

Multistep Single-Field Strong Phase Transitions from New TeV Scale Fermions

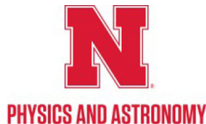
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in collaboration with Peisi Huang

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Introduction and Motivation

- Baryon Asymmetry in the Universe (BAU)?
→ Sakharov conditions:
 - B -number violation;
 - C and CP violation;
 - interactions out of thermal equilibrium;
- Interactions out of thermal equilibrium?
→ Strongly First Order (SFO) Electroweak Phase Transition (EWPT)!
- Solution within the Standard Model (SM)?
→ No strong EWPT! (plus not enough CP) \Rightarrow new physics needed!
- Usually, new bosons $\rightarrow \mathcal{O}(100)$ papers ...

WHAT ABOUT NEW FERMIONS AND PHASE TRANSITIONS?

Extra Dimensions, Composite Higgs, ... \Rightarrow new fermions!

Rather uncharted territory (but: Carena+ '04, Fok+ '08, Davoudiasl+ '12, Fairbairn+ '13, Egana-Ugrinovic '17).

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- 2 New Dirac Fermions and the Phase Structure of the Universe
- 3 Gravitational Wave (and Collider) Signatures
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Overview

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A Minimal Vector-Like Lepton (VLL) Model

- Dirac fermion model for strong PTs in the Early Universe?
→ need strong couplings to the Higgs!
- However: strong Yukawas \Rightarrow large custodial symmetry breaking!
- Solution \rightarrow a minimal model which can possess (approximate) custodial symmetry:

$$L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} \sim (1, 2, -1/2), \quad N'_{L,R} \sim (1, 1, 0), \quad E'_{L,R} \sim (1, 1, -1).$$

- VLL masses + Yukawa couplings (assume negligible mixing with the SM):

$$\begin{aligned} -\mathcal{L}_{VLL} = & y_{N_R} \bar{L}_L \tilde{H} N'_R + y_{N_L} \bar{N}'_L \tilde{H}^\dagger L_R + y_{E_R} \bar{L}_L H E'_R + y_{E_L} \bar{E}'_L H^\dagger L_R \\ & + m_L \bar{L}_L L_R + m_N \bar{N}'_L N'_R + m_E \bar{E}'_L E'_R + \text{h.c.} \end{aligned}$$

- EW symmetry breaking \Rightarrow mass matrices ($v = 246$ GeV, $v_h = v/\sqrt{2} \simeq 174$ GeV):

$$\mathcal{M}_N = \begin{pmatrix} m_L & v_h y_{N_L} \\ v_h y_{N_R} & m_N \end{pmatrix}, \quad \mathcal{M}_E = \begin{pmatrix} m_L & v_h y_{E_L} \\ v_h y_{E_R} & m_E \end{pmatrix}.$$

- Diagonalization \Rightarrow eigenmasses $m_{N_1} < m_{N_2}$, $m_{E_1} < m_{E_2}$ and interaction basis couplings.

Approach

- Calculate the 1-loop finite T effective potential (on-shell renormalization scheme, $V(0, T) \equiv 0$):

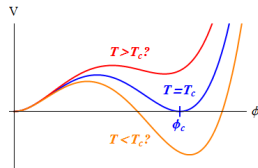
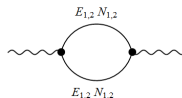
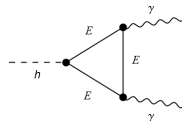
$$V(\phi, T) = V_{\text{tree}}^{\text{SM}}(\phi) + V_{1\text{-loop}}^{\text{SM}}(\phi, T) \\ + V_{1\text{-loop}}^{\text{VLL}}(\phi, T) + V_{\text{Daisy}}(\phi, T);$$

- Many parameters \Rightarrow scan approach:

$$m_L, m_N, m_E \in [500, 1500] \text{ GeV},$$

$$y_{N_{L,R}}, y_{E_{L,R}} \in [2, \sqrt{4\pi}];$$

- Impose $0.71 \leq \mu_{\gamma\gamma} < 1.29$ (1802.04146), $\Delta\chi^2(S, T) \leq 6.18$;
- Calculate PT strength for each point $\rightarrow \xi \equiv \phi_c / T_c$.



