CSM tests in $gb \rightarrow \gamma b, Hb, Zb, W^-t$ processes.

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Abstract

We show that the processes of $\gamma b, Hb, Zb, W^-t$ production in gluon+bottom collision can give interesting informations about possible Higgs boson, top and bottom quark compositeness. We make illustrations of the ratios of new cross sections over standard ones. Specific energy dependences appear for each assumption about $b_L, b_R, t_L, t_R$ compositeness and CSM constraints concerning the Higgs sector.

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1 INTRODUCTION

We have recently looked at the effects of Higgs boson, top and bottom quark compositeness in several processes occurring in $e^+e^-$, photon-photon and hadronic collisions. The motivation was essentially to test the concept of Compositeness Standard Model (CSM), see ref.[1, 2].

This concept consists in assuming that the SM can be constructed in a simple way, for example starting from substructures like in [2], and that its main properties are preserved at low energies. The first CSM effects could be the appearance of form factors (but no anomalous coupling) and of effective s-dependent masses. The reproduction of the SM structures implies the preservation of the Goldstone equivalence with the longitudinal gauge boson amplitudes (we will often denote this property as CSMG).

General compositeness of the top quark and of the Higgs boson has been studied in [4, 5, 6, 7]. The observability of top compositeness has also been discussed in [8]. In our studies we wanted to see how one could immediately differentiate compositeness effects corresponding to CSM conservation from those corresponding to CSM violation. A strategy starting from the detection of form factor effects in simple processes and then pursuing with more involved processes producing gauge and Higgs bosons, top and bottom quarks, has been proposed in [1, 2].

In this short paper we just want to add a few more tests realizable with the $gb \rightarrow \gamma b, Hb, Zb, W^\pm t$ processes. This is done in Section 2 where we give detailed illustrations for each process and each compositeness assumption. A summary is given in Section 3.

2 $gb \rightarrow Xf$ Processes

We consider the four processes corresponding to $Xf \equiv \gamma b, Hb, Zb, W^\pm t$. At Born level they occur through the s-channel and u-channel diagrams drawn in Fig.1. With compositeness the point-like couplings may be replaced by effective s-dependent quantities that we represent by test form factors of the type:

$$F(s) = \frac{s_0 + M^2}{s + M^2}$$

(1)

with the new physics scale $M$ taken for example in the few TeV range. We will compute the effects of such form factors on the cross sections of the various processes and show them by drawing the ratios of the new cross sections over the SM ones. We will illustrate their energy dependence (for an arbitrary scattering angle of 30 degrees) and when they are important, their angular dependence which is essentially generated by the u-channel exchange term.

In these illustrations we will use the following notations, tL, tR, tLR for pure $t_L$ or $t_R$ or
both form factors; tLm, tRm, tLRm for form factors together with effective $m_t(s)$ mass; and similarly bL, bR, bLRm, bLm, bRM, BLRM for bottom compositeness and tLbL, tRbR, tLRbLR, tLmbLm, tRMbRm, tLRmbLRm for both top and bottom compositeness. As discussed for example in ref. [7] there is the possibility of mixing of elementary states with composite ones. We will illustrate the full compositeness cases. Partial compositeness should give intermediate effects obtained by factorizing the mixing angles.

$gb \rightarrow \gamma b$

After $e^+e^- \rightarrow \bar{b}b$ this process may be also interesting for providing direct simple tests of bottom compositeness. It will allow to test the presence of $gbb$ and $\gamma bb$ form factors. If these form factors arise from bottom substructure they could depend on the colour and on the electric charge of the constituents, such that $gbb$ and $\gamma bb$ form factors may be different.

In Fig.2 we illustrate the effects of the choice of eq. (1) for pure $b_L$ compositeness or pure $b_R$ compositeness or for both. For simplicity we take the same form factors for $gbb$ and $\gamma bb$ couplings. The angular distribution of the ratios is constant in this case. With only transverse real photons there is no visible bottom mass effect.

