CSM analyses of $t\bar{t}H, t\bar{t}Z, t\bar{b}W^-$ production in gluon-gluon and photon-photon collisions.

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

Abstract
We extend our previous analysis of $t\bar{t}H, t\bar{t}Z, t\bar{b}W$ production in $e^+e^-$ collisions within the CSM (Composite Standard Model) concept of Higgs boson and top quark compositeness to the case of gluon-gluon and photon-photon collisions. We show that remarkable differences may indeed appear between the effects generated by CSM conserving and by CSM violating sets of form factors.

PACS numbers: 12.15.-y, 12.60.-i, 14.80.-j; Composite models
1 INTRODUCTION

In view of the search of signals of Higgs and/or top quark compositeness we have recently considered the $e^+e^- \rightarrow t\bar{t}H, t\bar{t}Z, t\bar{b}W^-$ processes [1]. We made this analysis within a concept that we called Composite Standard Model (CSM) which assumes that compositeness preserves the main SM properties at low energy, for example the gauge structure and the Goldstone equivalence. We do not base our analyses on a specific model, we only assume that such a model may exist using the various proposals of Higgs boson and the top quark compositeness (based on substructures or on additional sets of states), see ref.[2, 3, 4, 5, 6]. In this spirit, compositeness may reveal itself through the presence of form factors which are close to one at low energy and do not modify the SM properties. But as the energy increases the essential CSM property is the preservation of the typical SM combinations ensuring a good high energy behaviour [7]. This leads to specific relations (that we called CSM constraints) between several form factors in the Higgs and top quark sectors.

For the $e^+e^- \rightarrow t\bar{t}H, t\bar{t}Z, t\bar{b}W^-$ processes [1] we gave illustrations showing remarkable differences between the effects of CSM conserving and of CSM violating form factors. The most spectacular case concerns the W production process in which the above mentioned combinations (ensuring the cancellations of unitarity violating contributions) are the most striking.

In this paper we extend this type of analysis to $t\bar{t}H, t\bar{t}Z, t\bar{b}W^-$ production in gluon-gluon and photon-photon collisions. We make illustrations for each process. We show how these processes may give complementary results to those of the $e^+e^-$ set in particular for distinguishing effects from form factors satisfying or violating CSM constraints. In these illustrations we only show the ratios of new cross sections over SM ones. We do not discuss the quantitative observability of the modifications because we do not have yet a precise model to test.

Contents: In Sect.2 we present the SM diagrammatic contents of each process. In Sect.3 we recall the choices of CSM conserving and CSM violating form factors already used in the previous $e^+e^-$ case. In Sect.4 we show and discuss the corresponding illustrations for gluon-gluon and photon-photon collisions. Conclusions are given in Sect.5.

2 TREATMENT OF THE $gg, \gamma\gamma \rightarrow t\bar{t}H, t\bar{t}Z, t\bar{b}W^-$ PROCESSES

The corresponding diagrams are drawn in Fig.1 for gluon-gluon collisions and in Fig.2 for photon-photon.

$t\bar{t}H$ production

This proceeds through two types of diagrams. The first one corresponds to $t\bar{t}$ produc-
tion by top exchange and $H$ emission from the final lines or from the intermediate top. Symmetrization with respect to the two initial beams is applied. The second type only occurs in the gluon-gluon case where the $t\bar{t}$ pair is produced by an intermediate gluon and $H$ emission appears from the $t$ or from the $\bar{t}$ line.

The couplings that can be affected by Higgs and top compositeness are $gtt$, $\gamma tt$ and $H tt$.

A specific effective form factor may be attributed to each of them as discussed in the next section, with or without CSM constraint. In the illustrations we will introduce $F_{tR}(s)$, $F_{tL}(s)$ (for simplicity the same for gluon and photon) and $F_{Htt}(s)$ form factors.

$t\bar{t}Z$ production

The diagrams are exactly of the same type as in the above $t\bar{t}H$ case. The $H tt$ coupling is now replaced by the left and right $Z tt$ couplings with corresponding $F_{tR}^{Z}(s)$, $F_{tL}^{Z}(s)$ form factors (again for simplicity chosen similar to $gtt$ and $\gamma tt$ ones).

