HIGGS IN SPACE!

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In some classes of WIMP models, the Higgs boson could be copiously produced in association with a photon from dark matter annihilations or decays in our galaxy. The resulting photon spectrum possesses a line whose energy reflects the mass of the Higgs and of the WIMP and whose intensity depends on the WIMP spin and statistics. Gamma-ray telescopes such as Fermi could provide information on the Higgs and dark matter complementary to that obtained at the LHC.

1 Introduction

The Higgs and Dark Matter will be the two most searched for particles in the next few years. The gigantic experimental effort towards the discovery of the Higgs boson is all taking place at the Large Hadron Collider (LHC). Besides, there is a fervent activity in trying to identify the nature of the Dark Matter (DM) and in contrast with the search for the Higgs boson, this effort is spread on many different fronts, using three very different approaches. First, DM will be searched for at the LHC as missing energy events. However, even if we were to detect events at the LHC with large missing energy, we would not be able to conclusively say that we have discovered dark matter. It would only mean that we have produced a particle with at least a nanosecond lifetime. We will therefore need complementary information from direct detection experiments. Here, the idea is to search for recoil energy events in underground detectors. There are tens of such competing experiments all around the earth. Another flourishing activity is to search for DM indirectly, by looking for the products of annihilation or decay of DM, like positrons, electrons, photons, neutrinos, antiprotons...

Note that all these approaches assume that DM is a Weakly Interacting Massive Particle, which is a very compelling (but not unique) possibility.

In contrast with DM, the Higgs is being searched solely at colliders, although the LHC and Tevatron are not the only places in the universe where the Higgs could be produced today. Indeed, it may be copiously produced in our galaxy in dark matter annihilations or decays. Nevertheless, being unstable, the only way to probe it outside of colliders is if the Higgs is being produced in association with a stable particle, which can be detected, such as a photon[a]. We are therefore interested in processes depicted in Fig.1. The reason why this is interesting is that DM

[a] Another indirect way to probe the Higgs using cosmological observations could be to use gravitons rather than photons. Indeed, in the early universe, the Higgs could have produced gravitational waves if the electroweak phase transition was first-order [1]. The corresponding relic background of gravity waves would encode information about the higgs potential. This is an interesting point since we cannot hope to probe the nature of the electroweak phase transition at the LHC.

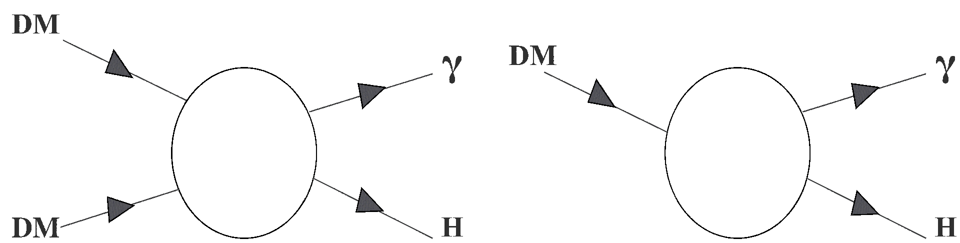

Figure 1: Higgs production in association with a photon from DM annihilation or DM decay.

being non-relativistic today, the photon is monochromatic and its energy gives us information about the higgs and DM masses:

$$E_\gamma^{anni} = M\left(1-\frac{M_h^2}{4M^2}\right) \quad , \quad E_\gamma^{decay} = \frac{M}{2}\left(1-\frac{M_h^2}{M^2}\right) \tag{1}$$

If the WIMP hypothesis is correct and if DM is connected to the dynamics of EW symmetry breaking, it is natural to expect the WIMP to have couplings which favor the most massive states of the Standard Model. Here, we explore the possibility that the WIMP has important couplings to the top quark, through which it can couple at the loop level both to photons and to Higgs bosons as shown in Fig.2.

