Dark matter interaction between massive standard particles.

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Abstract

We propose further tests of the assumption that the mass of the heavy standard particles ($Z, W, t, ...$) arises from a special coupling with dark matter. We look for effects of new interactions due to dark matter exchanges between heavy particles in several $e^+e^-$ and hadronic collision processes.
1 INTRODUCTION

In a previous paper ([1]) we have supposed that heavy standard particles (for example \(Z, W, t, \ldots\)) get their mass from the dark matter (DM) environment. The connection between heavy SM particles and DM (whose status is for example reviewed in [2]) could occur through mediators (scalar, vector,..., see [2, 3]), or through a yet undefined more complex way. In our work it was described by effective couplings (for example \(Z - Z - DM\)) which may then also generate dark matter production in association with heavy particles. We have given illustrations for \(e^+e^- \rightarrow Z + X, W^+W^- + X, t \bar{t} + X\) where \(X\) represents invisible multiparticle DM.

This picture has some similarity with the hadronic case where hadrons get their mass from the strong quark binding interaction and where multiparticle production is automatically generated through the parton model description.

In the present paper we explore another consequence of our assumption of the existence of a special connection between heavy SM particles and DM. It would consist in the presence of a new interaction between heavy SM particles resulting from the exchange of this invisible set of multiparticle DM. This may be again somewhat similar to the hadronic case where strong final state interactions appear between hadrons after their production through electroweak processes.

This can appear through an involved mechanism and not simply through a mediator (for example a Higgs boson) exchange. Our aim is only to show what type of effects could appear that way and which specific relations may exist between the various processes involving heavy SM particles.

We will consider the production of pairs of heavy particles, \(t \bar{t}, ZZ, W^+W^-\) in \(e^+e^-, \gamma\gamma\) and hadronic collisions.

Without a precise model for these new DM interactions we will make illustrations using an arbitrary effective description which protects the SM prediction at low energy (see the CSM concept [4]).

A strategy for the determination of the actual interaction between heavy pairs will be proposed by comparing its effects in the various processes.

Contents: Presentation of the effective interaction in Section 2; applications to several processes in Section 3. Further developments and other possible interpretations of new interactions among heavy particles will be discussed in the conclusion.

2 EFFECTIVE DM INTERACTION

Following the assumption presented in the introduction we will consider possible DM interactions between \(t \bar{t}, ZZ, WW\) pairs. This could appear either after their standard production from light states (not submitted to DM interactions) like final state interaction in hadronic production or during their production from heavy states (the new DM
interaction occurring in the initial state, in the final state or in the $t, u$ exchange channels).

In the absence of a specific model for the description of the DM interaction we will use an effective form allowing the computation (not necessarily perturbative) of its initial, final or exchange effects.

In the simplest case with only an $s$-channel final state interaction in a 2 body production of heavy particles ($AB$) from initial light particles insensitive to DM interactions, we write the corresponding amplitude as

$$R = R_{SM}[1 + F_{AB}(s)]$$

In this first study we do not specify the helicity amplitudes of the $AB$ state. In a more involved analysis we may use separate functions for each helicity combination.

The simplest examples, shown in Fig.1, are $e^+e^- \to t\bar{t}$, $gg \to t\bar{t}$ (from which one can deduce the $\gamma\gamma \to t\bar{t}$ case by suppressing the second Born diagram and replacing the gluon coupling by the photon one), $e^+e^- \to ZZ$ and $e^+e^- \to W^+W^-$. The corresponding DM interactions in the $t\bar{t}$, $ZZ$ or $WW$ final states only appear in the $s$ channel and are described by the $F_{t\bar{t}}(s)$, $F_{ZZ}(s)$ and $F_{WW}(s)$ functions.

We then consider the richer processes $ZZ \to ZZ$ (Fig.2), $WW \to WW$ (Fig.3), $ZZ \to W^+W^-$ (Fig.4), $ZZ \to t\bar{t}$ (Fig.5) and $W^+W^- \to t\bar{t}$ (Fig.6). As we can see in the corresponding figures they involve DM interactions between heavy pairs in $s$, $t$ and $u$ channels. Precisely, for the respective processes, we write

