2HDM with Z_2 symmetry in light of new LHC data

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Abstract. Properties of the Z_2-symmetric Two Higgs Doublet Models (2HDM) are discussed and confronted with new LHC data for a 125 GeV Higgs particle. The particle discovered at LHC in 2012 has properties expected for it in the Standard Model (SM), with a possible enhancement in the $\gamma\gamma$ channel. SM-like Higgs scenarios can be realized in the Two Higgs Doublet Models with Z_2 (D) symmetry within the normal Mixed Model (with scalar sector as in MSSM) and the Inert Doublet Model (IDM), where a good Dark Matter (DM) candidate is present. Here we discuss both of the models.

1. Introduction

In the Two Higgs Doublet Models (2HDM) there are two doublets of SU(2), with the weak hypercharge Y=1. They give masses to W, Z (leading at the tree-level to $\rho = 1$) and in principle also to the photon. Fermion masses are generated via Yukawa interactions, for which various models are considered: Model I, II, III, IV, X, Y,... [1]. Five scalars appear in these models, two charged H^+ and H^- and three neutral ones. If CP is conserved there are two CP-even h, H and one CP-odd A particle. In the model with CP violation three neutral particles h_1, h_2, h_3 with undefined CP parity appear.

2. D-symmetric 2HDM

Study of the symmetry properties of the Lagrangian as well as of the vacuum states is crucial for understanding a real content of the theory. Here we assume the Z_2 symmetry of the potential $\phi_S \to \phi_S,\ \phi_D \to -\phi_D$, which we call below the D symmetry.[1]

In the Mixed Model both doublets have non-zero vacuum expectation values (vev's) and are involved in the mass generation. There are five Higgs bosons and sum rules hold for the relative couplings of the neutral Higgs particles h, H, A: e.g. $(\chi^h_{VV})^2 + (\chi^H_{VV})^2 + (\chi^A_{VV})^2 = 1$, $V = W/Z$. Model II is assumed for the Yukawa interactions: doublet ϕ_S couples to the down-type quarks and charged leptons, while ϕ_D couples to the up-type quarks. D symmetry is spontaneously violated. In this model SM-like scenarios are possible for both h and H, with $\chi^{h/H}_{VV} = 1$.

In contrast, in the Inert Doublet Model (IDM), only one doublet (ϕ_S) is involved in the mass generation and there is only one SM-like Higgs boson h. The second doublet is inert (it has vev=0) and contains four scalars. Yukawa interactions are as in Model I, so the D symmetry is exact here and the neutral scalar H (or A) may play a role of the Dark Matter (DM).

[1] In such case CP is conserved.

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Table 1: Types of extrema for a D-symmetric potential.

type of extremum	condition
EWs (EWs)	$u = v_D = v_S = 0$
Inert (I_1)	$u = v_D = 0, v_S \neq 0$
Inertlike (I_2)	$u = v_S = 0, v_D \neq 0$
Mixed (M)	$u = 0, v_S \neq 0, v_D \neq 0$
Charged (CB)	$u \neq 0, v_S \neq 0, v_D = 0$

The D-symmetric potential has the following form:

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$

$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right],$$

with all parameters real. We take $\lambda_5 < 0$ without loss of generality [2].

Such potential has various possible extrema (vacua), with the following vacuum expectation values:[2]

$$\langle\phi_S\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_S\end{pmatrix}, \qquad \langle\phi_D\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}u\\ v_D\end{pmatrix}. \tag{1}$$

Neutral vacua are realized for $u = 0$. The charged vacuum with $u \neq 0$ corresponds to breaking of $U(1)_{QED}$ symmetry and the appearance of the massive photon. The list of possible extrema, which can be realized as local or global minima (i.e. vacua) is given in table 1. The EWs case corresponds to the EW symmetry, i.e. lack of spontaneous breaking of EW symmetry.

