# A TeV-scale model for neutrino mass, DM and baryon asymmetry



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# What is discussed

- Although the success of the SM, today we have definite reasons to consider new physics beyond the SM.
  - Neutrino oscillation
  - Evidence of Dark Matter
  - Baryon Asymmetry of the Universe

- In this talk, an extension of the SM is proposed, which can explain these phenomena with less unnatural fine tuning.

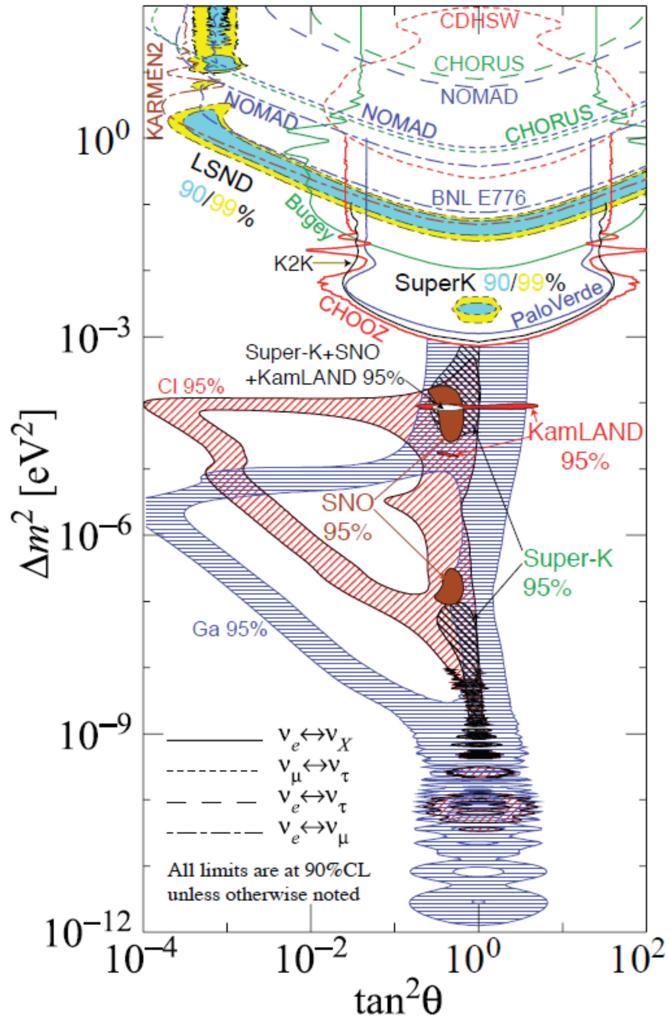
- The model predicts lots of interesting phenomenological features, in particular, in Higgs physics

# Neutrino Oscillation

- Information from Data
  - Two Mass Scales $\Delta m_{sol}^2 \sim 8 \times 10^{-5}\ eV^2$
  - Mixing Angles $\Delta m_{atm}^2 \sim 0.0021\ eV^2$

    $\theta_{sol} \sim 0.553$

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




- In the SM, such phenomenon cannot be explained
  - No Right-handed Neutrino
  - No Source for Majorana Masses
- New Physics
  - Seesaw
  - Quantum Effect by extended Higgs sectors

# Seesaw

Yanagida
Gell-Mann et al

- Super Heavy RH Neutrino ($M_{NR}$ ~ $10^{13\text{-}16}$GeV)
  - Hierarchy between $M_{NR}$ and $M_D$ generates that between $M_D$ and tiny $m_\nu$ ($M_D$ ~ 100 GeV)

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

  - Simple, compatible with GUT

- Problem? (or complain?)
  - Has the problem really been solved ?

Hierarchy for hierarchy !

  - Introduction of super high scale

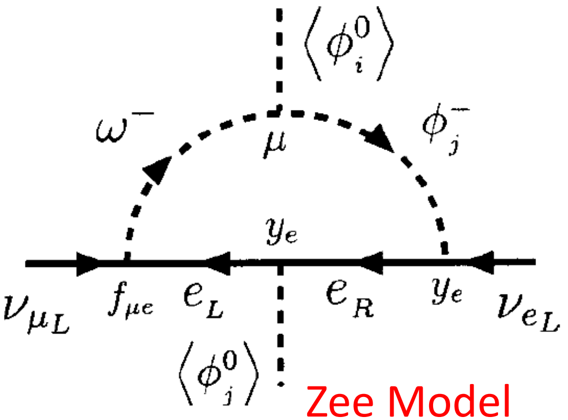
= far from experimental reach…

# Quantum Effects

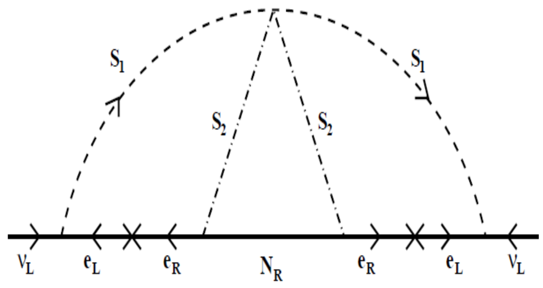
- Tiny ν-Masses may come from loop effects
  - Zee (1980, 1985)
  - Zee-Babu
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), …..
- Merit
  - Super large mass scales are not necessary
  - Tiny neutrino masses are radiatively generated

No hierarchy problem

Physics at TeV: Testable at collider experiments




Zee Model




Krauss et al

# Motivation of our model

Is it possible to extend the SM to include

- Neutrino Masses
- Dark Matter
- Baryon Asymmetry of the Universe

in the framework of a renormalizable field theory of at most TeV scale ?

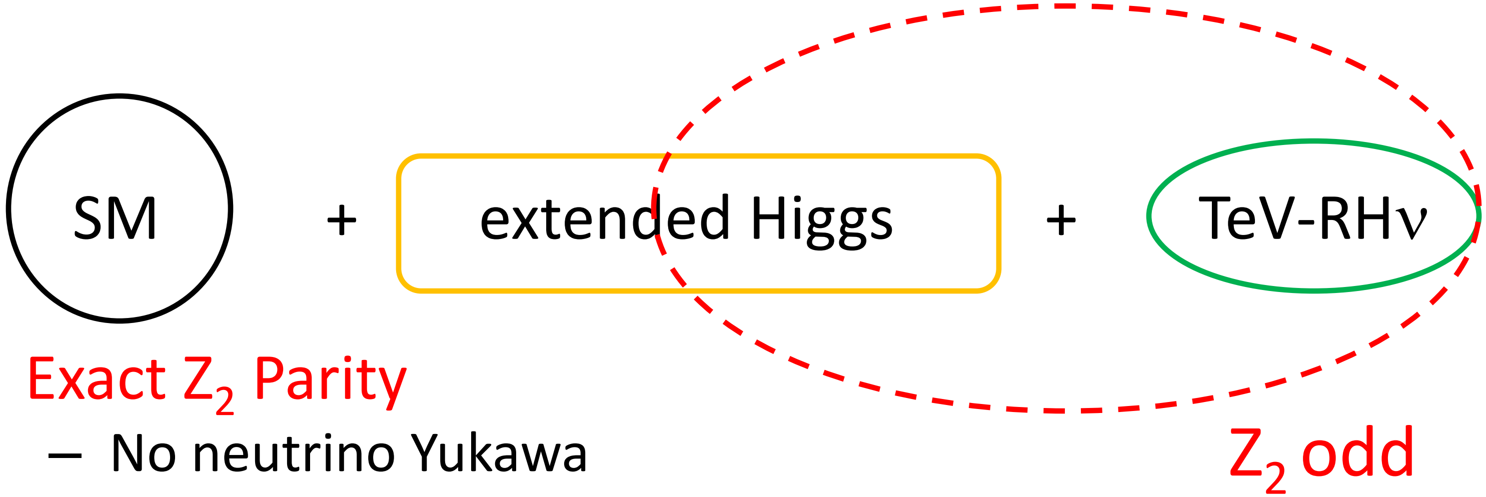
- No more large mass scales
- No more unnatural fine tuning among coupling constants,...

