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

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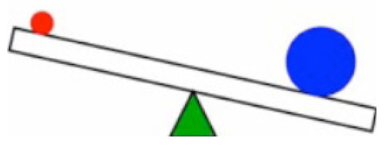
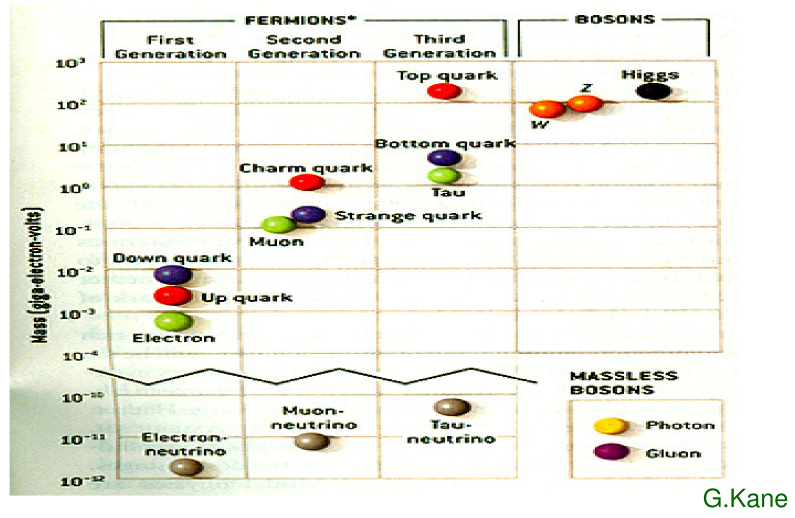
Introduction

- 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**.



$$(\nu_L \;\; \nu_R)\begin{pmatrix} & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix} \;\Rightarrow\; m_\nu = \frac{m_D^2}{M} << m_D$$



G.Kane

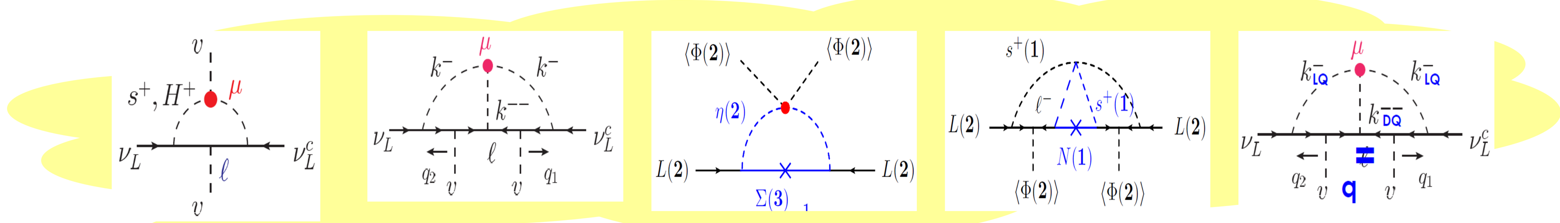
Seesaw Mechanism and Radiative Seesaw Models:

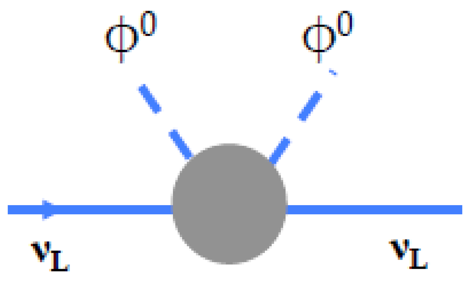
- Dimension 5 effective operator $\mathcal{L} = \frac{c_{ij}}{2\Lambda}\overline{\nu^c}^i_L \nu^j_L \phi^0\phi^0$ gives neutrino mass matrix $M_\nu^{ij} = c_{ij}\langle\phi^0\rangle^2/\Lambda$

