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

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M. Aoki, SK, O. Seto, PRL 102, 051805 (2009) [arXiv:0807.0361]
M. Aoki, SK, K. Tsumura, K. Yagyu, arXiv: 0902.4665
M. Aoki, SK, O. Seto, arXiv:0904.3829

PPP8, 20-23. May 2009, NCKU, Tainan, Taiwan

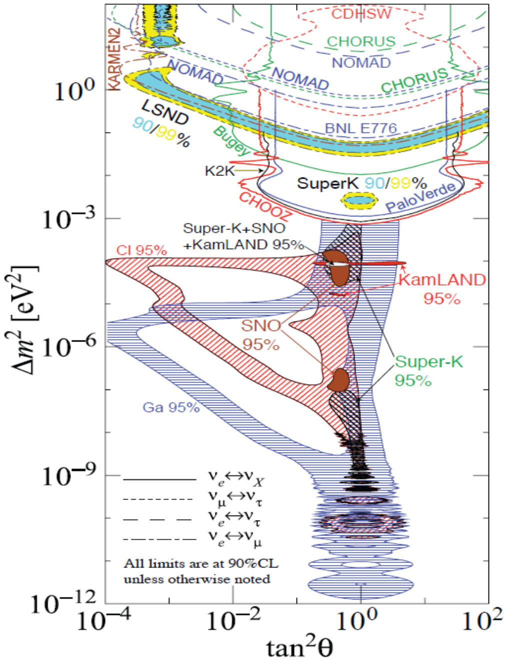
Introduction

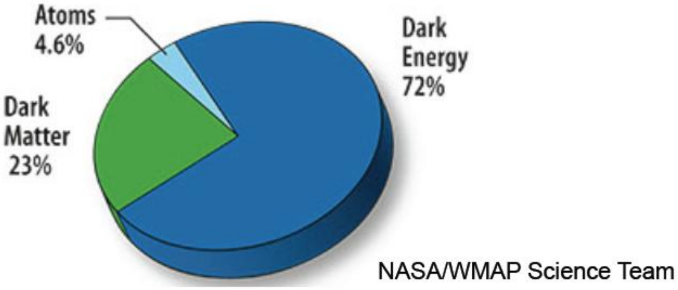
- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

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

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

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





NASA/WMAP Science Team

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

BSM: Neutrino Mass

Neutirno Mass Term (= Effectively Dim-5 Operator)

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

$<\phi> = v = 246\text{GeV}$

Mechanism for tiny masses:

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

Seesaw (tree level)

$$m^{\nu}{}_{ij} = y_i y_j\ v^2/M \qquad M = 10^{13\text{-}15}\text{GeV}$$

Quantum Effects   N-th order of perturbation theory

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

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Quantum Effects

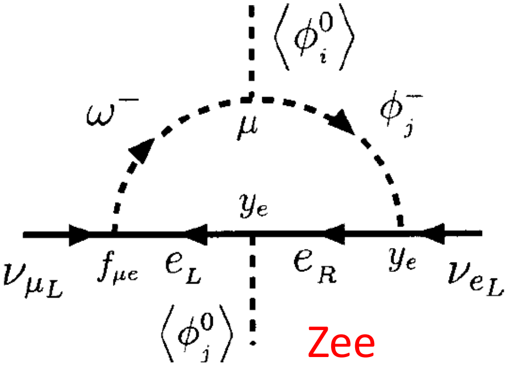
N-th order of perturbation theory

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

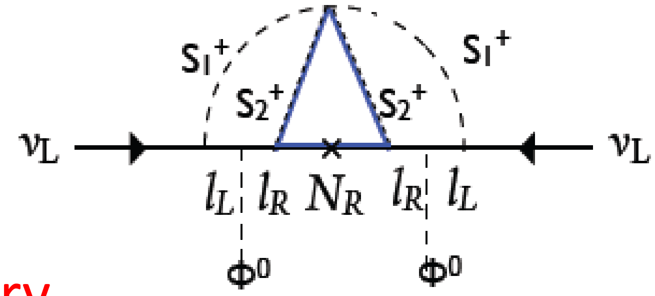
M=1 TeV

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), …..



Zee



Krauss et al
Cheung, Seto

- 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

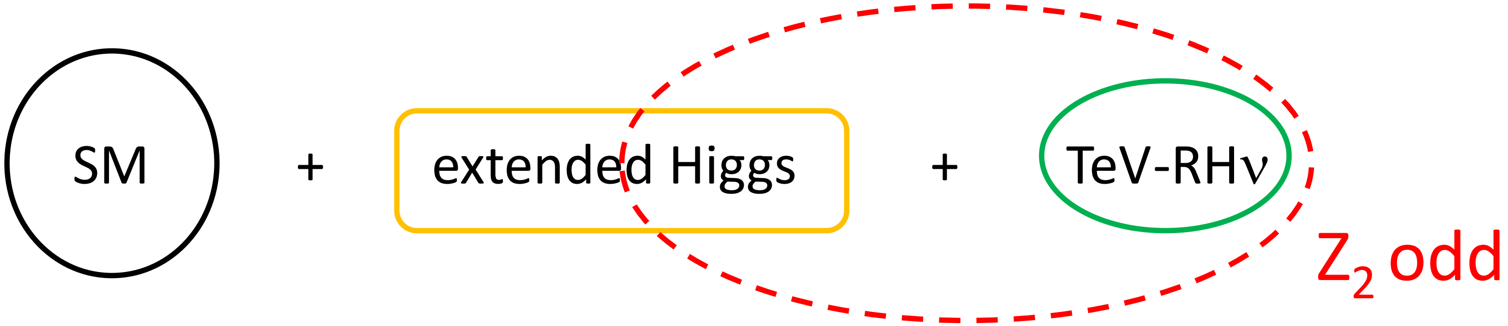
  Neutrino Mass

  Dark Matter

  Baryon Asymmetry of the Universe

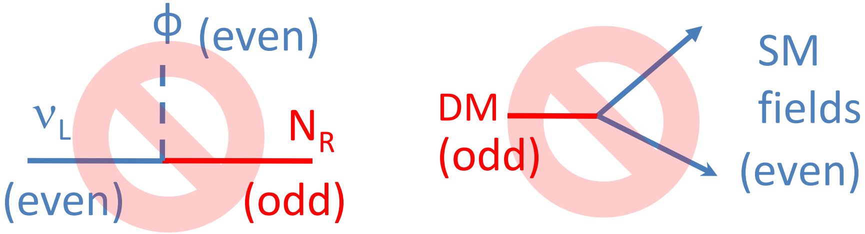
  by TeV scale physics without introducing large scales.
- Review of the model
- Phenomenology of the model

