Higgs boson structure from the shape of the cross section in exchange processes.

F.M. Renard
Laboratoire Univers et Particules de Montpellier, UMR 5299
Université de Montpellier, Place Eugène Bataillon CC072
F-34095 Montpellier Cedex 5, France.

Abstract

We show how the Higgs boson exchange processes may indicate the occurrence of special Higgs boson structures (substructures or peculiar interactions with dark matter) from a possible modification of the s-dependence of their cross section. We illustrate the simplest example with the $\mu^+\mu^- \rightarrow f\bar{f}$ process.
1 Introduction

The existence of a peculiar structure of the Higgs boson is a BSM possibility which has been considered for various reasons. In SM the peculiar fermion spectrum, with enormously different mass scales, can be taken into account within the Higgs description by using an adequate set of couplings with the Higgs doublet, but its origin is not explained. The origin of mass has been discussed since a long time, see for example [1, 2, 3]. Among the various possibilities an extension of the SU(3)*SU(2)*U(1) gauge structure may be done in order to describe the presence of 3 families. But even if this can differentiate the families the description of the specific mass spectrum for each family does not seem quantitatively trivial.

The nearby values of the top quark and Higgs boson masses can suggest some common origin (for example a substructure) but the very different scales for the masses of the other fermions would require additional peculiar structures; [4, 5, 6, 7, 8]. On another hand the Higgs boson may be a mediator between the standard set and a new set, for example between our usual world and a new world responsible for the dark matter (DM); [9, 10, 11].

Like in the hadronic case with QCD, contributions to the mass may occur from the various interactions of each fermion, the SM ones and the ones from a new sector possibly through the Higgs mediation. Interferences with different orders of virtual effects between the SM gauge group and the new structure could create these different fermionic mass scales.

Our point is that, as a consequence of such an origin of mass, an energy dependence of the Higgs coupling constants may be generated. With the usual operators connecting fermion and Higgs fields one describes the fermion mass \( m_f \) and the \( Hff \) coupling \( g_{Hff} \) but the above structures may create off-shell dependences; an effective mass \( m_f(s) \) [12], like in the QCD case, and an s-dependent \( Hff \) coupling \( g_{Hff}(s) \) when the Higgs boson is off-shell. The relation between \( g_{Hff} \) and \( m_f \) may differ from the SM case like in [13] but with specific s-dependences.

Simple high order virtual corrections (with sufficiently large couplings and low scales in order to produce visible effects) may occur. A trivial case is the presence of resonant structures related to additional Higgs bosons, but richer substructure dependences may also appear.

Effects of H and t compositeness in several processes have already been studied, [12, 14]. But the situation may be different for light fermions the smallness of their masses implying a less direct Higgs connection.

An other aspect in this domain concerns the whole SU(2) structure of the Higgs states. In SM this concerns the goldstone triplet \( G^0,\pm \). If the CSM hypothesis, [15], is still valid and the equivalence principle maintained this should determine the properties of the longitudinal \( W_L \) and \( Z_L \) states, [16].

So our point will also be to check if the above mentioned new structures affect similarly
H and G, and therefore the $W_L$ and $Z_L$ states and their exchange processes.

In the present paper we want to explore how one can test these various assumptions. Obviously the best way to test these s-dependent Higgs properties is to study the Higgs exchange processes. The magnitudes of the corresponding cross sections should therefore be sufficiently large. With this aim a fermion-antifermion system should be polarized in order to have only equal helicities (as required by the Higgs coupling).

We will illustrate the case of $\mu^+\mu^- \to f\bar{f}$ processes assuming that adequate polarized muon beams will be available. About such possibilities see [17] and [18]. We will explore the sensitivity to the mentioned new Higgs structures by introducing an s-dependence through adequate form factors and by looking at the resulting s-shape of the cross section.

Contents: In Section 2 we recall the precise expressions of the SM helicity amplitudes of the $\mu^+\mu^- \to f\bar{f}$ process; in Section 3 we introduce new structures for the $H$ and $G^0$ couplings and we give illustrations for the $\mu^+\mu^- \to b\bar{b}$ polarized cross sections.

## 2 The $\mu^+\mu^- \to f\bar{f}$ process

In SM, at Born level, this process involves both gauge and Higgs boson exchanges. In the unpolarized case the dominant process is the gauge boson ($\gamma, Z$) exchange; the Higgs ($H$) and Goldstone($G^0$) boson exchanges are reduced by the $\frac{m_\mu}{m_W}$ and $\frac{m_f}{m_W}$ factors. If one selects equal helicities separately in the initial and final states the gauge amplitudes are reduced by the $\frac{m_\mu}{\sqrt{s}}$ and $\frac{m_f}{\sqrt{s}}$ factors and become of comparable size to that of the $(H, G^0)$ exchange.

