Strong First-Order Phase Transitions, Models and Probes

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What do we *really* know about the Higgs?

- We have discovered the Higgs boson and measured its properties with precisions.
- However, we know very little about the Higgs potential.
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• However, we know very little about the Higgs potential.

\[ V(\Phi) = \frac{1}{2} m^2_0 \Phi^2 + c_0 T^2 \Phi^4 + c_6 \Phi^6 \]

\[ m_h \simeq 125 \text{ GeV} \]

\[ v \simeq 246 \text{ GeV} \]

\[ \langle \Phi \rangle, \text{measured from } G_F \]

\[ \text{Higgs mass measured at the LHC} \]
What do we really know about the Higgs?

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Completely specify the Higgs potential in the SM, but **NOT** directly measured:

$$V = -\mu^2 H^\dagger H + \lambda_h (H^\dagger H)^2$$

$$\mu^2 = m_h^2/2 \approx (88\text{GeV})^2$$

$$\lambda_h = m_h^2/2v^2 \approx 0.13$$
What do we *really* know about the Higgs?

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- However, we know very little about the Higgs potential.

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Self coupling, Limited sensitivity at HL-LHC
What do we *want* to know about the Higgs?

- The shape of the Higgs potential is closely related to the electroweak phase transition.

Know nothing beyond $v$, and $m_h$  

EW symmetry restored
Electroweak Phase Transitions

- First Order?
  - In the SM, the EW symmetry is broken by a smooth cross over.
  - \( v (T) \) changes smoothly
  - No energy barrier; no bubbles;
  - no cosmological relics
Electroweak Phase Transitions

- First Order Phase Transition
- $v$ is discontinuous
- $V_{\text{eff}}$ has a barrier, bubbles nucleated
- Possibly interesting cosmological relics!

New physics to generate a barrier
Outline

How can we probe the new physics?

• Gravitational waves
• Colliders

What kind of models?

• Other model-dependent probes of the new physics?
Outline

How can we probe the new physics?

• Gravitational waves

Chala, Krause, and Nardini, 1802.02168
Outline

How can we probe the new physics?

- Gravitational waves
- Colliders

What kind of models?

- Other model-dependent probes of the new physics?
Probes?
Generate the Barrier

\[ V(\phi, T) = \frac{m^2 + a_0 T^2}{2} (\phi^\dagger \phi) + \frac{\lambda}{4} (\phi^\dagger \phi)^2 + \frac{c_6}{8 \Lambda^2} (\phi^\dagger \phi)^3 \]

\[ \lambda_3 = \left. \frac{\partial^3 V}{\partial \phi^3} \right|_{\phi=v} = \frac{3m_h^2}{v} \left( 1 + \frac{2c_6 v^4}{m_h^2 \Lambda^2} \right) \]

Critical temperature

\[ T_c^2 = \frac{3c_6}{4\Lambda^2 a_0} (v^2 - v_c^2) \left( v^2 - \frac{v_c^2}{3} \right) . \]

\[ (\phi^\dagger_c \phi_c) = v_c^2 = -\frac{\lambda \Lambda^2}{c_6} . \]

Requiring first order phase transition

\[ \frac{5}{3} \lambda_3^{SM} < \lambda_3 < 3 \lambda_3^{SM} \]
Generate the Barrier – Adding Higher-dim Operators

\[
V(\phi, 0) = \frac{m^2}{2}(\phi^+\phi) + \frac{\lambda}{4}(\phi^+\phi)^2 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}} (\phi^+\phi)^{n+2}
\]

\[\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1\]

First order Phase Transition

- First order PTs tend to be associated with enhancements in the trilinear coupling, while suppressions tend to be associated with second order PTs.

- The trilinear coupling could deviate significantly from its SM value in the region consistent with a first order EWPT.

