Potential for probing the Majorana nature in radiative neutrino masses at a future linear collider

Mayumi AOKI (Kanazawa U./ MPIK)

MA, S. Kanemura, PLB689 (2010)
MA, S. Kanemura, H. Yokoya, paper in preparation

LCWS12 22-26 Oct. 2012, U. of Texas, Arlington, USA

1. Introduction

Definite reasons for physics beyond the SM

Neutrino mass	Dark Matter	Baryon Asymmetry

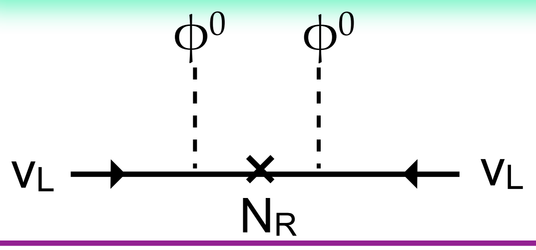
An extension of the SM is required to explain these phenomena.

(tree-level) seesaw model

$$m_\nu^{ij} = \frac{f_{ij}}{\Lambda} v^2$$

- Λ ~O(10^{14}) GeV for f_{ij} ~ O(1).

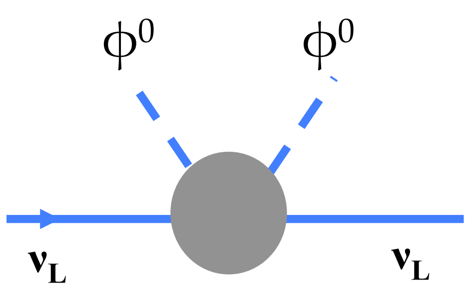
Type-I seesaw model



Radiative seesaw model

Neutrino masses are generated via the radiative effect.

***N*-loop:** $$m_\nu^{ij} = \left(\frac{1}{16\pi^2}\right)^N \frac{f_{ij}}{\Lambda} \langle\phi^0\rangle^2$$



- Due to the loop suppression factor, Λ can be lower.

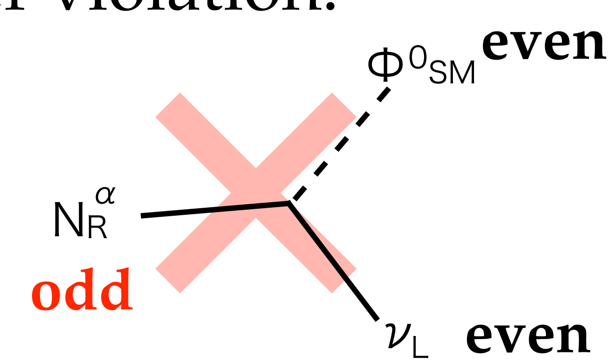
Neutrino masses would be explained by the TeV-scale physics.

1. Introduction

Radiative seesaw model with N_R

- Majorana mass term of N_R is the source of the lepton number violation.
- Z_2 symmetry **N_R: odd, SM: even**

  - forbids the Dirac ν mass term.
  - guarantees the stability of the DM.

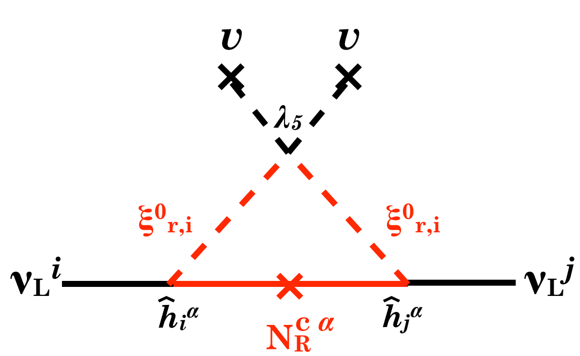


⇒ **The model would explain the neutrino mass and the DM.**

Ma model Ma, PRD73 (2006)

2HDM (Φ, ξ) + N_R

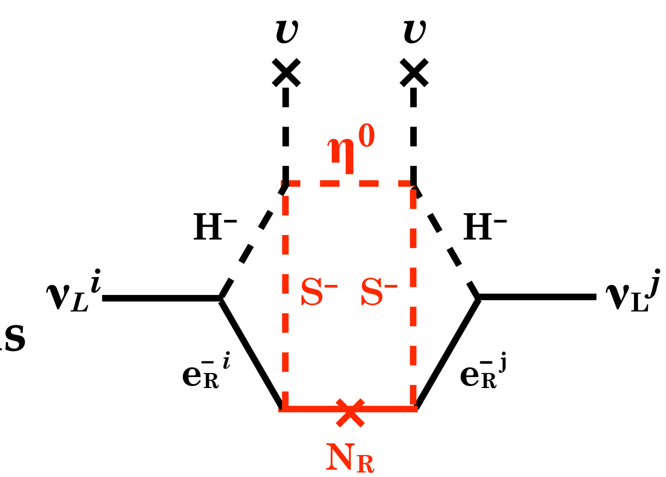
↑ **Inert doublet**



AKS model MA, Kanemura, Seto PRL102 (2009)

2HDM (Φ_1, Φ_2)
+ singlet scalars + N_R

Room for EW Baryogenesis
- CP violation
- strong 1st order PT



+ baryon asymmetry

1. Introduction

Common feature

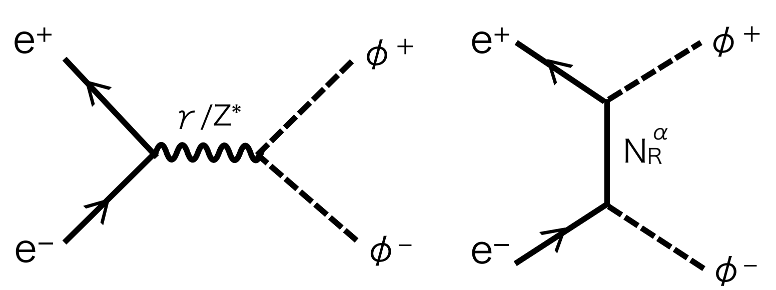
1. Extend scalar sector **2. N_R (Majorana nature)**

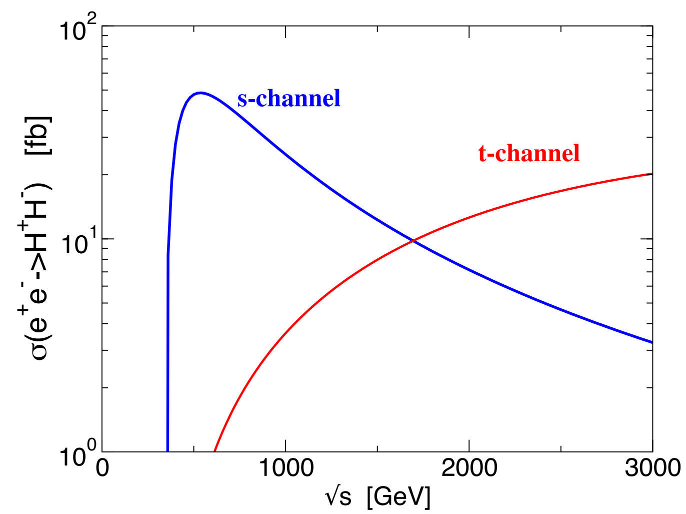
1. The discovery of extra scalar bosons can give partial evidence.
2. The detection of the N_R can be a fatal probe to identify the model.

ILC

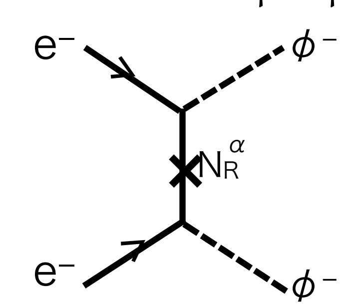
Z_2 odd charged scalar

$$e^+ e^- \to \phi^+ \phi^-$$





$$e^- e^- \to \phi^- \phi^-$$



- There are diagrams of the t-channel exchange of N_R.
- These t-channel effects show specific dependences on the √s in the production cross section.

Atwood, Bar- Shalom, Soni, PRD76 (2007)

→ One of the discriminative features of radiative seesaw models.

