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Constraining the Inert Doublet Model

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The Inert Doublet Model is presented among other versions of 2HDM. Possibility of constraining it at the colliders is discussed.

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1. 2HDM and its symmetries

Two-Higgs-Doublet Model (2HDM) is a useful laboratory for testing physics beyond the Standard Model. It opens a window to many interesting effects, like CP nonconservation, lepton-number nonconservation, existence of the charged and various neutral Higgs bosons, and it offers a candidate for a dark matter. Some of these effects can be potentially in conflict with observation like FCNC, and should be kept small by some ad hoc assumptions [1].

The 2HDM Lagrangian posses explicit gauge SU(2)$_L$xU(1)$_Y$ symmetry and allows for spontaneous violation of this symmetry (BEH mechanism). Introducing two SU(2)$_L$ doublets of scalar fields $\phi_{1,2}$ with identical weak hypercharge $Y = +1$ the most general Higgs potential which can be constructed contains 14 different terms, quadratic and quartic in doublets fields, with 14 real coefficients. The generic form of the potential retains under any global linear transformations U(2) between two doublets (change of base in the space of the Higgs Lagrangians L_H leaving invariant canonical kinetic energy terms) with an appriopriate, induced transformation of the parameters (reparametrization transformation) [1, 2, 3, 4]. Such change of basis and the corresponding change of coordinates (ie. parameters) in space of the L_H can not change the physical content of the model, in particular physical observables. This is called reparametrization-invariance (or freedom) of the 2HDM. Various attempts to build a basis-invariant or a reparametrization-invariant formulation for the 2HDM (NHDM) have appeared recently in the literature [3, 4]. The global transformation U(2) = SU(2) x U(1) consists of the subgroup SU(2), parameterized by three parameters, and a phase of U(1), which is not relevant for change of basis from the standpoint of the L_H (containing only bilinear combinations), however it causes a change in the vacuum expectation values.

Keeping in mind reparametrization freedom a question arises how to establish what kind of a global explicit symmetry is present in the Higgs Lagrangian *itself* [5]. If after a specific transformation of scalar doublets in the $\phi_1 - \phi_2$ basis by some $S-$ unitary matrix (to keep gauge-kinetic term invariant) the coefficients in front of all terms in L$_H$ do not change one can conclude that L_H posses an explicit symmetry. However, the presence of the symmetry in L$_H$ may be obscure in other basis [5]. In practice this means, that going to other basis we indeed observe an explicit symmetry however not under S but under other unitary matrix, S', related to S. Of course, S and S' should lead to the same physical predictions.

As discussed in [5] analysis of the quartic term is sufficient to establish that possible simple symmetries of the 2HDM are Z$_2$ transformations, changing some fields to their negatives, or Peccei-Quinn types. (Simple symmetry means here, that in a fixed basis only one explicit symmetry is assumed.) Note however, that symmetry under Z_2 transformation (eg. $\phi_1 \to \phi_1, \phi_2 \to -\phi_2$) in the $\phi_1 - \phi_2$ basis may look as a symmetry under permutation transformation $\phi'_1 \leftrightarrow \phi'_2$ in the $\phi'_1 - \phi'_2$ basis given by $\phi'_{1/2} = (\phi_1 \pm \phi_2)/\sqrt{2}$ [5].

If the Yukawa interaction is included in the 2HDM Lagrangian the most general case corresponds to the Model III, where both doublets are involved in the generations of masses of all fermions. Other typical models like Model I and Model II are based on idea of natural flavour conservation [1], where an explicit symmetry under the Z_2 transformation of the scalar fields and also of the right-handed quark fields is assumed. This way masses of quarks with a definite charge are generated by only one scalar doublet. In the Model I only one doublet is involved in the mass generation of all fermions, like in the SM, on the other hand two vev's appear here, in contrast to

SM. Also couplings to bosons and fermions, even for neutral Higgs bosons, may differ significantly from the corresponding SM ones. In the Model II one doublet gives masses to the up-type quarks and other doublet to the down-type quarks and charged leptons.

