Multistep Single-Field Strong Phase Transitions from New Fermions

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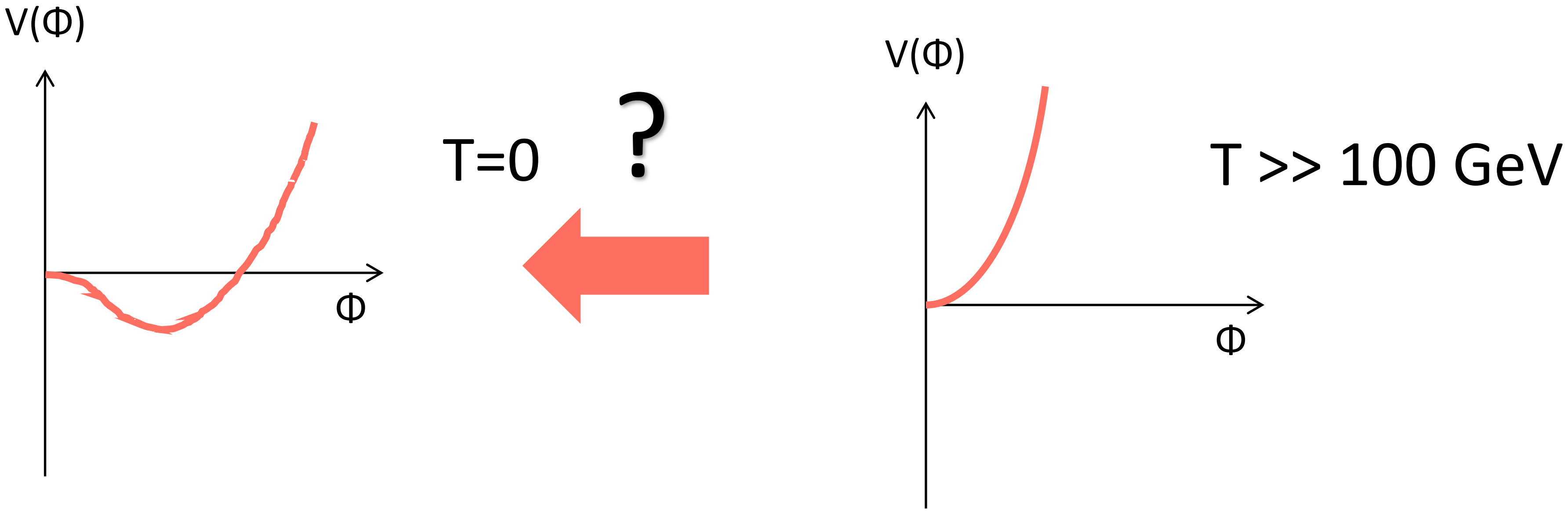
Based on work with Andrei Angelescu, 1812.08293, PRD

