Status of a Scalar Portal to Dark Matter

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In these proceedings, I discuss the current status of a specific scalar portal, the so-called Inert Doublet Model, with a focus on the issue of dark matter. I will particularly emphasize some of the most recent developments caused by the discovery of the Standard Model Scalar around 125 GeV at the LHC, the possible interplay between the electroweak phase transition and the properties of the dark matter candidate, and the prospects for its direct detection.

1 Introduction

The Inert Doublet Model (IDM) is one among the very simplest extensions of the Standard Model that may accommodate a dark matter candidate. First discussed in 1977 as a particular symmetry breaking pattern in Two Higgs Doublets models [1], it has been revamped in 2006 [2] in an attempt to give weight to the Standard Model Scalar (SMS, *aka* the Higgs) and almost simultaneously [3] as a way to give radiative masses to the light neutrinos. The latter work also illustrates the versatility of the IDM, which is clearly more a phenomenological framework for 'Beyond the Standard Model physics at the TeV scale' than a model. For instance the discrete symmetry that is required to enforce the stability of dark matter is put by hand, and has no obvious connection with other issues of the SM (a notable exception is [4]). Despite such limitations, the IDM has a very rich and interesting phenomenology, as is witnessed by the many works that have been devoted to exploring its implications, in particular regarding the existence of dark matter.

In these proceedings I will quickly review the status of the model, in light of the recent discovery, not of dark matter unfortunately, but of the SMS around 125 GeV at the LHC. I will also focus on some very interesting recent developments regarding the electroweak phase transition and direct detection.

2 The dark matter candidates

In the IDM and its siblings, the dark matter candidate is taken to be the lightest neutral component doublet scalar H_2, which is taken to be odd under a discrete symmetry that is assumed to be unbroken in vacuum. In absence of other extra particles, the scalar doublet has no couplings to quarks and leptons (hence the name inert doublet), and so its only interactions are through the SMS, noted here h (the SMS is otherwise just like in the SM) and electroweak gauge bosons. In particular, the relevant new parameters that determine the relic abundance of the dark matter candidate, which we will call H_0 (it is a WIMP, so we assume a standard freeze-out scenario), are: its mass, m_{H_0}, its trilinear coupling with h, and, in case of co-annihilation, the mass of the other odd scalars. The possible mass splittings within the inert doublet are constrained by electroweak precision measurements, in particular of the ΔT parameter [2]. Also the mass of the other neutral, A_0, and charged, $H^{\pm}$ partners are constrained by LEP searches to $m_{H^{\pm},A_0} \gtrsim 70 - 90$ GeV [5,6].

Back in 2006, there existed three possibilities that were compatible with all observational and experimental constraints, including WMAP [7]. There was a light WIMP, in the few GeV range, a middle or vanilla WIMP, with a mass around, but below the threshold for W^+W^- pair production, and a heavy WIMP, with a mass above about 500 GeV. The latter is reminiscent of Minimal Dark Matter [8], a framework in which dark matter is supposed to have only electroweak interactions. Thanks to interactions in the scalar sector, the allowed mass range for a heavy H_0 extends to up to 58 TeV, a limit which is set by the requirement of unitarity [7,9]. As of today, the first option is excluded, while the middle one is challenged by direct detection (with the exception of some fine-tuned cases), so that it is fair to say that only remains the possibility of a heavy, TeV-scale candidate. Let me briefly explain these points.

A light H_0, $m_{H_0} \sim$ few GeV has some interest, in particular with regards to the puzzling measurements reported by some direct detection experiments (the most recent one is from CDMS-Si [10]). It is effectively like a singlet scalar, since the other components of the inert doublet are constrained by LEP to be much heavier[a]. For these candidates, the cosmic abundance requires a large coupling $\lambda_{H_0} = \mathcal{O}(1)$ of H_0 to the SMS (the lightest candidate has $m_{H_0} \gtrsim m_\tau$ corresponding to $\lambda_{H_0} \sim 4\pi$). Such large couplings have two immediate implications. First the spin-independent H_0-nucleon cross-section, which is in one-to-one correspondence with the annihilation cross-section, is so large that all the light candidates heavier than about 5 GeV are excluded by direct detection experiments, baring the usual assumption regarding the energy density of dark matter in the vicinity of the Sun. Second, and more dramatically, they imply that the SMS would be essentially invisible: for $m_{H_0} = 7$ GeV, one has $\mathrm{BR}(h \to H_0 H_0) = 99.5\%$. Clearly this possibility has been definitively ruled out by the discovery of the SMS. Of course this conclusion is not specific to the IDM or singlet scalar scenarios, as any light WIMP that interacts dominantly through the so-called Higgs portal is excluded, but regarding the IDM, constraints from invisible SMS decay essentially exclude any candidate lighter than $m_h/2$ [13].