Color coding are for different hierarchies of the coefficients.

arxiv:1512:00068 PH, A. Joglekar, B. Li, and C. Wagner
Collider Probes – Double Higgs Production

At NNLO, 14 TeV,

\( \lambda^3 = \lambda^3_{SM} \sigma(pp \rightarrow hh) = 40 \text{ fb} \)

\( \lambda^3 = 5\lambda^3_{SM} \sigma(pp \rightarrow hh) = 100 \text{ fb} \)

De Florian and Mazzitelli, Grigo, Melnikov, and Steinhauser

Spira, figure from Barger, Everett, Jackson, and Shaughnessy
Collider Probes – Double Higgs Production

\[ V(\phi, T) = \frac{m^2 + a_0 T^2}{2} (\phi^\dagger \phi) + \frac{\lambda}{4} (\phi^\dagger \phi)^2 + \frac{c_6}{8 \Lambda^2} (\phi^\dagger \phi)^3 \]

\[ \frac{5}{3} < \kappa_\lambda < 3 \]

\[ V(\phi, 0) = \frac{m^2}{2} (\phi^\dagger \phi) + \frac{\lambda}{4} (\phi^\dagger \phi)^2 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2(n+2) \Lambda^{2n}} (\phi^\dagger \phi)^{n+2} \]

\[ \lambda_3^{\text{max}} \sim 7 \lambda_3^{\text{SM}} \]

The LHC has a very limited sensitivity in the region where the EWPT can be strongly-first-order.
Limited sensitivity with large $\lambda_3$

- The destructive interference occurs between the real part of the triangle and the box diagrams
- Above the $tt$ threshold, the amplitudes develop imaginary parts, the cancellation does not occur
- When $\lambda_3$ increases, the amplitudes increases more below the $tt$ threshold than above the threshold
- $m_{hh}$ shifts to smaller value for large $\lambda_3$
Limited sensitivity with large $\lambda_3$

SM: peaked at large invariant mass. A cut of $m_{hh} > 2m_{top}$ or something equivalent is currently used in both experimental and phenomenology studies.

$\lambda_3 > 3\lambda_3^{SM}$, $m_{hh}$ distribution is much softer than the SM case.
How can we probe the new physics?

• Gravitational waves
• Collider
  • The trilinear coupling deviates significantly from the SM
  • Need to change the $m_{hh}$ cut
Models
Heavy Scalar Singlet

\[ V(\phi_h, \phi_s, T) = \frac{m_0^2 + a_0 T^2}{2} \phi_h^2 + \frac{\lambda_h}{4} \phi_h^4 + a_{hs} \phi_s \phi_h^2 + \frac{\lambda_{hs}}{2} \phi_s^2 \phi_h^2 + t_s \phi_s^3 + \frac{m_s^2}{2} \phi_s^2 + \frac{a_s}{3} \phi_s^3 + \frac{\lambda_s}{4} \phi_s^4 \]

Integrate out the singlet,

\[ y = v^2/m_s^2, \quad V_{\text{eff}}(H, T) = \frac{m_0^2 + a_0 T^2}{2} H^2 + \left( \frac{\lambda_h}{4} - \frac{z}{2y} - \frac{2m^2 z}{3v^2} \right) H^4 + \frac{8z^2 - 4yz\lambda_h + 3yz\lambda_{hs}}{6v^2 y} H^6. \]

- Collider probes/constraints
  - Higgs signal strength
  - Resonance decaying to vector bosons and Higgs bosons
- Electroweak precision observables

PH, A. Joglekar, B. Li, and C. Wagner, arxiv:1512.00068
PH, A. Hooper, and C. Wagner, work in progress
Heavy Scalar Singlet, Lepton Colliders

The singlet kinetic term modifies the wave function of the physical and therefore shifts all Higgs couplings universally

\[ \frac{1}{2} \left( \partial_{\mu} \phi_s \right) \left( \partial^{\mu} \phi_s \right) \approx \frac{2a_{hs}^2}{m_s^4} \left( \Phi^\dagger \partial_{\mu} \Phi + \text{h.c.} \right)^2 \left[ 1 + O(\lambda_{hs} \Phi^\dagger \Phi/m_s^2) \right] \]

HL-LHC expects to measure the Higgs couplings to percent level. \( O(2-10\%) \)

hZZ coupling can be measured to high precisions with lepton colliders.