Contents

Ma Model

2. Ma Model

Inert doublet model + N_R

Ma, PRD73,077301 (2006)

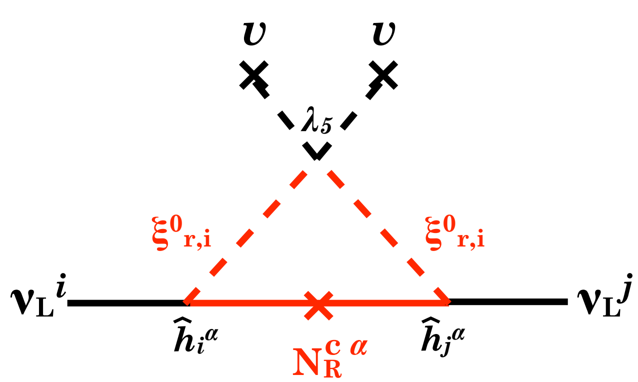
field	$SU(2)_L \times U(1)_Y$	Z_2
(ν_{Li}, l_i)	$(2, -1/2)$	$+$
l_i^c	$(1, 1)$	$+$
$\Phi = (\Phi^+, \Phi^0)$	$(2, 1/2)$	$+$
$\Xi = (\xi^+, \xi^0)$	$(2, 1/2)$	$-$
N_R^c	$(1, 0)$	$-$

- Ξ does not have the vev.

  $\xi^0 = (\xi_r + i\xi_i)/\sqrt{2}$

Scalar sector:
Z_2 even : h (SM-like)
Z_2 odd: ξ_r, ξ_i, $\xi^\pm$

- **Neutrino mass matrix**



$$M^\nu_{ij} = -\sum_\alpha \left(\frac{1}{16\pi^2}\right) \frac{\hat{h}_i^\alpha \hat{h}_j^\alpha \lambda_5 v^2}{M_{N_R^\alpha}} \frac{1}{1-r^\alpha}\left(1 + \frac{1}{1-r^\alpha}\ln r^\alpha\right),$$

$$|\hat{h}_i^\alpha \hat{h}_j^\alpha \lambda_5| \lesssim 10^{-9}$$

$$\lambda_5 = \frac{m^2_{\xi i} - m^2_{\xi r}}{2v^2}$$

- **DM** ξ_r, ξ_i, N_R

  <u>ξ_r DM</u>

  Relic density, Direct search → $m_{\xi r}$ =45-78 GeV

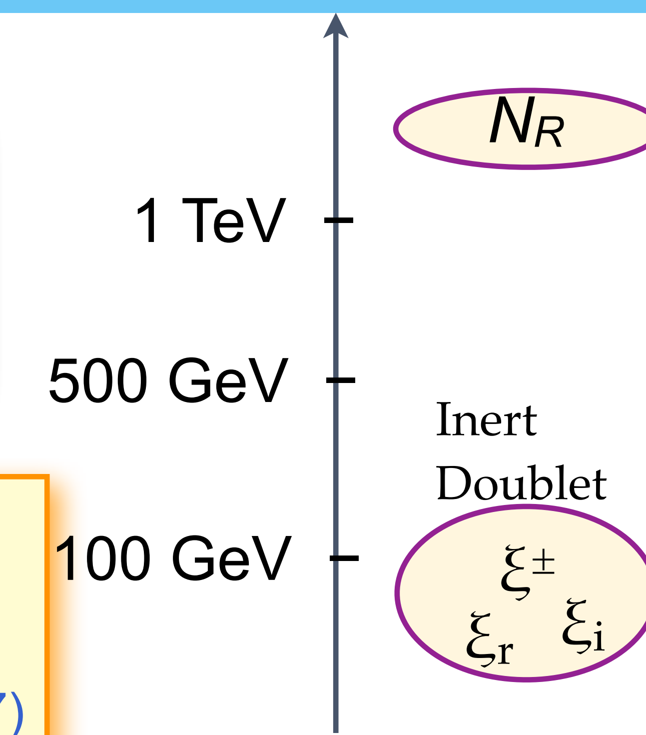
Gustafsson et al., arXiv:1206.6316 [hep-ph]

2. Ma Model

Benchmark scenario :

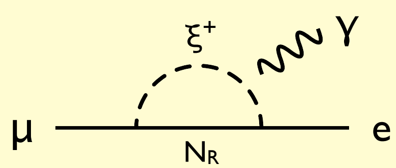
$m_{\xi r}$ =70 GeV, $m_{\xi i}$=78 GeV , $m_{\xi\pm}$=120 GeV,

$m_{NR}^1 = m_{NR}^2 = m_{NR}^3 \sim$ 3TeV, $h_i^\alpha \sim O(0.01)$



constraints:

- LFV $\mu \rightarrow e\gamma$

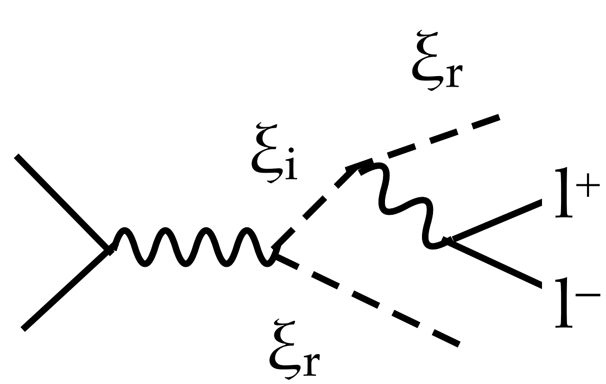


- DM search
- Precision EW constraints
- BSM search at LEP
- Theoretical constraints (vacuum stability, perturbativity)

Cao, Ma, Rajasekaran, PRD76, 095011 (2007)
Lopez Honorez et al., JCAP02 (2007)
Dolle, Su, PRD80 (2009)
Gustafsson et al., arXiv:1206.6316 [hep-ph]

LHC-14

ξiξr production



signals: Dilepton

Our benchmark scenario: Leptons too soft to detect.

$\mathcal{L}$ = 100 fb^{-1} $m_{\xi r}$ ↓ $m_{\xi\pm} - m_{\xi r}$ ↓ $m_{\xi i} - m_{\xi r}$ ↓

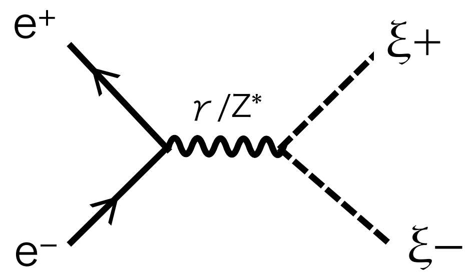
Benchmark	m_h (GeV)	m_S (GeV)	δ_1 (GeV)	δ_2 (GeV)	S/B	$S/\sqrt{B}$
LH1	150	40	100	100	0.04	3.87
LH2	120	40	70	70	1.53	11.66
LH3	120	82	50	50	0.52	3.04
LH4	120	73	10	50	0.57	3.29
LH5	120	79	50	10	0.02	0.02

Dolle et. al PRD81 (2010)