$gb \rightarrow Hb$

This process makes one more step as it involves in addition to the $gbb$ form factor, a sensitivity to the bottom mass appearing in the $Hbb$ coupling. As introduced in [9] compositeness may generate an effective s-dependent bottom mass. This $Hbb$ coupling appears in the left and in the right terms of the s- and u- channel diagrams which combine and partially cancel in the SM case. So when one introduces different $b_L$ or $b_R$ modifications this affects the cancellations and leads to an increase of the cross section as one can see with the ratios drawn in Fig.3(up). These effects are strongly angular dependent essentially due to the u-channel contributions and if a deviation from SM is observed the study of its angular distribution should be instructive; see Fig.3(down). We can observe the separate effects of gluon form factors for $b_L$, for $b_R$ or for both and similarly the additional effect of an effective mass $m_b(s) = m_b F(s)$. One can also check that the SM cancellations are recovered when both $b_L$ and $b_R$ are affected by the same form factor such that, in this case, the ratios decrease strongly with the energy.

$gb \rightarrow Zb$

We first treat separately the transverse $Z_T$ and the longitudinal $Z_L$ production as illustrated in Fig.4. A priori the $Z_Tb$ case should be rather similar to the above $\gamma b$ one. This is true apart from the fact that the $Z_Rbb$ coupling is smaller than the $Z_Lbb$ one (whereas they were equal in the photon case) such that the $b_L$ and $b_R$ curves now differ,
see Fig.4(up).
The $Z_L$ case is however much more informative. There appears now a big sensitivity to
the bottom mass which arises after the typical SM cancellation of the longitudinal ampli-
tudes leading to an $m_b$ term in agreement with the Goldstone equivalence which predicts,
up to $m_Z^2/s$ terms, that the $gb \rightarrow Z_L b$ amplitude should be equal to the $gb \rightarrow G^0 b$ one.
In Fig.4(middle) one can see the separate sensitivity of the cross section ratios to the $b_{L,R}$
form factors and to the $m_b(s)$ effective mass.
In Fig.4(down) we show what would be the influence of the form factors and of the ef-
effective bottom mass on $Z_L$ production if the substructure effects respect the Goldstone
equivalence as required by the CSMG assumption.
All these informations would be very interesting, however the rate of $Z_L$ production con-
trolled by $m_b$ (less than 1 percent of the total $Z$ rate at low energy and decreasing strongly
with the energy) will probably not allow their observability. Only the unpolarized case,
with effects similar to the $Z_T$ ones shown in Fig.4(up) may be observable.
Hopefully the $W$ production process, that we will now study, should be more adequate in
this respect due to the larger top mass.

\[ gb \rightarrow W^- t \]

For this process we will make 3 types of studies corresponding to the effects of top or
of bottom compositeness or of both. In each case we will also separate the effect of pure
Left compositeness, of pure Right compositeness and of both.
We will look at the effects on $W_T^-$, on $W_L^-$ and on the unpolarized $W^-$ production. As
expected the $W_T^-$ ratios are not sensitive to the top and bottom effective masses and
allow to only test the presence of the form factors in the couplings, essentially the left-
handed ones which appear with the pure Left W couplings. On the opposite the $W_L^-$
ratios are very sensitive to the effective masses (essentially the top one) because they
control the resulting quantities after the cancellation of the usual increasing (unitarity
violating) contributions to the longitudinal amplitudes. Because of these properties the
$W_L^-$ contributions are now important and lead also to modifications of the unpolarized
$W^-$ cross sections as we can see in the following figures.

Effects of pure t compositeness

In Fig.5(up, middle, down) one sees the effects of $t_{L,R}$ compositeness on the $W_T^-$, $W_L^-$
and $G^-$ ratios. One can also see the effects of an effective s-dependent top mass on the
$W_L^-$ and $G^-$ ratios.
In Fig.6, for energy and Fig.7 for angular distributions, we show the resulting effects in
the unpolarized $W^-$ ratios, with $W_T^-$ and pure $W_L^-$ (up), or with $W_T^-$ and $G^-$ (down) as
suggested by the CSMG equivalence.
The comparison of the middle and down figures shows how the CSMG hypothesis can be
tested from its specific behaviours, with larger energy decreases than in the CSM violating
cases.
Effects of pure b compositeness

The same illustrations are made in Fig.8,9,10 with the effects of $b_{L,R}$ compositeness. As expected only the effects of $b_L$ compositeness are significant and essentially no effect of an effective bottom mass can be observed.

