A TeV-scale model for neutrino mass, dark matter and baryon asymmetry

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arXiv:0904.xxxx [hep-ph]

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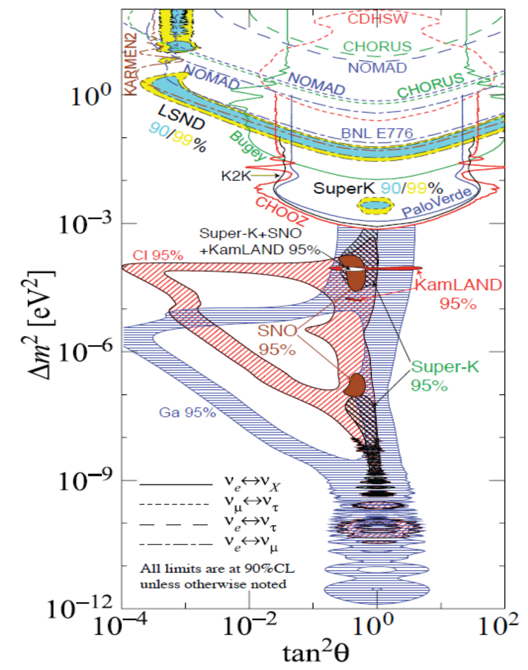
Introduction

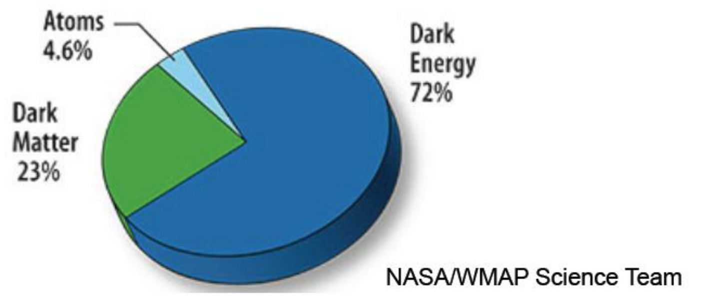
- In SM, Higgs remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

    $\Delta m^2 \sim 8\times10^{-5}\,eV^2,\ \Delta m^2 \sim 3\times10^{-3}\ eV^2$
  - Dark Matter

    $\Omega_{DM}h^2 \sim 0.11$
  - Baryon Asymmetry of the Universe

    $n_B/s \sim 9\times10^{-11}$





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

BSM: Neutrino Mass

Neutirno Mass Term (= Effectively 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:

$$m^{\nu}{}_{ij} = (c_{ij}/M)\, v^2 < 0.1\ \text{eV}$$

Seesaw (tree level)

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

$M=10^{13\text{-}15}\text{GeV}$

Quantum Effects

N-th order of perturbation theory

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

$M=1$ TeV

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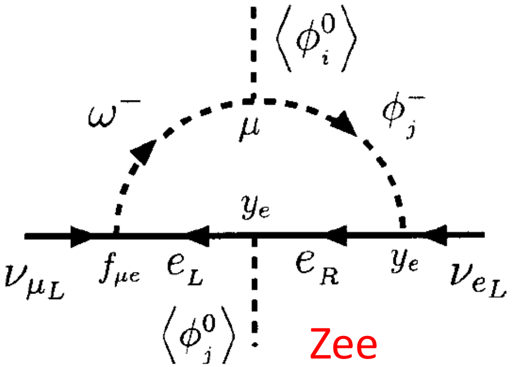
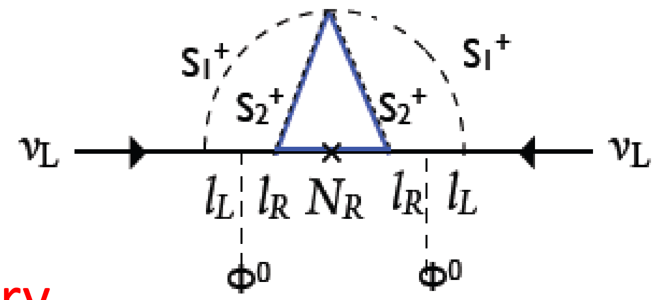
Quantum Effects N-th order of perturbation theory

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

Scenario of radiative $\nu\nu\phi\phi$ generation

- Tiny ν-Masses come from loop effects
  - Zee (1980, 1985)
  - Zee-Babu, Ma, Sarker, …..
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), …..





- Merit
  - Super heavy particles are not necessary

    Size of tiny m_ν can naturally be deduced from TeV scale by higher order perturbation
  - Physics at TeV: Testable at collider experiments

In this talk

- We consider a model to explain

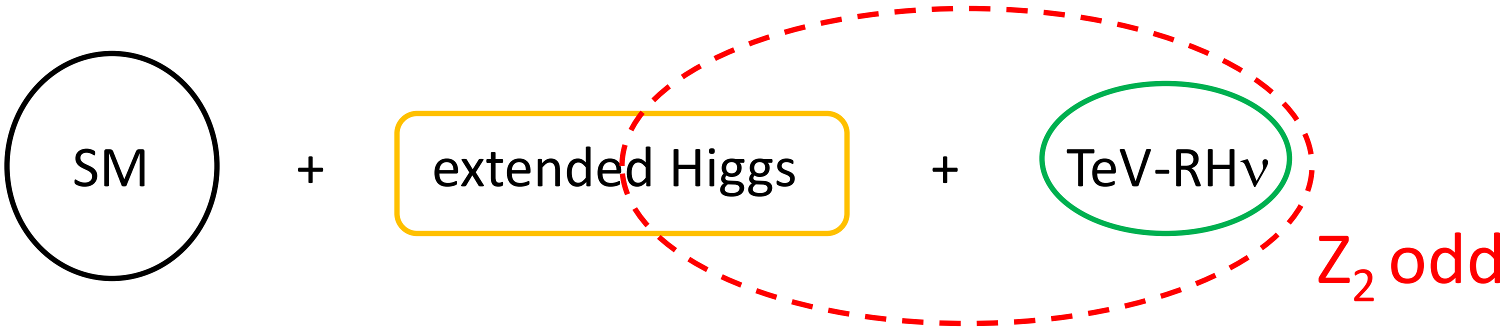
    Neutrino Mass

    Dark Matter

    Baryon Asymmetry of the Universe

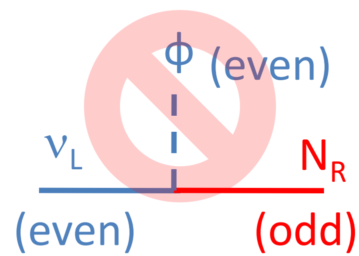
  by TeV scale physics without introducing large scales.
- Review of the model
- Collider signatures