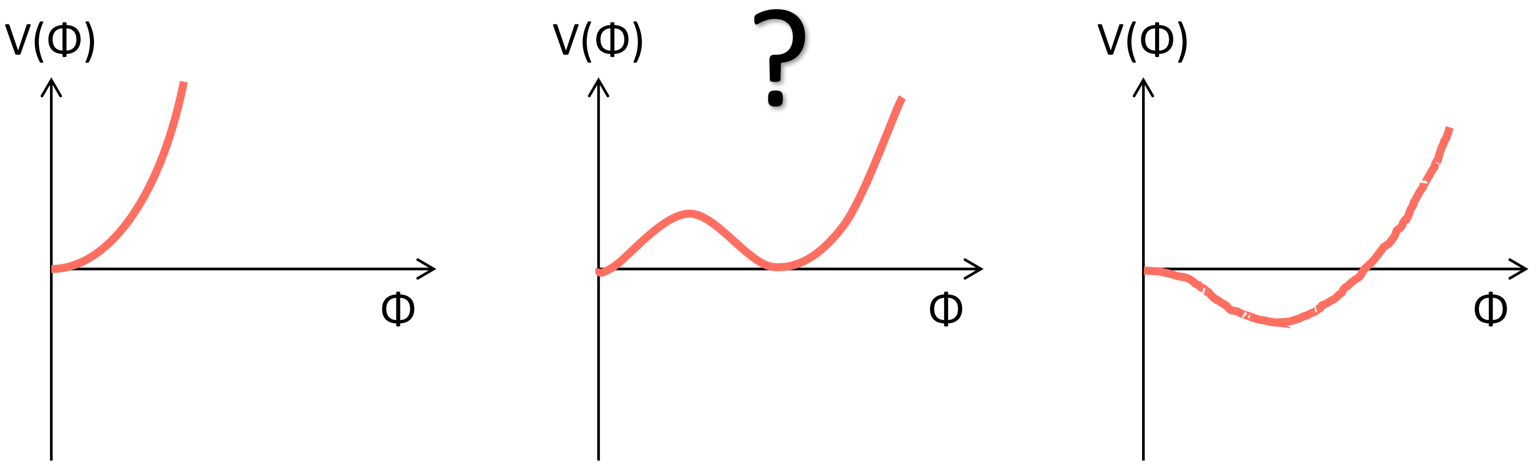
The Higgs Potential

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



Know nothing beyond v, and m_h EW symmetry restored

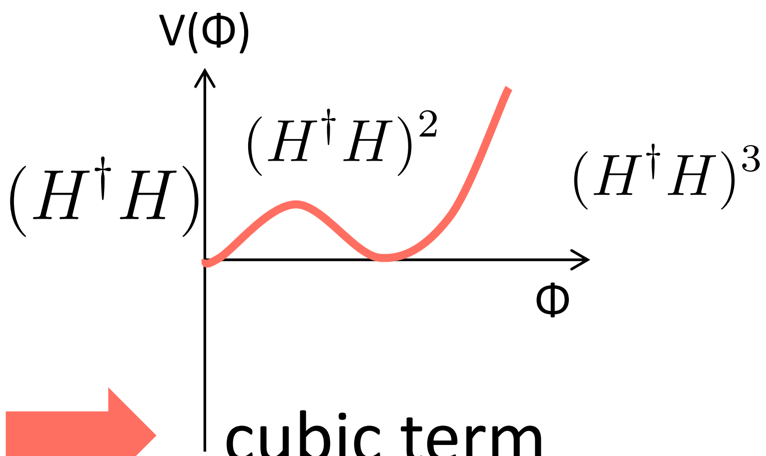
The Higgs Potential at Finite Temperature



- First order phase transition or cross over?
- Baryogenesis requires the phase transition to be strongly first order
- At the temperature of the electroweak phase transition, we need a barrier in the potential.

$$\boxed{v(T_c)/T_c \gtrsim 1.3}$$

Generating a barrier



- Scalars
  - Integrating out → $(H^\dagger H)^3$
  - Thermal effect (high T expansion) → cubic term
- Fermions
  - Low T, scalars and fermions contribute equally

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

Consider the possibility of generating a barrier through fermions in this talk

Outline

- Consider a Vector-Like Lepton (VLL) model.
    - A non-trivial thermal history of the universe.
- Signatures
    - Gravitational Wave signatures
    - Collider signatures

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

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

- The most general Lagrangian is,

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

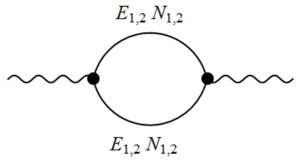
A Minimal Vector-Like Lepton (VLL) Model

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

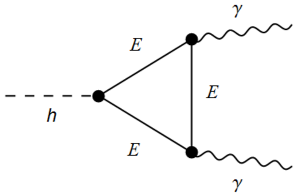
- 2 neutral and 2 charged VLLs
- Ranges of the parameters considered,

$$m_L, m_N, m_E \in [500, 1500]\ \text{GeV}, \qquad y_{N_{L,R}}, y_{E_{L,R}} \in [2, \sqrt{4\pi}].$$

- Constraints:



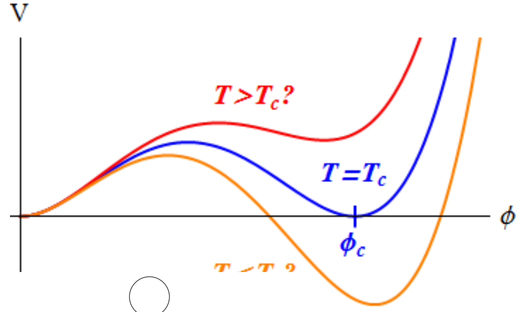
  - S & T parameters
  - Diphoton signal strength, $0.71 < \mu_{\gamma\gamma} < 1.29$ ATLAS, 1802.04146
  - Masses of the lighter states, $m_{E_1} > 100$ GeV and $m_{N_1} > 90$ GeV



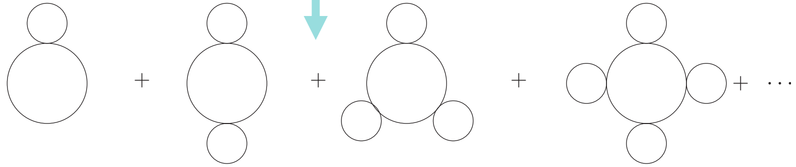
LEP2, Phys Rept 427(2006)257-454

Thermal Evolution of the Effective Potential

- For each surviving point, calculate the phase transition strength, $\xi = \phi_c / T_c$



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



- Benchmark A,

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

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

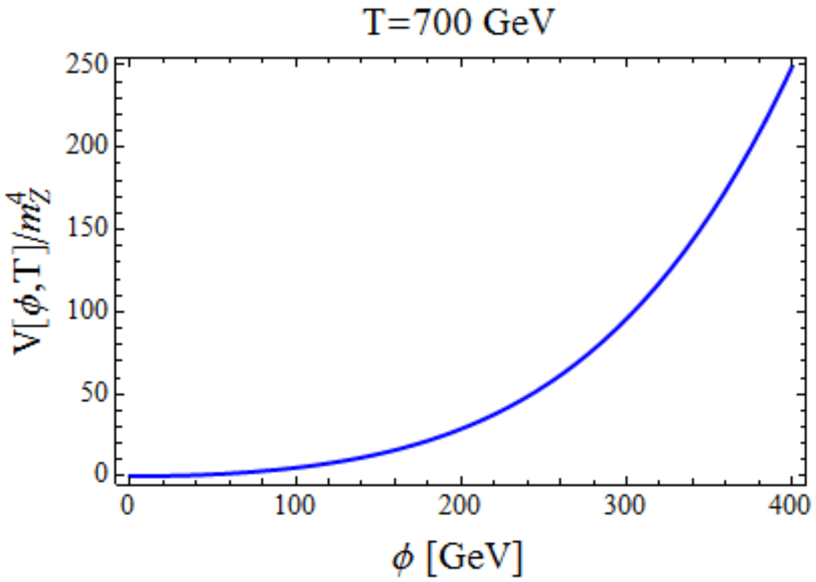
$$\mu_{\gamma\gamma} = 1.28,\ \Delta\chi^2(S, T) = 1.33,\ m_{N_1} = 400\ \text{GeV},\ m_{E_1} = 592\ \text{GeV}.$$

