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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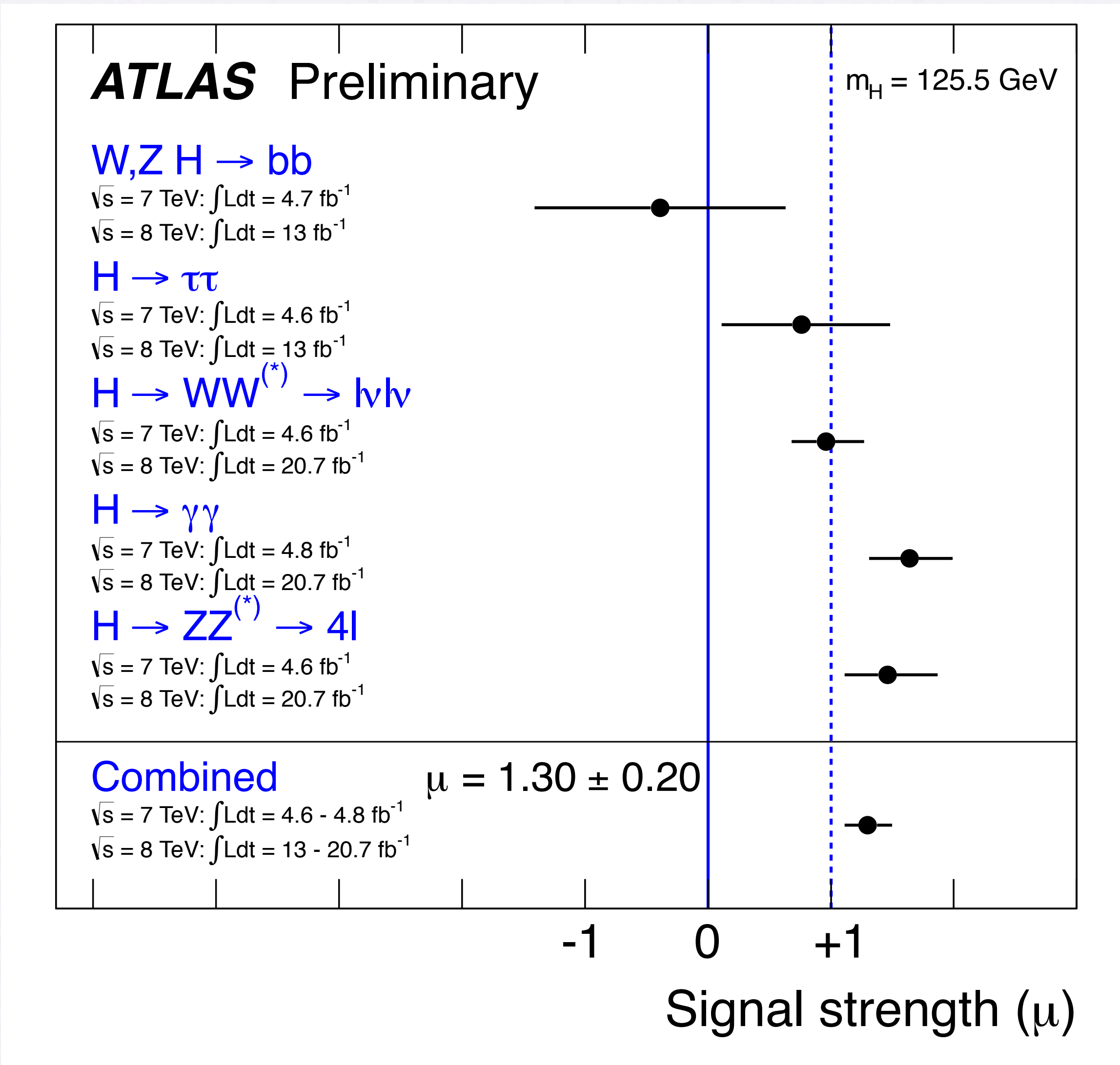
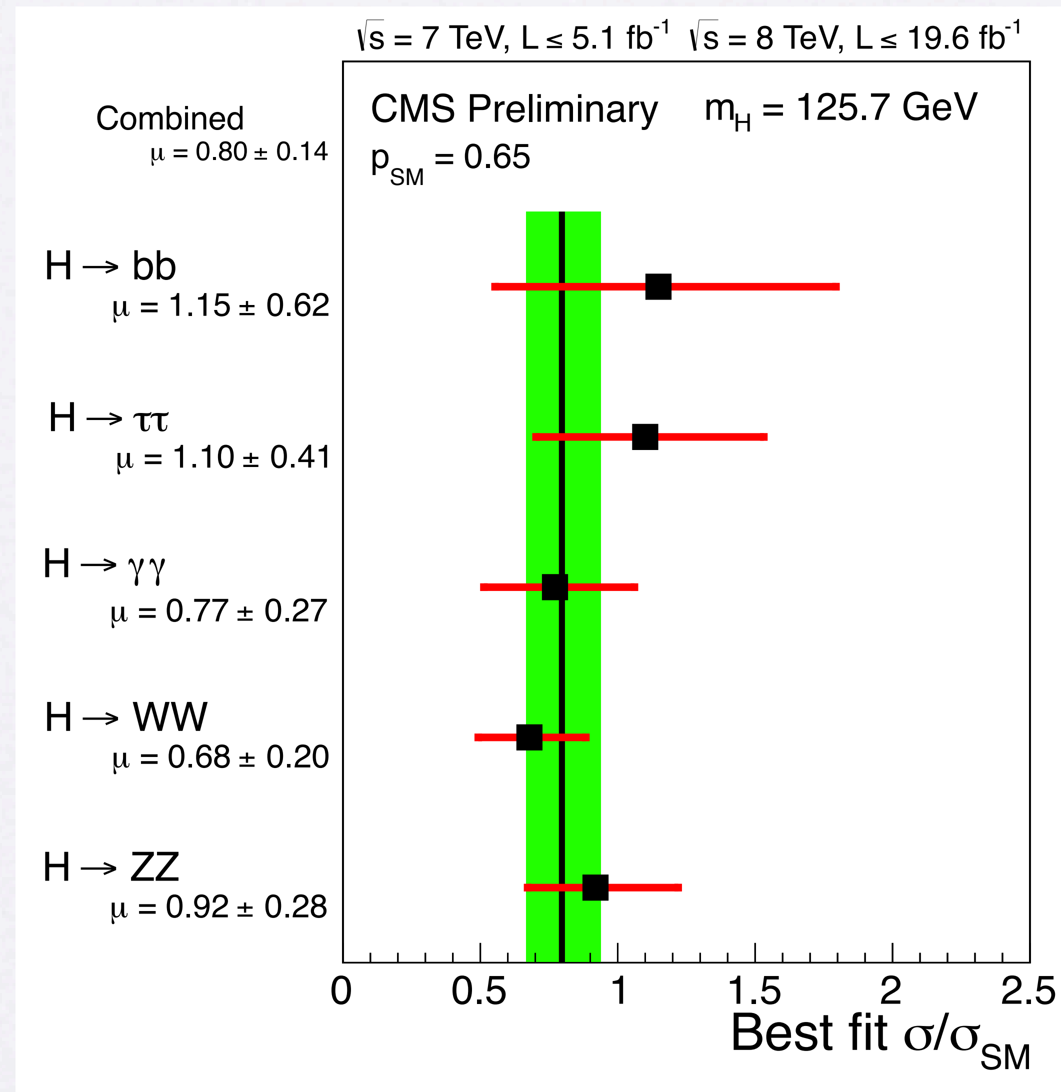
A SM-like Higgs

