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

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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 $\not{C}\not{P}$) ⇒ new physics needed!
- Usually, new bosons → $\mathcal{O}(100)$ papers ...

What about new fermions and phase transitions?

Extra Dimensions, Composite Higgs, ... ⇒ new fermions!

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

Contents

Overview

A Minimal Vector-Like Lepton (VLL) Model

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

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

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

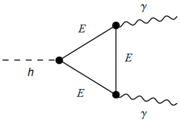
$$\mathcal{M}_N = \begin{pmatrix} m_L & v_h\, y_{N_L} \\ v_h\, y_{N_R} & m_N \end{pmatrix}, \quad \mathcal{M}_E = \begin{pmatrix} m_L & v_h\, y_{E_L} \\ v_h\, y_{E_R} & m_E \end{pmatrix}.$$

- 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, $V(0,T) \equiv 0$):

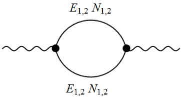
$$V(\phi, T) = V^{\rm SM}_{\rm tree}(\phi) + V^{\rm SM}_{1-\rm loop}(\phi, T) + V^{\rm VLL}_{1-\rm loop}(\phi, T) + V_{\rm Daisy}(\phi, T);$$



- Many parameters $\Rightarrow$ scan approach:

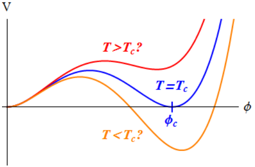
$$m_L, m_N, m_E \in [500, 1500] \ \ {\rm GeV},$$

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



- 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 $\longrightarrow$ $\xi \equiv \phi_c / T_c$.



Thermal Evolution of the Effective Potential: Multistep Phase Transition

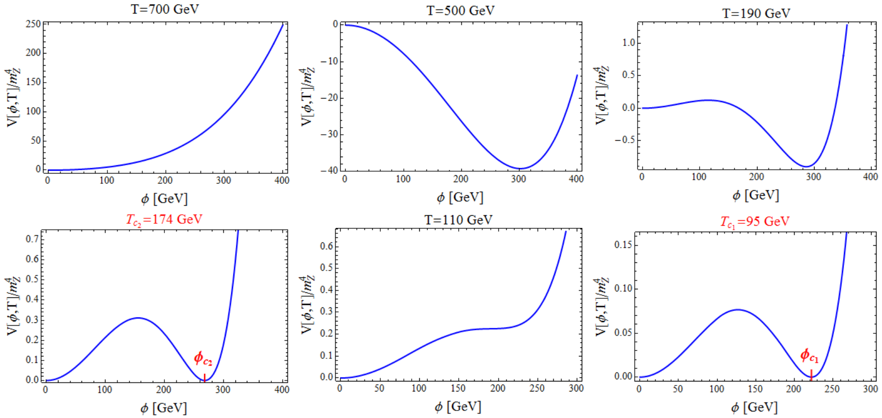
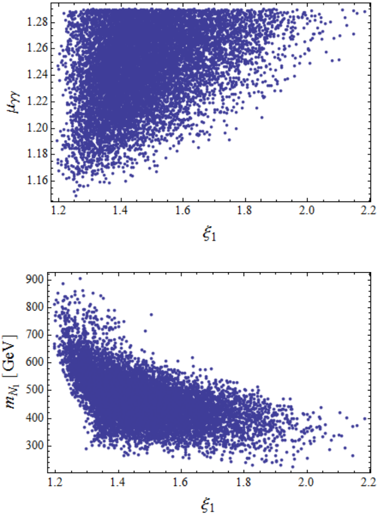


Figure: Typical temperature dependence of the 1–loop effective potential in the VLL model under study.

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

Correlations Between Observables



Overview

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:

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

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

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

- Typically, for our VLL model:

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

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

GW Spectrum Calculation and Detection Prospects

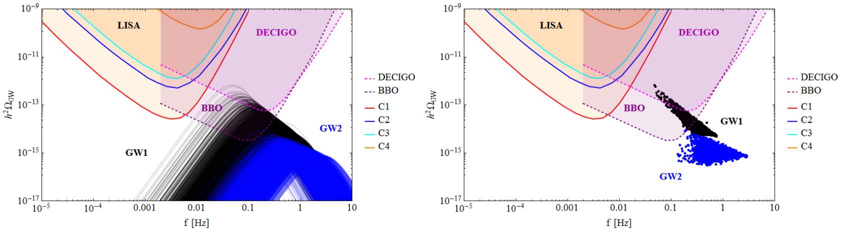
- Compute the bounce action $S_3(T)$, find the temperature at which the PT occurs:

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

- Calculate α and β for the two SFOPTs:

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

- Compute GW spectrum → GW detectable by DECIGO/BBO:



Collider Predictions

Benchmark point $\rightarrow$ strongest PT:

$$y_{N_L} \simeq 3.4,\ y_{N_R} \simeq 3.49,\ y_{E_L} \simeq 3.34,\ y_{E_R} \simeq 3.46,$$
$$m_L \simeq 1.06\ \mathrm{TeV},\ m_N \simeq 0.94\ \mathrm{TeV},\ m_E \simeq 1.34\ \mathrm{TeV}.$$

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

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

Direct production of VLLs suppressed ...