We can construct such a model.

# The Model

SM + extended Higgs + TeV-RH$\nu$

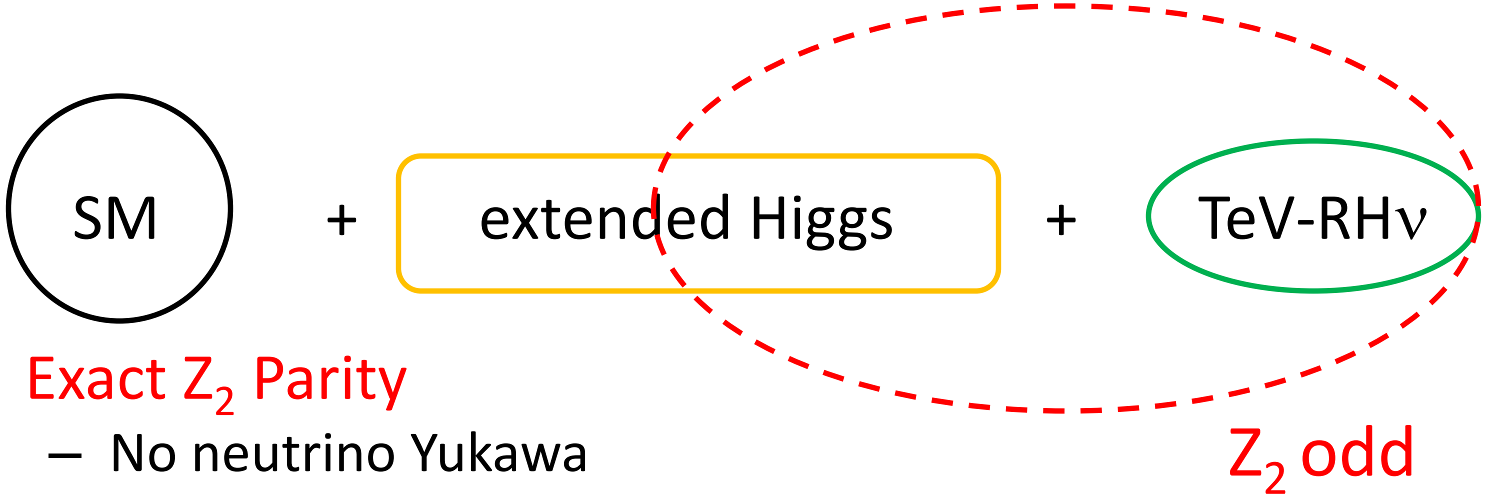
# The Model




- Exact $Z_2$ Parity
  - No neutrino Yukawa
  - Stabilize Dark Matter

- TeV-scale RH neutrinos: $N_R$

# The Model




- Exact $Z_2$ Parity
  - No neutrino Yukawa
  - Stabilize Dark Matter

- TeV-scale RH neutrinos: $N_R$
- Extended Higgs: 2HDM + gauge singlets ($\eta^0$, $S^+$)
  - Tiny ν-mass: 3-loop ($N_R$, $\eta^0$, $S^+$, $H^+$, $e_R$)
  - DM candidate ($\eta^0$)
  - EW Baryogenesis [1st Order PT, Source of CPV](2HDM)

# Type-X Yukawa coupling

In our model, a light $H^+$ ($m_{H^+}$=100 GeV) is required to satisfy $\nu$-data.
In the type II 2HDM, such a light H+ is excluded because of $b \to s\gamma$ result

Alternative Yukawa coupling (type-X) under the additional $\tilde{Z}_2$ parity

Glashow -Weinberg

Type-X 2HDM

Some people call it as Model-IV (Berger et al), or Model-II' (Grossmann), ...

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

- $\Phi_1$ only couples to Leptons
- $\Phi_2$ only couples to Quarks

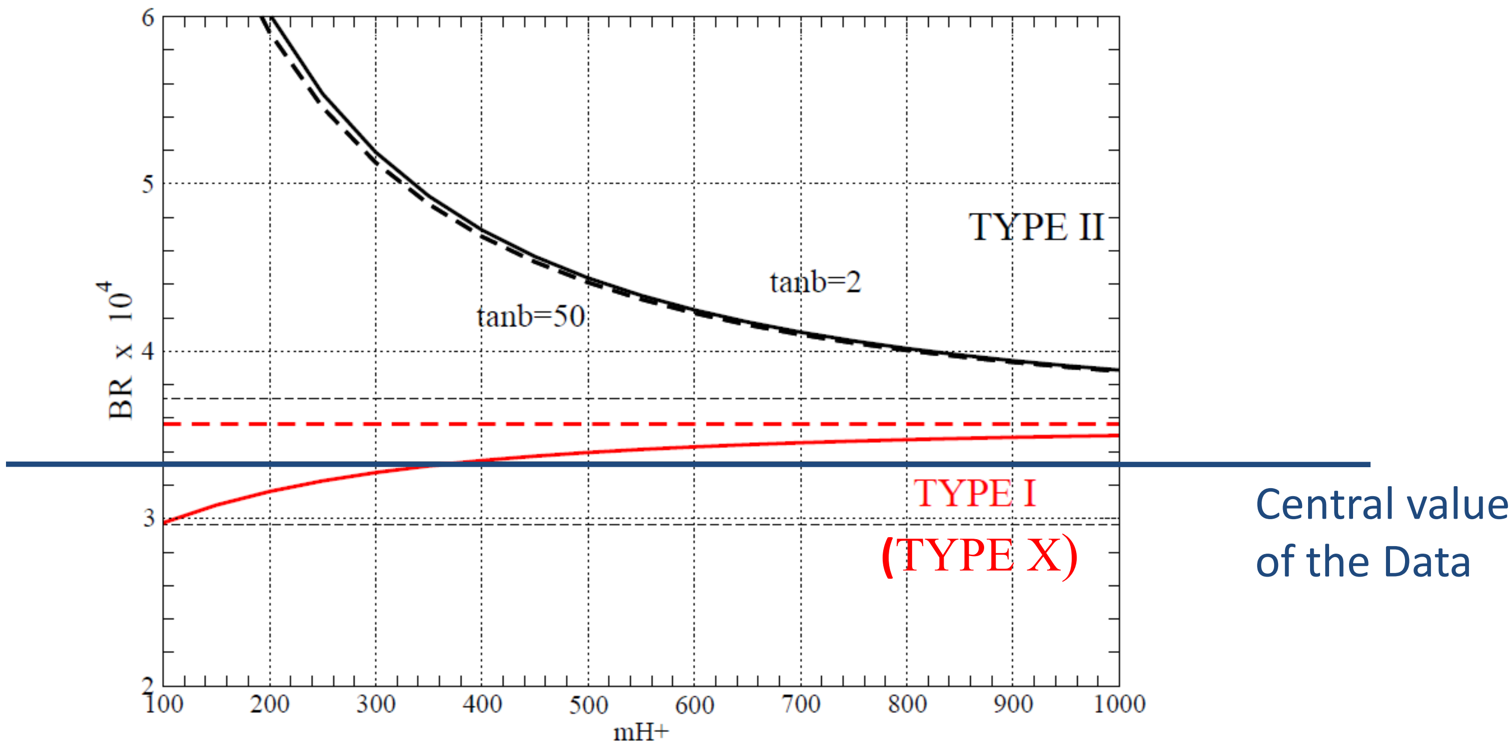
Discriminative Higgs phenomenology

# b→sγ

NLO by
Ciuchini et al '98

Boltmati/Greub
Chetyrkin/Misiak/Munz
Kagan/Neubert

## The NLO calculation and the data




M. Aoki, S.K., K. Tsumura, K. Yagyu, in preparation

Type-X scenario is free from the b-s $\gamma$ result even $m_H$+=100GeV

# Lagrangian

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

$Z_2$ even(2HDM) + $Z_2$odd($S^+$, $\eta^0$ , $N_R^\alpha$)

