The Higgs Sector of the Lee-Wick Extension of the Standard Model

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NEGATIVE METRIC AND THE UNITARITY OF THE S-MATRIX

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Finite Theory of Quantum Electrodynamics*

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Modern Treatment PRD**77** 025012 (2008), PRD**77** 085002 (2008)
PRD**78** 105005 (2008), JHEP 0804 026 (2008), PRD**79** 035016 (2009)

The original idea in these two papers...

- Studied possibility of promoting the Pauli-Villars regulator to a physical degree of freedom.
- The regulator in the photon propagator is a higher derivative version of QED.
- Had a massive photon with wrong sign pole and kinetic term.
- *This lead to several predictions not realized in nature.*
- Wrong sign widths and kinetic terms ...
- ... but that is OK. All physical quantities are positive.
- This also required a different contour for Feynman diagrams.

Some (interesting) facts about LW models...

- There are no quadratic divergencies in the Higgs sector
- Negative norm states exist in the theory (classically unstable)
- Minimal LW has five Higgs with one vacuum expectation value
- Supressed, but richer flavour structure
- mg (LW fermion) is a renormalization group invariant
- Minimal LW are not GUTs (sprinting coupling constants)
- QED sector is unitary, unknown for gauge sector
- LW theory can be acausal, but boundary conditions can fix this
- Precision EW puts new physics scale as low as a few TeV
- Neutrino masses work very well, gives DM candidate

Look at Toy Model

$$\mathcal{L}_{\rm hd} = \frac{1}{2}\partial_\mu \hat{\phi}\partial^\mu \hat{\phi} - \frac{1}{2}m^2\hat{\phi}^2 - \frac{1}{2M^2}(\partial^2\hat{\phi})^2 - \frac{1}{3!}g\hat{\phi}^3$$

$$\hat{D}(p) = \frac{i}{p^2 - p^4/M^2 - m^2}, \qquad p^2 \simeq m^2, M^2 \qquad M \gg m$$

Introduce auxillary field, $\tilde{\phi}(M)$, exchange $\phi = \hat{\phi} + \tilde{\phi}$, integrate by parts...

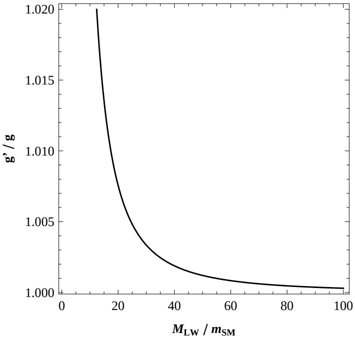
$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi\partial^\mu \phi - \frac{1}{2}\partial_\mu \tilde{\phi}\partial^\mu \tilde{\phi} - \frac{1}{2}m^2(\phi - \tilde{\phi})^2 + \frac{1}{2}M^2\tilde{\phi}^2 - \frac{1}{3!}g(\phi - \tilde{\phi})^3$$

$$\begin{pmatrix} \phi \\ \tilde{\phi} \end{pmatrix} = \begin{pmatrix} \cosh\theta & \sinh\theta \\ \sinh\theta & \cosh\theta \end{pmatrix} \begin{pmatrix} \phi' \\ \tilde{\phi}' \end{pmatrix}, \qquad \tanh 2\theta = \frac{-2m^2/M^2}{1 - 2m^2/M^2}, \qquad M > 2m$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi' \partial^\mu \phi' - \frac{1}{2}\partial_\mu \tilde{\phi}' \partial^\mu \tilde{\phi}' - \frac{1}{2} m'^2 \phi'^2 + \frac{1}{2} M'^2 \tilde{\phi}'^2 - \frac{1}{3!}(\cosh\theta - \sinh\theta)^3 g(\phi' - \tilde{\phi}')^3$$

$$g' = (\cosh\theta - \sinh\theta)^3 g$$

$$\tilde{D}(p) = \frac{-i}{p^2 - M^2 + \Sigma(p^2)}, \qquad \Gamma = -\frac{g^2}{32\pi M}\sqrt{1 - \frac{4m^2}{M^2}}$$



