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)

M. Aoki, SK, K. Tsumura, K. Yagyu, PRD 80, 015017 (2009)

M. Aoki, SK, O. Seto, PRD 80, 033007 (2009)

M. Aoki, SK, O. Seto, PLB 685,313-317 (2010)

M. Aoki, SK , PLB 689, 28-35 (2010)

M. Aoki, SK, K. Yagyu, in preparation.

2010年7月10日 京都産業大学 益川塾 セミナー

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

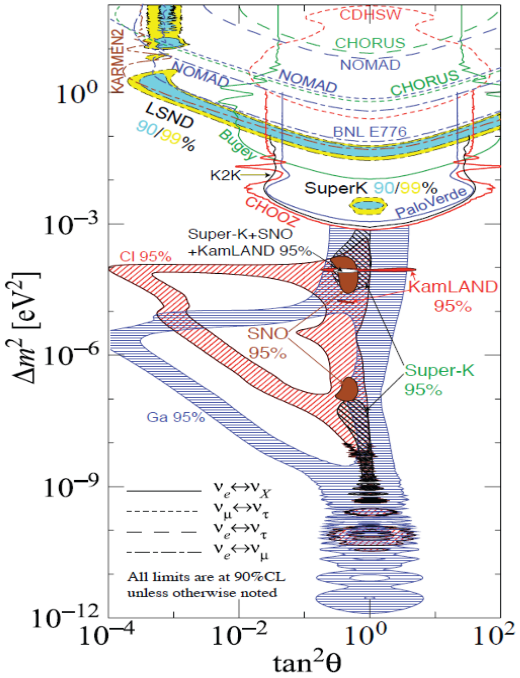
    $\Delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2,\ \Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$

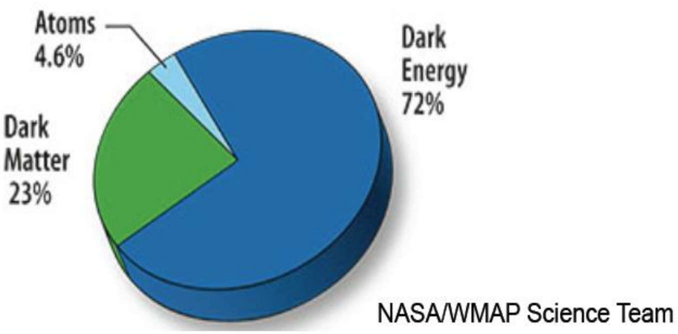
  - Dark Matter

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

  - Baryon Asymmetry of the Universe

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





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

BSM: Neutrino Mass

Neutirno Mass Term (= Effectively Dim-5 Operator)

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

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

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 $\qquad$ N-th order of perturbation theory

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

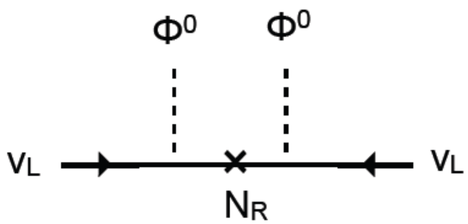
Seesaw Mechanism?

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

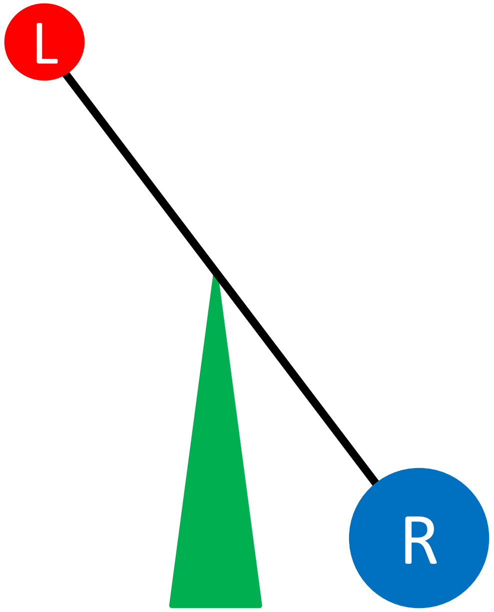
- Hierarchy between M_{NR} and m_D generates that between m_D and tiny m_ν ($m_D \sim 100$ GeV)

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

$\nu\nu\phi\phi$



Minkowski
Yanagida
Gell-Mann et al



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

Hierarchy for hierarchy!

Far from experimental reach…

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:

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

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

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

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

<u>Quantum Effects</u>

N-th order of perturbation theory

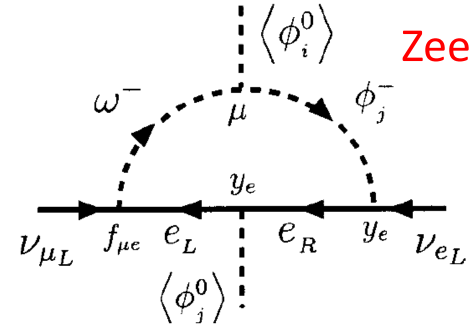
$$m^\nu{}_{ij} = [1/(16\pi^2)]^N\, C_{ij}\, v^2/M$$

$M = 1$ TeV

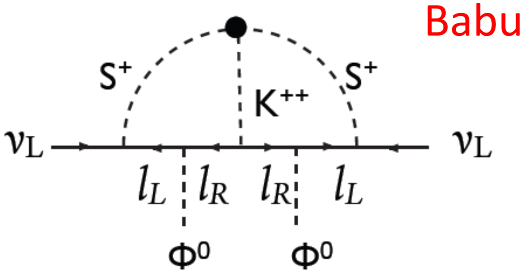
Scenario of radiative $\nu\nu\phi\phi$ generation

- Tiny ν-Masses come from loop effects
  - Zee (1980, 1985)
  - Zee, Babu (1988)
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), …..
- Merit
  - Super heavy particles are not necessary

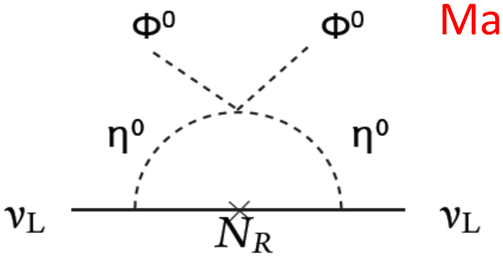
    Size of tiny m_ν can naturally be deduced from TeV scale by higher order perturbation
  - Physics at TeV: Testable at collider experiments



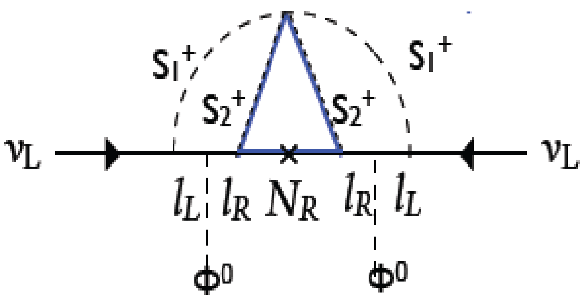
Zee



Babu



Ma



Krauss et al

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.

A renormalizable theory at a TeV scale

- All mass scales in the Lagrangian are TeV or below
- No dim-5 or higher order operator in the Lagrangian

M. Aoki, SK, O. Seto, PRL 102, 051805 (2009)
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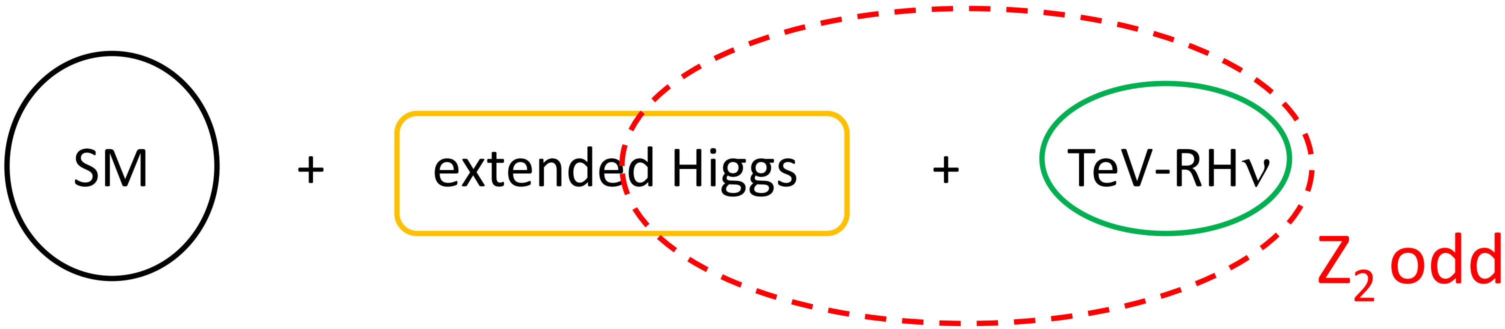
M. Aoki, SK, O. Seto, PRD 80, 033007 (2009)