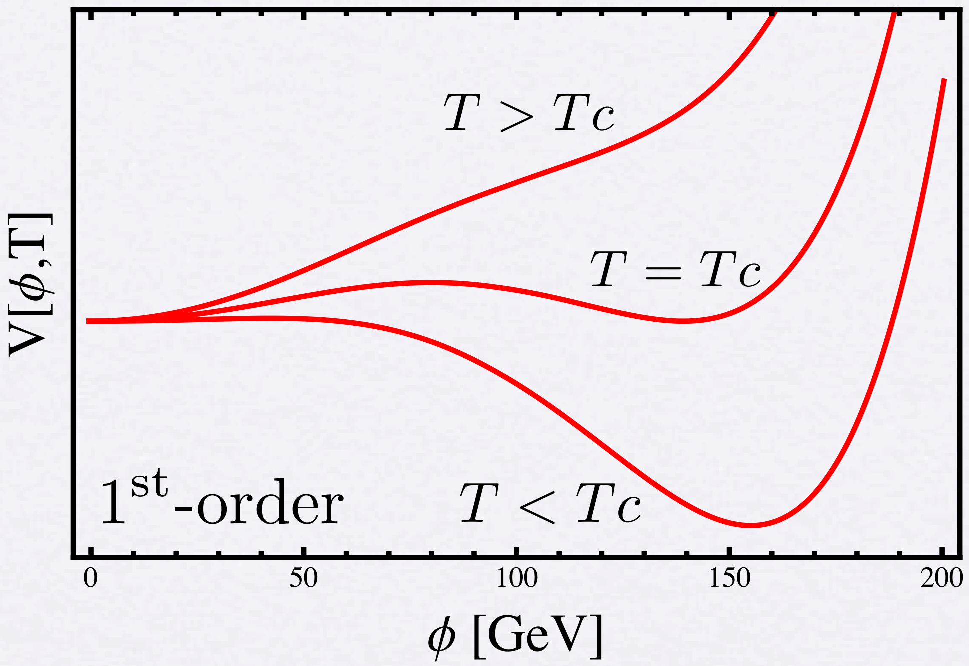


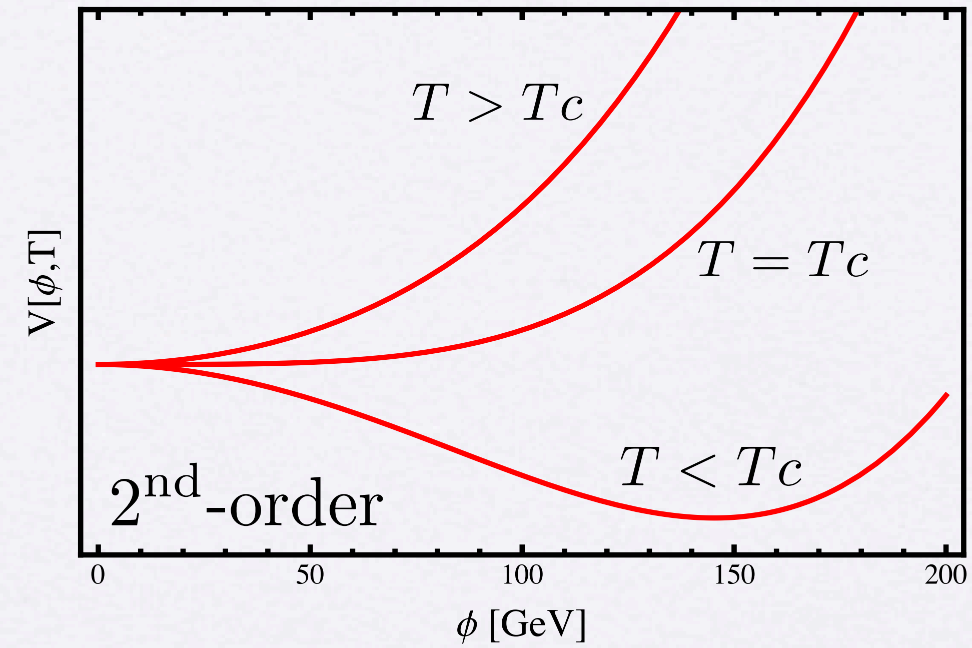


Overall good agreement with SM expectations... but still room for interesting deviations.

The Nature of the EWPhT

Precise measurement of Higgs properties can illuminate nature of EW phase transition





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

(Rummukainen et. al., hep-lat/9805013)

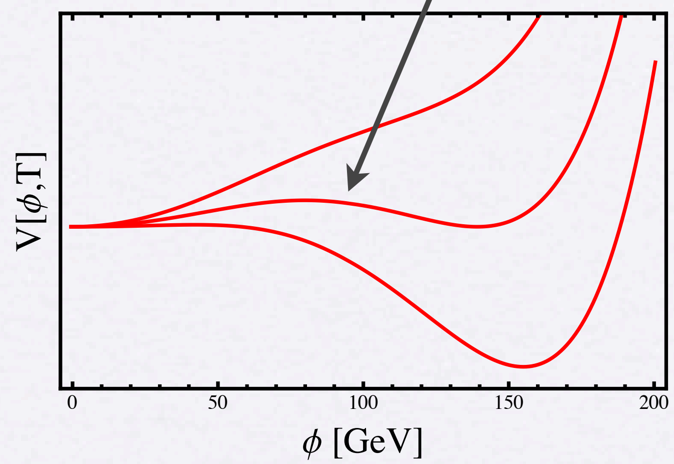
But deviations (due to new physics) might have potentially important implications

- Baryon Asymmetry of the Universe

- Gravitational wave signals

The EWPhT in the SM

Barrier? Not in the SM



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

$$V(\phi, T) \sim \underbrace{m(T)^2\phi^2}_{} + \underbrace{ET\phi^3 + \lambda(T)\phi^4}_{}$$

when positive: min. at origin

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

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

Should be > 1, for EW baryogenesis

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

(need non-perturbative methods to establish nature of phase transition)

