W polarization in $e^+e^-$, gluon-gluon and $\gamma\gamma \rightarrow Wt\bar{b}$ for testing the top quark mass structure and the presence of final interactions.

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 analyze the $Wt\bar{b}$ production processes and especially the rate of longitudinal $W$ polarization sensitive to a possible top quark mass scale dependence and to the presence of strong final state $Wt$ interactions for example generated by a dark matter environment. We give illustrations for the three processes $e^+e^-$, gluon-gluon and $\gamma\gamma \rightarrow Wt\bar{b}$. 
1 INTRODUCTION

In previous papers we have made an analysis of the $Z$ longitudinal polarization in the three processes $e^+e^-$, gluon-gluon and $\gamma\gamma \rightarrow Zt\bar{t}$, \cite{1,2}. We have checked that, after the well-known gauge cancellation, the rate of longitudinal $Z$ polarization, equivalent to the rate of $G^0t\bar{t}$ production \cite{3}, is directly sensitive to any modification of the top quark mass. We have then shown that a scale dependent top quark mass mentioned in \cite{4,5}, for example generated by substructures, \cite{7,8,9,10,11}, may immediately lead to observable effects on this rate. On another hand, new interactions between heavy particles, for example generated by a dark matter (DM) environment \cite{12,13}, may lead to final state interactions between $Z$ and top quarks and then also to strong modifications of the $Z_L$ rate.

We now want to see if similar modifications of the SM predictions could be generated in the charged sector. We will also first check, in the three considered processes, the equivalence at high energies of $W^-t\bar{b}$ production with the $G^-t\bar{b}$ one in the pure SM case. We will then illustrate the modifications of the $W^-_L$ rates which appear when we replace $m_t$ by a scale dependent $m_t(s)$. The presence of the small bottom quark mass is negligible. Using the same test functions as in the $Ztt$ cases we will finally discuss the effects of final state interactions between $W$ and top quark.

The comparison with the previous $Ztt$ cases allows us to conclude that the $W^-t\bar{b}$ processes may be almost as interesting as the $Ztt$ ones and that their analysis may be complementary and contribute to the determination of the basic structure of the underlying dynamics responsible for such possible SM modifications.

Contents: Section 2 contains three subsections respectively devoted to the $e^+e^-$, gluon-gluon and $\gamma\gamma \rightarrow Zt\bar{t}$ processes, presents the basic SM diagrams and illustrates the locations of the considered modifications corresponding to the chosen explicit expressions for the new dynamics. Conclusions are summarized in Section 3.

2 ANALYSES OF $Wt\bar{b}$ PRODUCTION PROCESSES

2.1 $e^+e^- \rightarrow Wt\bar{b}$

The Born SM diagrams are given in Fig.1. It is well-known that the $E_W/m_W$ behaviour of the components of the $W_L$ amplitude cancel when adding all diagrams, leaving, up to $m_W^2/E_W^2$ corrections, a contribution proportional to $m_t$ (and a negligible $m_b$) equivalent to the Goldstone production $G^-t\bar{b}$ amplitude with the left and right couplings

$$ c_L = \frac{e m_t}{\sqrt{2} s_W m_W} \quad c_R = -\frac{e m_b}{\sqrt{2} s_W m_W}. \quad (1) $$

This equivalence is shown in Fig. 2a,b for $\sqrt{s} = 5$ TeV and $\theta_W = \frac{\pi}{6}$ and $\frac{\pi}{2}$. The computation of $G^-t\bar{b}$ production is done with similar diagrams as in Fig.1 replacing the external $W^-$ line by a $G^-$ one.
This is the starting point of our study of the $m_t$ scale dependence. If it occurs like in the neutral $Ztt$ case, an $m_t(s)$ behaviour

$$m_t(s) = m_t\left(\frac{m_{th}^2 + m_0^2}{s + m_0^2}\right)$$

would immediately reflect in the $W_L$ rate

$$R_L = \frac{\sigma(W_Ltb)}{\sigma(W_Ttb) + \sigma(W_Ltb)}$$

as shown in Fig.3a,b with $m_0 = 2, 4$ TeV, curves $m2$ and $m4$.

The result is somewhat weaker than in the $e^+e^- \rightarrow Zt\bar{t}$ case, essentially at low angles because of the presence of $W_T$ emission from the $e^\pm$ lines which have no Goldstone counterpart.