2 A Top quark– Dark Matter connection

We illustrate this on a very simple toy model. More details can be found in [2], on which this report is based. We take the WIMP to be a Dirac fermion ν which is a singlet under the SM gauge interactions. It is charged under a (spontaneously broken) $U(1)'$ gauge symmetry, the massive gauge boson of which acts as a portal to the SM by coupling to the top quark. The effective Lagrangian contains,

$$\begin{aligned}\mathcal{L} \;&=\; \mathcal{L}_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + M_{Z'}^2 Z'_\mu Z'^\mu + \frac{\chi}{2}\hat{F}'_{\mu\nu}\hat{F}_Y^{\mu\nu} + g_t^{Z'}\;\bar{t}\gamma^\mu P_R Z'_\mu t \\ &\quad + i\bar{\nu}\gamma^\mu\left(\partial_\mu - i g_\nu^{Z'} P_R Z'^\mu\right)\nu + M_\nu\bar{\nu}\nu \end{aligned} \tag{2}$$

where $F'_{\mu\nu}$ ($F^Y_{\mu\nu}$) is the usual Abelian field strength for the Z' (hypercharge boson), $g_t^{Z'}$ is the Z' coupling to right-handed top quarks, and $g_\nu^{Z'}$ is the coupling to right-handed WIMPs. M_ν is the WIMP mass. One can easily include a coupling to the left-handed top (and bottom). Our choice to ignore such a coupling fits well with typical Randall–Sundrum (RS) models [3], balancing the need for a large top Yukawa interaction with control over corrections to precision electroweak observables. The parameter χ encapsulates the strength of kinetic mixing between the Z' and SM hypercharge bosons.

We have included hypercharge-Z' kinetic mixing through the term proportional to χ. Such a term is consistent with the gauge symmetries, and even if absent in the UV, will be generated in the IR description by loops of top quarks[b]. The kinetic mixing parameter χ generates an effective coupling of SM states to the Z', and through electroweak symmetry breaking, mass mixing of the Z' with the SM Z gauge boson resulting in a coupling of ν to the SM Z boson.

[b] χ can be engineered to vanish in the UV, for example, by embedding $U(1)'$ into a larger gauge group which breaks down at scales of order $M_{Z'}$.

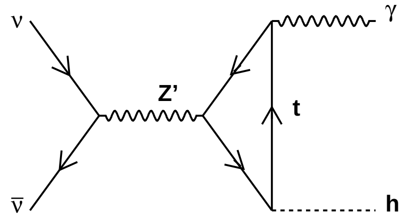

Figure 2: One-loop annihilation of Dirac neutrino Dark Matter into γh.

Our setup arises naturally in models of "partial compositeness" in which the top quark acquires its large mass (after EWSB) through large mixing with composite states in a new strong sector, as in 4d duals to Randall-Sundrum Models.

In the early universe, ν annihilates dominantly into top quark pairs. For couplings of order $\mathcal{O}(1)$, the correct dark matter abundance is reproduced from the standard thermal relic density calculation if the dark matter mass is of order the top mass, typically in the 100 GeV – 170 GeV mass range. In the limit of strong coupling, this feature is not strongly dependent on the mass of the Z'. This is a perfect mass range for searches with the Fermi LAT for gamma rays from WIMP annihilations, which we find has very good prospects for a discovery in the near future.

3 Gamma-ray lines from DM annihilations

The interesting aspect of this class of models is that gamma ray lines are particularly important because (unlike a typical model of WIMP DM, for which the photon continuum is usually much larger than the loop suppressed gamma ray lines), for $M_\nu < m_t$ (as is favored by the relic density in the strong coupling regime), the annihilation processes at the origin of the continuum photon emission are themselves a one loop process into $b\bar{b}$ (tree level annihilations into light SM particles are suppressed by the kinetic mixing parameter χ), enhancing the relative prominence of annihilation into γh and γZ. Even for $M_\nu \gtrsim m_t$, the continuum originating from annihilation into top quark pairs is rather soft, and the lines remain visible.