BSM and the EWPhT

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

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

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

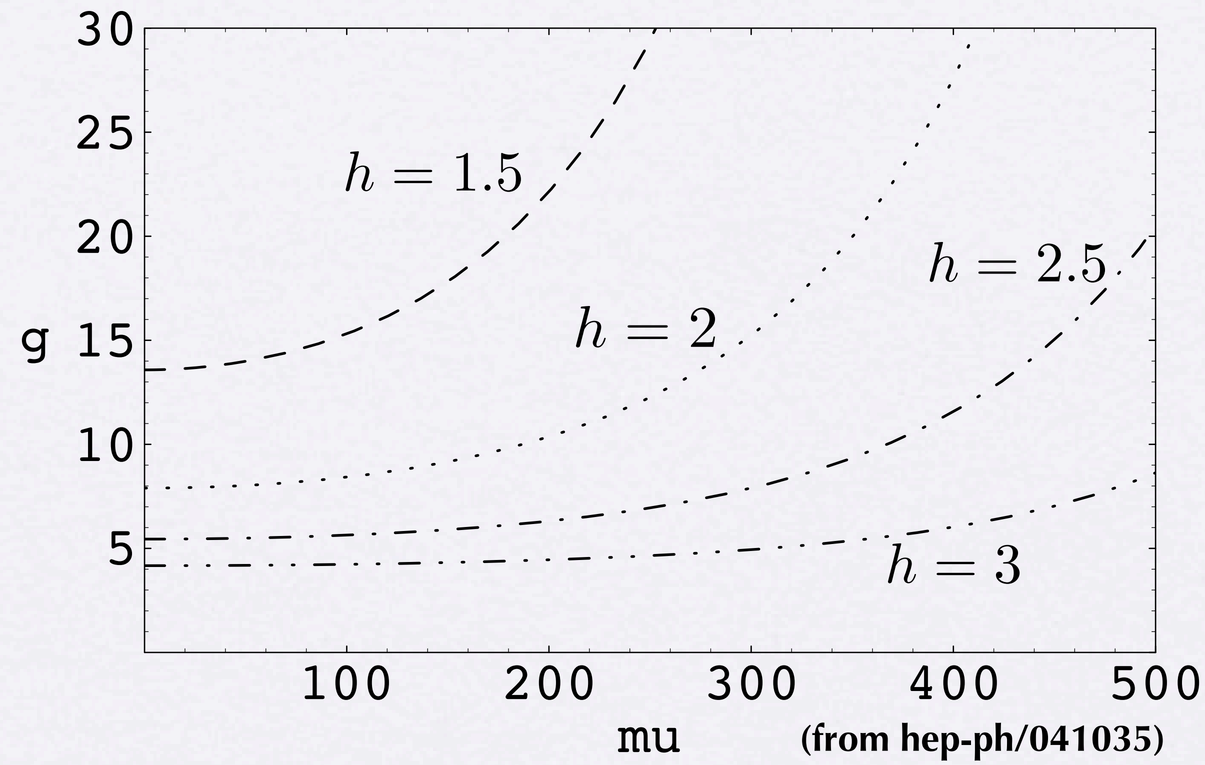
Can Fermions Help?

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 ϕ_c/T_c

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



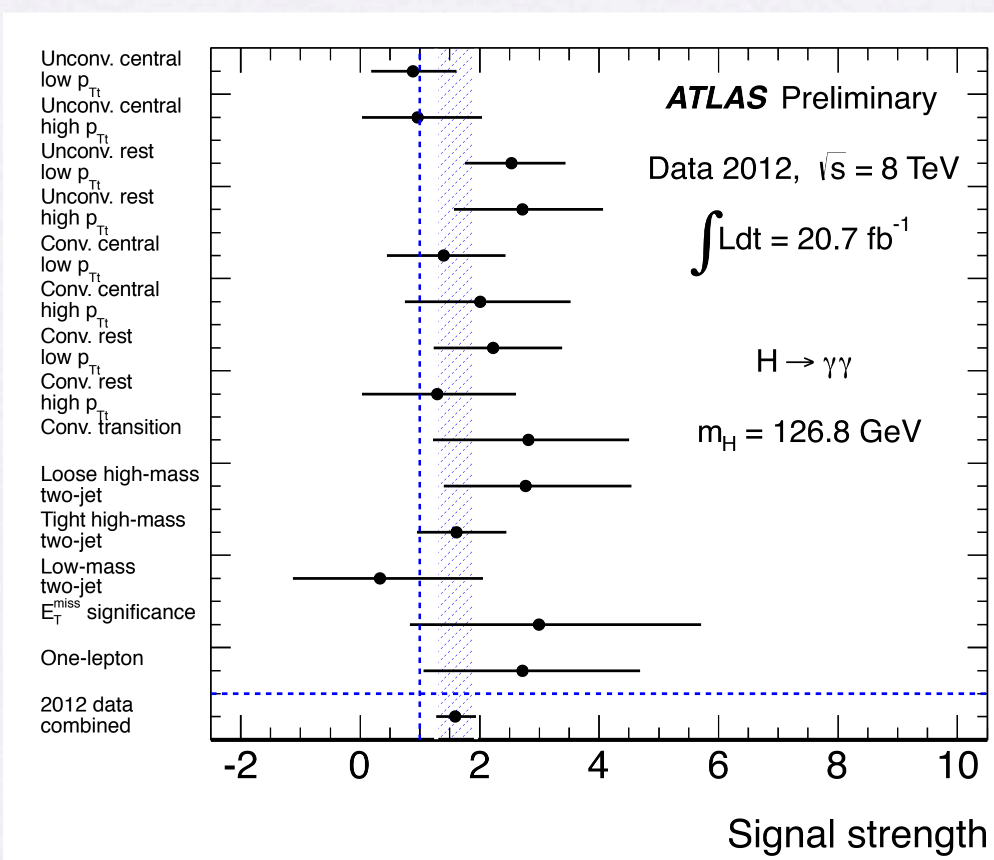
(from hep-ph/041035)

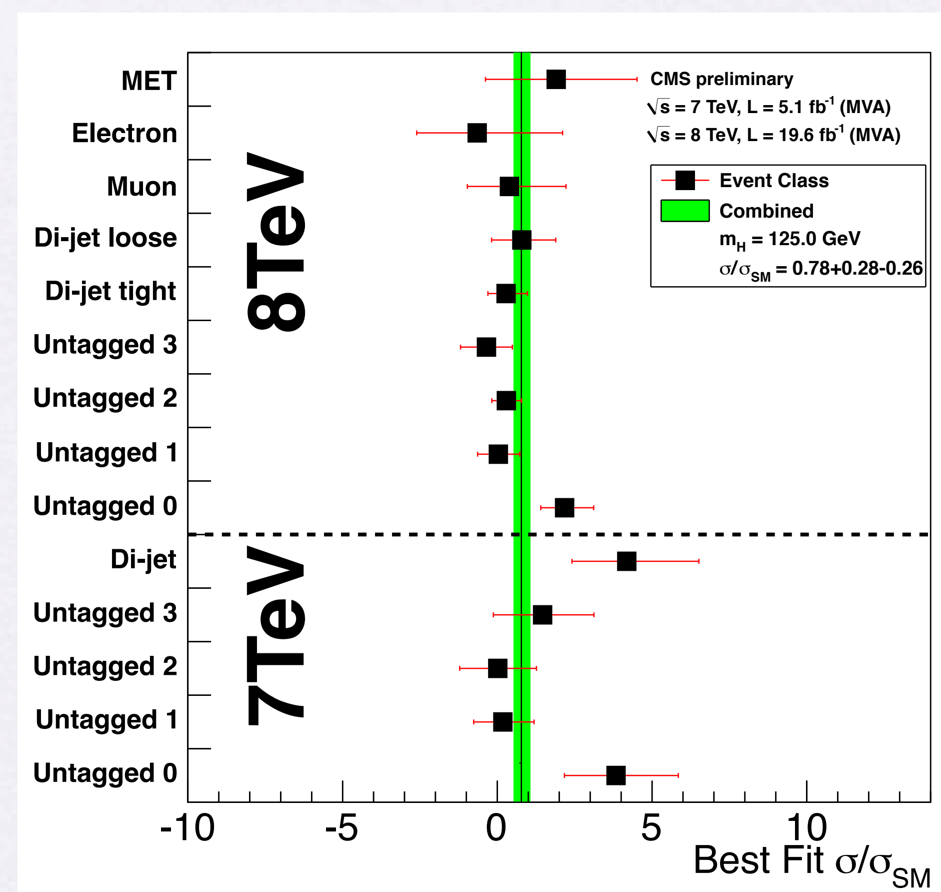
Higgs Di-photon Rate

Loop-level processes prime suspects for deviations from SM

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

$$R^{\text{ATLAS}}_{\gamma\gamma} = \cancel{1.65^{+0.34}_{-0.30}}\ 1.55^{+0.33}_{-0.28} \qquad R^{\text{CMS}}_{\gamma\gamma} = 0.78^{+0.28}_{-0.26} \begin{cases} 1.69^{+0.65}_{-0.59} & (7\ \text{TeV}) \\ 0.55^{+0.29}_{-0.27} & (8\ \text{TeV}) \end{cases}$$ (post-Moriond 2013)



