Leptogenesis in Classically Scale Invariant extensions of the Standard Model

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1. Classical Scale Invariance

2. Leptogenesis via Neutrino Oscillations

3. Higgs Vacuum Stability and Dark Matter

4. Conclusion

Beyond the Standard Model

Open questions in the Standard Model:

- **Dark Matter** - No particle in the SM can account for measurements of extra non-baryonic mass on galactic and cosmological scales
- **Matter anti-matter asymmetry** - The Standard Model can not explain why there is more matter than anti-matter
- **Neutrino masses** - What gives neutrinos their very small mass?
- **Non-stable Higgs Potential** - In SM $\lambda_h(\mu = 10^9) < 0$ so the Higgs potential is not stable.

Hierarchy Problem: Loop corrections to the Higgs mass are quadratically sensitive to new physics scales Λ_{NP} and UV cut-off Λ_{UV}

Classical Scale Invariance

SM would be Classically scale invariant if the only scale was dynamically generated $\mu^2 = -\lambda_p \langle\phi\rangle^2$

$$V(H) = -\mu^2 HH^\dagger + \frac{\lambda_H}{2}(HH^\dagger)^2$$

Bardeen 95: The quadratic sensitivity to the cut-off would then be unphysical as the regulator breaks the symmetry.

Anomalous breaking of scale invariance does **not** reintroduce the quadratic divergences, only logarithmic divergences

Scales will be generated via the Coleman-Weinberg mechanism.

$$\langle\phi\rangle \sim \Lambda_{UV} \exp\left(-\frac{const}{e_\phi^2}\right)$$

Englert, Jaeckel,Khoze and Spannowsky 2013

Classical Scale Invariance

For **Classically Scale Invariance** to be a solution of the Hierarchy Problem we need to extend the SM to solve all sub-planckian problems **without** introducing new large scales

All scales need to be dynamically generated.

We propose a minimal extension where we only have **one** scale. All scales, including masses of new particles, have to be proportional to the Higgs vev

Open questions about a UV completion and gravity.

Classically Scale invariant models still provide minimal, calculable and testable BSM models

Classically Scale Invariant Extended Standard Models

Classically Scale Invariant Extended Standard Models (CSI ESM) with a new gauge group G

We have considered:

- $G = U(1)$ Hempfling 96
- $G = U(1)_{B-L}$ Iso, Okada,Orikasa 2009
- $G = SU(2)$ Hambye and Strumia 2013 and Carone and Ramos 2013

Scalar potential for all groups:

$$V(\phi, H) = \frac{\lambda_\phi}{2}(\phi^\dagger\phi)^2 - \lambda_{\rm P}(H^\dagger H)(\phi^\dagger\phi)^2 + \frac{\lambda_{\rm H}}{2}(H^\dagger H)^2$$

Scales will be **dynamically generated** by the **Coleman-Weinberg mechanism** in the hidden sector $\phi \to \langle\phi\rangle$, which will lead to EWSB with $\mu^2 = -\lambda_p \langle\phi\rangle^2$

CSI $U(1)_{B-L}\times$SM

Need to include 3 right handed neutrinos ν_R to cancel anomalies.

Scalar field ϕ has $B-L$ charge 2.

$$\mathcal{L}_{\rm int}^{\nu_R} = -\frac{1}{2}(Y^{\rm M}_{ij}\phi\,\overline{\nu^c_R}_i\nu_{Rj} + Y^{\rm M\,\dagger}_{ij}\phi^\dagger\,\overline{\nu_R}_i\nu^c_{Rj}) - Y^{\rm D}_{ia}\overline{\nu_R}_i(\epsilon H)l_{L\,a} - Y^{\rm D\,\dagger}_{ai}\overline{l}_{La}(\epsilon H)^\dagger\nu_{R\,i}$$

When $\phi\to\langle\phi\rangle$ we get:

Majorana masses for neutrinos: $M_{ij} \;=\; Y^{\rm M}_{ij}\langle|\phi|\rangle$

Active neutrino masses via **see-saw**:

$$m_\nu \approx \frac{(Y^D\langle H\rangle)^2}{Y^M\langle\phi\rangle} = \lambda_p\langle\phi\rangle\frac{(Y^D)^2}{Y^M}$$

Can get the $m_\nu \sim 10meV$ with $\lambda_p \sim 10^{-5}, \langle\phi\rangle \sim 10\,TeV$, $Y^D \sim 10^{-7}$ and $M_R \sim 1GeV$

Matter anti-matter asymmetry

Does Leptogenesis work in classically scale invariant models?

In the standard approach to Leptogenesis a lepton asymmetry is generated by **CP-violating out of equilibrium decays** of right-handed neutrinos.