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 [1st Order PT, Source of CPV]

The Higgs sector

- The Higgs sector

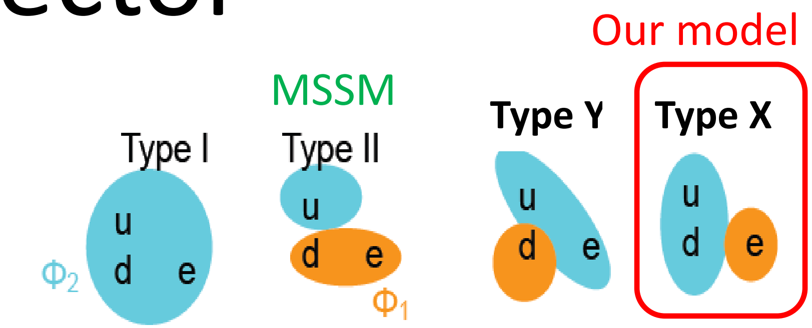
  Φ_1, Φ_2 (2HDM) + S^+, η (singlets)

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

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

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

- 4 types of Yukawa interactions!

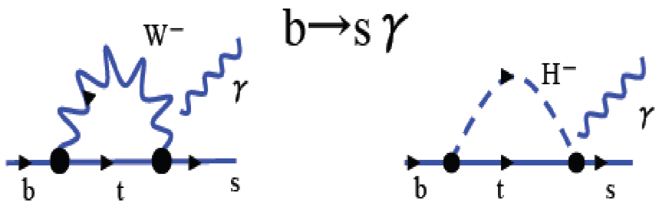


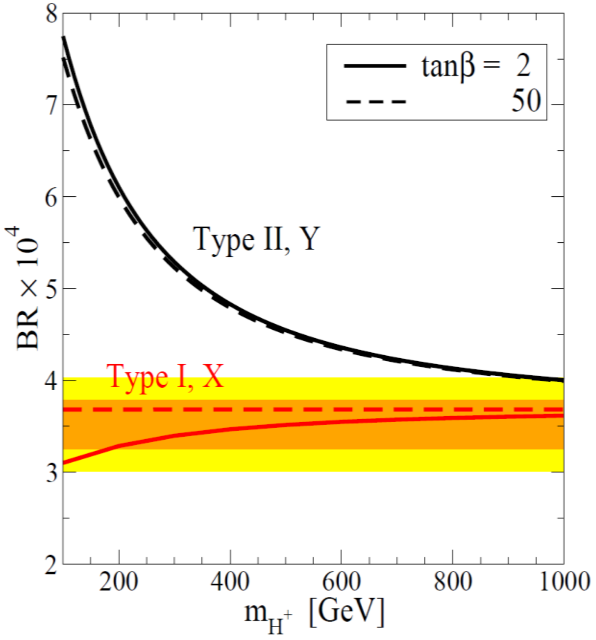
Neutrino data prefer a light H^+(< 200GeV)

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

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

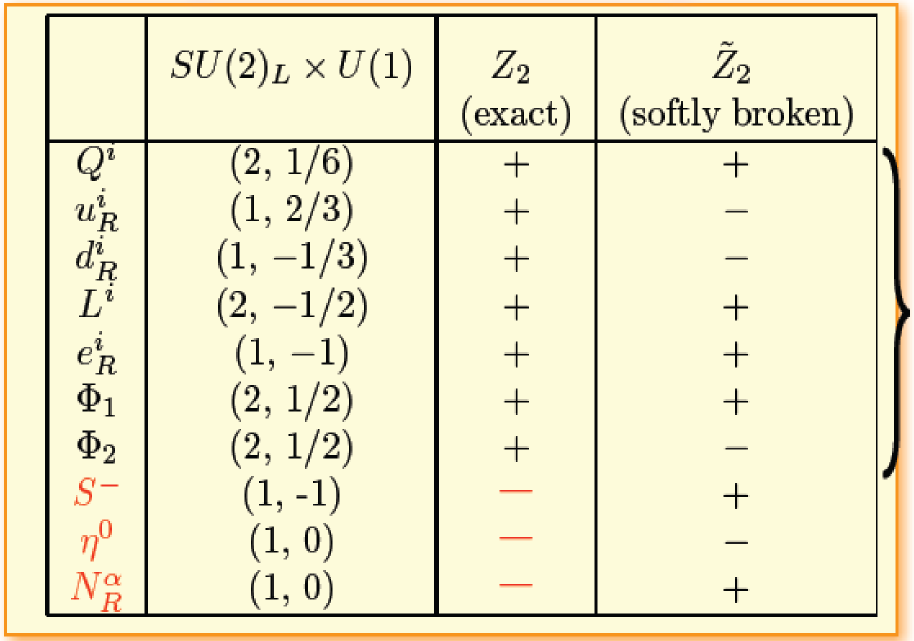
Aoki, SK, Tsumura, Yagyu, arXiv:0902.4665[hep-ph]

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

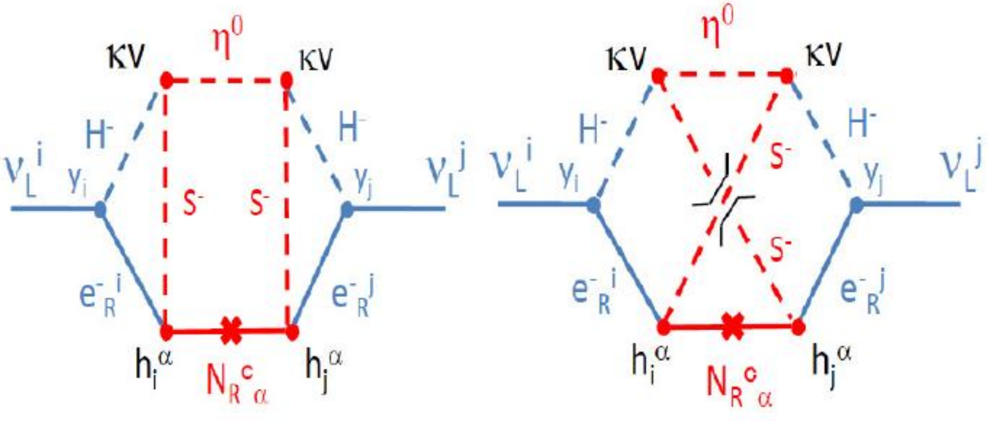
Z_2-even physical states
h (SM like Higgs)
H, A, H^- (Extra scalars)
Z_2-odd states
η, S^+, N_R

