Two Higgs doublet models with local $U(1)_H$ gauge symmetry and dark matter

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We propose to implement the softly broken Z_2 symmetry in the usual two Higgs doublet model (2HDM) to spontaneously broken local $U(1)_H$ gauge symmetry, and show that the resulting phenomenology can be very rich and is distinctly different from the usual 2HDMs. Likewise, the exact Z_2 symmetry in ordinary inert doublet model (IDM) could be a remnant of spontaneously broken local $U(1)_H$ symmetry stabilizing dark matter (DM). In this case, new channels for DM pair annihilation into $U(1)_H$ gauge boson(s) open up, allowing the DM mass below $\lesssim 40$ GeV, unlike the usual IDM.

1 Two Higgs doublet Models

After the discovery of a new boson at the LHC [1], the most important task in particle physics phenomenology would be the precise measurements of properties of the new boson. Up to now, the boson looks like a Standard-Model(SM)-like Higgs boson [2]. However, this SM-like Higgs boson could be one of Higgs bosons from the extended Higgs sectors rather than the SM Higgs boson. In fact, a lot of high energy theories like SUSY, GUT *etc* predict various extensions of the SM Higgs doublet, such as two Higgs doublet models (2HDMs).

The two Higgs double model itself is quite interesting. It has a lot of scalar bosons, which have rich phenomenology at the LHC. Also depending on the setup, the models could have interesting connections to dark matter physics, baryon number asymmetry of the universe, and neutrino mass generation. The recent experimental anomalies in the top forward-backward asymmetry at the Tevatron and in $B \to D^{(*)}\tau\nu$ branching ratios at BABAR might be explained in non minimal flavor violating 2HDM with flavor dependent chiral $U(1)$ interactions [3].

In generic 2HDMs, there appear Higgs-mediated flavor changing neutral current (FCNC) problems if both doublets couple to the SM fermions. These problems are typically avoided by assigning ad hoc Z_2 discrete symmetry. With proper Z_2 parity assignments to the SM fermions and two Higgs doublets, one can construct 2HDMs without FCNCs at the tree level. However, discrete symmetry could generate a domain wall problem when it is spontaneously broken. Commonly, softly broken Z_2 terms are added to the models, but the origin of this soft breaking of Z_2 is rather unclear. Recently, it was proposed that the softly broken Z_2 symmetry can be replaced by local $U(1)_H$ gauge symmetry associated with Higgs flavors [4]. The local $U(1)_H$ gauge symmetry could be the origin of Z_2 symmetry in the usual 2HDM, and the softly broken terms are generated after $U(1)_H$ symmetry breaking. One example is given by the $U(1)_H$-invariant term, $H_1^\dagger H_2 \Phi$, where Φ is SM-singlet and $U(1)_H$-charged. After symmetry breaking, Φ has a vacuum expectation value (VEV) and the $H_1^\dagger H_2$ term is generated.

By proper $U(1)_H$ charge assignments to the SM fermions, one can construct new 2HDMs

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with $U(1)_H$ symmetry (denoted by 2HDMw$U(1)_H$), which get reduced to the usual Type-I, -II, -X, and -Y 2HDMs [4] when the $U(1)_H$ gauge boson becomes very heavy. In the Type-I case, it is possible to construct the 2HDMw$U(1)_H$ without extra chiral fermions except right-handed neutrinos. For example, assigning zero charges to all the SM fermions in Type-I 2HDM, the model becomes anomaly-free 2HDM. In this case, the new gauge boson Z_H does not couple to the SM fermions and it becomes naturally fermiophobic. However, for Type-II or other cases, extra chiral fermions are required to cancel gauge anomalies involving the new $U(1)_H$. And one of the extra chiral fermions could be a good candidate for cold dark matter (CDM).

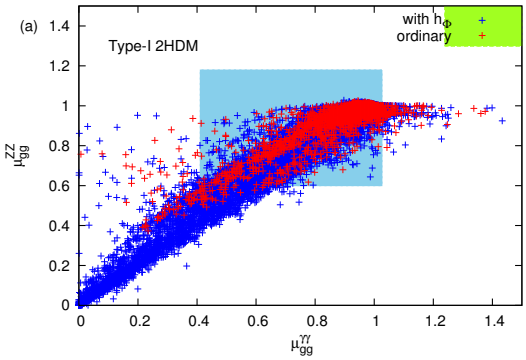

Figure 1 – Signal strengths $\mu_{gg}^{\gamma\gamma}$ and μ_{gg}^{ZZ} in the Type-I 2HDMs.