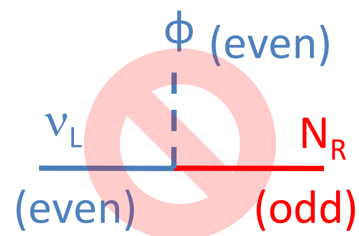
Contents

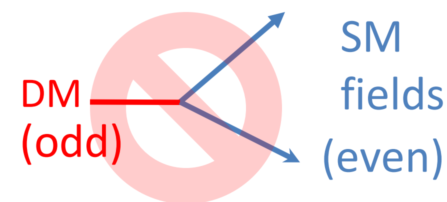
- Introduction
- Model
- Phenomenology
  - Flavor Physics
  - Type X THDM
  - Physics of charged singlets
  - Direct test of Majorana nature
- Conclusion

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

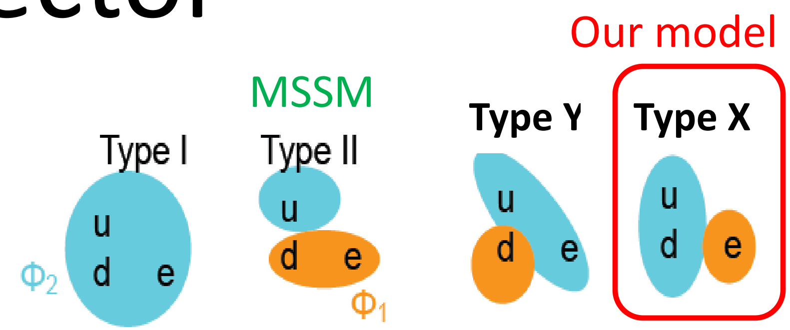
  Φ_1, Φ_2 (2HDM) + S^+, η (singlets)

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

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

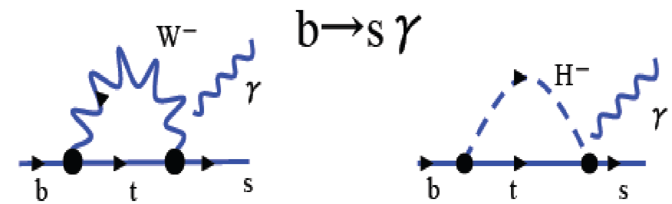
  by which each quark/lepton couples to only one of the Higgs doublets.

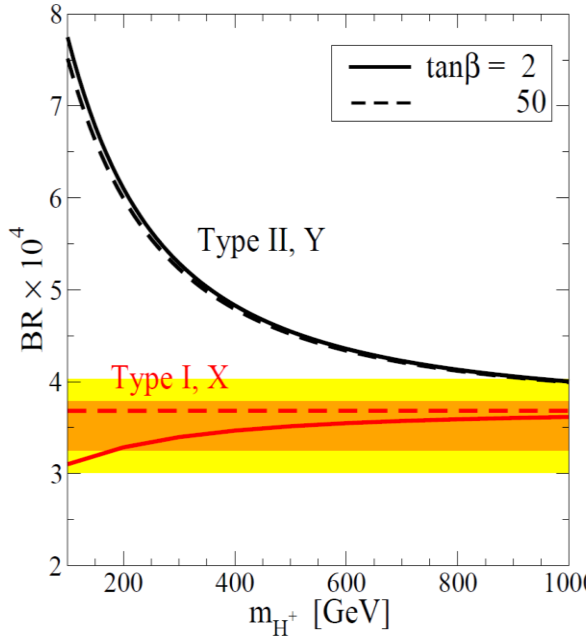
- 4 types of Yukawa interactions!



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

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





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

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks

Aoki, SK, Tsumura, Yagyu, PRD 80, 015017 (2009)

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 (Q^i through Φ_2)

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

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 , $N_R{}^\alpha$)

$V = -\mu_1^2\|\Phi_1\|^2 - \mu_2^2\|\Phi_2\|^2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \lambda_1\|\Phi_1\|^4 + \lambda_2\|\Phi_2\|^4 + \lambda_3\|\Phi_1\|^2\|\Phi_2\|^2 + \lambda_4\|\Phi_1^\dagger\Phi_2\|^2 + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\}$	Z_2 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
$+\sum_{a=1}^{2}\left\{\rho_a\|\Phi_a\|^2\|S\|^2 + \sigma_a\|\Phi_a\|^2\frac{\eta^2}{2}\right\} + \sum_{a,b=1}^{2}\left\{\kappa\epsilon_{ab}(\Phi_a^c)^\dagger\Phi_b S^-\eta + \text{h.c.}\right\}.$	Interaction

RH neutrinos

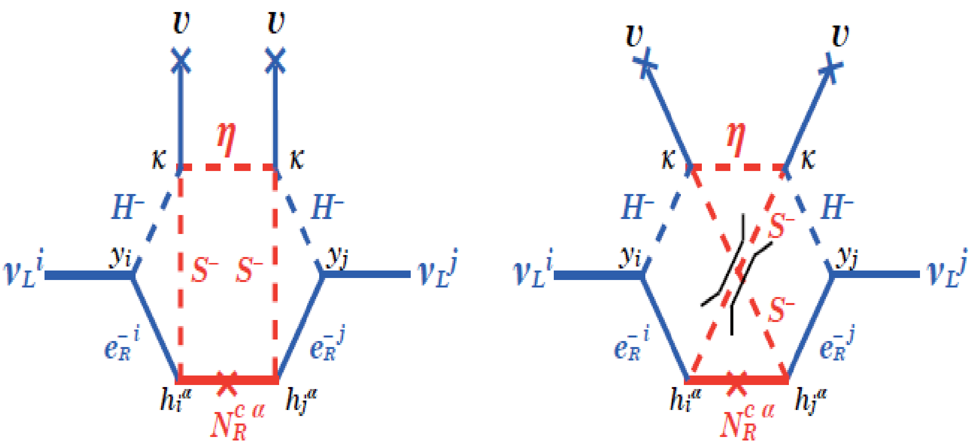
$$\mathcal{L}_Y = -\sum_{\alpha=1}^{2}\sum_{i,j=1}^{3} h_i^\alpha (e_R^i)^c N_R^\alpha S^- + \sum_{\alpha=1}^{2} m_N^\alpha N_\alpha^c N_\alpha + \text{h.c.}.$$

Neutrino Mass

Tree neutrino Yukawa is forbidden by Z_2

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

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



- 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

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
$\theta_{sol} \sim 0.553$
$\theta_{atm} \sim \pi/4$

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

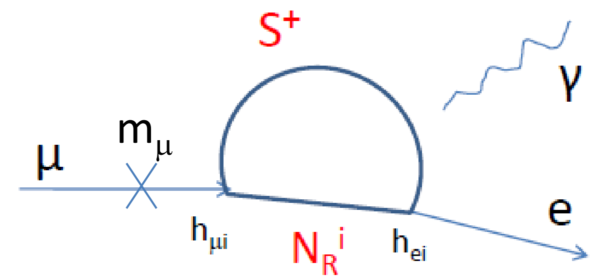
$$m_\nu^{\rm diag} \equiv \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sqrt{\Delta m^2_{\rm solar}} & 0 \\ 0 & 0 & \sqrt{\Delta m^2_{\rm atom}} \end{bmatrix} \qquad U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1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

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

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}

The model can reproduce all the neutrino data

LFV



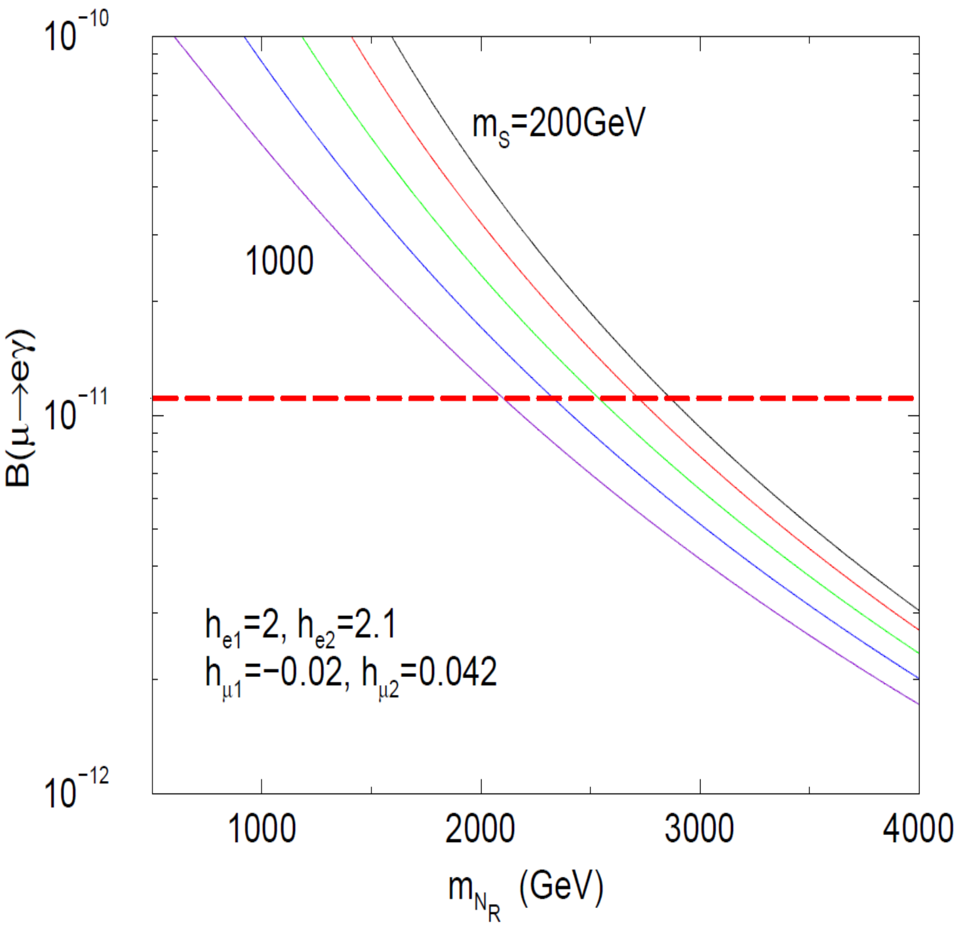
The parameters receive strong bounds from μ→eγ , which prefer heavy N_R and S^+