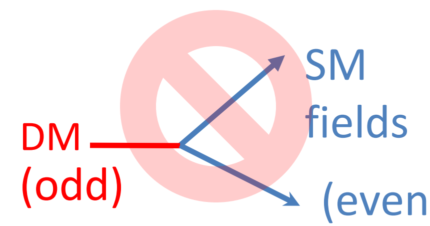
Model



Exact Z_2 Parity

- No neutrino Yukawa coupling
- Stabilize Dark Matter





RH neutrinos: N_R (M_{NR} = TeV scale)

Extended Higgs: 2HDM (Φ_1, Φ_2) + singlet scalars (η^0, S^+)

Tiny neutrino mass: 3 loop effect (N_R, η^0, S^+, H^+, e_R)
DM candidate: Lightest Z_2-odd particle (η^0)
EW Baryogenesis: Extended Higgs [1^{st} Order PT, Source of CPV]

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 :

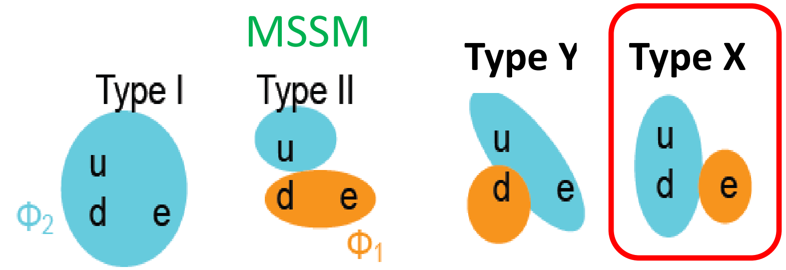
  $\Phi_1 \rightarrow + \Phi_1, \quad \Phi_2 \rightarrow - \Phi_2$

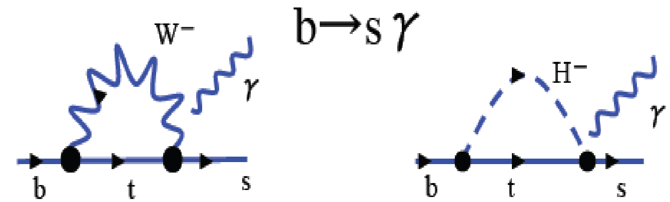
  by which each quark or lepton couples to only one of the Higgs doublets.

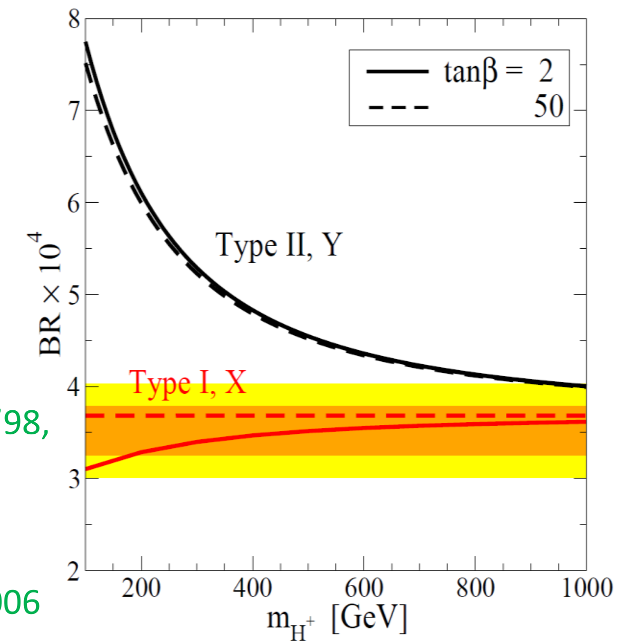
  No FCNC at tree level
- 4 types of Yukawa interactions!
- Neutrino data prefer a light H^+(< 200GeV)
- Choose Type-X Yukawa to avoid the constraint from $b \rightarrow s\gamma$.

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks

Our model







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

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

The model

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

Z_2 (exact) : to forbid ν-Yukawa
to stabilize DM
$\tilde{Z}_2$ (softly-broken): to avoid FCNC

	$SU(2)_L \times U(1)$	Z_2 (exact)	$\tilde{Z}_2$ (softly broken)
Q^i	(2, 1/6)	+	+
u_R^i	(1, 2/3)	+	−
d_R^i	(1, −1/3)	+	−
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)	−	+

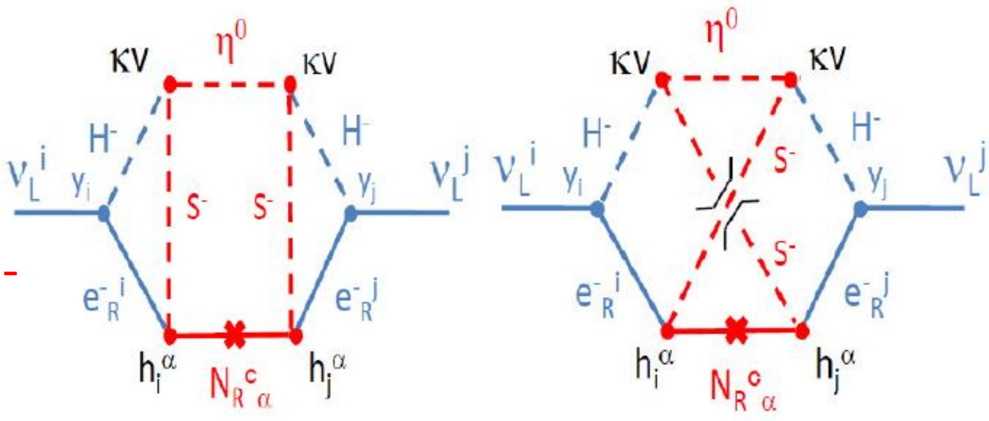
} Type-X 2HDM (rows Q^i to Φ_2)

Z_2-even physical states
h (SM like Higgs)
H, A, H^- (Extra scalars)
Z_2-odd states
η, S^+, N_R

Neutrino Mass

Tree neutrino Yukawa is forbidden by Z_2

$$M_{ij} = \sum_{\alpha=1}^{2} C_{ij}^{\alpha} F(m_H, m_S, m_{N_R^\alpha}, m_\eta)$$