$$ZZ \to ZZ \quad R = R_{SM}[1 + 2F_{ZZ}(s) + 2F_{t\bar{t}}(s) + 2F_{ZZ}(u)]$$

$$W^+W^- \to W^+W^- \quad R = R_{SM}[1 + 2F_{WW}(s) + 2F_{WW}(t) + 2F_{WW}(u)]$$

$$ZZ \to W^+W^- \quad R = R_{SM}[1 + F_{ZZ}(s) + F_{WW}(s) + 2F_{ZW}(t) + 2F_{ZW}(u)]$$

$$ZZ \to t\bar{t} \quad R = R_{SM}[1 + F_{t\bar{t}}(s) + 2F_{t\bar{t}}(t) + 2F_{t\bar{t}}(u)]$$

$$W^+W^- \to t\bar{t} \quad R = R_{SM}[1 + F_{WW}(s) + F_{t\bar{t}}(s) + 2F_{WL}(t) + 2F_{WL}(u)]$$

A possible simplification could arise (especially at high energy) from the structures of the diagrams of Fig.1-6

$$F_{AB}^2(x) = F_{AA}(x)F_{BB}(x)$$

so that the only unknowns are $F_{t\bar{t}}(x)$, $F_{ZZ}(x)$ and $F_{WW}(x)$ for $x = s, t, u$.

A strategy for the search and for the analysis of such DM effects could be the following one:
First the $F_{tt}(s)$ function could be determined in $e^+e^- \rightarrow t\bar{t}$, and/or in $\gamma\gamma \rightarrow t\bar{t}$ and/or in $gg \rightarrow t\bar{t}$, these different processes allowing to make consistency checks.

Separately $F_{ZZ}(s)$ could be determined in $e^+e^- \rightarrow ZZ$ and checked in the $t, u$ channels with $ZZ \rightarrow ZZ$.

One would also obtain $F_{WW}(s)$ in $e^+e^- \rightarrow W^+W^-$ and/or also in $\gamma\gamma \rightarrow W^+W^-$ and check it in the $t, u$ channels with $W^+W^- \rightarrow W^+W^-$.

Then, mixed effects, involving different heavy pairs, in $ZZ \rightarrow W^+W^-$, $ZZ \rightarrow t\bar{t}$ and $W^+W^- \rightarrow t\bar{t}$ should globally confirm the DM assumption and its characteristics obtained from the studies of the preceding simple processes.

In the next section we give simple illustrations of these possibilities using trial forms for the effective functions. We will use a simple form inspired by the one appearing at high energy from usual triangle and box diagrams ([5]) where, depending on the spin and couplings of the exchanged particles, $\log$ or $\log^2$ terms may appear. In our cases the exchange may contain the basic Higgs boson, possible excited states and more complex DM sets. For simplicity we use a single logarithmic energy dependence with a scale obtained by imposing the normalization to the SM value at threshold (this could be motivated by the CSM concept [4]).

$$F(s) = c \ln \frac{-s}{s_{th}},$$

where $c$ is for the moment an unknown strength coefficient and $s_{th}$ corresponds to the threshold for production of the pair of heavy particles. A priori one could expect that the sizes of the $F_{tt}(x)$, $F_{ZZ}(x)$ and $F_{WW}(x)$ functions would be somewhat different. They may be related to the masses, $m_t$, $m_Z$ and $m_W$, if the involved DM interaction is the one which creates these masses ([1]). In the illustrations we will use $c = m_{t,Z,W}^2/m_0^2$ with $m_0 = 0.5$ TeV. But we repeat that these choices are totally arbitrary. They are only made in order to easily do computations in the various channels and to clearly illustrate a strategy for the determination of the structure of the assumed DM interaction.

3 PRECISE APPLICATIONS

3.1 Simple processes $e^+e^- \rightarrow t\bar{t}$, $gg \rightarrow t\bar{t}$, $e^+e^- \rightarrow ZZ$, $e^+e^- \rightarrow W^+W^-$

Following Fig.1 the usual Born diagram would be corrected by a final state DM interaction between the top quarks or $ZZ$ or $W^+W^-$, according to eqs. ([1],[8]) with a function $F_{tt}(s)$, $F_{ZZ}(s)$ or $F_{WW}(s)$. In the illustration of Fig.7 the corresponding energy dependence of the cross section is shown for $\theta = \pi/3$ with $s_{th} = 4m_{t,Z,W}^2$ and $c = m_{t,Z,W}^2/m_0^2$. No
modification of the shape of the angular distribution is expected from such a final state interaction.