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

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

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

$Z_2$ even 2HDM

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

$Z_2$ odd scalars

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

Interaction

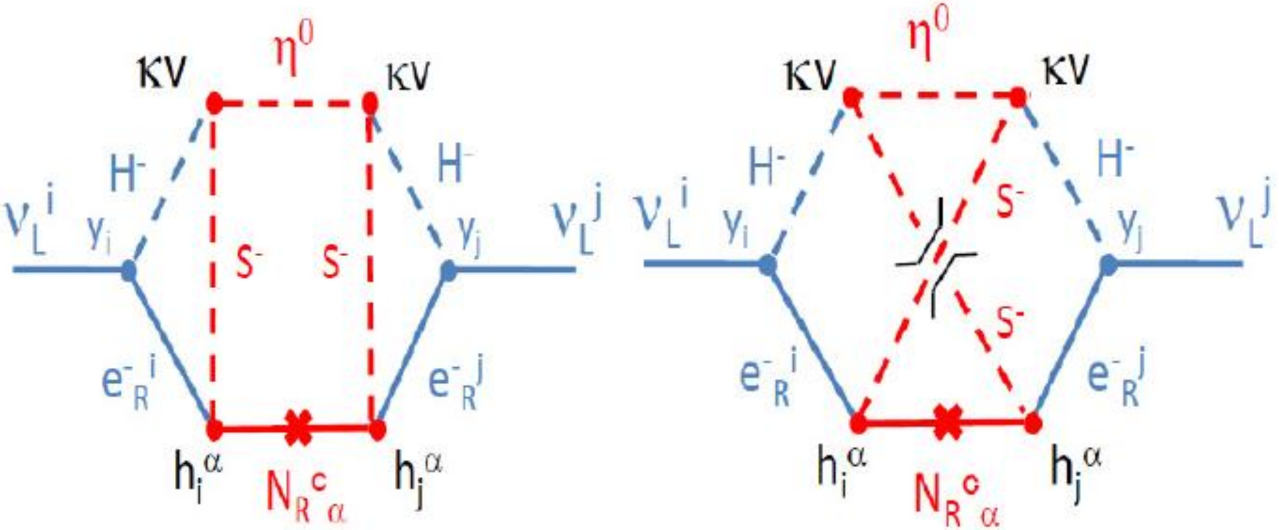
RH neutrinos

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

# Neutrino Mass
## (radiative $\nu\nu\phi\phi$ generation)

Tree level neutrino Yukawa is forbidden by exact $Z_2$

Neutrino mass matrix is generated at the 3-loop level.




$Z_2$-even physical states

h (SM like Higgs)

H, A, $H^-$ (Extra scalars)

$Z_2$-odd states

$\eta$, $S^+$, $N_R$

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

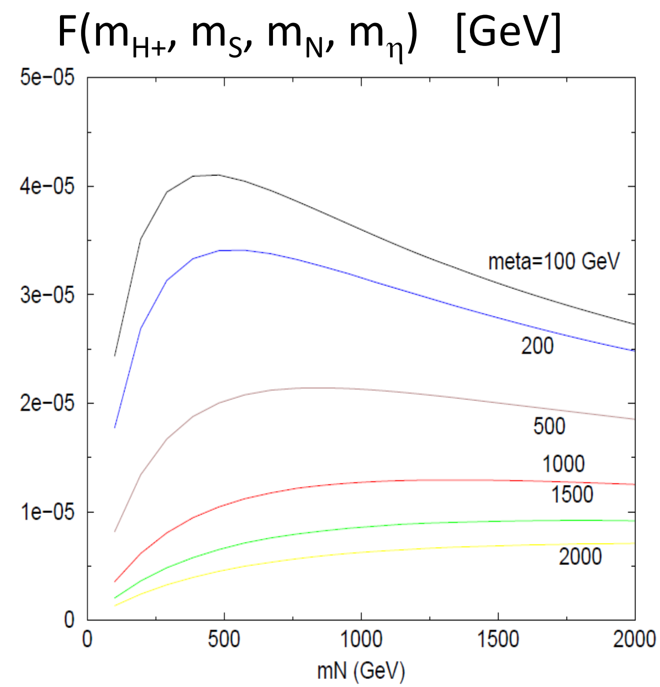
$$C_{ij}^{\alpha} = 4\kappa^2 \tan^2\beta (y_{\ell_i}^{\rm SM} h_i^\alpha)(y_{\ell_j}^{\rm SM} h_j^\alpha)$$

# Neutrino Masses

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

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

$$F(m_{H^\pm}, m_{S^\pm}, m_{N_R}, m_\eta) = \left(\frac{1}{16\pi^2}\right)^3 \frac{(-m_{N_R} v^2)}{m_{N_R}^2 - m_\eta^2}$$
$$\times \int_0^\infty dx \left[ x \left\{ \frac{B_1(-x, m_{H^\pm}, m_{S^\pm}) - B_1(-x, 0, m_{S^\pm})}{m_{H^\pm}^2} \right\}^2 \right.$$
$$\left. \times \left( \frac{m_{N_R}^2}{x + m_{N_R}^2} - \frac{m_\eta^2}{x + m_\eta^2} \right) \right], \quad (m_{S^\pm}^2 \gg m_{e_i}^2), \qquad (6)$$



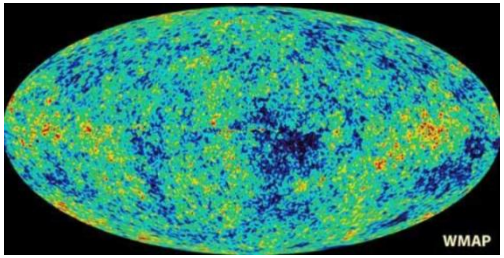

Mixing Structure is determined by

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

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

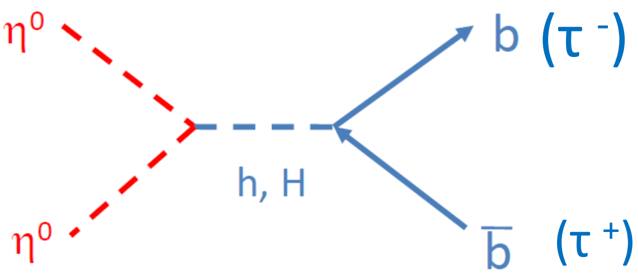
# Thermal Relic Abundance of $\eta^0$

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



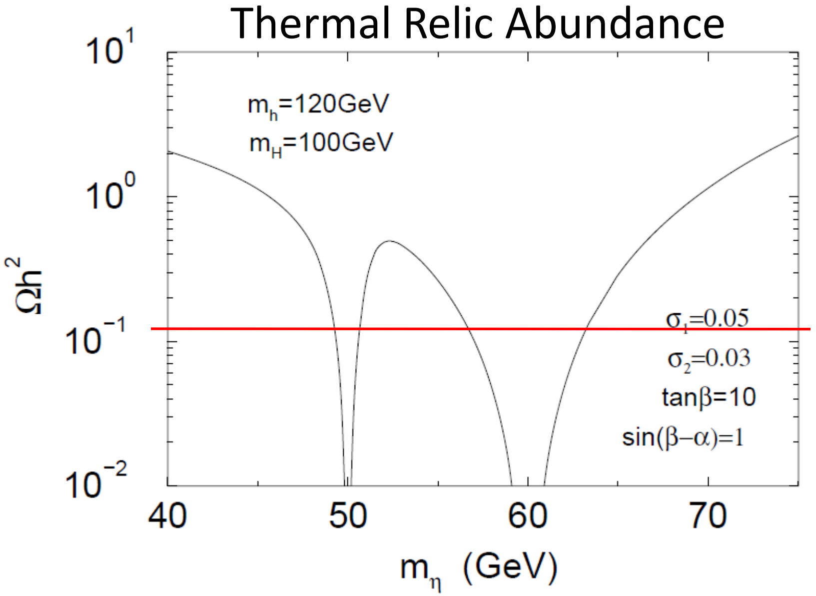

Candidate for cold DM: $\eta$ or $N_R$ (heavy)