As in the previous cases we have also looked at a possible final state interaction between heavy particles (here only $Wt$), for example generated by a DM environment, modifying the $W_L\bar{t}b$ amplitudes by the $[1 + C(s_{Wt})]$ "test factor" with

$$C(x) = 1 + \frac{m_t^2}{m_0^2} \ln\left(\frac{-x}{(m_W + m_t)^2}\right),$$

for the subenergy $x = s_{Wt}$ and $m_0 = 0.5$ TeV, like in [13] and in the $Ztt$ case.

We can appreciate in Fig.4a,b the similarity of the effects (although relatively smaller) as compared to those of the $e^+e^- \rightarrow Zt\bar{t}$ case (with only the $Wt$ final interaction, curve $DMW$, or by adding the $Gt \rightarrow Wt$, curve $DMWG$).

Experimental possibilities for such processes can be found in [14].

### 2.2 $gg \rightarrow Wt\bar{b}$

We do the same analysis for the gluon-gluon process whose SM diagrams are given in Fig.5.

The difference with the $e^+e^-$ case is essentially the absence of direct W emission from the initial state.

The corresponding results are shown in Fig.6a,b; 7a,b and 8a,b.

Apart from a somewhat different angular dependence the qualitative effects of an $m_t$ scale dependence or of final state interactions are rather similar to the ones in $Ztt$.

The LHC possibilities can be found in [15, 16].

### 2.3 $\gamma\gamma \rightarrow Wt\bar{b}$

This process may be particularly interesting because of the additional different type of diagrams with self gauge boson couplings as shown in Fig.9.
The results are shown in Fig. 10a,b; 11a,b and 12a,b. The shapes of the distributions are also slightly different from the gluon-gluon ones and could provide independent tests of the considered new physics effects. The possibilities with photon-photon collisions are reviewed in [17].

3 CONCLUSION

In this paper we have extended our previous study of the possible effects of a scale dependent top quark mass $m_t(s)$ and of the presence of final state interactions between heavy particles. These effects may originate from the top quark substructure and/or a special interaction with a dark matter environment. For this type of search we had previously considered $Z$ polarization in $Z \bar{t}t$ production processes. We have now enlarged our study to $Wt \bar{b}$ processes in order to allow a comparison of the charged and of the neutral sectors. The rates of $Z_L$ and of $W_L$ production are indeed directly sensitive to these new dynamical features. In the $Wt \bar{b}$ case the absence of $m_b$ effects and the restriction of the new final interactions to the ($Wt$) couple leads to relatively smaller but nevertheless still important observable effects with typical shapes. We have made illustrations by using arbitrary test functions not originating from a well-defined model. Their purpose is just to show that the measurement of the longitudinal polarization rates may be very instructive for determining the nature of the underlying dynamics responsible for these effects.

To summarized them, a decrease of $m_t(s)$ leads immediately to a corresponding decrease of the $Z_L$ and $W_L$ rates. On another hand a final ($Zt$) or ($Wt$) interaction (for example generated by dark matter environment specific to heavy particles) can also directly lead to a modification of these rates. Dedicated experimental studies should then be done in order to transform our present illustrations into modifications of observable quantities.

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Figure 1: SM diagrams for $e^+e^- \rightarrow W^-t\bar{b}$ Born amplitudes.
Figure 2: $e^+e^- \rightarrow W_L \bar{t} \bar{b}$ ratio compared to the Goldstone case.
Figure 3: $e^+e^- \rightarrow W_L\bar{t}\bar{b}$ ratio for 2 cases of scale dependent top mass compared to the SM case.
Figure 4: $e^+e^- \rightarrow W_L t\bar{b}$ ratio for 2 cases of Dark Matter final state interactions.
Figure 5: SM diagrams for $gg \rightarrow W^- t\bar{b}$ Born amplitudes.
Figure 6: SM $gg \to W_L \bar{t}b$ ratio compared to the Goldstone case.
Figure 7: $gg \rightarrow W_L t\bar{b}$ ratio for 2 cases of scale dependent top mass compared to the SM case.
Figure 8: $gg \rightarrow W_L t\bar{b}$ ratio for 2 cases of Dark Matter final state interactions.
Figure 9: SM diagrams for $\gamma \gamma \rightarrow W^- t \bar{b}$ Born amplitudes. Internal wavy lines represent both virtual gauge and goldstone bosons.
Figure 10: SM $\gamma\gamma \rightarrow W_L t\bar{t}$ ratio compared to the Goldstone case.
Figure 11: $\gamma\gamma \rightarrow W_L t\bar{b}$ ratio for 2 cases of scale dependent top mass compared to the SM case.
Figure 12: $\gamma\gamma \rightarrow W_L t\bar{b}$ ratio for 2 cases of Dark Matter final state interactions.