In the middle mass range, things are a bit more complex, as a number of processes may be relevant to determine the relic abundance of the H_0. The most significant features are 1/ the abundance is essentially suppressed above the threshold for production of W-pairs. Essentially because there used to be a tiny, yet viable corner of parameter space for which destructive interference between different channels allowed for $m_{H_0} \gtrsim m_{W^\pm}$ [12]. This possibility is now excluded by the latest limit set by Xenon-100 [14], as is shown in Fig.1, which I have borrowed from [15], except for the Xenon100, 225 kg-day exposure limit, which I have included for the sake of this review. Also shown in the Fig.1 are the many candidates that reach the observed relic abundance either through co-annihilation or resonant annihilation through the SMS (the vertical band in the figure between 50 and 70 GeV), hence with small coupling λ_{H_0}. Although perfectly viable, one should acknowledge the fact that these candidates live on the edge of parameter space and are not as "natural" as one would like them to be. To put in in other words, it seems to me that most of the "natural" candidates are now excluded. Perhaps it is worth reminding

[a] Notice that, although the mass splittings are limited by perturbativity, $\Delta m^2 \sim \lambda v^2$ (rem: they are also constrained by stability of the potential), decoupling is protected by the existence of a custodial symmetry, see e.g. [20].

that just a few years ago the strongest exclusion limits (by then set by CDMS) were about 2 orders of magnitude weaker than there are now...

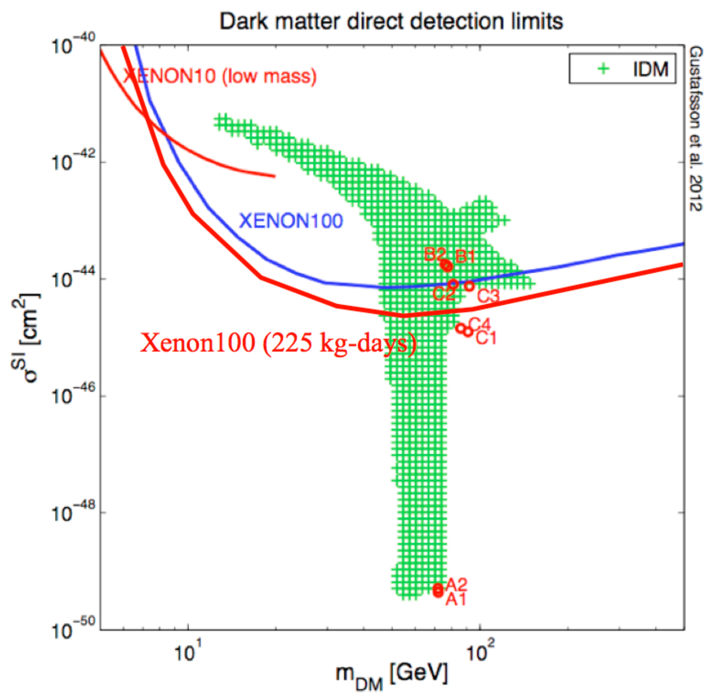

Figure 1: Scattered plot of H_0 candidates taken from Gustafsson *et al.* Notice that many candidate actually correspond to $m_h \gg 125$ GeV and so are now excluded, but the figure nevertheless reveals the gross features of the IDM candidates in the middle mass range.

The third and last possibility corresponds to heavy dark matter candidates, typically with a mass in the TeV range. Although for sure potentially a bad news direct production of dark matter and thus for the LHC, there are a few generic features that make such candidates quite appealing, both theoretically and experimentally. First, for what it is worth, in it is phase with the hope that new physics should lurk around the TeV scale. Then, as neatly illustrated by Minimal Dark Matter, TeV is actually the natural mass scale of WIMPs, *i.e.* weakly interacting particles [b] Indeed, for $m_{DM} \gg M_{W,Z}$, one expects $\sigma v \propto \alpha_W/m_{DM}^2$, which, depending on the quantum number of the candidates, leads to m_{DM} around 1 TeV ($m_{H_0} \approx 500$ GeV for the H_0). In practice, other couplings are relevant, either simply because there are other channels, or because of the production of longitudinal gauge boson modes, which is typically dominant at high energies (see for instance [12]). Ultimately one reaches the limit sets by unitarity, which in the case of the H_0 corresponds to $m_{H_0} \approx 58$ TeV.[c]

3 Some new developments

There are three interesting recent developments that I would like to address briefly. The first one has to do with the branching ratio of the SMS at 125 GeV in diphotons within the framework of the IDM. As this topic is covered in the talk by Bogumila Swiezewska at the same meeting, I will be very brief [17] (see also [18]). This is of course motivated by the hints of a possible enhancement in this channel compared to the expectation for the SM. The latest results of the experiments are a bit contradictory, so for the time being it is probably an interesting

[b] An extreme version is provided by charged dark matter, or CHAMPS [16].