  Original seesaw model: c_{ij}~O(1) and Λ~M_R~10^{14}GeV. Minkowski, Yanagida, Gell-Mann,,,

$$M_\nu^{ij} \sim 0.1\text{eV} \rightarrow \boxed{c_{ij}/\Lambda \sim 1/(10^{14}\text{GeV})}$$

- **Radiative seesaw models**: c_{ij}~$(1/16\pi^2)^n$ with Λ~TeV. **← accessible at collider!**





- ➢ Derive small coefficients by quantum (loop) effects.
- ➢ Varieties of models have been proposed: Zee,Zee-Babu,Ma,Ma-Suematsu,Krauss-Nasri-Trodden,Aoki-Kanemura-Seto,,,
- ➢ Here, we focus on the Ma & AKS models: Models with **extended Higgs sector**, **right-handed neutrinos**, → DM candidate in the model
  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):

Aoki,Kanemura(10), Aoki,Kanemura,HY in progress

Ma model (THDM(Inert) + N_R)

Ma (06)

- Particle contents: Φ_1, Φ_2, N_R (Z_2-odd)

  Additional doublet scalar Φ_2 does not get VEV → "Inert"
  Exact Z_2 symmetry forbid Dirac mass for neutrinos.

- Inert scalars $\Phi_2 = \left(\xi^+, \frac{1}{\sqrt{2}}(\xi_r + i\xi_i)\right)$

  Another possibility: N_R DM Kubo,Ma,Suematsu (06)

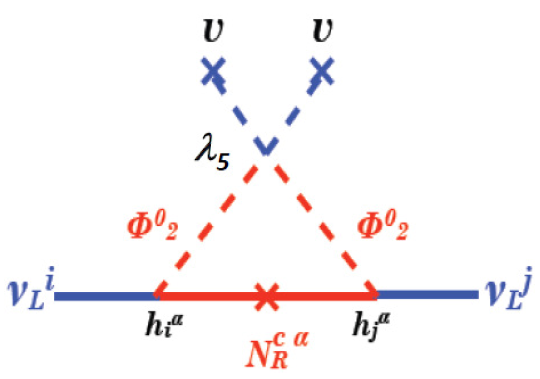
  Lightest scalar is a candidate of DM (we assume it is ξ_r)

  Direct search, Relic density $\rightarrow m_{\xi_r} = 45 - 80$ GeV — Honorez etal(07), Gustafsson etal(12)

  Decays: (off-shell) gauge-boson plus DM
  $\xi^\pm \rightarrow W^\pm\xi_r,\ \xi_i \rightarrow Z\xi_r$

- Neutrino masses:

$$M_\nu^{ij} \simeq \frac{1}{16\pi^2}\cdot\frac{h_i^\alpha h_j^\alpha \lambda_5 v^2}{M_{N_R^\alpha}}$$



$$h_i^\alpha h_j^\alpha \lambda_5 \sim 10^{-9}$$

h~O(10^{-2}–10^{-5}); small couplings with RHN.

LEP II limits: $\Delta M = m_{\xi_r} - m_{\xi_i} < 8$ GeV or $m_{\xi_i} > 100$ GeV — Lundstrom etal(09)

LHC search: Multi-lepton + missing E_T signatures $pp \rightarrow \xi^+\xi^-, \xi^\pm\xi_{r/i}, \xi_r\xi_i$ — Cao etal(07), Dolle etal(10), Mia etal(10), Gustafsson etal(12)