In Fig. 3, we show the predicted photon fluxes at the galactic center for different choices of particle physics parameters which give the correct thermal relic abundance and satisfy the constraints from direct detection. For comparison we plot the HESS observations of the same angular region[4] and the EGRET data on the unidentified source 3EG J1746-2851[5,6], corresponding instead to $\Delta\Omega = 10^{-3}$, appropriate for a detector with an angular resolution of $\sim 1°$. Fermi satellite preliminary results fill the region in energy between HESS and EGRET, providing the most powerful probe of WIMP annihilation into gamma rays to date. The detection of gamma ray lines *per se* would represent a smoking-gun evidence for dark matter, but it would not tell us which processes are responsible for the observed lines. However, additional indirect dark matter searches, direct detection experiments, and LHC observations can complement the information from gamma-ray telescopes. For example, the energies of gamma-lines probe the masses of the particles in the associated annihilation process, c.f. Eq. (1), and this could be combined with independent measurements of particle masses at colliders. This cross-check could prove extremely useful to identify a given long-lived particle produced at colliders as a significant fraction of the dark matter present in the galaxy.

The detection and identification of the $Z\gamma$ and $h\gamma$ lines could also allow one to determine the Higgs mass. Fig. 4 shows the region in the M_ν-m_h plane where these two lines are potentially separately observable. The $h\gamma$ line can be distinguished from the $Z\gamma$ line if the energy separation is at least twice the energy resolution of the experiment, which for the Fermi LAT is $\delta E \sim 10\%$

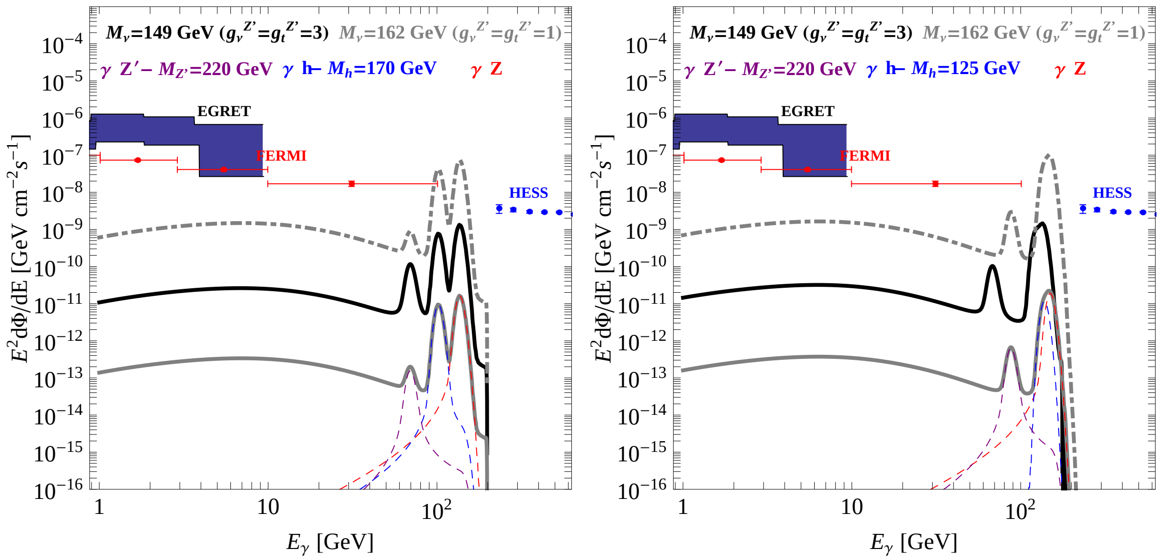

Figure 3: Photon spectra obtained for choices of mass parameters, couplings and kinetic mixing ($\eta = 10^{-3}$) that lead to the correct relic density and satisfy direct detection constraints. $\Delta\Omega = 10^{-5}$, and a NFW dark matter profile is assumed. Dot-dashed lines are for the adiabatically-contracted profile. EGRET data are from [5,6], HESS from [4] and Fermi from [8]. For a heavy Higgs (left plot), the γZ and γh lines are well separated while they merge for low higgs mass (right).

for the energies of interest [7]. The maximum Higgs mass which can be probed in $\nu\bar{\nu} \to h\gamma$ annihilation is $2M_\nu$. For $2M_\nu > M_{Z'}$, the $Z'\gamma$ line is also present. In Fig. 4 we show, for the representative cases of $M_{Z'} = 220$ GeV and 500 GeV, the combination of Higgs and ν masses for which all three of the lines are distinguishable by an experiment with $\sim 10\%$ energy resolution.