It is a tight relation between symmetry under the Z_2 transformation and CP conservation in the multi-Higgs doublet models. If Z_2 is explicitly conserved in the Lagrangian of 2HDM, then CP is conserved in the 2HDM [1]. If Z_2 is softly violated by the quadratic terms in the L_H, then CP can be violated both explicitly or spontaneously Finally, for a hard Z_2 violation by quartic terms in L_H new phenomena, like FCNC and CP violation without CP mixing may appear [6] at the tree level.

Model with two scalar SU(2)$_L$ doublets with an exact Z_2 symmetry, which is conserved both explicitly and spontaneously, is called the Inert Doublet Model (IDM) or Dark Doublet Model [7, 8]. Here one assumes that the SU(2)$_L$ doublet ϕ_1 and all known SM fundamental fields are Z_2-even, while the doublet ϕ_2 is Z_2-odd. Therefore the vacuum expectation of the ϕ_2 has to be equal to zero.

The first doublet in IDM plays a role identical to the scalar doublet in the SM, being responsible for a generation of masses of gauge bosons and fermions. Here the only Higgs particle is a SM-like Higgs boson h, with tree-level couplings to gauge bosons and fermions equal to the corresponding couplings for the SM-Higgs boson. The second scalar doublet has nothing to do with mass generation, nor it has direct couplings to fermions (vev = 0) - it is "inert" from this point of view. Physical particles are scalars H, A, H^+, H^- with Z_2-odd quantum number. Since Z_2 symmetry is strictly conserved in the model, these particles can be produced and annihilated only in pairs. Therefore the lightest dark scalar is stable being a candidate for dark matter particle.

The phenomenology of the Inert Dark Model is very distinct from all other 2HDM versions, although formally it is similar to the Model I and in some aspects it is very close to the SM. Some of the constraints can be derived from the Model II analysis performed at LEP. Constraints on this model may also come from the astrophysical data.

2. The 2HDM with an explicit Z_2 symmetry - different vacua

The 2HDM potential with explicit Z_2 symmetry is given by:

$$V_{2HDM} = \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2)\right\},\ \lambda_{1-4}, m_{11,22}^2 \in R.$$

Note, that V is invariant under Z_2 transformation ($\phi_1 \to \phi_1, \phi_2 \to -\phi_2$), and simultaneously under $Z_2' : \phi_1 \to -\phi_1, \phi_2 \to \phi_2$. Since CP is conserved we can fix λ_5 to be real.

One can anticipate the most general vev's in the form

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}v_1 \end{pmatrix},\ \langle\phi_2\rangle = \begin{pmatrix} u \\ \frac{1}{\sqrt{2}}v_2 \end{pmatrix},$$

with v_1, v_2, u real, $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$, $v_1 > 0$. Z_2 is spontaneously broken if v_2 or $u \neq 0$. (Here Z_2' is broken spontaneously by construction.) Note, that $u \neq 0$ corresponds to *a charged vacuum*, with a heavy photon, charge nonconservation, etc. [9, 10, 4]. Extremum conditions can be derived from vanishing of the first derivatives of V. Investigating these conditions one sees why a solution obtained for zero vacuum expectation value v_2 can not be a limiting case of the solutions with $v_2 \neq 0$. Consider for example a following condition (for u=0):

$$[\lambda_2 v_2^2 + (\lambda_3+\lambda_4+\lambda_5)v_1^2 - m_{22}^2]\, v_2 = 0,$$

from which the equation for parameter m_{22}^2 arises only for $v_2 \neq 0$ case. On general there are three types of solutions: two corresponding to the $u=0$, $v_1, v_2 \neq 0$ (Normal extremum), $v_1 \neq 0, v_2 = 0$ (Inert Model extremum) and one with $u \neq 0, v_1 \neq 0, v_2 = 0$ (Charge Breaking extremum).

Positivity (vacuum stability) constraints are: $\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > -\sqrt{\lambda_1\lambda_2}$, $\lambda_3+\lambda_4 \pm |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$. To get local minimum all eigenvalues of the squared mass matrix (second derivatives, corresponding to the squared masses of physical scalar particles) should be positive (minimum constraint). All these conditions define regions of parameters in which local minimum of a certain type can be realized. Phase diagram in the $\lambda_4 - \lambda_5$ space is very useful in such analysis, see [11]. Note that, for Normal extremum $m_{11}^2, m_{22}^2 > 0$, while for the IDM only m_{11}^2 has to be positive.