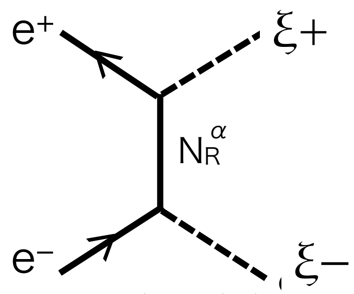
2. Ma Model

ILC

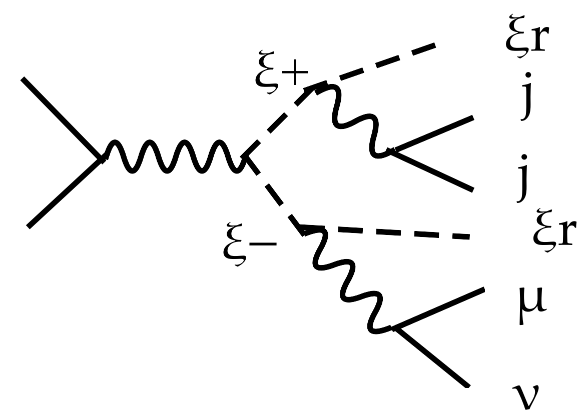
$\xi^+\xi^-$ production



Dominant



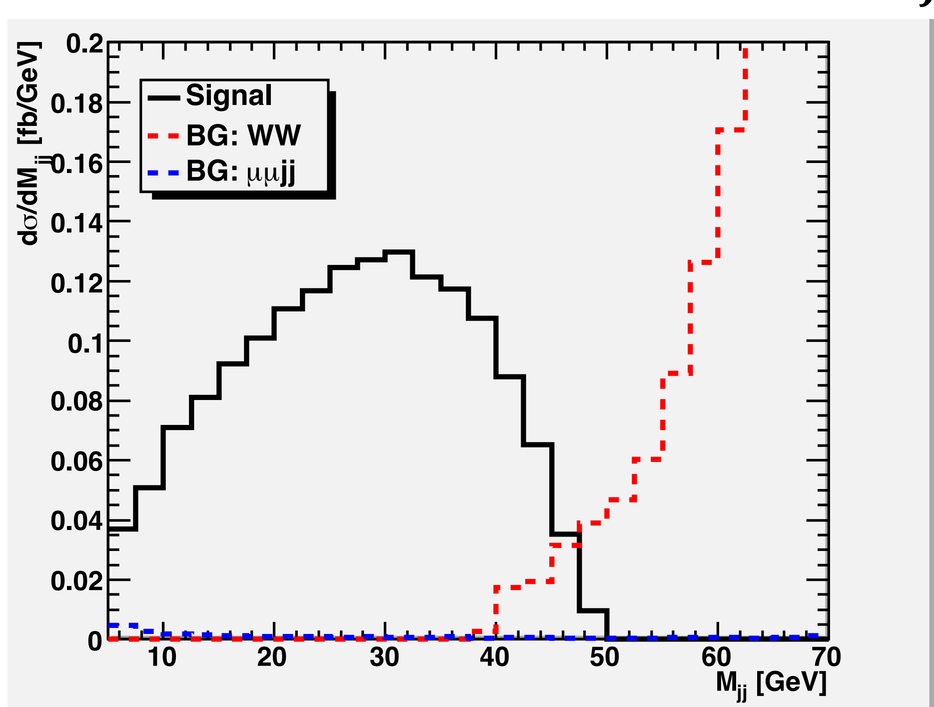
Negligible



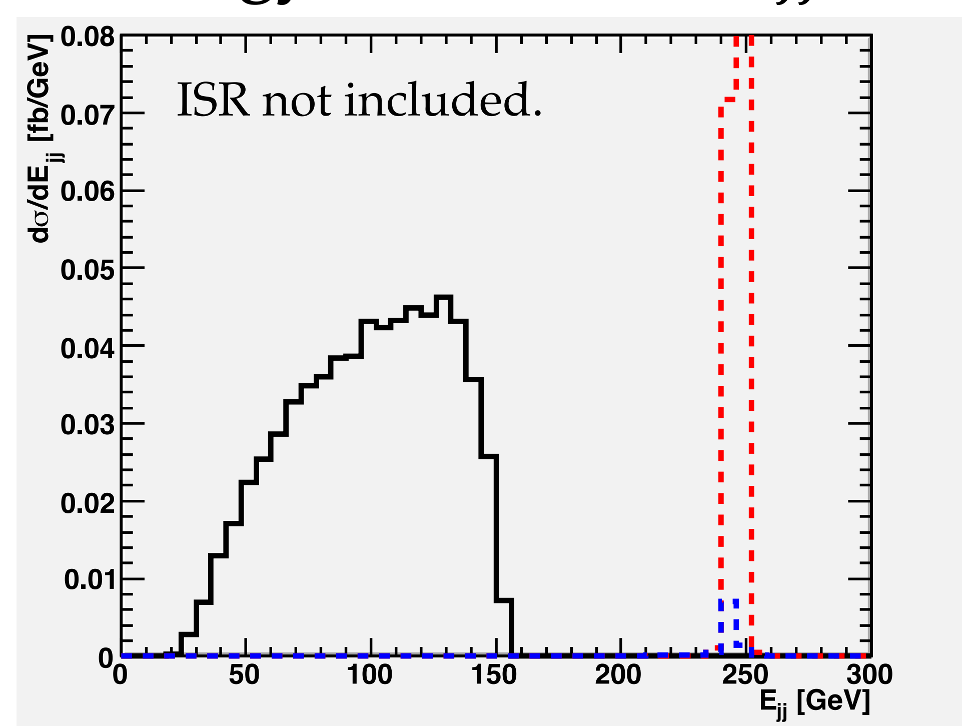
signal: jjμ + $\not{E}$

ILC-500

Invariant mass distribution M(jj)



Energy distribution E(jj)



μ : pT>1GeV, |cos|<0.95,
jet: pT>10GeV, |cos|<0.95,
R_{μμ}>0.4

- **The signal can be observed.**
- **The masses can be measured.**

$$M(jj)_{\max} = m_{\xi^+} - m_{\xi_r}$$
(= 50 GeV)

$$E(jj)_{\max/\min} = \frac{\sqrt{s}}{4}\left(1 - \frac{m_{\xi_r}^2}{m_{\xi^+}^2}\right)\left(1 \pm \sqrt{1 - \frac{4m_{\xi^+}^2}{s}}\right)$$
(= 155 GeV / 10 GeV)

AKS Model

3. AKS Model

2HDM + singlet scalars ($\eta, S^{\pm}$) + N_R

MA, Kanemura, Seto, PRL102 (2009), PRD80 (2009)
MA, Kanemura, Yagyu, PRD83 (2011)

	$SU(2)_L \times U(1)_Y$	Z_2
L^i	$(2, -1/2)$	$+$
e_R^i	$(1, -1)$	$+$
Φ_1	$(2, 1/2)$	$+$
Φ_2	$(2, 1/2)$	$+$
S^-	$(1, -1)$	$-$
η^0	$(1, 0)$	$-$
N_R^α	$(1, 0)$	$-$

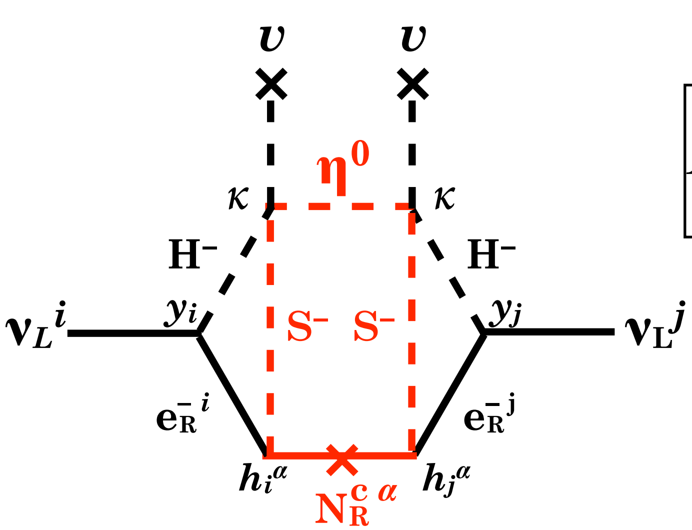
Scalar sector:
Z_2 even : h (SM-like), H, A, $H^{\pm}$
Z_2 odd: η^0, $S^{\pm}$

} to avoid FCNC → **Type-X Yukawa coupling**

$$\mathcal{L}_Y = -y_{u_i}\overline{Q}^i\tilde{\Phi}_2 u_R^i - y_{d_i}\overline{Q}^i\Phi_2 d_R^i - y_{e_i}\overline{L}^i\Phi_1 e_R^i + \text{h.c.}$$

→ $m_{H^{\pm}}$ ~100 GeV is possible.
(Type-II: $m_{H^{\pm}} \geqq 300$ GeV by $b \to s\gamma$ constraint)

- **Neutrino mass**

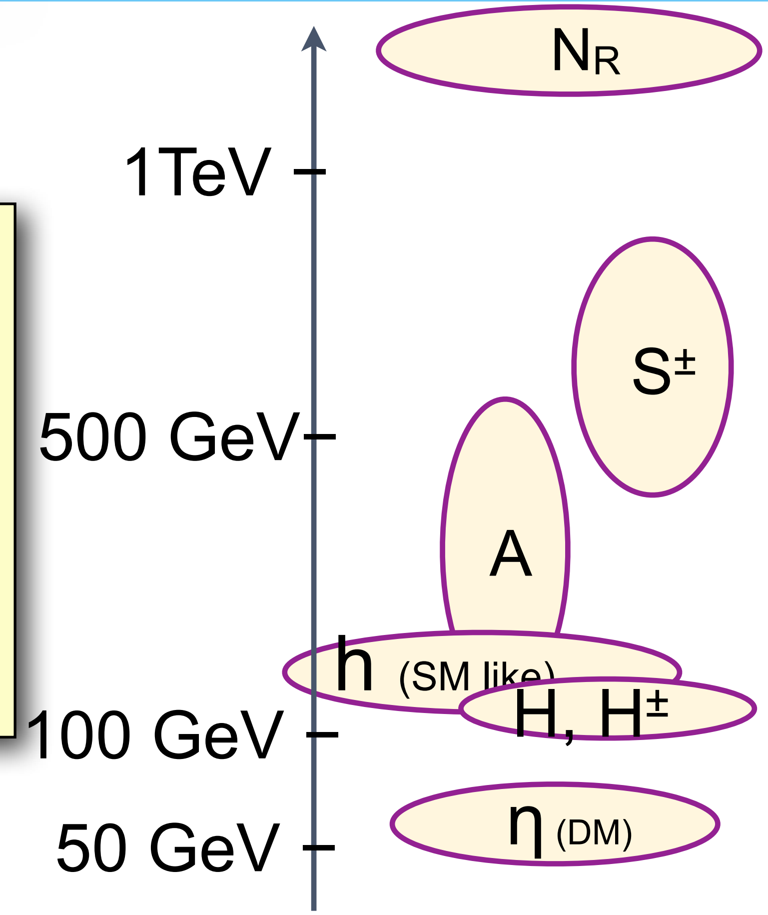


$$M_{ij} = \left(\frac{1}{16\pi^2}\right)^3 \sum_{\alpha=1}^{2} 4\kappa^2 \tan^2\beta (y_{e_i}^{\rm SM} h_i^\alpha)(y_{e_j}^{\rm SM} h_j^\alpha) \frac{(-m_{N_R} v^2)}{m_{N_R}^2 - m_\eta^2} F(m_{H^\pm}, m_{S^\pm}, m_{N_R^\alpha}, m_\eta)$$