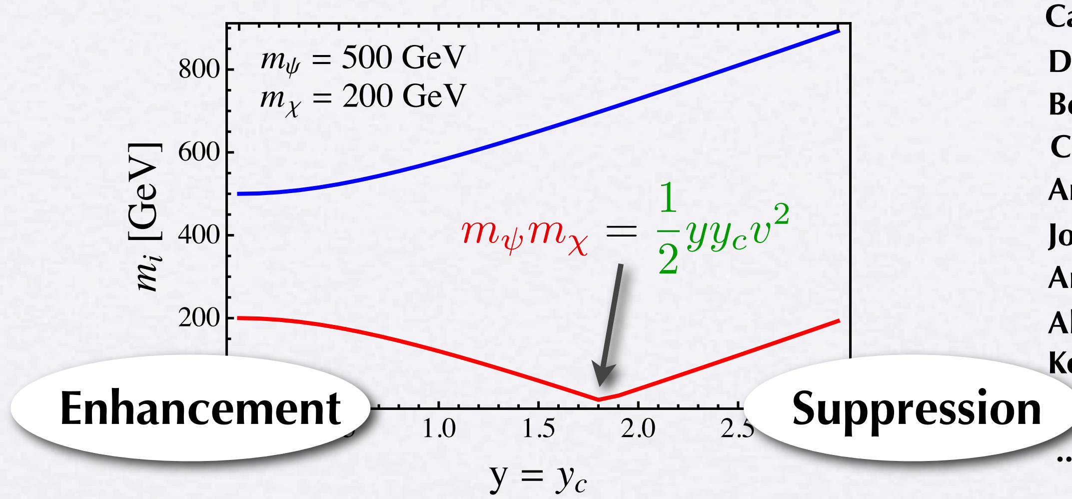


Vector-like Systems

Higgs diphoton rate, normalized to SM $$R_{\gamma\gamma} \simeq \left| 1 - \frac{F_{1/2}(\tau_1)\, Q_1^2}{F_{\rm SM}} \frac{\partial \ln m_1(v)}{\partial \ln v} \right|^2$$

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

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



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
...

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):

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

(``vector-like leptons")

Mass and Yukawa terms:

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

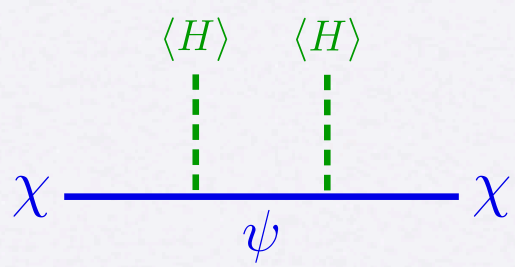
Interesting region for EWPhT when fermion masses hierarchical. Assume $m_\psi \gg m_\chi$

EFT analysis with 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"):



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

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

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):

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

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

Interesting diphoton enhanc. when

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

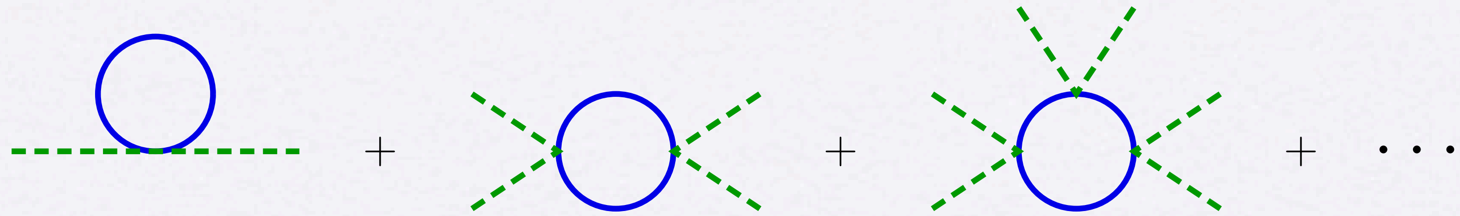
$m_1 \sim 100 - 200$ GeV

T = 0 Potential in EFT

(Davoudiasl, Lewis & EP, 1211.3449)

1-loop effective potential (T = 0)

$\Delta V_{\rm Eff} =$



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

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

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

$\bar{\gamma}$ 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

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

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

$\left(Z_\gamma, Z_\delta = 1 \text{ at lowest order} \right)$

and running contributions

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

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

- 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)

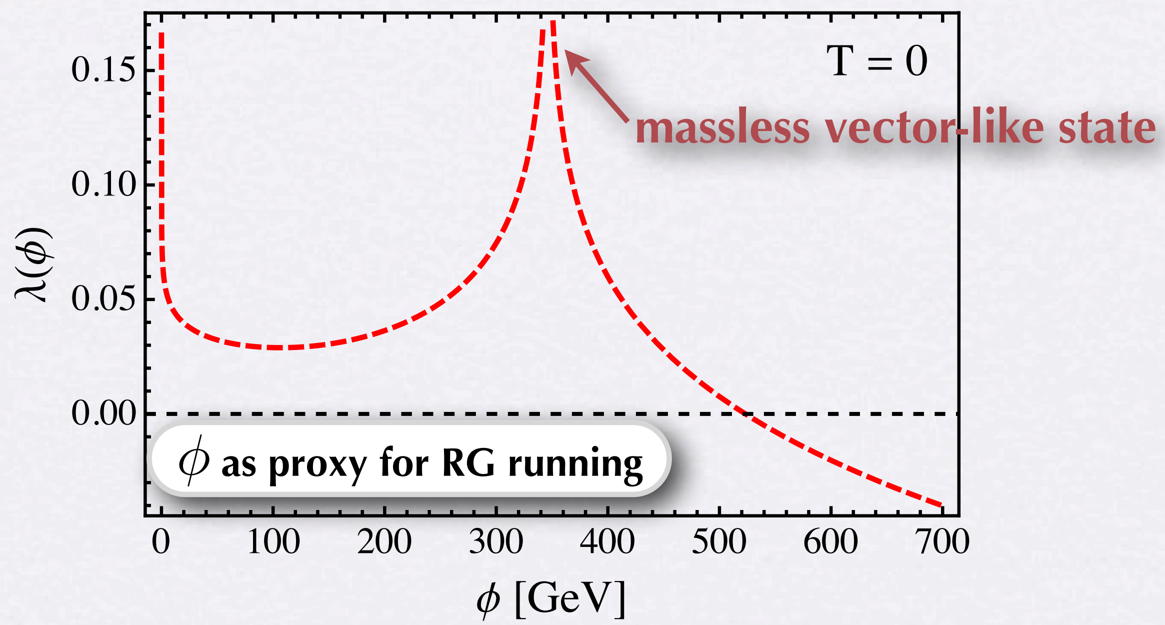
RG running of Higgs quartic (below m_ψ):