Neutrino Mass

Tree neutrino Yukawa is forbidden by Z_2

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

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



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

●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_R 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

$\Delta m_{sol}^2 \sim 8 \times 10^{-5}$ eV^2

$\Delta m_{atm}^2 \sim 0.0021$ eV^2

$\theta_{sol} \sim 0.553$

$\theta_{atm} \sim \pi/4$

Case of 2 generation N_R^α

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

$$m_\nu^{\rm diag} \equiv \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sqrt{\Delta m^2_{\rm solar}} & 0 \\ 0 & 0 & \sqrt{\Delta m^2_{\rm atom}} \end{bmatrix}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\tilde{\alpha}} & 0 \\ 0 & 0 & e^{i\tilde{\beta}} \end{bmatrix}$$

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

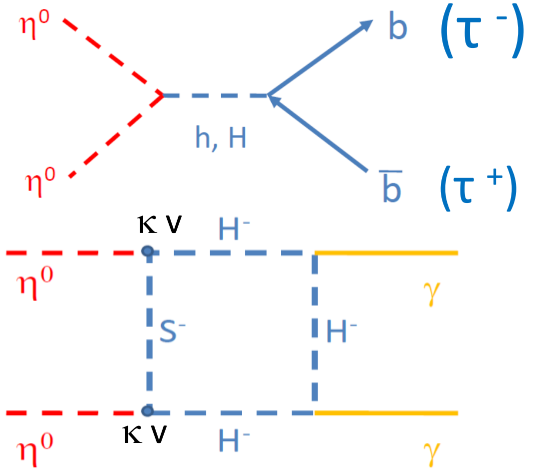
Set	Mass (TeV)				Yukawa couplings						LFV
(hierarchy, $\sin^2 2\theta_{13}$)	m_η	m_S	m_{Ni}	$\kappa \tan\beta$	h_e^1	h_e^2	h_μ^1	h_μ^2	h_τ^1	h_τ^2	$B(\mu \to e\gamma)$
A (normal, 0)	0.05	0.4	3	29	2.0	2.0	0.041	-0.020	0.0012	-0.0025	6.8×10^{-12}
B (normal, 0.14)	0.05	0.4	3	34	2.2	2.1	0.0087	0.037	-0.0010	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}

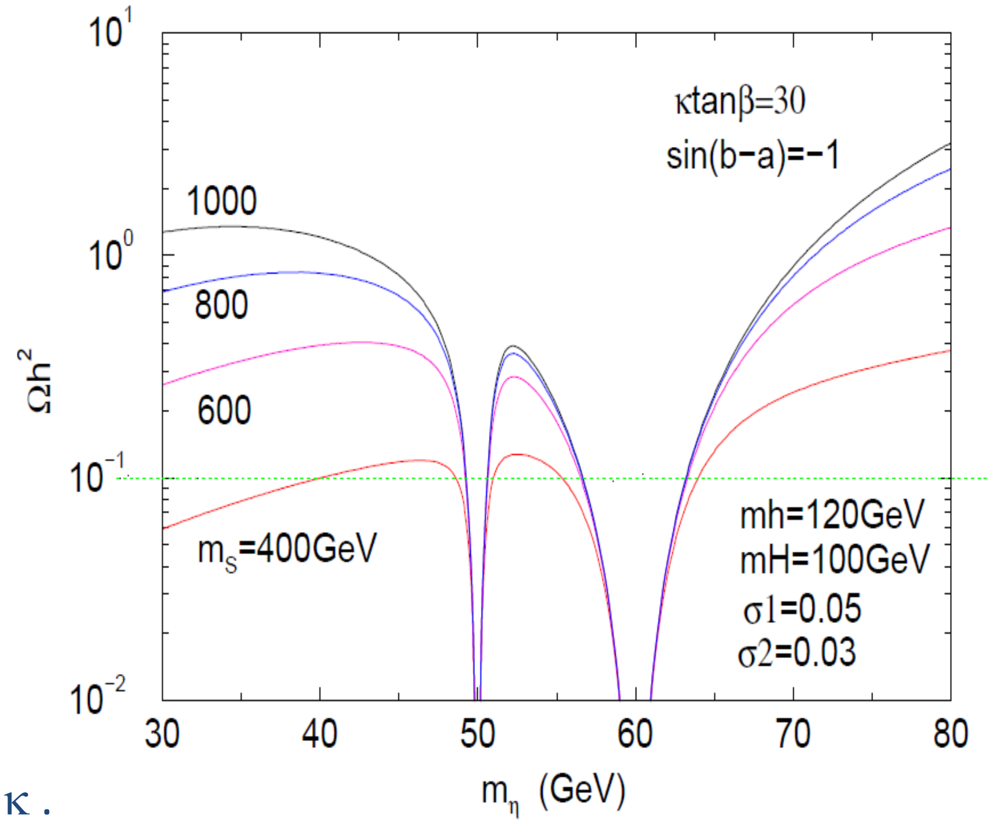
The model can reproduce all the neutrino data

Thermal Relic Abundance of η^0

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

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





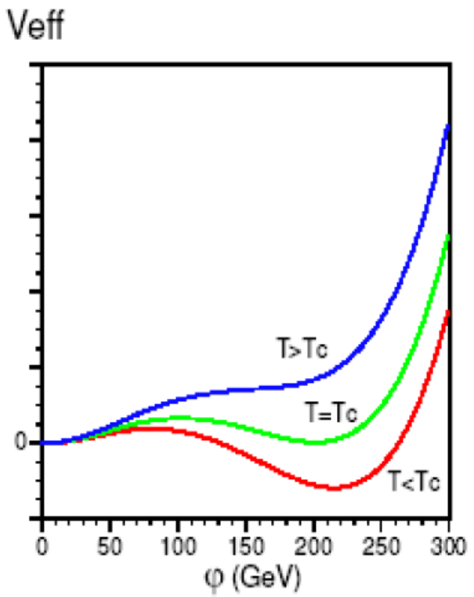
The 1-loop process γγ can be comparable to the bb and ττ processes, when σ, Y_f << κ .