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

⇧ $O(1)$

3. AKS Model



Typical scenario :

$$m_{H^\pm} = m_H = 100 \text{ GeV},\ m_{S^\pm} = 400 \text{ GeV},\ m_\eta = 50 \text{ GeV},$$
$$m_{N_R^1} = m_{N_R^2} = 5 \text{ TeV}$$

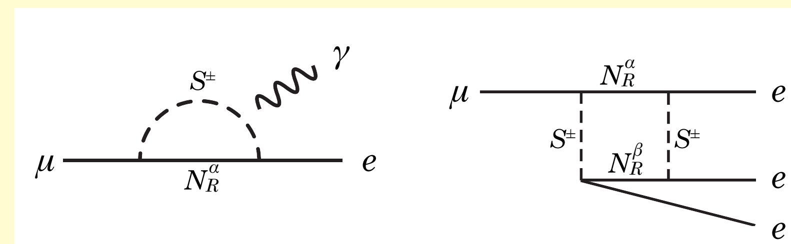
$h_e^1 = h_e^2 = 1.1$, $h_\mu^\alpha = 0.01\text{-}0.001$, $h_\tau^\alpha = 0.001$,

$\kappa \sim 2$, $\tan\beta \sim 35$

constraints:

- LFV : $\mu \to e\gamma$, $\mu \to 3e$ → $m_{N_R} \geq 5$ TeV, $m_{S^\pm} \geq 400$ GeV
- LEP precision measurement : $\rho \approx 1$

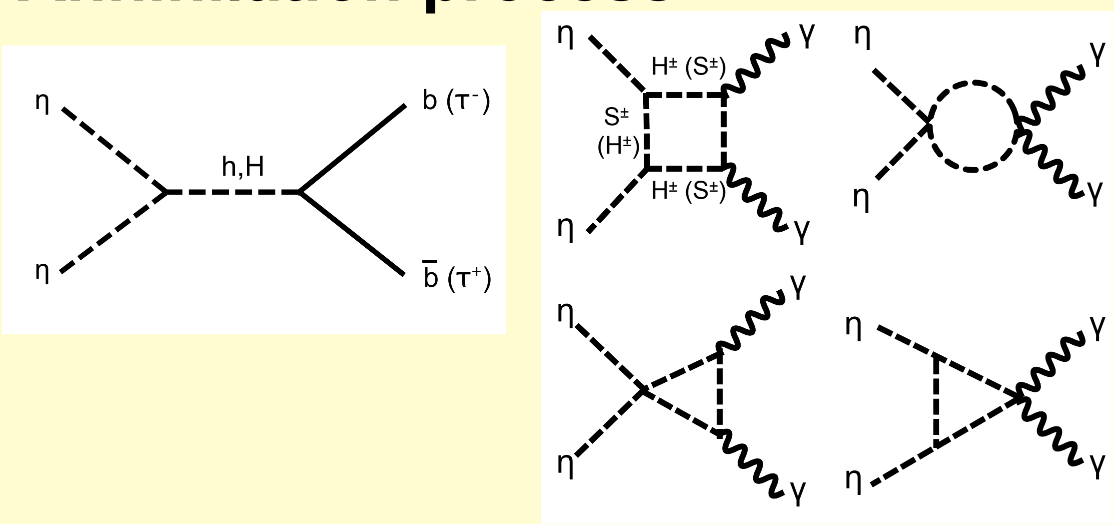
  → $m_{H^\pm} = m_H$ for $\sin(\beta-\alpha) = 1$
- Theoretical constraints (vacuum stability & triviality)



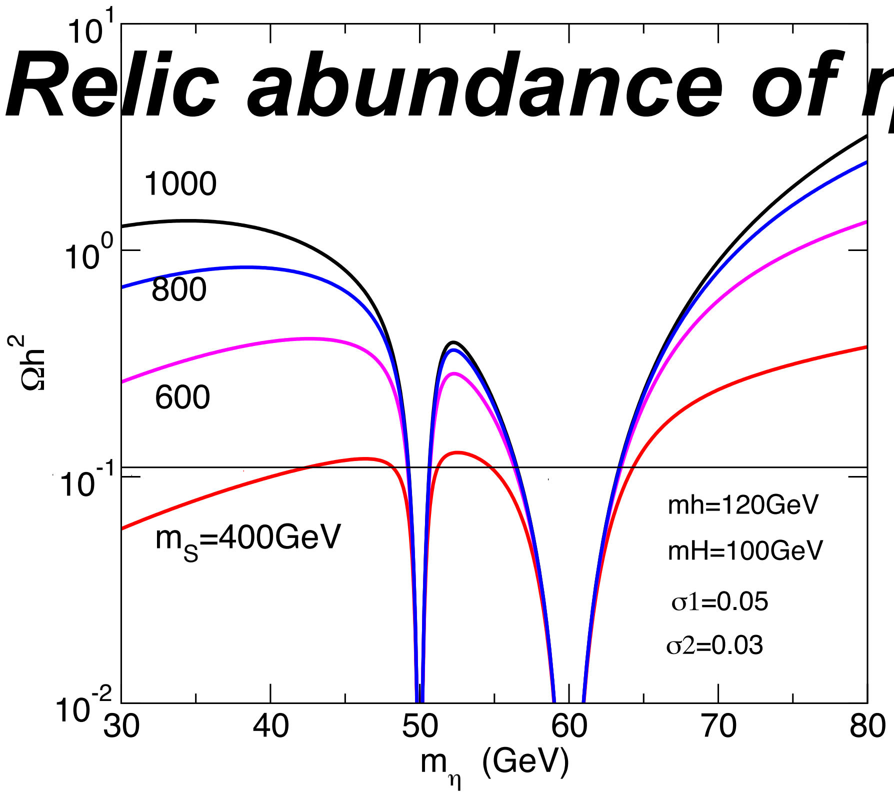
3. AKS Model

Dark Matter

Annihilation process



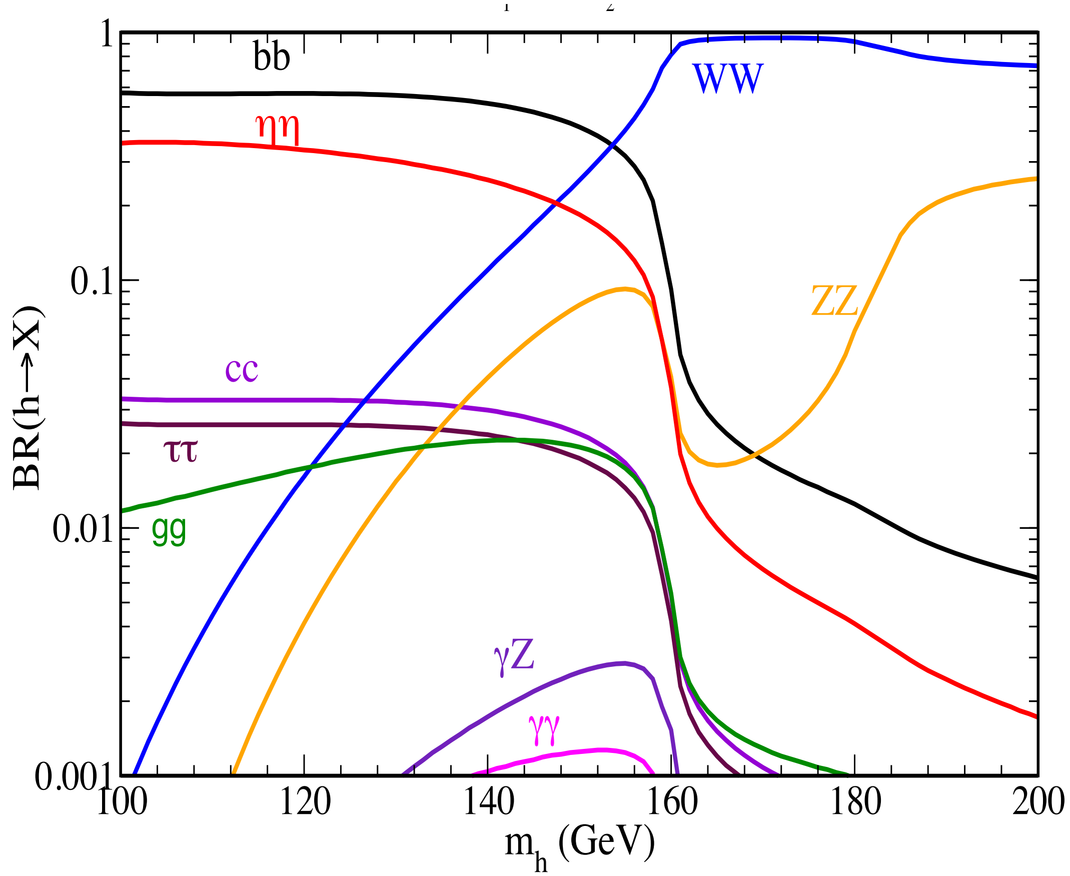
Relic abundance of η



Invisible decay of h_{SM}

$h \to \eta\eta$

sin(β-α)=1 m_η=48GeV



MA, Kanemura, Seto, PRD80 (2009)

$m_\eta \sim$ 48 - 63 GeV $\Rightarrow B(h \to \eta\eta) \sim 20\text{-}30\%$

$m_S > 400$ GeV

LHC: 25% can be tested

ILC: a few %

DM scenario can be testable.

