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

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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 $CP$) ⇒ new physics needed!

Usually, new bosons → $O(100)$ 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).
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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 ⇒ large custodial symmetry breaking!
- Solution → a minimal model which can possess (approximate) custodial symmetry:
  \[ L_{L,R} = \left( \begin{array}{c} N \\ E \end{array} \right)_{L,R} \sim (1, 2, -1/2), \quad N'_{L,R} \sim (1, 1, 0), \quad E'_{L,R} \sim (1, 1, -1). \]

- VLL masses + Yukawa couplings (assume negligible mixing with the SM):
  \[ -\mathcal{L}_{VLL} = y_{N_R} \bar{L}_L \hat{H} N'_R + y_{N_L} \bar{N}'_L \hat{H} L_R + y_{E_R} \bar{L}_L H E'_R + y_{E_L} \bar{E}'_L H^\dagger L_R \\
  + m_L \bar{L}_L L_R + m_N \bar{N}'_L N'_R + m_E \bar{E}'_L E'_R + \text{h.c.}. \]

- EW symmetry breaking ⇒ mass matrices \((\nu = 246 \text{ GeV, } v_h = \nu/\sqrt{2} \simeq 174 \text{ GeV}):\n  \mathcal{M}_N = \begin{pmatrix} m_L & \nu y_{N_R} \\ \nu y_{N_L} & m_N \end{pmatrix}, \quad \mathcal{M}_E = \begin{pmatrix} m_L & \nu y_{E_R} \\ \nu y_{E_L} & m_E \end{pmatrix}. \]

- Diagonalization ⇒ eigenmasses \(m_{N_1} < m_{N_2}, m_{E_1} < m_{E_2}\) and interaction basis couplings.
Model and Approach

Approach

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

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

- Many parameters $\Rightarrow$ scan approach:

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

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

- 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

- Left top: \( \mu_{\gamma\gamma} \) vs. \( \xi_1 \)
- Right top: \( \xi_2 \) vs. \( \xi_1 \)
- Left bottom: \( m_{\phi_1} \) vs. \( \xi_1 \)
- Right bottom: \( m_{\phi_1} \) vs. \( \xi_1 \)
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Gravitational Wave Signature

- **Strong PTs in the Early Universe** ⇒ **Gravitational Wave (GW) stochastic background!**
  → **Detectable** by future GW experiments, such as LISA/DECIGO/BBO?

- **GW amplitude and spectrum** controlled (mostly) by two parameters:
  \[ \alpha = \frac{\text{latent heat}}{\text{radiation energy}}, \quad \frac{\beta}{H_{\text{PT}}} = \text{"inverse PT duration"} \]

- **Main GW sources** → bubble collisions (\(\Omega_{\text{col}}\)), MHD turbulence (\(\Omega_{\text{turb}}\)), sound waves (\(\Omega_{\text{sw}}\)):
  \[ h^2 \Omega_{\{\text{col, turb, sw}\}}(f) \propto \left( \frac{\beta}{H_{\text{PT}}} \right)^{-\{2,1,1\}} \left( \frac{\alpha}{1 + \alpha} \right)^{\{2, \frac{3}{2}, 2\}} S_{\{\text{col, turb, sw}\}}(f; \beta/H_{\text{PT}}) \]

- Typically, for our **VLL** model:
  \[ \alpha = \mathcal{O}(10^{-1} - 10^{-2}), \quad \frac{\beta}{H_{\text{PT}}} = \mathcal{O}(10^3 - 10^4), \]

  ⇒ **SW contribution dominant** for \(f \in [10^{-3}, 1] \text{ Hz} \) (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:
  $$\frac{S_3(T_{PT})}{T_{PT}} \approx 142;$$

- Calculate $\alpha$ and $\beta$ for the two SFOPTs:
  $$\alpha = \frac{|V(\phi_{broken}, T_{PT})| + T_{PT} \left| \frac{\partial V(\phi_{broken}, T)}{\partial T} \right|}{\rho_{\text{rad}}(T_{PT})}, \quad \frac{\beta}{H_{PT}} = T_{PT} \frac{d}{dT} \left( \frac{S_3}{T} \right) \bigg|_{T_{PT}}.$$

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

Benchmark point $\rightarrow$ strongest PT:

$$y_{NL} \simeq 3.4, \ y_{NR} \simeq 3.49, \ y_{EL} \simeq 3.34, \ y_{ER} \simeq 3.46,$$
$$m_L \simeq 1.06 \text{ TeV}, \ m_N \simeq 0.94 \text{ TeV}, \ m_E \simeq 1.34 \text{ TeV}.$$ 

- $N_1$ not a suitable Dark Matter candidate $\Rightarrow$ SM-VLL mixing should be present!
- Measurements: $W_{\tau\nu}$ and $Z_{\tau\tau}$ couplings $\Rightarrow$ take $y_{\tau E} \simeq 0.05$;
- 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:

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

**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;

- $\mu\gamma\gamma = \text{most promising collider signature} \rightarrow 5\% \text{ precision @ HL-LHC!}$
  (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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Other Correlations
Choice of Bubble Wall Velocity

Figure: Ratio of bulk kinetic energy over to vacuum energy $\kappa$ (efficiency factor) as a function of the bubble wall velocity, $\xi_w$, 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

\[ h^2 \Omega_{\text{col}}(f) = 1.67 \times 10^{-5} \left( \frac{0.11 \xi^3_{s_{w}}}{0.42 + \xi^2_{s_{w}}} \right) \left( \frac{\beta}{H_{\text{PT}}} \right)^{-2} \left( \frac{\kappa_{\text{col}} \alpha}{1 + \alpha} \right)^2 \left( \frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{3.8 (f/f_{\text{col}})^{2.8}}{1 + 2.8 (f/f_{\text{col}})^{3.8}}, \]

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

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

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

\[ f_{\text{col}} = (1.65 \times 10^{-5} \ \text{Hz}) \left( \frac{0.62}{1.8 - 0.1 \xi_{w} + \xi^2_{s_{w}}} \right) \left( \frac{\beta}{H_{\text{PT}}} \right) \left( \frac{T_{\text{PT}}}{100 \ \text{GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}, \]

\[ f_{\text{turb}} = (2.7 \times 10^{-5} \ \text{Hz}) \left( \frac{1}{\xi_{w}} \right) \left( \frac{\beta}{H_{\text{PT}}} \right) \left( \frac{T_{\text{PT}}}{100 \ \text{GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}, \]

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

\[ f_{\text{sw}} = (1.9 \times 10^{-5} \ \text{Hz}) \left( \frac{1}{\xi_{w}} \right) \left( \frac{\beta}{H_{\text{PT}}} \right) \left( \frac{T_{\text{PT}}}{100 \ \text{GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}. \]
Typical values for our case:

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