43 \qquad \text{(pre-Moriond 2013)}$$

$$R_{\gamma\gamma}^{\rm ATLAS} = 1.65^{+0.34}_{-0.30} \qquad R_{\gamma\gamma}^{\rm CMS} = 0.78^{+0.28}_{-0.26} \begin{cases} 1.69^{+0.65}_{-0.59} & (7~{\rm TeV}) \\ 0.55^{+0.29}_{-0.27} & (8~{\rm TeV}) \end{cases} \qquad \text{(post-Moriond 2013)}$$

Jury still out on potential enhancement of Higgs diphoton rate.

Here: will explore a possible consequence **if such a deviation existed**

- Connection to the EW Phase Transition (EWPhT)?
- Generation of the Baryon Asymmetry of the Universe (BAU)?

Given experimental trend, should take with a grain of salt...

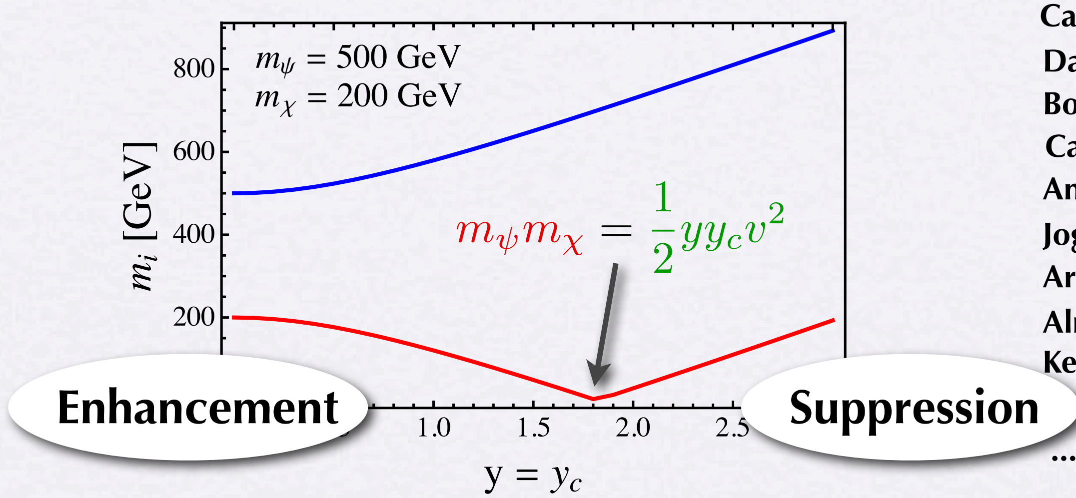
Vector-like Systems

- Indication of new (charged) states coupling strongly to the Higgs $\longrightarrow$ Higgs Potential

- Enhancement in $R_{\gamma\gamma} \simeq \left| 1 - \frac{F_{1/2}(\tau_1)\, Q_1^2}{F_{\rm SM}} \frac{\partial \ln m_1(v)}{\partial \ln v} \right|^2 \longrightarrow \frac{\partial \ln m_1(v)}{\partial \ln v} < 0$

Sparked recent interest in ***vector-like systems***: appeal to ``level repulsion":

$$M = \begin{pmatrix} m_\psi & \frac{1}{\sqrt{2}} y v \\ \frac{1}{\sqrt{2}} y_c v & m_\chi \end{pmatrix}$$



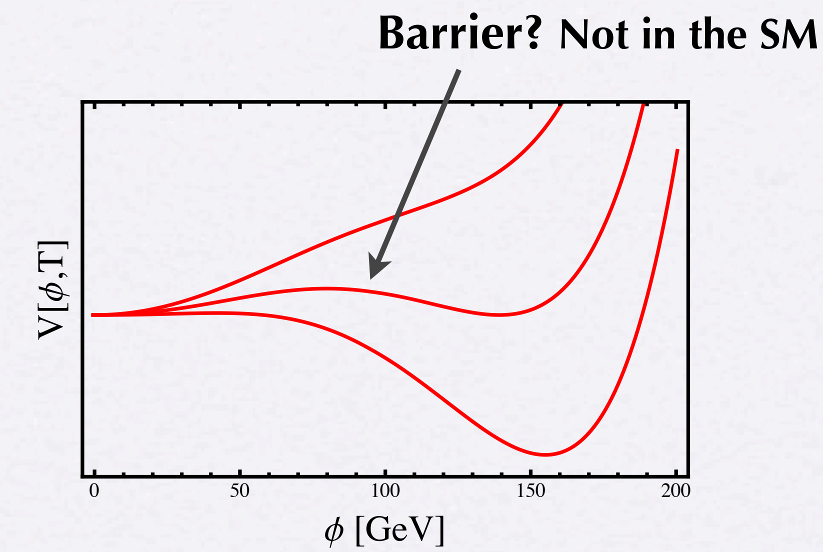
Carena, Gori, Shah & Wagner, 1112.3336
Dawson and Furlan, 1205.4733
Bonne and Moreau, 1206.3360
Carena, Low & Wagner, 1207.1093
An, Liu and Wang, 1207.2473
Joglekar, Schwaller and Wagner, 1207.4235 & 1303.2969
Arkani-Hamed, Blum, D'Agnolo & Fan, 1207.4482
Almeida, Bertuzzo, Machado and Funchal, 1207.5254
Kearney, Pierce and Weiner, 1207.7062
...loshin, 1208.4303
...