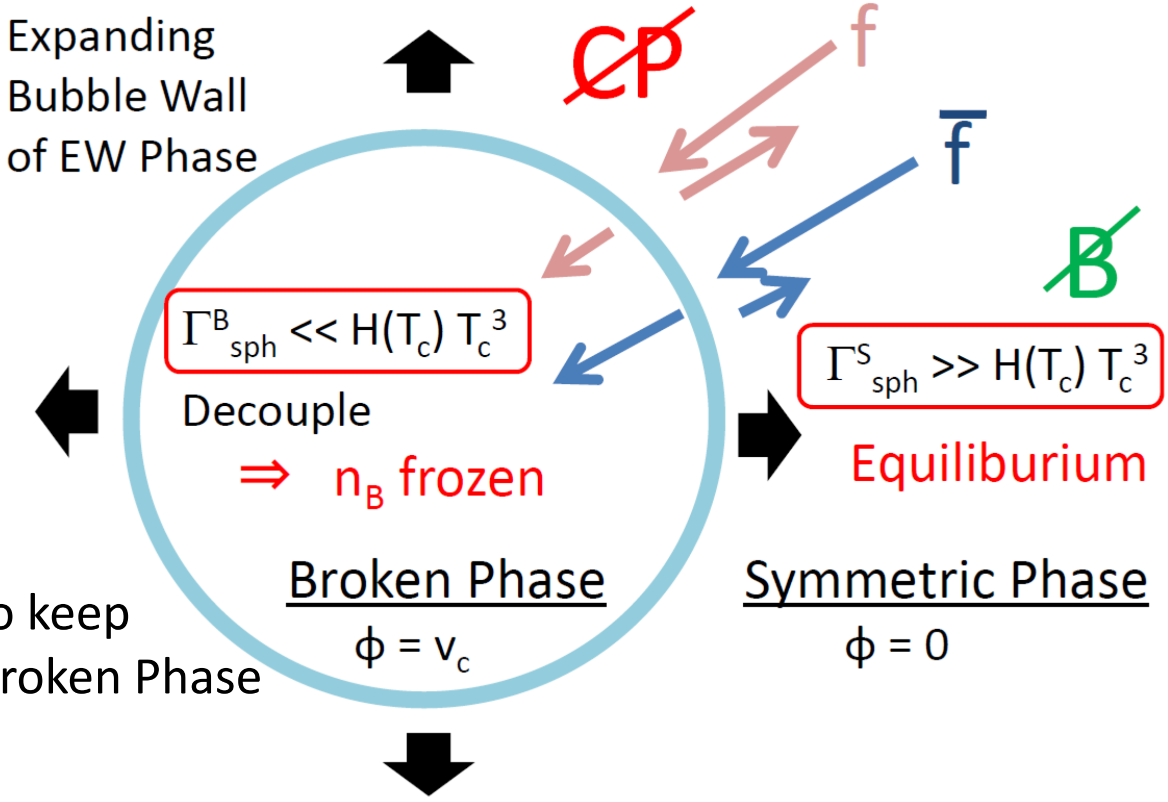
m_η would be around 40-65 GeV for m_S = 400GeV

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





Expanding Bubble Wall of EW Phase

$\cancel{CP}$

f

$\bar{f}$

$\cancel{B}$

$\Gamma^{B}_{sph} << H(T_c)\, T_c^{3}$

Decouple

$\Rightarrow$ n_B frozen

Broken Phase

$\phi = v_c$

$\Gamma^{S}_{sph} >> H(T_c)\, T_c^{3}$

Equiliburium

Symmetric Phase

$\phi = 0$

Quick sphaleron decoupling to keep sufficient Baryon number in Broken Phase

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

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

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

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

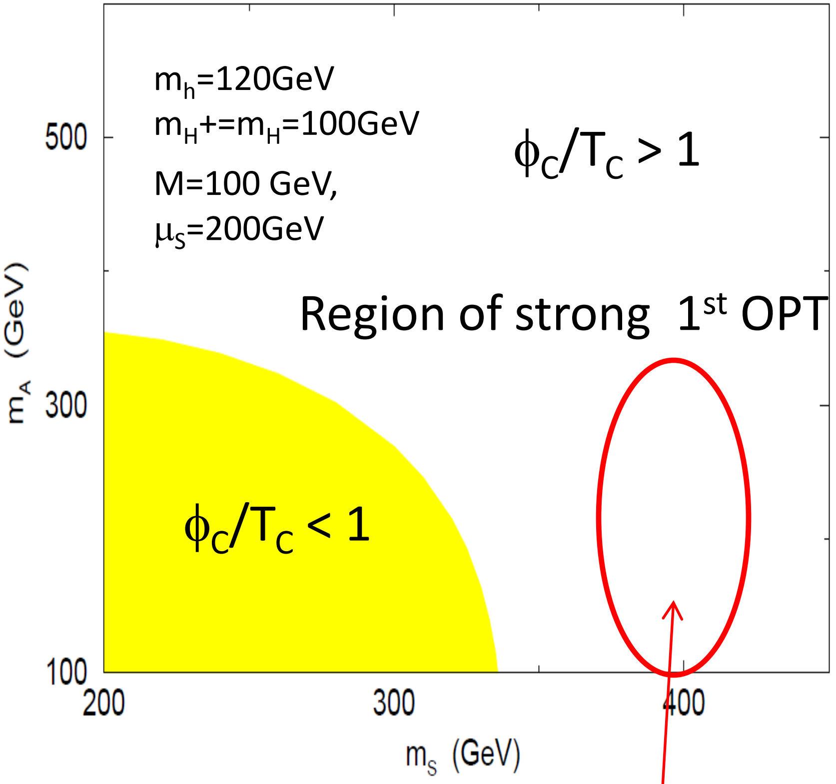
In SM, m_h is too smaller than LEP bound

Our Model

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

The condition can be satisfied with $m_h > 114$ GeV, when A and/or S^+ have non-decoupling property.

