Probing the Majorana nature in radiative seesaw models at collider experiments

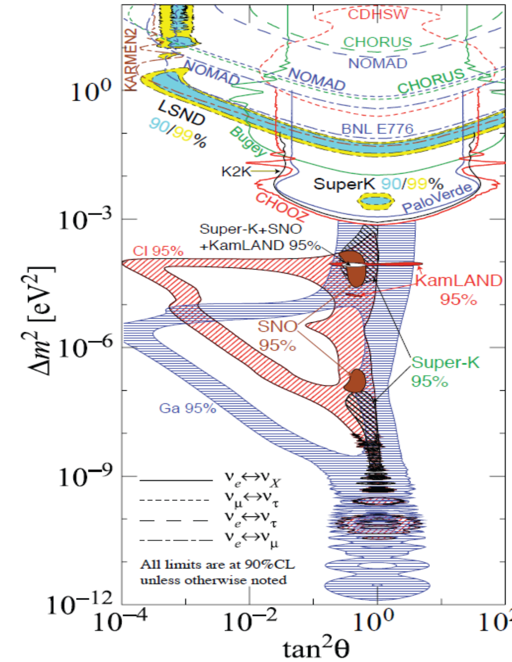
Shinya KANEMURA (U. of Toyama)

M. Aoki, SK and O. Seto, PRL 102, 051805 (2009).
M. Aoki, SK and O. Seto, PRD80, 033007 (2009).
M. Aoki, SK, K. Tsumura, K. Yagyu, PRD80, 015017(2009).
M. Aoki and SK, arXiv: 1001.0092.

LCWS2010, Beijing, China, March 26-30. 2010

Introduction

- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

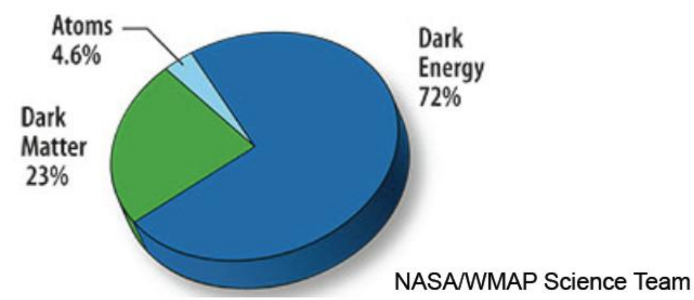


$\Delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2,\ \ \Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$

  - Dark Matter

$\Omega_{DM} h^2 \sim 0.11$

  - Baryon Asymmetry of the Universe



$n_B/s \sim 9 \times 10^{-11}$

To understand these phenomena, we need to go beyond-SM

Neutrino Mass

Neutirno Mass Term (= effective Dim-5 Operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

$\langle\phi\rangle = v = 246\text{GeV}$

Mechanism for tiny masses:

$$m^{\nu}{}_{ij} = [c_{ij}\,(v/M)\,]\, v \; < 0.1\ \text{eV}$$

Seesaw (tree level)

$$m^{\nu}{}_{ij} = y_i y_j\, v^2/M$$

$M \sim 10^{14}\text{GeV}$ (for $y_i = O(1)$)

Quantum Effects (Radiative Seesaw)

N-th order of perturbation

$$m^{\nu}{}_{ij} = [1/(16\pi^2)]^N\, C_{ij}\, v^2/M$$

$M = O(1)$ TeV

Neutrino Mass

Neutirno Mass Term (= effective Dim-5 Operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

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<u>Seesaw (tree level)</u>

$m^\nu{}_{ij} = y_i y_j\, v^2/M$ $\qquad M \sim 10^{14}\text{GeV}$ (for $y_i = O(1)$)

<u>Quantum Effects (Radiative Seesaw)</u> N-th order of perturbation

$m^\nu{}_{ij} = [1/(16\pi^2)]^N\, C_{ij}\, v^2/M$ $\qquad M = O(1)$ TeV

Radiative Seesaw Model

A Neutrino Mass Generation Mechanism at Loop

Feature

1. Extended Higgs (scalar) sector
2. Majorana nature

Merit

– A super high scale is not necessary.

Tiny m_ν can naturally be deduced from TeV scale physics by higher order perturbation

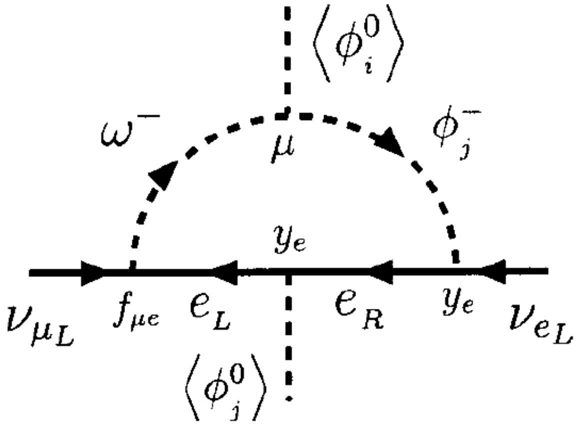
– Physics at TeV:

Testable at collider experiments

Zee Model

2HDM + (charged singlet ω^+)

Lepton # violaiting interaction μ



Zee, PLB93,389 (1980)

Excluded by the data

Models of radiative ννϕϕ generation

Tiny ν-Masses come from loop effects

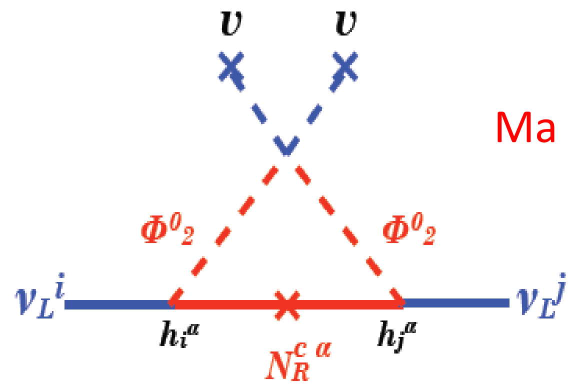
- Ma (1-loop)
  Ma, PRD73,077301 (2006)
- Zee-Babu (2-loop)
  Babu, PLB203,132(1988)
- Aoki-Kanemura-Seto (3-loop)
  PRL102, 051805(2009)

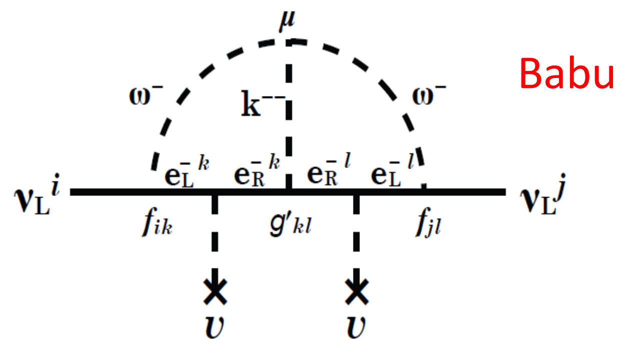
m^{ν}_{ij} = $[1/(16\pi^2)]^N$ C_{ij} v^2/M M=O(1) TeV

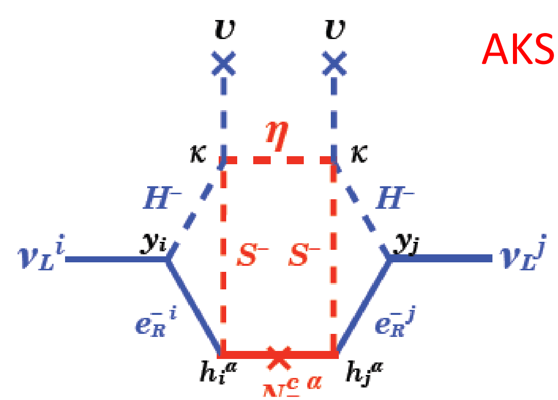
Common features

Extended Higgs sector

Source of the Majorana nature







The Zee-Babu model

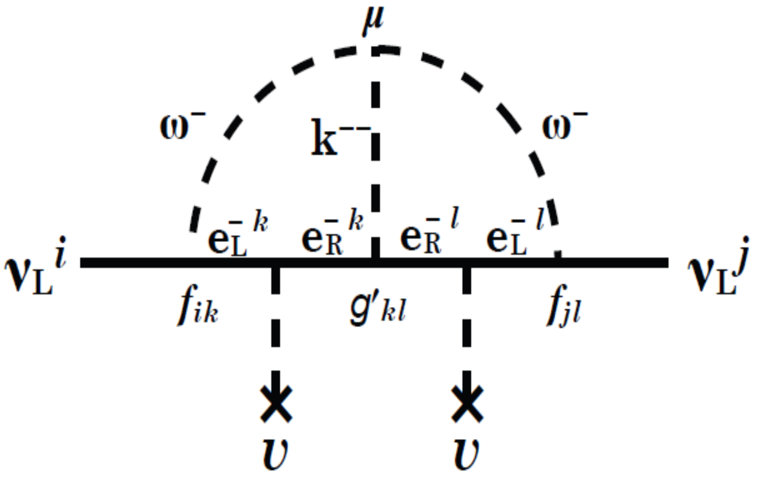
Model:

SM + ω^{+}, κ^{++} (charged scalar singlets: L#=2)

Babu, PLB203,132(1988)

Source of the Majorana nature:

LNV interaction (μ)

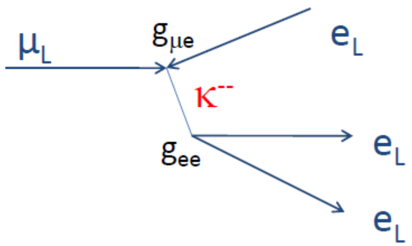


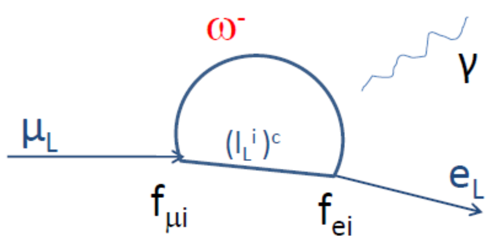
Neutrino masses generated at 2-loop

$f_{em} \sim f_{e\tau} \sim f_{\mu\tau}/2$ (Normal Hierarchy)

$g_{\mu\mu} : g_{\mu\tau} : g_{\tau\tau} \sim 1 : m_{\mu}/m_{\tau} : (m_{\mu}/m_{\tau})^2$

Constraints on couplings from LFV data





Bound on the masses: $m_{\omega} > 160$ GeV, $m_{\kappa} > 770$ GeV (for $g_{\mu\mu} \sim 1$)

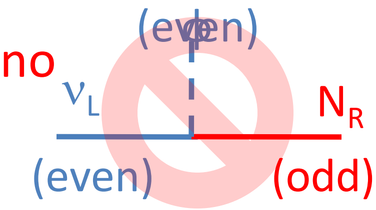
Babu, Macesanu (2003), Aristizabal Sierra, Hirsch (2006)

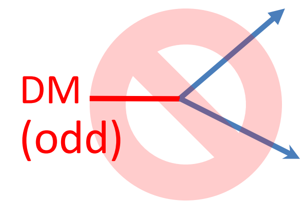
The Ma model

Ma, PRD73,077301 (2006)

Source of the Majorana nature: TeV-scale RH neutrino

No tree-level neutrino Yukawa: Exact Z_2-parity



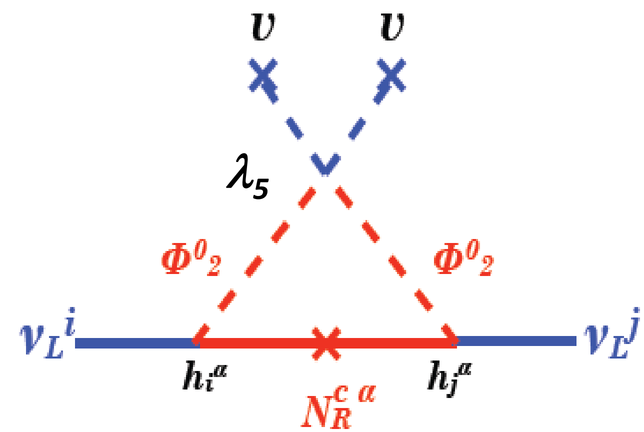


Model: 2HDM (Z_2-even Φ_1 , Z_2-odd Φ_2)
+ RH-Neutrino (Z_2-odd N_R)

Neutrino masses generated at 1-loop

The lightest Z_2odd particle can be DM

DM candidate: Either Φ^0_2 (ξ^0_r , ξ^0_i) or N_R



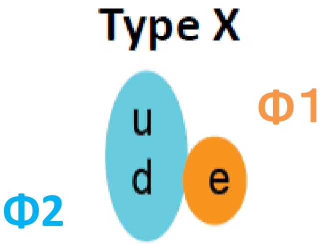
A special 2HDM: $\Phi_2 = (\xi^+, \xi^0_r + i\, \xi^0_i)$ does not receive VEV

The second doublet is so-called Inert Doublet, or Dark Doublet

Example of parameters that explain the neutrino data, LFV data and the WMAP:

$M_N{}^\alpha$=3 TeV, $M_{\xi r}$ =50 GeV, $M_{\xi i}$=60GeV, $M_{\xi +}$ =100GeV

λ_5=O(10^{-2}) $h_i{}^\alpha$=O(10^{-5})

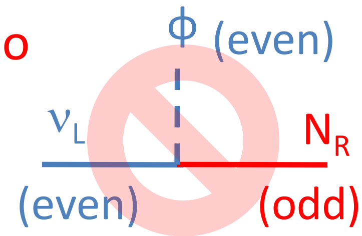


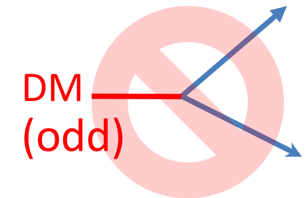
The 3-loop model (AKS)

M.Aoki, SK, O.Seto, PRL 102,051805(2009)

Source of the Majorana nature: TeV-scale RH neutrino

Exact Z_2-parity : No tree-level neutrino Yukawa





Model:	Type-X 2HDM (Z_2-even Φ_1 , Φ_2)
	+ singlet scalars (Z_2-odd η, S-)
	+ RH-Neutrino (Z_2-odd N_R)

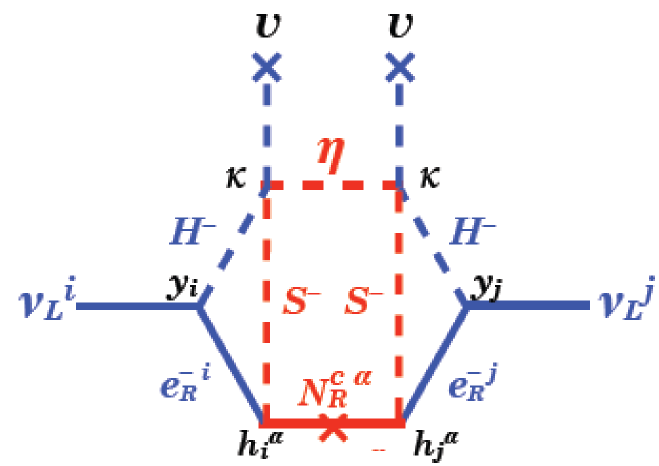
1. Neutrino masses are generated at 3-loop.
2. DM: the lightest Z_2odd particle .