Annihilation Cross Sections determine the abundance




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

Both bb and ττ included

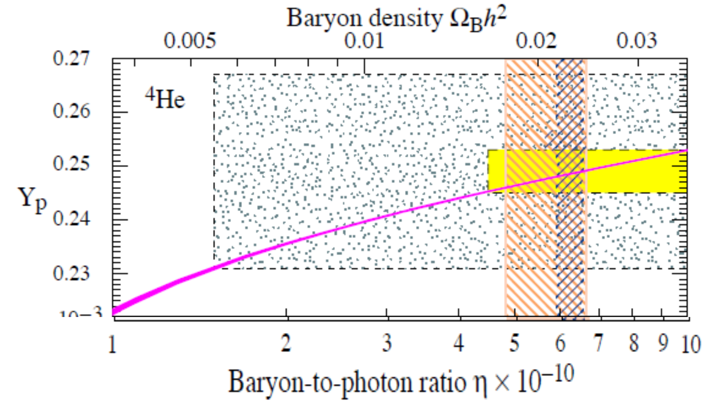



$m_\eta$ would be around 49-64 GeV

$\eta$ can be a DM candidate

# Electroweak Baryogenesis

$$n_B/s = (9.2 \pm 1.1) \times 10^{-11} (WMAP)$$




Sakharov's 3 conditions:

- Baryon number violation
- C, and CP violation
- Departure from thermal equilibrium

EW baryogenesis:

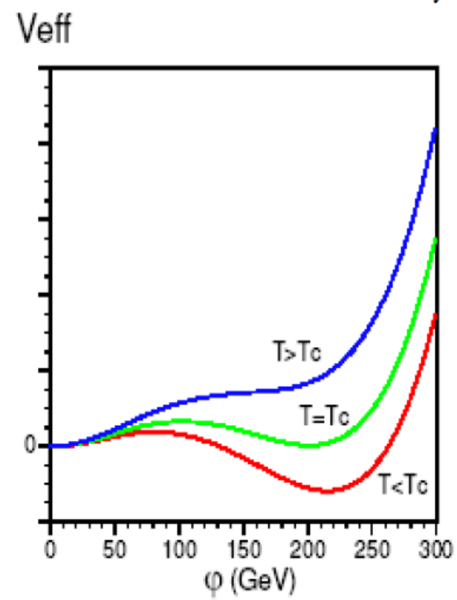
Strong 1st Order Phase Transition

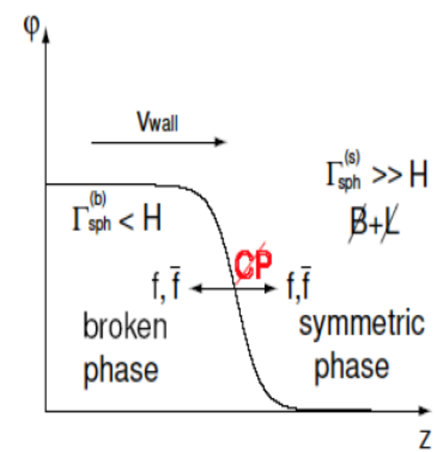
= rapid sphaleron decoupling in the broken phase

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

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

$$\frac{\varphi_c}{T_c} \left( = \frac{2E}{\lambda_{T_c}} \right) \gtrsim 1$$




EW baryogenesis

# Strong 1st Order Phase Transition

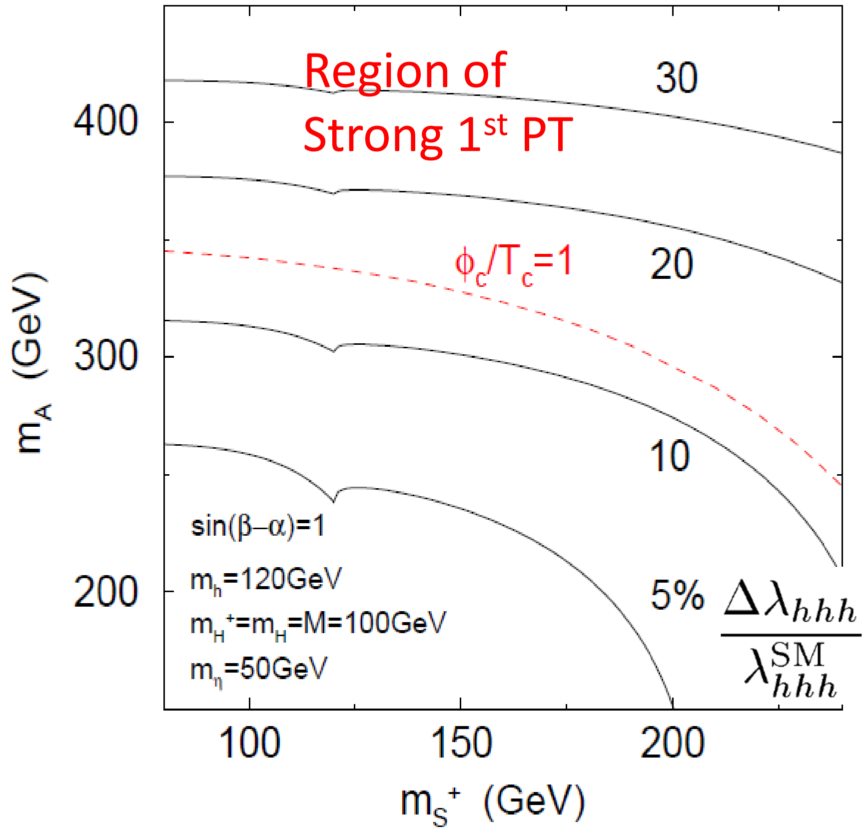
Condition for strong 1st OPT

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

$$E=\frac{1}{12\pi v^3}(6m_W^3+3m_Z^3+\underbrace{m_H^3+m_A^3+2m_{H\pm}^3}_{\text{additional contributions}})$$

SM only satisfies this for a light Higgss

$m_h$ < 50-60 GeV (Excluded)




In our model, the condition can be satisfied for mh=120GeV

We require non-decoupling effect in the Higgs sector.

mA> 350 GeV (Mass difference between A and $H^+$)