So we will consider the $F_{\gamma,Z,H,G}^{\lambda_\mu\lambda_{\mu^-}\lambda_f\lambda_f}(\lambda_\mu^+=\lambda_{\mu^-}^=\pm\frac{1}{2}$ and sum over both (RR) and LL) final states with $\lambda_f^+=\lambda_f^-$, i.e.

$$\sum |F|^2 = |F_{RRRR}|^2 + |F_{RRLL}|^2$$

leading to $\sigma_R$, or $|F_{LLLL}|^2 + |F_{LLRR}|^2$ leading to $\sigma_L$, which will lead to the same value after integration over cos $\theta$.

Each amplitude is the sum of 4 terms corresponding to photon, $Z$, $H$ and $G^0$ exchanges.

$$F_{LLLL}^H = F_{LLRR}^H = F_{RRLL}^H = F_{RRRR}^H = -4e^2 gH_{\mu\nu}gH_{f\bar{f}} \frac{lp}{D_H(s)}$$

(2)
\[
 F^G_{LLLL} = -F^G_{LLRR} = -F^G_{RRLL} = F^G_{RRRR} = -4e^2 g_{G\mu\nu} g_{ff} \frac{P^0 P^0}{D_G(s)} \tag{3}
\]

with
\[
 g_{Hff} = \frac{-m_f}{2s_W m_W} \quad g_{Gff} = \frac{-im_f I_3^f}{s_W m_W} \tag{4}
\]

and for \( V = \gamma, Z \)
\[
 F^V_{LLLL} = F^V_{RRRR} = \frac{e^2 m_\mu m_f}{D_V(s)} [(g^V_{\mu L} - g^V_{\mu R})(g^V_{f L} - g^V_{f R}) - (g^V_{\mu L} + g^V_{\mu R})(g^V_{f L} + g^V_{f R}) \cos \theta] \tag{5}
\]
\[
 F^V_{LLRR} = F^V_{RRLL} = \frac{-e^2 m_\mu m_f}{D_V(s)} [(g^V_{\mu L} - g^V_{\mu R})(g^V_{f L} - g^V_{f R}) + (g^V_{\mu L} + g^V_{\mu R})(g^V_{f L} + g^V_{f R}) \cos \theta] \tag{6}
\]

with
\[
 g^g_{\gamma_L} = g^g_{\gamma_R} = Q_f \tag{7}
\]
\[
 g^g_{f L} = \frac{I_3^f - Q_f s_W^2}{s_W c_W} \quad g^g_{f R} = \frac{-Q_f s_W}{c_W} \tag{8}
\]

The illustrations will be done for the bottom quark (\( f = b \)) with \( \mu^+ \mu^- \to \gamma, Z, H, G^0 \to b\bar{b} \). See Fig.1 (solid line for SM) showing the \( s \)-dependence of the angular integrated cross section \( \sigma_L = \sigma_R \) with the peaks at threshold, at \( s = m_Z^2 \) and at \( s = m_H^2 \) due to photon, \( Z, G^0 \) and \( H \) exchanges.

### 3 New structures for \( H, G^0 \) couplings

We now want to explore the sensitivity of the cross section to a modification of the Higgs coupling or of both \( H, G^0 \) couplings.

We use a test form for the modification of the product of couplings as suggested by possible loop (or compositeness) structure.

\[
 f(s) = 1 + c log(1 + \frac{s}{m_0^2}) \tag{9}
\]

A first illustration is given in Fig.1(up) by multiplying only the \( H \) term or both \( H, G^0 \) terms by \( f(s) \) with \( c = 1 \) and \( m_0 = 0.1 \) TeV.

One can see the separate effects of the modification of \( H \) contribution or of a modification of both \( H \) and \( G^0 \) contributions while the \( \gamma, Z \) ones keep their SM forms. The chosen \( f(s) \) modification in eq.(9) is totally arbitrary. It just shows how the SM Breit-Wigner shapes can be differently modified, especially when the complete Higgs sector (with \( H \) and \( G^0 \) contributions) is affected.

As a second illustration we impose the SM value to the \( H \) couplings at \( s = m_H^2 \) and to the \( G^0 \) couplings at \( s = m_Z^2 \), using
\[ f_H(s) = 1 + c \log \left[ \frac{s + m_0^2}{m_H^2 + m_0^2} \right] \]  
(10)

\[ f_G(s) = 1 + c \log \left[ \frac{s + m_0^2}{m_Z^2 + m_0^2} \right] \]  
(11)

with \( m_0^2 = m_b^2 \).

In Fig.1(down) we can also compare the basic SM shape to that of the two cases where \( f_H(s) \) or both \( f_H(s) \) and \( f_G(s) \) are applied, leading to notably different modifications.

