Distinguishing the nature of dark matter particle of dark scalar doublet model from that of supersymmetry and little Higgs models

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- There are many indications for the existence of new physics.
- Dark matter: The anisotropies in the cosmic microwave background radiation, as measured by WMAP, indicates

$$0.096 \le \Omega_m h^2 = \frac{\rho_m}{\rho_c} \le 0.122$$

These numbers are atleast 5 times larger than the contribution due to the known matter, and it indicates the presence of an unknown matter which is termed as dark matter.

- In the standard model there is no particle which can fit the WMAP data.
- Neutrino physics: Neutrino oscillation data indicate that neutrinos are massive particles with mass

$$m_{\nu} \leq 0.1 \,\mathrm{eV}$$

In the standard model, the smallness of neutrino masses can be explained with the neutrino Yukawa couplings suppressed to of order 10^{-12} , which seems to be unrealistic explanation.

Dark Scalar Doublet Model by E. Ma

- Dark scalar doublet model is an extension of the standard model and it can explain the dark matter and neutrino masses.
- This model has discrete Z_2 symmetry and contains additional particles like: three right-handed neutrinos (N_i) and a scalar doublet $\eta = (\eta^+, \eta^0)$. Both N_i and η are odd under Z_2 .
- The invariant Lagrangian would be

$$\mathcal{L}_Y = h_{ij} L_i \eta N_j + \frac{1}{2} M_{ij} N_i N_j + \text{h.c.}$$

 Since η doesn't acquire a vev, neutrinos would be massless at the tree level. But in this model neutrinos acquire mass at one loop level.

- The smallness of neutrino masses can be naturally explained in this model for the Majorana mass scale of 10^9 GeV.
- Since η is Z_2 -odd and their masses could be at the electroweak scale, the lightest neutral component of η can be a dark matter particle.

The invariant potential in a Z_2 parity model is

$$V(\Phi,\eta) = m_1^2 \Phi^{\dagger} \Phi + m_2^2 \eta^{\dagger} \eta + \frac{1}{2} \lambda_1 (\Phi^{\dagger} \Phi)^2 + \frac{1}{2} \lambda_2 (\eta^{\dagger} \eta)^2 + \lambda_3 (\Phi^{\dagger} \Phi) (\eta^{\dagger} \eta)$$
$$+ \lambda_4 (\Phi^{\dagger} \eta) (\eta^{\dagger} \Phi) + \frac{1}{2} \lambda_5 [(\Phi^{\dagger} \eta)^2 + \text{h.c.}]$$

The masses of the various scalar particles are

$$m_h^2 = \lambda_1 v^2, \quad m^2(\eta^{\pm}) = m_{\pm}^2 = m_2^2 + \frac{\lambda_3}{2} v^2,$$

$$m^2(\eta_R^0) = m_R^2 = m_2^2 + (\lambda_3 + \lambda_4 + \lambda_5) \frac{v^2}{2},$$

$$m^2(\eta_I^0) = m_I^2 = m_2^2 + (\lambda_3 + \lambda_4 - \lambda_5) \frac{v^2}{2}.$$

The boundedness of the potential from below gives the conditions

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 \pm \lambda_5 > -\sqrt{\lambda_1 \lambda_2}.$$

In this model either η_R^0 or η_I^0 can be a dark matter particle. Specifically, we analyze η_I^0 to be the dark matter particle.

The relavant formula for the relic abundance is

$$\Omega h^{2} = \frac{1.07 \times 10^{9} x_{f}}{\sqrt{g_{*}} m_{PL} \langle \sigma \mathbf{v} \rangle},$$

$$x_{f} = \ln X - .5 \ln(\ln X),$$

$$X = .038 \left(\frac{3}{\sqrt{g_{*}}}\right) m_{PL} m_{I} \langle \sigma \mathbf{v} \rangle$$

The various annihillation processes in our present model are

$$\begin{split} \eta_I^0 \eta_I^0 &\to W^+ W^-, \ ZZ, \ hh \\ &\to h \to f\bar{f}, \ W^+ W^-, \ ZZ, \ hh \ \ (\text{s-channel}) \\ &\to \eta^+ \to W^+ W^- \ \ (\text{t-channel}) \\ &\to \eta^- \to W^+ W^- \ \ (\text{t-channel}) \\ &\to \eta_R^0 \to ZZ \ \ (\text{t-\&u-channels}) \\ &\to \eta_I^0 \to hh \ \ (\text{t-\&u-channels}) \end{split}$$

Relic abundance plots



We have taken $m_{\eta_R} = 140 \text{ GeV}$ and $m_{\eta^{\pm}} = 160 \text{ GeV}$.