   DM candidate: ~~Either~~ η ~~or N_R~~

3. Electroweak Baryogenesis

   1st order phase transition

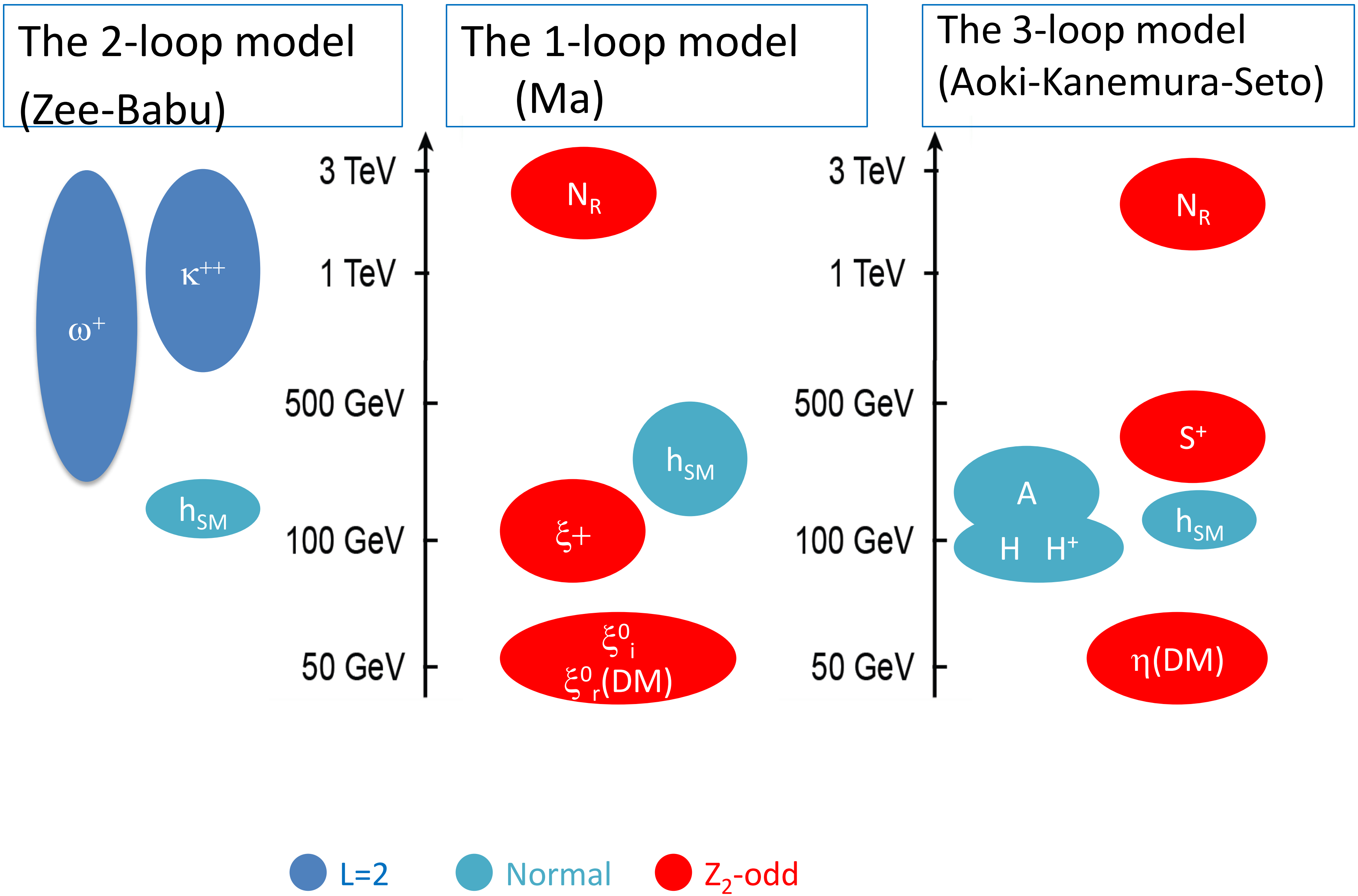
   Extra CP Phases



In addition, 3-loop generation may be more natural to explain tiny neutrino masses by the TeV-scale dynamics. [with Coupling = O(1)]

$$h_e^{1,2} = \kappa = O(1) >> h_\mu^{1,2} >> h_\tau^{1,2} \text{ for } M_{NR}{}^\alpha = 3\text{TeV}, \ldots$$

Typical mass spectra in RSMs



Test of the models at collider experiments

Common features of the radiative seesaw models

Extended Higgs sector

Charged Higgs physics (all)

Physics of κ^{++} (Zee-Babu model)

Scalar DM (Ma, AKS) → invisible decay of the SM-like Higgs

The Majorana nature

LNV couplings (Zee-Babu)

or TeV-scale N_R with Z_2 parity (Ma, AKS)

LHC: pp

(7 TeV 1fb^{-1}, 14 TeV 10-100fb^{-1})

Structure of Higgs sector, Invisible decay of Higgs can be explored

ILC: e^+e^-, e^-e^-

(E=300GeV-1TeV, 100fb^{-1}-1ab^{-1})

Not only the Higgs sector and DM, but also Majorana nature can be explored

Physics of Extra Higgs at LHC

Ma model

Cao, Ma, PRD76, 095011 (2007)

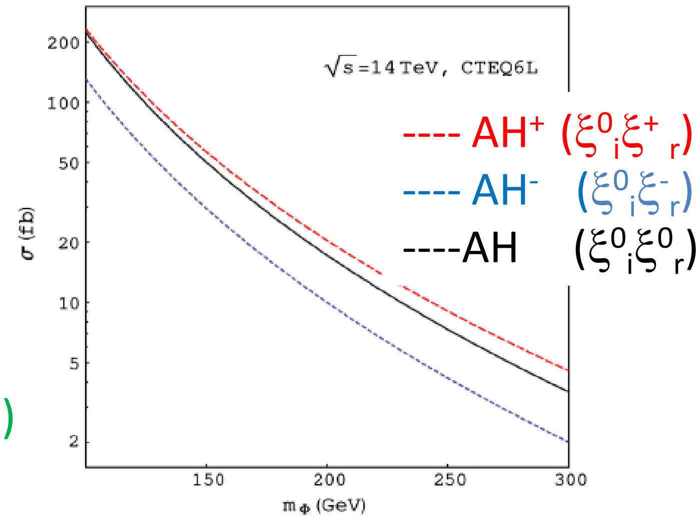
$$pp \to \xi^0{}_i \xi^0{}_r \to Z^* \xi^0{}_r \xi^0{}_r \to f\bar{f}\ \xi^0{}_r \xi^0{}_r$$

$\mathcal{L} = 100\ \text{fb}^{-1}$ $m_{\xi 0}$=150GeV

Signal: ll + $\not{E}_T$

	Basic	Optimal
signal	117	37
BG (WW,ZZ)	1.3×10^5	62
$S/\sqrt{B}$	0.32	4.70

Pair production of
the second doublet scalars



3-loop (AKS) model

Aoki, SK, Tsumura, Yagyu (2009)

$$pp \to AH^\pm \to \tau^+\tau^-\tau\nu$$ (Type-X Yukawa)

$\mathcal{L} = 100\ \text{fb}^{-1}$

(type-II 2HDM: $b\bar{b}\tau\nu$)

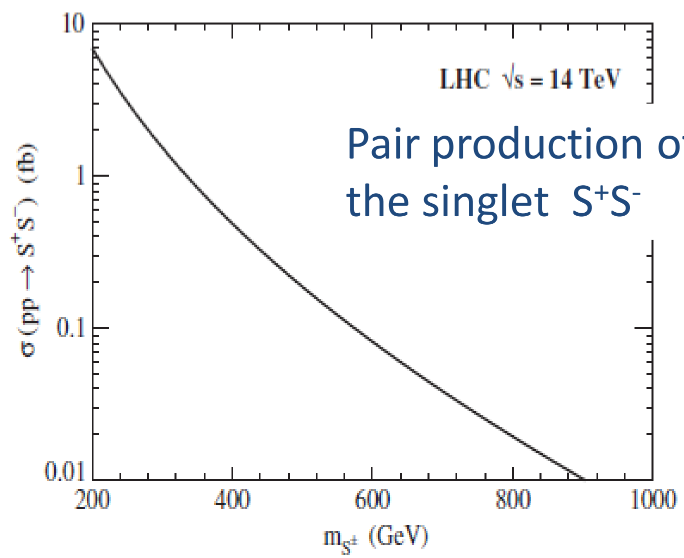
	Basic
$\tau^+\tau^-\tau\nu$	1.7×10^4
BG($ZW^\pm$)	1.1×10^4
$S/\sqrt{B}$	162

For the singlet S^+ ,
challenging @ LHC

$pp \to S^+S^- \to H^+H^-\ \eta\eta$ (0.37fb)

$pp \to H^+H^-$ (54fb)

m_S=400GeV, m_{H+} =150GeV



Physics of Extra Higgs at LHC

Zee-Babu model

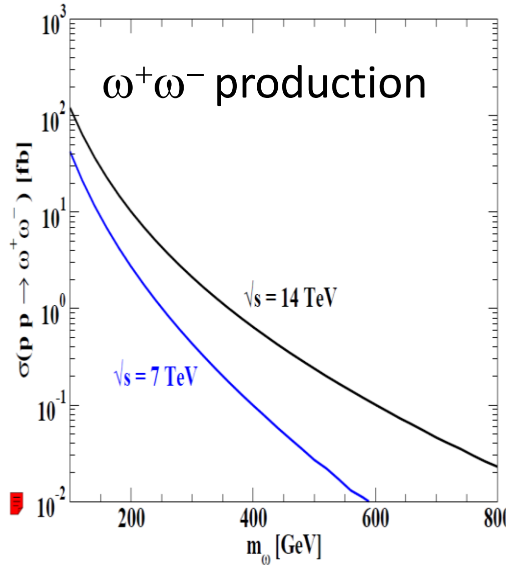
- Singly charged Higgs
- Doubly charged scalars can be discovered at LHC if it is lighter than 800 GeV