3. AKS Model

Electroweak Baryogenesis

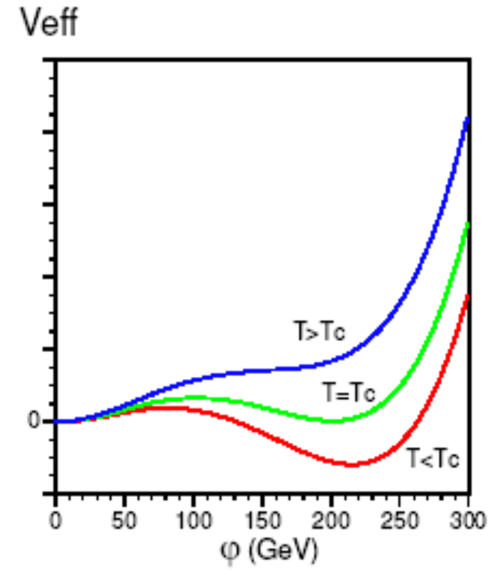
– Source of CP violation → 2HDM: There is a physical phase in the Higgs potential.

– "Strong" 1st order phase transition

MA, Kanemura, Seto, PRL102 (2009), PRD80 (2009)

$$\frac{\varphi_c}{T_c} \gtrsim 1 \quad \Leftrightarrow \quad \frac{2E}{\lambda_{T_c}} \gtrsim 1$$

φ_c : critical value of φ,
T_c : critical temperature

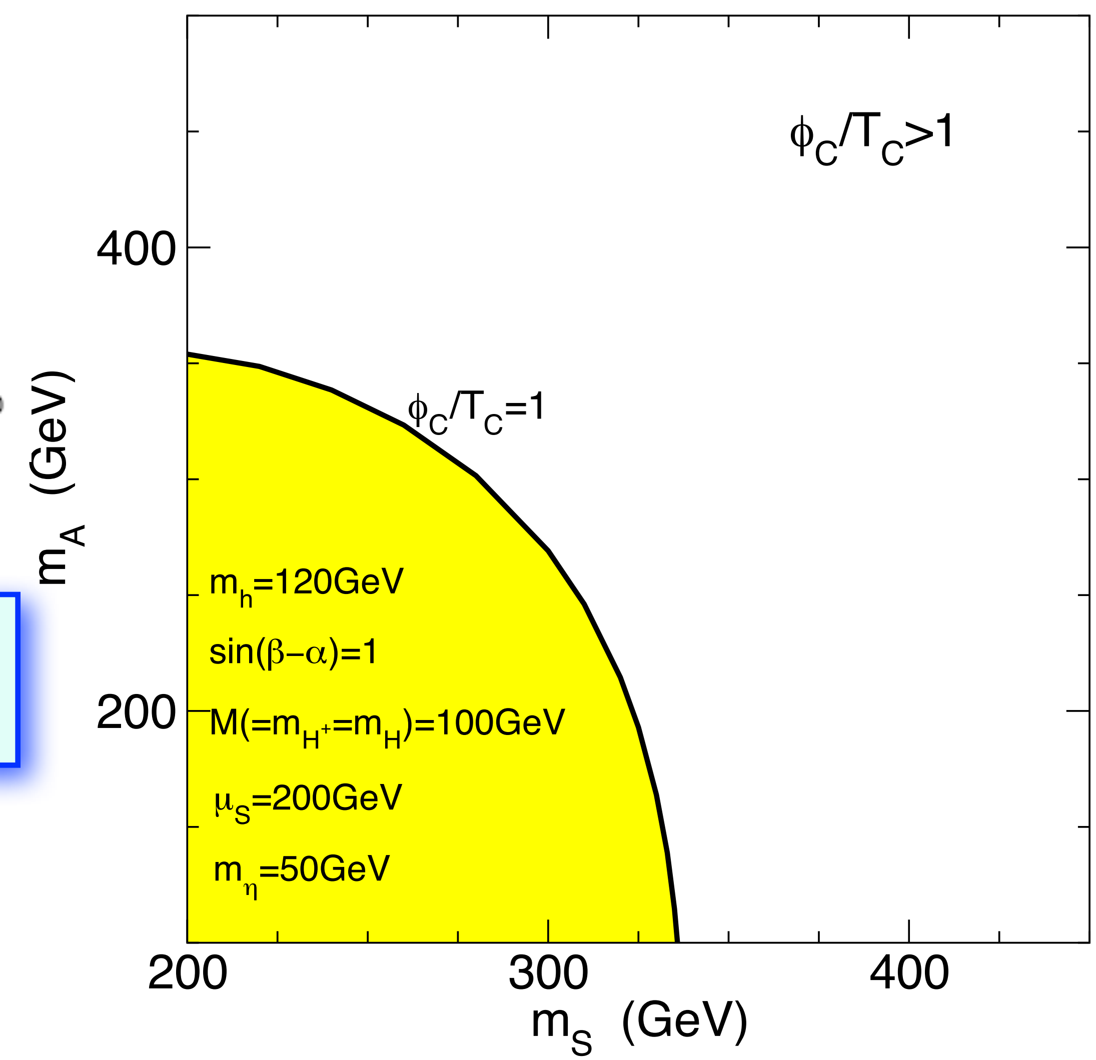


・Effective potential at finite temperature

$$V_{eff}[\varphi, T] = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \ldots,$$

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

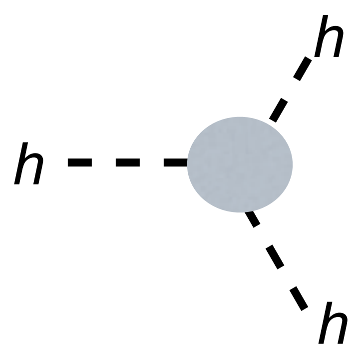
Region of strong 1st order EWPT



3. AKS Model

Higgs self-coupling

The self coupling measurement can provide an important test of the EWBG scenario.