May be bosonic (as in SUSY) or fermionic (KK excitations?)

Focus here on fermion systems:
- ``naturally light" (without SUSY)
- Larger impact due to more d.o.f.
- **RG-induced ``instabilities": may be interesting for the EWPhT!**

The EWPhT in the SM

Finite temperature: thermal masses + new cubic term in ϕ :



$$V(\phi,T) \;\sim\; \underbrace{m(T)^2}_{\text{when positive: min. at origin}}\phi^2 + \underbrace{ET\phi^3 + \lambda(T)\phi^4}_{\text{``far away min.'': } \phi \sim ET/\lambda}$$

when positive:
min. at origin

``far away min.": $\phi \sim ET/\lambda$

$$\rightarrow \quad \frac{\phi_c}{T_c} \sim \frac{E}{\lambda} \sim \frac{Ev^2}{m_h^2}$$

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

(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": new bosonic degrees of freedom to enhance the *E*-term

Can Fermions Help?

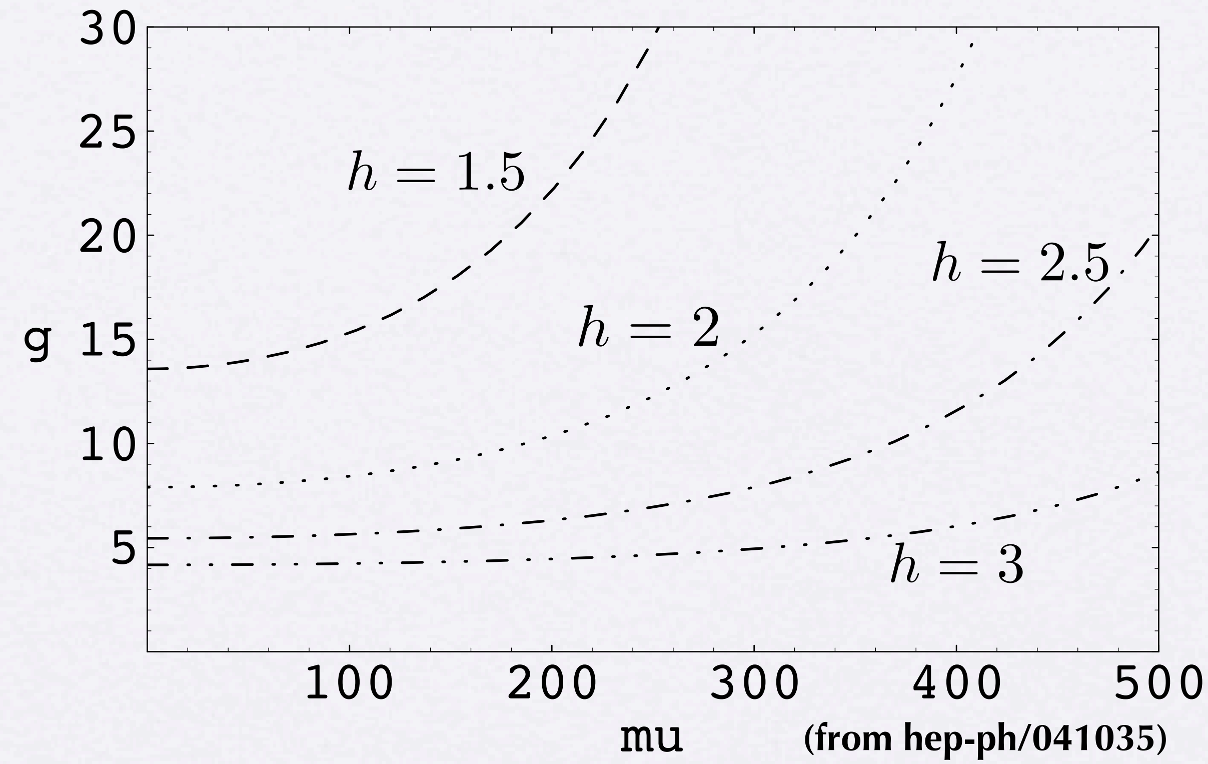
I know of one previous example where fermions can help the EWPhT:

Carena, Megevand, Quirós & Wagner, hep-ph/041035

- Use the fact that the (vector-like) fermion mass depends on the Higgs vev, hence is different in the broken and unbroken phases.

- **Decoupling** from thermal bath in **broken phase** leads to reheating, delaying the phase transition:

  ⟶ increase in ϕ_c/T_c



(from hep-ph/041035)

Observations:

- Need strong coupling/large number of d.o.f.
- Correlated with *suppression* of diphoton rate

We will see that there is a *different mechanism*, 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):

$(\psi, \psi^c) \sim (1,2)_{\pm 1/2}$ $\quad$ $(\chi, \chi^c) \sim (1,1)_{\mp 1}$ $\quad$ (``vector-like leptons”)

Mass and Yukawa terms:

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

When $y = y_c^*$, Yukawa terms become

$$-y^* \tilde{H} \overline{\Psi} X^+ + \text{h.c.} \qquad \Psi \equiv \begin{pmatrix} \psi \\ \overline{\psi^c} \end{pmatrix} \qquad X^+ \equiv \begin{pmatrix} \chi^c \\ \overline{\chi} \end{pmatrix}$$

and phase in Yukawa is unphysical $\longrightarrow$ For BAU, would like to keep most general possibility.