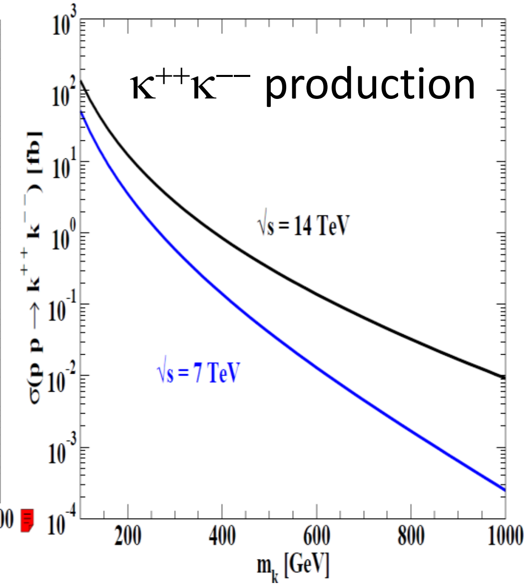
Discrimination from triplet models?

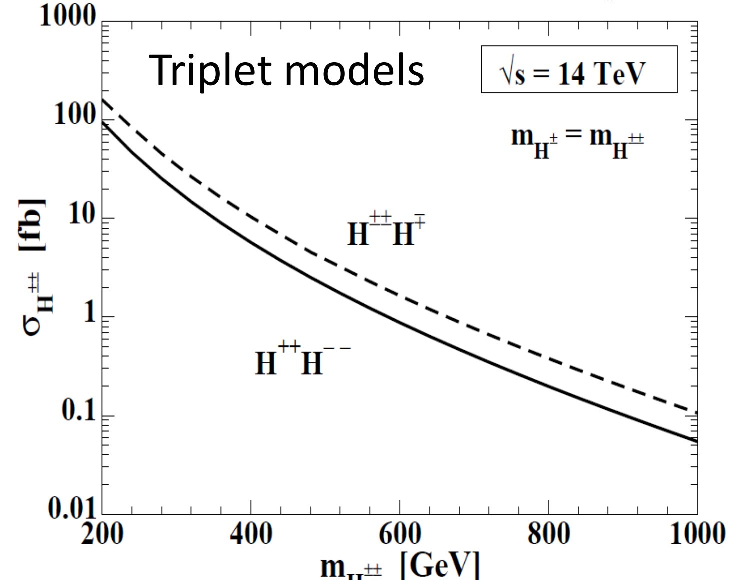
Triplet: (H^{++}, H^{+}, H^{0})

$W^{+}H^{+}H^{--}$ coupling is a useful probe

- Derivative gauge coupling in the triplet model
- No-such coupling in Zee-Babu model





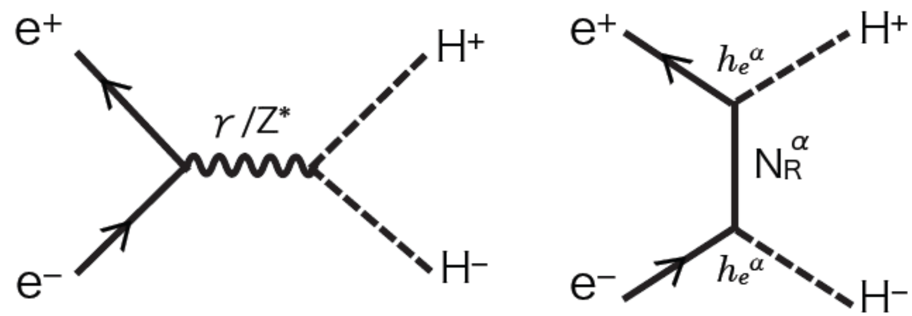


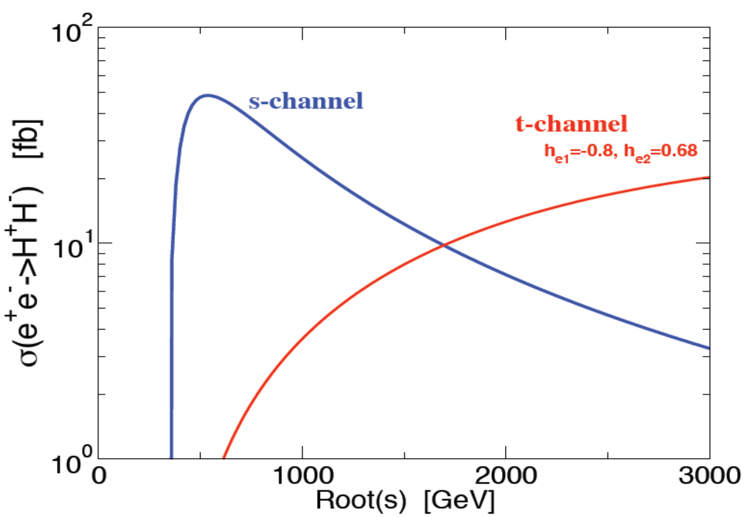
ILC

TeV Right handed neutrinos at ILC

Radiative Seesaw

- Z_2-odd RH neutrinos
- Differently from tree level seesaw scenario, h_e^α coupling can be even O(1) in RSMs
- The t-channel NR mediation diagram can be significant

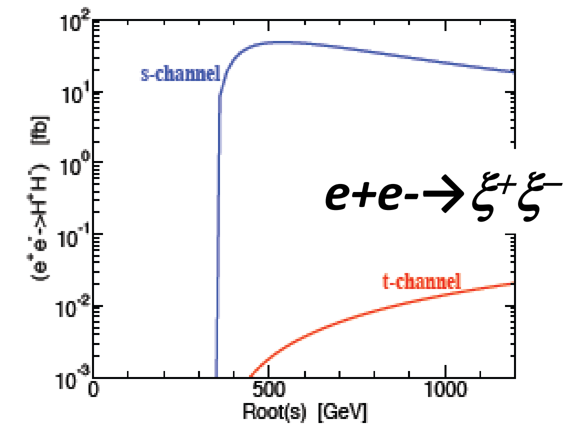




1-loop model (Ma)

$h_e^\alpha < 10^{-2}$

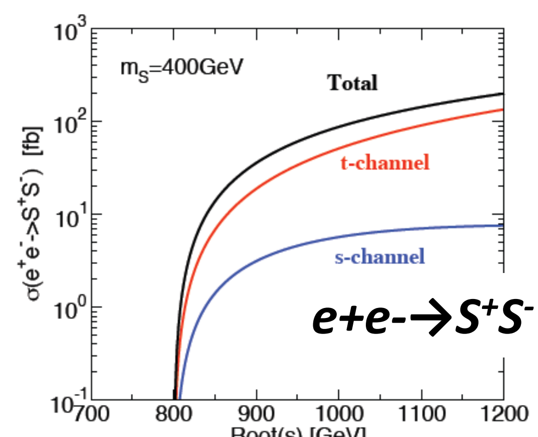
s-channel dominannt



3-loop model (AKS)