Side Note, Large Yukawas

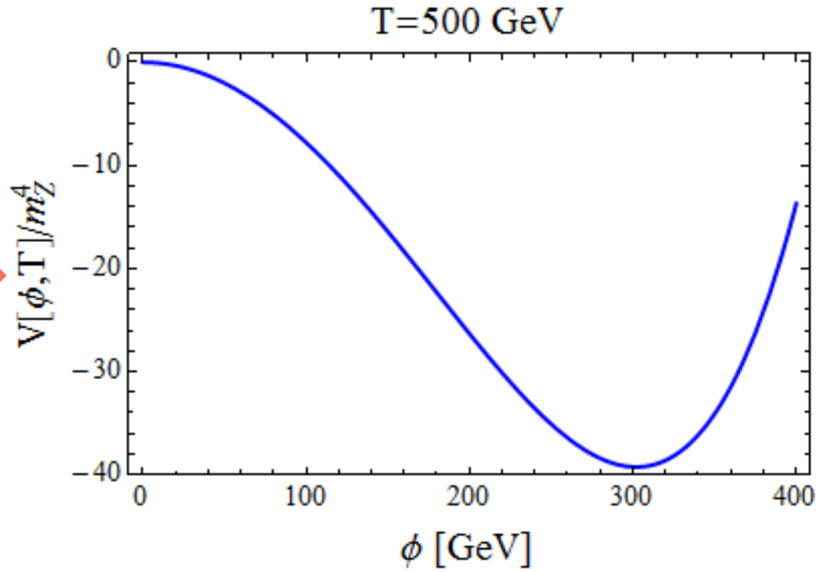
- Vacuum stability
  - For the benchmark point we consider, the effective potential becomes negative at around 3 TeV.
  - Solution : add dim-6 operators.
- Landau pole
  - For the benchmark point we consider, the Landau pole is around 10 TeV.
- Unitarity
  - Unitarity implies $y^2 < 4\pi$