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



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+

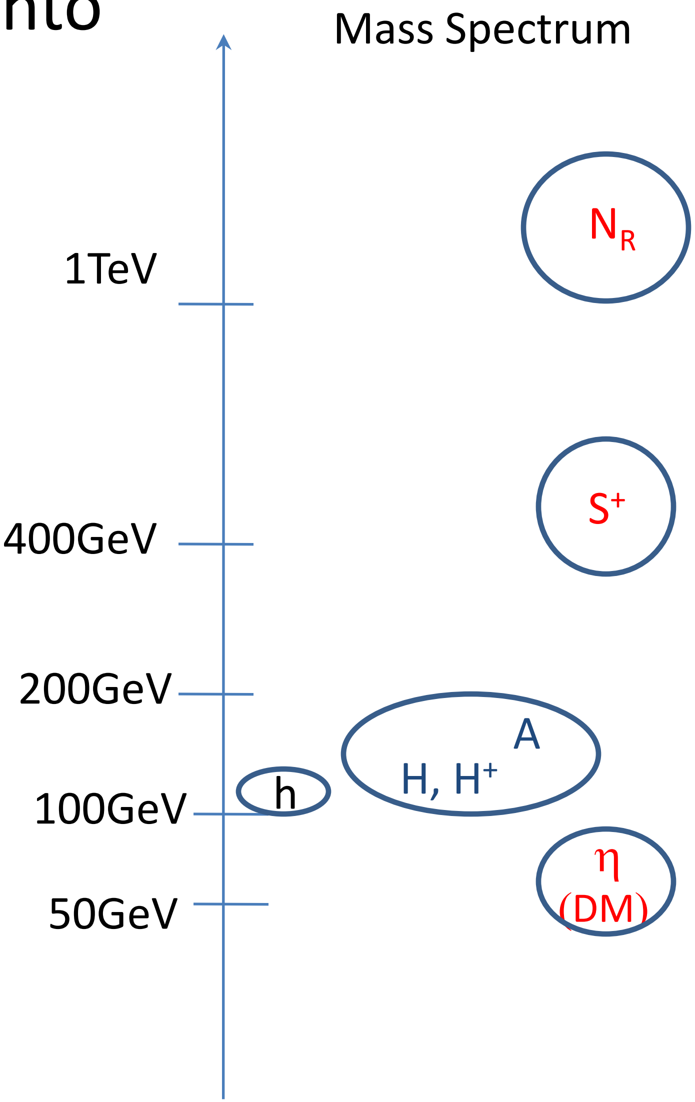
B physics: B → $X_s\gamma$, B→$\tau\nu$

Tau Leptonic Decays, LFV (μ→e γ), g-2

Theoretical Consistencies

Outline of the mass spectrum is determined

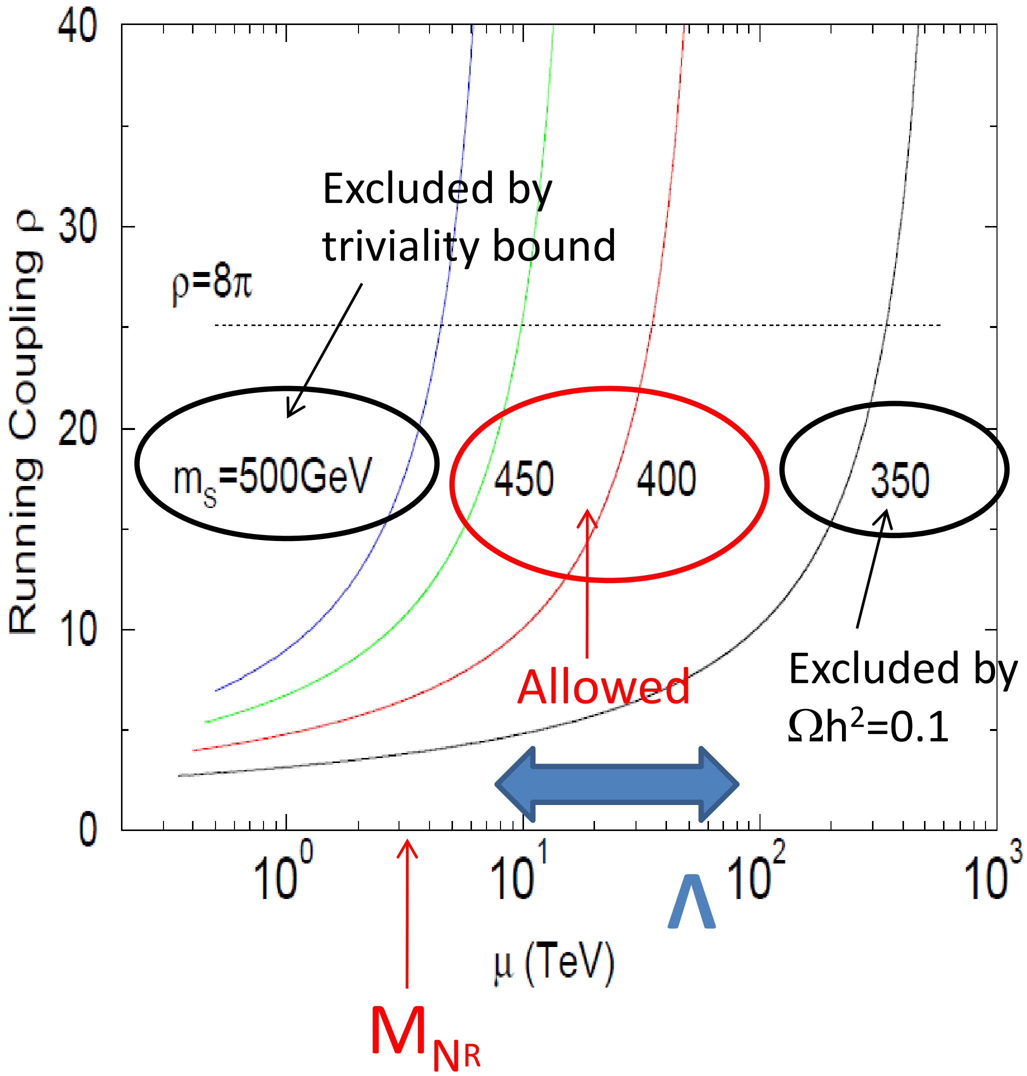
Many discriminative predictions !



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

$\Lambda = O(10\text{-}100)$ TeV.