Existence of a stable vacuum requires [3]:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1\lambda_2} > 0 \;\; (\lambda_{345} = \lambda_1 + \lambda_2 + \lambda_3),$$

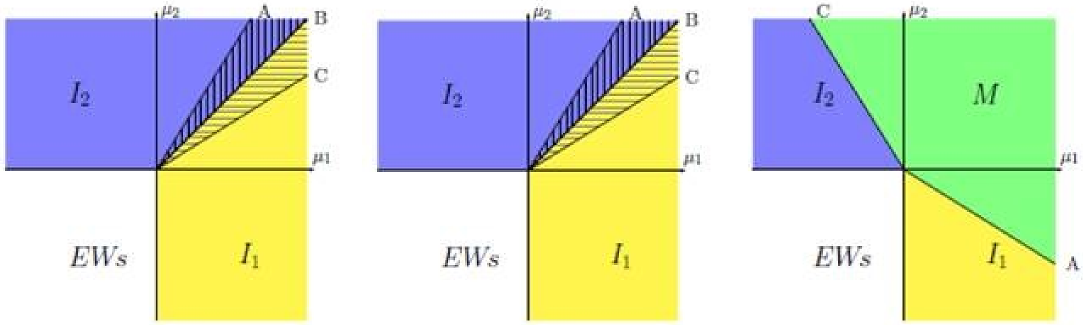
so that $R = \frac{\lambda_{345}}{\sqrt{\lambda_1}\sqrt{\lambda_2}} > -1$. Various vacua can be realized for various values of vev's, which can be represented in the phase diagram (μ_1, μ_2), where

$$\mu_1 = \frac{m_{11}^2}{\sqrt{\lambda_1}}, \quad \mu_2 = \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$

There are three regimes of parameter R which correspond to very different phase patterns shown in fig. 1.

In principle a model for today's Universe could be based either on the Mixed or the Inert vacuum. From theory side we assume that the considered vacua are stable and parameters of V are constrained by the perturbative unitarity: $|\Lambda_i| < 8\pi$ [4–6], where Λ_i are the eigenvalues of the high-energy scattering matrix of the scalar sector. This leads to the upper limits on $\lambda_{1,2}$

[2] With u, v_S, v_D real.



(a) $R > 1$ (b) $1 > R > 0$ (c) $0 > R > -1$

Figure 1: Phase diagrams for $D-$symmetric potential. Regions of μ_1, μ_2 where various neutral extrema (minima) EWs, I_1, I_2, M can be realized are shown. The hatched region on the left panel corresponds to the coexistence of I_1, I_2 minima.

equal 8.38, while λ_3 and λ_{345} are allowed to be in the regions (-6.05, 16.53) and (-8.10,12.38), respectively.

In any case a condition for the existence of the particular vacuum has to be fulfilled. Existence of the Mixed vacuum is equivalent to having positive scalars' masses squared (condition for the minimum) while for the Inert vacuum this is not enough since a coexistence of Inert and Inertlike minima is possible (see fig. 1). For Inert to be the global minimum a following condition has to be fulfilled in addition [2]:

$$\frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$

From the Higgs boson mass $M_h^2 = m_{11}^2 = \lambda_1 v^2 = (125\,\mathrm{GeV})^2$ and unitarity limit $\lambda_2^{\max} = 8.38$ a following limit on m_{22}^2 arises [6]:

$$m_{22}^2 \lesssim 9 \cdot 10^4\,\mathrm{GeV}^2. \qquad (2)$$

3. Experimental constraints

We consider both Mixed Model and IDM, taking into account also the following experimental constraints:

Electroweak Precision Tests (EWPT) Values of S and T parameters are demanded to lie within 2σ ellipses in the S, T plane, with the following central values [7]: $S = 0.03 \pm 0.09$, $T = 0.07 \pm 0.08$, with correlation equal to 87%.

