Direct Probing of Majorana and Extended Higgs Particles in Radiative Seesaw Models at the ILC

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Introduction

- After the discovery of Higgs(-like)-boson at the LHC in July 2012, "Higgs Mechanism" is going to be established as the origin of masses of elementary particles except neutrinos.
- Then, we would ask "what is the origin of tiny masses of neutrinos?"
- Theoretically, it has been proposed that the "Seesaw Mechanism" could explain it by introducing right-handed neutrinos and Majorana masses.

Seesaw Mechanism and Radiative Seesaw Models:

- Dimension 5 effective operator $\mathcal{L} = \frac{C_\nu}{2\Lambda} \bar{\nu}^I \nu^I \Phi \Phi^*$ gives neutrino mass matrix $M^{ij}_\nu = C_{\nu ij} \langle \Phi \rangle^2 / \Lambda$.

  Original seesaw model: $C_\nu \sim \mathcal{O}(1)$ and $\Lambda \sim 10^{14}$ GeV.
  - Minakawa, Yanagida, Gell-Mann,
- Radiative seesaw models: $C_\nu \sim (1/16\pi)^4$ with $\Lambda \sim$ TeV.
  - Here, we focus on the Ma & AKS models: Models with extended Higgs sector, right-handed neutrinos, and which introduce a discrete symmetry ($Z_2$) to forbid tree-level Dirac mass of neutrinos, and study the ILC search and mass determination.

Collider Phenomenology of Radiative Seesaw Models (Ma & AKS):

- **Ma model (THDM(Inert) + $N_R$)**
  - Particle contents: $\Phi_1, \Phi_2, N^R (Z_2 -$odd)
  - Additional doublet scalar $\Phi_2$ does not get VEV → "Inert"
  - Exact $Z_2$ symmetry forbid Dirac mass for neutrinos.

- **Inert scalars** $\Phi_2 = \left( \epsilon^+, \epsilon^0 \right)$
  - Lightest scalar is a candidate of DM (we assume it is $\xi^0$)
  - Direct search, Relic density
    - $m_{\xi^0} \approx 45 - 80$ GeV
  - Decays: (off-shell) gauge-boson plus DM
    - $\xi^0 \rightarrow W^\pm \xi, Z \xi$

- Neutrino masses:
  - $M_{ij}^{\nu} \sim \frac{1}{16\pi^2} \frac{k^{N_R} (\Phi_1^0)^2}{M_{N_R}^2}$
  - $\Lambda \sim (1/10^6 - 10^{-4})$; small couplings with RHN.

- **AKS model (THDM(Type-X) + singlet scalars + $N_R$)**
  - Particle contents: $\Phi_1, \Phi_2, S, e, \eta, N^R (Z_2 -$odd)
    - THDM: avoid FCNC
    - $b \rightarrow s$ constraint
    - reproduce neutrino data
    - LEP precision data
  - Singlet Scalars
    - $Z_2 -$odd neutral particle $\eta = $DM
      - a room for Electroweak Baryogenesis (1st order PT and CP phase)
      - constraints from LFV $m_{\eta \gamma} > 400$ GeV, $m_{\eta \nu} > 5$ TeV
  - Neutrino masses:
    - $M_{ij}^{\nu} \sim \frac{1}{16\pi^2} \frac{k^{N_R} (\eta^0)^2}{M_{N_R}^2}$
      - $\Lambda \sim (1/10^6 - 10^{-4})$ hierarchy to RHN

Conclusion

- Radiative seesaw models are one of the possibility to realize the seesaw mechanism at the TeV scale, which consist of extended Higgs sector and right-handed neutrinos (source of Majorana nature).
- We studied detailed collider phenomenology for these models; LHC has chance to see some signals; ILC (with $\nu e$ option) is the best machinery to probe these models.
- We discussed kinematical methods for mass determination at the ILC.