But, too heavy S^+ breaks natural generation of the ν-mass scale

S^+ several times 100 GeV

N_R several times 1 TeV

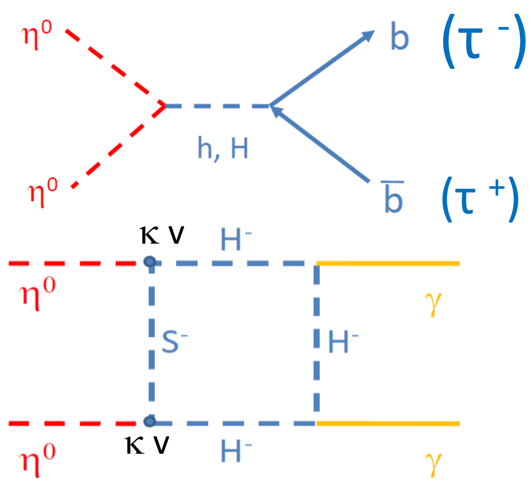
η is DM candidate !

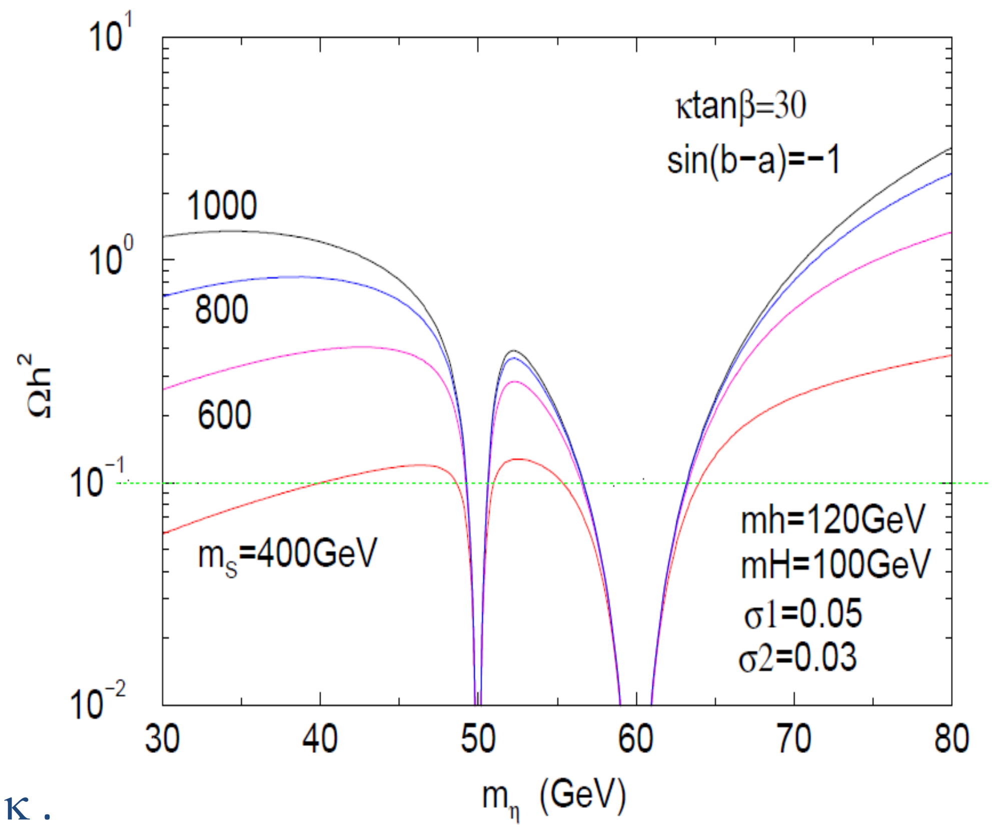


Thermal Relic Abundance of η^0

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

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





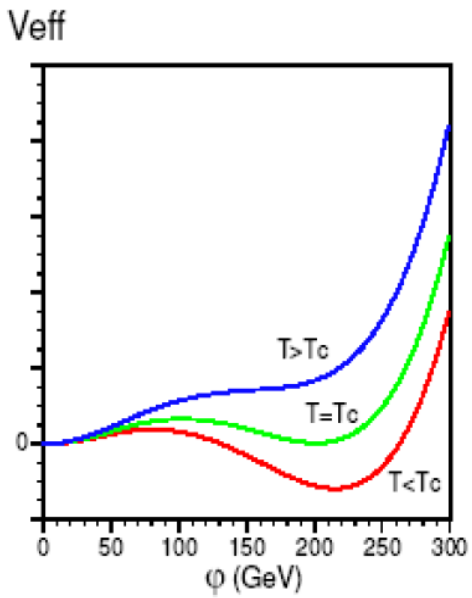
The 1-loop process $\gamma\gamma$ can be comparable to the bb and $\tau\tau$ processes, when σ, $Y_f \ll \kappa$.

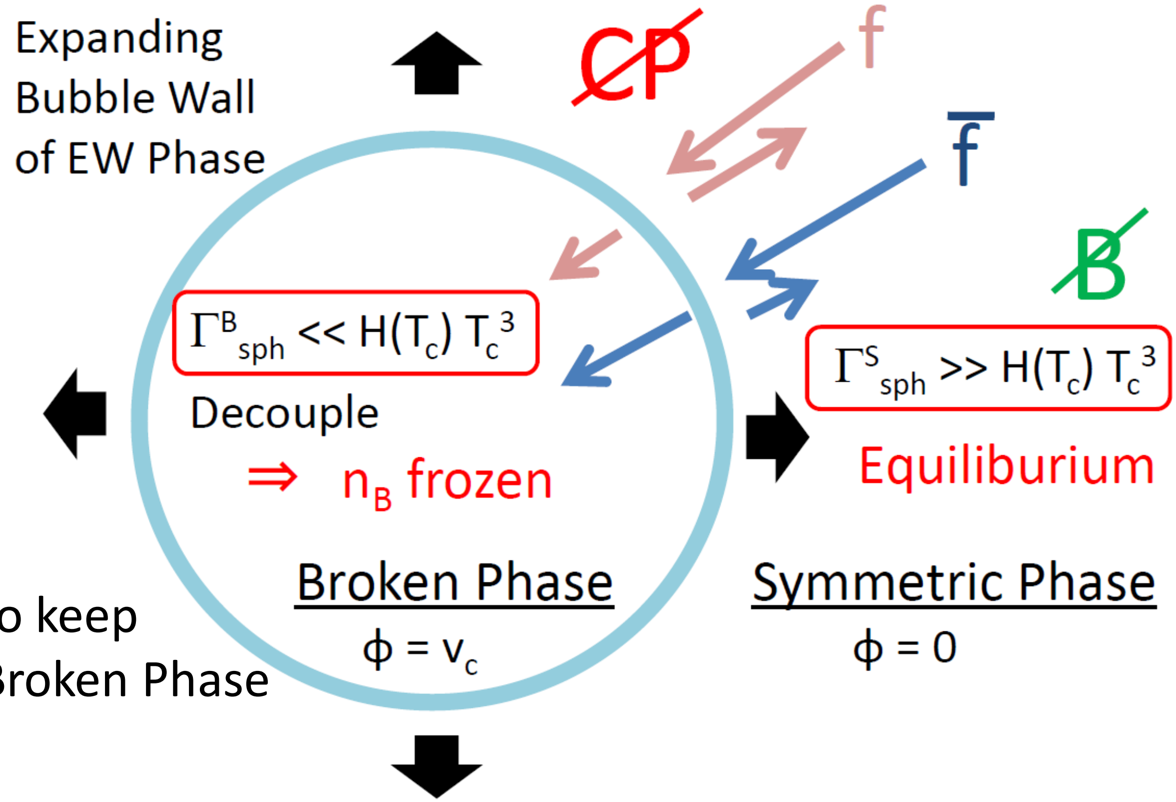
m_η would be around 40-65 GeV for m_S = 400GeV

Electroweak Baryogenesis

Sakharov's conditions:

- B Violation → Sphaleron transition at high T
- C and CP Violation → CP Phases in 2HDM
- Departure from Equilibrium → 1^{st} 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