- hZZ coupling can be probed by the Higgsstralung process
- Large production cross section around 240 GeV to 250 GeV \( \sim 200 \) fb
- Expect 0.25\% precision in hZZ coupling at future lepton colliders!
Heavy Scalar Singlet, Lepton Colliders, GWs

1\textsuperscript{st} order phase transition
Strong first order phase transition

Current constraints: Higgs signal strength
HL-LHC can start to probe the hZZ coupling to percent level
Next generation lepton colliders can basically cover the whole region
Scalar Doublets

\[ V = \frac{1}{2} m_0 \phi_h^2 + \frac{\lambda_h}{4} \phi_h^4 \]
\[ + m_Q^2 (|\tilde{u}|^2 + |\tilde{d}|^2) + m_U^2 |\tilde{U}|^2 + \lambda_Q (|\tilde{u}|^2 + |\tilde{d}|^2)^2 + \lambda_U (|\tilde{U}|^2) \]
\[ + \lambda_{QU} (|\tilde{u}|^2 + |\tilde{d}|^2) |\tilde{U}|^2 + \frac{\lambda_{hU}}{2} \phi_h^2 |\tilde{U}|^2 \]
\[ + \frac{\lambda_{hQ}}{2} (|\tilde{u}|^2 + |\tilde{d}|^2) \phi_h^2 + \frac{\lambda'_{hQ}}{2} |\tilde{u}|^2 \phi_h^2 + \frac{\lambda''_{hQ}}{2} |\tilde{d}|^2 \phi_h^2 \]
\[ + \left[ \frac{a_{hQU}}{\sqrt{2}} \tilde{u}\phi_h \tilde{U}^* + \text{h.c.} \right] . \]

\[ M_l^2 = \begin{pmatrix} m_Q^2 + \frac{1}{2} (\lambda_{hQ} + \lambda'_{hQ}) v^2 \frac{a_{hQU} v}{\sqrt{2}} & \frac{a_{hQU} v}{\sqrt{2}} \\ \frac{a_{hQU} v}{\sqrt{2}} & m_U^2 + \frac{1}{2} \lambda_{hU} v^2 \end{pmatrix} \]
\[ m_b^2 = m_Q^2 + \frac{1}{2} (\lambda_{hQ} + \lambda''_{hQ}) v^2 \]

\[ \tilde{Q} \sim (1, 2, 1/3) \times 3 \text{ flavor} \]
\[ \tilde{U} \sim (1, 1, 4/3) \times 3 \text{ flavor} \]

For simplicity, consider \( \langle \tilde{Q} \rangle = (0, 0) \) and \( \langle \tilde{U} \rangle = 0 \)

\[ \lambda_Q = \lambda_U = \lambda_{QU} = \lambda_{hU} = \lambda_{hQ} = \lambda'_{hQ} = \lambda''_{hQ} = \lambda \]

\[ \text{Spectrum} \]

With the new stop-like particle content, the scalar potential can be written as:

\[ \text{Lagrangian} \]

In the MSSM, the stops play a critical role in making the EWPT first order. However, since we get cubic terms in the effective potential (background-dependent free energy density) goes as:

\[ \langle \tilde{Q} \rangle = (0, 0) \quad \text{and} \quad \langle \tilde{U} \rangle = 0 \]

In general the model has 12 parameters, 3 copies (flavors) of scalar doublets and complex scalar

\[ \text{flavors has been suppressed. In general the model has 12 parameters,} \]

\[ \text{2 flavor} \]

\[ \text{couplings can give rise to a first order electroweak phase transition. However, since we} \]

\[ \text{consider} \]

\[ \langle \tilde{Q} \rangle = (0, 0) \quad \text{and} \quad \langle \tilde{U} \rangle = 0 \]

\[ \lambda_Q = \lambda_U = \lambda_{QU} = \lambda_{hU} = \lambda_{hQ} = \lambda'_{hQ} = \lambda''_{hQ} = \lambda \]
Scalar Doublets, Collider Probes

Modified hZZ couplings,

\[
\delta Z_h = 3 \sum_{i,j=1}^{2} \frac{|g_{h\tilde{t}_i\tilde{t}_j}|^2 v^2}{32\pi^2} I(m_h^2; m_{\tilde{t}_i}^2, m_{\tilde{t}_j}^2) + 3 \frac{|g_{h\tilde{b}\tilde{b}}|^2 v^2}{32\pi^2} I(m_h^2; m_{\tilde{b}}^2, m_{\tilde{b}}^2)
\]