Universal scale is determined by the 3-loop function factor F

$$F(m_{H^\pm}, m_{S^\pm}, m_{N_R}, m_\eta) = \left(\frac{1}{16\pi^2}\right)^3 \frac{(-m_{N_R} v^2)}{m_{N_R}^2 - m_\eta^2}$$
$$\times \int_0^\infty dx \left[x \left\{ \frac{B_1(-x, m_{H^\pm}, m_{S^\pm}) - B_1(-x, 0, m_{S^\pm})}{m_{H^\pm}^2} \right\}^2 \right.$$
$$\left. \times \left(\frac{m_{N_R}^2}{x + m_{N_R}^2} - \frac{m_\eta^2}{x + m_\eta^2} \right) \right], \quad (m_{S^\pm}^2 \gg m_{e_i}^2),$$

Mixing structure is determined by

$$C_{ij}^{\alpha} = 4\kappa^2 \tan^2\beta (y_{\ell_i}^{\rm SM} h_i^\alpha)(y_{\ell_j}^{\rm SM} h_j^\alpha)$$

Neutrino data and LFV data require that

H^+ should be light (< 200 GeV)

N_Rs should be O(1) TeV

We can describe all the neutrino data (tiny masses and angles) without unnatural assumption among mass scales

Solution of ν mass and mixing

Case of 2 generation N_R^{α}

$\Delta m_{sol}^2 \sim 8 \times 10^{-5}$ eV^2
$\Delta m_{atm}^2 \sim 0.0021$ eV^2
$\theta_{sol} \sim 0.553$
$\theta_{atm} \sim \pi/4$

$$M_{ij} = U_{is}(M_\nu^{\rm diag})_{st}(U^T)_{tj}$$

$$m_\nu^{\rm diag} \equiv \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sqrt{\Delta m^2_{\rm solar}} & 0 \\ 0 & 0 & \sqrt{\Delta m^2_{\rm atom}} \end{bmatrix} \qquad U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\tilde{\alpha}} & 0 \\ 0 & 0 & e^{i\tilde{\beta}} \end{bmatrix}$$

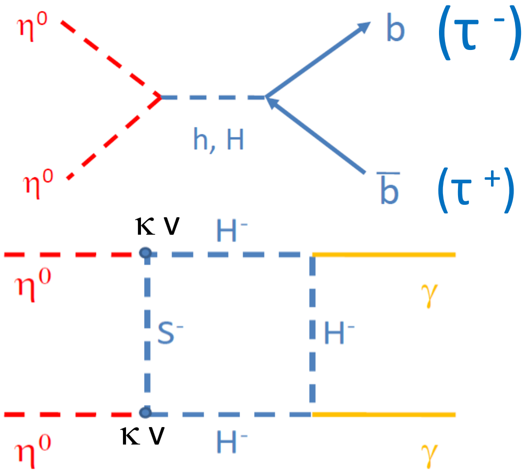
$$C_{ij}^{\alpha} = 4\kappa^2 \tan^2\beta (y_{\ell_i}^{\rm SM} h_i^{\alpha})(y_{\ell_j}^{\rm SM} h_j^{\alpha})$$

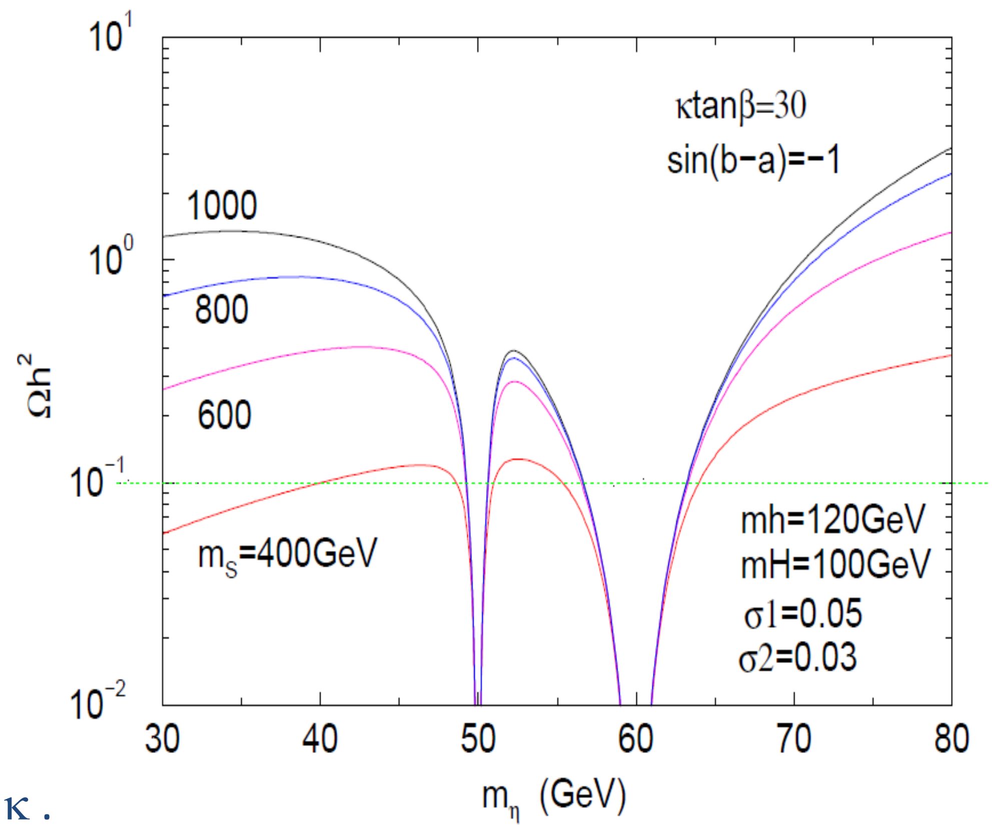
Set	Mass (TeV)				Yukawa couplings						LFV
(hierarchy, $\sin^2 2\theta_{13}$)	m_η	m_S	m_{Ni}	$\kappa \tan\beta$	h_e^1	h_e^2	h_μ^1	h_μ^2	h_τ^1	h_τ^2	$B(\mu \to e\gamma)$
A (normal, 0)	0.05	0.4	3	29	2.0	2.0	0.041	-0.020	0.0012	-0.0025	6.8×10^{-12}
B (normal, 0.14)	0.05	0.4	3	34	2.2	2.1	0.0087	0.037	-0.0010	0.0021	5.3×10^{-12}
C (inverted, 0)	0.05	0.4	3	66	3.8	3.7	0.013	-0.013	-0.00080	0.00080	4.2×10^{-12}
D (inverted, 0.14)	0.05	0.4	3	66	3.7	3.7	-0.016	0.011	0.00064	-0.00096	4.2×10^{-12}