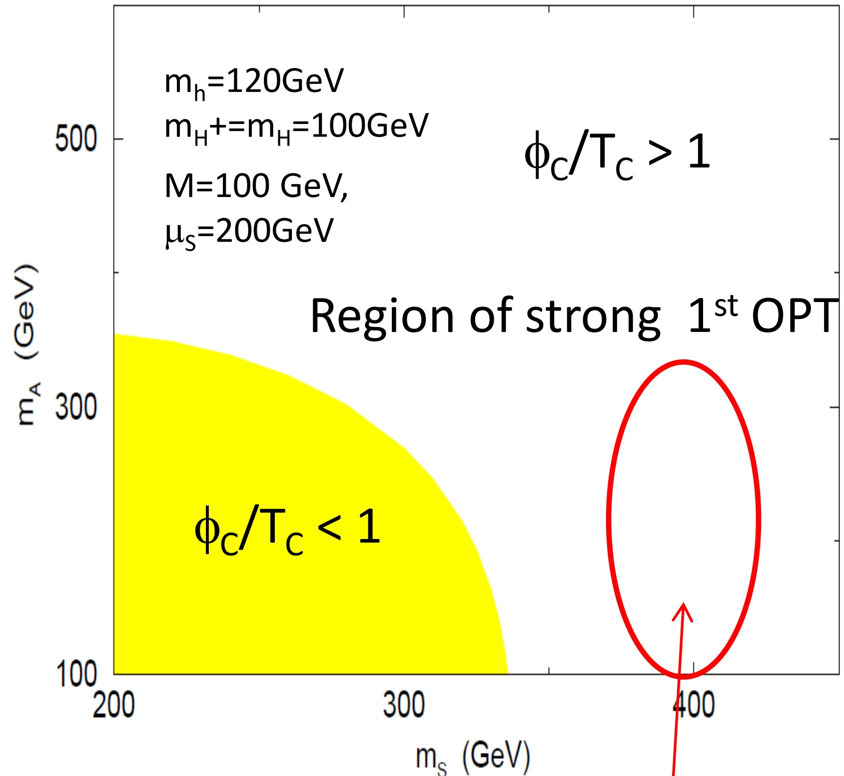
$$\frac{\varphi_c}{T_c}\left(= \frac{2E}{\lambda_{T_c}}\right) \gtrsim 1 \qquad \lambda_T \sim \frac{2m_h^2}{v^2}$$

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.

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

This region is compatible with neutrino data and DM abundance.

Successful scenario under current data

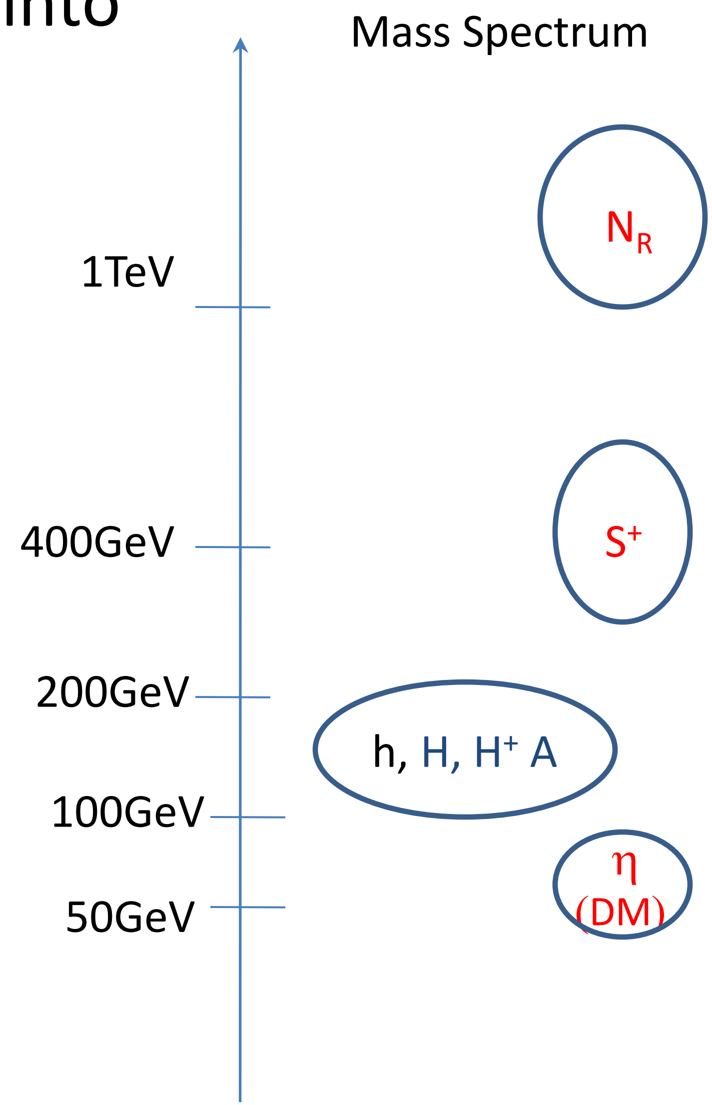
The requirement and data taken into account

- Neutrino Data
- DM Abundance
- Condition for Strong 1st OPT
- LEP Bounds on Higgs Bosons
- Tevatron Bounds on m_{H+}
- B physics: $B \to X_s \gamma$, $B \to \tau\nu$
- Tau Leptonic Decays, LFV ($\mu \to e\gamma$), g-2
- Theoretical Consistencies

The mass spectrum is uniquely determined

All masses are O(0.1)-O(1) TeV

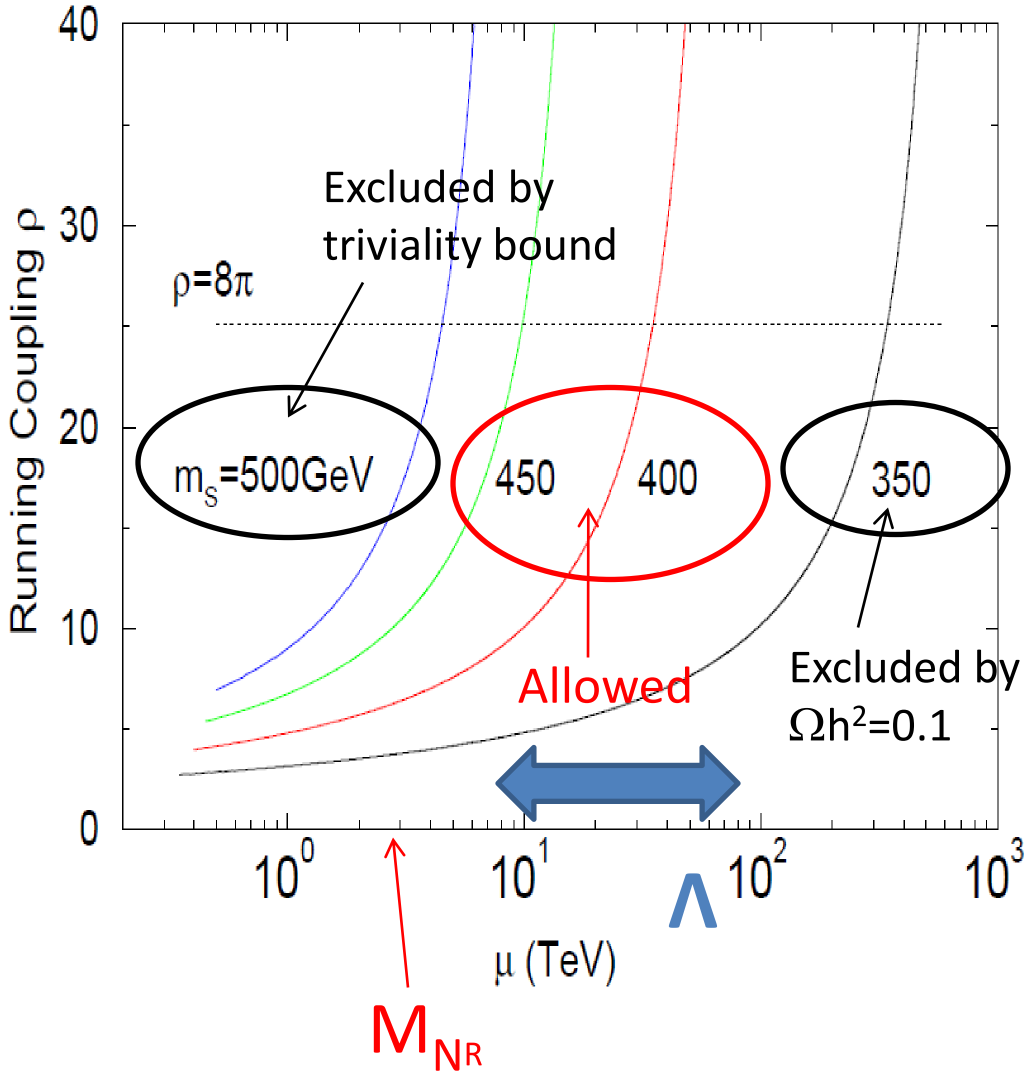
Many discriminative predictions !



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.