# Mass Spectrum

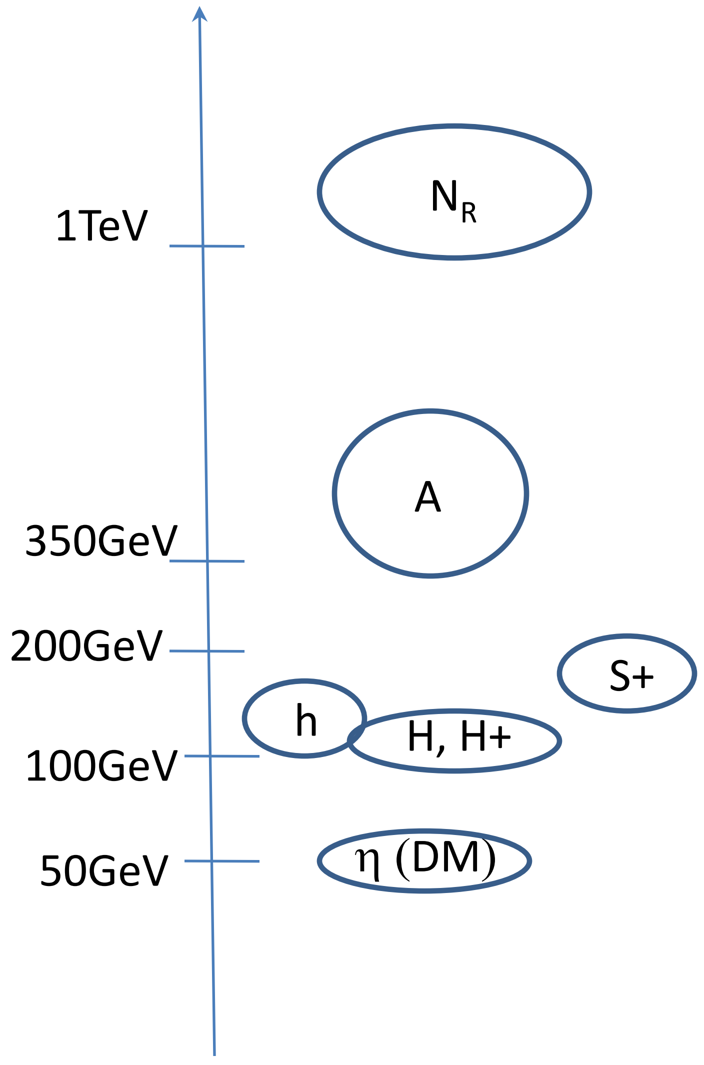
The current data and requirement for

- LFV ($\mu$ to e $\gamma$)
- Neutrino oscillation
- Abundance of DM
- Strong 1st order EW phase transition
- LEP bounds (direct and indirect)
- b to s$\gamma$ (actually no bound because of Type-X)
- Perturbative unitarity and vacuum stability

They give constraints on the masses

| | |
|---|---|
| – $\eta$ (DM candidate): | around 50 GeV |
| – Light $H^+$, H, $S^+$ | ~100 GeV |
| – Strong coupled A | $m_A$>350GeV |
| – RH-$\nu$ | O(1) TeV |

All the masses are predicted as O(100) GeV – O(1) TeV



# DM physics

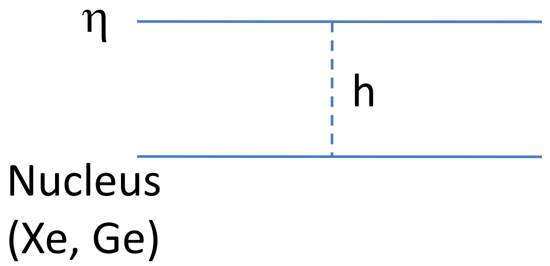
Physics of η

- h is the SM-like Higgs boson but decays into ηη

  $B(h \to \eta\eta) = 50\%$ (37%)
  for $m_\eta$=48 (57) GeV

  Testable via the invisible Higgs decay at the LHC

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




Observing the release energy

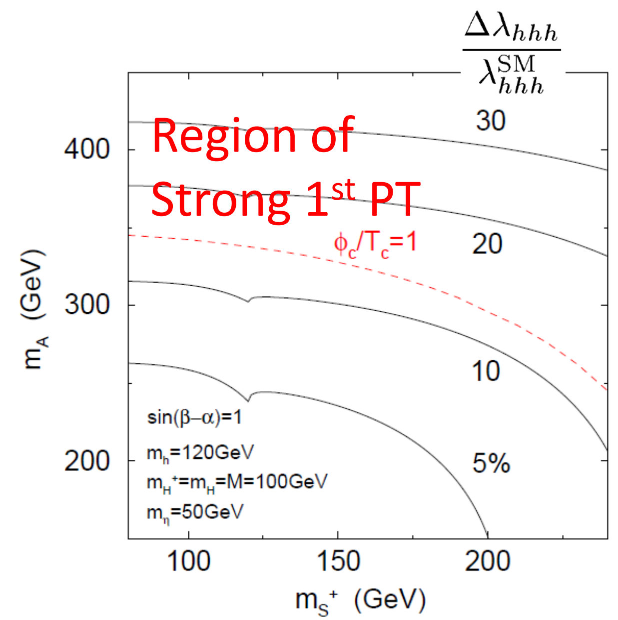
# Non-decoupling property

EWBG requires a large mass splitting between $m_A$ and $m_{H+}$

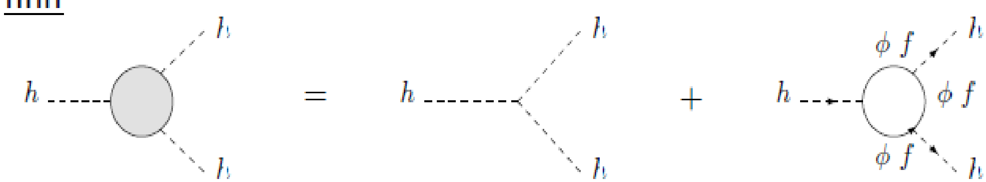
$$m_A^2 - m_{H^\pm}^2 = (\lambda_4 - \lambda_5)v^2$$