$h_e^\alpha = O(1)$

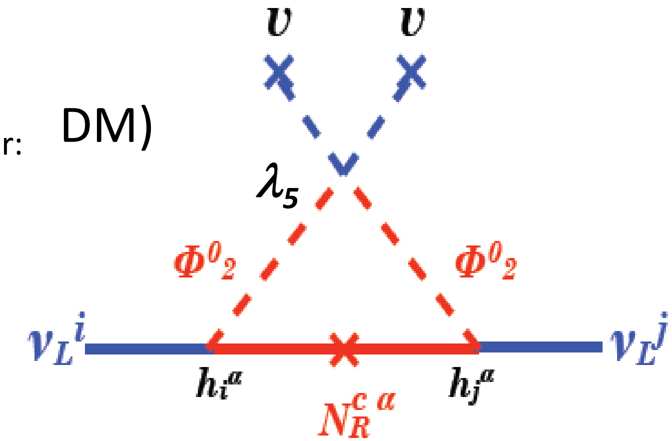
t-channel dominannt



Ma model

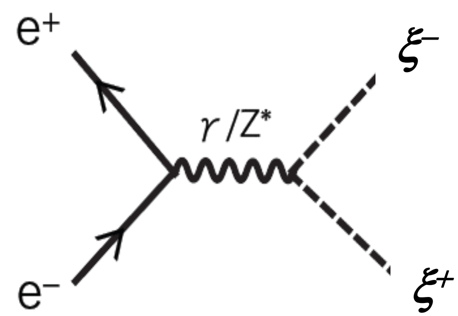
M_N^{α}=3 TeV, $M_{\xi r}$ =50 GeV,
$M_{\xi i}$=60GeV, $M_{\xi +}$ =100GeV
λ_5=O(10^{-2}) h_i^{α}=O(10^{-5})

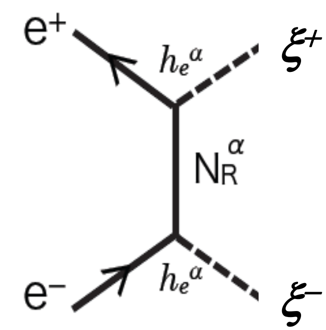
(ξ^0_r: DM)



$\sigma(e+e- \to \xi^+\xi^-)$ = 92 (10) fb
(m_{H+} =100 (150) GeV for E=500GeV)

$e+e- \to \xi^+\xi^-$
$\to W^+W^{-(*)}\ \xi^0_r\xi^0_r$
$\to$ jjjj $\xi^0_r\xi^0_r$ (jj$\mu\nu$ $\xi^0_r\xi^0_r$)



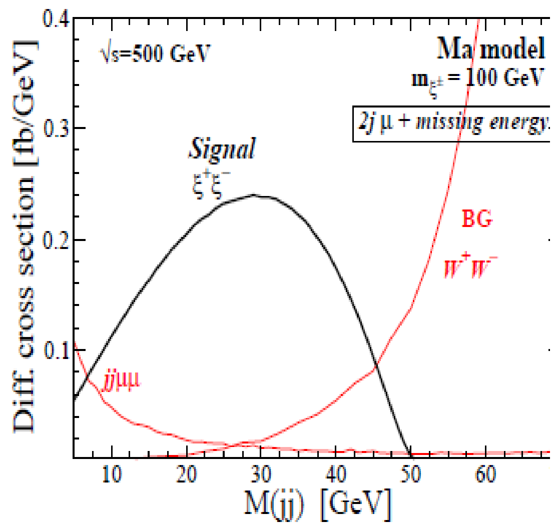


$m_{\xi +}$ =100GeV

Signal: jj μ+ $\not{E}$

Main BG: WW *

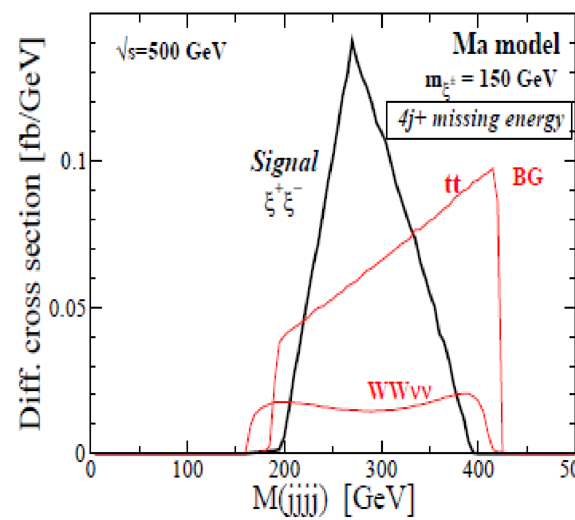
ZZ, $\gamma\gamma$, Zγ with a μ missing



$m_{\xi +}$ =150GeV

Signal: 4 jjjj + $\not{E}$

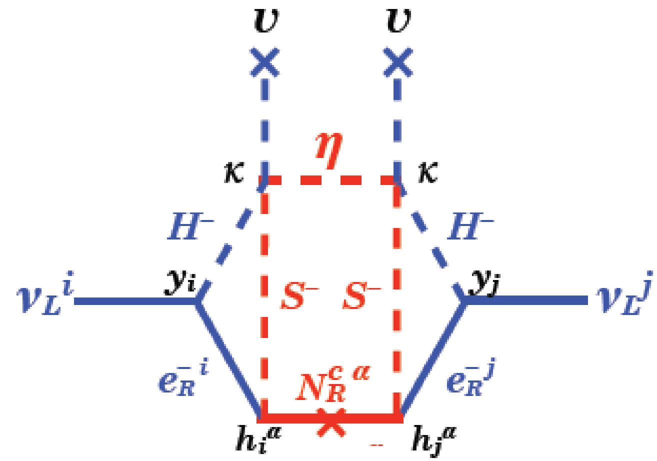
Main BG: WW $\nu\nu$, tt



Aoki, SK, arXiv:1001.0092

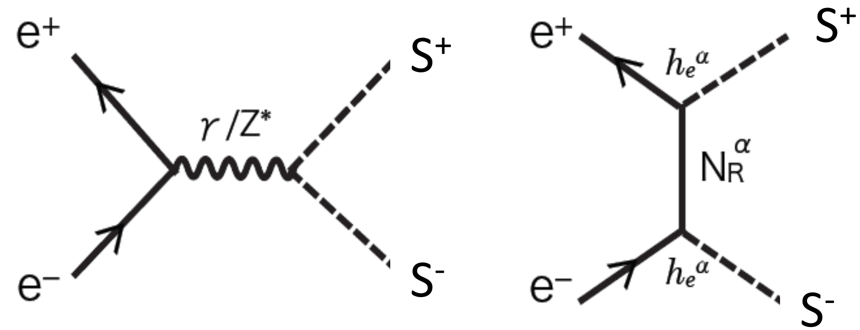
3-loop Model (AKS)

$h_e^{1,2} = \kappa = O(1) >> h_\mu^{1,2} >> h_\tau^{1,2}$
for M_{NR}^α = 3TeV, m_{H+} =100 GeV, m_η=50GeV



t-channel effect dominant

$\sigma(e^+e^- \to S^+S^-)$ = 87 fb
(m_{S+} =400 GeV for E=1TeV)

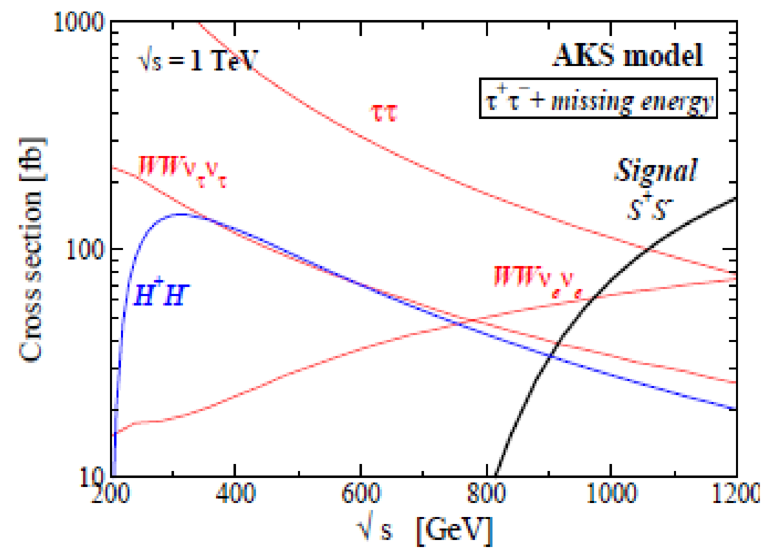


$B(S^+ \to H^+\eta)$ = 100 %
$B(H^+ \to \tau^+\eta)$ ~ 100 %

$e^+e^- \to S^+S^-$
$\to H^+H^- \ \eta\eta$
$\to \tau^+\tau^- \ \nu\nu \ \eta\eta$