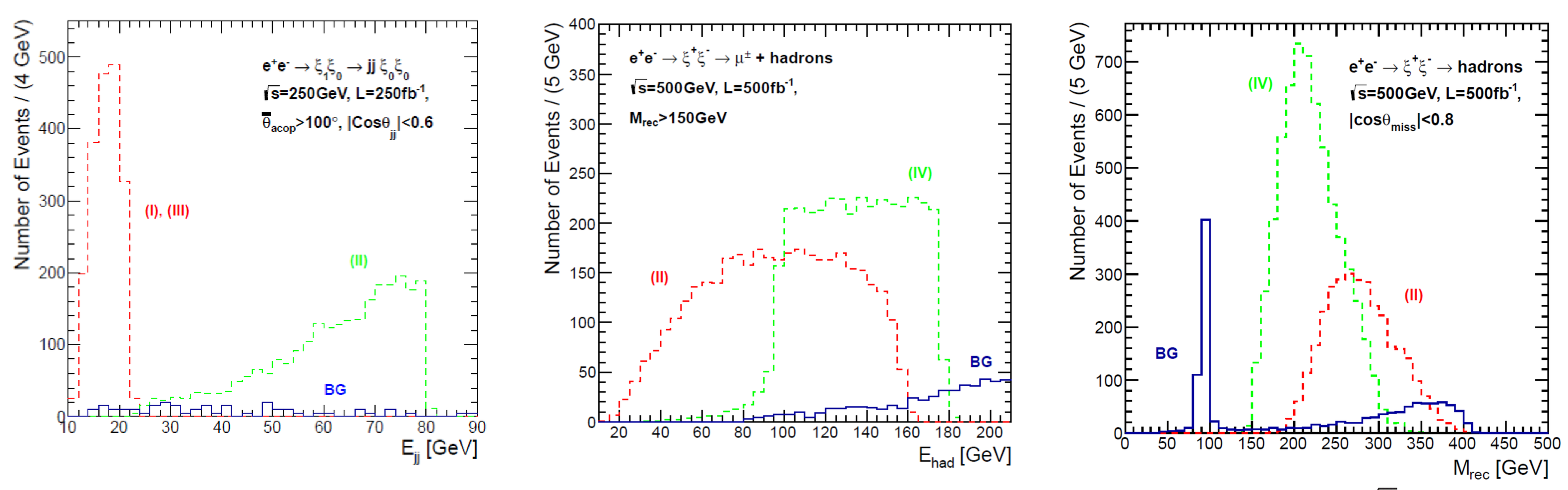
Signal for large ΔM case may be seen.

ILC search & Mass measurements:

Aoki,Kanemura(10), Aoki,Kanemura,HY in progress

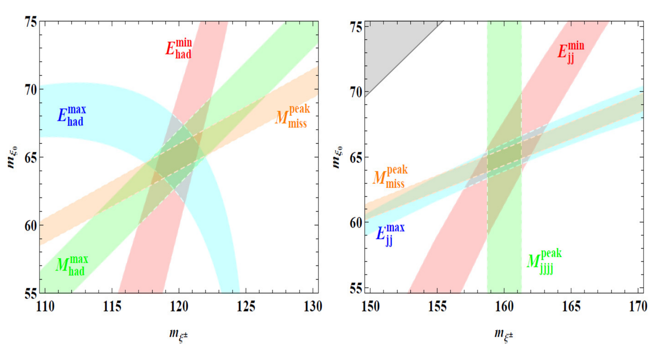
Benchmark points: (I) $(m_{\xi^\pm}, m_{\xi_i}, m_{\xi_r}) = (120, 73, 65)$ GeV, (II) $(120, 120, 65)$ GeV, (III) $(160, 73, 65)$ GeV, (IV) $(160, 160, 65)$ GeV.

$e^+e^- \rightarrow \quad \xi_r\xi_i \rightarrow \ell^+\ell^-(jj)\xi_r\xi_r$, [dilepton (dijet) + missing energy]
$\xi^+\xi^- \rightarrow W^+W^-\xi_r\xi_r$ [semi-leptonic or all-hadronic modes]



$(M_{jj}^{max} = m_{\xi_i} - m_{\xi_r})$; $E_{had}^{max/min} = \gamma_\xi \bar{E} \pm \gamma_\xi\beta_\xi \bar{p}$, $\gamma_\xi = \frac{\sqrt{s}}{2m_{\xi^\pm}}$ and $\bar{E} = \frac{m_{\xi^\pm}^2 + m_W^2 - m_{\xi_r}^2}{2m_{\xi^\pm}}$; $M_{rec}^{peak} = \frac{\sqrt{s}m_{\xi_r}}{m_{\xi^\pm}}$ $\left(M_{had}^{peak} = \frac{\sqrt{s}m_W}{m_{\xi^\pm}}\right)$

At the ILC, clear signatures can be observed even for small ΔM case, and the masses are precisely determined!