Effects of both t and b compositeness

Finally in Fig.11,12,13 we show the resulting modifications appearing when both $t_{L,R}$ and $b_{L,R}$ compositeness are introduced. The comparison with the two above cases (pure $t$ and pure $b$) shows different behaviours. Globally the ratios are weaker than the ones due to pure $t$ or pure $b$ compositeness because of a better factorization of the form factor effects preserving the SM combinations.

3 Summary

We have computed the cross sections of the $gb \rightarrow \gamma b, Hb, Zb, W^- t$ processes with point-like couplings of $\gamma, H, Z, W^-$ to top or bottom quarks modified by the introduction of specific form factors suggested by $t_L, t_R, b_L, b_R$ compositeness.

We also looked at the possible effects of $s$-dependent effective top or bottom masses $m_f(s)$. We treated separately the transverse and the longitudinal gauge boson production. In the longitudinal case we have compared the crude results due to the introduction of form factors in the gauge boson couplings to those suggested by the CSMG assumption which assumes an effective equivalence with the Goldstone bosons $G^{0,-}$ amplitudes including now form factors in the Goldstone couplings.

We have given illustrations for the ratios of modified cross sections over standard ones. Specific modifications of the energy and angular dependences of these ratios are produced depending on the location of the form factors. So interesting informations about compositeness and the CSM concept should be obtained from the measurements of these ratios. They should confirm the corresponding results that would be obtained from other processes involving Higgs boson, top and bottom quarks in $e^+e^-$, in photon-photon and in hadronic collisions,[1] [2].

The observability of such processes can be for example found in [10] [11] [12] for $e^+e^-$, [13] [14] for proton-proton and [15] for photon-photon.

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Figure 1: Born diagrams for $gb \rightarrow Xf$; $Xf \equiv Hb, Zb, W^\pm t$.

Figure 2: Ratios for $gb \rightarrow \gamma b$ with $b_L, b_R$ compositeness or both.
Figure 3: Ratios for $gb \rightarrow Hb$, energy dependence (up), angular dependence at 10 TeV (down), with $b_L, b_R$ compositeness or both.
Figure 4: Ratios for $gb \to Zb$, with $b_L$, $b_R$ compositeness or both.
Figure 5: Ratios for $gb \rightarrow W^- t$, with $t_L$, $t_R$ compositeness or both.
Figure 6: Ratios for $gb \rightarrow W-t$, from $W_T + W_L$ (up), from $W_T + G$ (down), with $t_L, t_R$ compositeness or both.
Figure 7: Angular distributions at 10 TeV of ratios for $gb \rightarrow W^{-}t$, from $W_{T} + W_{L}$ (up), from $W_{T} + G$ (down), with $t_{L}, t_{R}$ compositeness or both.
Figure 8: Ratios for $gb \rightarrow W^- t$, with $b_L$, $b_R$ compositeness or both.
Figure 9: Ratios for $gb \to W^{-t}$, from $W_T + W_L$ (up), from $W_T + G$ (down), with $b_L$, $b_R$ compositeness or both.
Figure 10: Angular distributions at 10 TeV of ratios for $gb \rightarrow W^- t$, from $W_T + W_L$ (up), from $W_T + G$ (down), with $b_L$, $b_R$ compositeness or both.
Figure 11: Ratios for $gb \rightarrow W^- t$, with $t_L, b_L$ or $t_R, b_R$ compositeness or both.
Figure 12: Ratios for $gb \to W^- t$, from $W_T + W_L$ (up), from $W_T + G$ (down), with $t_L, b_L$ or $t_R, b_R$ compositeness or both.
Figure 13: Angular distribution at 10 TeV of ratios for $gb \rightarrow W^- t$, from $W_T + W_L$ (up), from $W_T + G$ (down), with $t_L, b_L$ or $t_R, b_R$ compositeness or both.