Possible search for dark matter connected to massive standard particles in $e^+e^-$ collisions.

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Abstract

We assume that the mass of the heavy standard particles ($Z, W, t, ...$) arises from a special coupling with dark matter and that this implies a corresponding peculiar connection of these particles to the dark sector. We give examples of possible tests of this assumption in $e^+e^- \rightarrow Z + X$, $W^+W^- + X$, $t\bar{t} + X$ and we mention other possible studies.
1 INTRODUCTION

Dark matter (DM) has been discovered through its gravitational interaction with usual matter. DM particles have been and are still searched in various processes at the high energy colliders. For a recent review with many references see [1].

Many (hundreds of) models have been proposed for the structure of dark matter and its possible (necessary weak) interaction with usual matter through various types of extensions of the standard model (SM). No signal has been found yet. This may be due to the very small strength of the involved interactions or to the very heavy mass of the DM constituents.

Probably because of its invisibility DM should not have gauge (strong, weak, em) interactions with SM particles, but only some new type of interaction.

In the worst case DM may consist of a new set of particles with their own self-interactions and only gravitational interactions will appear with the SM sector.

But the role played by the mass may suggest other possibilities.

One of them consists in assuming that, both in the SM sector and in the dark sector, mass is generated by a Higgs mechanism. If this mechanism is common to the two sectors then it may generate a connection between them; for example simply through Higgs boson exchange or even through a richer set of Higgs bosons; see [2] for the "portal" concept.

Another possibility is that the mass of the SM particles is generated through special interactions with the dark sector. A naive picture consists in assuming that SM particles get their mass from an environment of DM. This may be the origin of the Higgs potential generating the SM masses but also additional interactions between SM and DM particles. We propose tests of these two possibilities with processes involving the heaviest SM particles (Z, W, top quark,...) which should be the best places for revealing a connection with DM, either a direct SM-DM connection or a connection through Higgs boson (and possibly other bosons) exchanges between SM and DM.

We are not working with a precise model for the connection to DM; we use a kind of effective coupling between heavy SM particles and invisible DM ones. For example in the case of the Z boson no gauge coupling "Z-DM-DM" would exist but only some type of mass generating coupling "Z-Z-DM" would appear. A similar assumption will be done for W and for the top quark.

In this paper we consider the $e^+e^-$ collision processes $e^+e^- \rightarrow Z + X$, $W^+W^- + X$, $t\bar{t} + X$ where X represents the invisible dark matter.

Using the mentioned effective couplings we compute the inclusive mass distributions $\frac{d\sigma}{dM_X}$ and discuss their shape reflecting the type of connection between the heavy SM particle and the invisible DM ones.

We conclude by mentioning that other processes (more difficult to analyze) may be considered for example in hadronic or in photon-photon collisions.
2 Analysis of $e^+e^- \rightarrow Z + X$

As explained in the introduction one possibility of connection to invisible matter would be through the mass generation of the $Z$ boson.

Without a specific model the description can be done with an effective $Z - Z - DM$ coupling.

With a kind of substructure picture for the dynamical generation of the mass (like in the hadronic case with quark binding) we will use a $ZZss'$ coupling with a pair of scalars $s, s'$ DM "partons" which then (like hadronic partons) automatically create the multiparticle DM final (invisible) state. The $Z$ mass may be generated according to the picture of the upper diagram in Fig.1. The corresponding DM emission will appear from the left lower level diagram.

One may then also consider (as a part of the above contribution or as an additional one) the possibility of Higgs boson production like in the SM case with the process $e^+e^- \rightarrow Z \rightarrow Z + H$ then completed by the $H \rightarrow DM$ vertex; see the right lower level diagram of Fig.1. This would correspond to the idea that the Higgs boson, and possibly heavier (excited?) $H'$, are portals to the dark sector [2].

Several previous works about this process have been done, for example in [3] for the search of possible signals of Higgs boson compositeness [4, 5, 6]. The possibilities at high energy $e^+e^-$ colliders have been reviewed in [7, 8].

We have computed the inclusive (invisible) $M_X$ mass distributions $\frac{d\sigma}{dM_X}$ associated to these different possibilities corresponding to the diagrams of Fig.1 where $M_X^2 = (p_{e^+} + p_{e^-} - p_Z)^2$.

In Fig.2 we have plotted them (as well as their total) by using arbitrary couplings and masses in order that the shapes appear clearly, with $m_{H'} = 0.7$ TeV, $\Gamma_{H'} = 0.1$ TeV and $(0.01, 0.1, 0.5$ TeV) for the $s, s'$ masses.

In the upper level we show the individual $H$, $H'$ peaks and the continuum due to the effective $ZZss'$ coupling for a parton mass of 0.01 TeV. In the lower level we show the total for the three choices of parton mass (0.01, 0.1, 0.5 TeV) with clear threshold effects.

The quantitative values have no predictive meaning, our aim is just to see what effects these various dynamical assumptions can produce.

Precise analyses should also consider backgrounds with invisible productions like $e^+e^- \rightarrow ZZ$ followed by one $Z \rightarrow \nu\bar{\nu}$ decay producing a peak at $M_X = M_Z$.

3 Analysis of $e^+e^- \rightarrow W^+W^- + X$

A similar analysis can be done for the process $e^+e^- \rightarrow W^+W^- + X$.

