Theory and phenomenology of the Lee-Wick Standard Model

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Outline

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3. Higgs boson pair production

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Lee Wick Standard Model

- Lee and Wick made the assumption that the regulator employed in the framework of Pauli-Villars regularization indeed is a physical degree of freedom.[1]
- GOW proposed a minimal extension of the SM which is free from quadratic divergences. [2]
- The GOW model (aka LWSM) is a higher derivative theory and as such contains propagators with wrong sign residues about the new poles. Lee and Wick, and Cutkosky et al. provided a prescription for handling this issue.

[1] T. D. Lee and G. C. Wick, Nucl. Phys. B **9**, 209 (1969); Phys. Rev. D **2**, 1033 (1970)

[2] B. Grinstein, D. O'Connell and M. B. Wise, Phys. Rev. D **77**, 025012 (2008) [arXiv:0704.1845 [hep-ph]]

Higgs boson sector

The higher derivative Lagrangian for the Higgs doublet $\hat{H}$ is given by

$$\mathcal{L}_{hd} = (\hat{D}_\mu \hat{H})^\dagger (\hat{D}^\mu \hat{H}) - \frac{1}{M_H^2} (\hat{D}_\mu \hat{D}^\mu H)^\dagger (\hat{D}_\nu \hat{D}^\nu H) - V(\hat{H}) \,, \tag{1}$$

with covariant derivative

$$\hat{D}_\mu = \partial_\mu + i g_2 \hat{W}_\mu^a + i g_1 \hat{B}_\mu Y \,, \tag{2}$$

and potential

$$V(\hat{H}) = \frac{\lambda}{4} \left(\hat{H}^\dagger \hat{H} - \frac{v^2}{2} \right)^2 \,. \tag{3}$$

Higgs boson sector

In the unitary gauge,

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} , \qquad \tilde{H} = \begin{pmatrix} \tilde{h}^{+} \\ \frac{\tilde{h}+i\tilde{P}}{\sqrt{2}} \end{pmatrix} \tag{4}$$

For this choice, the mass Lagrangian of the Higgs scalar, h, its partner, $\tilde{h}$, the charged LW–Higgs, $\tilde{h}^{\pm}$, and the pseudo–scalar LW–Higgs, $\tilde{P}$ is given by

$$\mathcal{L}_{mass} = -\frac{\lambda}{4} v^2 (h - \tilde{h})^2 + \frac{M_H^2}{2} (\tilde{h}\tilde{h} + \tilde{P}\tilde{P} + 2\tilde{h}^{+}\tilde{h}^{-})\,. \tag{5}$$

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Yukawa Interactions

In the higher derivative formalism, the quark Yukawas are

$$\mathcal{L}_Y = g_u^{ij}\bar{\hat{u}}_R^i \hat{H}\epsilon \hat{Q}_L^j - g_d^{ij}\bar{\hat{d}}_R^i \hat{H}^\dagger \hat{Q}_L^j + H.c. \tag{6}$$

where repeated flavour indices are summed.

Mass eigenstates

There is a mixing between the Higgs scalar and its LW–partner. The mass matrix is diagonalized by a symplectic rotation:

$$\begin{pmatrix} h \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cosh\phi_h & \sinh\phi_h \\ \sinh\phi_h & \cosh\phi_h \end{pmatrix} \begin{pmatrix} h_{phys} \\ \tilde{h}_{phys} \end{pmatrix} . \qquad (7)$$

The symplectic mixing angle ϕ_h and the physical masses are

$$\tanh\phi_h = \frac{-\lambda v^2/M_H^2}{1-\lambda v^2/M_H^2} , \qquad (8)$$

and

Mass eigenstates

$$m^2_{h,phys} = \frac{1}{2}\left(M_H^2 - \sqrt{M_H^4 - 2v^2\lambda M_H^2}\right) , \quad (9)$$

$$m^2_{\tilde{h},phys} = \frac{1}{2}\left(M_H^2 + \sqrt{M_H^4 - 2v^2\lambda M_H^2}\right) .$$

The quartic coupling can be computed from the physical Higgs masses

$$\lambda v^2 = \frac{2 m^2_{h,phys} m^2_{\tilde{h},phys}}{m^2_{h,phys} + m^2_{\tilde{h},phys}} . \quad (10)$$

Yukawa interactions

The neutral Higgs–top interaction is given by

$$\mathcal{L} = -\frac{1}{v}(h - \tilde{h})\overline{\Psi^t_R} g_t \Psi^t_L + H.c. \, , \qquad (11)$$

with

$$\Psi^{t\top}_L = (T_L, \tilde{T}_L, \tilde{t}'_L) \, , \qquad \Psi^{t\top}_R = (t_F, \tilde{t}_R \tilde{T}'_R) \, . \qquad (12)$$