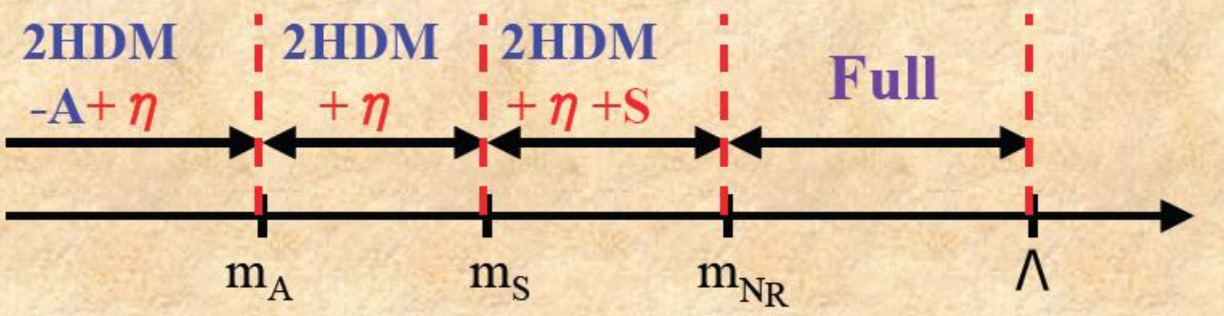
Triviality bound

- 理論に含まれる全ての結合定数をrunningさせたとき、カットオフまで、結合定数が強結合にならないことを要請する。

スカラーカップリング: $\lambda(\mu),\ \sigma(\mu),\ \rho(\mu),\ \kappa(\mu),\ \xi(\mu) < 4\pi|_{\mu=\Lambda}$

湯川カップリング: $y_t(\mu),\ y_b(\mu),\ y_\tau(\mu),\ h(\mu) < 4\pi\ |_{\mu=\Lambda}$

- Renormalization Group Equation (RGE)を数値的に解き、あるカットオフにおけるパラメータのallowed regionを求める。このときthreshold効果を考慮に入れる。



Aoki, SK, Yagyu, in preparation

Vacuum Stability

十分遠方でポテンシャルが負にならないことを要請する。

$$\lim_{r\to\infty} V(r\phi_1, r\phi_2, \ldots, r\phi_N) > 0$$

必要条件

$$\lambda_1(\mu) > 0, \quad \lambda_2(\mu) > 0, \quad \sigma_3(\mu) > 0$$

$$\sigma_1(\mu) + \sqrt{\lambda_1(\mu)\sigma_3(\mu)/2} > 0$$

$$\sigma_2(\mu) + \sqrt{\lambda_2(\mu)\sigma_3(\mu)/2} > 0$$

$$\bar{\lambda}(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)/2} > 0$$

$$\bar{\lambda}(\mu) = \lambda_3(\mu) + \min[0, \lambda_4(\mu) + \lambda_5(\mu), \lambda_4(\mu) - \lambda_5(\mu)]$$

RGE in the AKS model

スカラー結合

$$\beta(\lambda_1) = \frac{1}{16\pi^2}\Big[12\lambda_1^2 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 4\lambda_3\lambda_4 + 2\sigma_1^2 + \rho_1^2 + \frac{9}{4}g^4 + \frac{6}{4}g^2 g'^2 + \frac{3}{4}g'^4 - 4y_\tau^4 + (4y_\tau^2 - 9g^2 - 3g'^2)\lambda_1\Big]$$

$$\beta(\lambda_2) = \frac{1}{16\pi^2}\Big[12\lambda_2^2 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 4\lambda_3\lambda_4 + 2\sigma_2^2 + \rho_2^2 + \frac{9}{4}g^4 + \frac{6}{4}g^2 g'^2 + \frac{3}{4}g'^4 - 12y_t^4 - 12y_b^4 + (12y_t^2 + 12y_b^2 - 9g^2 - 3g'^2)\lambda_2\Big]$$

$$\beta(\lambda_3) = \frac{1}{16\pi^2}\Big[6\lambda_1\lambda_3 + 2\lambda_1\lambda_4 + 6\lambda_2\lambda_3 + 2\lambda_2\lambda_4 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 2\sigma_1\sigma_2 + \rho_1\rho_2 + 4\kappa^2 + \frac{9}{4}g^4 + \frac{3}{4}g'^4 - \frac{6}{4}g^2 g'^2 + (6y_t^2 + 6y_b^2 + 2y_\tau^2 - 9g^2 - 3g'^2)\lambda_3\Big]$$

$$\beta(\lambda_4) = \frac{1}{16\pi^2}\Big[2(\lambda_1 + \lambda_2 + 4\lambda_3 + 2\lambda_4)\lambda_4 + 8\lambda_5^2 - 8\kappa^2 + 3g^2 g'^2 + (6y_t^2 + 6y_b^2 + 2y_\tau^2 - 9g^2 - 3g'^2)\lambda_4\Big]$$

$$\beta(\lambda_5) = \frac{1}{16\pi^2}\Big[2(\lambda_1 + \lambda_2 + 4\lambda_3 + 6\lambda_4)\lambda_5 + (6y_t^2 + 6y_b^2 + 2y_\tau^2 - 9g^2 - 3g'^2)\lambda_5\Big]$$

$$\beta(\sigma_1) = \frac{1}{16\pi^2}\Big[6\lambda_1\sigma_1 + 4\lambda_3\sigma_2 + 2\lambda_4\sigma_2 + 2\sigma_1\sigma_3 + 4\sigma_1^2 + \rho_1\xi + 8\kappa^2 + 3g'^4 + (-\frac{15}{2}g'^2 - \frac{9}{2}g^2 + 2\sum_{i,\alpha}(h_i^\alpha)^2 + 2y_\tau^2)\sigma_1\Big]$$

$$\beta(\sigma_2) = \frac{1}{16\pi^2}\Big[6\lambda_2\sigma_2 + 4\lambda_3\sigma_1 + 2\lambda_4\sigma_1 + 2\sigma_2\sigma_3 + 4\sigma_2^2 + \rho_2\xi + 8\kappa^2 + 3g'^4 + (-\frac{15}{2}g'^2 - \frac{9}{2}g^2 + 2\sum_{i,\alpha}(h_i^\alpha)^2 + 6y_t^2 + 6y_b^2)\sigma_2\Big]$$

$$\beta(\sigma_3) = \frac{1}{16\pi^2}\Big[8\sigma_1^2 + 8\sigma_2^2 + 5\sigma_3^2 + 2\xi^2 + 24g'^4 - 12g'^2\sigma_3 + 4\sum(h_i^\alpha)^2\sigma_3 - 8\sum\sum h_i^\alpha h_i^\beta h_j^\beta h_j^\alpha\Big]$$

$$\beta(\rho_1) = \frac{1}{16\pi^2}\Big[6\lambda_1\rho_1 + (4\lambda_3 + 2\lambda_4)\rho_2 + \rho_1\rho_3 + 2\sigma_1\xi + 16\kappa^2 + (-\frac{9}{2}g^2 - \frac{3}{2}g'^2 + 2y_\tau^2)\rho_1\Big]$$

$$\beta(\rho_2) = \frac{1}{16\pi^2}\Big[6\lambda_2\rho_2 + (4\lambda_3 + 2\lambda_4)\rho_1 + \rho_2\rho_3 + 2\sigma_2\xi + 16\kappa^2 + (-\frac{9}{2}g^2 - \frac{3}{2}g'^2 + 6y_t^2 + 6y_b^2)\rho_2$$

$$\beta(\rho_3) = \frac{1}{16\pi^2}\Big[12(\rho_1^2 + \rho_2^2) + 3\rho_3^2 + 6\xi^2\Big]$$

$$\beta(\kappa) = \frac{1}{16\pi^2}\kappa\Big[2\lambda_3 - 2\lambda_4 + 2\xi + 2\rho_1 + 2\rho_2 + 2\sigma_1 + 2\sigma_2 + \sum_{\alpha,i}(h_i^\alpha)^2 - \frac{9}{2}g^2 - \frac{9}{2}g'^2 + 3y_t^2 + 3y_b^2 + y_\tau^2\Big]$$

$$\beta(\xi) = \frac{1}{16\pi^2}\Big[4\sigma_1\rho_1 + 4\sigma_2\rho_2 + 2\sigma_3\xi + \rho_3\xi + 4\xi^2 - 6g'^2\xi + 2\sum_{\alpha,i}(h_i^\alpha)^2\xi\Big]$$

湯川結合

$$\beta(y_t) = \frac{1}{16\pi^2}\Big[-8y_t g_s^2 - \frac{9}{4}g^2 y_t - \frac{17}{12}g'^2 y_t + \frac{9}{2}y_t^3 + \frac{3}{2}y_t y_b^2\Big]$$

$$\beta(y_b) = \frac{1}{16\pi^2}\Big[-8y_t g_s^2 - \frac{9}{4}g^2 y_t - \frac{5}{12}g'^2 y_t + \frac{9}{2}y_b^3 + \frac{3}{2}y_t^2 y_b\Big]$$

$$\beta(y_\tau) = \frac{1}{16\pi^2}\Big[-\frac{9}{4}g^2 y_\tau - \frac{15}{4}g'^2 y_\tau + \frac{5}{2}y_\tau^3\Big]$$

$$\beta(h_i^\alpha) = \frac{1}{16\pi^2}\sum_{\alpha,i}\Big[-5g'^2 h_i^\alpha + \frac{1}{2}h_i^\alpha\sum_j(h_j^\alpha)^2 + \frac{1}{2}h_i^\alpha\sum_\beta(h_i^\beta)^2 + h_i^\alpha\sum_{j,\beta}(h_j^\beta)^2\Big]$$