More promising search avenue? $\longrightarrow \mu_{\gamma\gamma}$!

Overview

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!

THANK YOU FOR YOUR ATTENTION!

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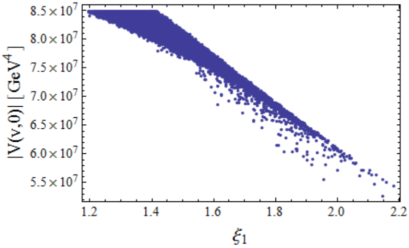
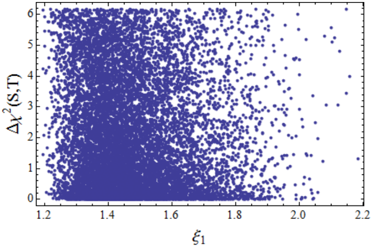
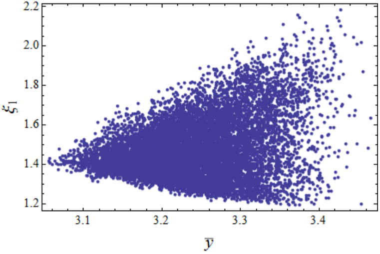
Thank you for your attention!

Other Correlations







Choice of Bubble Wall Velocity

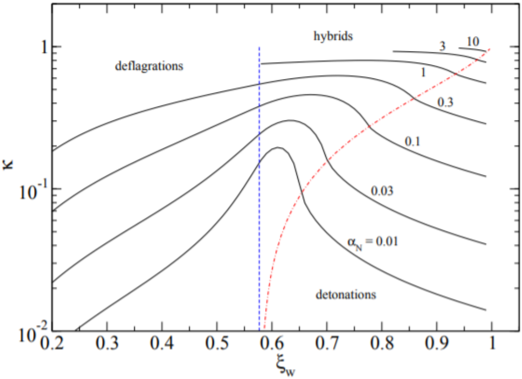


Figure: Ratio of bulk kinetic energy over to vacuum energy κ (efficiency factor) as a function of the bubble wall velocity, ξ_w, for various values of $\alpha_N \equiv \alpha$ (result from 1004.4187).

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

GW Spectrum Formulae

$$h^2\Omega_{\rm col}(f) = 1.67\times 10^{-5}\left(\frac{0.11\xi_w^3}{0.42+\xi_w^2}\right)\left(\frac{\beta}{H_{\rm PT}}\right)^{-2}\left(\frac{\kappa_{\rm col}\alpha}{1+\alpha}\right)^2\left(\frac{g_{\rm eff}}{100}\right)^{-1/3}\frac{3.8\,(f/f_{\rm col})^{2.8}}{1+2.8\,(f/f_{\rm col})^{3.8}},$$

$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\xi_w\left(\frac{\beta}{H_{\rm PT}}\right)^{-1}\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{g_{\rm eff}}{100}\right)^{-1/3}\frac{(f/f_{\rm turb})^3}{(1+f/f_{\rm turb})^{11/3}(1+8\pi f/h_*)},$$

$$h^2\Omega_{\rm sw}(f) = 2.62\times 10^{-6}\xi_w\left(\frac{\beta}{H_{\rm PT}}\right)^{-1}\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{g_{\rm eff}}{100}\right)^{-1/3}\frac{7^{3.5}\,(f/f_{\rm sw})^3}{\left(4+3\,(f/f_{\rm sw})^2\right)^{3.5}}.$$

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

$$f_{\rm col} = (1.65\times 10^{-5}\,{\rm Hz})\left(\frac{0.62}{1.8-0.1\xi_w+\xi_w^2}\right)\left(\frac{\beta}{H_{\rm PT}}\right)\left(\frac{T_{\rm PT}}{100\,{\rm GeV}}\right)\left(\frac{g_{\rm eff}}{100}\right)^{1/6},$$

$$f_{\rm turb} = (2.7\times 10^{-5}\,{\rm Hz})\left(\frac{1}{\xi_w}\right)\left(\frac{\beta}{H_{\rm PT}}\right)\left(\frac{T_{\rm PT}}{100\,{\rm GeV}}\right)\left(\frac{g_{\rm eff}}{100}\right)^{1/6},$$

$$h_* = (1.65\times 10^{-5}\,{\rm Hz})\left(\frac{T_{\rm PT}}{100\,{\rm GeV}}\right)\left(\frac{g_{\rm eff}}{100}\right)^{1/6},$$

$$f_{\rm sw} = (1.9\times 10^{-5}\,{\rm Hz})\left(\frac{1}{\xi_w}\right)\left(\frac{\beta}{H_{\rm PT}}\right)\left(\frac{T_{\rm PT}}{100\,{\rm GeV}}\right)\left(\frac{g_{\rm eff}}{100}\right)^{1/6}.$$

Contribution of Various GW Sources

Typical values for our case:

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