The $\gamma\gamma \to t\bar{t}$ case can be deduced from $gg \to t\bar{t}$ keeping only the first $gg \to t\bar{t}$ Born diagram (with its symmetrical term); with the same $F_{t\bar{t}}(s)$ one obtains similar effects.

As mentioned in the previous sections the illustrations correspond to an arbitrary choice only used for presenting a global strategy of analyzing possible DM interactions among heavy particles. In practice a fit of the experimental results would determine the presently unknown $F_{t\bar{t}}(s)$, $F_{ZZ}(s)$, $F_{WW}(s)$ functions.

\section*{3.2 \textit{ZZ} \to \textit{ZZ}}

This is a more complex process which only involves \textit{ZZ} DM interaction but which would occur simultaneously in $s$, $t$ and $u$ channels as one can see in Fig.2 with the corresponding Born diagrams (with \textit{ZZ} symmetrization). The functions $F_{ZZ}(s)$, $F_{ZZ}(t)$, $F_{ZZ}(u)$ will now appear with

$$ R = R_{SM}[1 + 2F_{ZZ}(s) + 2F_{ZZ}(t) + 2F_{ZZ}(u)] ,$$

The results are shown in Fig.8 for the energy and the (symmetrical) angular dependences.

Effects are obviously larger then in the case of simple processes when using the same functions.

\section*{3.3 \textit{WW} \to \textit{WW}}

Similarly this process will involve the \textit{WW} DM interaction in $s$, $t$ and $u$ channels as one can see in Fig.3 with the corresponding Born diagrams. The functions $F_{WW}(s)$, $F_{WW}(t)$, $F_{WW}(u)$ will also appear with

$$ R = R_{SM}[1 + 2F_{WW}(s) + 2F_{WW}(t) + 2F_{WW}(u)]$$

The results are shown in Fig.9 for the energy and the (forward peaked) angular dependences.

\section*{3.4 \textit{ZZ} \to \textit{WW}}

This is a new case whose diagrams are drawn in Fig.4 and which involves simple $F_{ZZ}(s)$, $F_{WW}(s)$ and mixed $F_{ZW}(t)$, $F_{ZW}(u)$ functions (with $x_{th} = (m_Z + m_W)^2$, $x = t, u$); using (7) we write

$$ R = R_{SM}[1 + F_{ZZ}(s) + F_{WW}(s) + 2F_{ZW}(t) + 2F_{ZW}(u)]$$

$$ \approx R_{SM}[1 + F_{ZZ}(s) + F_{WW}(s) + F_{ZZ}(t) + F_{WW}(t) + F_{ZZ}(u) + F_{WW}(u)] \quad (11)$$
The results are shown in Fig.10 for the energy and the (symmetrical) angular dependences.

### 3.5 $ZZ \to t\bar{t}$

This is another type of new case (see Fig.5) involving simple $F_{ZZ}(s)$, $F_{t\bar{t}}(s)$ and mixed $F_{Zt}(t)$, $F_{Zt}(u)$ functions (with $x_{th} = (m_Z + m_t)^2$); using (7)

$$
R = R_{SM}[1 + F_{ZZ}(s) + F_{WW}(s) + 2F_{ZW}(t) + 2F_{ZW}(u)]
\simeq R_{SM}[1 + F_{ZZ}(s) + F_{t\bar{t}}(s) + F_{ZZ}(t) + F_{tt}(t) + F_{ZZ}(u) + F_{tt}(u)]
$$

(12)

The results are shown in Fig.11 for the energy and the (symmetrical) angular dependences.

### 3.6 $W^+W^- \to t\bar{t}$

Finally we consider the similar process (see Fig.6) involving simple $F_{WW}(s)$, $F_{tt}(s)$ and mixed $F_{Wt}(t)$, $F_{Wt}(u)$ functions (with $x_{th} = (m_W + m_t)^2$), using (7)

$$
R = R_{SM}[1 + F_{WW}(s) + F_{tt}(s) + 2F_{Wt}(t) + 2F_{Wt}(u)]
\simeq R_{SM}[1 + F_{WW}(s) + F_{tt}(s) + F_{WW}(t) + F_{tt}(t) + F_{WW}(u) + F_{tt}(u)]
$$

(13)

The results are shown in Fig.12 for the energy and the (forward peaked) angular dependences.

We stop there our illustrations but obviously other processes could be considered with for example different initial gauge bosons or quarks and possibly with production of Higgs bosons.