From these simple examples one can expect that precise measurements of the shape of the s-dependence of the \( \mu^+\mu^- \rightarrow b\bar{b} \) cross section could reveal what type of Higgs structure may occur.

More complex s-dependences with resonances, threshold effects or other dynamical features, ... may also appear.

4 Conclusion

In this study we wanted to test the sensitivity of Higgs exchange processes to the occurrence of an Higgs boson structure (substructure, DM cloud,...) even if the on-shell coupling constants agree with the SM prediction (no change in the decay branching ratios, neither in the on-shell production rates).

As a simple example we have considered the \( \mu^+\mu^- \rightarrow \gamma, Z, H, G^0 \rightarrow b\bar{b} \) process. In order to increase the sensitivity to the \( H, G^0 \) contributions one should use polarized \( \mu^\pm \) beams with \( \lambda_{\mu^+} = \lambda_{\mu^-} \) and restrict the final states to \( \lambda_b = \lambda_{\bar{b}} \).

We have illustrated how modifications (form factors) of the \( Hff \) couplings and possibly of both \( Hff \) and \( G^0ff \) ones, even preserving their SM on-shell value, can notably affect the shape of the s-dependence of the corresponding polarized cross section.

In order to be applicable to precise analyses this study should be completed by taking into account high order SM effects (bremsstrahlung, radiative corrections) and experimental detection features.

In addition to this idealistic example other possibilities may be considered. One possibility may be multibody production processes for example \( t\bar{t}ff \) in \( e^+e^- \) or hadronic collisions. The contribution of the \( H, G^0 \) exchanges (with \( t\bar{t}H, G^0 \) production followed by \( H, G^0 \rightarrow f\bar{f} \)) would also be favored by selecting equal helicities for both \( t\bar{t} \) and \( f\bar{f} \) systems. Such a study would require a very complex experimental analysis of the \( t\bar{t}ff \) final state. See for example [19] for LHC and [20] for future \( e^+e^- \) colliders.
References

[1] F. Wilczek, arXiv: 1206.7114.

[2] J. Hansson, arXiv: 1402.7033.

[3] J. Hozek and J. Adam, arXiv: 1708.08233.

[4] H. Terazawa, Y. Chikashige and K. Akama, Phys. Rev. D15, 480 (1977); for other references see H. Terazawa and M. Yasue, Nonlin. Phenom. Complex Syst. 19, 1 (2016); J. Mod. Phys. 5, 205 (2014).

[5] D.B. Kaplan and H. Georgi, Phys. Lett. 136B, 183 (1984).

[6] K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B719, 165 (2005); hep/ph 0412089.

[7] G. Panico and A. Wulzer, Lect. Notes Phys. 913, 1 (2016).

[8] R. Contino, T. Kramer, M. Son and R. Sundrum, J. High Energy Physics 05 (2007) 074.

[9] B. Penning, arXiv: 1712.01391. We also thank Mike Cavedon for interesting informations about this subject.

[10] F.M. Renard, arXiv: 1712.05352.

[11] F.M. Renard, arXiv: 1801.10369.

[12] G.J. Gounaris and F.M. Renard, arXiv: 1611.02426.

[13] M. Bauer, M. Carena and A. Carmona, arXiv: 1801.00363.

[14] F.M. Renard, arXiv: 1803.10466, 1805.06379, 1807.00621, 1807.08938.

[15] F.M. Renard, arXiv: 1708.01111.

[16] J.M. Cornwall, D.N. Leivin and G. Tiktopoulos, Phys. Rev. D10 (1974) 1145; D11 (1975) 972E; C.E. Vayonakis, Lett. Nuovo Cimento 17 (1976) 383; B.W. Lee, C. Quigg and H. Thacker, Phys. Rev. D16 (1977) 1519; M.S. Chanowitz and M.K. Gaillard, Nucl. Phys. B261 (1985) 379; M.S. Chanowitz, Ann. Rev. Nucl. Part. Sci. 38 (1988) 323; G.J. Gounaris, R. Koegerler and H. Neufeld, Phys. Rev. D34 (1986) 3257.

[17] Y. Alexahin et al, arXiv: 1307.6129.

[18] Z. Parsa C98-06-22, Cline et al, arXiv: [hep-ph] 9609002, Norum et al, arXiv: [hep-ph] 9604002.

[19] E. Alvarez and M. Estevez, arXiv: 1701.04427 and their refs. (20,21).

[20] G. Moortgat-Pick et al, Eur. Phys. J. C75, 371 (2015), arXiv: 1504.01726.
Figure 1: Shapes of $\sigma(\mu^+\mu^- \to b\bar{b})$ without normalization at $s = m_H^2$ and at $s = m_Z^2$ (up); with normalization at $s = m_H^2$ and at $s = m_Z^2$ (down).