Signal: $\tau^+\tau^- + \not{E}$

Main BG $\tau^+\tau^-$, $\tau^+\tau^- \nu\nu$,
H^+H^-



Aoki, SK, arXiv:1001.0092

Direct Test of Majorana Nature at $e^- e^-$ collisions at ILC

- Tree Seesaw
- 1-loop Seesaw

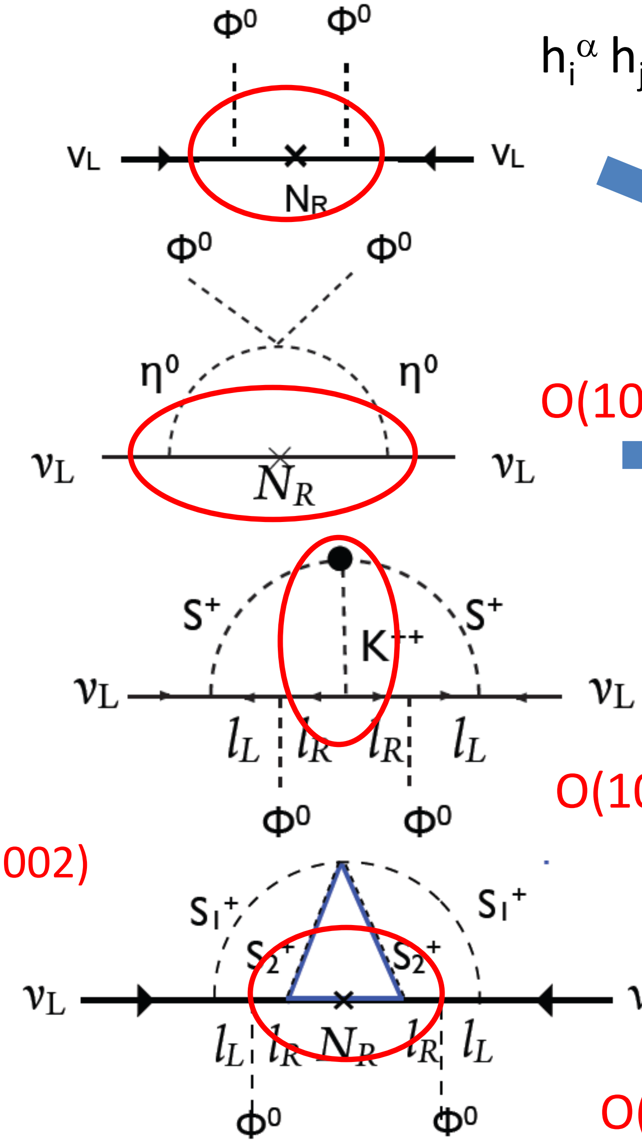
E. Ma

- 2-loop Seesaw

Zee-Babu

- 3-loop Seesaw

Krauss, Nasri, Trodden (2002)
Aoki, SK, Seto (2009)

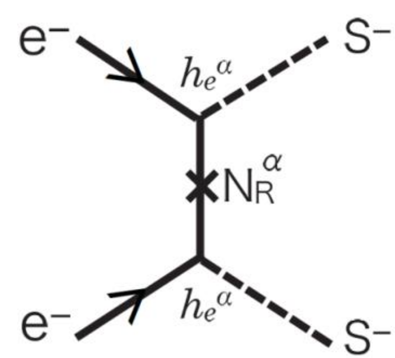


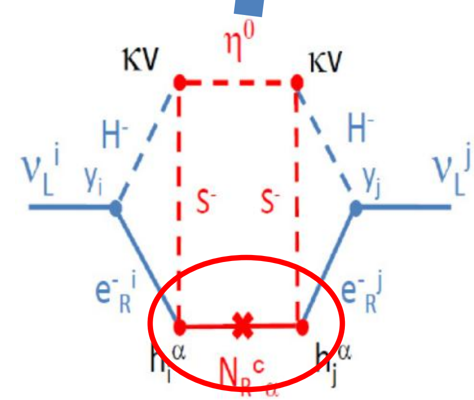
$h_i^\alpha h_j^\alpha (v/M_N) = O(10^{-12})$

$O(10^{-4})$

$O(10^{-1})$

$O(1)$

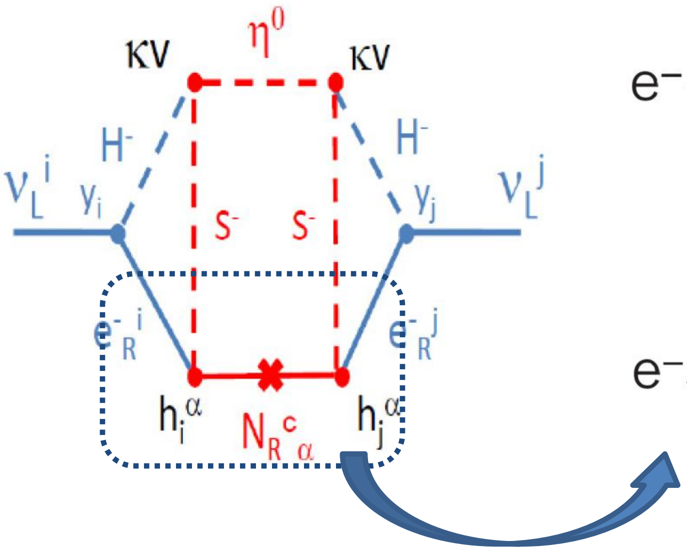


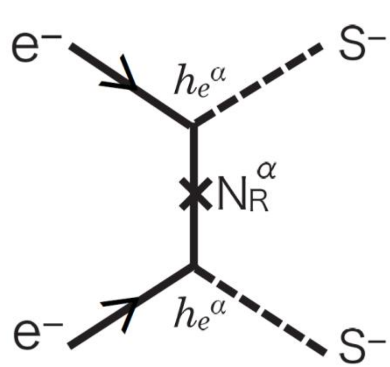


Test the Majorana Nature at ILC

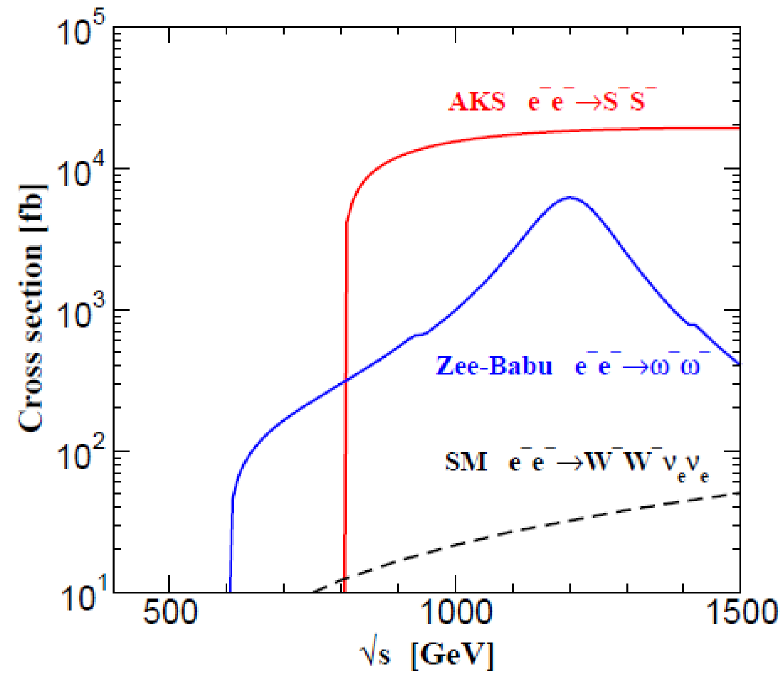
- The sub-diagram itself can be directly measured at the e^-e^- collision.