Predictions

- Physics of η (DM)
- Type X THDM with a light H^+.
- Non-decoupling effect of S^+.
- Direct test for Majorana structure.

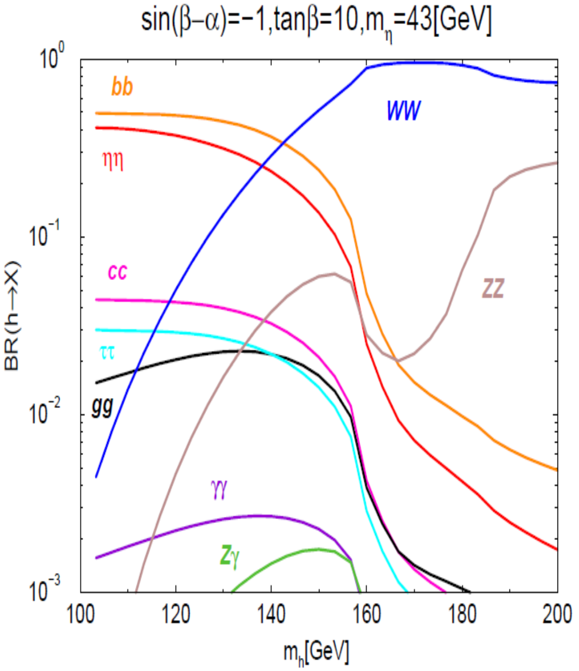
Physics of η (DM)

Invisible Decay of h

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

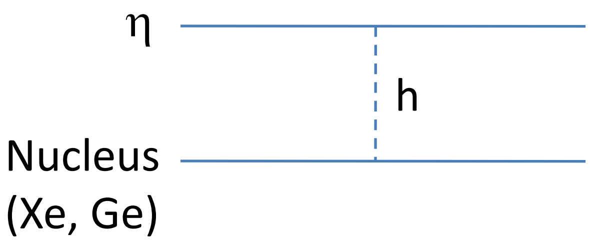
B(h→ηη) = 36 (34) % for m_η=48 (55) GeV

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)



η

h

Nucleus
(Xe, Ge)

Observing the release energy

Predictions of Type X 2HDM

Decays:

H, A decay into ττ, not bb.

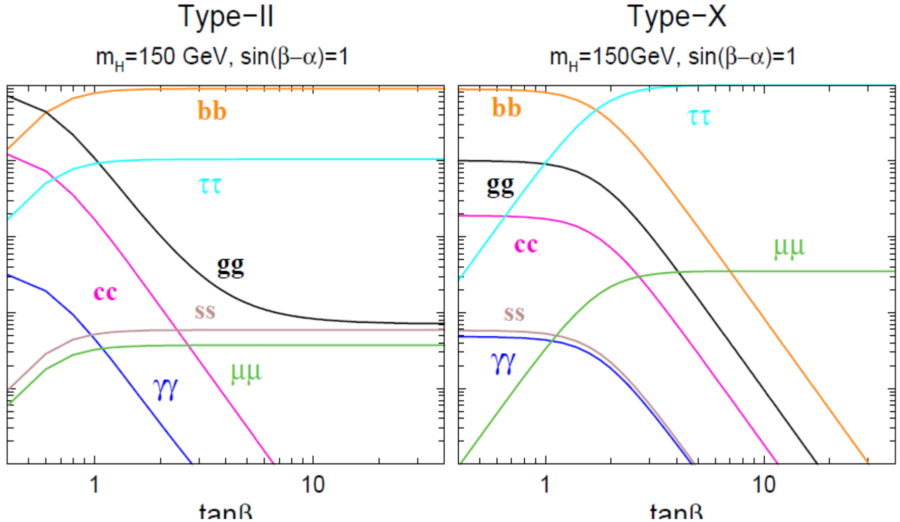
At LHC,
Type X 2HDM can be discriminated from MSSM (Type-II) by the combination of ττ gluon fusion

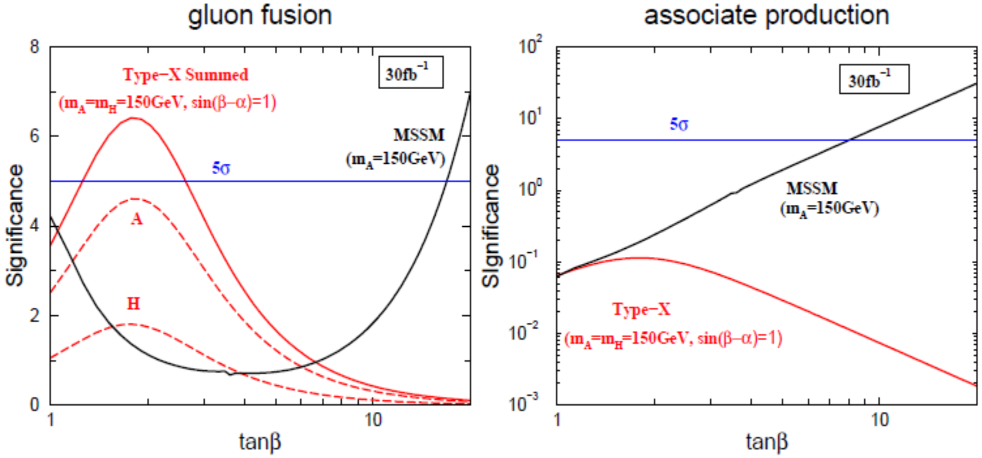
pp→A (H) → ττ

and bb associate (H)A production

pp → bbA (bbH)

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





Type X Yukawa structure of the mode can be well tested at LHC and ILC.