Nevertheless, for simplicity, analytical expressions for EWPhT given in limit $y = y_c^*$ and real

(numerically, explore most general case)

The Viable Region

(Davoudiasl, Lewis & EP, 1211.3449)

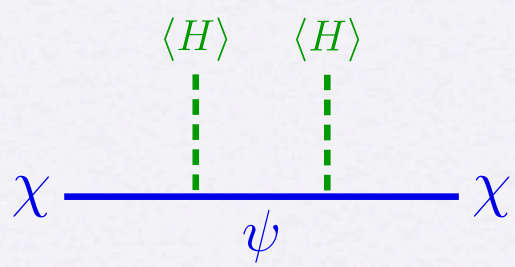
- Electroweak precision constraints: $m_\psi \gg v, m_\chi$
- Strongly first-order EWPhT (semi-perturbative couplings)
- Charged states above (naive) LEP 2 bound
- Consistent with possible diphoton enhancement

EFT analysis with ψ integrated out: may be more general than simple model

EFT Analysis

(Davoudiasl, Lewis & EP, 1211.3449)

For $m_\psi \gg v, m_\chi$, integrate out "ψ" and obtain EFT for (SM + "χ"):



$\rightarrow$

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

where $\quad G_m = \dfrac{y^2}{2(m_\psi - m_\chi)} > 0$

Light vector-like fermion mass is $m_1 = m_\chi \underbrace{- G_m v^2}$

``level repulsion"

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

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

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

Interesting diphoton enhanc. when

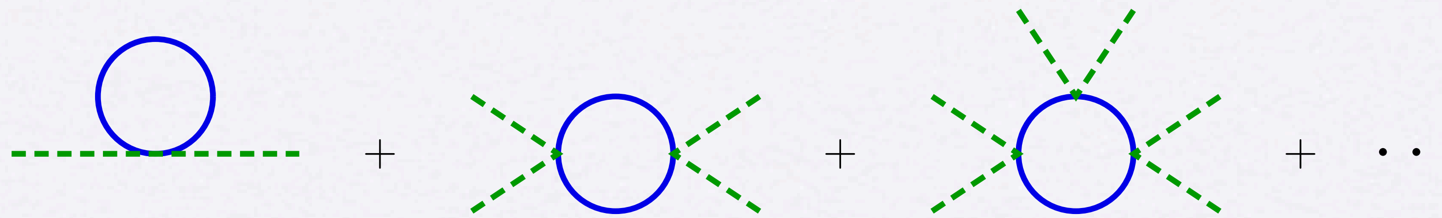
$y_{\text{eff}} \sim \mathcal{O}(1)$ **and**

$m_1 \sim 100 - 200 \text{ GeV}$

T = 0 Potential in EFT

(Davoudiasl, Lewis & EP, 1211.3449)

1-loop effective potential (T = 0)

$\Delta V_{\text{Eff}} =$ 

$$= -\frac{4}{64\pi^2}\, m_1(\phi)^4 \left[\ln \frac{m_1(\phi)^2}{\mu^2} - \frac{3}{2}\right] + \text{counterterms} \qquad \text{(in } \overline{MS} \text{ scheme)}$$

Noting that ϕ^6 and ϕ^8 terms are divergent:

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

$\bar{\gamma}$ and $\bar{\delta}$ arbitrary within EFT

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

Matching and Running

(Davoudiasl, Lewis & EP, 1211.3449)

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

$$\bar{\gamma} = \bar{\gamma}_{\rm th} + \bar{\gamma}_{\rm RG} \qquad\qquad \bar{\delta} = \bar{\delta}_{\rm th} + \bar{\delta}_{\rm RG}$$

with threshold contributions

$$\bar{\gamma}_{\rm th} = \frac{Z_\gamma y^6}{16\pi^2} \frac{m_\psi(m_\psi^2 + 7 m_\chi m_\psi - 2 m_\chi^2)}{(m_\psi - m_\chi)^5} \sim \frac{y^6}{16\pi^2}\frac{1}{m_\psi^2}$$

$$\bar{\delta}_{\rm th} = -\frac{Z_\delta y^8}{48\pi^2} \frac{7 m_\psi^3 + 27 m_\chi m_\psi^2 - 4 m_\chi^3}{(m_\psi - m_\chi)^7} \sim -\frac{7 y^8}{48\pi^2}\frac{1}{m_\psi^4}$$

$\left(Z_\gamma, Z_\delta = 1 \right.$ at lowest order $\left.\right)$

and running contributions

$$\bar{\gamma}_{\rm RG} \approx -\frac{3 G_m^3 m_\chi}{2\pi^2} \ln\left(\frac{m_\psi^2}{\mu^2}\right)$$

$$\bar{\delta}_{\rm RG} \approx \frac{G_m^4}{2\pi^2} \ln\left(\frac{m_\psi^2}{\mu^2}\right)$$

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

Quartic Instabilities?