Thermal Relic Abundance of η^0

WMAP data $\Omega_{\rm DM} h^2 \simeq 0.113$

$$\Omega_\eta h^2 = 1.1 \times 10^9 \, \frac{(m_\eta / T_d)}{\sqrt{g_*} M_P \langle \sigma v \rangle}\bigg|_{T_d} \quad {\rm GeV}^{-1}$$





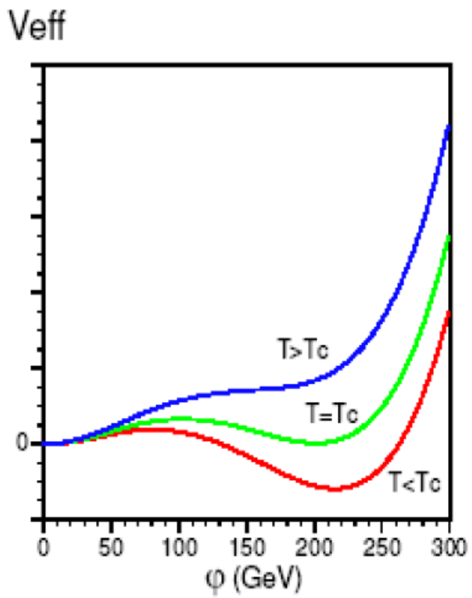
The 1-loop process $\gamma\gamma$ can be comparable to the bb and $\tau\tau$ processes, when σ, $Y_f \ll \kappa$.

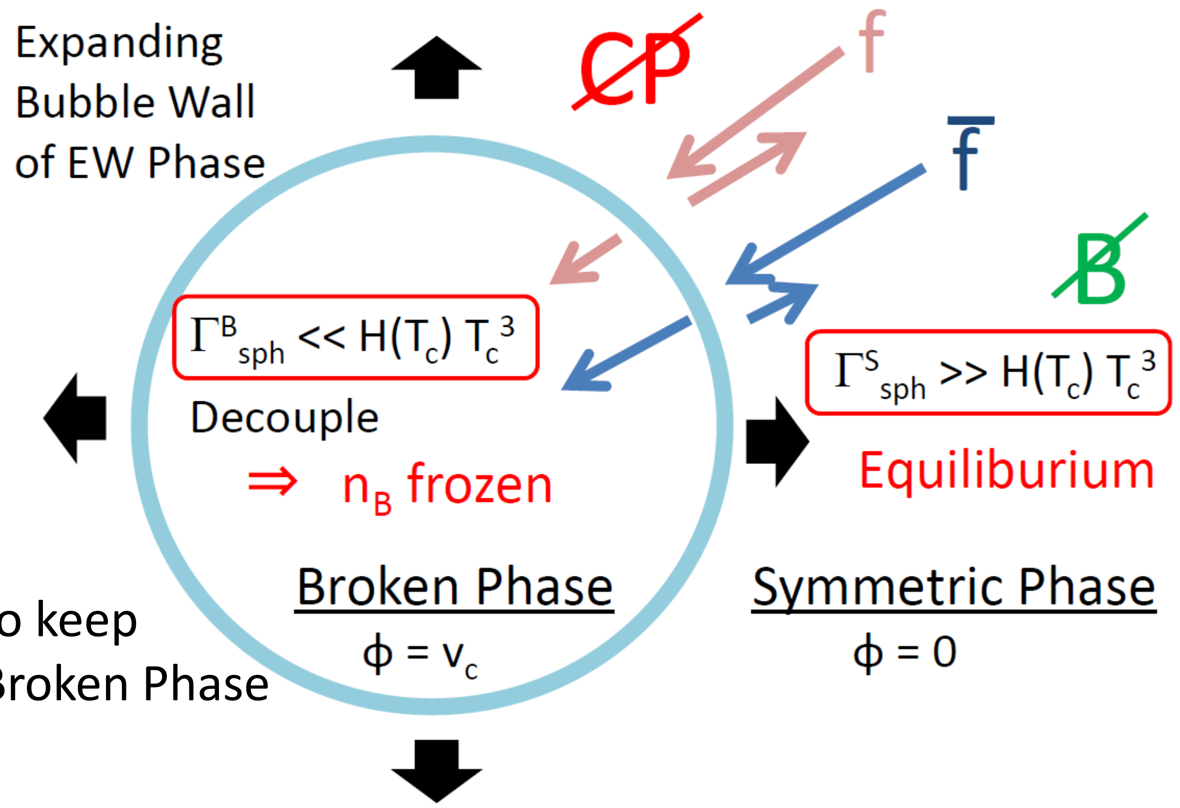
m_η would be around 40-65 GeV for m_S = 400GeV

Electroweak Baryogenesis

Sakharov's conditions:

- B Violation → Sphaleron transition at high T
- C and CP Violation → CP Phases in 2HDM
- Departure from Equilibrium → 1st Order EW Phase Transition





Quick sphaleron decoupling to keep sufficient Baryon number in Broken Phase

$$\frac{\varphi_c}{T_c} \gtrsim 1$$

Strong 1st Order Phase Transition

Effective Potential at high T

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

Sphaleron decoupling

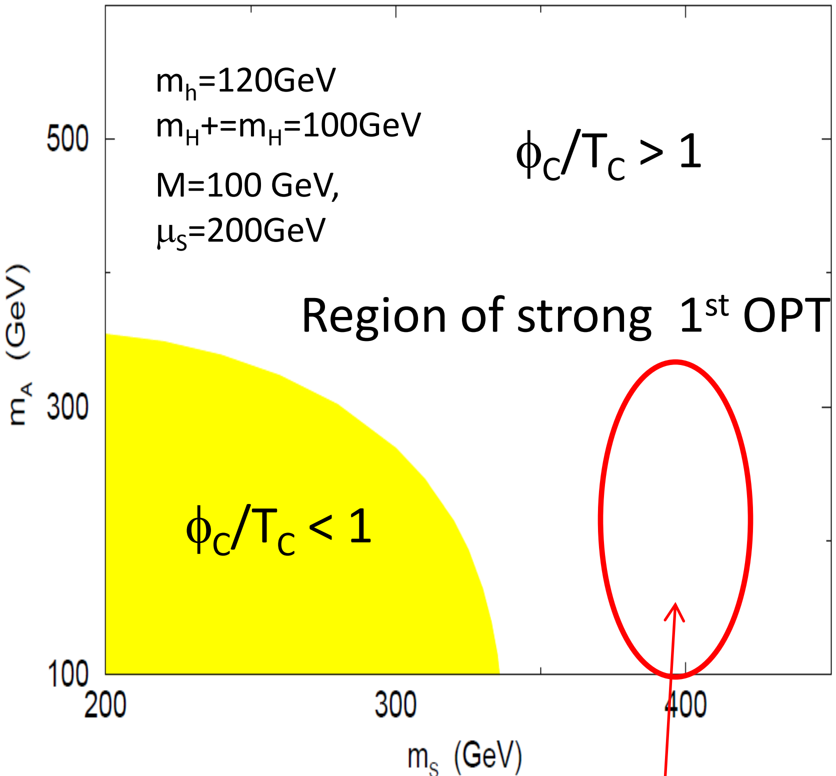
$$\frac{\varphi_c}{T_c}\left(= \frac{2E}{\lambda_{T_c}}\right) \gtrsim 1 \qquad \lambda_T \sim \frac{2m_h^2}{v^2}$$

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. $\quad m_{S+} \sim \lambda_S v^2$

This region is compatible with neutrino data and DM abundance.