Mass and coupling relations

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}\left(-\sin^2\beta M^2 + \sin^2\alpha m_h^2 + \cos^2\alpha m_H^2\right)$$

$$\lambda_2 = \frac{1}{v^2\sin^2\beta}\left(-\cos^2\beta M^2 + \cos^2\alpha m_h^2 + \sin^2\alpha m_H^2\right)$$

$$\lambda_3 = -\frac{M^2}{v^2} + 2\frac{m_{H^\pm}^2}{v^2} + \frac{1}{v^2}\frac{\sin 2\alpha}{\sin 2\beta}(m_H^2 - m_h^2)$$

$$\lambda_4 = \frac{1}{v^2}\left(M^2 + m_A^2 - 2m_{H^\pm}^2\right)$$

$$\lambda_5 = \frac{1}{v^2}\left(M^2 - m_A^2\right)$$

$$m_S^2 = \mu_S^2 + \frac{v^2}{2}\sigma_1\cos^2\beta + \frac{v^2}{2}\sigma_2\sin^2\beta$$

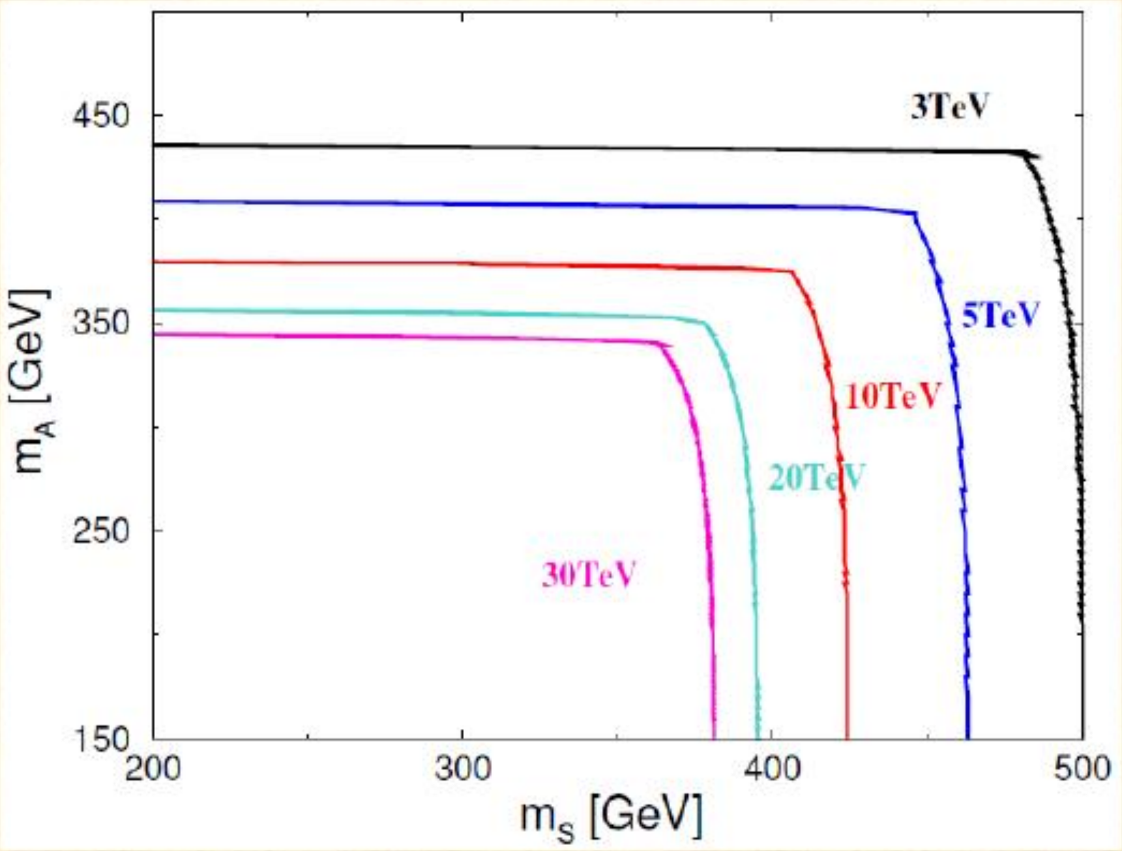
$$m_\eta^2 = \mu_\eta^2 + \frac{v^2}{2}\rho_1\cos^2\beta + \frac{v^2}{2}\rho_2\sin^2\beta$$

$$\tan\beta = \frac{\langle\Phi_2\rangle}{\langle\Phi_1\rangle}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$M^2 = m_3^2/\sin\beta\cos\beta$$