$t\bar{b}W^-$ production

There is now an essential difference between gluon-gluon and photon-photon collisions. In the gluon-gluon case the set of diagrams is again the same as in the $t\bar{t}H$, $t\bar{t}Z$ processes, with now only the pure left-handed $W tb$ coupling.

In the photon-photon case one has 4 additional diagrams (with the necessary symmetrization) involving $W$ exchange and the 3-leg or 4-leg photon-$W$ couplings. In the CSM spirit with the $W_L - G_L$ equivalence, Higgs compositeness suggests the presence of form factors in these couplings.

3 Test form factors

We will make illustrations in the same way as in ref.[1] by affecting to each top and Higgs coupling form factors satisfying or violating the CSM constraints.

We use the same "test" expression

$$ F(s) = \frac{(m_Z + m_H)^2 + M^2}{s + M^2} $$

with the new physics scale $M$ taken for example with the value of 4 TeV chosen for making the illustrations clearer.

CSM conserving cases will be denoted as "CSM..." and CSM violating cases as "CSMv...". In addition, for $W_L^-$ production, we will consider special CSM conserving cases, denoted
"CSMG...", which assume that (apart from $m^2/s$ suppressed contributions) the amplitudes remain equivalent to those for $G^-$ production even with the effects of CSM conserving form factors.

Precisely in Fig.3-9 we find:

— CSMtLR and CSMGtLR referring to the presence of $t_L$ and $t_R$ left and right top form factors put in any gauge (gluon, photon, Z and W) coupling, and simultaneously Higgs and Goldstone -top coupling form factor satisfying the CSM relation recalled in eq.(1) of [1].

— CSMtR and CSMGtR for pure $t_R$ compositeness, $F_{tR}(s) \equiv F(s)$ while $F_{tL}(s) = 1$, and an effective top mass $m_t(s) = m_t F(s)$ controlling all Higgs sector couplings and the top kinematical contributions, see [8].

— CSMvt, violating CSM constraints because of different form factors; $F_{tR}(s)$ with $M = 8$ TeV differs from $F_{tL}(s)$ with $M = 12$ TeV (also present with the $Wtb$ coupling) and from $F_{VW^+_L W^-_L}(s) = F_{Ht}(s) = F_{Gtt}(s) \equiv F(s)$ with $M = 4$ TeV, the top mass being fixed at its on-shell value.

— CSMvH for the case of no top form factor and only one $F(s)$ form factor affecting the $VW^+_L W^-_L$ vertices, the top mass being also fixed at its on-shell value.

We recall that the aim of these choices is only to illustrate the sensitivity of the observables to compositeness effects. The compositeness structure may be much richer (excited states, resonances,..., see for example [9]), which would require a more involved effective adequate form factor.

4 DISCUSSION OF RESULTS

In fig.3-9 illustrations are given for the ratios of cross sections (in the center of the 3-body final state) with form factor effects over pure SM cross sections.

$t\bar{t}H$

The energy dependence shapes are similar in gg (Fig.3a) and in $\gamma\gamma$ collisions (Fig.3b) (of course when assuming that the $gtt$ and the $\gamma tt$ form factors are similar).

As compared to the $e^+e^-$ case, [1] one observes a stronger decrease with energy due to the presence of additionnal top form factors in gluon or photon couplings.
We can then also compare the different CSM conserving or CSM violating cases. The ordering of the size of the effects, CSMvH/CSMtR/CSMvt/CSMtlR from the less affected case to the strongest one, corresponds to the simultaneous presence of different form factors.

\( \bar{t}tZ \)

We now illustrate separately the \( Z_L \) (Fig.4a,b), the \( Z_T \) (Fig.5a,b) and the unpolarized \( Z \) case (Fig.6a,b), with (a) for gluon-gluon and (b) for \( \gamma\gamma \) process.

The various shapes are due to different left, right top couplings form factors and to the possible use of an effective top mass. Note that in the gluon-gluon process CSMvH produces no effect as no 3-boson coupling is involved in this process.

For \( Z_L \) the ordering is now CSMvH/CSMvt/CSMtR/CSMtlR because of the possible presence of a specific \( Z_L = G \) form factor and the additional decrease due to an effective top mass in the CSMtR case.

For \( Z_T \) without these properties the ordering is CSMvH/CSMtR/CSMvt/CSMtlR.

The unpolarized case corresponds clearly to the addition of the \( Z_L \) and \( Z_T \) contributions with their respective weights.