Thermal Evolution of the Effective Potential: Multistep Phase Transition

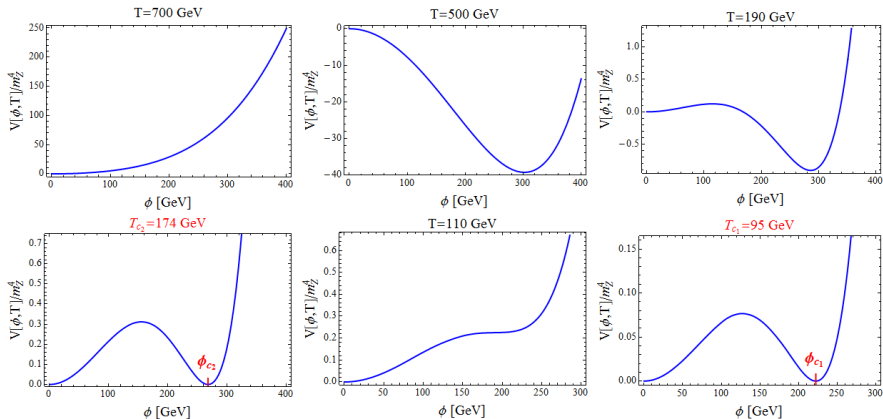
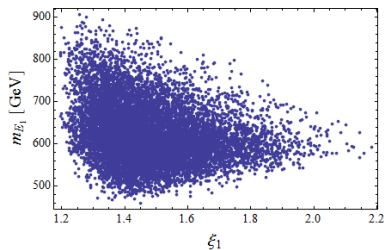
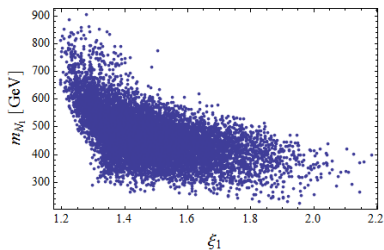
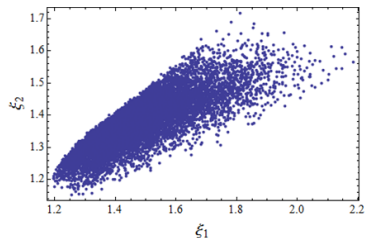
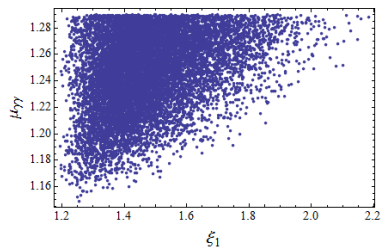


Figure: Typical temperature dependence of the 1-loop effective potential in the VLL model under study.

N.B.: Only the **last SFOPT** is responsible for generating the **BAU**! $\Rightarrow \xi_1 \geq 1.3$.

Correlations Between Observables



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Gravitational Wave Signature

- **Strong PTs** in the Early Universe \Rightarrow **Gravitational Wave (GW)** stochastic background!
 \rightarrow **Detectable** by future GW experiments, such as **LISA/DECIGO/BBO**?
- **GW amplitude and spectrum** controlled (mostly) by two parameters:

$$\alpha = \frac{\text{latent heat}}{\text{radiation energy}}, \quad \frac{\beta}{H_{\text{PT}}} = \frac{\text{"inverse PT duration"}}{\text{Hubble rate}}$$

- Main **GW sources** \rightarrow **bubble collisions** (Ω_{col}), **MHD turbulence** (Ω_{turb}), **sound waves** (Ω_{sw}):

$$h^2 \Omega_{\{\text{col}, \text{turb}, \text{sw}\}}(f) \propto \left(\frac{\beta}{H_{\text{PT}}} \right)^{-\{2, 1, 1\}} \left(\frac{\alpha}{1 + \alpha} \right)^{\{2, \frac{3}{2}, 2\}} S_{\{\text{col}, \text{turb}, \text{sw}\}}(f; \beta/H_{\text{PT}})$$

- Typically, for our **VLL** model:

$$\alpha = \mathcal{O}(10^{-1} - 10^{-2}), \quad \frac{\beta}{H_{\text{PT}}} = \mathcal{O}(10^3 - 10^4),$$

\Rightarrow **SW contribution dominant for $f \in [10^{-3}, 1]$ Hz** (**LISA/DECIGO/BBO** max sensitivity).