3. The Inert Doublet Model

As we already mentioned, in the Inert Doublet Model the Z_2-symmetry is conserved both explicitly and spontaneously. The vacuum expectation values are: $<\phi_1>= v$ and $<\phi_2>=0$ and Z_2-parity is odd for ϕ_2, while Z_2-parity is even for ϕ_1 and for all SM fields [7, 8].

The Higgs doublet and the Higgs boson h Only doublet ϕ_1 is a standard Higgs doublet and contains one physical Higgs boson h with the tree-level couplings to gauge bosons and fermions as in SM. Its mass is equal to

$$M_h^2 = m_{11}^2 = \lambda_1 v^2.$$

The Dark doublet and Dark scalars The Dark doublet ϕ_2 contains four physical spin-0, Z_2-odd particles $H^{\pm}, H, A$, called Dark scalars (collectively denoted by D). Their masses are given by

$$M_{H+}^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3}{2}v^2, \;\; M_H^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2}v^2, \;\; M_A^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2}v^2.$$

Note, that the parameter λ_2 appears only in the self-interaction. More precisely all quartic couplings which involve solely Dark scalars are proportional to λ_2. Both quartic and cubic couplings between Higgs boson h and Dark scalars D, are proportional to $M_D^2 + m_{22}^2/2$. Those involving $H^{\pm}$ are proportional to λ_3 solely. Dark scalars do couple to W/Z, but there are no couplings violating Z_2 of types: W^+W^-H, W^+W^-A. Relevant for searches are following trilinear vertices involving gauge bosons: $H^{\pm}W^{\mp}H$, $H^{\pm}W^{\mp}A$, AZH.

4. Constraints on Inert Doublet Model

It is important to realize how one can discriminate between various versions of the explicitly Z_2-symmetric 2HDM and how existing limits can be used to constrain IDM. Note, that in all considered versions of 2HDM there are two charged and three neutral physical scalar (spin-0) particles. Since CP is conserved here, neutral scalars have definite CP-parity (h, H are CP-even, while A is CP-odd). In phenomenological analysis one can use masses of $h, H, A, H^{\pm}$, and additional parameters, eg. for IDM m_{22}^2 and λ_2.

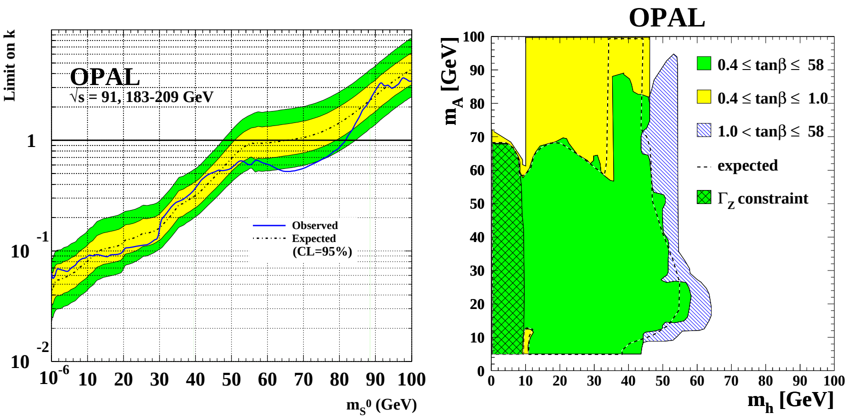

Figure 1: Upper limits on couplings χ_V^2, and mass exclusion plot for h(H)-A from LEP [12].