In this work we consider the Type-I fermiophobic 2HDMw$U(1)_H$. There are many theoretical and experimental constraints on the model parameters. The Higgs potential must satisfy constraints from conditions on perturbativity, unitarity and vacuum stability. We also take into account constraints from electroweak precision observables, exotic top decay, $b \to s\gamma$, heavy Higgs boson search at the LHC, and SM-like Higgs boson search at the LHC. Finally, if the SM-like Higgs boson can decay into non-SM particles, search for invisible Higgs decay at the LHC also strongly constrain the parameters in the 2HDMw$U(1)_H$ [5]. If both Higgs doublets develop VEVs, there is a tree-level mixing between Z and Z_H. If one of them does not develop a VEV, there is no mixing between Z and Z_H at the tree level. However in general, the mixing can be generated at the one-loop level, and the mixing angle ξ is strongly constrained by experiments: $\sin\xi \lesssim O(10^{-2}) \sim O(10^{-3})$. Figure 1 shows the signal strengths $\mu_{gg}^{\gamma\gamma}$ and μ_{gg}^{ZZ} in the Type-I 2HDMs. The red and blue points satisfy all constraints in the 2HDM with Z_2 symmetry (2HDMwZ_2) and 2HDMw$U(1)_H$, respectively. Both models are consistent with CMS data in the 1σ level, but with ATLAS data in the 2σ level. In the region $\mu_{gg}^{ZZ} \lesssim 0.4$, the 2HDMw$U(1)_H$ could be distinguished from the 2HDMwZ_2. If the Higgs boson properties are found to be close to the SM prediction, it would be essential to discover the extra scalar boson and new gauge boson to distinguish the 2HDMw$U(1)_H$ from the 2HDMwZ_2 as well as from the SM.

2 Inert doublet Model (IDM)

There are many evidences for the existence of nonbaryonic cold dark matter (CDM) in our universe. Among many models for CDM, a weakly interacting massive particle (WIMP) is an interesting scenario. In the 2HDMwZ_2, the dark matter candidate can be one of extra scalars when one of Higgs doublets does not develop a VEV and an exact Z_2 symmetry is imposed. This modes is called as the inert doublet model (IDMwZ_2) [6]. Under the Z_2 symmetry, SM particles including the ordinary Higgs doublet responsible for electroweak symmetry breaking are Z_2-even. And the other Higgs doublet has Z_2-odd particles, H^+, H, and A. In this work, we assume the neutral Z_2-odd scalar H is dark matter. In the Higgs potential the dim-2 terms $(H_1^\dagger H_2 + h.c.)$ do not appear because of the exact Z_2 symmetry.

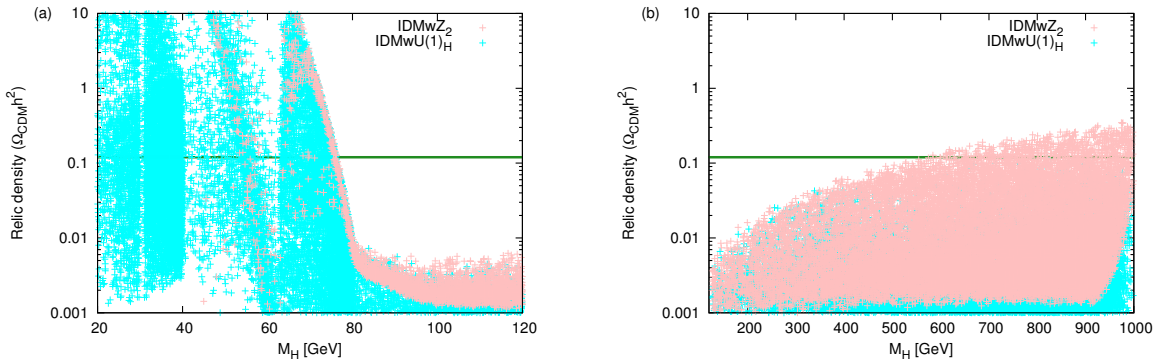

Figure 2 – Dark matter mass and relic density (a) in the light H scenario and (b) in the heavy H scenario.

As in the 2HDMw$U(1)_H$, the Z_2 symmetry can be replaced by local $U(1)_H$ gauge symmetry [7]. In this case, we have to add a SM-singlet scalar Φ. Without Φ, the $U(1)_H$ symmetry would be unbroken, resulting in massless Z_H boson. The remnant symmetry of $U(1)_H$ is the origin of the exact Z_2 symmetry stabilizing dark matter H. The dim-2 terms $H_1^\dagger H_2 + h.c$ are forbidden by $U(1)_H$ symmetry. In addition, the λ_5 terms $(H_1^\dagger H_2)^2 + h.c.$ in the usual inert doublet models are also forbidden by the $U(1)_H$ symmetry. Without λ_5 terms, the neutral boson H and pseudoscalar boson A are degenerate. Then the cross section for $HN \to AN$, where N is a nucleon, through the Z boson exchange could be large so that search for direct detection of dark matter in the XENON100 or LUX experiments would exclude this model immediately. The λ_5 terms can be generated effectively by a higher-dimensional operator (see Ref. [7] for more detail). And after $U(1)_H$ symmetry breaking, small λ_5 terms are induced and generate mass difference between H and A so that the $HN \to AN$ process is kinematically forbidden.