Can only be viewed as a low energy effective description

Thermal Evolution of the Effective Potential



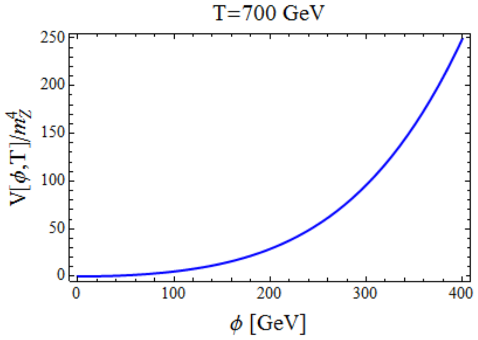
Cross over

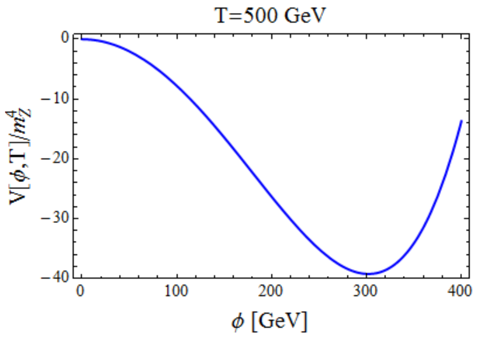


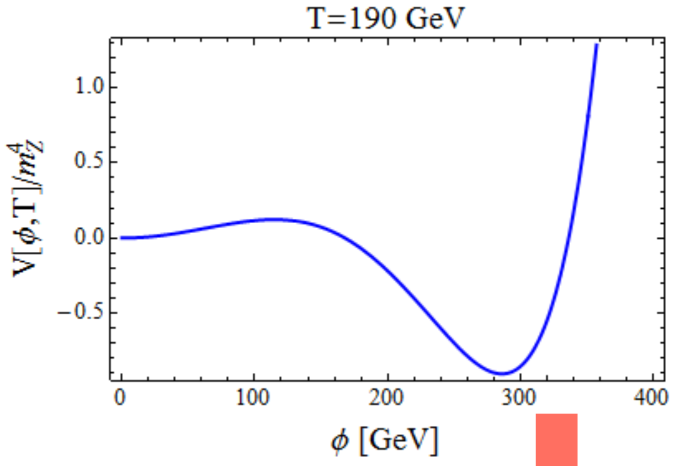
Early universe, symmetric

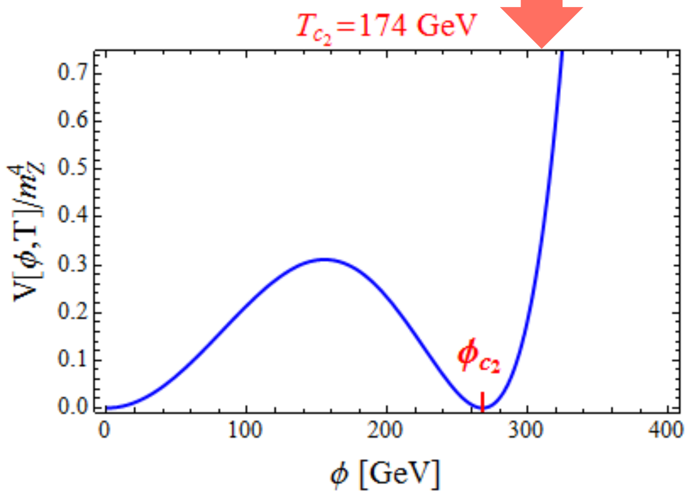
EWSB

Thermal Evolution of the Effective Potential





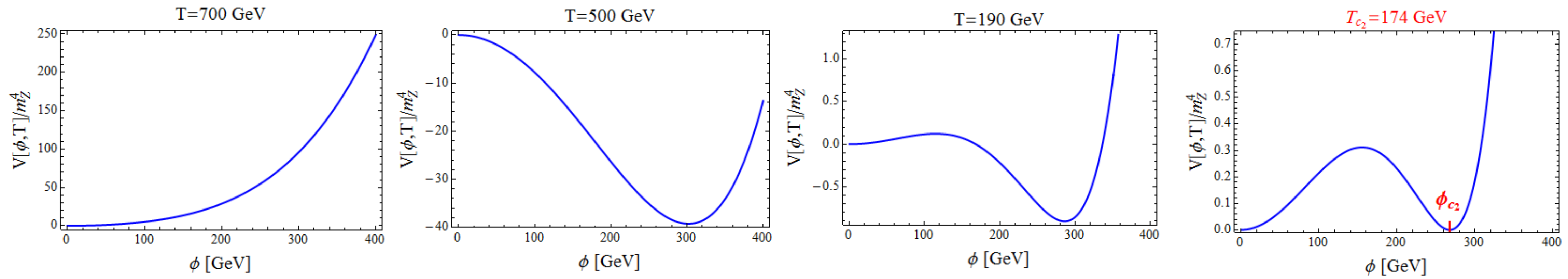


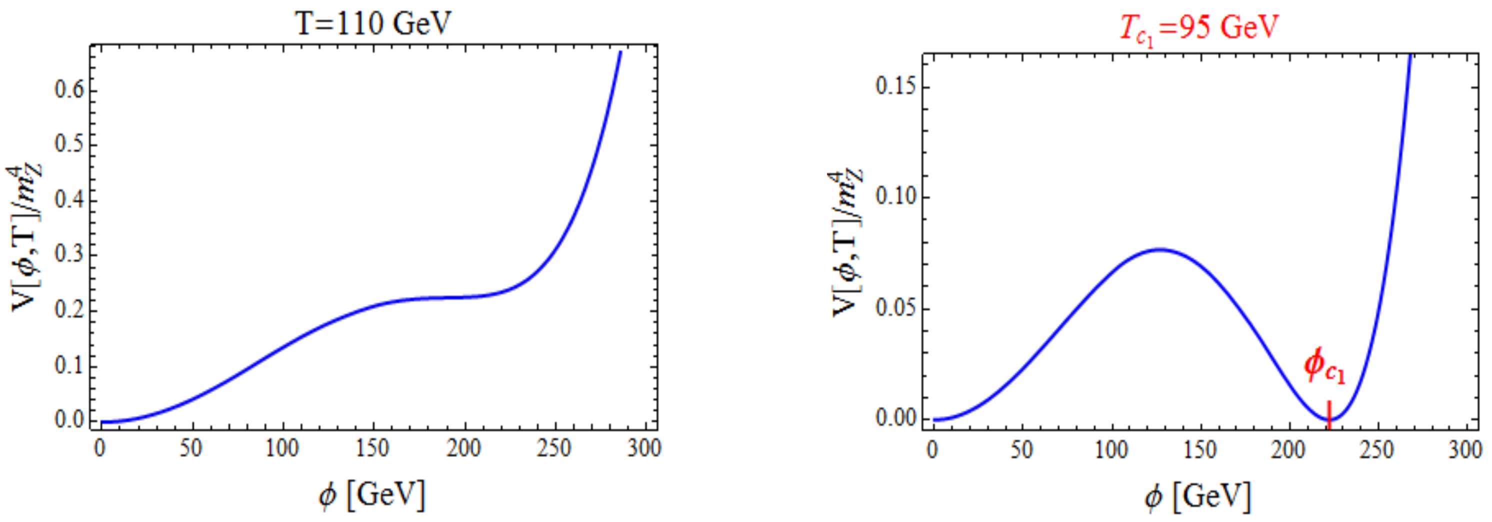


- The broken minimum becomes less and less deep
- A potential barrier starts developing between the symmetric phase and the broken phase
- At T_{c2} , a strong first order phase transition
- The universe tunnels back to the symmetric phase