Invisible Higgs decays

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Total Higgs decay width



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Production of η 's at the ILC



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- At the ILC the charged and neutral components of η can be pair produced.

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$$e^+e^- \to \eta^0_R \eta^0_I, \quad \eta^0_R \to Z \eta^0_I \quad (2)$$

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The process (1) has similarities with some processes in the supersymmetry and little Higgs models.

Supersymmetry



- In the minimal supersymmetric standard model (MSSM) with conserved R-parity, the lightest neutralino (χ^0) is a good candidate for the dark matter.
- Its charged counter-parts are charginos (χ_1^{\pm} and χ_2^{\pm}).
- The masses of the charginos depend on: SU(2) gaugino mass M_2 , μ parameter and $\tan \beta$.
- For consistent supersymmetric parameters, the following process can happen at the ILC.

$$e^+e^- \to \chi^+\chi^-, \quad \chi^\pm \to W^\pm\chi^0$$

little Higgs models



- Little Higgs models are effective field theories having an upper cut-off of 10 TeV.
- These models have higher gauge symmetry which breaks into electroweak gauge group at around TeV.
- In the little Higgs model with T-parity, heavy photon (A_H) can be a dark matter candidate and its charged counter-part is heavy gauge boson W_H^{\pm} .

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- These models have higher gauge symmetry which breaks into electroweak gauge group at around TeV.
- In the little Higgs model with T-parity, heavy photon (A_H) can be a dark matter candidate and its charged counter-part is heavy gauge boson W_H^{\pm} .
- At the ILC, we can have process

$$e^+e^- \to W^+_H W^-_H, \quad W^\pm_H \to W^\pm A_H$$

Distinguishing the nature of dark matter particles at the ILC

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Dark scalar doublet model:

$$e^+e^- \rightarrow Z, \gamma \rightarrow \eta^+\eta^- (s - \text{channel process})$$

 $e^+e^- \rightarrow N \rightarrow \eta^+\eta^- (t - \text{channel process})$

MSSM with R-parity:

$$e^+e^- \rightarrow Z, \gamma \rightarrow \chi^+\chi^- (s - channel process)$$

 $e^+e^- \rightarrow \tilde{\nu} \rightarrow \chi^+\chi^- (t - channel process)$

little Higgs model with T-parity:

$$e^+e^- \rightarrow Z, \gamma \rightarrow W^+_H W^-_H \text{ (s-channel process)}$$

 $e^+e^- \rightarrow \nu_H \rightarrow W^+_H W^-_H \text{ (t-channel process)}$

Angular distributions



Angular distributions



Total cross sections



Total cross sections



- Dark scalar doublet model is a viable model to explain the neutrino masses and dark matter
- The scalar dark matter particle of this model effects the Higgs boson decays in some parametric regions. For the Higgs boson mass less than 160 GeV, the Higgs would decay invisibly and give missing enery signals.
- The scalar charged particles of this model can be pair produced at the ILC, and they sbusequently decay into a *W*-boson and dark matter particle.
- This signal has similarities with some signals in the MSSM with R-parity and little Higgs with T-parity models.
- We have studied the angular distributions of the charged scalar particles and the analogous processes in the supersymmetry and little Higgs models.
- From the distributions, it seems to be the nature of the dark matter particle of these three models can be distinguished.
- Currently, we are doing simulations for these three processes at the ILC.

Back-up slide



Total cross section is 1 fb for $m_{\eta^{\pm}} = 200$ GeV.

Back-up slide



Total cross section is 15.5 fb for $m_{\eta^{\pm}}$ =200 GeV.