Baryon asymmetry generated from lepton asymmetry by $B + L$ violating non-perturabtive **sphalerons**.

Can give the right baryon anti baryon asymmetry if right handed neutrinos have mass $M \gtrsim 10^9 GeV$ Davidson and Ibarra 2002 (or there is a resonant enhancement $\Delta M^2 \ll M^2$)

Incompatible with classical scale invariance

Leptogenesis by Neutrino Oscillation

Akhmedov,Rubakov and Smirnov 1999 proposed a new mechanism for leptogenesis based on **oscillations** of right handed neutrinos

Idea: Right handed neutrinos can oscillate with $\not{CP}$ such that $L_i = N(\nu_{Ri}) - N(\bar{\nu}_{Ri}) \neq 0$ while $L = L_1 + L_2 + L_3 = 0$

Sphalerons only couple to left handed leptons and "turn-off" at T_{EW}.
If:

$$\Gamma_{2,3}(T_{EW}) > H(T_{EW}), \Gamma_1(T_{EW}) < H(T_{EW})$$

the sphalerons will "see" a Lepton asymmetry that will be turned into a baryon asymmetry even if $L = 0$.

M. Drewes and B. Garbrecht 2013 showed that we can get the right baryon asymmetry for $M_R \approx 1GeV$

Leptogenesis by Neutrino Oscillation

T_{osc}

$$\mathbf{L_1 = L_2 = L_3 = 0}$$

$$\nu_{Ri} \overset{\not{CP}}{\longleftrightarrow} \nu_{Rj}$$

$$\mathbf{L_1 \neq L_2 \neq L_3\,,\, L = 0}$$

$$\nu_{R2,3} \to l_{L2,3}H \quad \nu_{R1} \not\to l_{L1}H$$

$$\mathbf{L_\mu \neq 0 \ L_\tau \neq 0 \ L_e = 0}$$

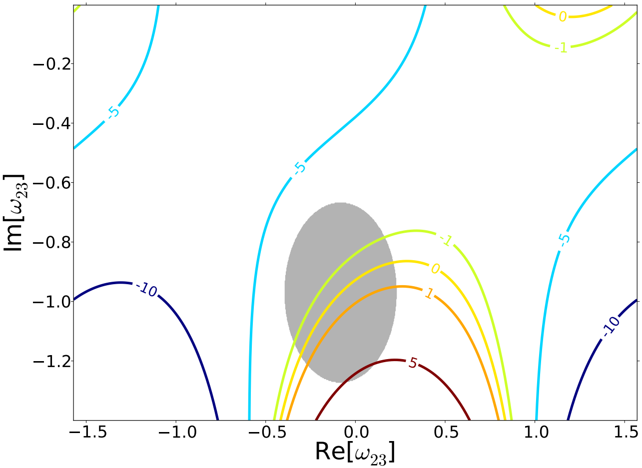
T_{EW}

$$L_\mu + L_\tau \xrightarrow{\text{Sphaleron}} B$$

$$\mathbf{B \propto -L_1 \neq 0}$$

T

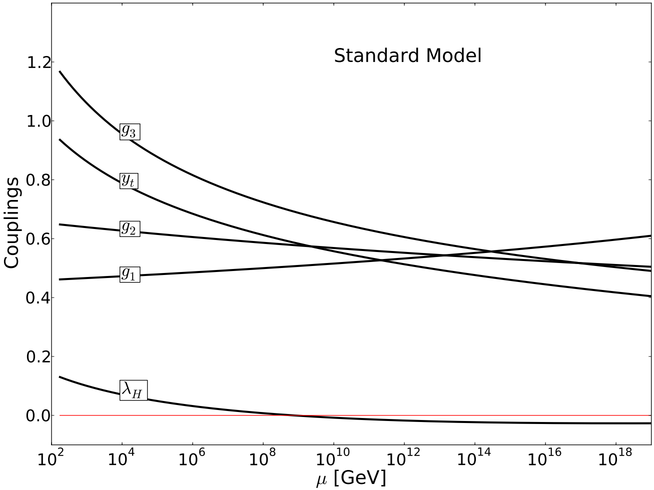
Results



Contours show produced baryon asymmetry normalized to the observed baryon asymmetry. Shaded region show where washout conditions are fulfilled. ω_{23} is a right-handed neutrino mixing angle

Higgs Vacuum Stability

In the SM the Higgs potential is **not** stable as $\lambda_H(\mu > 10^9\,GeV) < 0$



Higgs Vacuum Stability

Stability can be **improved** in minimal CSI ESM models due to the mixing between ϕ and the Higgs

We investigated this effect for $U(1)$, $U(1)_{B-L}$ and $SU(2)$.