EW symmetry restored

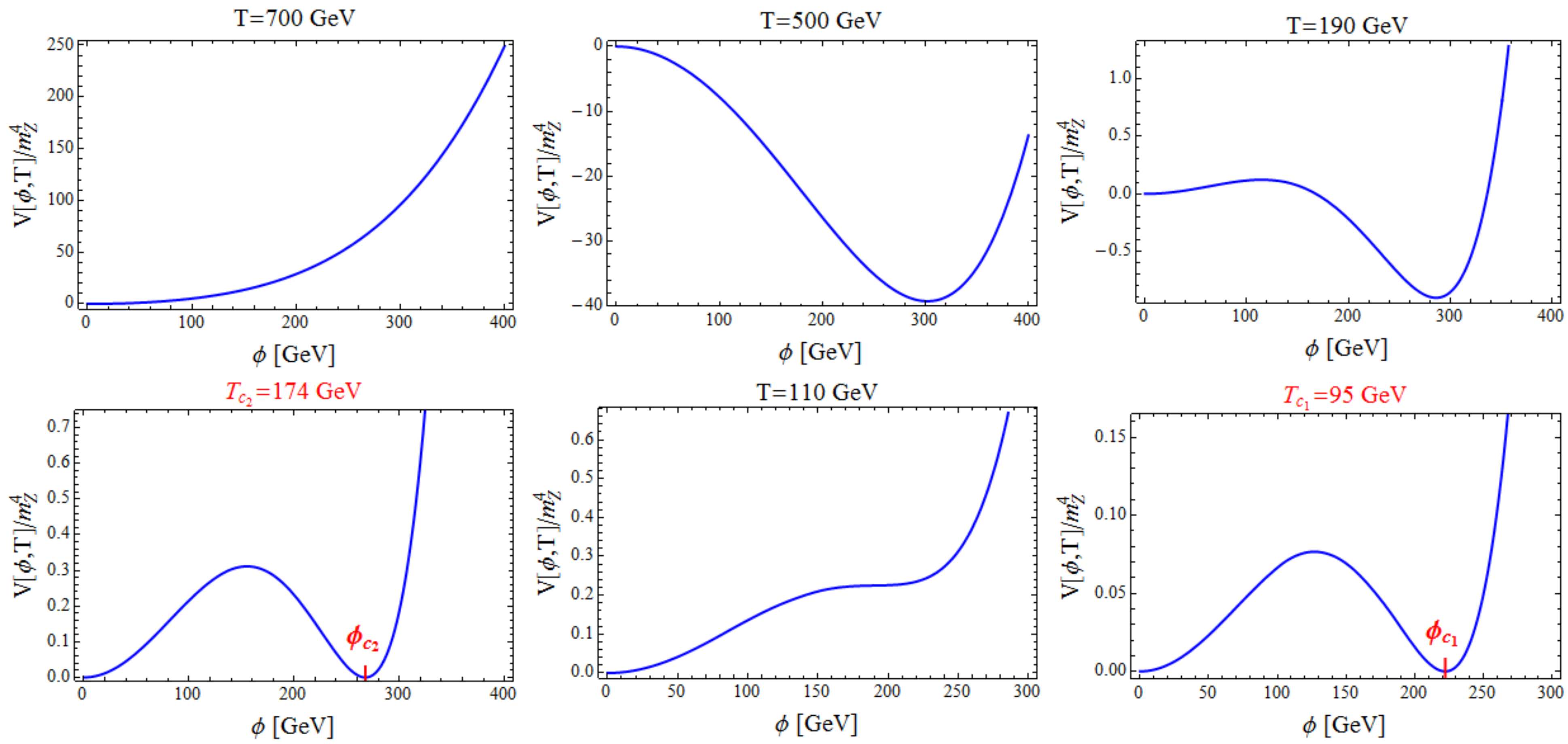
Thermal Evolution of the Effective Potential





EWSB again through a strongly first order phase transition, at T_{c1}

Thermal Evolution of the Effective Potential



Responsible for the BAU

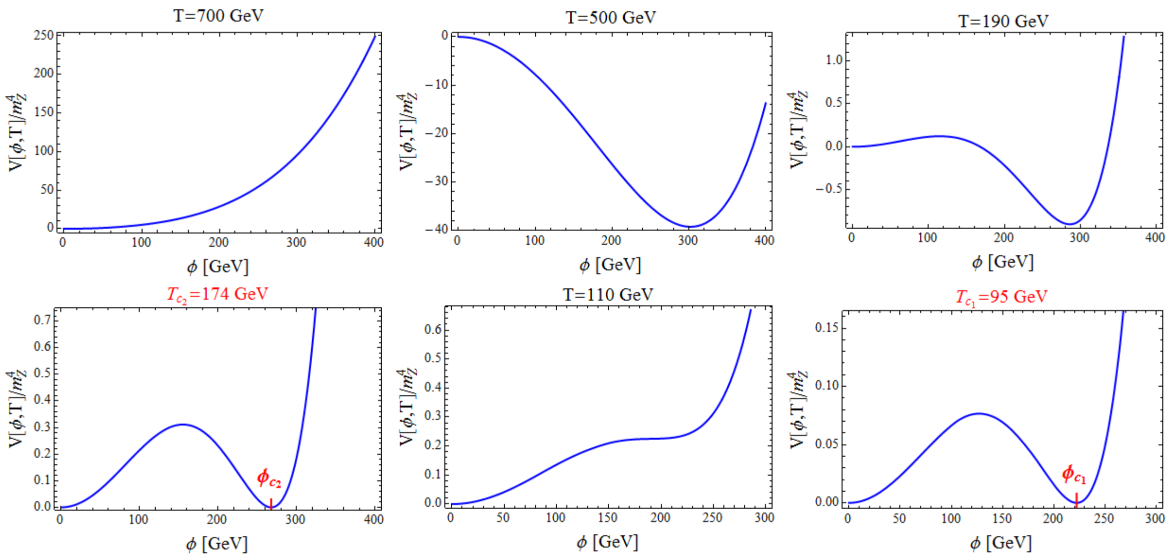
Outline

- Consider a Vector-Like Lepton (VLL) model.