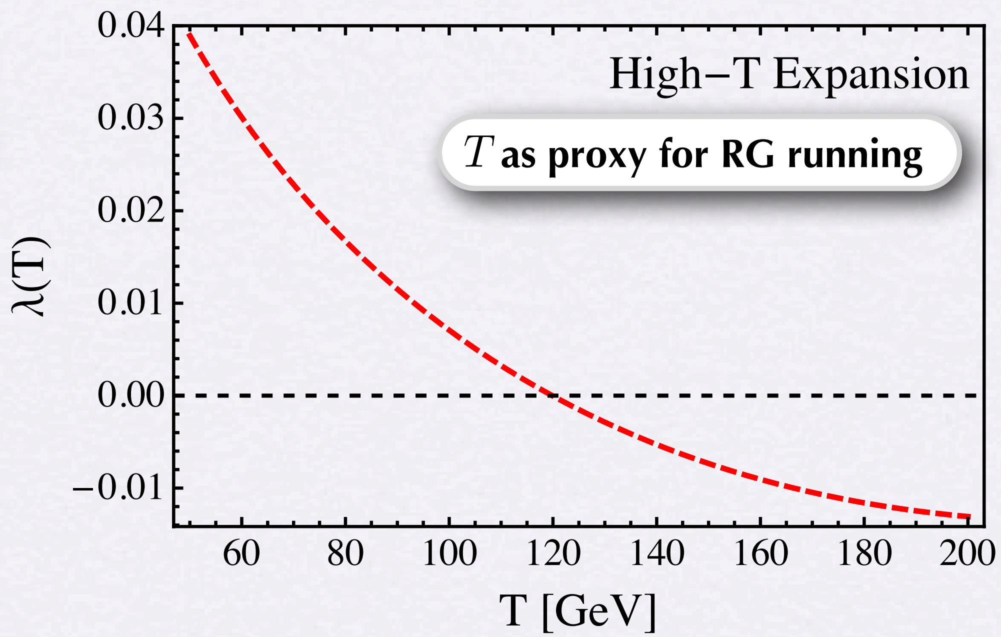
from new light fermion

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

fermionic terms induce ``instability"

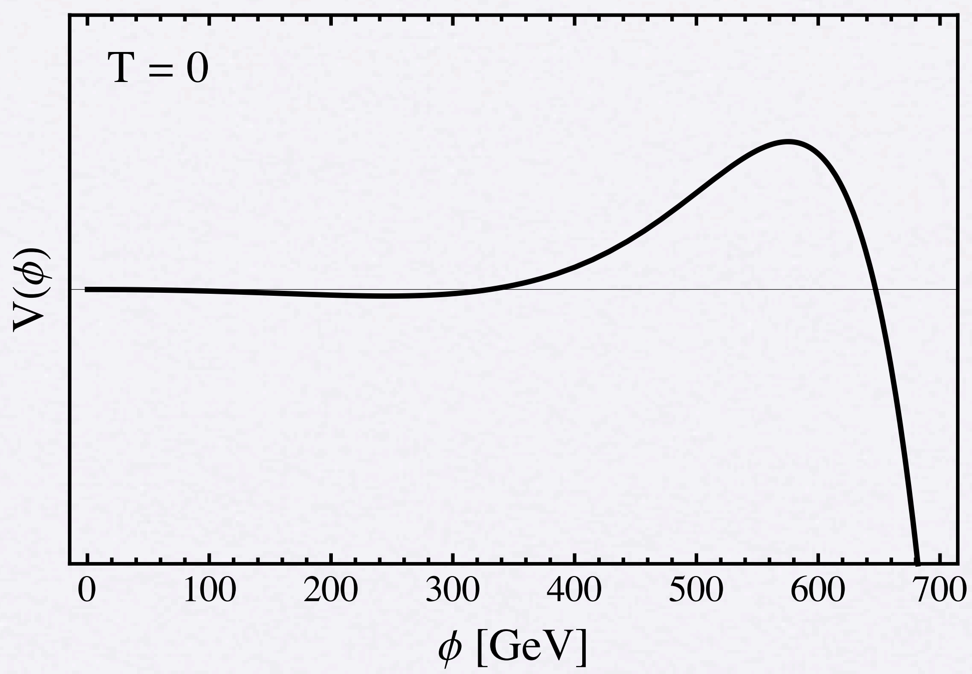
Quartic coupling from effective potential at low and high temperatures:





The Shape of the Eff. Pot.

(Davoudiasl, Lewis & EP, 1211.3449)



- **Effective Potential in EFT shows instability at**

  $\sim 600 \text{ GeV} \gg \text{EW scale}$

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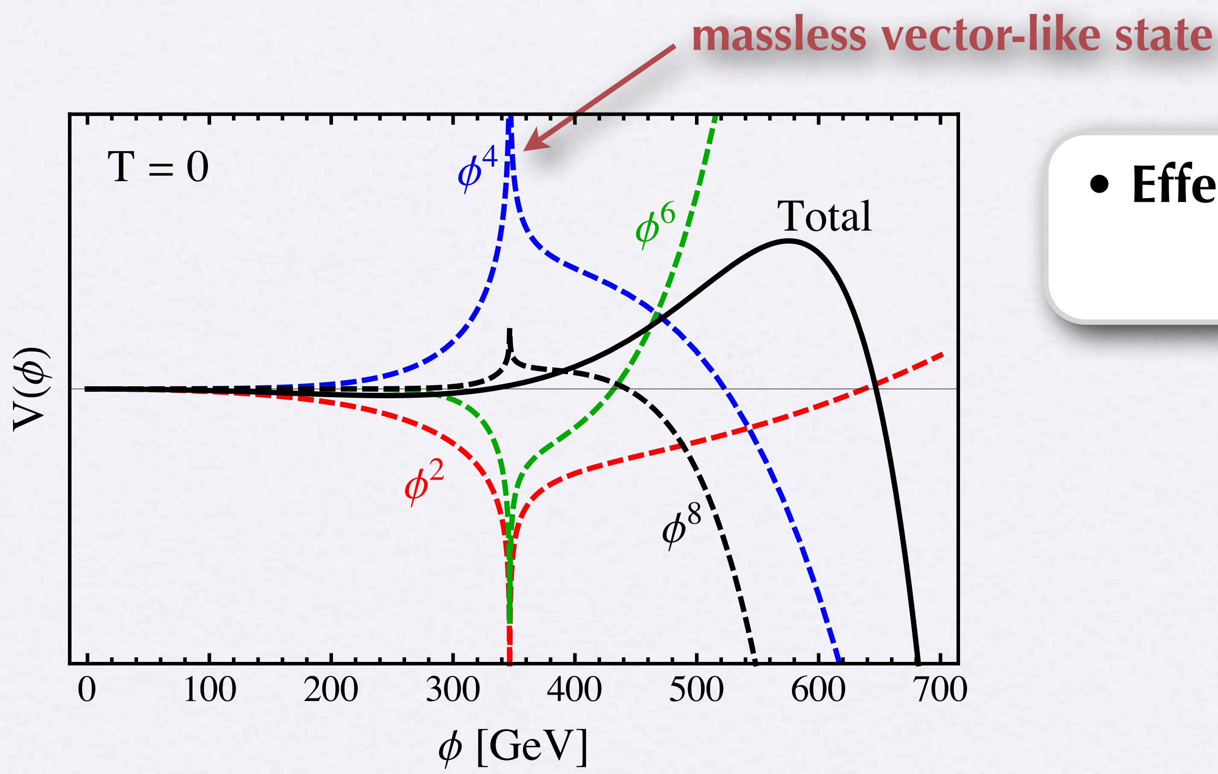