(Davoudiasl, Lewis & EP, 1211.3449)

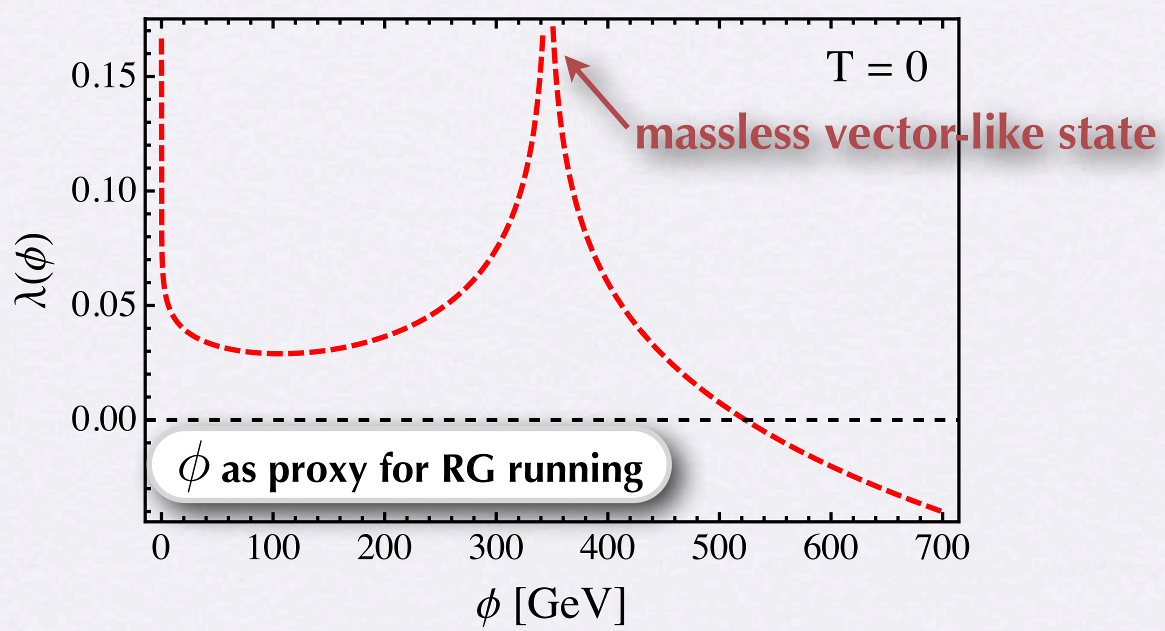
RG running of Higgs quartic (below m_ψ):

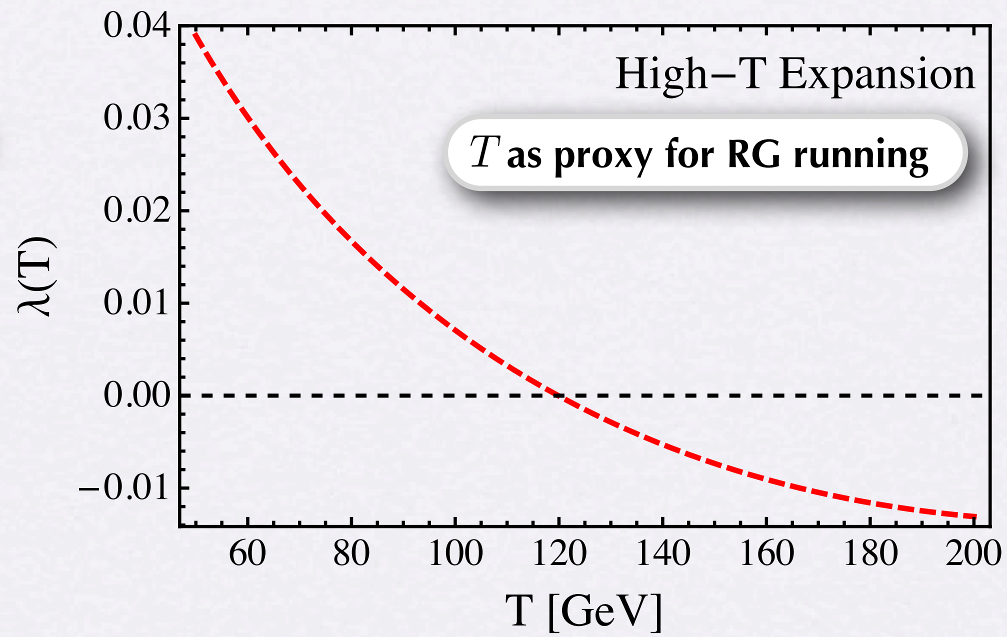
from new light fermion

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

fermionic terms induce ``instability"