GW Spectrum Calculation and Detection Prospects

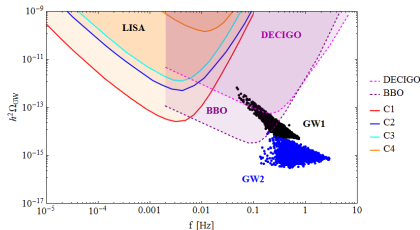
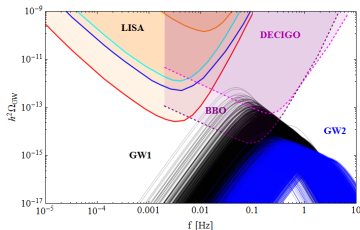
- Compute the bounce action $S_3(T)$, find the temperature at which the PT occurs:

$$\frac{S_3(T_{\text{PT}})}{T_{\text{PT}}} \simeq 142;$$

- Calculate α and β for the two SFOPTs:

$$\alpha = \frac{|V(\phi_{\text{broken}}, T_{\text{PT}})| + T_{\text{PT}} \left| \frac{\partial V(\phi_{\text{broken}}, T)}{\partial T} \right|_{T_{\text{PT}}}}{\rho_{\text{rad}}(T_{\text{PT}})}, \quad \frac{\beta}{H_{\text{PT}}} = T_{\text{PT}} \frac{d}{dT} \left(\frac{S_3}{T} \right) \Big|_{T_{\text{PT}}}.$$

- Compute GW spectrum \rightarrow GW detectable by DECIGO/BBO:



Collider Predictions

Benchmark point \rightarrow **strongest PT**:

$$y_{N_L} \simeq 3.4, y_{N_R} \simeq 3.49, y_{E_L} \simeq 3.34, y_{E_R} \simeq 3.46,$$

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

- N_1 not a suitable Dark Matter candidate \Rightarrow **SM-VLL mixing** should be present!
- Measurements: $W_{T\nu}$ and $Z_{T\tau}$ couplings \Rightarrow take $y_{TE} \simeq 0.05$;
- For simplicity, $y_{\nu N} \simeq 0 \Rightarrow \text{BR}(N_1 \rightarrow W\tau) = 1$;
- Predictions for the benchmark $\rightarrow m_{N_1} \simeq 400 \text{ GeV}$, $m_{E_1} \simeq 600 \text{ GeV}$, and:

$$\text{BR}(E_1 \rightarrow N_1 W) \simeq 1, \quad \sigma(pp \rightarrow \psi_{\text{NP}}\psi_{\text{NP}}) \simeq 0.3 \text{ fb}, \quad \sigma(pp \rightarrow \psi_{\text{NP}}\psi_{\text{SM}}) \simeq \mathcal{O}(10^{-4}) \text{ fb}$$

DIRECT PRODUCTION OF VLLs SUPPRESSED . . .

MORE PROMISING SEARCH AVENUE? $\rightarrow \mu\gamma\gamma$!

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Summary and Conclusions

- Studied the impact of **new VLLs** on the **phase structure** of the Universe;
→ Indeed, **TeV-scale VLLs** with **strong Yukawas** can induce **SFOEWPTs**!
- Interestingly, such a **simple model** predicts a **complex PT structure**:
→ First example of **single-field multistep SFOPT**!
- **GW signature** → multiple peaks, possibly **detectable by DECIGO or BBO**;
- **Collider** searches → **direct production** and detection of VLLs **not promising**;
- $\mu\gamma\gamma$ = **most promising collider** signature → **5% precision** @ HL-LHC!
(CMS 1307.7135, ATLAS 1307.7292)
⇒ **HL-LHC** can **fully test** our model for **VLL-induced SFOEWPTs**!

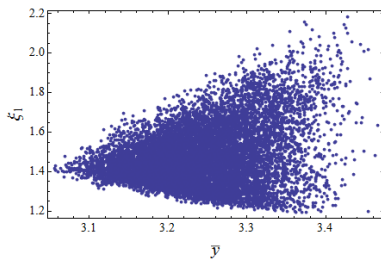
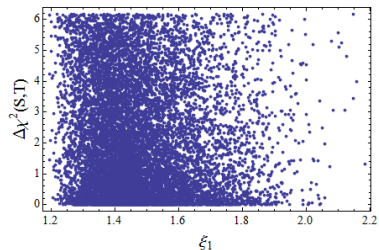
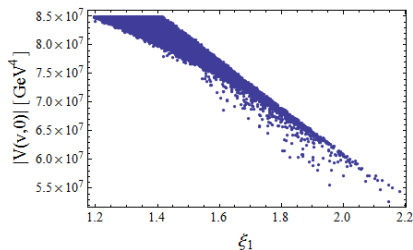
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Other Correlations