Cut off scale from Triviality



$\sin(\beta - \alpha) = 1$

$\tan\beta = 25$

$\kappa = 1.2$

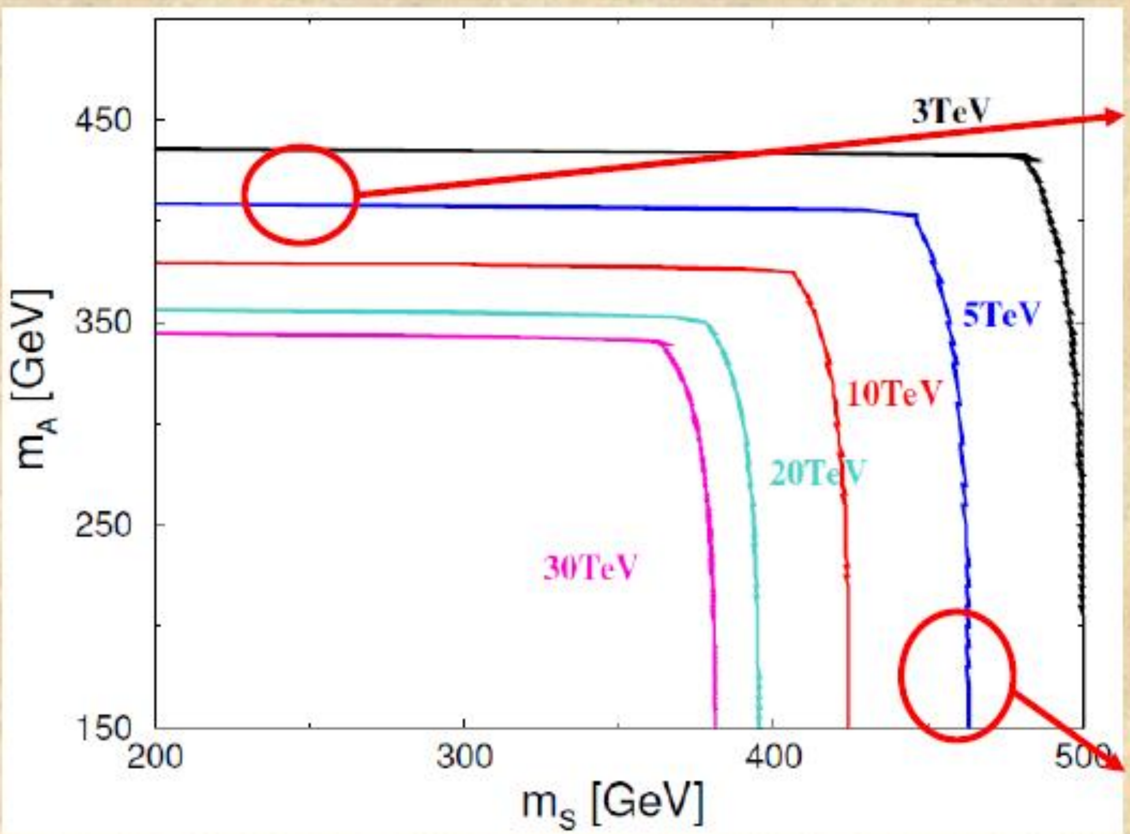
$\xi = 3.0$

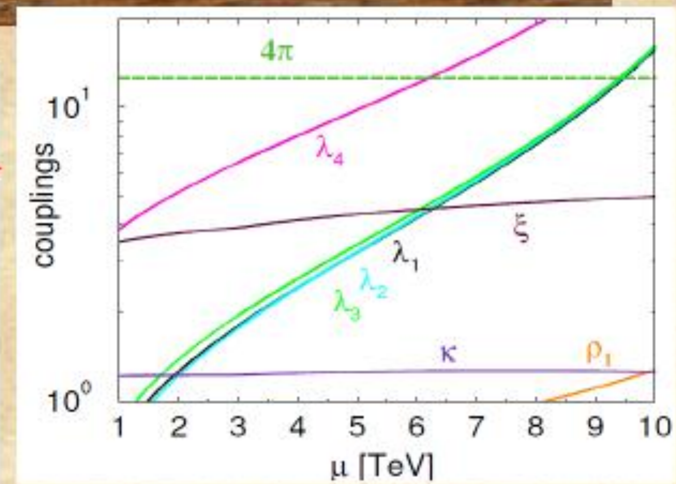
$m_h = 120\mathrm{GeV}$

$M = m_{H+} = m_H = 100\mathrm{GeV}$

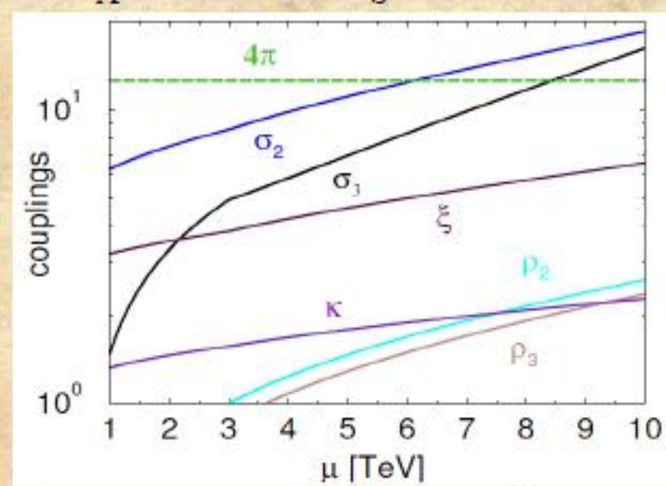
$\mu_S = 200\mathrm{GeV}$

Cut off scale from Triviality



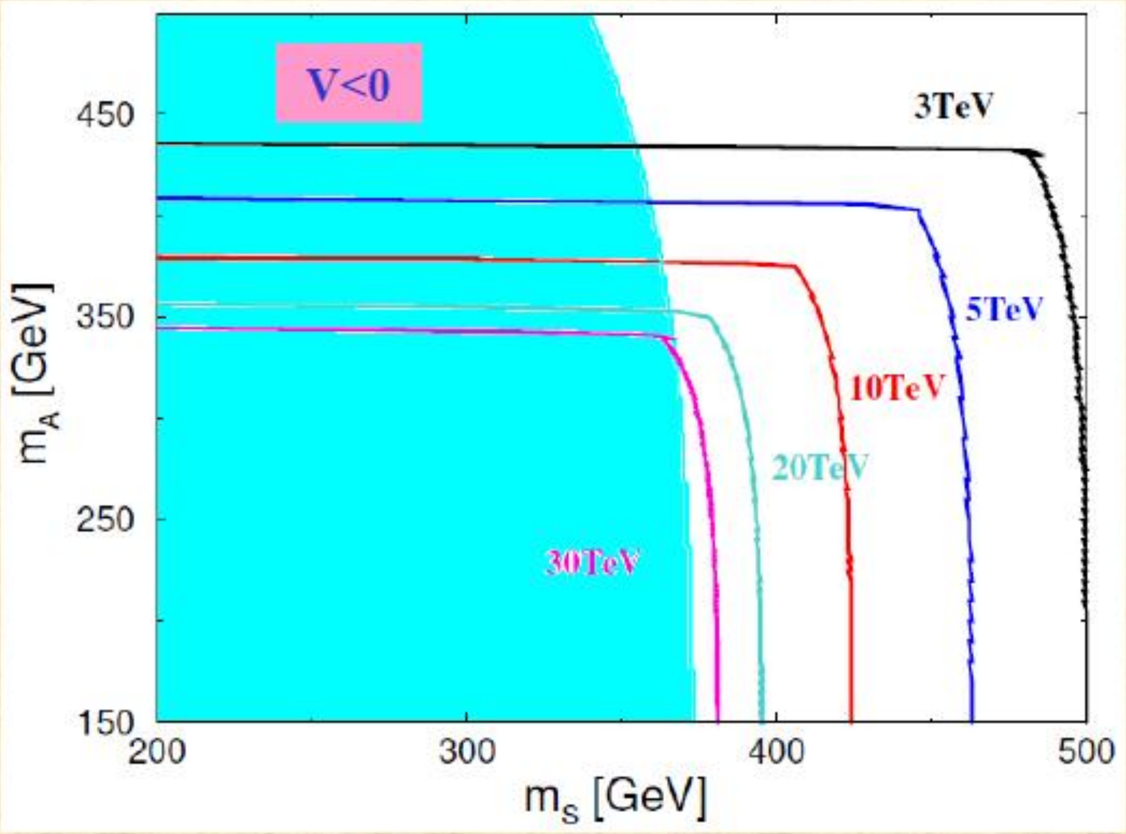


m_A=400GeV, m_S=150GeV



m_A=150GeV, m_S=450GeV

Allowed regions from Vacuum Stability



$\sin(\beta - \alpha) = 1$

$\tan\beta = 25$

$\kappa = 1.2$

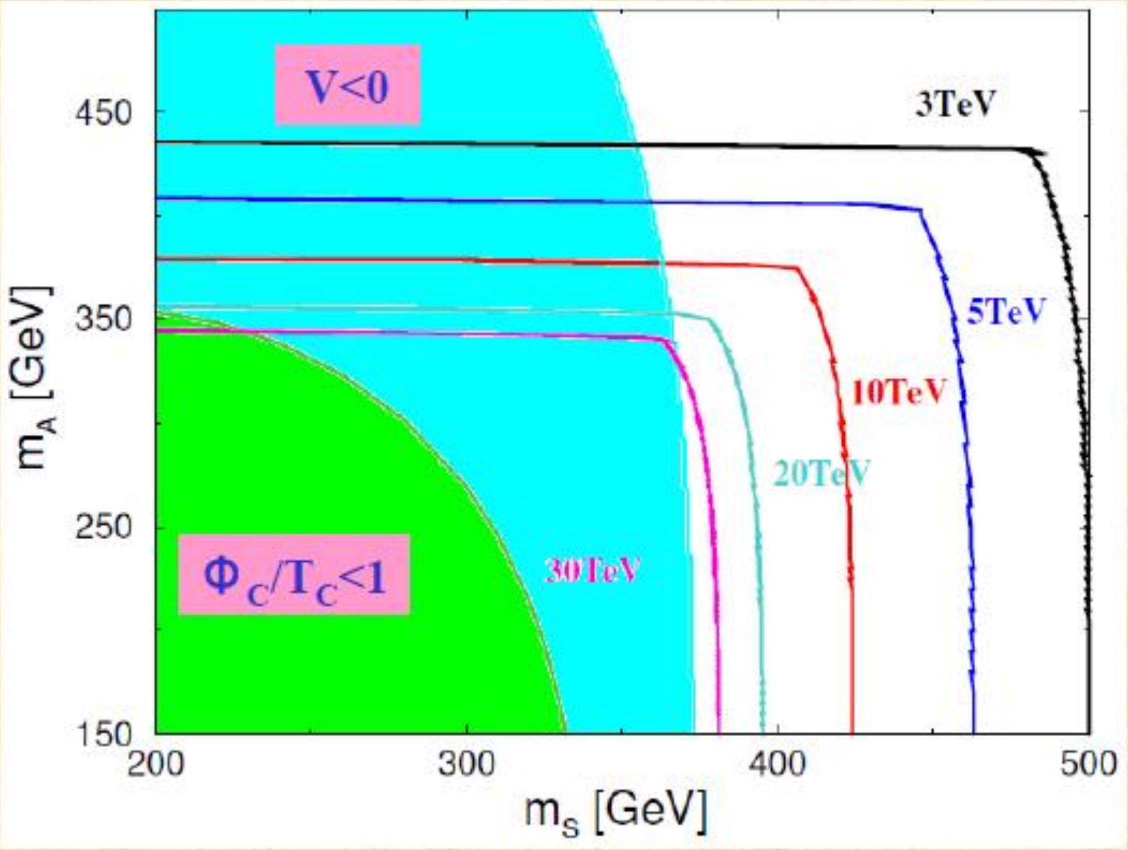
$\xi = 3.0$

$m_h = 120\text{GeV}$

$M = m_{H+} = m_H = 100\text{GeV}$

$\mu_S = 200\text{GeV}$

Allowed regions from Vacuum Stability +1st-OPT



$\sin(\beta - \alpha) = 1$

$\tan\beta = 25$

$\kappa = 1.2$

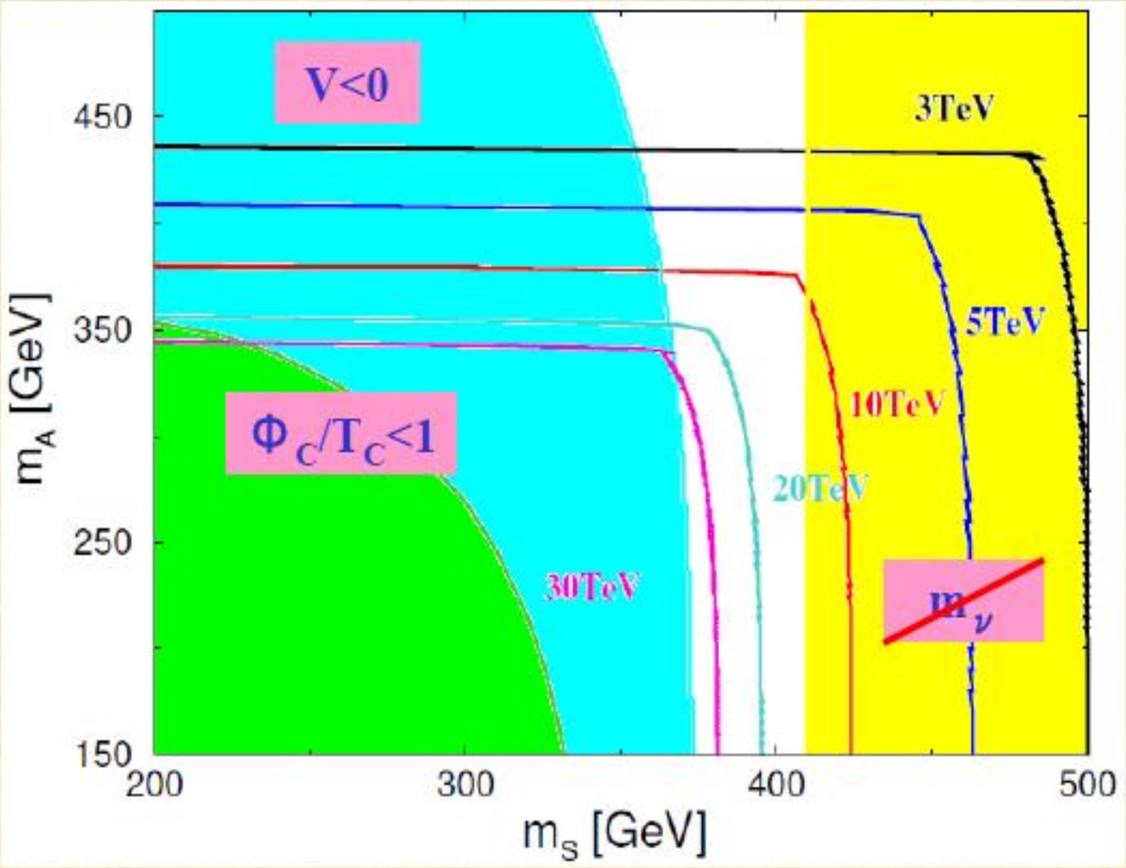
$\xi = 3.0$