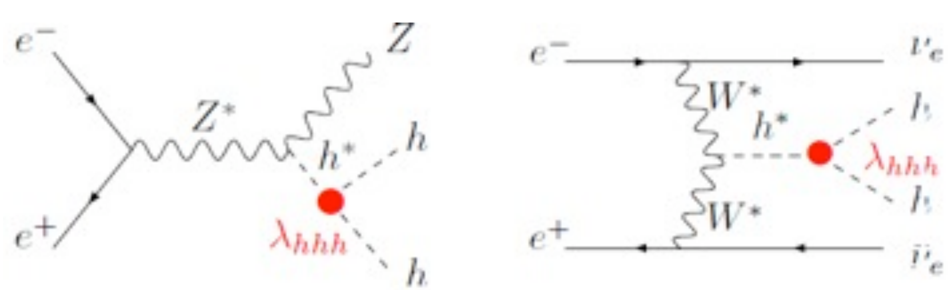


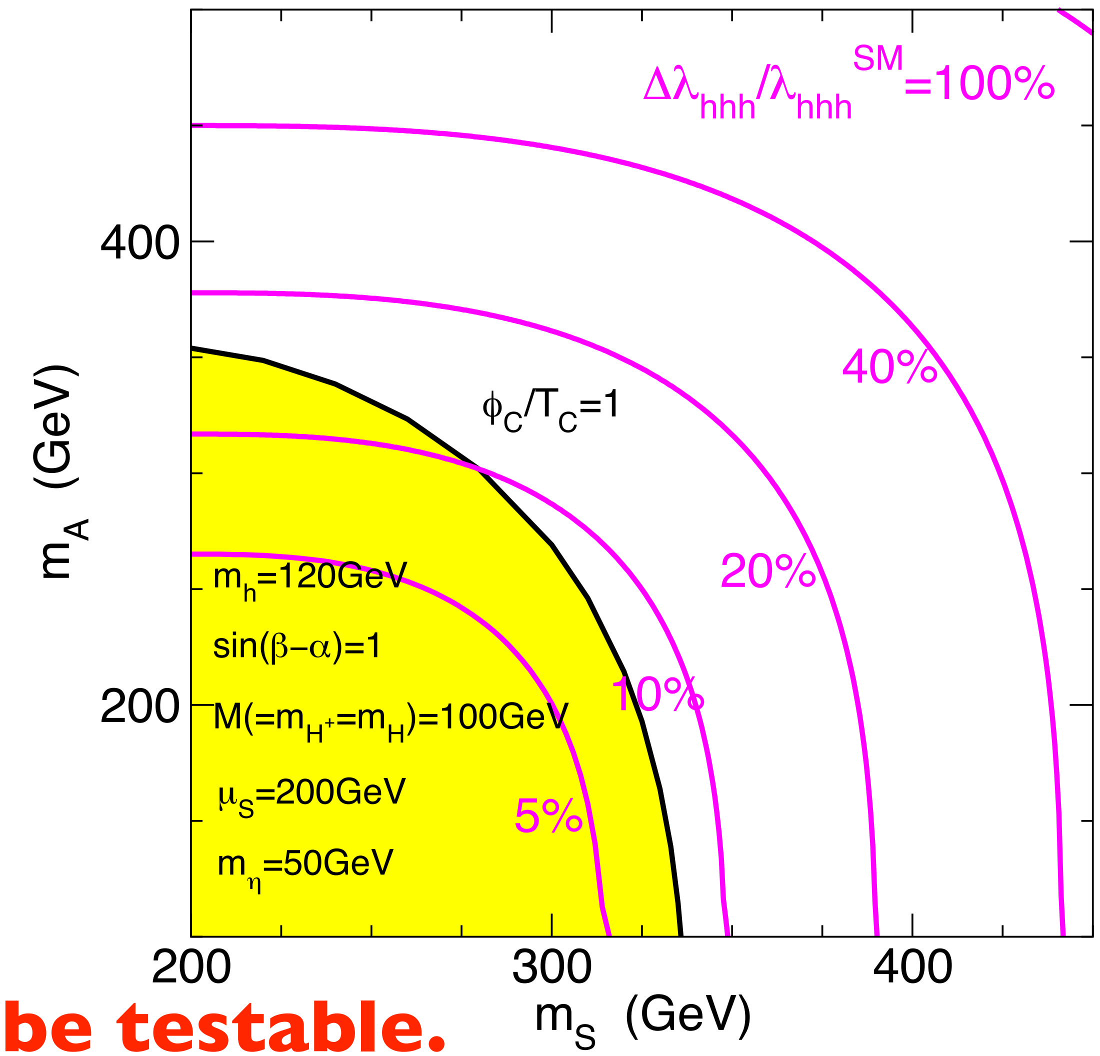
$$\frac{\partial^3}{\partial\varphi^3} V_{eff}[\varphi]\Big|_{\varphi=v} = \lambda_{hhh}$$

Kanemura, Okada, Senaha (2005)

Deviations in the hhh coupling from the SM value ($\Delta\lambda_{hhh} = \lambda_{hhh} - \lambda_{hhh}^{SM}$)

- In the region for the strong 1st order PT, the deviation becomes more than 10-20%, which is expected to be tested at the ILC.





Strong 1st order PT in our model can be testable.

3. AKS Model

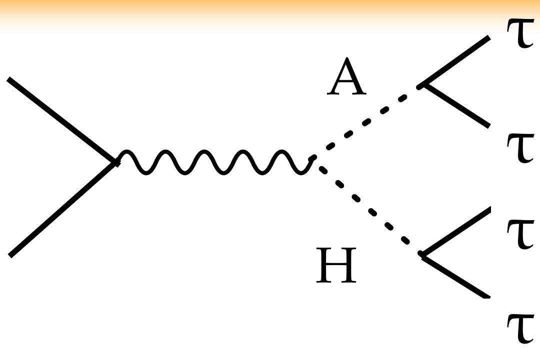
Type-X 2HDM

MA, Kanemura, Tsumura, Yagyu, PRD80 (2009)
Kanemura, Tsumura, Yokoya, PRD85 (2012), Proceedings of LCWS11

	Type-X 2HDM	Type-II 2HDM
AH+ production	$AH^{\pm} \to \tau\tau\tau\nu$	$\to bb\tau\nu$
AH production	$AH \to \tau\tau\tau\tau$	$\to bbbb$

- **AH production**

mH=130 GeV, mA=170 GeV



→ talk by Dr.Tsumura
Kanemura, Tsumura, Yokoya, PRD85 (2012)

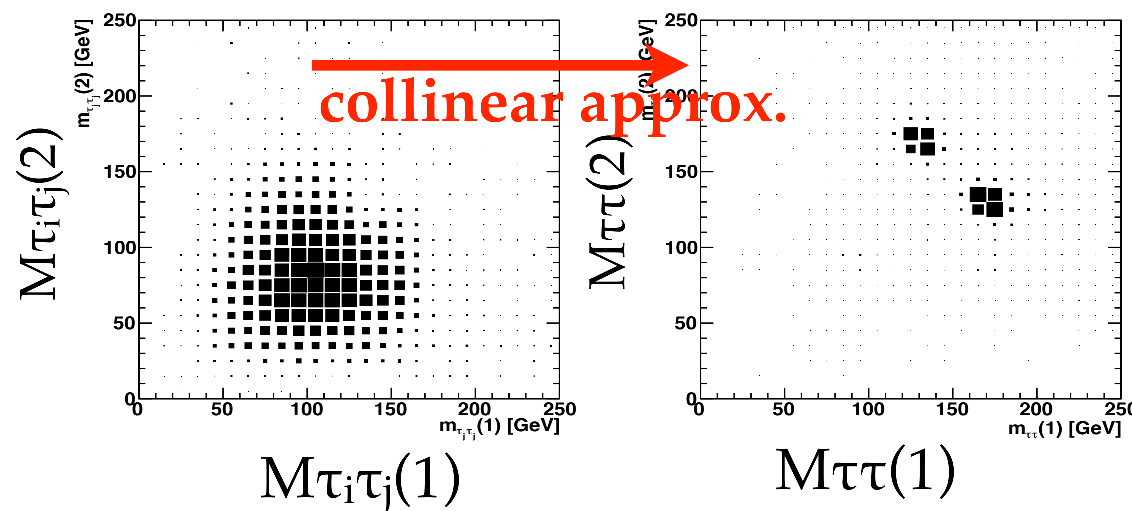
LHC-14

$4\tau_h$ event analysis	HA	s/b	S (100 fb^{-1})
Pre-selection	324.	0.1	4.7
$p_T^{\tau h} > 40$ GeV	67.2	1.9	9.4
$\not{E}_T > 30$ GeV	48.6	2.8	9.3
$H_T^{\rm jet} < 50$ GeV	34.2	3.9	8.7
$H_T^{\rm lep} > 350$ GeV	27.6	7.5	9.3

- The excess can be observed.
- The masses may be measured by the endpoints of $M_{\tau h \tau h}$ distributions.

ILC-500

Kanemura, Tsumura, Yokoya, Proceedings of LCWS11



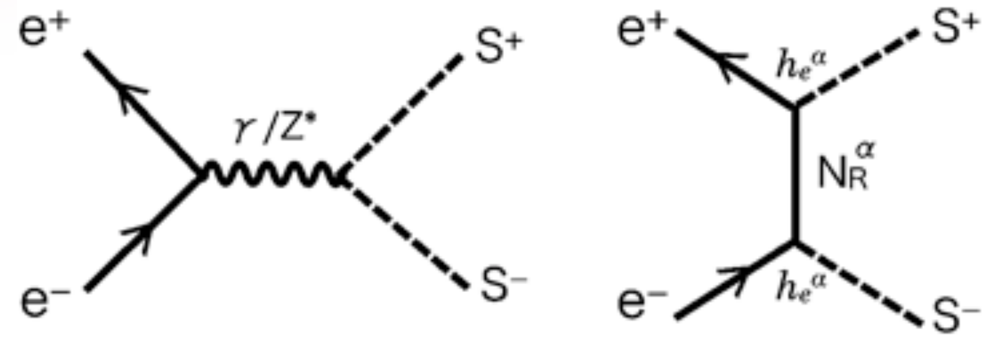
$\mathcal{L}$ = 100 fb^{-1}

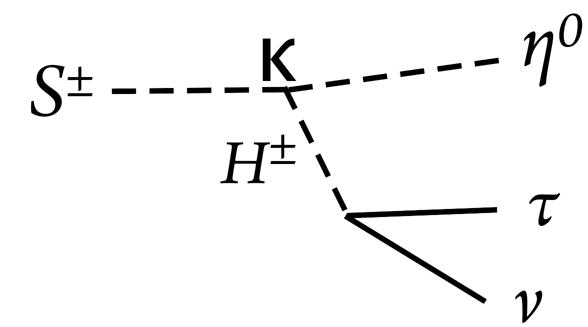
- The masses can be measured by using the collinear approximation.