Aoki, SK, arXiv:1001.0092





$h_e^\alpha = O(1)$

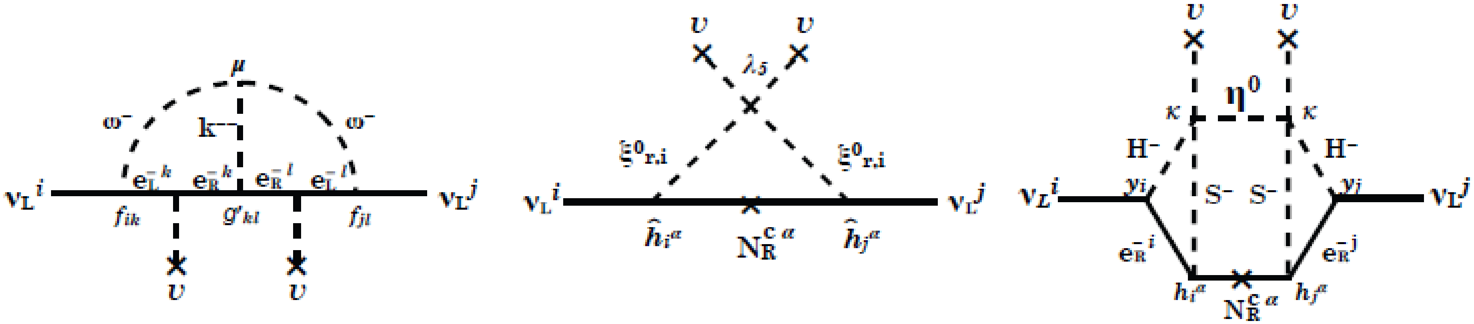


$$\sigma(e^-e^- \to S^-S^-) = \int_{t_{\min}}^{t_{\max}} dt \frac{1}{64\pi s} \left| \sum_{\alpha=1}^{n} (|h_e^\alpha|^2 m_{N_R^\alpha}) \left(\frac{1}{t - m_{N_R^\alpha}^2} + \frac{1}{u - m_{N_R^\alpha}^2} \right) \right|^2$$

Signal: $\tau^-\tau^- + \not{E}$ (AKS); $\mu^-\mu^- + \not{E}$ (Zee-Babu)

There is no substantial BG, the signals can be easily seen

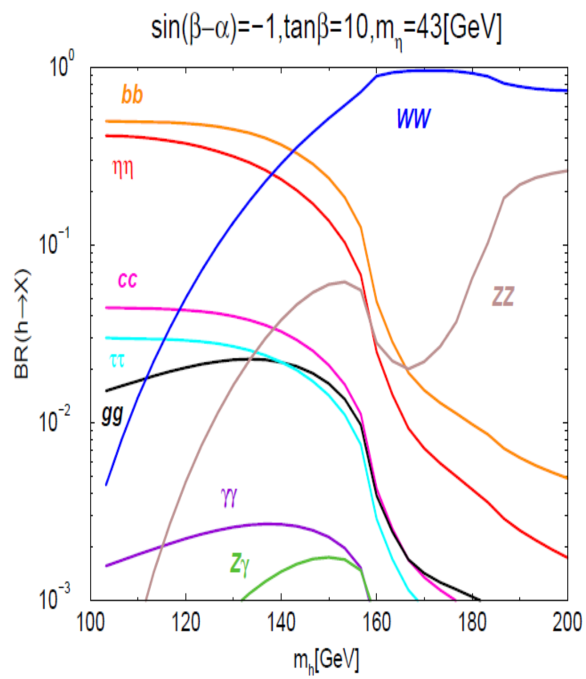
Summary



- Radiative seesaw models are interesting , where the scale of neutrino mass generation can be lowered to TeV scales.
- We discussed collider phenomenology in these models
- They are characterized by
  - Extended Higgs sector
  - The Majorana nature (LNV interaction, TeV RH neutrinos)
- At the LHC, the Higgs sectors can be tested at LHC.
- The Majorana nature can also be directly tested at the ILC.
- The combined study at LHC and ILC (e^+e^-, e^-e^-) can clarify the possibility of radiative seesaw scenarios.

Backup

Physics of η (DM)



Invisible Decay of h

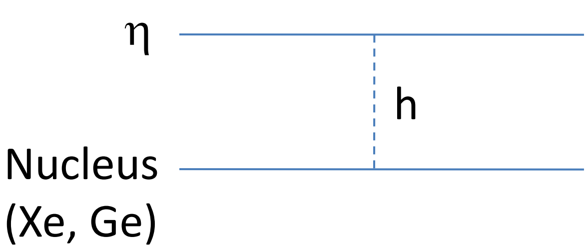
h is the SM-like Higgs but can decay into ηη.

B(h→ηη) = 36 (34) % for m_η=48 (55) GeV

Testable via the invisible Higgs decay at LHC

Direct Search

η from the halo can basically be detected at the direct DM search (CDMS, XMASS)



Observing the release energy

Extended Higgs sector in RSMs

Higgs Invisible decay

Ma $h_{SM} \to \xi^0_r\, \xi^0_r$

AKS $h_{SM} \to \eta\eta$

Extra Neutral Higgs bosons

Ma $\xi^0_i \to Z^*\, \xi^0_r$ (Inert doublet)

AKS $H^0 \to \tau\,\tau$ (Type-X 2HDM)

[MSSM $H^0 \to bb$ (Type-II 2HDM)]

Singly charged Higgs bosons

Zee-Babu $\omega^+ \to \mu\nu,\ \tau\,\nu$ $(> e\,\nu)$

Ma $\xi^+ \to l^+\,\nu\,\xi^0_r$ (Inert doublet)

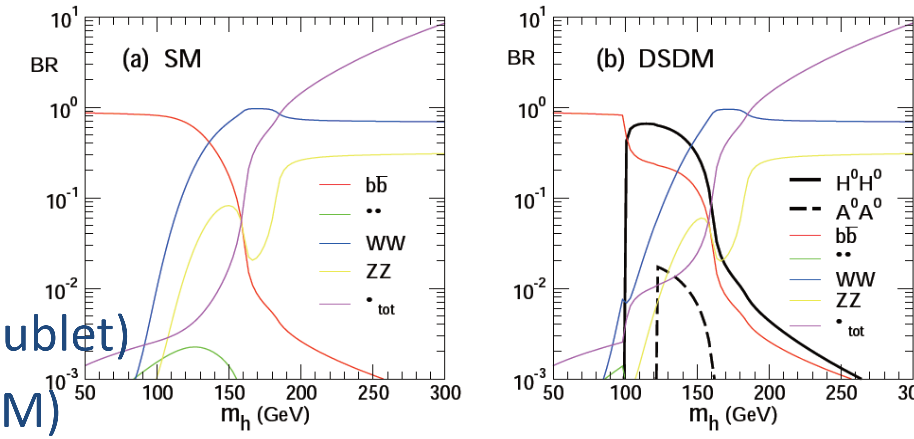
AKS $H^+ \to \tau\,\nu$ (Type-X 2HDM)

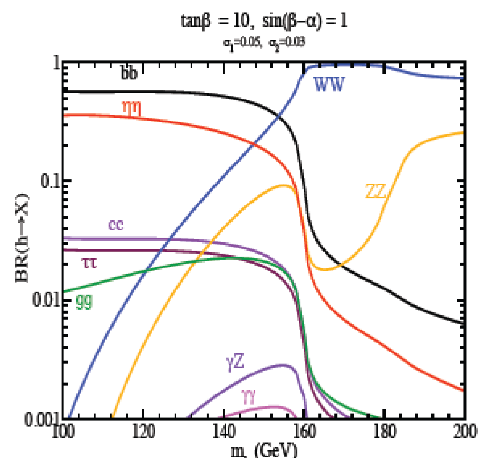
$S^+ \to H^+\,\eta \to \tau\,\nu\,\eta$

[MSSM $H^+ \to t\,b,\ \tau\,\nu$ (Type-II 2HDM)]

Doublely charged Higgs boson

Zee-Babu $\kappa^{--} \to \mu^-\mu^-$





m_η=48GeV

m_h=120GeV

$B(h\to\eta\eta)$=34%

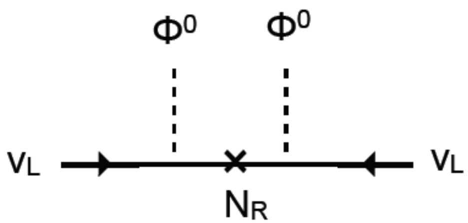
Seesaw Mechanism?