Scalar Doublet, Modified di-photon coupling

\[ \Gamma_{h \rightarrow \gamma\gamma} = G_F \alpha^2 \frac{M_h^3}{128\sqrt{2}\pi^3} \left| A_W + A_t + A_{\tilde{t}} + A_{\tilde{b}} \right|^2 \]

\[ A_W = F_1 \left( \frac{M_h^2}{4M_W^2} \right) \]
\[ A_t = \frac{4}{3} F_{1/2} \left( \frac{M_h^2}{4M_t^2} \right) \]
\[ A_{\tilde{t}} = \sum_{i=1,2} 3 \left( \frac{2}{3} \right)^2 g_{h\tilde{t}_i\tilde{t}_i} \frac{v^2}{M_{\tilde{t}_i}^2} F_0 \left( \frac{M_h^2}{4M_{\tilde{t}_i}^2} \right) \]
\[ A_{\tilde{b}} = -3 \left( \frac{1}{3} \right)^2 g_{h\tilde{b}\tilde{b}} \frac{v^2}{M_{\tilde{b}}^2} F_0 \left( \frac{M_h^2}{4M_{\tilde{b}}^2} \right) \]

Djouadi, Driesen, Hollik, Illana, 2005
Scalar Doublets

1st order phase transition
Strong first order phase transition
Lisa

In the region where the EWPT is strongly first-order, hZZ and Higgs diphoton couplings deviate significantly from the SM. Will be fully tested by HL-LHC.

Fermions?
Integrating out new fermions?

Take a general vector-like fermion model,

\[ \mathcal{L}_{VLL} = \bar{L}(i\gamma_\mu D^\mu_L - m_L)L + \bar{E}'(i\gamma_\mu D^\mu_E - m_E)E' + \bar{N}'(i\gamma_\mu D^\mu_N - m_N)N' - \left[ \bar{L} H (y_{EL} P_L + y_{ER} P_R) E' + \bar{L} \tilde{H} (y_{NL} P_L + y_{NR} P_R) N' + \text{h.c.} \right], \]

\[ 16\pi^2 \mathcal{L}_{H}^{CP} \supset + \left( \frac{4}{3} + 2\log\frac{\mu^2}{m^2} \right) |y_N|^2 |y_E|^2 |D_\mu H|^2 \]

\[ - \left( 1 + 3\log\frac{\mu^2}{m^2} \right) (|y_N|^2 + |y_E|^2) m^2 |H|^2 \]

\[ + \left( \frac{16}{3} + 2\log\frac{\mu^2}{m^2} \right) (|y_N|^4 + |y_E|^4) |H|^4, \]

\[ - \frac{2(|y_N|^6 + |y_E|^6)}{15m^2} O_6 \]

Does not have the barrier we want as in the singlet extension.

A. Angelescu, PR 2006.16532
S. Ellis, J. Quevillon, P. Vuong, T. You, and Z. Zhang 2006.16260
Possible to have a barrier from fermions?

Low T, scalars and fermions contribute equally

\[- \frac{T^2 m^2(\phi)}{2\pi^2} K_2 \left( \frac{m(\phi)}{T} \right) + \mathcal{O}(T^2 m(\phi)^2 e^{-2m(\phi)/T})\]

Consider the possibility of generating a barrier through fermions
A Minimal Vector-Like Lepton (VLL) Model

• Fermion models for strong first order phase transitions?
  • Strong couplings to the Higgs!