Successful scenario under current data

The requirement and data taken into account

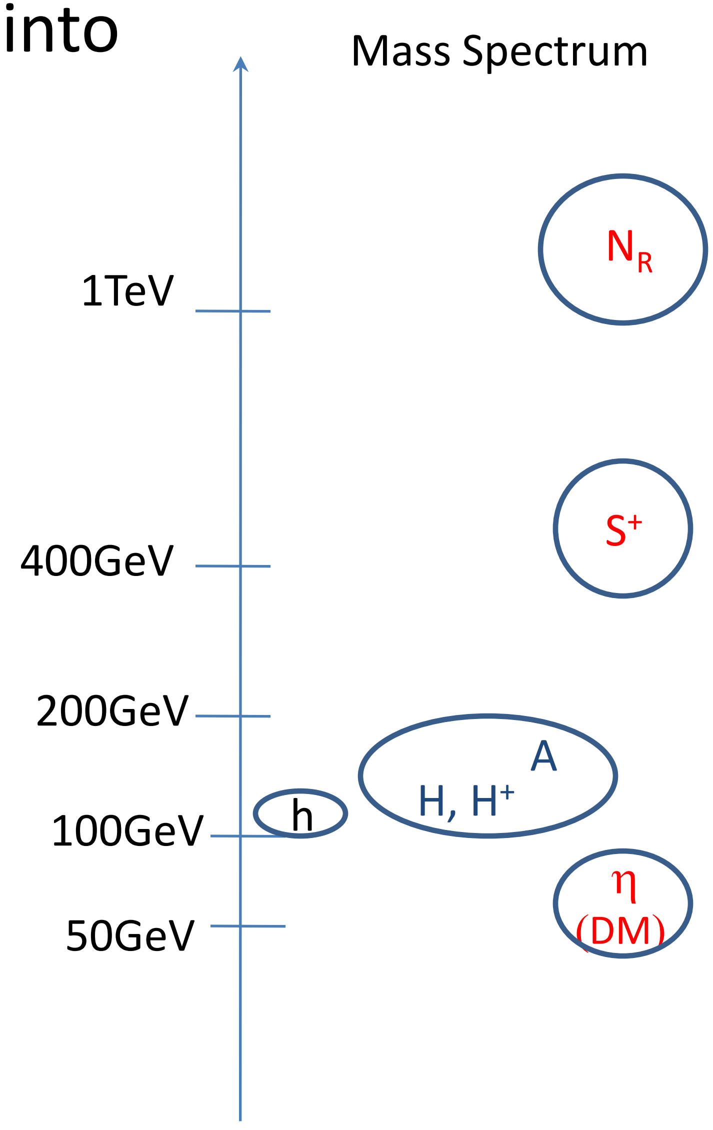
- Neutrino Data
- DM Abundance
- Condition for Strong 1st OPT
- LEP Bounds on Higgs Bosons
- Tevatron Bounds on mH+
- B physics: $B \to X_s \gamma$, $B \to \tau\nu$

Tau Leptonic Decays, LFV ($\mu \to e\,\gamma$), g-2

Theoretical Consistency

Outline of the mass spectrum is determined

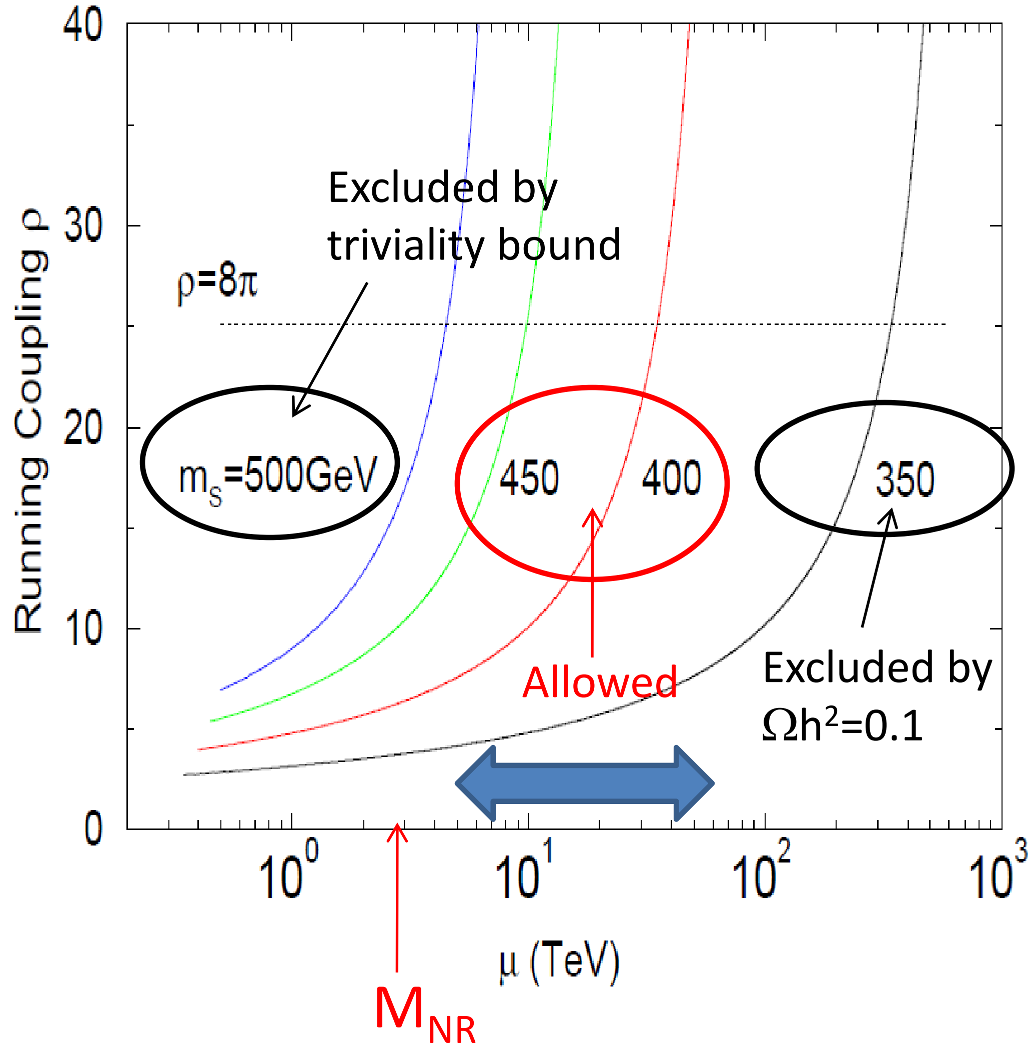
Many discriminative predictions!!