LEP We apply a model-independent limit: $M_{H^\pm} > 70$ GeV from the direct LEP measurements. For Mixed Model the lower limit for mass of $H^\pm$ is 360 GeV from $b \to s\gamma$ NLO analysis [8]. For the IDM we use the LEPI and LEPII bounds on the scalar masses [9, 10]:

$$M_{H^\pm} + M_H > M_W, \quad M_{H^\pm} + M_A > M_W, \quad M_H + M_A > M_Z \qquad (3)$$

excluding region where simultaneously: $M_H < 80\,\mathrm{GeV}, M_A < 100\,\mathrm{GeV}, M_A - M_H > 8\,\mathrm{GeV}$.

***H* as DM candidate** In the IDM we take H as the DM candidate, $M_H < M_A, M_{H^\pm}$.

4. Results for the Mixed Model with a 125 GeV Higgs

Perturbative unitarity gives the following upper limits on the Higgs masses in the Mixed Model: $M_h^{\max} = 499$ GeV, $M_H^{\max}$ and $M_{H^\pm}^{\max}$ equal 690 GeV, $M_A^{\max} = 711$ GeV. Moreover, by setting mass

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of h equal to 125 GeV, an important limit on $\tan\beta = v_D/v_S$ is obtained, namely $0.18 < \tan\beta < 5.59$ (independently of $\sin(\beta - \alpha)$!). Notice, that it is possible to have SM-like H, however h needs then to have a very suppressed coupling to gauge boson, see eg. [11–13].

Even when all direct decay widths of h are as in SM, the loop decay widths $\gamma\gamma$, $Z\gamma$ for h may still be modified due to $H^\pm$ contribution, or/and the negative sign of $\chi_{f\bar{f}h}$ coupling [14]. The $H^\pm$ loop contribution leads to a 10 % (5%) suppression with respect to the SM for $\gamma\gamma$ ($Z\gamma$). The change of sign of the tth coupling has a strong influence on the decay widths $\gamma\gamma$ and $Z\gamma$ by changing the destructive interference between the t and W contributions to the loop couplings present in the SM into the constructive one. The enhancement with respect to SM up to 2.3 (1.2) is possible for $\Gamma_{\gamma\gamma}$ ($\Gamma_{Z\gamma}$). For the hgg coupling change of the relative sign of the b and t contributions leads to a enhancement up to 1.25.

5. Results for IDM with a 125 GeV Higgs

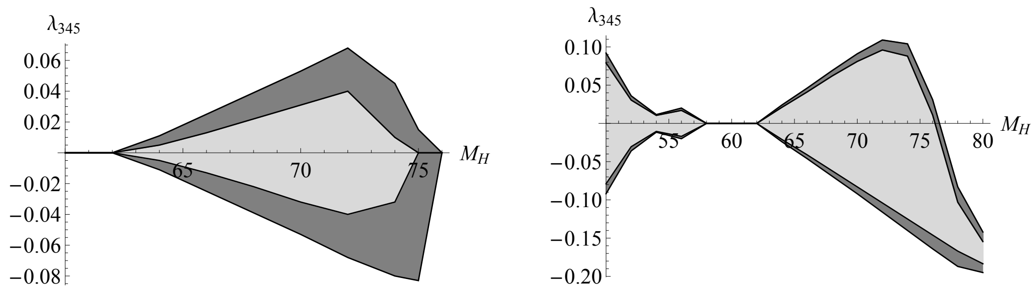
The Universe is described by the IDM if the vacuum state is given by I_1. IDM predicts the existence of four dark scalars H, $A, H^\pm$ and the SM-like Higgs particle h (we assume its mass equal to 125 GeV). λ_{345} is related to a triple and quartic coupling between SM-like Higgs h and DM candidate H. λ_2 gives the quartic DM self-couplings, while λ_3 describes the Higgs particle interaction with charged scalars.

5.1. Relic density

IDM provides a good DM candidate in three regions of M_H [15–26]: (i) light DM particles with mass below 10 GeV, (ii) medium mass regime of $50 - 150$ GeV and (iii) heavy DM of mass larger than 500 GeV. In those regions one can get the DM relic density $\Omega_{DM}h^2$ in agreement with the astrophysical data $\Omega_{DM}h^2 = 0.112 \pm 0.009$ [27].