3. AKS Model

ILC

S+S- production

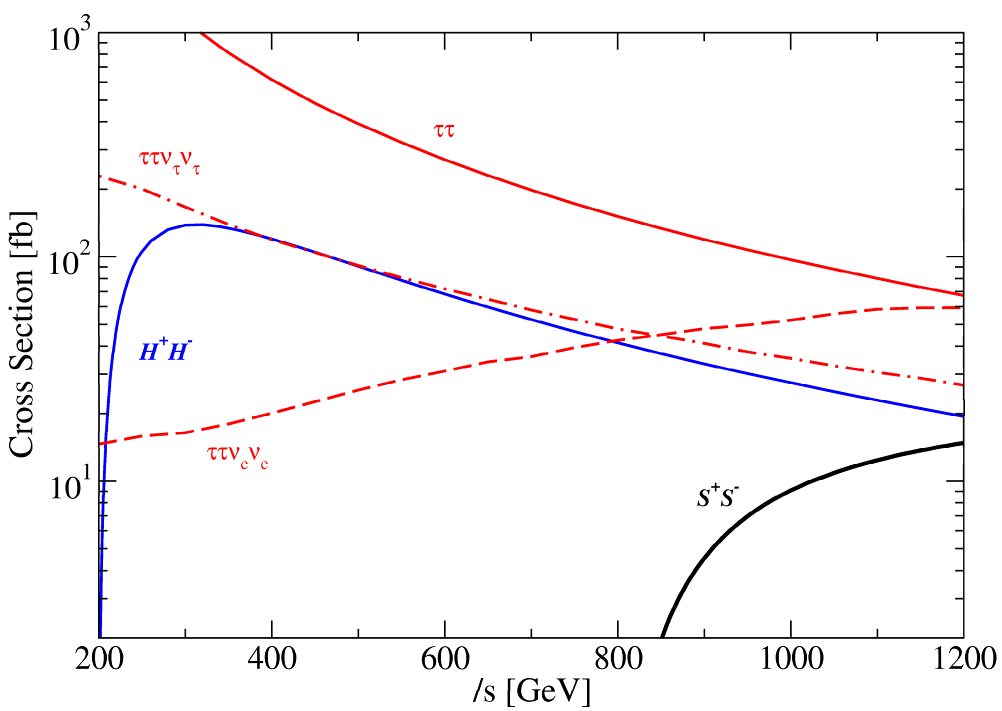


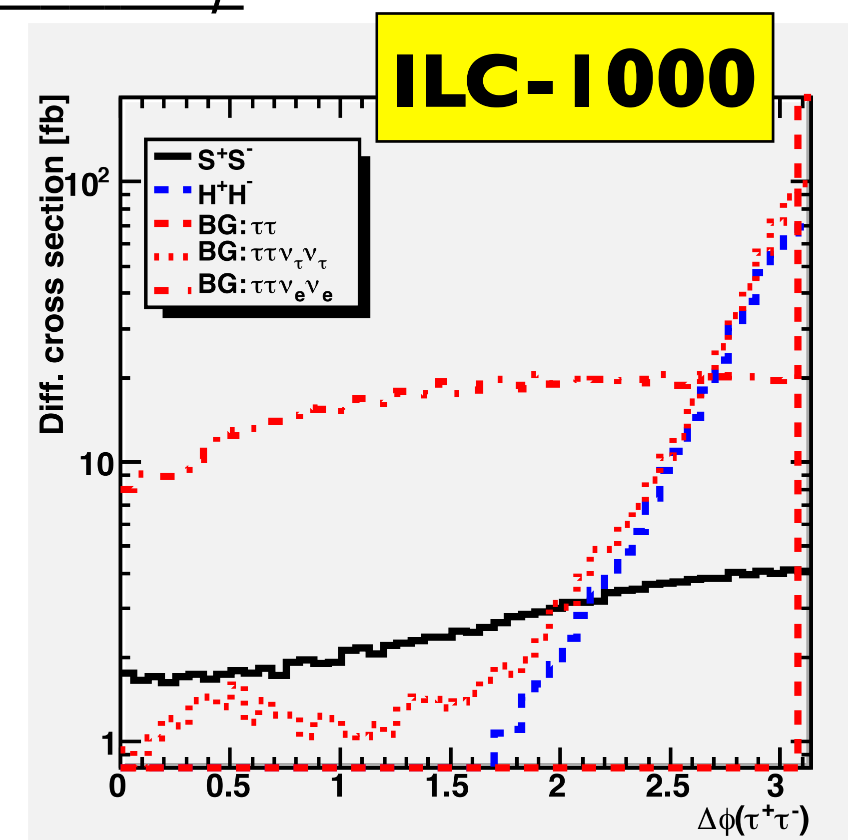


$m_{H^\pm} = 100$ GeV, $m_{S^\pm} = 400$ GeV, $m_\eta = 50$ GeV

$e^+ e^- \to S^+ S^- \to H^+ H^- \eta^0 \eta^0 \to \tau\tau\nu\nu\eta^0\eta^0$

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

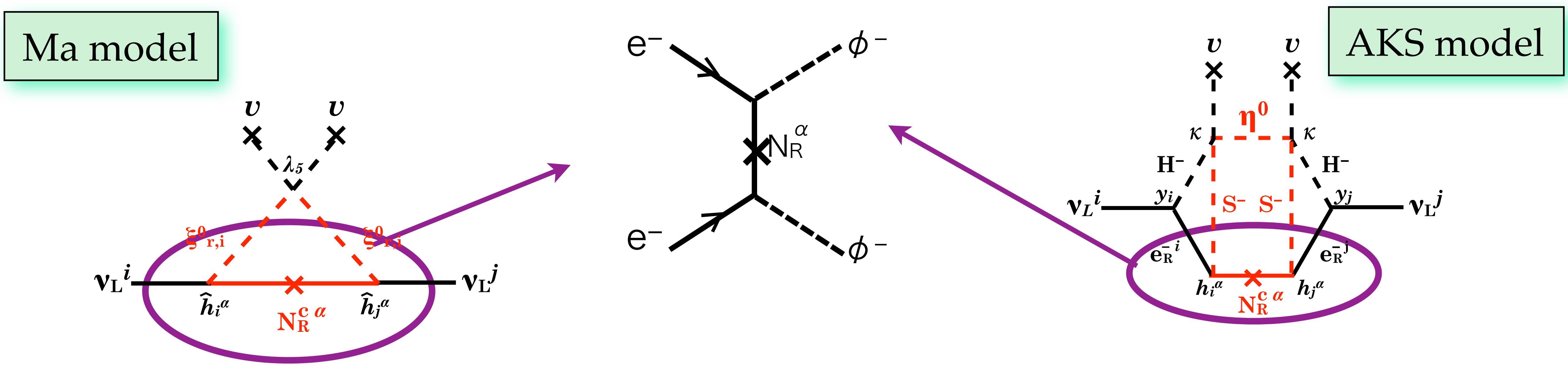




- $\sqrt{s}$=1 TeV, Lum=500 fb^{-1}, S/$\sqrt{B}$= 12.8
- $\sqrt{s}$ scan helps to confirm that the signal rate comes from the t-channel diagrams.

e⁻e⁻ collision option

D=5 operator, e-e-ϕ+ϕ+, is the sub-diagram of the loop diagrams for ν mass.