Cutoff scale of the model

- This model contains lots of scalars.
- Running couplings become larger for higher energies.
- Our scenario is consistent with the RGE analysis with

  Λ=O(10-100) TeV.



Predictions

- Physics of eta (DM candidate)
- Type X THDM [Key Yagyu's Talk]
- Non-decoupling effect of S^+ Physics at ILC!
- Detect Majorana structure! Physics at ILC!

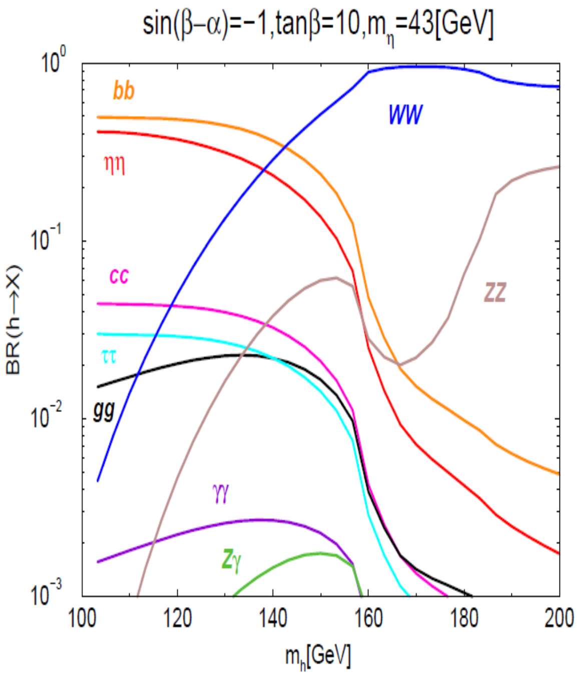
Physics of η (DM)

Invisible Decay of h

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

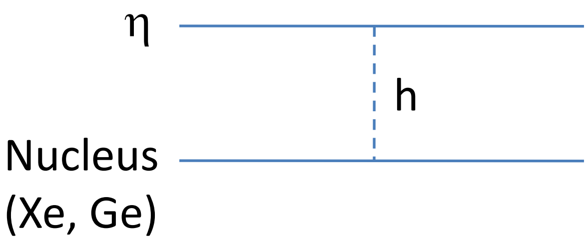
B(h→ηη) = 36 (34) % for m_η=48 (55) GeV

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

Non-decoupling effect

Successful EWBG requires

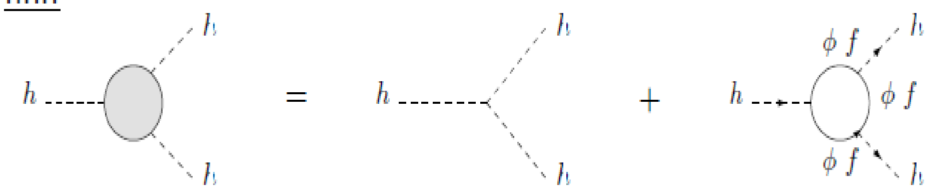
Non-decoupling property for S^+ (or A)

SK, Okada, Senaha 2005

$$m_{S+}{}^2 = \mu_S{}^2 + \lambda_s v^2 \quad (\lambda_s v^2 >> \mu_S{}^2)$$

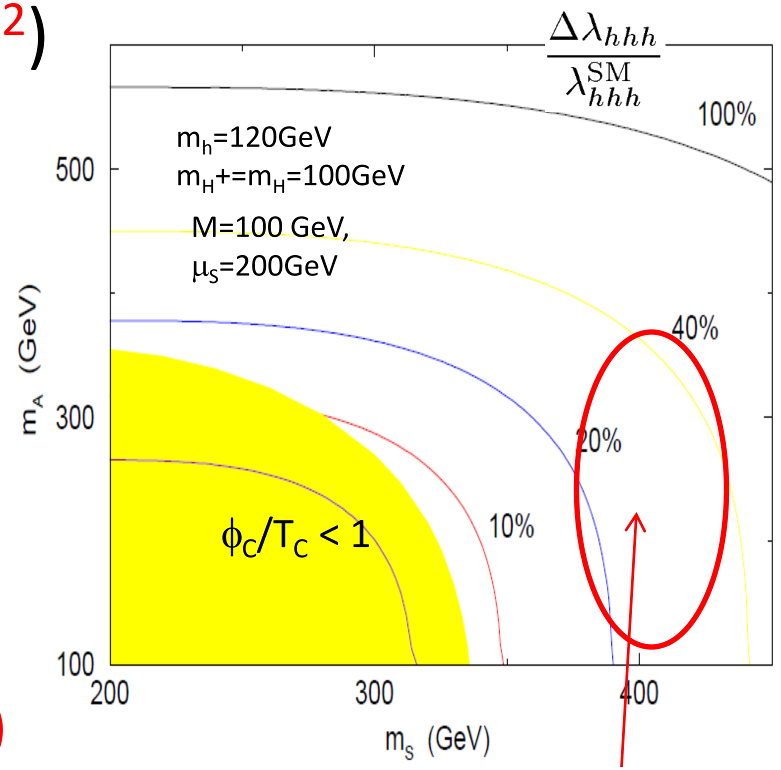
Deviation in the hhh coupling

hhh



Strong 1st OPT

→ A large quantum effect on λ_{hhh} (20-40%!!)