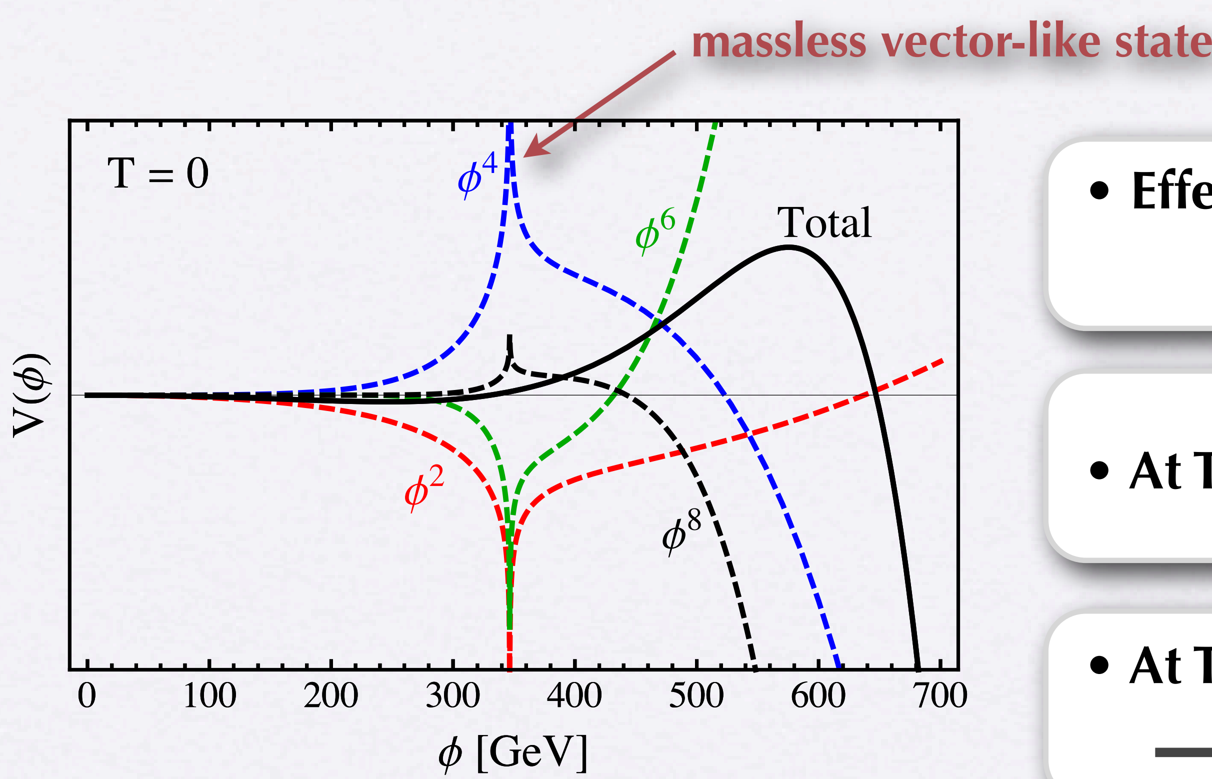
Quartic coupling from effective potential at low and high temperatures:





The Shape of the Eff. Pot.

(Davoudiasl, Lewis & EP, 1211.3449)