- N_R is very difficult because of too small couplings. dNeeds some hints from LFV, 0νββ.

Figures are preliminary, Aoki,Kanemura,HY in progress

AKS model (THDM(Type-X) + singlet scalars + N_R)

Aoki,Kanemura,Seto(09), Aoki,Kanemura,Yagyu(11)

- Particle contents: $\Phi_1,\ \Phi_2 = \left(H^+, \frac{1}{\sqrt{2}}(H + iA)\right),\ S^\pm,\ \eta,\ N_R$ (Z_2-odd)

THDM
- avoid FCNC
- b→sγ constraint
- reproduce neutrino data
- LEP precision data

⇒
- $m_{H^+} \simeq$ 100-200 GeV
- only couple to leptons ⇒ **Type-X Yukawa int.**
- $m_H \simeq m_{H^+}$

Singlet Scalars
- Z_2-odd neutral particle η=DM
- a room for Electroweak Baryogenesis (1st order PT and CP phase)
- constraints from LFV $m_{S^\pm} > 400$ GeV, $m_{N_R} > 5$ TeV

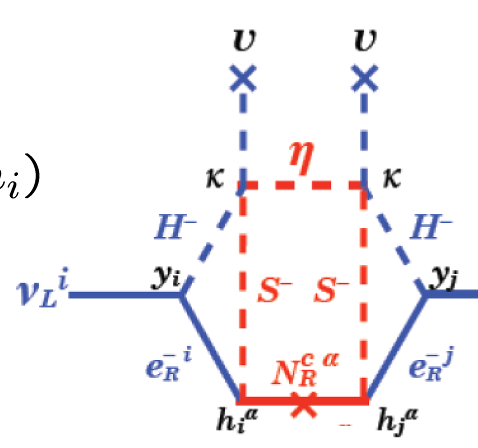
- Neutrino masses:

$$M_\nu^{ij} \simeq \left(\frac{1}{16\pi^2}\right)^3 \kappa^2 (y_{e_i}h_i^\alpha)(y_{e_j}h_j^\alpha)F^\alpha(m_i)$$

$$\boxed{\Sigma_\alpha^{1,2}(h_e^\alpha)^2 > \Sigma_\alpha^{1,2}(h_\mu^\alpha)^2 > \Sigma_\alpha^{1,2}(h_\tau^\alpha)^2}$$

⇧O(1)

hierarchal couplings to RHN

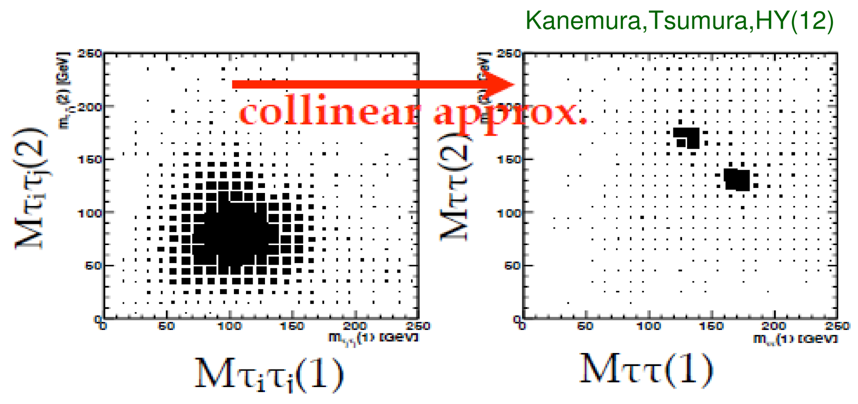


- Collider signatures of Type-X THDM = multi-τ events: Aoki,Kanemura,Tsumura,Yagyu(09), Kanemura,Tsumura,HY(12)