This estimation of $\Omega_{DM}h^2$ may be used to constrain the λ_{345} coupling depending on the chosen values of masses of H and other scalars [18, 20]. $\Omega_{DM}h^2$ does not limit the λ_2 parameter, although indirect constraints come from its relation to λ_{345} parameter through the vacuum stability constraints and existence of I_1 vacuum [25, 26].

Limits for M_H and λ_{345} coming from $\Omega_{DM}h^2$ are presented in fig. 2. For masses $M_H \lesssim 72$ GeV the allowed region (dark gray) of λ_{345} is symmetric around zero with small values of λ_{345} excluded (light gray region) due to a nonefficient DM annhilation. As the mass increases, the region of proper relic density shifts towards the negative values of λ_{345}, which is due to opening of the annihilation channels into the gauge bosons final state.



(a) $M_A = M_H + 8$ GeV (b) $M_A = M_H + 50$ GeV

Figure 2: Limits for (M_H, λ_{345}) parameters coming from astrophysical estimations of DM relic density ($\Omega_{DM}h^2$). Dark gray: $\Omega_{DM}h^2$ in agreement with WMAP measurements, $0.1018 < \Omega_{DM}h^2 < 0.1234$; light gray: $\Omega_{DM}h^2$ above WMAP limits (excluded); white: $\Omega_{DM}h^2$ below WMAP limits (subdominant DM). We set $M_h = 125$ GeV and $M_{H^\pm} = M_H + 50$ GeV.

As it will be shown below, in the IDM $R_{\gamma\gamma} > 1$ is possible for $\lambda_3 < 0$. If we consider H as a DM candidate then $\lambda_{345} < 0$ for $R_{\gamma\gamma} > 1$, meaning that it is possible to fulfill the LHC and relic density constraints for IDM.

5.2. $R_{\gamma\gamma}$

Here we concentrate on the two-photon decay rate of the Higgs boson, which in the IDM reads:

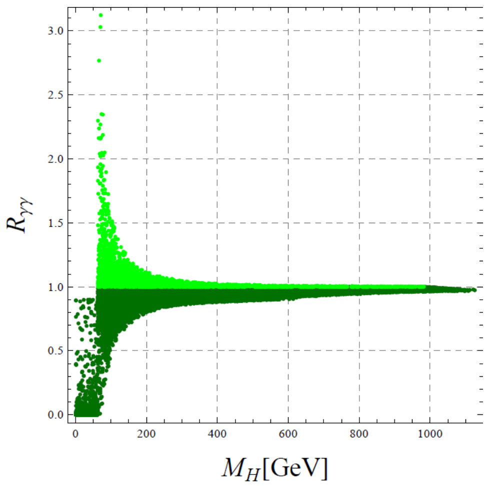
$$R_{\gamma\gamma} := \frac{\sigma(pp \to h \to \gamma\gamma)^{\text{IDM}}}{\sigma(pp \to h \to \gamma\gamma)^{\text{SM}}} \approx \frac{\text{Br}(h \to \gamma\gamma)^{\text{IDM}}}{\text{Br}(h \to \gamma\gamma)^{\text{SM}}}. \tag{4}$$

A deviation from the value of $R_{\gamma\gamma} = 1$ may be caused in IDM by two factors. Firstly, the partial decay width $\Gamma(h \to \gamma\gamma)^{\text{IDM}}$ is modified due to the existence of the charged scalar loop [28–32]:

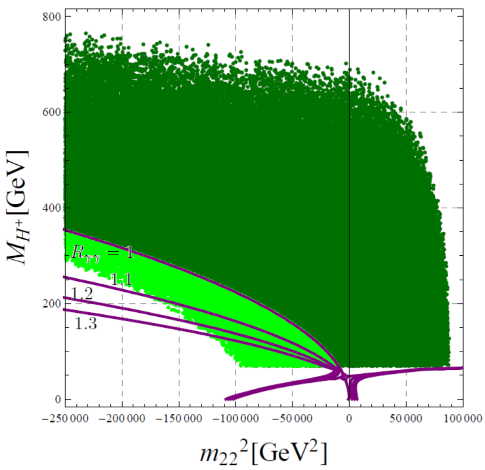
$$\Gamma(h \to \gamma\gamma)^{\text{IDM}} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left|\mathcal{M}^{\text{SM}} + \delta\mathcal{M}^{\text{IDM}}\right|^2,$$

where $\mathcal{M}^{\text{SM}}$ is the contribution from the SM and $\delta\mathcal{M}^{\text{IDM}} = \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right)$, with $2M_{H^\pm}^2 + m_{22}^2 = \lambda_3 v^2$. The charged scalar loop can interfere either constructively or destructively with the SM contribution. Secondly, the total decay width $\Gamma^{\text{IDM}}(h)$ can be increased with respect to the SM case due to the existence of the invisible decays: $h \to HH$ and $h \to AA$.

Performing a random scan of the parameter space, we found the regions where $R_{\gamma\gamma}>1$, with the maximal value of $R_{\gamma\gamma}$ around 3.4. Fig. 3a shows values of $R_{\gamma\gamma}$ allowed by the theoretical and experimental constraints as a function of M_H. It can be seen that enhanced values of $R_{\gamma\gamma}$ are not possible for $M_H < M_h/2$. It means that if the invisible channels are open, the total decay width is so big, that it suppresses other effects.



(a) Values of $R_{\gamma\gamma}$ allowed by the theoretical and experimental constraints as a function of the DM mass M_H for $-2 \cdot 10^6\ \text{GeV}^2 \leqslant m_{22}^2 \leqslant 9 \cdot 10^4\ \text{GeV}^2$.



(b) Region allowed by the constraints in the $(m_{22}^2, M_{H^\pm})$ plane. The curves correspond to the fixed values of $R_{\gamma\gamma}$ (for the invisible channels closed).

Figure 3: Results on $R_{\gamma\gamma}$ for IDM, points with $R_{\gamma\gamma} < 1$ ($R_{\gamma\gamma} > 1$) are displayed in dark green/gray (light green/gray).

Fig. 3b shows the region allowed by the theoretical and experimental constraints in the $(m_{22}^2, M_{H^\pm})$ plane together with the curves corresponding to constant values of $R_{\gamma\gamma}$ (calculated for the case with invisible decay channels closed). It can be seen that the enhancement is possible only for constrained m_{22}^2 region, namely:

$$m_{22}^2 < -9.8 \cdot 10^3\,\text{GeV}^2,$$

which is equivalent to the bound $\lambda_3 < 0$ (in agreement with Ref. [32]). On the contrary, $R_{\gamma\gamma} > 1$ can be achieved for any value of $M_{H^\pm}$. However, if bigger value of $R_{\gamma\gamma}$ is demanded, then allowed values of $M_{H^\pm}$ are constrained. For example, for $R_{\gamma\gamma} > 1.2$ we get the following bounds on $M_{H^\pm}$ and M_H (as $M_H < M_{H^\pm}$):

$$\begin{aligned} 62.5\,\text{GeV} <\; & M_H \;< 154\,\text{GeV}, \\ 70\,\text{GeV} <\; & M_{H^\pm} \;< 154\,\text{GeV}. \end{aligned}$$

6. Evolution of the Universe in 2HDM through different vacua in the past

We consider 2HDM with an explicit D symmetry and assume that today the IDM describes reality. In the simplest approximation λ_i terms in the potential are fixed and only mass terms vary with temperature:

$$m_{ii}^2(T) = m_{ii}^2 - c_i T^2 \;\; (i = 1, 2),$$

where $c_i = c_i(\lambda_{1-4}; g, g'; g_t^2 + g_b^2$ for $i = 1$). Here g, g' are EW gauge couplings, while g_t, g_b are the SM Yukawa couplings) [2].