Using LEP constraints on 2HDM (II) for Inert Doublet Model The LEP data exist for CP conserving 2HDM (Model II) with an explicit (but spontaneously broken) Z_2 symmetry. It can be parametrized by masses and α (mixing angle in the CP-even Higgs sector), $\tan\beta = v_2/v_1$. Couplings (relative to the SM) of h to VV (V=W/Z), down quarks/leptons and to up quarks are:

$$\chi_V = \sin(\beta-\alpha), \;\; \chi_d = \chi_V - \sqrt{1-\chi_V^2}\tan\beta, \;\; \chi_u = \chi_V + \sqrt{1-\chi_V^2}/\tan\beta.$$

Consider a case when h is the lightest Higgs boson and has coupling to gauge bosons as in the SM ($\chi_V = 1$). Then all its couplings to fermions are as in SM and the corresponding contraints for the SM-Higgs boson hold for h. These constraints can be applied for h from IDM, provided no new channels related to the D scalars are open. In such scenario in Model II, H has vanishing coupling HVV, like H in IDM. Of course, in Model II Yukawa couplings of H are nonzero (in contrast to H from IDM) and may differ strongly from the SM ones ($\tan\beta$ enhancement or suppression). In Model II with SM-like h there is no coupling W^-H^+h, while W^-H^+H exists as in the IDM case. Similarly, in this scenario ZhA is zero, while ZHA exists as in IDM. Finally AW^+W^-, AZZ as well as $H^+W^-\gamma$, H^+W^-Z are forbidden in 2HDM, and similarly there are absent in IDM.

It is important to stress that the lightest Higgs boson in Model II could be H - not h. There exists a upper limit for χ_V^2 from the analysis of Bjorken process $ZZh(H)$, see Fig. 1 (left). Since pair production involving $ZAh(H)$ is proportional to $(1-\chi_V^2)$, by combining results from both measurements mass exclusion can be derived (Fig. 1 (right)). Both these limits maybe relevant for IDM, as well as the model-independent lower limit from LEP for $H^\pm$ around 80 GeV.

In paper [7] colliders signal and constraints for IDM in the case $M_H^+ > M_A > M_H$, with stable H, were considered. The constraints from the direct measurements of the neutral sector at LEP II were summarized for $M_h = 105-110$ GeV in a following form: $M_H + M_A > M_Z$, $\Delta(A,H) = M_A - M_H = 5-30$ GeV. Recently a dedicated EW precision test for IDM has been performed [8] for $M_h = 400-600$ GeV with the result: $(M_{H^+}-M_A)(M_{H^+}-M_H) = M^2$, $M = 120^{+20}_{-30}$GeV.

The absence of a signal within searches for supersymmetric neutralinos at LEP II was used recently to constrain the IDM [13]. This analysis excludes IDM for $M_H < 80$ GeV, $M_A < 100$ GeV and $\Delta(A,H) > 8$ GeV.

Testing Inert Doublet Model at colliders Deviation from the SM decay rates for h may appear in the IDM due to additional decay channels, for relatively light Dark scalars. Significant modification of the branching ratios for h with mass 100-150 GeV may appear, due to h decay to Dark scalars HH with mass around 50 GeV. The total width of h is predicted to be enhanced up to factor 3 for mass of H^+ equal 170 GeV and $m_{22}^2 = -20$ GeV [7]. This effect may be observed at the LHC, as well as at the planned e^+e^- ILC or PLC during a SM-Higgs searches. LHC discovery potential for the Dark scalars was studied as well; as the best process the AH production was found [7].

Dark matter from Inert Doublet Model A direct annihilation of HH into $\gamma\gamma$ and $Z\gamma$, for mass of DM candidate between 40-80 GeV, was studied in [14]. Such DM line signal can be search for with FERMI (GLAST) satelite. M_H between 40-80 GeV, mass of H^+ =170 GeV, M_A =50 -70 GeV, M_h=500 GeV (and also for M_h=120 GeV) were considered. Other DM study within IDM was performed in [15], for M_h =120 GeV and large M_{H^+}, close to M_A = 400 - 550 GeV.

5. Summary

There is a basic question - is Z_2 symmetry accidental or real? If it is real and respected exactly then the Inert Doublet Model arises naturally. It is a simple yet phenomenologically very rich model, with SM-like Higgs h, Dark particles $D = H^\pm, A, H$ and a good candidate for dark matter.

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