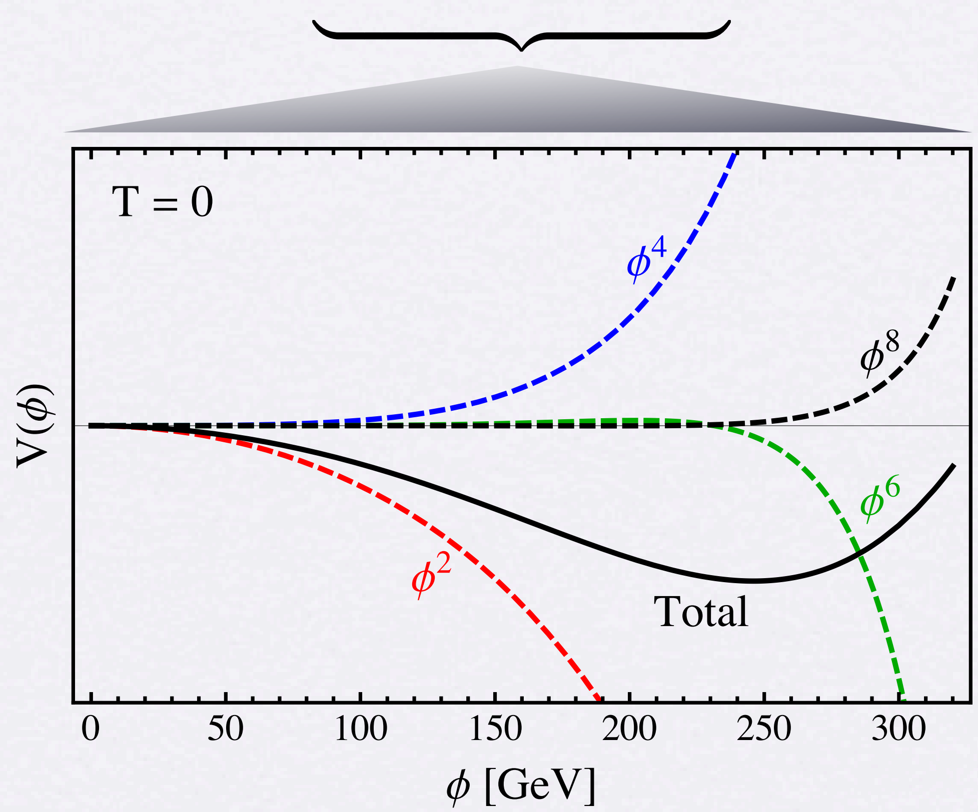


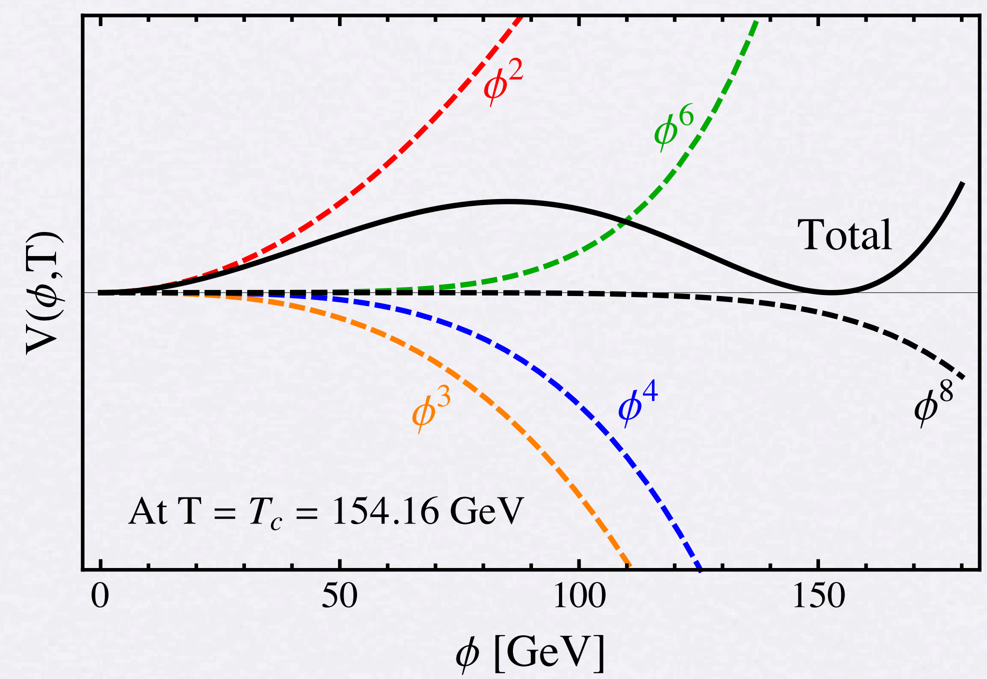
- **Effective Potential in EFT shows instability at** $\sim 600~\mathrm{GeV} \gg \mathrm{EW~scale}$

- **At T = 0 and** $\phi \sim \mathrm{EW}$ **:** $m^2 < 0,~~\lambda > 0$

- **At T ~ EW :** $m^2 > 0,~~\lambda < 0$
  $\longrightarrow$ **stabilization by higher-dim operators**

(Realization of idea in hep-ph/0407019)





Back to the Instability

(Davoudiasl, Lewis & EP, 1211.3449)

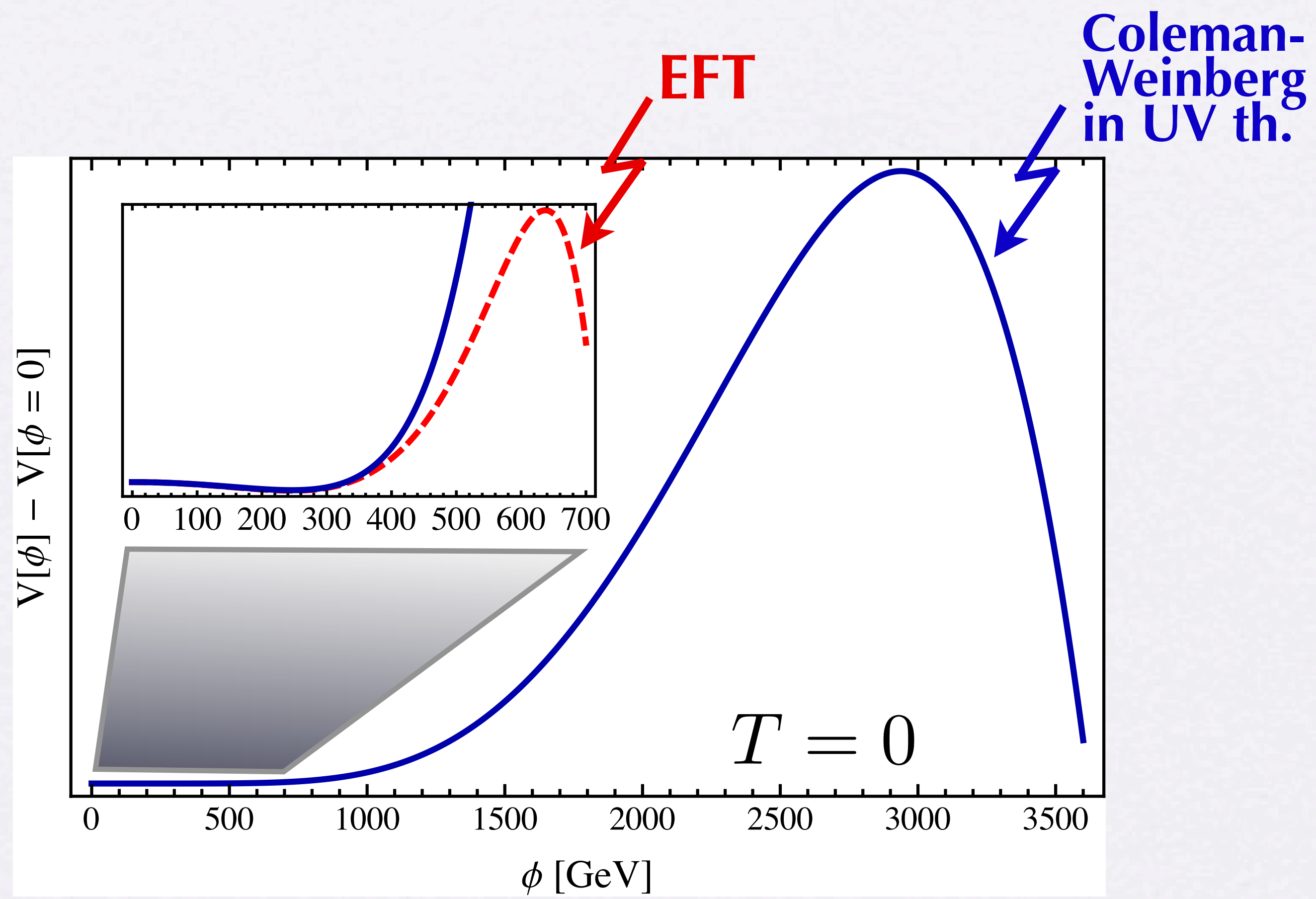
- EFT with ψ integrated out: match ϕ correlators and run from m_ψ to $m_\chi \sim v$