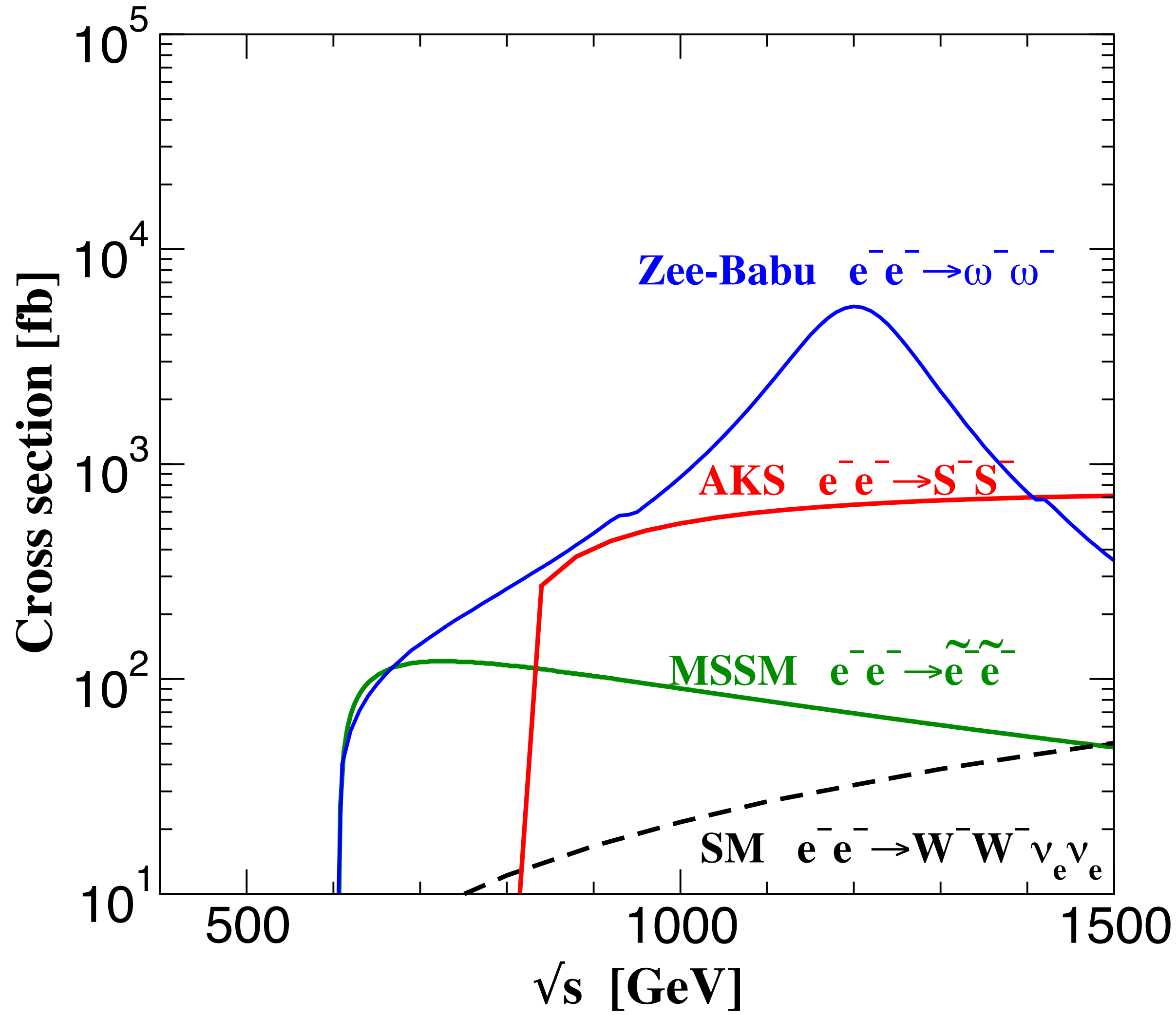
$$\sigma(e^-e^- \to S^-S^-) = \int_{t_{\min}}^{t_{\max}} dt \frac{1}{128\pi s}\left|\sum_{\alpha=1}^{2}(|h_e^\alpha|^2 m_{N_R^\alpha})\left(\frac{1}{t-m_{N_R^\alpha}^2}+\frac{1}{u-m_{N_R^\alpha}^2}\right)\right|^2$$

Direct test of the radiative seesaw models.

4. Discussion

ILC

$e^-e^- \to \phi^-\phi^-$



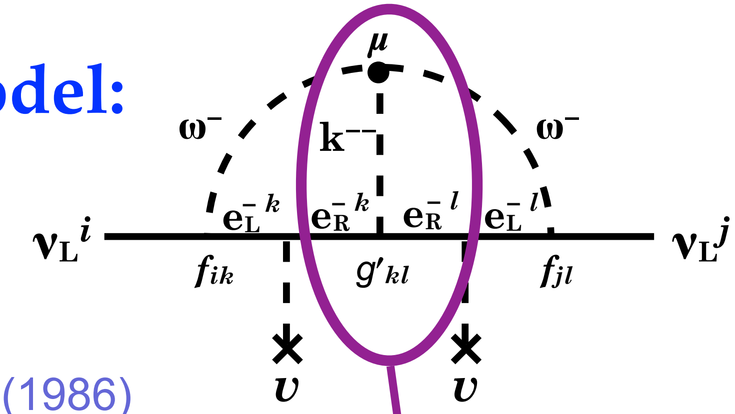
Zee-Babu model:

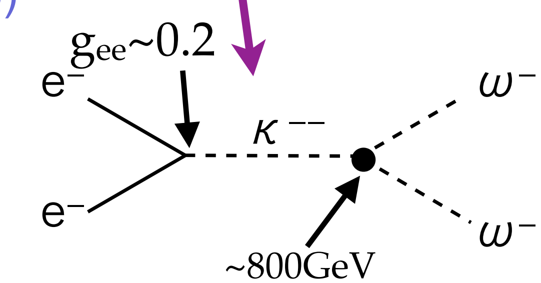
m_{K++}=1200GeV

$m_{\omega+}$=300GeV

$\omega^-\omega^-$ ($\to\mu^-\mu^-\nu\nu$)

Zee, NPB264,99 (1986)
Babu, PLB203,132 (1988)





AKS model:

m_{NR}=5TeV

m_{s+}=400GeV

S^-S^- ($\to\tau^-\tau^-\nu\nu\eta\eta$)

MSSM:

$m_{B\sim}$=130GeV

$m_{e\sim}$=300GeV

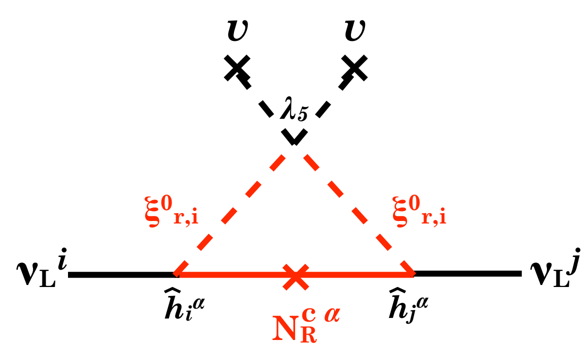
- The signal in the AKS model and the Zee-Babu model can be observed.
  The e-e- collision experiment is useful to test the Majorana nature of radiative seesaw models.

Summary

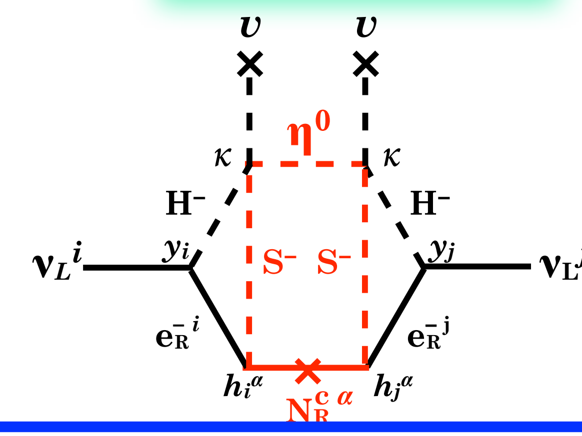
- Neutrino mass
- Dark matter
- (- Baryon asymmetry)

Radiative seesaw model with N_R

Ma model



AKS model

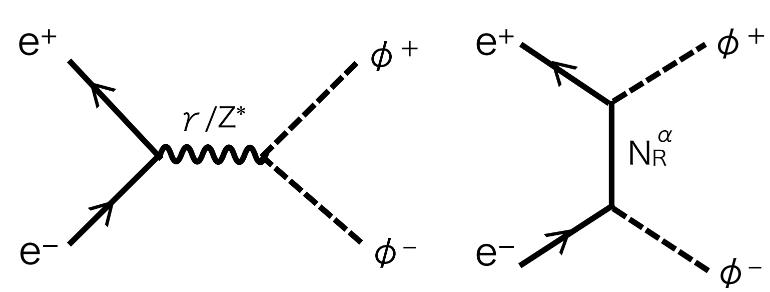


1. **Extend scalar sector** can be explored at (the LHC and) the ILC.

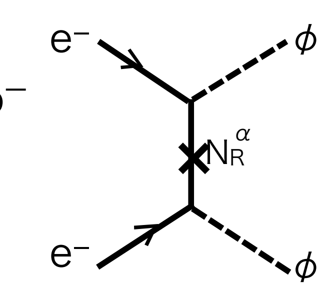
2. N_R **(Majorana nature)** can be tested at the ILC in AKS model via the t-channel processes.

ILC

$e^+e^- \to \phi^+\phi^-$



$e^-e^- \to \phi^-\phi^-$



Thank you for your attention.