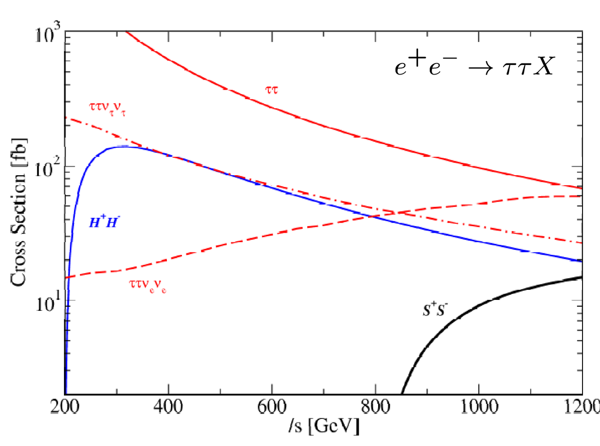
$$\begin{cases} pp \rightarrow HA \rightarrow 4\tau, \\ pp \rightarrow H^\pm H, H^\pm A \rightarrow 3\tau + \nu_\tau, \\ e^+e^- \rightarrow HA \rightarrow 4\tau \end{cases}$$

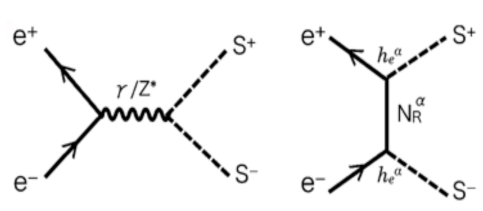
- At the LHC, excess can be easily seen.
- Mass may be measured by the $M_{\tau j \tau j}$ distribution.
- At the ILC, 4τ events can be fully reconstructed by using the collinear approximation.
  → peaks in reconstructed $M_{\tau\tau}$ distribution

Kanemura,Tsumura,HY(12)



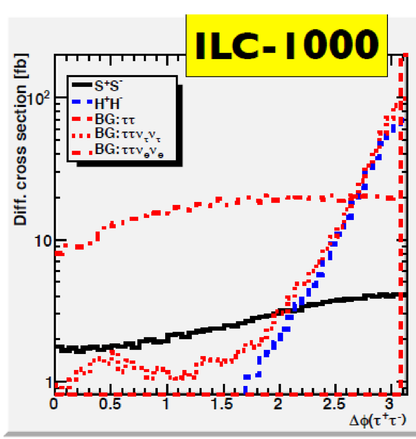
- Search for extra scalars at the ILC: $e^+e^- \rightarrow S^+S^- \rightarrow H^+H^-\eta\eta \rightarrow \tau\nu\tau\nu\eta\eta$



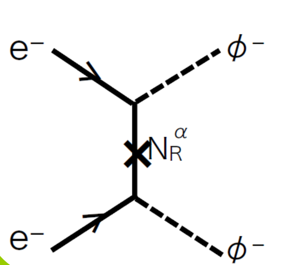


Benchmark point
$m_{S^\pm} = 400$ GeV, $m_{H^\pm} = 100$ GeV,
$m_\eta = 50$ GeV, $m_{N_R} = 5$ TeV

t-ch. RHN exchange effects (large h_e~1 coupling) can be disentangled by using energy dependence, angular distributions.



Electron-electron collider option:



- $e^-e^- \rightarrow \Phi^-\Phi^-$ process is sub-diagrams of the neutrino mass diagrams, thus it could be a direct probe the Majorana nature.
- It is an efficient and important option to the ILC.

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 e^-e^- option) is the best machinery to probe these models.
- We discussed kinematical methods for mass determination at the ILC.