  → captures ``small ϕ" 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:

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

When $\bar{\mu}^2 > 0, \bar{\lambda} < 0, \bar{\gamma} > 0$

``far away min.": $\phi \sim \sqrt{-\bar{\lambda}/\bar{\gamma}}$

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

Also estimate

$$\phi_c \sim \sqrt{\mu}/\gamma^{1/4}$$

→ **may get sizeable** ϕ_c/T_c **!**

Similar to proposal by Grojean, Servant & Wells. Here, $\lambda < 0$ **from fermions and finite Temp.**
(hep-ph/0407019)

EFT Agnostic Analysis

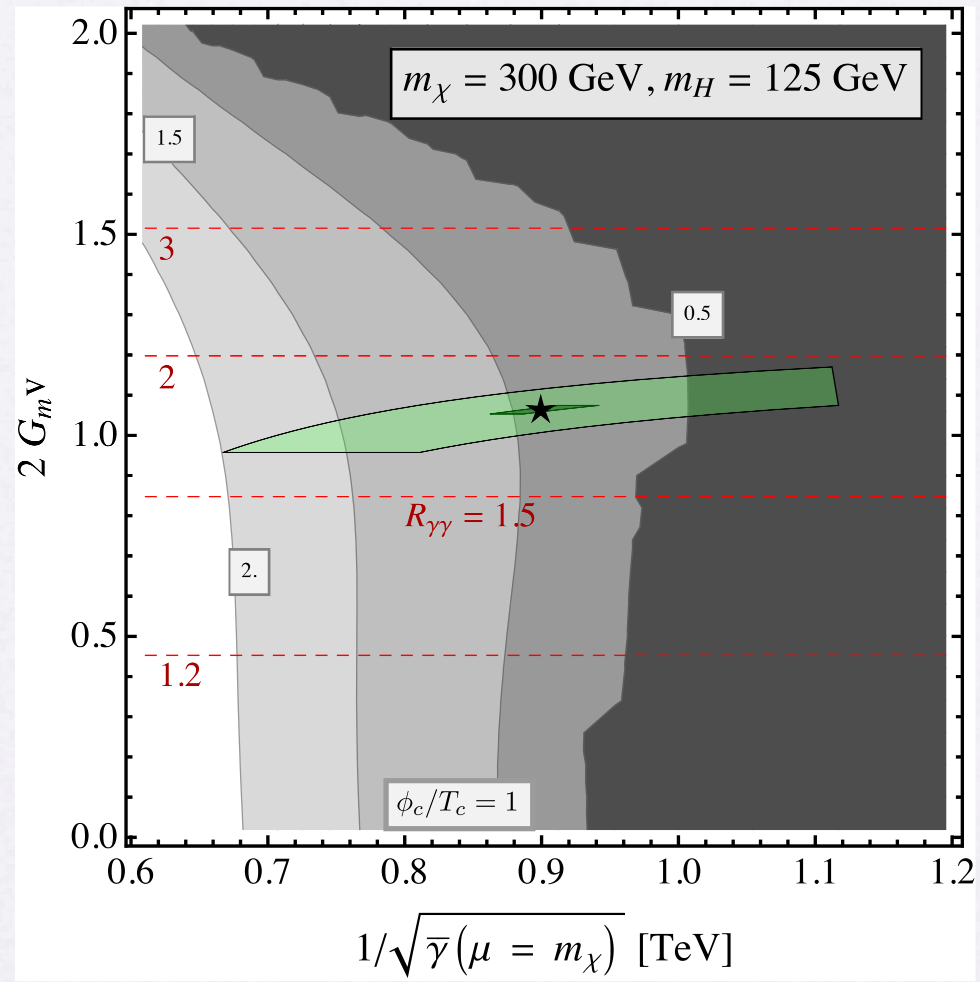
(Davoudiasl, Lewis & EP, 1211.3449)