Strong 1st Order EWPT

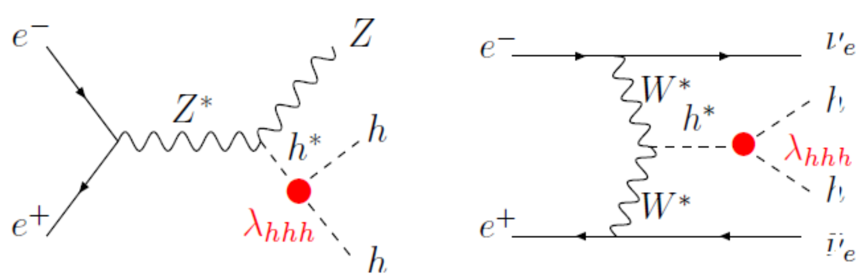
Deviation in hhh-coupling by 20-30 %

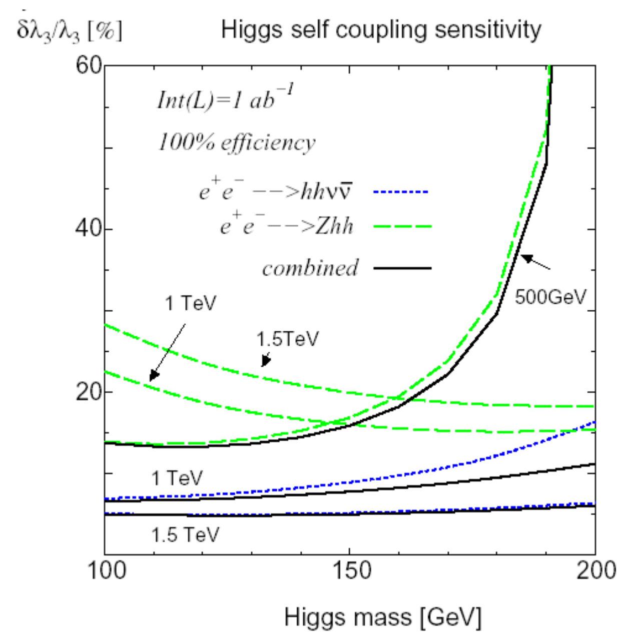



hhh




Testable at the ILC



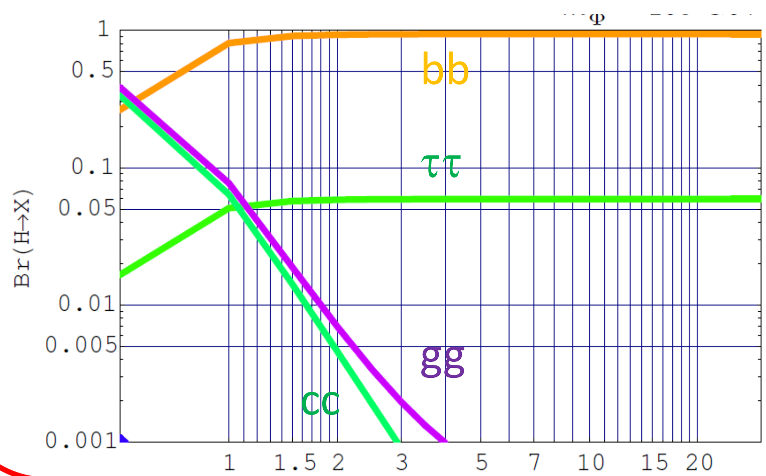



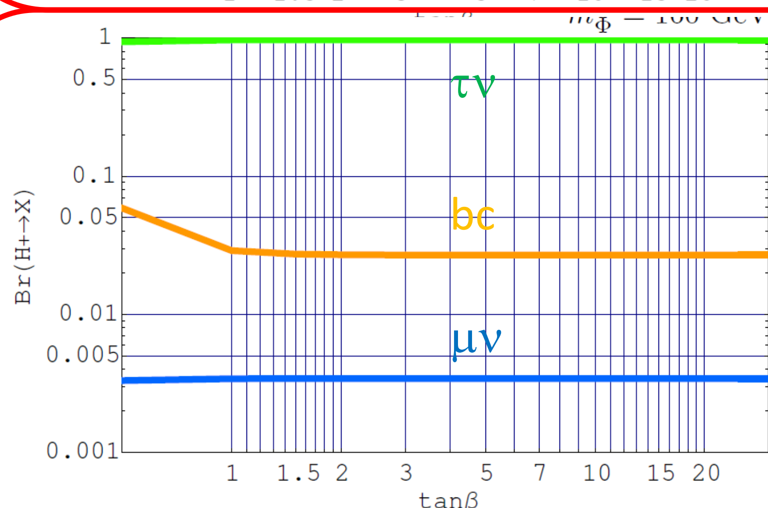
# Type-X Yukawa coupling

$\Phi_1$ only couples to Leptons
$\Phi_2$ only couples to Quarks

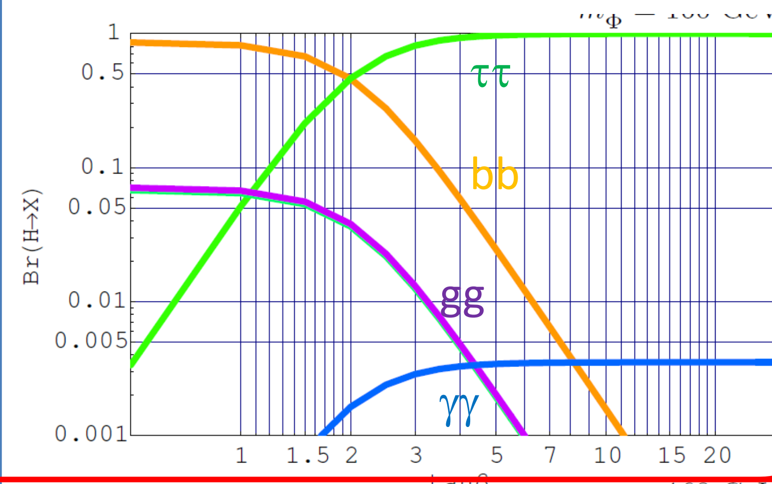
Decay of H, A, H+ completely different

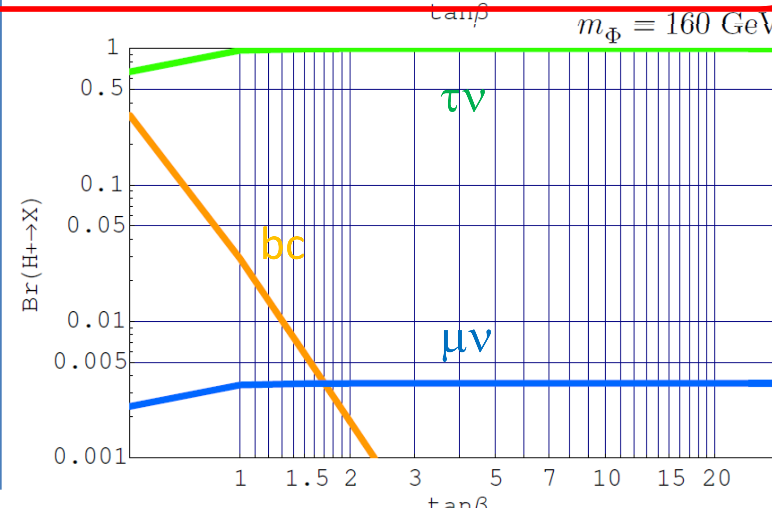
## Type II (MSSM)