Gauge Lagrangian works too

$$\mathcal{L}_{\rm hd} = -\frac{1}{2}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} + \frac{1}{M_A^2}(\hat{D}^\mu \hat{F}_{\mu\nu})(\hat{D}^\lambda \hat{F}^\nu_\lambda),$$

$$\hat{F}_{\mu\nu} = \partial_\mu \hat{A}_\nu - \partial_\nu \hat{A}_\mu - ig[\hat{A}_\mu, \hat{A}_\nu], \qquad \hat{A}_\mu = \hat{A}^A_\mu T^A$$

$$\mathcal{L} = -\frac{1}{2}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - M_A^2 \tilde{A}_\mu \tilde{A}^\mu + 2\hat{F}_{\mu\nu}\hat{D}^\mu \tilde{A}^\nu$$

Continues like Toy Model with color structure, propagators as expected...

$$D^{AB}_{\mu\nu}(p) = -\delta^{AB}\frac{i}{p^2}\left(\eta_{\mu\nu} - (1-\xi)\frac{p_\mu p_\nu}{p^2}\right)$$

$$\tilde{D}^{AB}_{\mu\nu}(p) = \delta^{AB}\frac{i}{p^2 - M_A^2}\left(\eta_{\mu\nu} - \frac{p_\mu p_\nu}{M_A^2}\right)$$

What about Higgs?

$$\mathcal{L}_{\mathrm{hd}} = (\hat{D}_\mu \hat{H})^\dagger (\hat{D}^\mu \hat{H}) - \frac{1}{M_H^2} (\hat{D}_\mu \hat{D}^\mu \hat{H})^\dagger (\hat{D}_\nu \hat{D}^\nu \hat{H}) - \frac{\lambda}{4} \left(\hat{H}^\dagger \hat{H} - \frac{v^2}{2} \right)^2, \qquad \hat{H} = H - \tilde{H}$$

$$\hat{D}_\mu = D_\mu + ig\tilde{A}_\mu^A T^A + ig_2 \tilde{W}_\mu^a T^a + ig_1 \tilde{B}_\mu Y,$$

$$D_\mu = \partial_\mu + igA_\mu^A T^A + ig_2 W_\mu^a T^a + ig_1 B_\mu Y, \qquad \tilde{\mathbf{A}}_\mu = g\tilde{A}_\mu + g_2 \tilde{W}_\mu + g_1 \tilde{B}_\mu$$

$$\mathcal{L} = (D_\mu H)^\dagger D^\mu H - (D_\mu \tilde{H})^\dagger D^\mu \tilde{H} + M_H^2 \tilde{H}^\dagger \tilde{H} + \cdots$$

For the two Higgs, we need two doublets

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}, \qquad \tilde{H} = \begin{pmatrix} \tilde{h}^+ \\ \frac{\tilde{h}+i\tilde{P}}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_{\mathrm{mass}} = -\frac{\lambda}{4} v^2 (h - \tilde{h})^2 + \frac{M_H^2}{2} (\tilde{h}\tilde{h} + \tilde{P}\tilde{P} + 2\tilde{h}^+ \tilde{h}^-)$$

Higgs and a LW partner (mix), two charged LW Higgs, and a pseudoscalar LW Higgs

The Factorization (Hierarchy) Problem

The LW partners regularize the scalar sector

$$\delta m_h^2 \sim (10^{18}\mathrm{GeV})^2 \to \delta m_h^2 \sim \frac{g^2 M_{LW}^2}{16\pi^2} \ln \frac{\Lambda^2}{M_{LW}^2}$$

The gauge fields and LW-gauge fields mix, so ρ parameter gets tree level corrections which are OK for LW masses $>$ a few TeV.
Don't forget the right handed neutrinos

$$m_\nu \sim \frac{v^2}{m_R}, \qquad m_R > 10^{11}\mathrm{TeV}$$

$$\delta m_h^2 \sim -\frac{g_Y^2}{8\pi^2} m_R^2 \ln \frac{m_R^2}{\mu^2} \to \delta m_h^2 \sim -\frac{g_Y^2}{8\pi^2} M_L^2 \ln \frac{m_R^2 + \Lambda^2}{m_R^2}$$

Conclusions

- Lee-Wick is an intriguing extention to the SM
- Presents a solution to factorization problem
- Better neutrino sector/scalar interactions
- Phenomenology is SUSY-like, but several differences
- Formal considerations of non-Abelian sector
- Another paradigm to look at data