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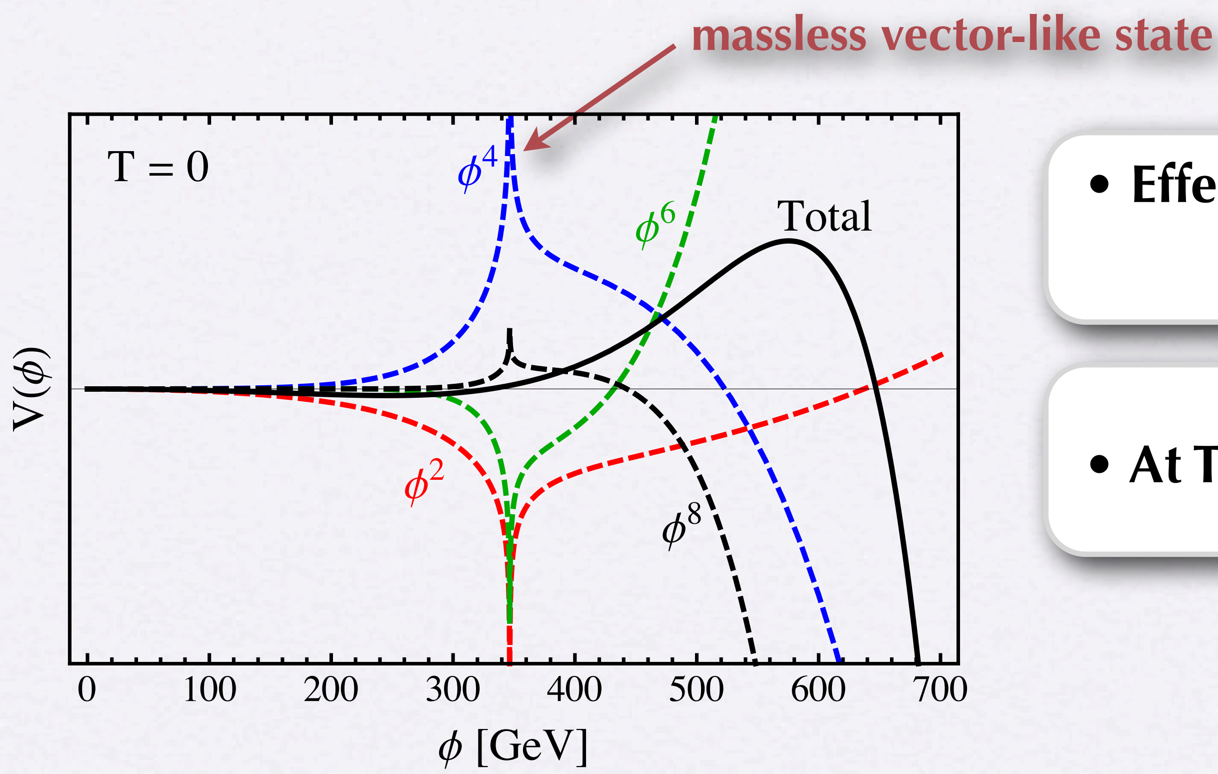
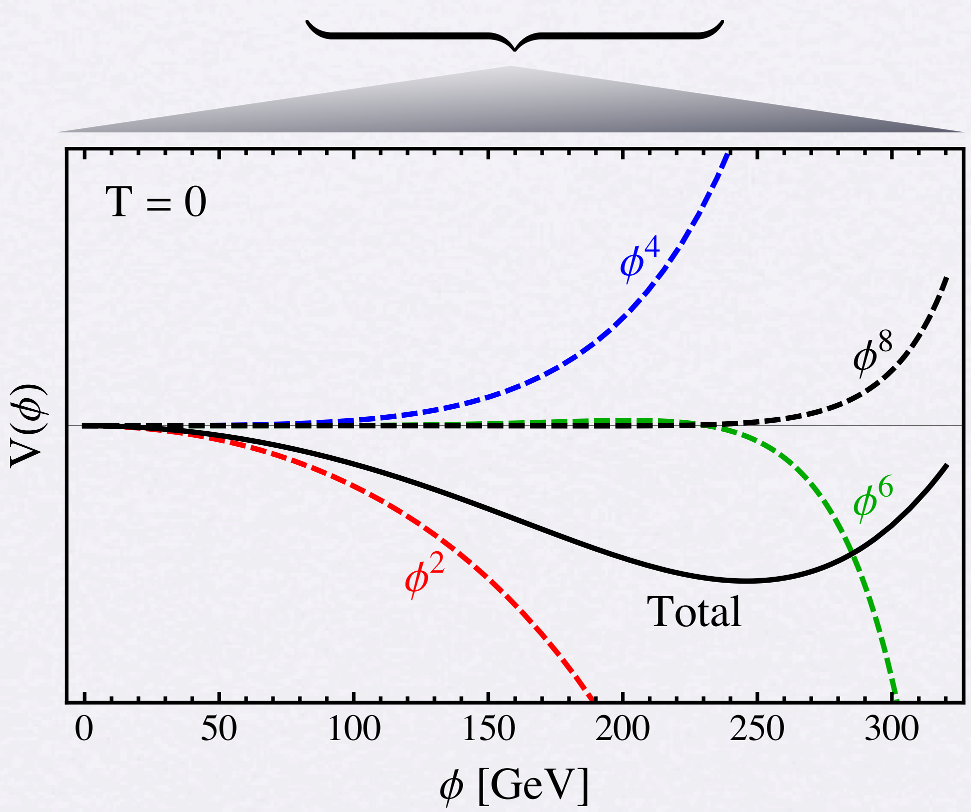


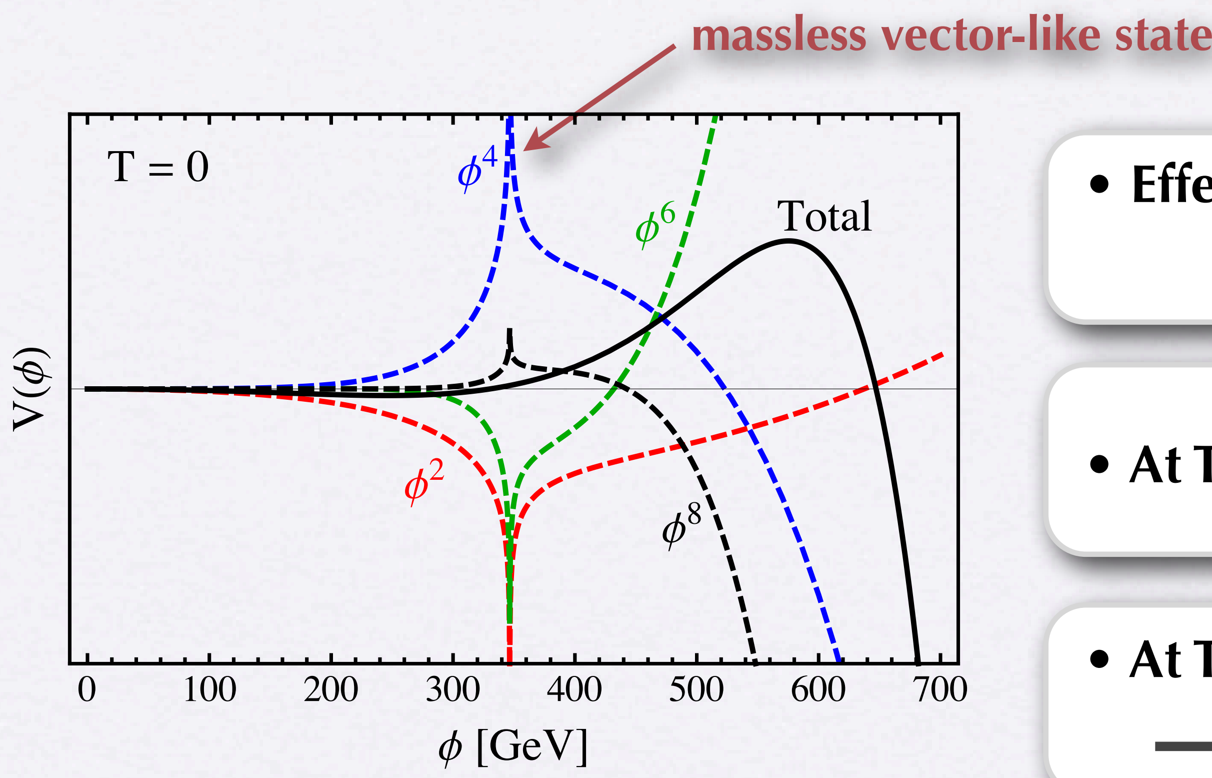


- **Effective Potential in EFT shows instability at** $\sim 600 \text{ GeV} \gg \text{EW scale}$

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

The Shape of the Eff. Pot.