T_L is a component of the third generation of the SM doublet Q_L

$$Q_{L3} = \begin{pmatrix} T_L \\ B_L \end{pmatrix} \, . \qquad (13)$$

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Higgs boson pair production

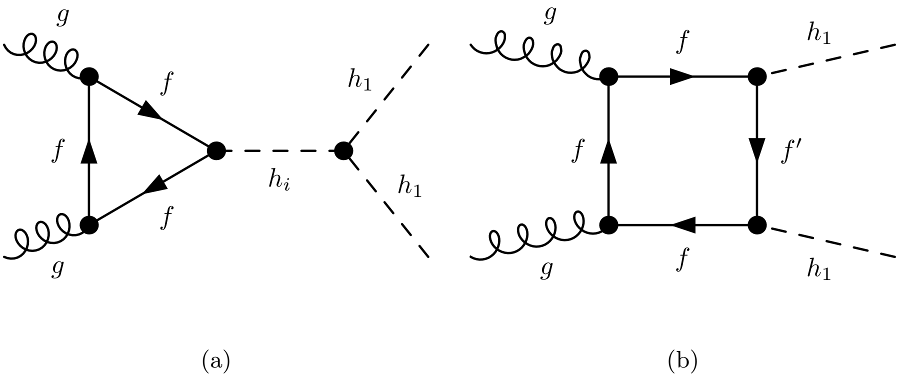
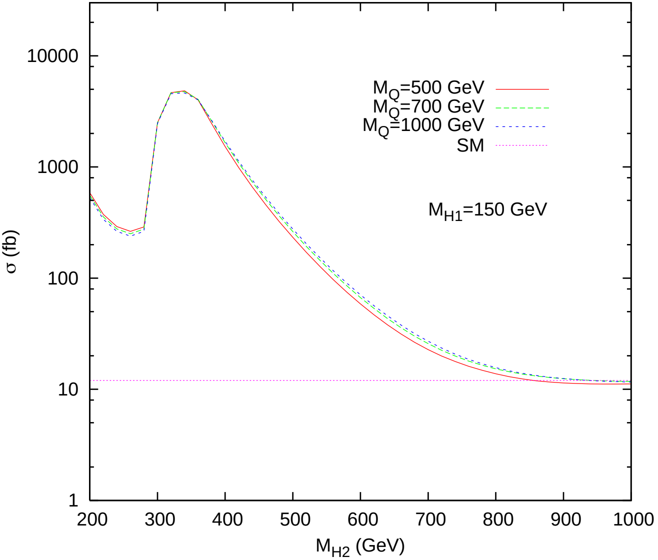
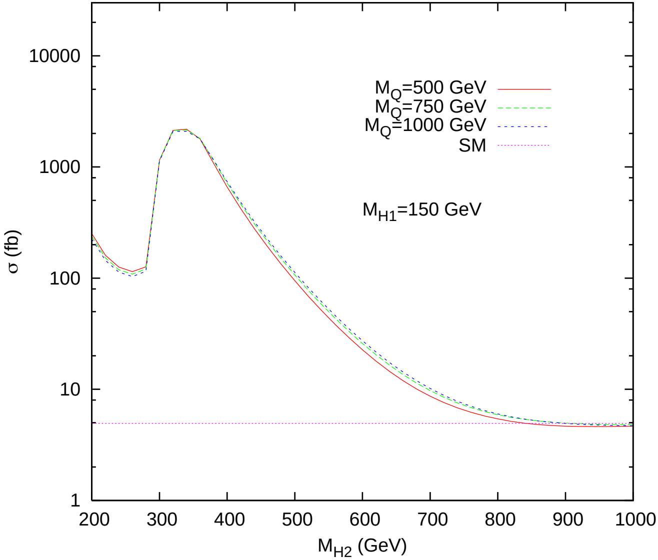


Figure: (a) Triangle graphs for $f = (t, \tilde{t}, \tilde{T}, b, \tilde{b}, \tilde{B})$ and (b) box graphs for $f, f' = (t, \tilde{t}, \tilde{T}, b, \tilde{b}, \tilde{B})$.

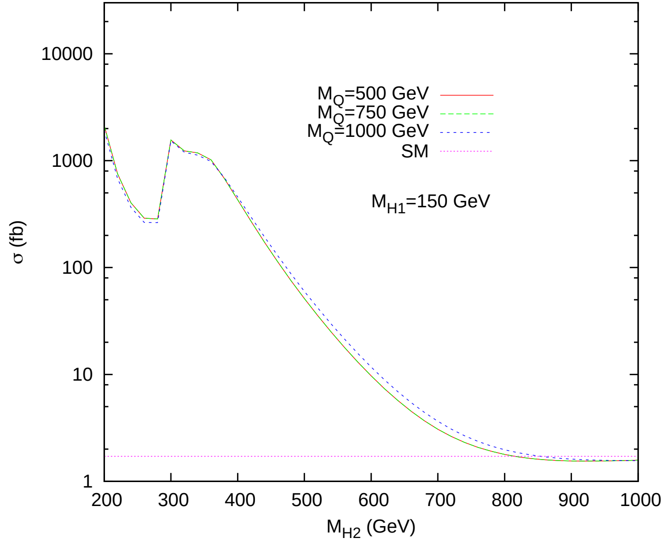
$pp \to H_1 H_1$ for $\sqrt{s} = 14$ TeV



$pp \to H_1 H_1$ for $\sqrt{s} = 10$ TeV



$pp \to H_1 H_1$ for $\sqrt{s} = 7$ TeV



Conclusions

- The LWSM is a minimal extension of the SM which is free of quadratic divergences.
- A consequence is the production and decay of LW-Higgs bosons.
- In the resonant region $M_{H_2} \geq 2M_{H_1}$ the inclusive cross section reaches ≈ 5 pb for $\sqrt{s} = 14$ TeV and ≈ 2 pb for $\sqrt{s} = 10$ TeV