Non-decoupling effect

Successful EWBG requires

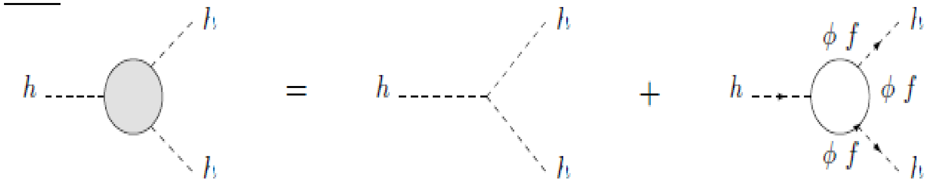
Non-decoupling property for S^+ (or A)

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

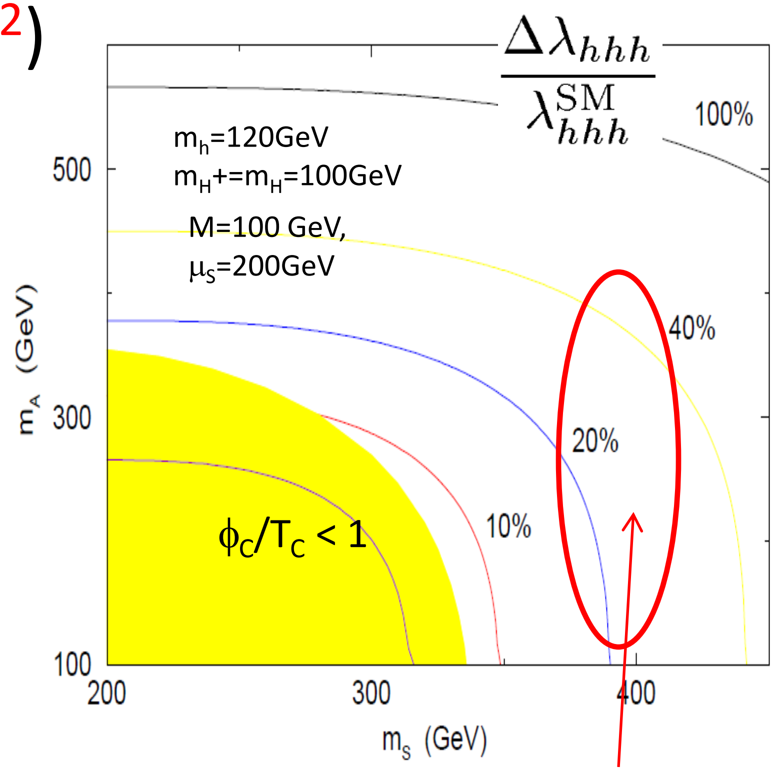
hhh



Strong 1st OPT

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

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



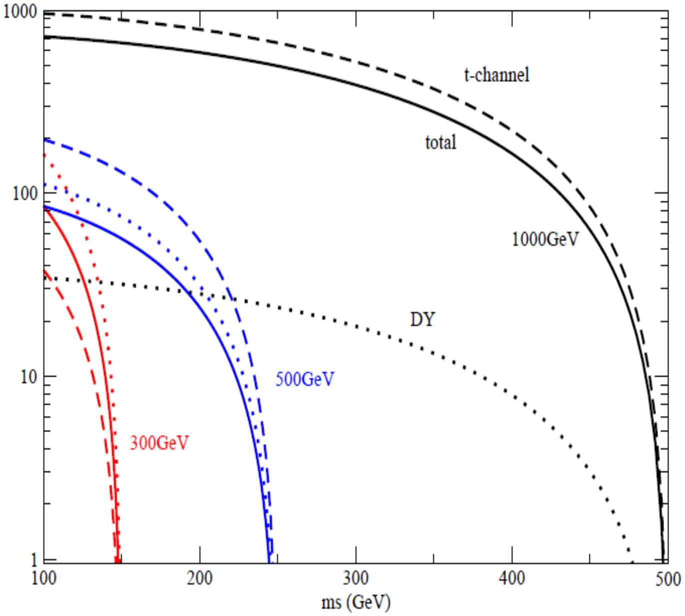
Favored region under DM data and Triviality