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

  - A non-trivial thermal history of the universe.

- Signatures
  - Gravitational wave signatures
  - Collider signatures



Signatures – Gravitational Waves

- Multi-peak gravitational waves from a single scalar field!
- GW spectrum is (mostly) determined by two parameters,

$$\boxed{\alpha = \frac{\text{latent heat}}{\text{radiation energy}}}$$

Larger α, stronger signal

$$\boxed{\beta = \text{inverse PT duration}}$$

Larger β, weaker signal, higher frequencies

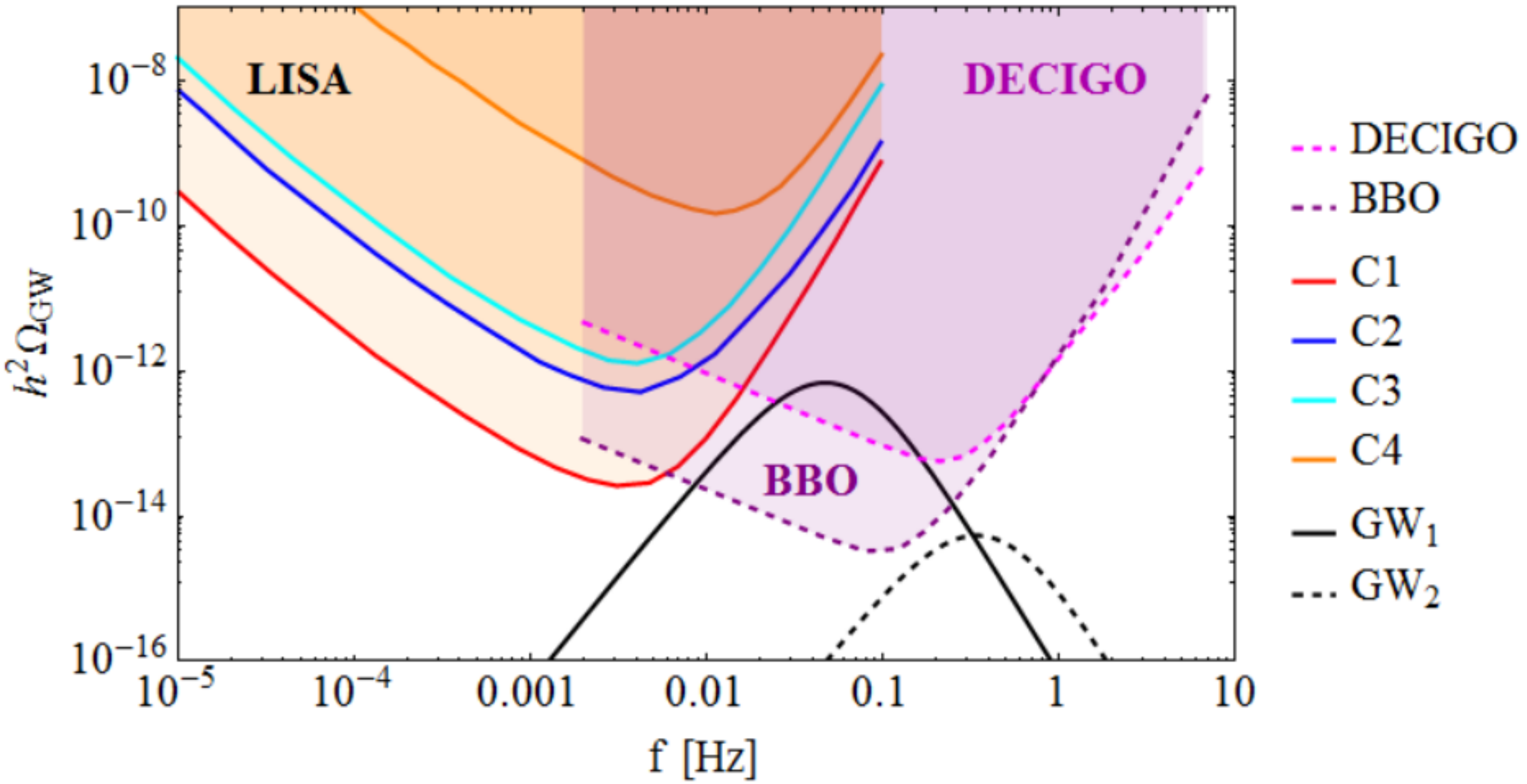
- Typically, for the later phase transition,

$$\boxed{\alpha \sim 0.01 - 0.1, \qquad \beta/H_{\rm PT} \sim 10^3 - 10^4.}$$

Singlet model, α ~ 0.1 -1, β/H_{PT} ~ 10 - 100

- For the earlier one, $\alpha_2 < \alpha_1$ and $(\beta/H_{\rm PT})_2 > (\beta/H_{\rm PT})_1$

Signatures – Gravitational Waves



- Peak frequency beyond Lisa (f~ 0.01 -1 Hz is typical for VLL models)
- DECIGO and BBO are sensitive to the later phase transition
- The earlier one is too weak.

