Electroweak Phase Transition, Higgs Diphoton Rate, & New Heavy Fermions

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arXiv:1211.3449 [hep-ph], H. Davoudiasl, E. Ponton

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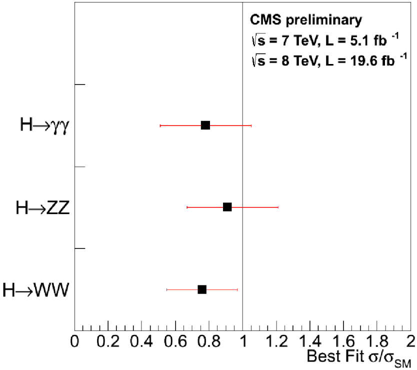
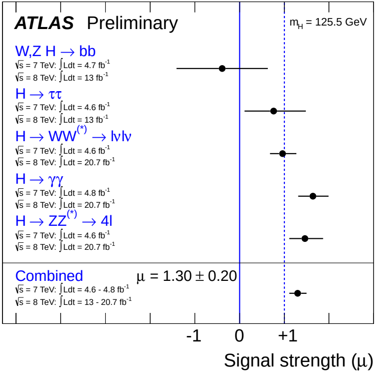
Outline

Signal Strengths





$$\mu_{\tau\tau} = 1.1 \pm 0.4$$

$$m_H = 125.8^{+0.4+0.4}_{-0.4-0.4}\ \text{GeV}$$

$$m_H = 125.5^{+0.5}_{-0.6}\ \text{GeV}$$

Now what?

- New boson at ~ 125 GeV, appears mostly Standard Model like.
- Is there still room for new physics coupling to the Higgs?
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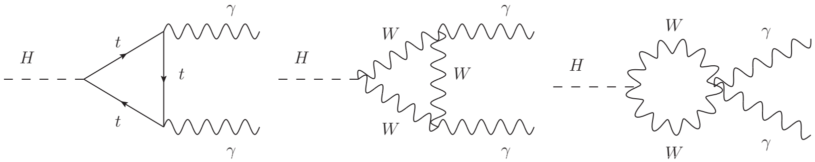
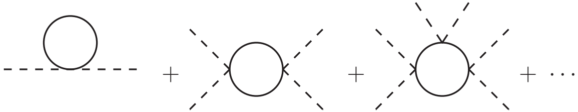
- Still room for new particles with $O(1)$ couplings to Higgs.
- If there is new physics, can it doing anything else for us?
- Will focus on correlation between increasing diphoton rate and electroweak phase transition.

Increasing Higgs DiPhoton



- Standard Model:
  - W and top loops destructively interfere.
  - W contribution to amplitude $\sim$ 4 times as large as top.
- Scalars and fermions whose mass arises from Higgs decrease $H \to \gamma\gamma$
  - Scalars have opposite sign mass term as W
  - Rate insensitive to fermion Yukawa coupling.
    - Higgs interaction flips chirality, while photon interactions preserve chirality.
    - Need mass insertion in top loop, $ym \sim y^2$
- Decouple mass and Higgs couplings:
  - Scalar mass term
  - Fermions with EW invariant mass terms, i.e. vector-like fermions

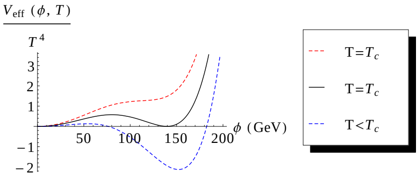
Effective Potential

$V_1(\phi) =$


- Expect new physics with $O(1)$ couplings to Higgs to manifest itself in other ways.
- For example, this new physics can effect the one-loop Higgs potential.
- Such effects could alter Higgs observables at the LHC, such as the Higgs trilinear coupling.
- Will also effect the evolution of the Higgs potential with temperature, and may provide a mechanism for a strong first-order electroweak phase transition.