In most DM models producing line signals, there will typically be one line from annihilation into $\gamma\gamma$ and/or γZ (these two lines can be resolved only if the wimp mass is in the $\sim 50 - 100$ GeV mass range). Measuring the energy of this line will provide useful information on the DM mass. In addition, if another less energetic line is detected, this will allow to estimate the mass of the new heavy particle X that DM annihilates into. Since we are considering gamma ray energies between a few GeV to a few hundreds of GeV, this means that the DM and X particles will be kinematically accessible at the LHC (if heavier than a TeV the corresponding gamma ray signal will be suppressed). Therefore any line signal observed with FERMI, MAGIC or HESS should be accompanied by a signal at the LHC.

4 Collider signatures

Since the coupling of Z' to light SM fermions is suppressed by the small kinetic mixing factor, the best probe of the dark sector is through the top portal. In particular, the Z' can be produced by being radiated from top quarks, which have a large QCD production cross section at hadron colliders. Depending on the masses and couplings, the Z' will predominantly decay into $t\bar{t}$, $\nu\bar{\nu}$, or into light fermions. Decays into top quarks lead to four-top events with a very large cross section compared to the SM four top rate, which can be visible through a same-sign dilepton signature [9,10] (see also [11] for studies of a $ttWW$ final state). The right-handed nature of the Z' coupling to tops implies top polarization also provides an interesting observable. When the Z' decays into WIMPs, a $t\bar{t}+$ missing energy final state results, which presents a more challenging search at the LHC, but is definitely worth investigating. Work in these directions is in progress [10,12].

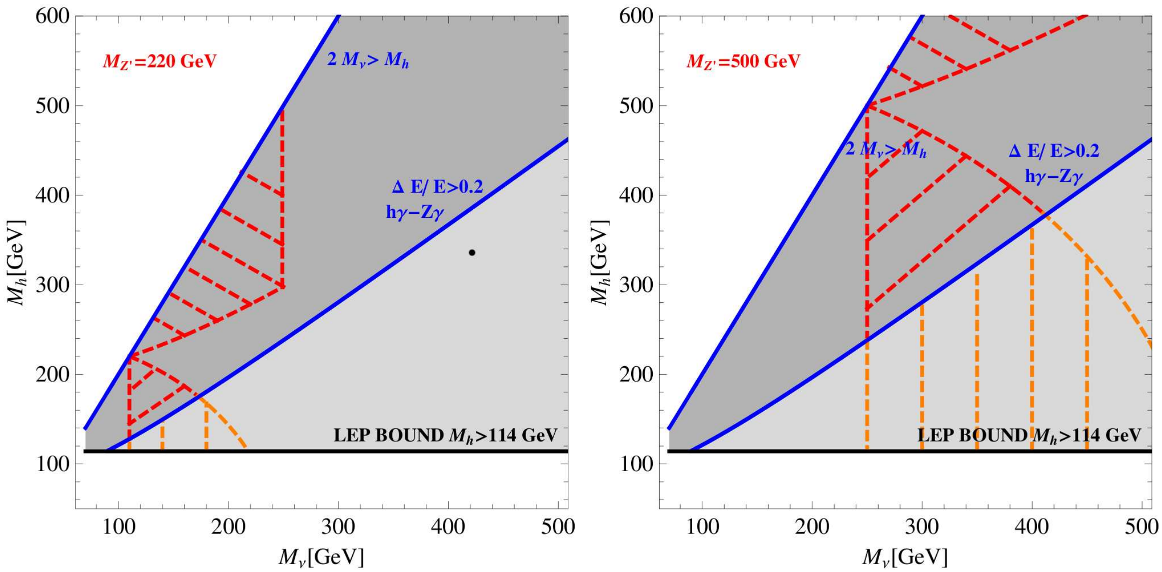

Figure 4: Regions of the M_ν-m_h parameter space (for $M_{Z'}$ = 220 GeV/500 GeV in the left/right panels) for which the γZ and γh lines can be distinguished by an experiment with 10% energy resolution (dark grey); in the light grey region they are merged. The red dashed area further shows the regions where the γZ, γh, and $\gamma Z'$ lines are distinguishable. In the dashed orange region γZ and γh lines are merged but distinguishable from the $\gamma Z'$ line.

Acknowledgments

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