Favored Region under DM data and Triviality

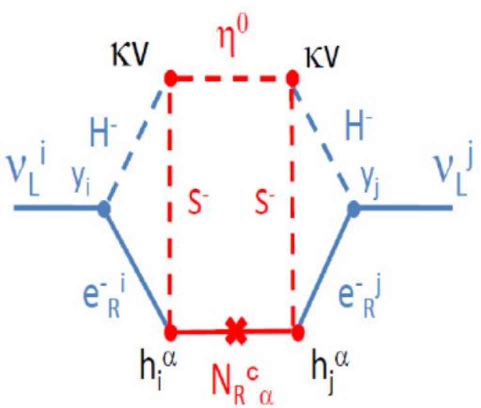
Testable at ILC (e^+e^- and PLC)

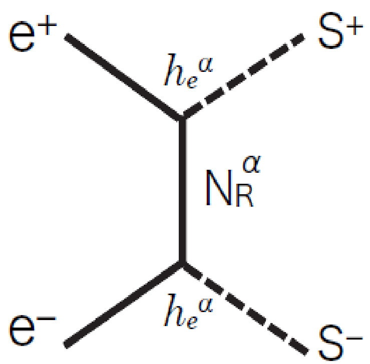
Important Test for our EWBG scenario

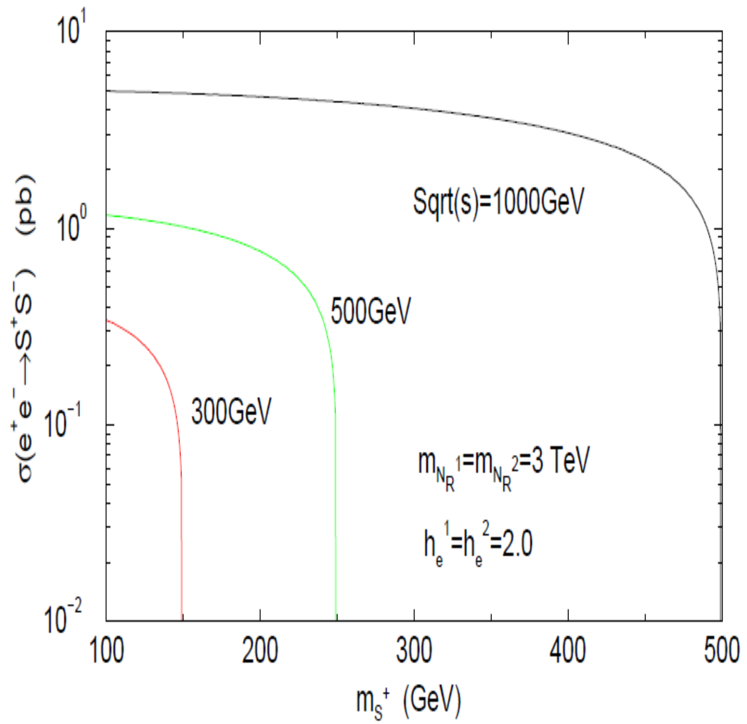
Measuring RH neutrino coupling h_e^{α} at ILC

3-loop induced ν-masses

- Z2-odd TeV scale N_R.
- Large couplings $h_e^{\alpha}=O(1)$





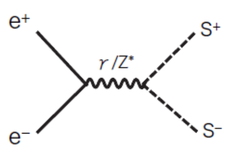


$\sigma(e^+e^- \to S^+S^-)=O(1)$pb!!

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

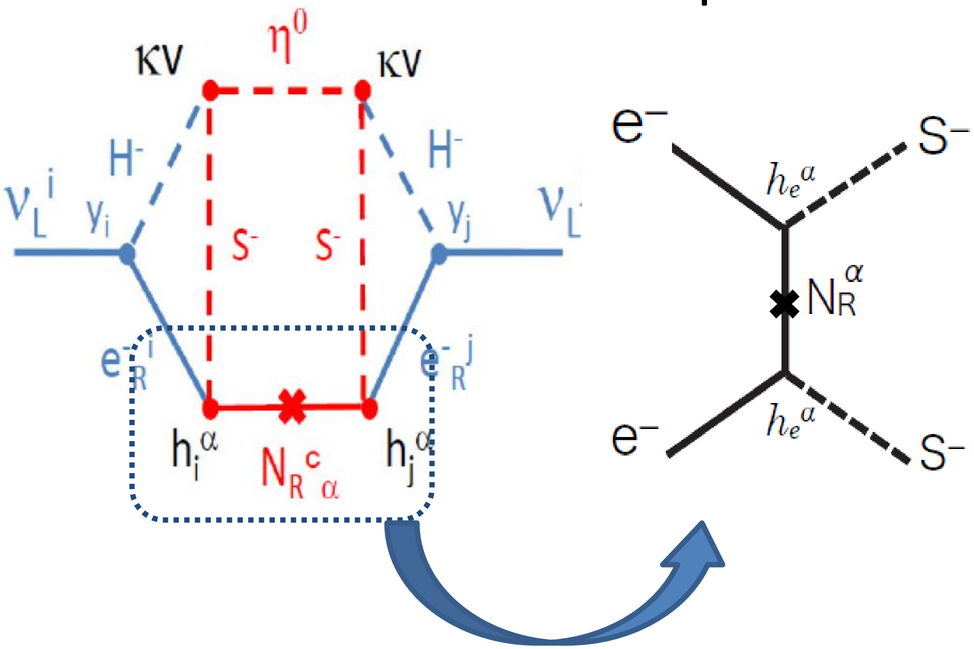
Signal: energitic $\tau^+\tau^-$ with large missing E