[c] Another interesting feature of TeV WIMPs, which however does not apply to the H_0 is stability. If instead of a discrete symmetry, one envisions a global continuous symmetry, breaking of this symmetry by particles around the GUT scale leads automatically to a lifetime of the order of 10^{26} seconds.

possibility to explore. Alternatively one may use the LHC measurements to constrain the IDM. The extra contribution to $h \to \gamma\gamma$ is solely from the charged $H^\pm$ partner of the H_0 (notice that h production is unaffected). Both constructive and destructive interference with the SM amplitude may occur. There is also the possibility of a modification of the branching's due to invisible decay $h \to H_0 H_0$ but this is fine tuned, as at best $m_{H_0} \approx m_h/2 = 62.5$ GeV is allowed. Regarding the possible constraint on $H^\pm$, from [17] one reads that, provided

$$R(h \to \gamma\gamma) \leq 1.2,$$

then $M_{H^\pm} \geq 154$ GeV, which would about a factor of two better than the limit sets by LEP. The current limit is weaker, at least if we combine the CMS and ATLAS measurements, but one gets the idea. The lesson to be drawn regarding the abundance of dark matter is not as direct. Taking for granted the above lower bound, the EW precision tests imply that the A_0 is about as heavy as the $H^\pm$, which leaves only annihilation through the h to determine the relic abundance if the H_0 is in the middle mass range, which actually is no problem.

Another interesting recent development is the calculation of the radiative corrections to σ_{SI} in the IDM [19]. That this may be relevant may be appreciated from the fact that, in the IDM, elastic scattering is through the SMS channel, a process that is determined by the coupling λ_{H_0}, which may actually be small for many candidates, for instance near the h pole or if co-annihilations is important. In [19] it is found that the pure one-loop contribution to σ_{SI} is in the range $10^{-11} - 10^{-10}$ pb, depending on the mass splittings and the mass of the H_0, which is within the expected reach of Xenon-1T. It turns out that, once the constraint $m_{H_0} \approx m_h/2 = 62.5$ GeV is taken into account, the radiative correction to σ_{SI} may or may not be important for viable candidates in the middle mass range. As a rule of thumb, the 1-loop corrections are dominant (a factor of enhancement of up to 100 is possible for some candidates) whenever λ_{H_0} is small, which is either near the pole and/or when co-annihilation play a dominant role in determining the abundance of H_0 (see figure 7 in [19]). The important conclusion is that 1-loop corrections put the middle mass range within reach of Xenon 1T, contrary to what is apparent is Fig.1 (which is based on tree-level σ_{SI}). Similar conclusions are reached for the case of heavy candidates. In brief, this implies that almost all the parameter space of the IDM will be probed by direct detection experiments, at least up to 1 TeV, a quite interesting prospect.

The last point I would like to discuss is the possible interplay between dark matter in the IDM and the electroweak phase transition (EWPT) at finite temperature. Before going on, let me briefly recall an idea which at the end of the day does not quite work for the IDM but which I think has still some appeal and is related to the electroweak at finite T. The idea was to study the impact of IDM fields on the breaking of electroweak symmetry *in vacuum*. In particular we considered an extreme regime (this is what does not work at the end of the day) in which the electroweak scale and the mass of dark matter are related through the Coleman-Weinberg mechanism [20]. The relevance of the inert doublet for such considerations is of course the fact that scalar fields give at 1-loop a correction to the effective potential which is opposite to that of the top quark. One issue of importance was the fact that the relevant couplings were quite large, which pointed to the existence of Landau poles are rather low scale. In other words, in our setup the IDM was only an effective theory valid below, say, the TeV scale. Regardless, the concrete realization of this scenario is now rule-out by direct detection experiments, because large quartic couplings were required, but the spirit stays and, furthermore, the finite T works face the same issue. Coming to this, regarding the finite temperature phase transition, there has been quite a few recent works, see for instance [21] and [22]. In the latter, the issue of large quartic couplings vs direct detection constraints are evaded by considering that the H_0 is a sub-dominant component of dark matter. To get a strongly first order phase transition, indeed couplings of order 1 are required, but unlike in other approaches, in which the focus is on DM candidates around $m_h/2$, both to have a dominant form of dark matter and to have significant contributions to the EWPT, the dominant effect comes from $m_{H_0} \sim 200$ GeV. Although the abundance is suppressed and the H_0 is not the dominant form of DM, the rather large couplings should lead to potentially observable signals by direct detection experiments. The need for an extra, dominant form of dark matter concur with the fact that in such scenarios, the IDM is only a low energy effective theory, which need to be completed by extra degrees of freedom in the UV (actually not far from the TeV scale) [22]. One last comment is that the main interest of a strongly first order phase transition is electroweak baryogenesis, which of course also requires CP violation on top of departure from thermal equilibrium. This feature is however absent from the scalar sector of the IDM, hence the picture is so far incomplete.

4 Conclusions

Despite its simplicity, it is amazing how much phenomenology has been extracted from the Inert Doublet Model. Here I have only scratched the surface, but one lesson to take home I believe is that simple models are interesting for their own sake. Another more concrete lesson is that it seems that most of the parameter space of the IDM will be soon tested by direct detection experiments, in particular Xenon-1T, in parts because loop corrections may play a dominant role in the elastic scattering of H_0. Interestingly there is very little freedom here, as the relevant couplings are actually gauge couplings so that the only relevant parameters are essentially the mass spectrum of the inert doublet, so there is no way out here. We notice that radiative corrections are also central to the two other aspects we have briefly reviewed, that is the contribution of the inert doublet to the decay of the SMS into diphotons (which may probe the charged component of the inert doublet) and the order of the electroweak phase transition.

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