\( \bar{t}bW^- \)

Illustrations are given in (Fig.7a,b) for \( W_L^- \), (Fig.8a,b) for \( W_T^- \) and (Fig.9a,b) for unpolarized \( W^- \).

As in other \( W^- \) production processes, because of the presence of additional diagrams the complicated procedure of cancellation for the \( W_L^- \) component plays an important role in the resulting effects of the presence of form factors. When form factors introduce temporary differences between growing contributions this generates an increase of the \( W_L^- \) amplitude. For example the fact that the top quark may be composite and have a form factor whereas the bottom quark remains elementary without form factor creates an important lack of cancellation. The ordering is then specific of each process because on the one hand form factors lead to a decrease with the energy whereas on the other hand the lack of cancellation leads to an increase. This is why we consider for this process also the Goldstone equivalent CSMGtLR and CSMGtR sets.

The CSM assumption of \( (Z_L, W_L^-) - (G^0, G^-) \) equivalence ensures a good high energy behaviour (even with new effects) such that the presence of form factors produces immediately a decreasing effect. We will see below the difference between CSMtLR and CSMGtLR as well as between CSMtR and CSMGtR.
Note that in the gluon-gluon process, as in the $t\bar{t}Z$ case, CSMvH produces no effect as no 3-boson coupling is involved.

With our choices of form factors described in Sect. 3 one gets the following results for the ordering, the details being shown in Fig.7-9:

For $W_L^-$ one gets $\text{CSMvH/CSMtLR/CSMtR/CSMGtR/CSMGtLR}$ in gluon-gluon and $\text{CSMvH/CSMvt/CSMGtR/CSMtR/CSMtLR/CSMGtLR}$ in $\gamma\gamma$,

for $W_T^-$, $\text{CSMvH/CSMtR/CSMvt/CSMtLR}$ in gluon-gluon and $\text{CSMvH/CSMtR/CSMtLR/CSMvt}$ in $\gamma\gamma$,

and in the unpolarized case, $\text{CSMvH/CSMtLR/CSMtR/CSMvt/CSMGtR/CSMGtLR}$ in gluon-gluon and $\text{CSMvH/CSMtvt/CSMtR/CSMGtR/CSMGtLR/CSMtLR}$ in $\gamma\gamma$.

5 CONCLUSIONS

In this paper we have shown how the processes of $t\bar{t}H, t\bar{t}Z, t\bar{b}W^-$ production in gluon-gluon and photon-photon collisions may indicate what type of Higgs and top quark compositeness would be at the origin of a possible departure with respect to SM predictions. We have concentrated our analysis on the shapes of the energy dependence of the cross sections possibly modified by specific Higgs and top quark form factors satisfying or violating the CSM constraints. Peculiar modifications appear in each process and especially in the case of $Z_L$ and $W_L$ production due to the perturbations of the specific gauge cancellations generated by such form factors. In this study as well as in the previous ones for other processes our purpose was to show what are the opportunities of testing CSM constraints. In order to go further a specific CSM model should be available in order to make precise predictions for all details of the corresponding cross sections. They could then be compared to expected possibilities at LHC and future colliders, see [10] and [11].
References

[1] F.M. Renard, arXiv: 1704.07985.

[2] 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).

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

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

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

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

[7] F.M. Renard, arXiv: 1701.04571.

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

[9] M. Hoffmann, A. Kaminska, R. Nicolaidou and S. Paganis, Eur. Phys. J. C74, 3181 (2014); arXiv: 1407.8000.

[10] F. Richard, arXiv: 1703.05046.

[11] V.I. Telnov, Nucl.Part.Phys.Proc. 273(2016)219.
Figure 1: Diagrams for gluon-gluon collisions
Figure 2: Diagrams for photon-photon collisions
Figure 3: Ratios for $t\bar{t}H$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.
Figure 4: Ratios for $t\bar{t}Z_L$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.
Figure 5: Ratios for $t\bar{t}Z_T$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.
Figure 6: Ratios for unpolarized $t\bar{t}Z$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.
Figure 7: Ratios for $t\bar{b}W_L$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.
Figure 8: Ratios for $t\bar{b}W_T$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.
Figure 9: Ratios for unpolarized $t\bar{b}W^-$ production, (a) in gluon-gluon collisions, (b) in photon-photon collisions.