Electroweak Phase Transition

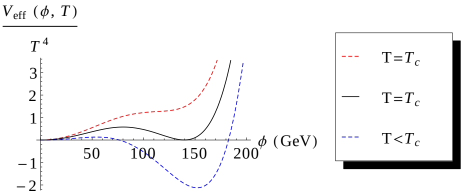
- Sakharov Conditions:
  - Baryon number violation
  - C and CP violation
  - Out of equilibrium interactions



- Strong first order phase transition provides the third point:
  - SM has baryon number violating processes that are in thermal equilibrium at high temperature.
  - If the phase transition is second-order, the processes can smoothly turn off, washing out any injected baryon number.
  - For a first order phase transition tunnel between symmetric and broken phases, suddenly turning off these processes and preserving any baryon number violation.
- Calculate the free energy: $V_{eff}(\phi, T) = V_0(\phi) + V_1(\phi) + \mathcal{F}_1(\phi, T)$
  - $V_0(\phi)$ is tree-level Higgs potential, $V_1(\phi)$ is 1-loop Coleman-Weinberg potential
  - $\mathcal{F}_1$ is the 1-loop thermal potential:

$$\mathcal{F}_1(\phi, T) = \sum_i \frac{g_i T^4}{2\pi^2} I_{\mp}\left(\frac{m_i(\phi)}{T}\right) \qquad I_{\mp}(z) = \pm \int_0^\infty dx x^2 \ln(1 \mp e^{-\sqrt{x^2+z^2}})$$

Electroweak Phase Transition



- Scalars
  - Temperature dependent one-loop potentials:
    $V_{eff}(\phi, T) \sim \frac{1}{2}\mu^2(T)\phi^2 + E(T)T\phi^3 + \frac{1}{4}\lambda(T)\phi^4$
- Effective Theory:
  - One-loop potential developes higher order terms:
    $V_{eff}(\phi, T) \sim \frac{1}{2}\mu^2(T)\phi^2 + \frac{1}{4}\lambda(T)\phi^4 + \frac{1}{6}\gamma(T)\phi^6$

    Zhang, PRD47; Grojean, Servant, Wells, PRD71; Delaunay, Grojean, Wells JHEP0804

One Extra Fermion

- Add a new vector-like fermion pair $(\chi, \chi^c) \sim (1,1)_{\mp 1}$ with mass term:

$$-\Delta\mathcal{L}_m = m_\chi \chi\chi^c - 2G_m \Phi^\dagger \Phi \chi\chi^c + \text{h.c.}$$

- Fermion has effective mass: $m_1(\phi) = m_\chi - G_m \phi^2$
- Coleman-Weinberg Potential in dim.reg:

$$V_1(\phi) = \sum \frac{m_i^4(\phi)}{64\pi^2} \left\{ - \left[\frac{1}{\varepsilon} - \gamma_E + \log 4\pi \right] + \log \frac{m_i^2(\phi)}{\mu^2} - \frac{3}{2} \right\}$$

- Effective operator induces UV divergences up to ϕ^8 in the Coleman-Weinberg potential, need "tree-level" operators:

$$V_0(\phi) = V_{\text{tree}} + \frac{1}{6}\bar{\gamma}\phi^6 + \frac{1}{8}\bar{\delta}\phi^8$$

One Extra Fermion

- Impose renormalization conditions on the one-loop effective potential:

$$V'(v) = 0 \quad V''(v) = m_H^2$$

- These fix quadratic and quartic terms, but ϕ^6 and ϕ^8 coefficients are still undetermined.
- Either need additional observables or match to a renormalizable theory.

UV Theory

- Two new vector-like fermion pairs:

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

- Mass terms:

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

  For simplicity assume $y = y_c$.
- Spectrum:
  - Two charged states:

$$m^2_{1,2}(\phi) = \frac{1}{2}\left(m^2_\psi + m^2_\chi\right) + \frac{1}{2}y^2\phi^2 \mp \frac{1}{2}(m_\psi + m_\chi)\sqrt{(m_\psi - m_\chi)^2 + 2y^2\phi^2}$$

  - One neutral state: $m_N = m_\psi$
- Will consider limit $m_\psi \gg yv$ and $m_\chi \sim \mathcal{O}(v)$

Matching

- Integrate out heavy fermion:

$$\Delta\mathcal{L} = 2G_m \Phi^\dagger \Phi \chi\chi^c + \text{h.c.} \quad G_m = \frac{Z_m y^2}{2(m_\psi - m_\chi)}$$

  where $Z_m = 1$ at tree-level
- Match IR potential and UV potential:
  - ϕ^6 terms:

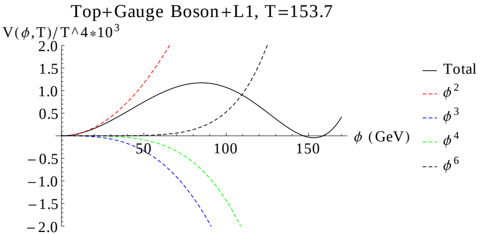
$$\bar{\gamma} = \frac{Z_\gamma y^6}{16\pi^2} \frac{m_\psi(m_\psi^2 + 7m_\chi m_\psi - 2m_\chi^2)}{(m_\psi - m_\chi)^5} - \frac{3G_m^3 m_\chi}{2\pi^2} \ln\left(\frac{m_\psi^2}{\mu^2}\right)$$