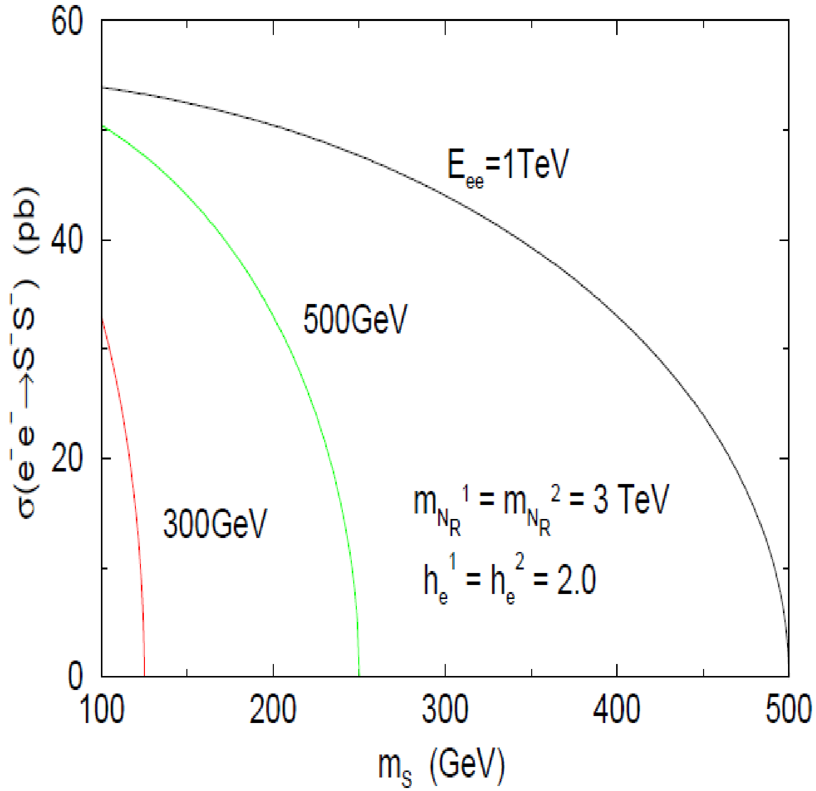
σ_{DY}=100 fb



Test the Majorana Nature at ILC

- The sub-diagram itself can be measured at the e^-e^- option





$\sigma(e^-e^- \to S^-S^-)$=O(10)pb!!

Signal: $\tau^-\tau^-$ with large missing E

Combination of e+e- and e-e- collisions is useful to test this model

Summary

We discussed a successful model for

Neutrino Mass, Dark Matter and Baryogenesis

via TeV-scale physics with Z_2 parity.

Φ_1, Φ_2 (Z_2 even) η, S^+, N_R (Z_2 odd)

Predictions

Invisible decay of SM-like h

Direct searches of DM

Physics of Type-X Yukawa coupling (Leptonic Higgs) → Yagyu's Talk

Non-decoupling property of S^+ (measure of the hhh coupling at ILC)

Majorana nature of the model is tested at the ILC

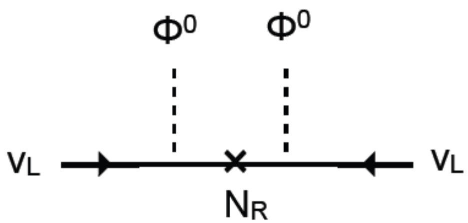
Seesaw Mechanism?

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

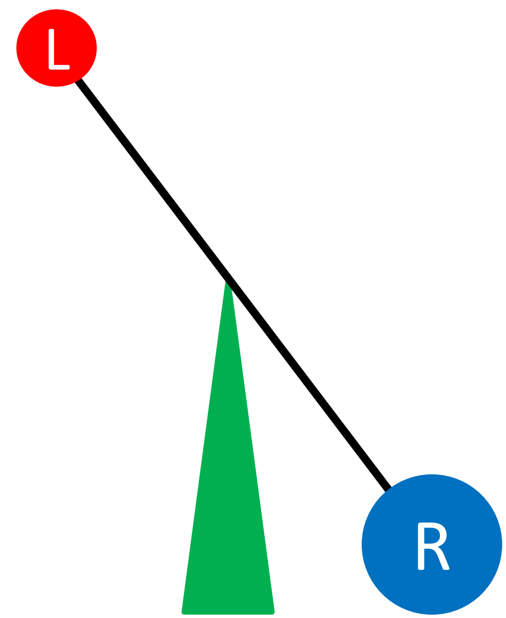
- Hierarchy between M_{N_R} and m_D generates that between m_D and tiny m_ν ($m_D \sim 100$ GeV)

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

$\nu\nu\phi\phi$



Minkowski
Yanagida
Gell-Mann et al



- Simple, compatible with GUT etc
- Introduction of a super high scale

Hierarchy for hierarchy!

Far from experimental reach…

Predictions

Physics of Type X 2HDM

Decays:

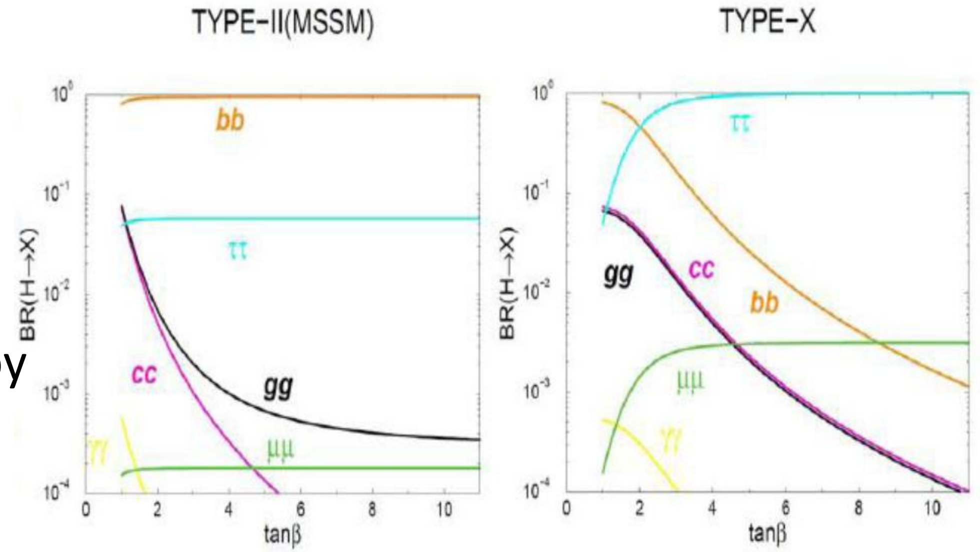
H, A decay into $\tau\tau$, not bb.

At LHC, Type X 2HDM can be tested by

$$pp \to AH^+(HH^+) \to \ell^+\ell^-\tau^+\nu$$

$\sigma(AH^+)$~200fb

In MSSM, bb$\tau\nu$ is signal



Aoki, SK, Tsumura, YagyuarXiv:0902.4665[hep-ph]

Heavy DM scenario

We would also take into account the PAMELA/ATIC results in our model

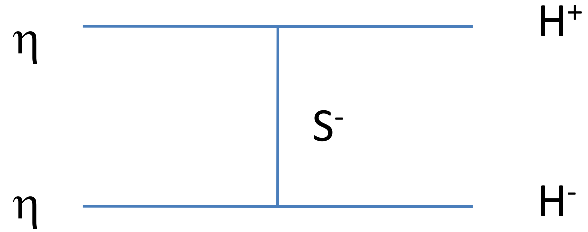
Heavy DM scenario:

m_η=700 GeV, m_S=3TeV, m_{NR}=5TeV:

can describe also Neutrino data

DM abundance

Strong 1st OPT



$H^+ \to \tau^+ \nu \to e^+ \nu\nu\nu\ldots$

Detailed study underway