Vector boson dark matter in a Classically Conformal U(1) extension of the Standard Model

Victor Baules
The University of Alabama

In Collaboration with Nobuchika Okada (U. of Alabama)
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Classically conformal extended SM

Radiative Symmetry breaking as origin of SM Higgs potential

- SM Higgs potential requires $-m^2$ term for EW symmetry breaking (EWSB); usually added by hand.

$$V = \boxed{-m^2(\Phi^\dagger\Phi)} + \lambda_\Phi(\Phi^\dagger\Phi)^2, \quad m^2 > 0 \tag{1}$$

- Alternative origin: Radiative symmetry breaking via Coleman-Weinberg mechanism (Coleman & Weinberg, 1973).
- Extend SM minimally with hidden $U(1)$ gauge group (dubbed $U(1)_H$), containing a Higgs scalar Φ.
- Implement CW mechanism for $U(1)_H$ by imposing classical conformality (Iso, Okada, & Orikasa, 2009).

Coleman-Weinberg Mechanism

Radiative Symmetry breaking as origin of SM Higgs potential

- Hidden $U(1)_H$ sector scalar effective potential of the form

$$\begin{aligned} V_\phi &= \lambda_\phi \left(\Phi^\dagger \Phi\right)^2 + V_{1loop} \\ &= \frac{1}{4}\lambda_\phi \phi^4 + \frac{\beta_\phi}{8}\phi^4 \left(ln\left[\frac{\phi^2}{v_\phi^2}\right] - \frac{25}{6}\right), \text{ where } \phi = \sqrt{2}\mathrm{Re}\left[\Phi\right] \end{aligned} \tag{2}$$

- Combined SM Higgs and Φ scalar potential is

$$V = \lambda_h \left(H^\dagger H\right)^2 - \boxed{\lambda_{mix}\left(H^\dagger H\right)\left(\Phi^\dagger \Phi\right)} + \lambda_\phi \left(\Phi^\dagger \Phi\right)^2 + V_{1loop} \tag{3}$$

- Radiative symmetry breaking in $U(1)_H$ sector at $\langle \phi \rangle = v_\phi$
- **With $\lambda_{mix} > 0$, $\langle \phi \rangle = v_\phi$ generates negative SM Higgs mass squared term, driving EW symmetry breaking.**

Coupling Analysis

$$\text{Conventional: } V = \frac{\lambda_h}{4}(h^2 - v_h^2)^2 + \frac{\lambda_\phi}{4}(\phi^2 - v_\phi^2)^2 + \frac{\lambda_{mix}}{4}(h^2 - v_h^2)(\phi^2 - v_\phi^2)$$

$$\text{Conformal: } V = \frac{\lambda_h}{4}h^4 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\beta_\phi}{8}\phi^4\left(\ln\left[\frac{\phi^2}{v_\phi^2}\right] - \frac{25}{6}\right) - \frac{\lambda_{mix}h^2\phi^2}{4}$$

- Mass-squared matrices defined as

$$M_{sq} = \begin{pmatrix} \partial_h^2 V & \partial_h\partial_\phi V \\ \partial_\phi\partial_h V & \partial_\phi^2 V \end{pmatrix}\Bigg|_{h=v_h,\phi=v_\phi} = \begin{pmatrix} m_h^2 & M^2 \\ M^2 & m_\phi^2 \end{pmatrix}$$

- Diagonalize M_{sq} to find mixing of eigenstates:

$$h = h_1\cos(\theta) + h_2\sin(\theta)$$
$$\phi = -h_1\sin(\theta) + h_2\cos(\theta)$$

In our analysis, we set $M_{h_1} > 2M_{h_2}, \theta \ll 1 \Rightarrow \boxed{h \sim h_1,\ \phi \sim h_2}$

Coupling Analysis

- Express potentials in terms of observables and extract couplings.

For $M_{h_1} > 2M_{h_2}, \theta \ll 1$, conventional system coupling goes as

$$g_{h_1 h_2 h_2} \simeq -\frac{M_{h_1}^2}{2v_\phi}\left(1 + 2\frac{M_{h_2}^2}{M_{h_1}^2}\right)\theta \quad \text{for} \quad \theta \ll \frac{v_h}{v_\phi}, \tag{4}$$

$$g_{h_1 h_2 h_2} \simeq \frac{M_{h_1}^2}{2v_h}\left(1 + 2\frac{M_{h_2}^2}{M_{h_1}^2}\right)\theta^2 \quad \text{for} \quad \frac{v_h}{v_\phi} \lesssim \theta, \tag{5}$$

while conformal system coupling goes as

$$g_{h_1 h_2 h_2} \simeq -\frac{M_{h_2}^2}{2v_h}\left(1 - 4\frac{M_{h_2}^2}{M_{h_1}^2}\right)\theta^2. \tag{6}$$

- Combination of cancellation of lower order θ terms and unique structure leads to coupling suppression in the conformal system.