## Type X



# Light Higgs scenario: Production at the LHC

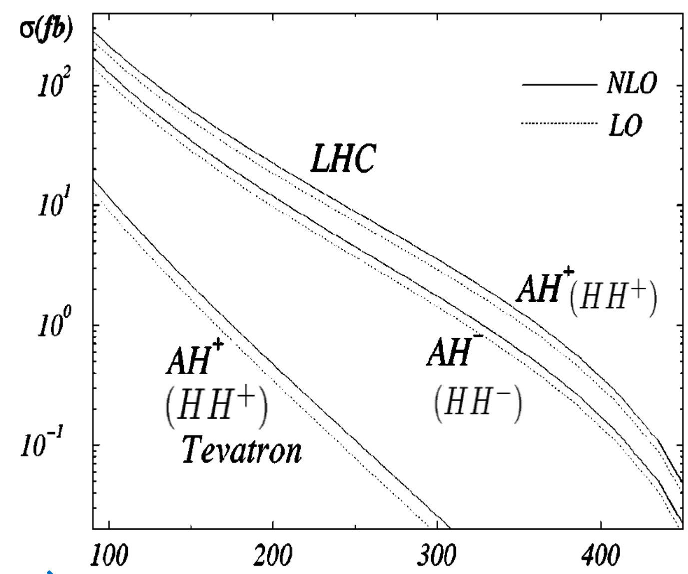
SK, Yuan
Cao, SK, Yuan
Baryaev et al

$$pp \to W^{\pm} \to HH^{+}(AH^{+})$$

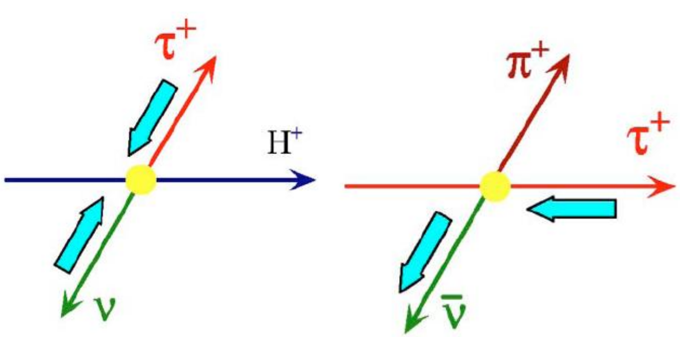
$$HH^{+} \to (\tau\tau)(\tau\nu)$$

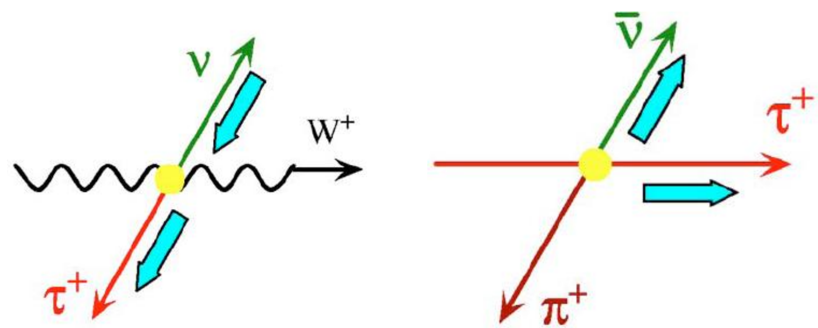
$$AH^{+} \to (W^{\pm}H^{\mp})(\tau\nu) \to jj(\tau\nu)(\tau\nu)$$

(MSSM) $pp \to AH^{+} \to (b\bar{b})\tau^{+}\nu \to (b\bar{b})(\pi^{+}\bar{\nu}\nu)$




Pions from H+→τν are harder than those from W+→τν




High energy pions

low energy pions

Bullock, Hagiwara, Martin

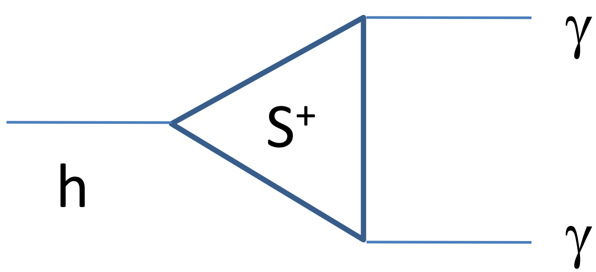
- $Z_2$-odd charged scalar $S^+$
  - Produced in pair

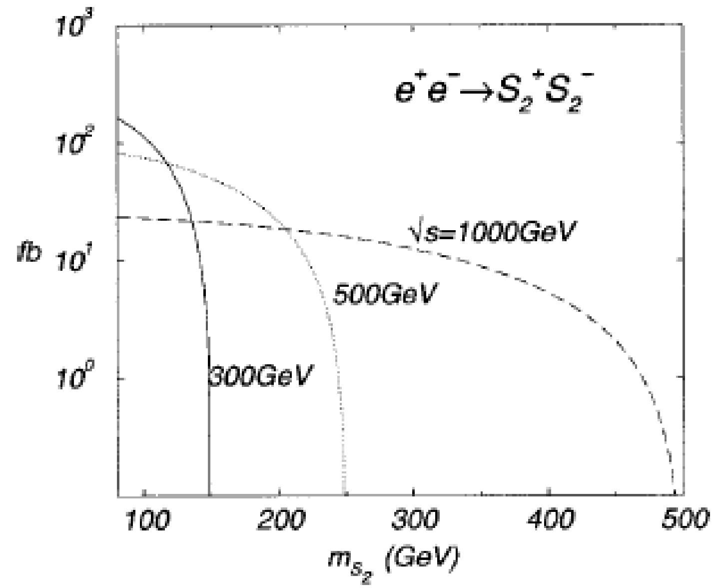
$$e^+e^- \to S^+S^-$$

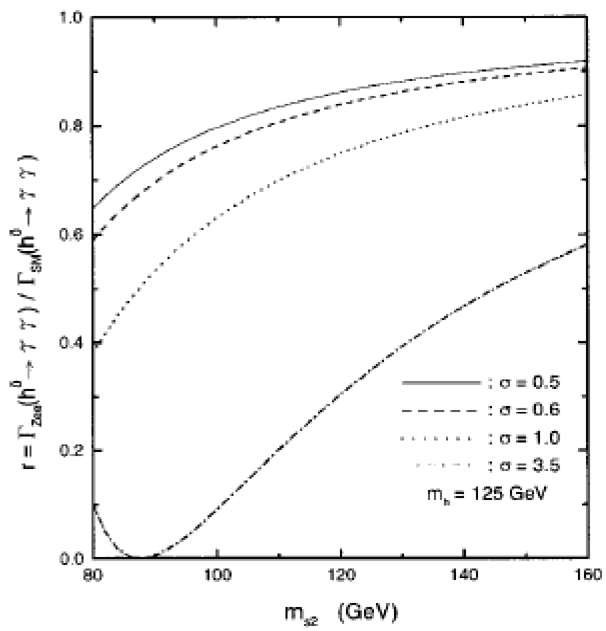
  - Signal should be hard pions with large missing energy

$$S^\pm \to H^\pm\eta \to \tau^\pm\nu\eta \to \pi^\pm\nu\eta$$

  - Indirect quantum effect can be large



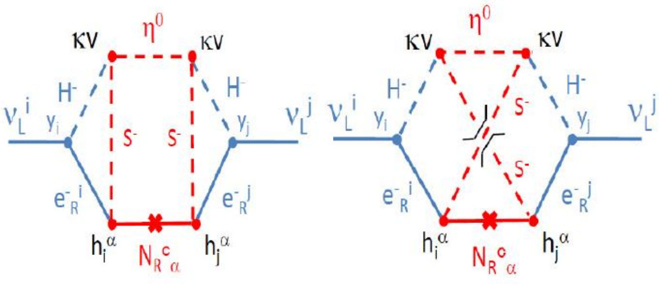



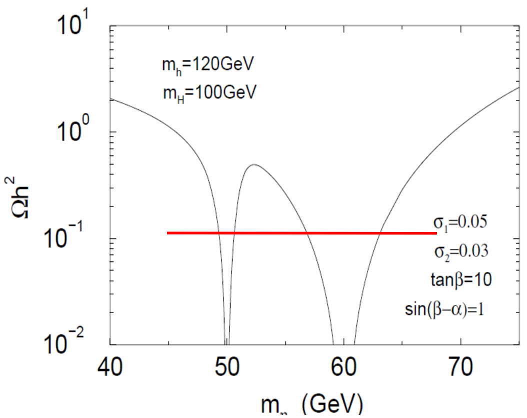



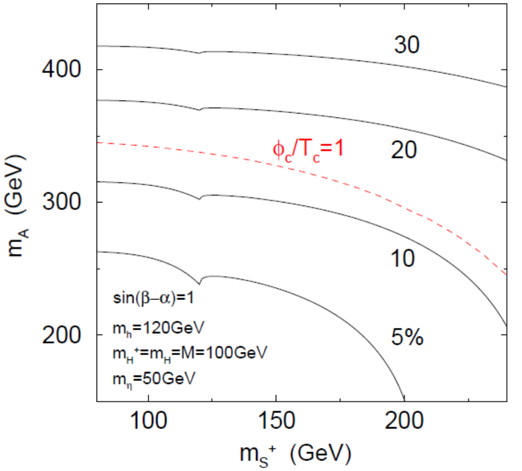

SK, Lin, Kasai, Okada, Yuan

# Summary

- Phenomena, which the SM cannot solve
  - Neutrino oscillation
  - Dark Matter
  - Baryon Asymmetry of Universe
- We construct a model to solve these problems by TeV-scale physics ($\Phi_1$, $\Phi_2$, $\eta$, $S^+$, $N_R$)
- The model gives many discriminative predictions in Higgs physics , LFV and DM physics
  - Invisible decay of h
  - Type-X Yukawa coupling
  - Light H+ (H, S) scenario
  - Non-decoupling property
- Testable at experiments (LHC, ILC)
- DM also testable by direct and indirect search
- Further phenomenological study is underway