Choice of Bubble Wall Velocity

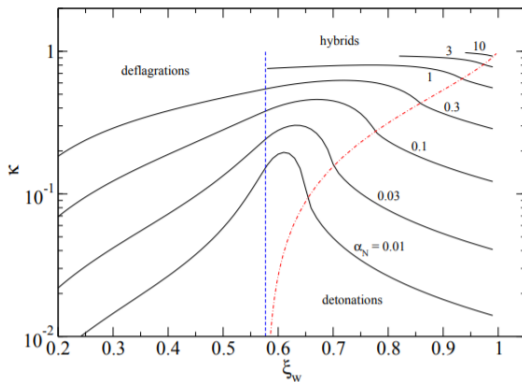


Figure: Ratio of bulk kinetic energy over to vacuum energy κ (efficiency factor) as a function of the bubble wall velocity, ξ_w , for various values of $\alpha_N \equiv \alpha$ (result from 1004.4187).

Our choice: $\xi_w = 0.6 \Rightarrow \kappa \simeq 0.4$ (for typical values of $\alpha \simeq 10^{-1}$).

GW Spectrum Formulae

$$\begin{aligned}
 h^2 \Omega_{\text{col}}(f) &= 1.67 \times 10^{-5} \left(\frac{0.11 \xi_w^3}{0.42 + \xi_w^2} \right) \left(\frac{\beta}{H_{\text{PT}}} \right)^{-2} \left(\frac{\kappa_{\text{col}} \alpha}{1 + \alpha} \right)^2 \left(\frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{3.8 (f/f_{\text{col}})^{2.8}}{1 + 2.8 (f/f_{\text{col}})^{3.8}}, \\
 h^2 \Omega_{\text{turb}}(f) &= 3.35 \times 10^{-4} \xi_w \left(\frac{\beta}{H_{\text{PT}}} \right)^{-1} \left(\frac{\kappa_{\text{turb}} \alpha}{1 + \alpha} \right)^{3/2} \left(\frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{(f/f_{\text{turb}})^3}{(1 + f/f_{\text{turb}})^{11/3} (1 + 8\pi f/h_*)}, \\
 h^2 \Omega_{\text{sw}}(f) &= 2.62 \times 10^{-6} \xi_w \left(\frac{\beta}{H_{\text{PT}}} \right)^{-1} \left(\frac{\kappa \alpha}{1 + \alpha} \right)^2 \left(\frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{7^{3.5} (f/f_{\text{sw}})^3}{(4 + 3 (f/f_{\text{sw}})^2)^{3.5}}.
 \end{aligned}$$

$$\kappa = 0.4, \epsilon = 0.05 \Rightarrow \kappa_{\text{turb}} = \epsilon \kappa = 0.02.$$

$$\begin{aligned}
 f_{\text{col}} &= (1.65 \times 10^{-5} \text{ Hz}) \left(\frac{0.62}{1.8 - 0.1 \xi_w + \xi_w^2} \right) \left(\frac{\beta}{H_{\text{PT}}} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{\text{eff}}}{100} \right)^{1/6}, \\
 f_{\text{turb}} &= (2.7 \times 10^{-5} \text{ Hz}) \left(\frac{1}{\xi_w} \right) \left(\frac{\beta}{H_{\text{PT}}} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{\text{eff}}}{100} \right)^{1/6}, \\
 h_* &= (1.65 \times 10^{-5} \text{ Hz}) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{\text{eff}}}{100} \right)^{1/6}, \\
 f_{\text{sw}} &= (1.9 \times 10^{-5} \text{ Hz}) \left(\frac{1}{\xi_w} \right) \left(\frac{\beta}{H_{\text{PT}}} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{\text{eff}}}{100} \right)^{1/6}.
 \end{aligned}$$

Contribution of Various GW Sources

Typical values for our case:

$$\alpha = 0.1, \quad \frac{\beta}{H_{\text{PT}}} = 2000, \quad T_{\text{PT}} = 100 \text{ GeV}, \quad g_{\text{eff}} = 100;$$