Super heavy RH neutrinos ($M_{N_R} \sim 10^{10\text{-}15}$GeV)

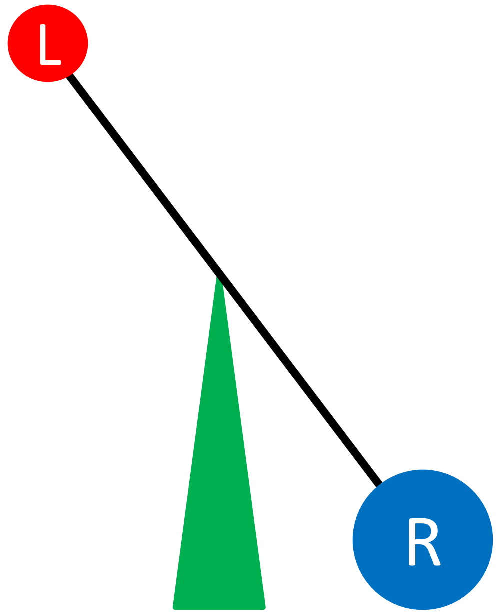
– Hierarchy between M_{N_R} and m_D generates that between m_D and tiny m_ν ($m_D \sim 100$ GeV)

$$m_\nu = m_D^2/M_{N_R}$$

$\nu\nu\phi\phi$



Minkowski
Yanagida
Gell-Mann et al



– Simple, compatible with GUT etc

– Introduction of a super high scale

Hierarchy for hierarchy!

Far from experimental reach…

The Higgs sector

- The Higgs sector

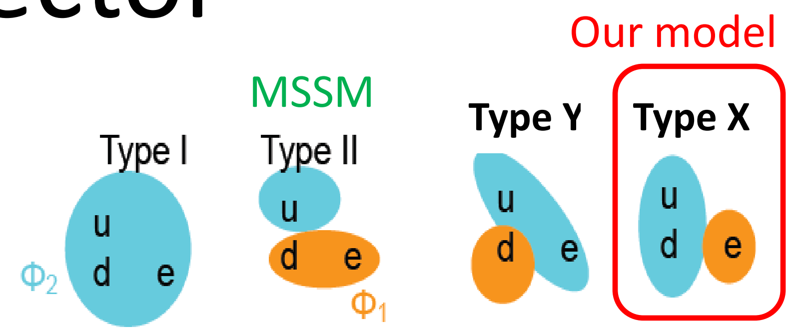
  Φ_1, Φ_2 (2HDM) + S^+, η (singlets)

- To avoid FCNC, additional softly-broken Z_2 symmetry is introduced :

  $$\Phi_1 \to +\Phi_1, \quad \Phi_2 \to -\Phi_2$$

  by which each quark/lepton couples to only one of the Higgs doublets.

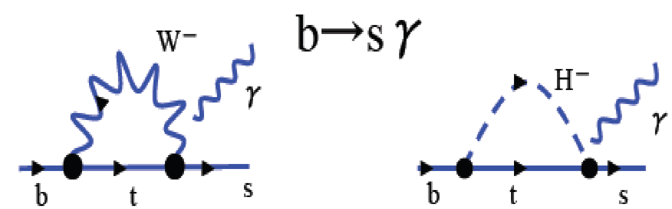
- 4 types of Yukawa interactions!

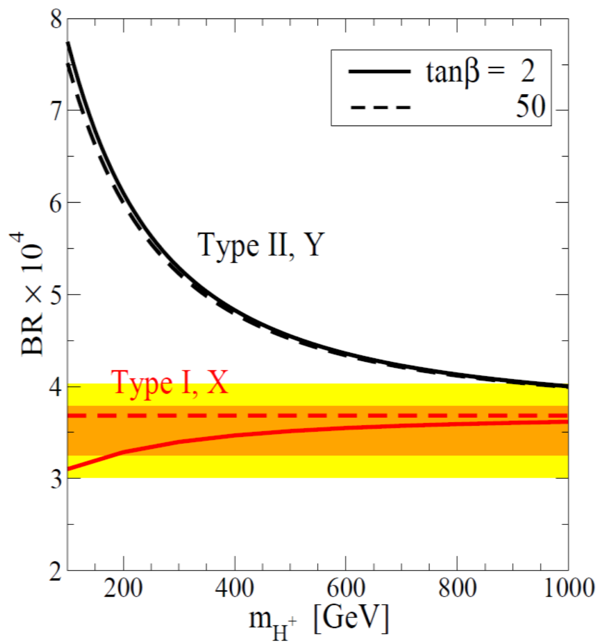


Neutrino data prefer a light H^+(< 200GeV)

- Choose Type-X Yukawa to avoid the constraint from $b \to s\gamma$.

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks





NLO, Ciuchini et al '98,
....
NNLO by
Misial et al. 2006
Becher, Neubert 2006

Aoki, SK, Tsumura, Yagyu, arXiv:0902.4665[hep-ph]

Lagrangian

$$SU(3)\times SU(2)\times U(1)\times Z_2\times \tilde{Z}_2$$

Z_2 (exact) : to forbid tree ν-Yukawa and to stabilize DM

$\tilde{Z}_2$ (softly-broken): to avoid FCNC

Z_2 even(2HDM) + Z_2odd(S^+, η^0 , N_R^α)

Z_2 even 2HDM

$$V = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\}$$

Z_2 odd scalars

$$+\mu_s^2|S|^2 + \lambda_s|S|^4 + \frac{1}{2}\mu_\eta\eta^2 + \lambda_\eta\eta^4 + \xi|S|^2\eta^2$$

Interaction

$$+\sum_{a=1}^{2}\left\{\rho_a|\Phi_a|^2|S|^2 + \sigma_a|\Phi_a|^2\frac{\eta^2}{2}\right\} + \sum_{a,b=1}^{2}\left\{\kappa\epsilon_{ab}(\Phi_a^c)^\dagger\Phi_b S^-\eta + \text{h.c.}\right\}.$$

RH neutrinos

$$\mathcal{L}_Y = -\sum_{\alpha=1}^{2}\sum_{i,j=1}^{3} h_i^\alpha(e_R^i)^c N_R^\alpha S^- + \sum_{\alpha=1}^{2} m_N^\alpha N_\alpha^c N_\alpha + \text{h.c.}.$$

Strong 1st Order Phase Transition

Effective Potential at high T

$$V_{\text{eff}} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4$$

Sphaleron decoupling

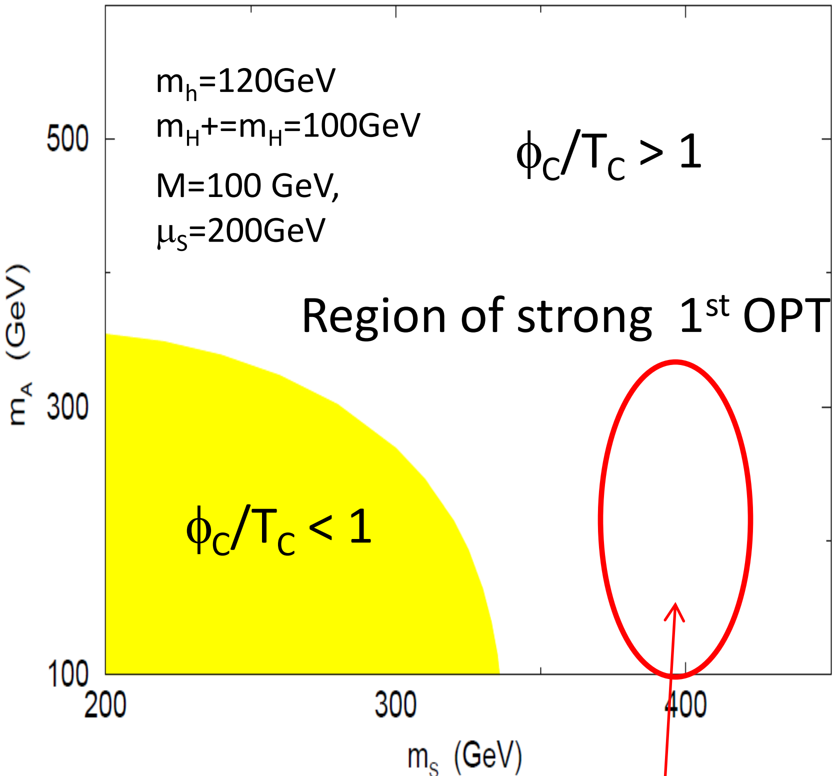
$$\frac{\varphi_c}{T_c}\left(=\frac{2E}{\lambda_{T_c}}\right) \gtrsim 1 \qquad \lambda_T \sim \frac{2m_h^2}{v^2}$$

SM $\quad E_{SM} \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad m_h \lesssim 65$ GeV

In SM, m_h is too smaller than LEP bound

Our Model

$$E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_A^3 + 2m_{S\pm}^3)$$



The condition can be satisfied with $m_h > 114$ GeV, when A and/or S^+ have non-decoupling property. $\quad m_{S+}^2 \sim \lambda_S v^2$

This region is compatible with neutrino data and DM abundance.