- Strength of the phase transition (ϕ_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 $y, y_c \sim$ few
- Sensitivity to UV completion through stabilizing higher-dim. operators
- Consistent with important Higgs diphoton rate *enhancement*

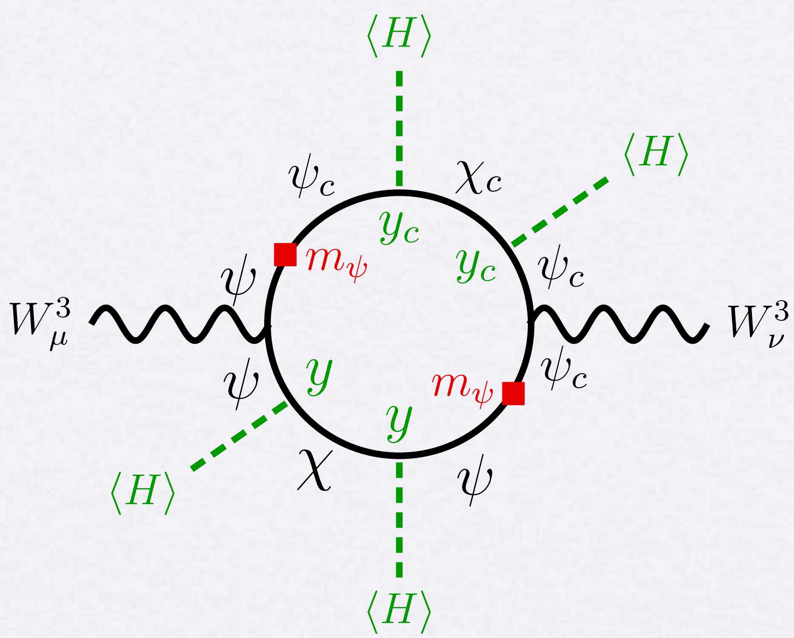
Star is a benchmark in UV model with:

$m_\psi = 4$ TeV	$m_\chi = 300$ GeV	$y = y_c = 4$

Green regions: effect of 10% (1%) higher-loop corrections at the matching scale

EW Precision Tests

In the heavy doublet limit: $m_\psi \gg m_\chi, v$, leading contribution to T from



$\longrightarrow$

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

(may be sizeable...)

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

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

A Custodial Extension

Two important shortcomings so far:

- In spite of large m_ψ, 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)

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

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 $\underset{(0,2)}{\xi^{(c)} \equiv \begin{pmatrix} n^{(c)} \\ -\chi^{(c)} \end{pmatrix}}$ $\underset{(2,2)}{\Phi \equiv \begin{pmatrix} H^{0*} & H^+ \\ -H^- & H^0 \end{pmatrix}}$

In this limit T = 0. Need to ensure neutral lightest state, which breaks custodial softly.

A Detailed Example

Input parameters:

$m_\psi = 4$ TeV	$m_\chi = 300$ GeV	$m_n = -250$ GeV	$y = 4$	$\tilde{y} = 4$	$y_c = 3.5$	$\tilde{y}_c = 3.5$

Vector-like spectrum:

At $T = 0$

Charged	Neutral
$m_2^\pm = 4.11$ TeV	$m_2^0 = 4.11$ TeV
$m_1^\pm = 189$ GeV	$m_1^0 = 140$ GeV

At $T = T_c$

Charged	Neutral
$m_2^\pm = 4.06$ TeV	$m_2^0 = 4.06$ TeV
$m_1^\pm = 240$ GeV	$m_1^0 = 191$ GeV

Phase transition:

$$\boxed{\begin{gathered}\phi_c = 179.3 \text{ GeV} \\ T_c = 158.4 \text{ GeV} \\ \phi_c/T_c = 1.13\end{gathered}}$$

Bubbles nucleate slightly below T_c

EWPT and diphoton enhancement:

$$\left.\begin{gathered}\Delta T \sim 10^{-4} \\ \Delta S \approx 0.04 \\ \Delta U \sim 10^{-6}\end{gathered}\right\}$$

Consistent at 95% CL
with current PDG ellipse

$$\boxed{R_{\gamma\gamma} \approx 1.5}$$

← **Look forward to further developments!**

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:

  - Triple Higgs coupling: $V'''(v) = 3m_H^2/v + \overbrace{8\bar{\gamma}v^3}^{\mathcal{O}(1)\text{ correction}}$

    ⟶ expect 40-60% suppression in $gg \to HH$

    ⟶ measurement of stabilizing effect (a crucial ingredient in underlying mechanism)

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

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

  Rather familiar from (warped) extra-dimensional constructions!