As mentioned in the previous section and at the beginning of this section, after a first experimental analysis devoted to the simple processes and having produced fits for $F_{tt}, F_{ZZ}, F_{WW}$, the illustrations in Fig.8-12 should be replaced by new ones obtained by using these fitted functions instead of the trial ones based on eq.(8).

### 4 Conclusion

Assuming that heavy standard particles may be sensitive to additional interactions related to the DM environment we have shown how this would affect the SM predictions for
several 2 body processes. In the simplest processes where heavy particles are produced by light ones the situation would be rather similar to the case of final state interactions in hadronic production through electroweak processes.

In this spirit we have illustrated possible effects of a DM interaction in the production of pairs of heavy particles ($Z, W, t, ...$) in $e^+e^-, \gamma\gamma$ and hadronic collisions by modifying the SM amplitudes with effective forms $F_{AB}(x), x = s, t, u$.

The comparison of these various processes should be instructive about the presence and the structure of such possible departures from SM expectations. With that aim we have proposed a strategy for the required analyses of the various processes:

1) determination of the basic $F_{AB}$ functions using the simplest processes with initial light (non DM interacting) states,
2) checks of their adequacy, of their structure, in particular of their factorization rule, eq.(7), in processes with initial heavy particles.

The experimental possibilities at present and future colliders can be found for example for $e^+e^-$ in [6, 7], for photon-photon collisions in [8], and for hadronic collisions in [9, 10].

Further developments of our proposal could concern the following phenomenological and theoretical points. Precise analyses should be done at the level of the helicity amplitudes with polarization measurements. For a better accuracy in the analyses of departures due to DM interactions higher order corrections, and not only Born amplitudes, will be required. Possible applications to more complex (3 body, 4 body, ...) processes may be considered.

Obviously there are fundamental theoretical points to examine like the modelization of the DM interaction between heavy particles and the role of the Higgs boson (occurring as an internal or an external contribution) in this DM exchange.

There are also other effects which may interfere with those of the yet undefined DM interactions, for example the possibility of compositeness [11], especially top quark and Higgs boson compositeness (affecting also the longitudinal gauge bosons) [12, 13, 14, 15, 16] which may create competitive anomalous effects among heavy particles ([4, 17, 18]). For example a compositeness form factor and a DM final state interaction may be largely competitive. Detailed studies of possible ways to identify the origin of such anomalous effects and to differentiate DM from compositeness should be done.

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Figure 1: Simple processes with production of a pair of massive particles submitted to final state DM interaction; $ZZ$ and $gg$ symmetrizations are applied.
Figure 2: The process $ZZ \rightarrow ZZ$ with DM interaction in both sides of the $s$, $t$ and $u$ channels. The center loop refers to the Born diagrams drawn at the lower level; $ZZ$ symmetrization is applied.
Figure 3: The process $W^+W^- \rightarrow W^+W^-$ with DM interaction in both sides of the $s, t$ and $u$ channels. The center loop refers to the Born diagrams drawn at the lower level.
Figure 4: The process $ZZ \rightarrow W^+W^-$ with DM interaction in both sides of the $s, t$ and $u$ channels. The center loop refers to the Born diagrams drawn at the lower level; $ZZ$ symmetrization is applied.
Figure 5: The process $ZZ \rightarrow t\bar{t}$ with DM interaction in both sides of the $s, t$ and $u$ channels. The center loop refers to the Born diagrams drawn at the lower level; $ZZ$ symmetrization is applied.
Figure 6: The process $W^+W^- \to t\bar{t}$ with DM interaction in both sides of the $s, t$ and $u$ channels. The center loop refers to the Born diagrams drawn at the lower level.
Figure 7: DM effects in $e^+e^- \rightarrow t\bar{t}$, $gg \rightarrow t\bar{t}$ (upper level and $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow ZZ$ (lower level).
Figure 8: DM effect in $ZZ \rightarrow ZZ$; energy dependence in upper level and angular dependence in lower level.
Figure 9: DM effect in $W^+W^- \rightarrow W^+W^-$; energy dependence in upper level and angular dependence in lower level.
Figure 10: DM effect in $ZZ \rightarrow W^+W^-$; energy dependence in upper level and angular dependence in lower level.
Figure 11: DM effect in $ZZ \rightarrow t \bar{t}$; energy dependence in upper level and angular dependence in lower level.
Figure 12: DM effect in $W^+W^- \to t\bar{t}$; energy dependence in upper level and angular dependence in lower level.