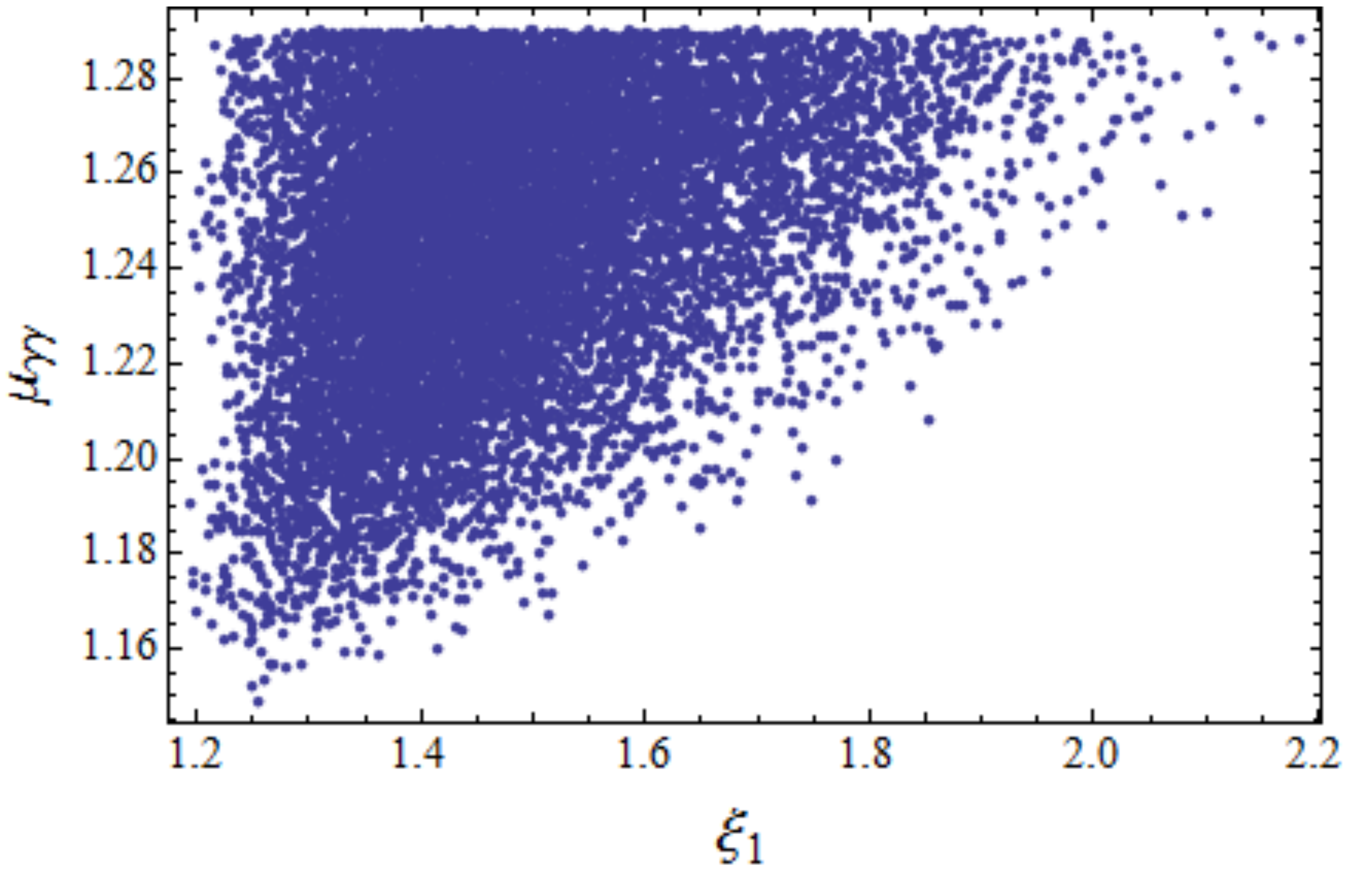
Signatures – Colliders, Direct Production

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

$$-\mathcal{L}_{\rm mix} = y_1\,\overline{L}_L H \tau_R + y_2\,\overline{L}^3_L H E'_R + \text{h.c.}\,,$$

- 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.
- Wil be fully tested at the HL-LHC.

Conclusion

- VLLs can give rise to a non-trivial thermal history of the universe.