  - ϕ^8 terms:

$$\bar{\delta} = -\frac{Z_\delta y^8}{48\pi^2} \frac{7m_\psi^3 + 27m_\chi m_\psi^2 - 4m_\chi^3}{(m_\psi - m_\chi)^7} + \frac{G_m^4}{2\pi^2} \ln\left(\frac{m_\psi^2}{\mu^2}\right)$$

High Temperature Expansion

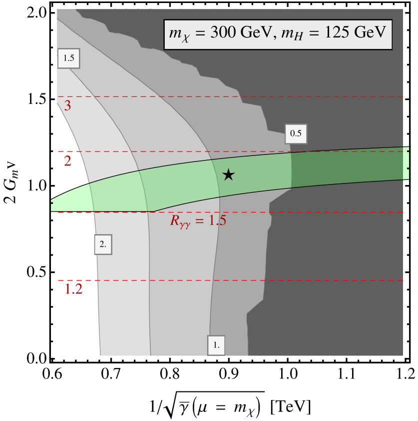
- To analyze the behaviour of the potential, we expand the effective potential in terms of m_i/T and as a polynomial is ϕ.



$$m_\psi = 4\text{ TeV}, \quad m_\chi = 300\text{ GeV}, \quad y = y_c = 4.3$$

- Have first order phase transition from fermions.
- Need baryon number violating processes to be sufficiently suppressed in broken phase: $\phi_c/T_c \gtrsim 1$

DiPhoton Rate and Strong EWPT

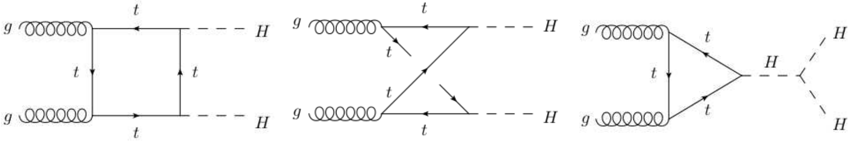


Computed using full finite temperature potential.

$$m_\psi = 4\text{ TeV},\quad m_\chi = 300\text{ GeV},\quad y = y_c = 4,\quad m_1 = 173\text{ GeV},\quad m_2 = 4130\text{ GeV}$$

$$T_c \approx 150\text{ GeV},\quad \phi_c \approx 140\text{ GeV},\quad \phi_c/T_c \approx 0.93$$

DiHiggs Production



- Sensitive to Higgs-trilinear coupling.
- However, destructive interference between box and triangle diagrams.
- Box diagrams dominate, hence moderate increase in trilinear coupling actually produces a decrease in the double Higgs rate at the LHC.
- For our scenario, expect the double Higgs rate to be 40% – 60% less than the Standard Model rate.

Comparison to Previous Work

- Know of one previous work that used TeV scale fermions to induce a strong EWPT Carena, Megevand, Quiros, Wagner, NPB716
- That work relied on fermions decoupling from thermal bath and delaying the phase transition.
- For that to work, the fermions masses need to increase as EW symmetry is broken, such physics would lead to a suppression in the $H \to \gamma\gamma$ rate.
- Our scenario is distinctly different: $m_1(\phi) = m_\chi - G_m \phi^2$
- Fermion masses decrease as EW symmetry is broken and lead to a diphoton enhancement.

Conclusions

- Discovered a boson at ~ 125 GeV that appears to be the Standard Model Higgs.
- Main production mode, $gg \to H$, and one of the main discovery modes, $H \to \gamma\gamma$, proceeds through loops.
- Although both ATLAS and CMS measure $H \to \gamma\gamma$ rates consistent with the Standard Model, there is still room for new physics at the electroweak scale with $O(1)$ couplings to the Higgs.
- We explored the connection between vector-like leptons that increase $H \to \gamma\gamma$ and their effect on the electroweak phase transition.
- Showed that vector-like leptons that increase $H \to \gamma\gamma$ via an effective operator are also correlated to a strong first order electroweak phase transition.
- Expect double Higgs rate at LHC to be 40% – 60% of the Standard Model rate.