Figure 2 shows the dark matter mass m_H and relic density (a) in the light H scenario and (b) in the heavy H scenario. The pink points are in the IDMwZ_2 while the cyan points are in the IDMw$U(1)_H$, respectively. All the points satisfy constraints from LUX experiments and the horizontal line is the current experimental value for the relic density. As shown in Fig. 2 (a), a larger parameter space is allowed in the IDMw$U(1)_H$ in the light H scenario. In particular, a light CDM scenario ($m_H \lesssim 40$ GeV) is still possible, because the $HH \to Z_H Z_H$ and $HH \to Z Z_H$ processes mainly contribute to the relic density. This is a new aspect of IDMw$U(1)_H$, which was not possible in ordinary IDMwZ_2. Near the SM-Higgs resonant region, $m_H \sim 60 - 80$ GeV, the co-annihilation of HA or HH^+ and the pair annihilation of AA and H^+H^- also contribute to the relic density. In the heavy H scenario, both models are not so different from each other because the annihilation cross sections for $HH \to WW$ and $HH \to ZZ$ are dominant ones. In most cases the predicted relic density in the IDMw$U(1)_H$ is slightly less than that in the IDMwZ_2 because of new channels $HH \to Z_H Z_H$ and $HH \to Z Z_H$.

Figure 3 shows m_H and the velocity-averaged annihilation cross section, $\langle \sigma v \rangle$ at present (a) in the light H scenario and (b) in the heavy H scenario. The pink points are in the IDMwZ_2 while the cyan points are in the IDMw$U(1)_H$, respectively. The lower horizontal line comes from constraint on the S-wave dark matter annihilation from the relic density observation, while the upper two curves denote constraints on $\langle \sigma v \rangle$ from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies. Two curves correspond to the $HH \to WW$ and $HH \to b\bar{b}$ dominant cases, respectively. The IDMw$U(1)_H$ is more complicated than the naive assumption so that we cannot apply the above constraints to the our models. We calculate the quantity $\Phi_{\rm PP}$, which is the part of the gamma ray flux from dark matter annihilation [8]. The 95% upper bound is given by 9.3×10^{-30} cm^{3}s^{-1}GeV^{-2} [8]. The yellow and green points in Fig. 3 satisfy this upper bound in the IDMwZ_2 and in the IDMw$U(1)_H$, respectively. In the light H scenario, the region $m_H \lesssim 40$ GeV is allowed only in the IDMw$U(1)_H$. Actually in this region, only $HH \to Z_H Z_H$ contribute to $\langle \sigma v \rangle$

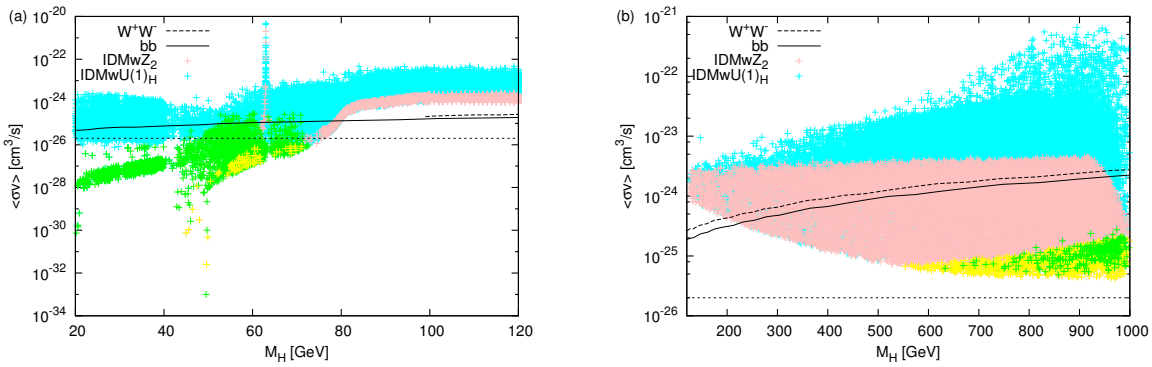

Figure 3 – M_H and $\langle\sigma v\rangle$ (a) in the light H scenario and (b) in the heavy H scenario.

and $m_H \sim m_{Z_H}$. In the heavy H scenario, the allowed region appears at $m_H \gtrsim 500$ GeV. For more detailed analysis we refer the reader to Ref. [7].

3 Conclusions

Two Higgs double models are interesting extensions of the SM and appear in many high-scale theories. We showed that the Higgs mediated FCNC problem in 2HDM could be resolved by considering gauged $U(1)_H$ symmetry instead of discrete Z_2 symmetry. After $U(1)_H$ symmetry breaking, the remnant symmetry would be the origin of the usual Z_2 symmetry. This $U(1)_H$ extension can also be applied to the IDM with exact Z_2 symmetry. The stability of dark matter in IDM with $U(1)_H$ symmetry is guaranteed by the remnant Z_2 symmetry of $U(1)_H$. We showed that in the type-I case, a light CDM scenario, which is ruled out in the typical IDM, is possible in the IDM with $U(1)_H$ symmetry.

Acknowledgments

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