# Mass and coupling

Masses are determined by vev and M (or $\mu_{S,\eta}$)

$m_h^2 = O(\lambda)\, v^2$ (SM like: $\sin(\beta-\alpha)=1$)

$m_H^2 = M^2 + O(\lambda)\, v^2$

$m_A^2 = M^2 + O(\lambda)\, v^2$

$m_{H+}^2 = M^2 + O(\lambda)\, v^2$

$$M = \frac{|\mu_{12}|}{\sqrt{\sin\beta\cos\beta}}$$

Soft breaking scale for $\tilde{Z}_2$

$m_{S+}^2 = \mu_{s+}^2 + O(\rho)\, v^2$

$m_\eta^2 = \mu_\eta^2 + O(\sigma)\, v^2$

# CP violating phases

- In Higgs potential $m_3^2$ and $\lambda_5$ are complex, that cause CP violation.
- Although the CP phase is crucial for generating baryon number, it does not affect much in the discussions on $m_\nu$ , DM and $1^{st}$ Order EWPT.
- We neglect it for simplicity
- Later comment on the case including it.

# Neutrino Masses from Higgs Sector

Quantum Effect by EW (TeV) physics

- Zee Model D+D+$S^+$

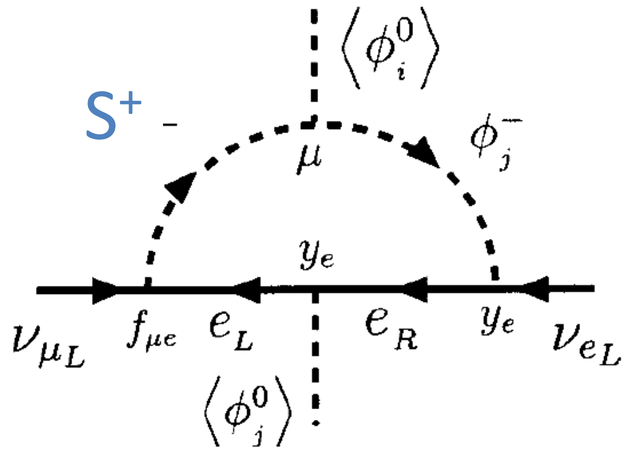
  No RH-ν

  S+ carries L=2

  $$m_{ij}=f_{ij}(m_{e_j}^2-m_{e_i}^2)\mu\cot\beta\frac{1}{16\pi^2}\frac{1}{m_{S_1}^2-m_{S_2}^2}\ln\frac{m_{S_1}^2}{m_{S_2}^2}$$

  1-loop induced

Zee




- Krauss et al. Model D+$S^+$+$S^+$+NR

  $Z_2$ symmetry

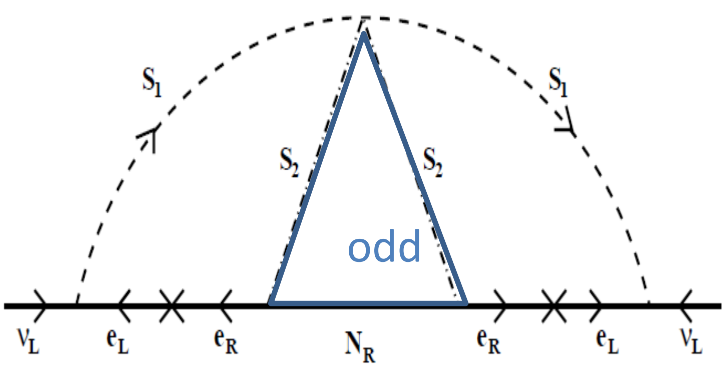
  3-loop induced

  (More Natural for neutrino masses)

  $N_R$ can be a DM candidate

Krauss et al

$Z_2$ odd




Two generation of $N_R$ explains the mixing

Cheung, Seto

# Physical States

- Exact $Z_2$ parity: even and odd states do not mix
- Masses of 2HDM fields can be diagonalized by the mixing angles α and β as usual.

$$\Phi_i = \begin{bmatrix} w_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + h_i + i z_i) \end{bmatrix}$$

$$\begin{bmatrix} w_1^{\pm} \\ w_2^{\pm} \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^{\pm} \\ H^{\pm} \end{bmatrix}$$

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} \quad \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z \\ A \end{bmatrix}$$

- $Z_2$-even physical states
  - h (SM like Higgs) for sin(β–α)=1 $g_{hWW}=1$
  - H, A, $H^-$ (Extra scalars) $g_{HWW}=0$

  $Z_2$-odd states
  - η, $S^+$, $N_R^{\alpha}$

# Symmetries of the model

- Gauge Symmetries SU(3) XSU(2)XU(1)
- Discrete symmetry $Z_2$ (Exact)
- In general 2HDM $\Phi_1, \Phi_2$ → FCNC !

  Another discrete symmetry is necessary: $\tilde{Z}_2$ (Softly broken)

  $\tilde{Z}_2$: $\Phi_1 \to +\Phi_1$, $\Phi_2 \to -\Phi_2$ ,

  $e_R \to +e_R$ , $L_L \to +L_L$

  Only $\Phi_1$ couples to charged leptons.

  This can be softly broken.

| | $Q^i$ | $u_R^i$ | $d_R^i$ | $L^i$ | $e_R^i$ | $\Phi_1$ | $\Phi_2$ | $S^\pm$ | $\eta$ | $N_R^\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $Z_2$ (exact) | $+$ | $+$ | $+$ | $+$ | $+$ | $+$ | $+$ | $-$ | $-$ | $-$ |
| $\tilde{Z}_2$ (softly broken) | $+$ | $-$ | $-$ | $+$ | $+$ | $+$ | $-$ | $+$ | $-$ | $+$ |

# Mass and mixing

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

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

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

| Set | $h_e^1$ | $h_e^2$ | $h_\mu^1$ | $h_\mu^2$ | $h_\tau^1$ | $h_\tau^2$ | $B(\mu\to e\gamma)$ |
|---|---|---|---|---|---|---|---|
| A | 1.2 | 1.2 | -0.011 | 0.025 | -0.0015 | 0.00070 | $5.3\times10^{-12}$ |
| B | 1.2 | 1.35 | 0.0037 | 0.022 | -0.00075 | 0.0012 | $4.5\times10^{-12}$ |

$m_{H+}=m_H=m_S=100$ GeV, $m_\eta=50$GeV, $m_{NR}^1=m_{NR}^2=3.5$ TeV
Set A (B): $\kappa \tan\beta = 36$ (42) and $U_{e3}=0$ (0.18).

# Numerical Evaluation

1. LFV data — $N_R$ must be O(1) TeV
2. $\nu$ data — Then, $m_{H+} < O(100)$ GeV
3. LEP direct search on $H^+$ — $m_{H+} > 90$GeV
4. LEP precision measurement — [$\rho$ parameter]

$\sin(\beta-\alpha) = 1$, $m_H{+}=m_H$

From natural assumption $\kappa \tan\beta < O(10)$, $h_e^{\alpha} = O(1)$, possible parameters are uniquely determined as

$\sin(\beta-\alpha) = 1$ (h is the SM-like Higgs),

$m_{H+}=m_H=100$GeV, $m_S=O(100)$ GeV

$m_N$=a few TeV