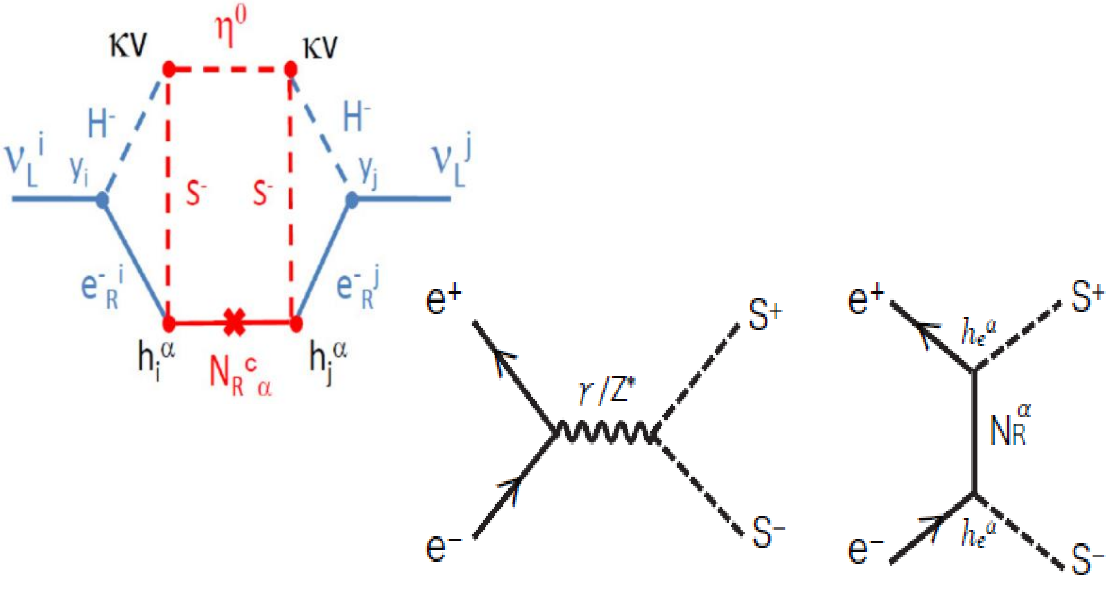
Important Test for our EWBG scenario

Measuring RH neutrino at ILC

3-loop induced ν-masses

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





$\sigma(e^+e^- \rightarrow S^+S^-)=100\text{fb}!$

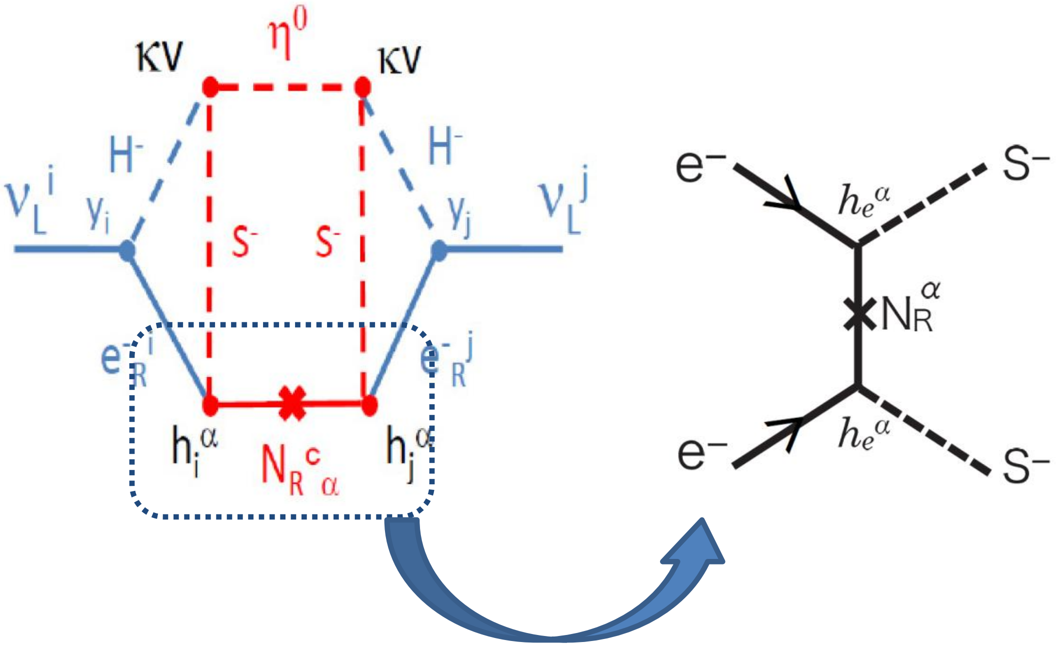
$(\sigma_{DY}=10\text{ fb})$

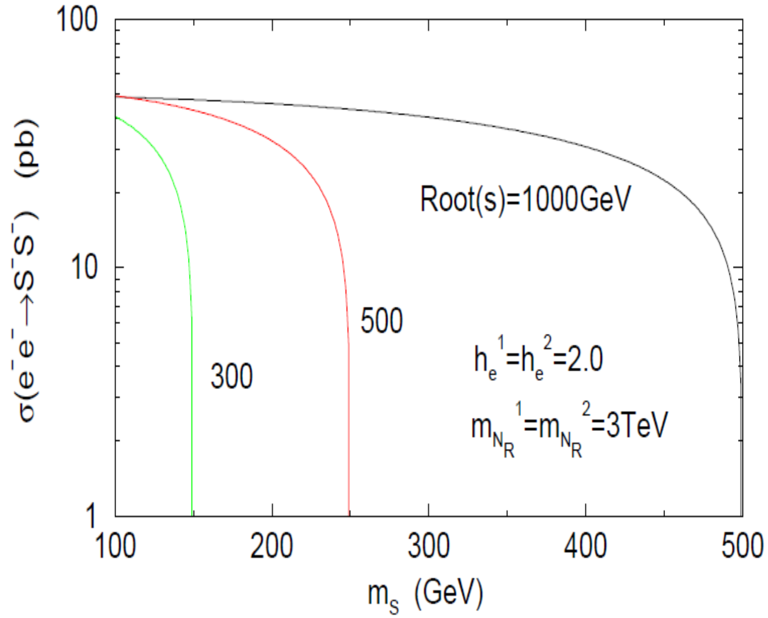
$e^+e^- \rightarrow S^+S^- \rightarrow (H^+\eta)(H^-\eta) \rightarrow (\tau^+\nu\eta)(\tau^-\nu\eta)$

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

Test the Majorana Nature at ILC

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





$h_e^\alpha=O(1)$

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

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

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

Summary

We discussed a successful model for

Neutrino Mass	--- 3 loop induced
Dark Matter	--- Z_2 odd scalar
Baryogenesis	--- Electroweak baryogenesis (1OPT)

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 [$h \to \eta\eta$]

Direct searches of η (DM)

Physics of Type-X Yukawa coupling (Leptonic Higgs) with a light H^+

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

Majorana nature of the model is testable at the ILC

The model can be tested at future experiments

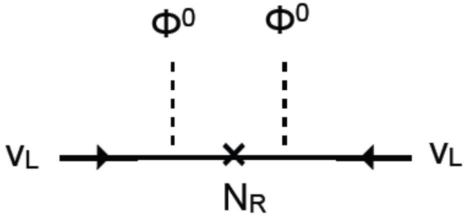
Seesaw Mechanism?

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

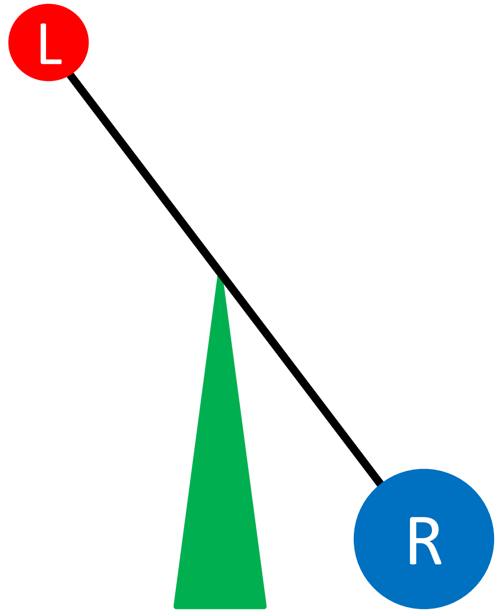
- Hierarchy between M_{NR} and m_D generates that between m_D and tiny m_ν ($m_D \sim 100$ GeV)

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

$\nu\nu\phi\phi$



Minkowski
Yanagida
Gell-Mann et al



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

Hierarchy for hierarchy!

Far from experimental reach…

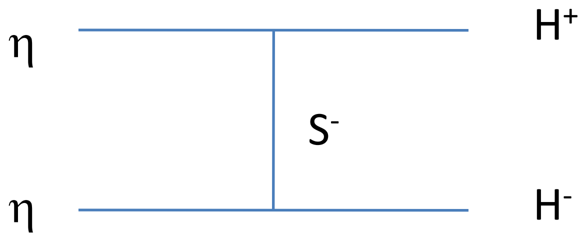
Heavy DM scenario

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



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

Detailed study underway