

Higgs Boson Pair Production within the Lee-Wick Standard Model

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CERN THEORY

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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.

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

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

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

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

with covariant derivative

$$\hat{D}_\mu = \partial_\mu + ig_2 \hat{W}_\mu^a + ig_1 \hat{B}_\mu Y, \quad (2)$$

and potential

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

In the unitary gauge,

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

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

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

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

$$\begin{pmatrix} h \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cosh \phi_h & \sinh \phi_h \\ \sinh \phi_h & \cosh \phi_h \end{pmatrix} \begin{pmatrix} h_{phys} \\ \tilde{h}_{phys} \end{pmatrix}. \quad (6)$$

The symplectic mixing angle ϕ_h and the physical masses are

$$\tanh \phi_h = \frac{-\lambda v^2 / M_H^2}{1 - \lambda v^2 / M_H^2}, \quad (7)$$

and

Mass eigenstates

$$\begin{aligned} m_{h,phys}^2 &= \frac{1}{2} \left(M_H^2 - \sqrt{M_H^4 - 2v^2 \lambda M_H^2} \right), \\ m_{\tilde{h},phys}^2 &= \frac{1}{2} \left(M_H^2 + \sqrt{M_H^4 - 2v^2 \lambda M_H^2} \right). \end{aligned} \quad (8)$$

The quartic coupling can be computed from the physical Higgs masses

$$\lambda v^2 = \frac{2m_{h,phys}^2 m_{\tilde{h},phys}^2}{m_{h,phys}^2 + m_{\tilde{h},phys}^2}. \quad (9)$$

In the higher derivative formalism, the quark Yukawas are

$$\mathcal{L}_Y = g_u^{ij} \bar{u}_R^i \hat{H} \hat{Q}_L^j - g_d^{ij} \bar{d}_R^i \hat{H}^\dagger \hat{Q}_L^j + H.c. \quad (10)$$

where repeated flavour indices are summed.

Yukawa interactions

The neutral Higgs–top interaction is given by

$$\mathcal{L} = -\frac{1}{v}(h - \tilde{h})\overline{\Psi}_R^t g_t \Psi_L^t + H.c., \quad (11)$$

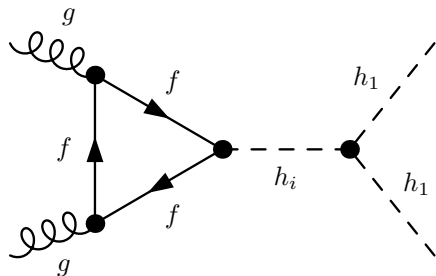
with

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

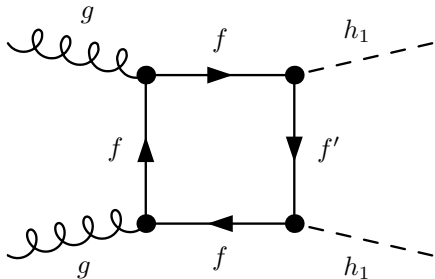
T_L is a component of the third generation of the SM doublet Q_L

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

Higgs boson pair production



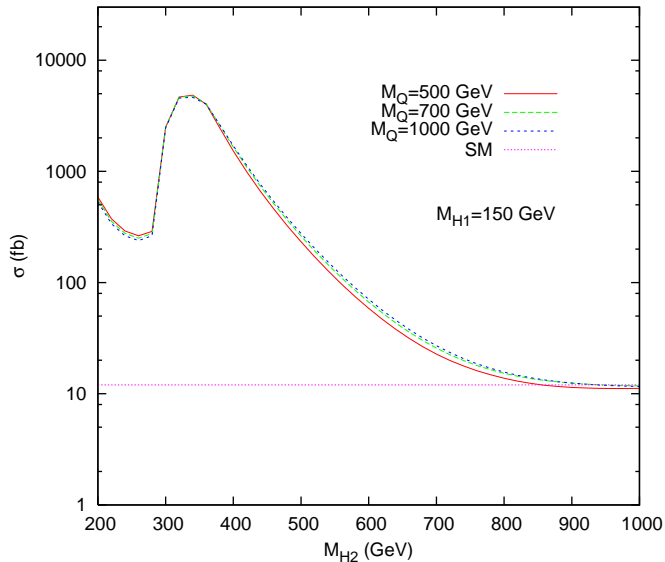
(a)



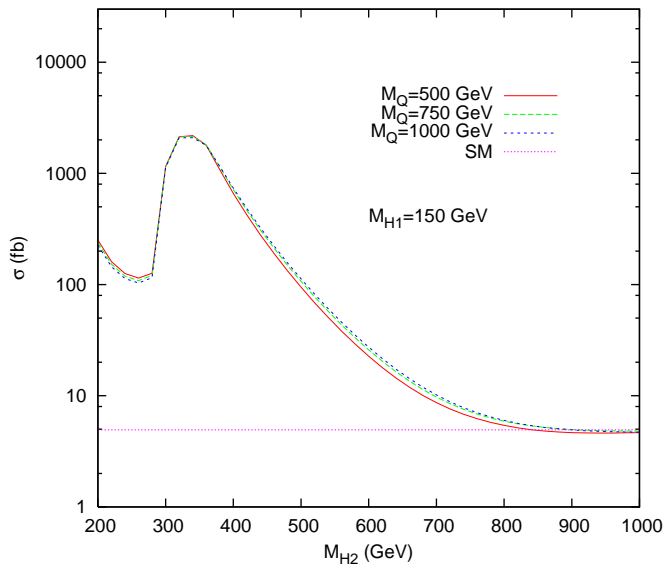
(b)

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

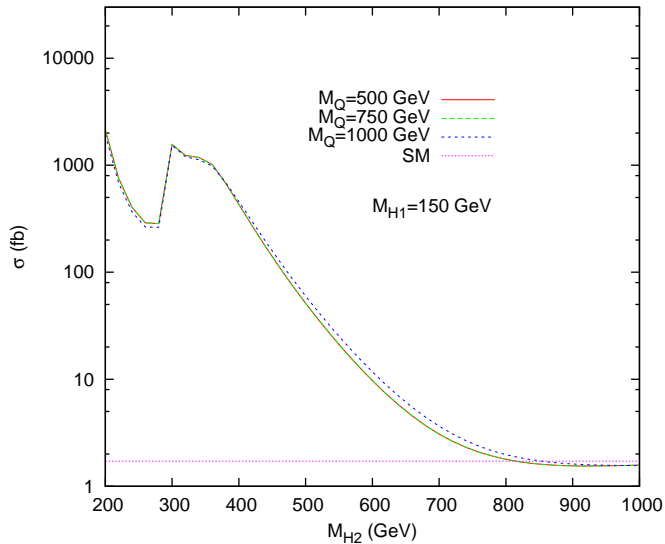
$pp \rightarrow H_1 H_1$ for $\sqrt{s} = 14$ TeV



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



$pp \rightarrow H_1 H_1$ 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