As the Universe cools down, the quadratic coefficients vary with T and the ground state of the potential V may change. Various types of evolution of the Universe from EWs phase into I_1 phase can be realized: in one ($EWs \to I_1$), two ($EWs \to I_2 \to I_1$) or three ($EWs \to I_2 \to M \to I_1$) steps. In general, in T^2 approximation phase transitions are of the 2nd order. The only exception is the transition between two degenerate minima I_2 and I_1 in the sequence with two phase transitions. This scenario can be realized only if $R > 1$. Notice, that if the Universe undergoes a series of phase transitions dark matter may appear later during the evolution, as it exists only in the Inert phase.

If $R < 0$ there is only one type of sequence that corresponds to the restoration of EW symmetry in the past (fig. 4a): $EWs \to I_1$. This sequence can be realized when $R_{\gamma\gamma} > 1$, which is suggested by the recent LHC data. In the other scenarios for $R < 0$ the initial state of the Universe is the one with broken EW symmetry (fig. 4b). The restoration of EW symmetry may be temporary (scenario Y), in other cases the EW symmetric state never existed.

For a certain parameter range there is a possibility of having a charged vacuum in the past (fig. 4c). This scenario can be realized only if today we have IDM with the charged DM particle [2]. Current model independent bounds require that charged DM is heavier than 100 TeV [33]. This can be achieved without breaking the perturbative unitarity conditions with large m_{22}^2. However, the sequence Z_+ requires that $c_2 < 0$ and $|c_2|/c_1 > |m_{22}^2|/m_{11}^2 \gtrsim (10^5 \div 10^6)$. This contradicts the requirement $c_1 > -c_2$ based on the positivity condition [2]. This means that during the evolution Universe cannot pass through the $U(1)_{QED}$ breaking phase.

7. Summary

The 2HDM is an excellent laboratory of the beyond SM physics. Although the discovery of the 125 GeV Higgs particle is in agreement with the Standard Model prediction, many extensions of the SM have some build-in SM-like scenarios. Here we consider two very different explicit Z_2-symmetric extensions with two SU(2) doublets – the very common Mixed Model and the Inert Doublet Model. Both can correspond to the SM tree-level decay modes, at the same time both may lead to the enhancement in the two-photon decay channel for the 125 GeV Higgs boson.

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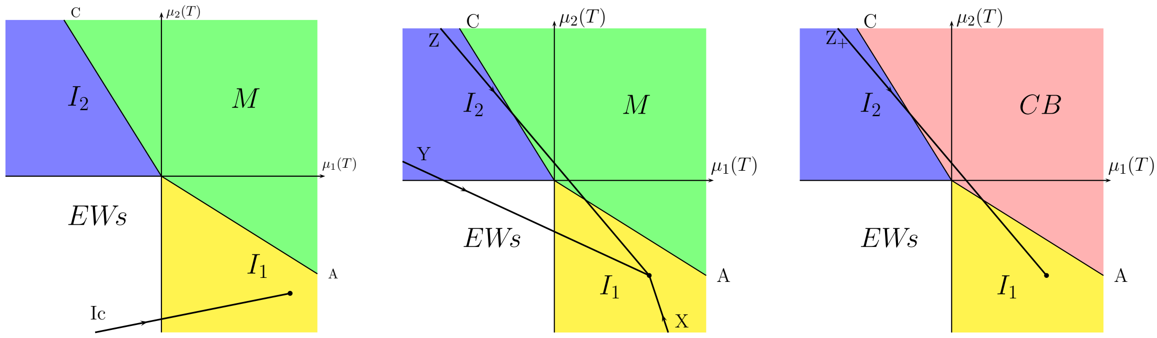

(a) $R < 0$, the only sequence for $R < 0$ that leads to restoration of EW symmetry in the past.

(b) $R < 0$, possible sequences of non-restoration of EW symmetry.

(c) Transition through the charged vacuum.

Figure 4: Possible sequences of phase transitions.

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