For $SU(2)$ a small region left with a **stable potential** which evades LHC limits on the non-detection of ϕ. No such region for $U(1)$ or $U(1)_{B-L}$

We add a singlet real scalar s

$$V_{\rm cl}(H,\phi,s) = \frac{\lambda_{Hs}}{2}|H|^2 s^2 + \frac{\lambda_{\phi s}}{2}|\Phi|^2 s^2 + \frac{\lambda_s}{4}s^4 + V_{\rm cl}(H,\Phi)$$

- s will stabilise the higgs potential if $\lambda_{Hs} > 0.35$.
- Can implement inflation with real singlet s. Khoze 2013

Dark Matter

There are **two DM candidates** in the models we have considered.

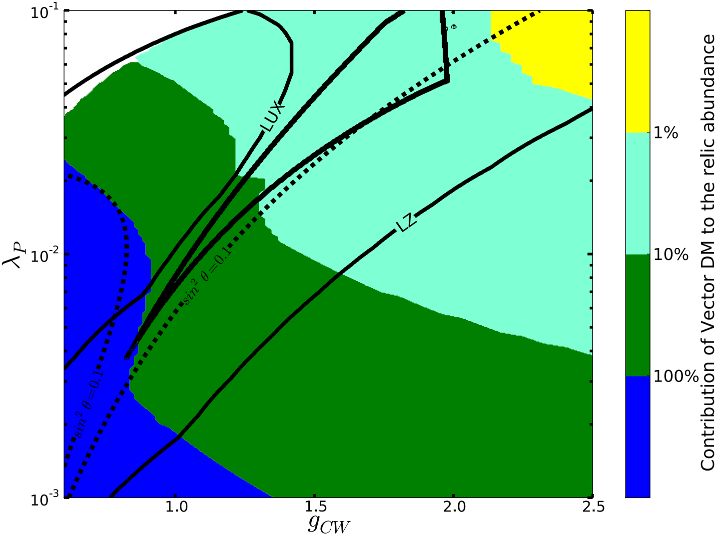
- **The singlet scalar**
  Stable due to a Z_2 symmetry which is automatic due to CSI and gauge invariance

- **The $SU(2)$ gauge bosons**
  Stable due to an $SO(3)$ symmetry and no kinetic mixing Hambye 2008.

The origin of the dark matter scale is the same as the origin of the EW scale as $m_{DM} \propto \langle \phi \rangle$

Relic abundance produced by standard freeze out mechanism

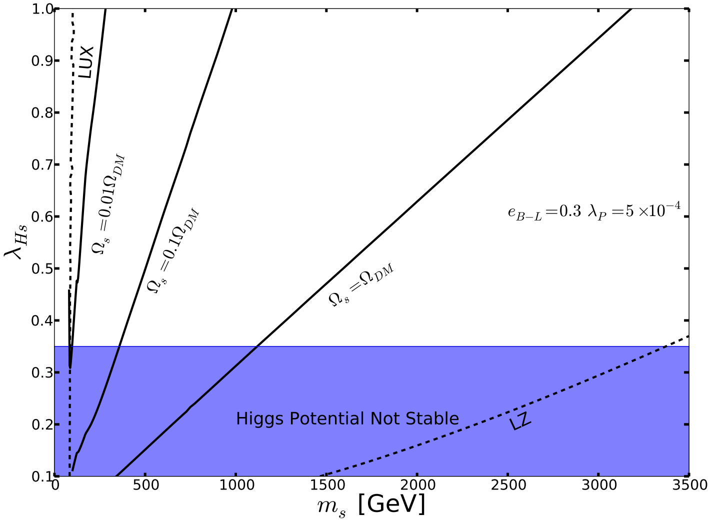
Vector DM



Higgs Potential is stable in wedge shaped region without adding an extra scalar. With an extra scalar no constraint from vacuum stability.

Scalar DM

Only Scalar Dark Matter



Conclusion

- Classically scale invariant models do not suffer from the hierarchy problem and are minimal BSM extensions
- To be viable the need to explain **all** problems with SM using only one dynamically generated scale.
- Have shown that leptogenesis via neutrino oscillations works in $SM \times U(1)_{B-L}$.
- CSI ESM models improve Higgs vacuum stability, but most models need an extra singlet
- Two viable dark matter candidates: Dark $SU(2)$ Gauge Bosons and Singlet scalars
- **Common origin of the Dark Matter scale and the Electroweak scale which also can explain the baryon anti-baryon asymmetry and stabilize the Higgs potential**

References

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