$$-\mathcal{L}_{VLL} = y_{N_R}\overline{L}_L\tilde{H}N'_R + y_{N_L}\overline{N}'_L\tilde{H}^\dagger L_R + y_{E_R}\overline{L}_L H E'_R + y_{E_L}\overline{E}'_L H^\dagger L_R$$
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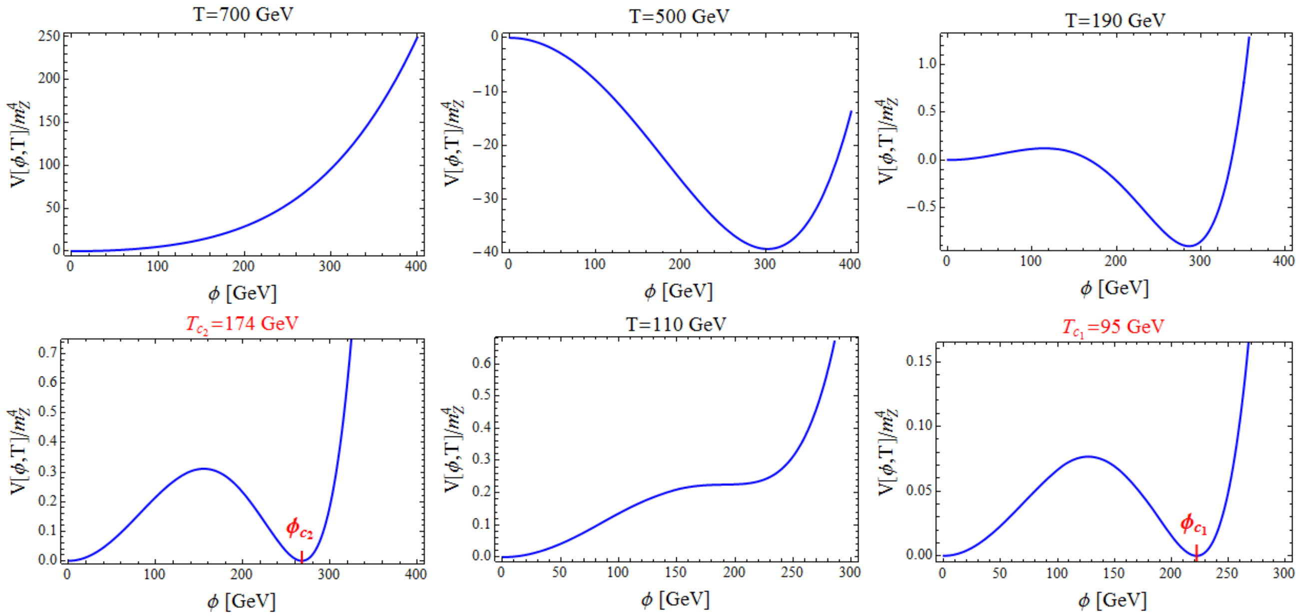
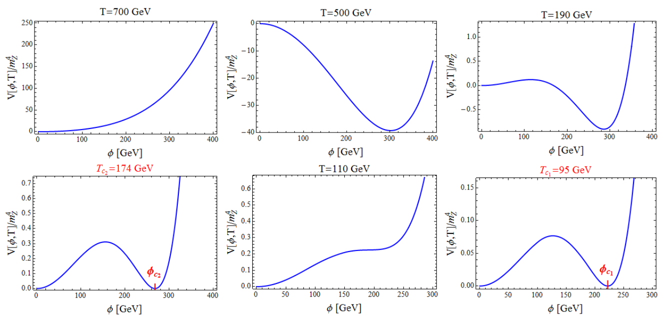
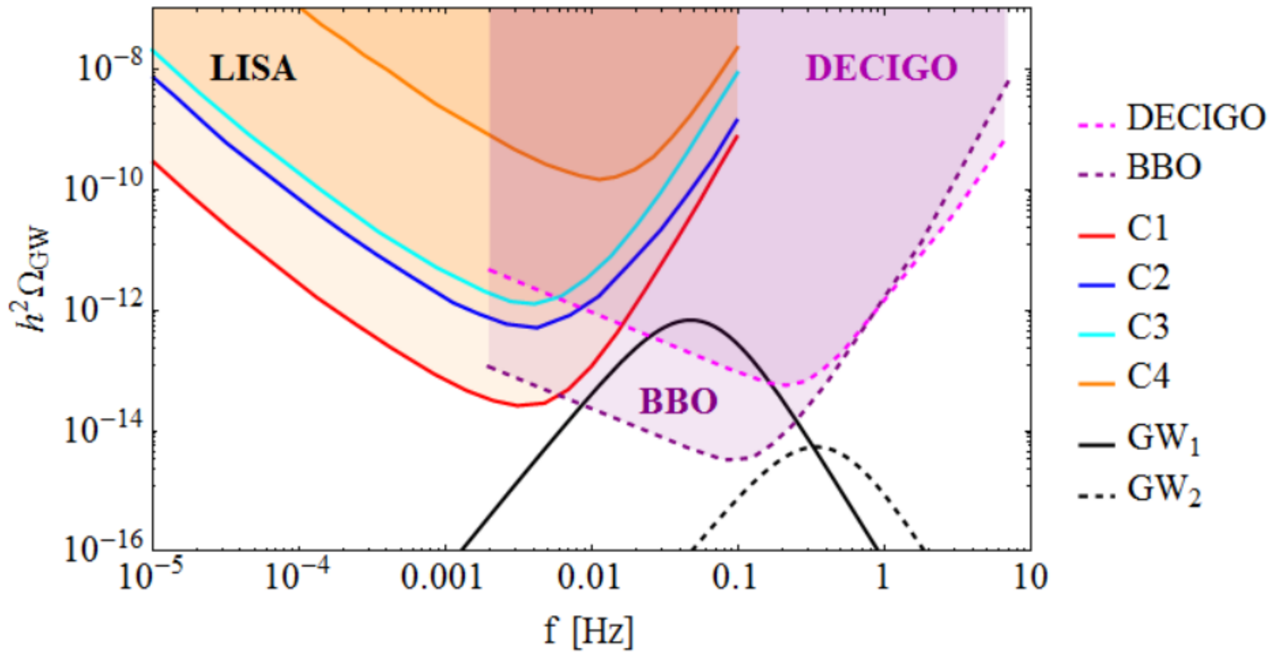


Conclusion



- VLLs can give rise to a non-trivial thermal history of the universe.
  - Multi-step phase transitions with a single scalar field!
- The later of the phase transition can be probed by BBO and DECIGO.



Conclusion

- VLLs can give rise to a non-trivial thermal history of the universe.
  - Multi-step phase transitions with a single scalar field!
- The later of the phase transition can be probed by BBO and DECIGO.
- At least 15% enhancement in the diphoton signal is expected, so the model will be fully tested by the HL-LHC.