(Davoudiasl, Lewis & EP, 1211.3449)

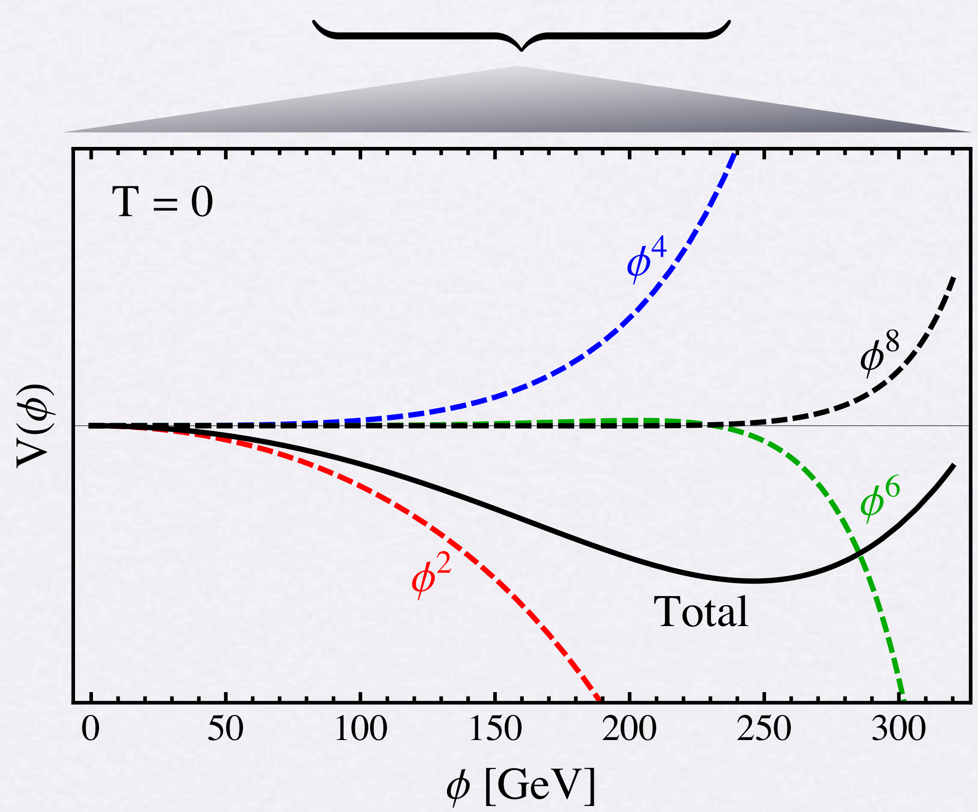


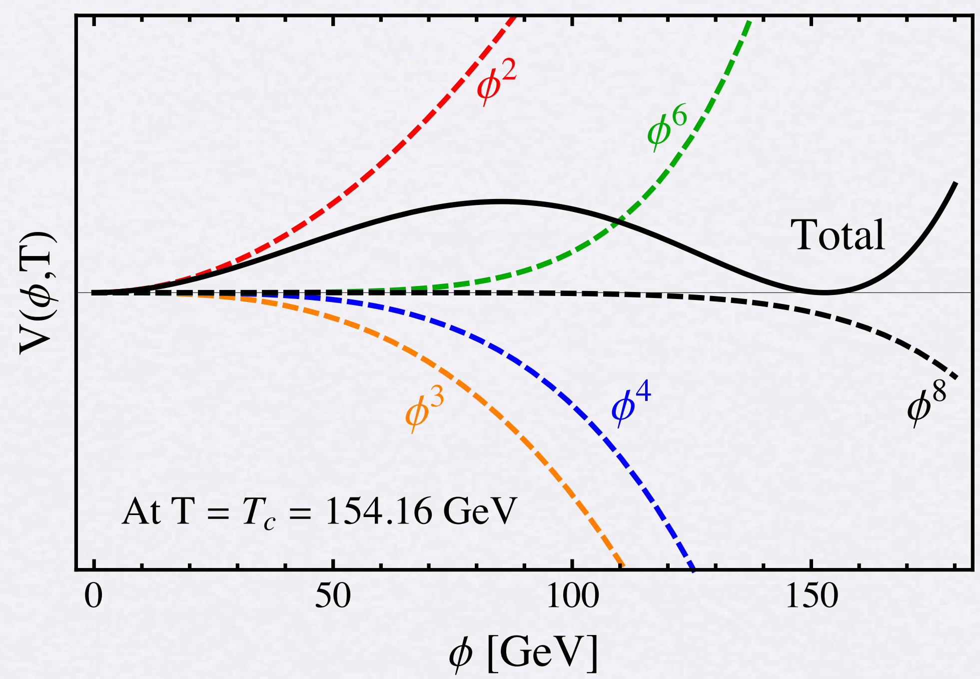
- **Effective Potential in EFT shows instability at** ~ 600 GeV $\gg$ EW scale

- **At T = 0 and** $\phi \sim$ 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)

