Higgs Parity, Strong CP, and Dark Matter

David Dunsky, Lawrence Hall, Keisuke Harigaya

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The Higgs Quartic

\[ V(H) = -m^2|H|^2 + \lambda|H|^4 \]

- 1967: \( \langle H \rangle = v \) Weinberg
- 2012: \( m, \lambda \) ATLAS, CMS

- Measured value \( \lambda \) of appears special

\[ \lambda \uparrow \lambda \downarrow \]
• Why is $\lambda \sim .01$ above $10^9$ GeV?

• Why $\lambda$ crosses 0 between $10^9 - 10^{13}$?

• Vanishing of $\lambda$ hint of new physics?

See Buttazzo, et al (2013)
Vanishing of Higgs Quartic by a $Z_2$

- Consider a $Z_2$  
  
  $SU(2) \leftrightarrow SU(2)'$
  
  $H \leftrightarrow H'$
  
  $(2,1) \leftrightarrow (1,2)$
Vanishing of Higgs Quartic by a $Z_2$

- Consider a $Z_2$ $SU(2) \leftrightarrow SU(2)'$
  $H \leftrightarrow H'$
  $(2,1) \leftrightarrow (1,2)$

- Most general potential
  
  $$V(H, H') = -m^2(|H|^2 + |H'|^2) + \frac{\lambda}{2}(|H|^2 + |H'|^2)^2 + \lambda'|H|^2|H'|^2$$
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  \]
  \[
  \langle H' \rangle^2 \equiv v'^2 = \frac{m^2}{\lambda} \gg v^2
  \]
  \[
  (174 \text{ GeV})^2
  \]
Vanishing of Higgs Quartic by a $Z_2$

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- Most general potential:
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  \]

  Integrate out $H'$
  \[
  \langle H' \rangle^2 \equiv v'^2 = \frac{m^2}{\lambda} \gg v^2
  \]

  Limited potential
  \[
  V_{LE}(H) = \lambda' v'^2 |H|^2 - \lambda' \left(1 + \frac{\lambda'}{2\lambda}\right) |H|^4
  \]

  \[ (174 \text{ GeV})^2 \]
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- Consider a $Z_2$ \[ SU(2) \leftrightarrow SU(2)' \]
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- Most general potential
  \[ V(H, H') = -m^2 (|H|^2 + |H'|^2) + \frac{\lambda}{2} (|H|^2 + |H'|^2)^2 + \chi' |H|^2 |H'|^2 \]

  Integrate out $H'$

  \[ \langle H' \rangle^2 \equiv v'^2 = \frac{m^2}{\lambda} \gg v^2 \]

  \[ V_{\text{LE}}(H) = \lambda' v'^2 |H|^2 - \chi' \left( 1 + \frac{\chi'}{2\lambda} \right) |H|^4 \]
  \[ -m_{\text{SM}}^2 \]

(174 GeV)$^2$
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  \[ V_{\text{LE}}(H) = \lambda'v'^2|H|^2 - \lambda' \left(1 + \frac{\lambda'}{2\lambda}\right)|H|^4 \]

  \[ -m_{\text{SM}}^2 \quad \lambda_{\text{SM}} \]

- Requiring $v \ll v'$  \[ \lambda' \ll 1 \quad \lambda_{\text{SM}} \approx 0 \]
RG Running of $\lambda$

$m_{\text{top}} = 173.0$ [GeV]

$10^9 \lesssim \nu' \lesssim 10^{13}$
Fine-Tuning

- Fine tuning required, but same as SM

\[
\frac{\nu^2}{m^2} \times \frac{m^2}{\Lambda^2} = \frac{\nu^2}{\Lambda^2}
\]

Tuning of \( \chi' \)  Tuning of \( \nu' \)
The Mirror Electroweak Sector

- (1) Extend $Z_2$ to mirror electroweak sector

- (2) Identify $Z_2$ with spacetime parity

\[ SU(2) \times U(1) \leftrightarrow SU(2)' \times U(1)' \]

\[ \bar{x}' \leftrightarrow -\bar{x} \]

\[ q, \bar{u}, \bar{d}, l, \bar{e} \leftrightarrow (q', \bar{u}', \bar{d}', l', \bar{e}')^\dagger \]

\[ H \leftrightarrow H' \]

- Implications?
Solves Strong CP Problem

- $SU(3) \times (SU(2) \times U(1)) \times (SU(2)’ \times U(1)’)$ solves strong CP

- Parity is a symmetry
  
  $\frac{\theta}{32\pi^2} G\tilde{G}$ forbidden

- No CP violation in Yukawa sectors

$\text{arg det} \begin{pmatrix} y_{u,d} & v & 0 \\ 0 & y_{u,d}^* & v' \end{pmatrix} = 0$

Babu, Chang, Senjanovic (1991)
Mirror Dark Matter

- Natural DM candidate lightest $U(1)'_{EM}$ particle, $e'$
- DM mass $m_{e'} = y_{e'} v' = m_{e} \frac{v'}{v}$ (1-10$^4$ TeV)
Signals: Neutron EDM

- Higher dimensional operators generate $\theta$

\[ \mathcal{L}_6 = \frac{C}{M_{Pl}^2} (|H|^2 - |H'|^2) G\tilde{G} \]

\[ \theta = 32\pi^2 C \left( \frac{v'}{M_{Pl}} \right)^2 = 5 \times 10^{-11} C \left( \frac{v'}{10^{12} \text{GeV}} \right)^2 \]

- Current neutron EDM limit $\theta < 10^{-10}$  

Baker, et al (2006)
Signals: Kinetic Mixing

- $\mathcal{L} \supset -\frac{\epsilon B}{2} B^{\mu \nu} B'_{\mu \nu}$ allowed
- Generated by

\[ \gamma' \sim \epsilon B^{\mu \nu} B'_{\mu \nu} \sim \gamma \]

(Calculable from 4-loop QCD beta function)

van Ritbergen, Vermaseren, Larin (1997)
Signals: Kinetic Mixing

Dunsky, Hall, Harigaya (2018) arXiv:1812.11116
$\Lambda = 10^{18}$ GeV

$\alpha_s(m_Z) = 0.1159$

$\alpha_s(m_Z) = 0.1170$

$\alpha_s(m_Z) = 0.1181$

$\alpha_s(m_Z) = 0.1192$

$\alpha_s(m_Z) = 0.1203$

Xenon1T

$\nu_{\text{floor}}$
Summary

- Observed Higgs mass imply next symmetry breaking scale of nature?
- Motivated by Strong CP → Higgs Parity, no QCD'
- Motivated by DM → mirror electroweak
- Same number of parameters as SM below \( v' \)
- Future measurements of \( \{m_t, m_h, \alpha_s(M_Z)\} \) will hone in on \( v' \)
- Entire parameter space will be probed by future detectors
Cosmology

- Freeze-Out and Freeze-In of $e'$ DM does not work
- Too much $u'$ produced $\rightarrow$ fractional charged hadrons
- Non-thermal production, kinematic suppression of $u'$