We had previously considered this process among others for the search of signals of $W$
compositeness, see [9]. Now we look more specifically at the hypothesis that DM is related to mass generation of the $W$ boson, with the same procedure as above for the $Z$ boson, and that this can be described with an effective coupling to an $ss'$ pair of subconstituents, $W^+W^-ss'$.

We then compute the corresponding inclusive (invisible) $M_X$ mass distributions $\frac{d\sigma}{dM_X}$ according to the diagrams of Fig.3.

Note that, at the same order, a contribution still appears through the $Z-Z-DM$ coupling.

As above we add the possibility of intermediate exchange of Higgs bosons $H$ and $H'$ connected to DM.

We make the illustrations with the same parameters as in the previous $Z$ process.

Fig.4 shows that effects similar to those observable in $e^+e^-\rightarrow Z+X$ could confirm the basic hypothesis. Note also the presence of the background $e^+e^-\rightarrow W^+W^-Z$ with $Z\rightarrow \nu\bar{\nu}$.

4 Analysis of $e^+e^-\rightarrow t\bar{t} + X$

Finally we consider the process $e^+e^-\rightarrow t\bar{t} + X$ that has also been a part of the studies, for example [10, 11, 12], of top quark compositeness [13]. Substructure models have been proposed since a long time [14].

We again assume that DM is related to mass generation of the top quark and that this can be described with an effective coupling to an $ss'$ pair of subconstituents, $ttss'$.

We then compute the corresponding inclusive (invisible) $M_X$ mass distributions $\frac{d\sigma}{dM_X}$ according to the diagrams of Fig.5.

Like in the $e^+e^-\rightarrow W^+W^-+X$ case a contribution involving the $Z-Z-DM$ coupling also appears.

Diagrams with intermediate exchange of Higgs bosons $H$ and $H'$ are also added.

The background from $e^+e^-\rightarrow t\bar{t}Z$ with $Z\rightarrow \nu\bar{\nu}$ is also present.

In Fig.6, with the same parameters as in the previous processes, we can see that it should be possible to check if the hypothesis of DM connection related to mass generation of the $Z,W$ gauge bosons also applies to the top quark.

5 Conclusion and further developments

In this paper we have assumed that invisible dark matter, in addition to gravitational interaction, may have other types of interactions with standard particles related to their mass.

This assumption suggests studies of $Z, W$ and the top quark production for revealing this property.

Using arbitrary effective couplings describing this special interaction we have computed the invisible inclusive distribution $\frac{d\sigma}{dM_X}$ for the three processes $e^+e^-\rightarrow Z+X$, $W^+W^-+$
$X$, $t\bar{t} + X$. The illustrations show how the shapes of these distributions reflect the various possibilities and the parameters controlling the effective couplings to DM. Other processes involving heavy SM particles and DM may be considered. In $e^+e^-$ collisions, see [7] for a general review, one example is $e^+e^- \rightarrow e^+e^- + ZZ$ with ZZ fusion into DM (directly or through Higgs-like bosons).

Obviously many other processes involving $Z$, $W$ and the top quark occur in hadronic collisions but require detailed and difficult phenomenological and experimental analyses, see [1] and also [15, 16].

Studies in photon-photon collisions may also be considered [17].

Other less massive SM particles could also be concerned. It is not yet experimentally established that the Higgs couplings proportional to the fermion masses. So non negligible direct couplings to dark matter may even also appear there. This may concern $b$ quark, muon and even electron. If a direct $e^+e^-$ coupling is too small (see although [18]), a muon collider, already known as a possible Higgs boson factory, could be an interesting place. One would look at the process $\mu^+\mu^- \rightarrow \gamma + DM$, involving $\mu^+\mu^- \rightarrow DM$ direct production or $\mu^+\mu^- \rightarrow H, H' \rightarrow DM$ and a photon emission from the $\mu^\pm$ line. Obviously this has to overwhelm (at least in some $M_X$ range) the background involving $Z \rightarrow \nu\bar{\nu}$.

Finally we should obviously add that quantitative predictions require the use of a precise theoretical description of DM and of its possible relation to the mass generation.

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Figure 1: Diagrams for $Z$ mass generation (upper level) and for $e^+e^- \rightarrow Z + X$ (lower level), direct continuum production (left diagram) and through $H$ and $H'$ (right diagram).
Figure 2: DM production in $e^+e^- \rightarrow Z + X$; upper level for $m_s = 0.01$ TeV: direct continuum, through H, through $H'$; lower level: total for $m_s = 0.01, 0.1, 0.5$ TeV.
Figure 3: Diagrams for $e^+e^- \rightarrow W^+ + W^- + X$; direct continuum production from $W$ and $Z$ masses; production through $H$ and $H'$ can be deduced in analogy with the $Z$ case of Fig.1.
Figure 4: DM production in $e^+e^- \rightarrow W^+ + W^- + X$; upper level for $m_s = 0.01$ TeV: direct continuum, through H, through $H'$; lower level: total for $m_s = 0.01, 0.1, 0.5$ TeV.
Figure 5: Diagrams for $e^+e^- \rightarrow t\bar{t} + X$; direct continuum production from top quark and $Z$ masses; production through $H$ and $H'$ can be deduced in analogy with the $Z$ case of Fig.1.
Figure 6: DM production in $e^+ e^- \rightarrow t + \bar{t} + X$; upper level for $m_s = 0.01$ TeV: direct continuum, through H, through H'; lower level: total for $m_s = 0.01, 0.1, 0.5$ TeV.