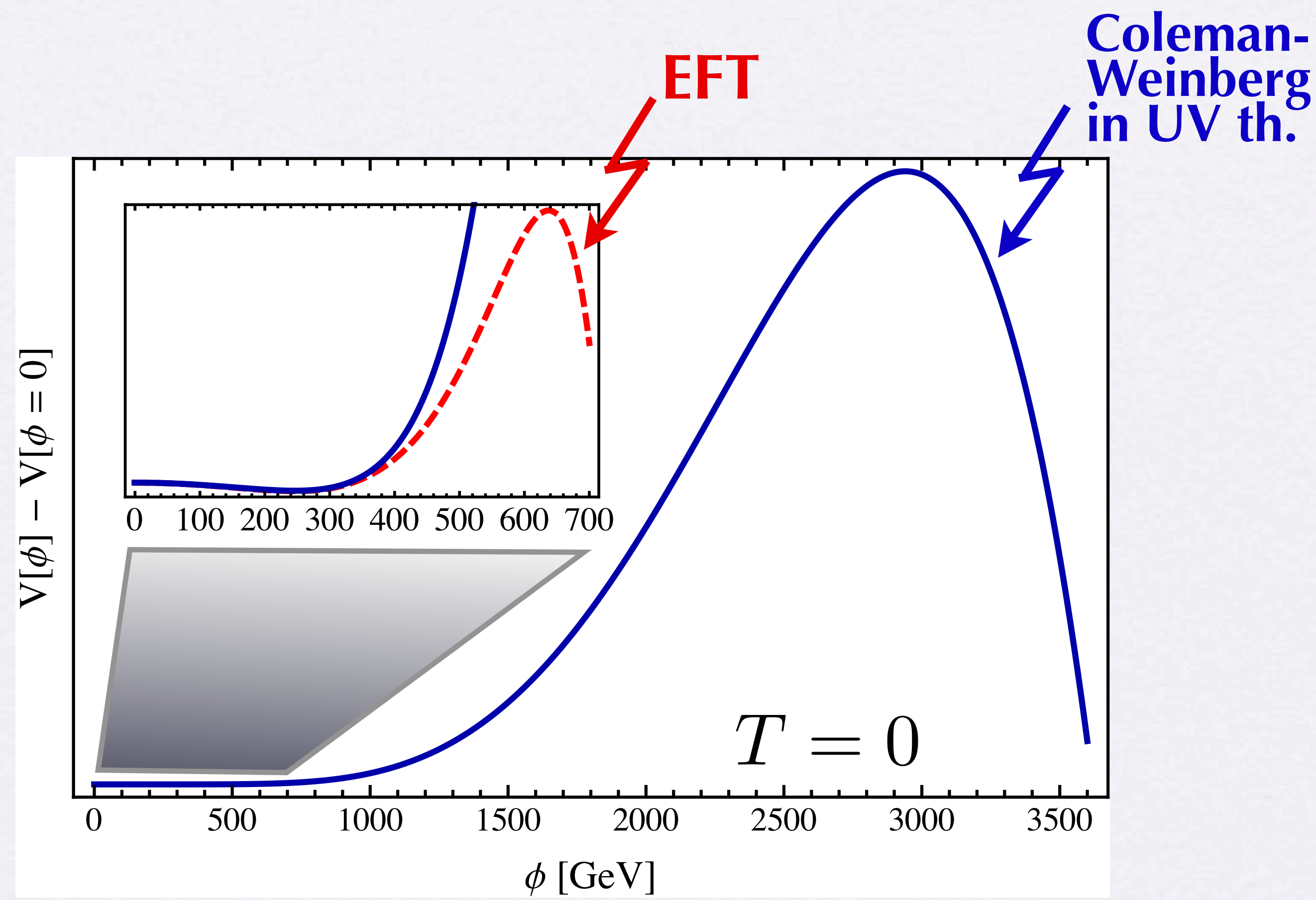
- EFT with ψ integrated out: match ϕ correlators and run from m_ψ to $m_\chi \sim v$

  → 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

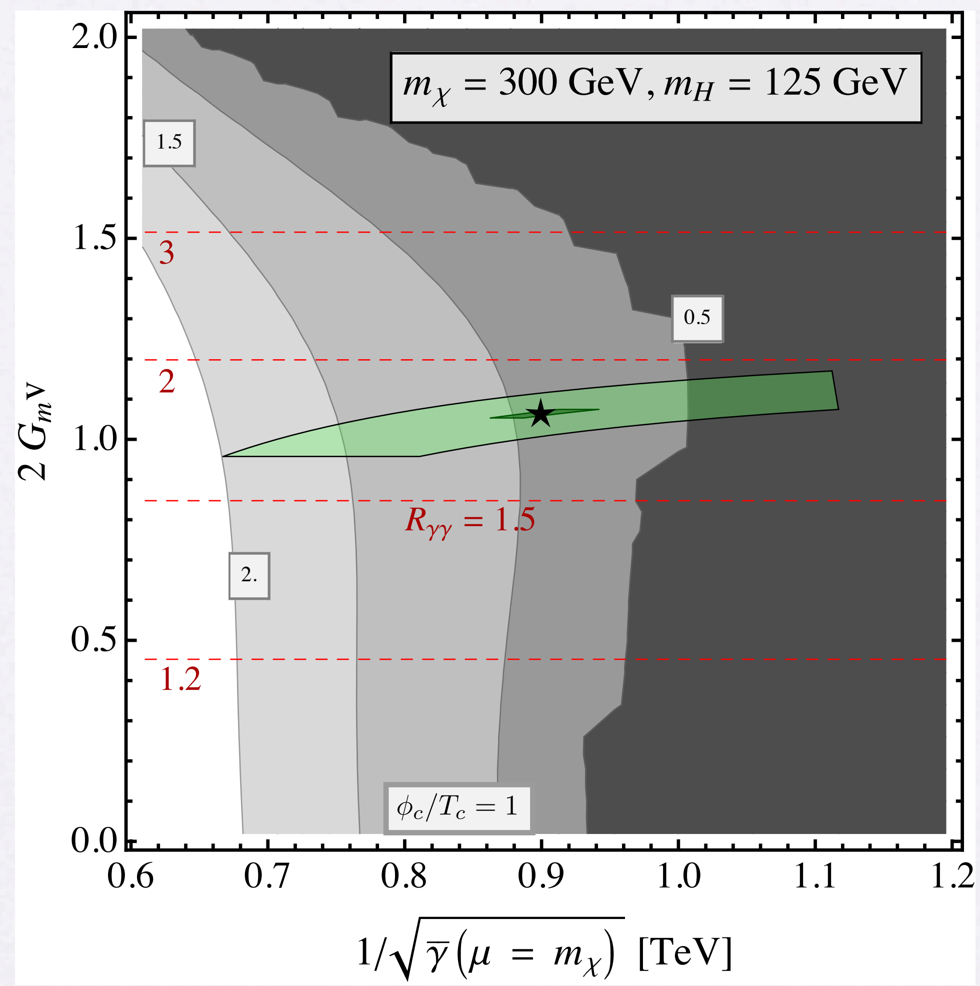
(Davoudiasl, Lewis & EP, 1211.3449)

- 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*

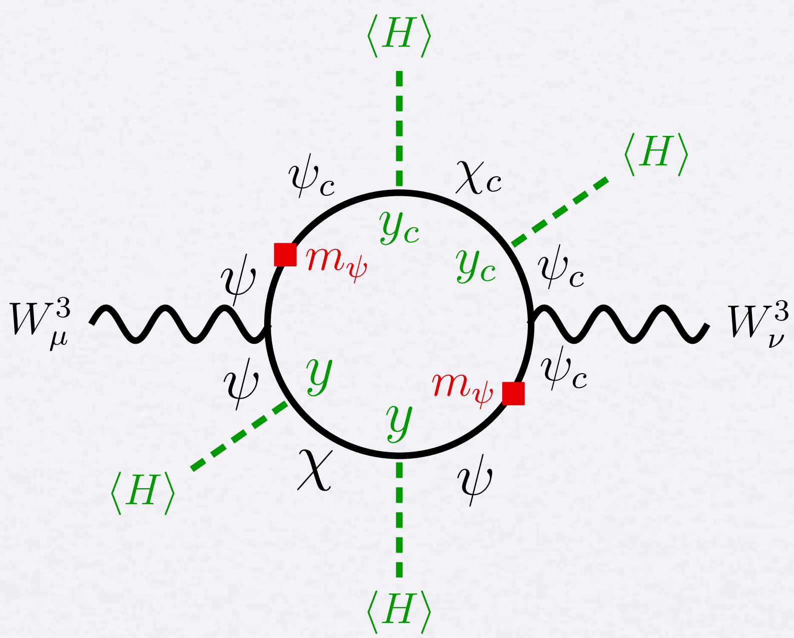
Star is a benchmark in UV model with:

$m_\psi = 4$ 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



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

(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:

$$\phi_c = 179.3 \text{ GeV}$$
$$T_c = 158.4 \text{ GeV}$$
$$\phi_c / T_c = 1.13$$

Bubbles nucleate slightly below T_c

EWPT and diphoton enhancement:

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

Consistent at 95% CL with current PDG ellipse

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

← **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!