• To avoid large mixing between the VLLs and SM leptons, and large contributions to the $T$ parameter, we add

$$L_{L,R} = \left( \begin{array}{c} N \\ E \end{array} \right)_{L,R} \sim (1, 2)_{-1/2}, \quad N'_{L,R} \sim (1, 1)_0, \quad E'_{L,R} \sim (1, 1)_{-1}$$

• The most general Lagrangian is,

$$-\mathcal{L}_{VLL} = y_{N_R} \bar{L}_L \tilde{H} N'_R + y_{N_L} \bar{N}'_L \tilde{H}^\dagger L_R + y_{E_R} \bar{L}_L H E'_R + y_{E_L} \bar{E}'_L H^\dagger L_R$$
$$\quad + m_L \bar{L}_L L_R + m_N \bar{N}'_L N'_R + m_E \bar{E}'_L E'_R + \text{h.c.} ,$$
A Minimal Vector-Like Lepton (VLL) Model

\[-\mathcal{L}_{\text{VLL}} = y_{N_R} \overline{L_L} \tilde{H} N'_R + y_{N_L} \overline{N'_L} \tilde{H} L_R + y_{E_R} \overline{L_L} H E'_R + y_{E_L} \overline{E'_L} H L_R + m_L \overline{L_L} L_R + m_N \overline{N'_L} N'_R + m_E \overline{E'_L} E'_R + \text{h.c.},\]

- 2 neutral and 2 charged VLLs
- Ranges of the parameters considered,
  \[m_L, m_N, m_E \in [500, 1500] \text{ GeV}, \quad y_{N,R}, y_{E,R} \in [2, \sqrt{4\pi}].\]
- Constraints:
  - S & T parameters
  - Diphoton signal strength, \( 0.71 < \mu_{\gamma\gamma} < 1.29 \) ATLAS, 1802.04146
  - Masses of the lighter states, \( m_{E_1} > 100 \text{ GeV} \) and \( m_{N_1} > 90 \text{ GeV} \)
Thermal Evolution of the Effective Potential

• For each surviving point, calculate the phase transition strength, \( \xi = \frac{\phi_c}{T_c} \)

\[
V(\phi, T) = V_{\text{tree}}^{SM}(\phi) + V_{1-\text{loop}}^{SM}(\phi, T) + V_{1-\text{loop}}^{VLL}(\phi, T) + V_{\text{Daisy}}(\phi, T)
\]

• Benchmark A,

\[
y_{N_L} \simeq 3.40, \ y_{N_R} \simeq 3.49, \ y_{E_L} \simeq 3.34, \ y_{E_R} \simeq 3.46,
\]

\[
m_L \simeq 1.06 \text{ TeV}, \ m_N \simeq 0.94 \text{ TeV}, \ m_E \simeq 1.34 \text{ TeV}.
\]

\[
\mu_\gamma = 1.28, \ \Delta \chi^2(S, T) = 1.33, \ m_{N_1} = 400 \text{ GeV}, \ m_{E_1} = 592 \text{ GeV}.
\]
Thermal Evolution of the Effective Potential

Cross over

Early universe, symmetric

EWSB
Thermal Evolution of the Effective Potential

- The broken minimum becomes less and less deep
- A potential barrier starts developing between the symmetric phase and the broken phase
- At $T_{c2}$, a strong first order phase transition
- The universe tunnels back to the symmetric phase

EW symmetry restored
Thermal Evolution of the Effective Potential

EWSB again through a strongly first order phase transition, at $T_{c1}$
Thermal Evolution of the Effective Potential

Responsible for the BAU
Signatures – Gravitational Waves

- Peak frequency beyond Lisa ($f \sim 0.01 - 1$ Hz is typical for VLL models)
- DECIGO, BBO, and AION are sensitive to the later phase transition
- The earlier one is too weak.
Signatures – Colliders, Direct Production

• $N_1$ can not be dark matter candidate – some mixing required.

$$-\mathcal{L}_{\text{mix}} = y_1 \bar{L}_L H \tau_R + y_2 \bar{L}_L H E'_R + \text{h.c.},$$

• From $W\tau\nu$ and $Z\tau\tau$ measurements, take $y_1 = y_2 = 0.05$

• The SM fermion + VLL production is suppressed by the mixing

• The dominant production mode is the pair production of VLLs, the typical production cross section is around 0.1 to 0.4 fb.

• Direct searches at the LHC very challenging.
Signatures – Colliders, Indirect Searches

- At least 15% enhancement for the diphoton signal.
- Will be fully tested at the HL-LHC.
Conclusion

How can we probe the new physics?
Conclusion

What kinds of models?

- Scalar Singlets
- Scalar Doublets
- Fermions
- Many More!