Coupling Analysis

Trilinear coupling ratio found to be

$$R \equiv \frac{|g_{h_1 h_2 h_2}|_{\rm conf}|}{|g_{h_1 h_2 h_2}|_{\rm conv}|} = \left(\frac{M_{h_2}^2}{M_{h_1}^2}\right) \frac{1 - 4\frac{M_{h_2}^2}{M_{h_1}^2}}{1 + 2\frac{M_{h_2}^2}{M_{h_1}^2}} < 0.0505 \quad \text{for} \quad \frac{v_h}{v_\phi} \lesssim \theta$$

$$R = \left(\frac{M_{h_2}^2}{M_{h_1}^2}\right) \frac{1 - 4\frac{M_{h_2}^2}{M_{h_1}^2}}{1 + 2\frac{M_{h_2}^2}{M_{h_1}^2}} \left(\frac{v_\phi}{v_h}|\theta|\right) \quad \text{for} \quad \theta \ll \frac{v_h}{v_\phi}$$

- Using $M_{h_1} = 125$ GeV, $M_{h_2} = 25$ GeV, $v_h = 246$ GeV, $v_\phi = 10^4$ GeV, and $|\theta| = 0.1$:

$$\text{Conventional system:} \quad g_{h_1 h_2 h_2} = 0.424$$

$$\text{CW system:} \quad g_{h_1 h_2 h_2} = -0.0107$$

Numerical Analysis: Br $(h_1 \to h_2 h_2)$

- Gray regions excluded by LHC (ATLAS, 2020) and LEP-II (for $M_{h_2} = 25$ GeV) (LEP-II, 2003)
- Prospective ILC search reach indicated by blue region for anomalous Higgs decay (Liu, Wang, Zhang, 2017) and red region for anomalous coupling (Barklow et. al., 2018).

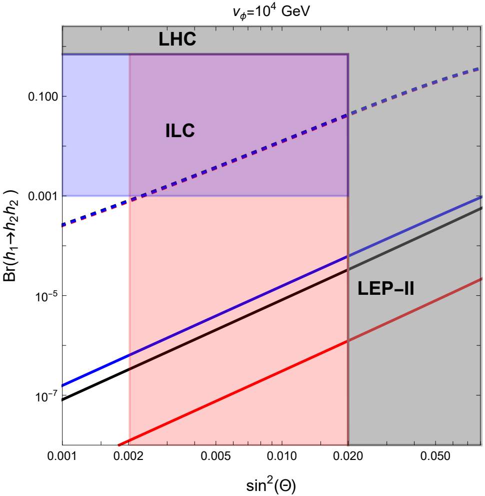

Figure: Conventional (dashed) and Conformal (solid) branching ratios. $M_{h_2} = 10$ (red), 25 (black), and 50 (blue) GeV.

$U(1)_H$ vector boson Dark Matter

- Consider Z', the gauge boson of $U(1)_H$, as DM candidate
- Four main annihilation processes for $Z'Z' \to h_2 h_2$
- Reproducing observed DM relic density $\Omega_{DM} h^2 = 0.12$ (Planck 2018) requires $\langle \sigma v_{rel} \rangle \sim 1$ pb

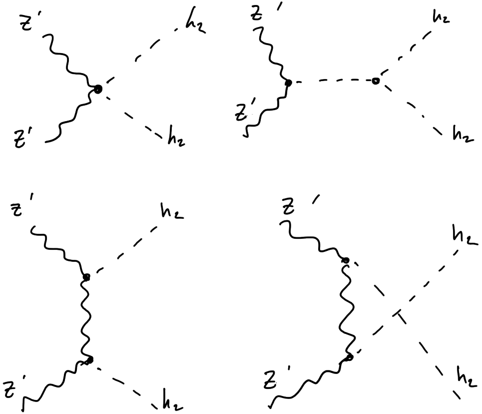

Figure: $Z'Z' \to h_2 h_2$ DM annihilation process diagrams

$U(1)_H$ vector boson Dark Matter

- Non-relativistic approx. for preliminary results.
- Red, Black, Blue lines correspond to non-excluded parameter space for θ below LEP-II bounds for $M_{h_2} = 10$ (red), 25 (black), and 50 (blue) GeV, respectively.
- $\langle \sigma v_{rel} \rangle \sim 1\text{pb}$ satisfied along purple curve. Conformal model satisfies this condition and reproduces $\Omega_{DM} h^2 = 0.12$ at intersection points.

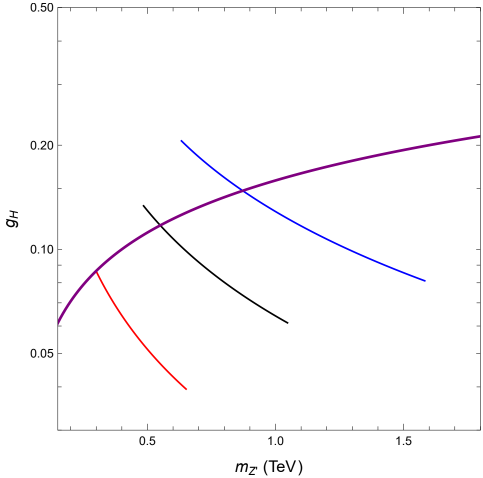

Figure: Gauge coupling g_H vs. Z' (DM) mass, for select values of m_{h_2}. $\Omega_{DM} h^2 = 0.12$ is reproduced along the purple line.

Summary

- Classical conformal structure & Coleman-Weinberg mechanism as origin of EW Symmetry breaking.
  - **Radiative symmetry breaking in $U(1)_H$ sector induces negative SM Higgs mass term, driving EW symmetry breaking**
- Unique structure of conformal potential greatly affects Higgs physics/phenomenology
  - **Most notably, trilinear coupling $g_{h_1 h_2 h_2}$ suppression in CW model vs. conventional model**
  - **Models distinguishable by precision measurement of anomalous Higgs coupling alongside (non-)observation of anomalous Higgs decay $h_1 \to h_2 h_2 \to b\bar{b}b\bar{b}$ at future e^+e^- colliders (ILC)**
- With Z' as DM candidate, $\Omega_{DM} h^2 = 0.12$ can still be satisfied for appropriate choice of scalar mass m_{h_2}.