$m_h = 120\mathrm{GeV}$

$M = m_{H+} = m_H = 100\mathrm{GeV}$

$\mu_S = 200\mathrm{GeV}$

Allowed regions from Vacuum Stability+ 1st-OPT+ DM abundance+Neutrino mass



$\sin(\beta - \alpha) = 1$

$\tan\beta = 25$

$\kappa = 1.2$

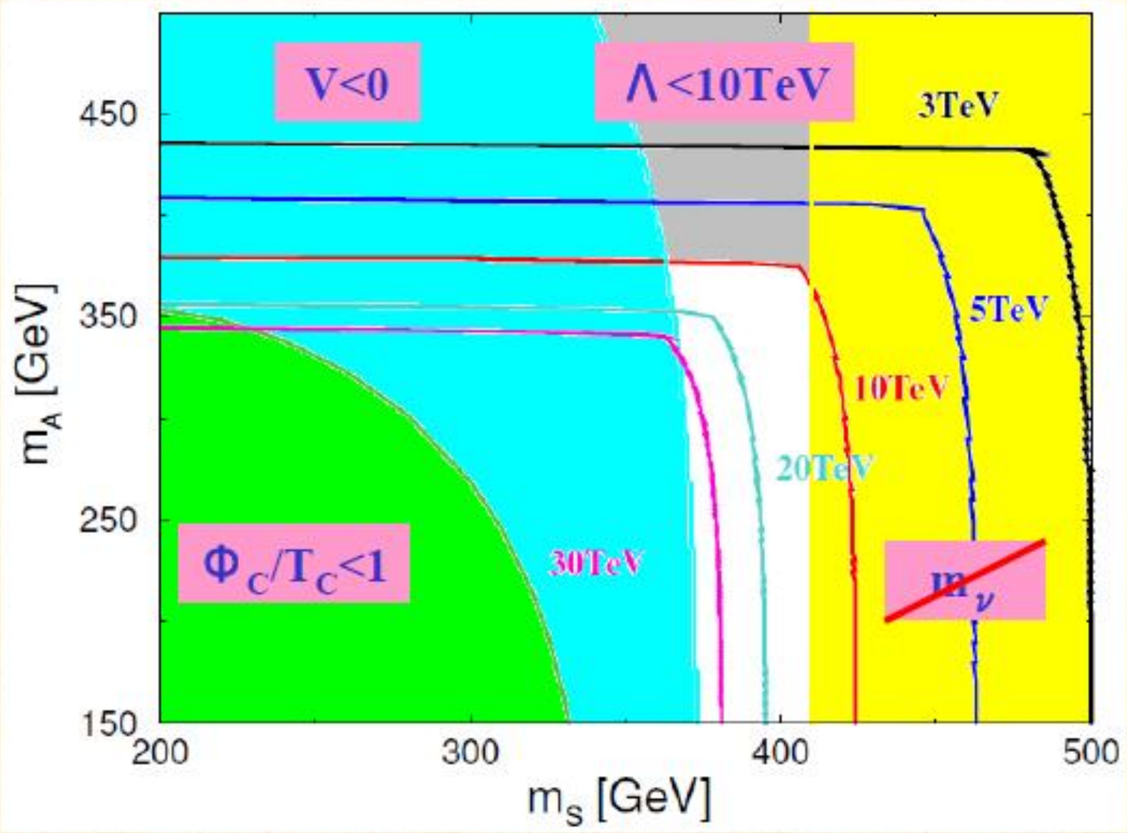
$\xi = 3.0$

$m_h = 120$GeV

$M = m_{H+} = m_H = 100$GeV

$\mu_S = 200$GeV

Allowed regions from Vacuum Stability+ 1st-OPT+ DM abundance+Neutrino mass



$\sin(\beta - \alpha) = 1$

$\tan\beta = 25$

$\kappa = 1.2$

$\xi = 3.0$

$m_h = 120\text{GeV}$

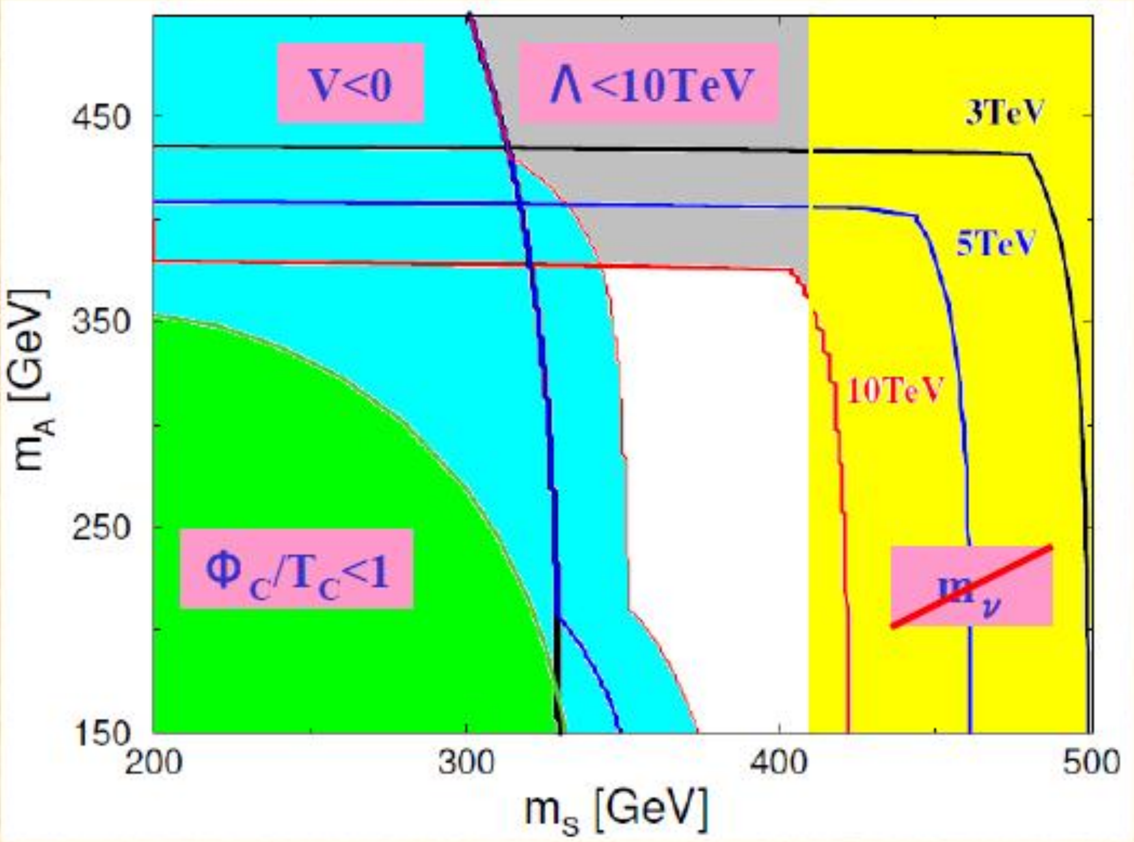
$M = m_{H+} = m_H = 100\text{GeV}$

$\mu_S = 200\text{GeV}$

許されるパラメータ領域では

10TeV以上まで理論が生き残る部分が存在する

Allowed regions from Vacuum Stability+ 1st-OPT+ DM abundance+Neutrino mass



$\sin(\beta - \alpha) = 1$

$\tan\beta = 25$

$\kappa = 1.2$

$\boldsymbol{\xi = 4.0}$

$m_h = 120\text{GeV}$

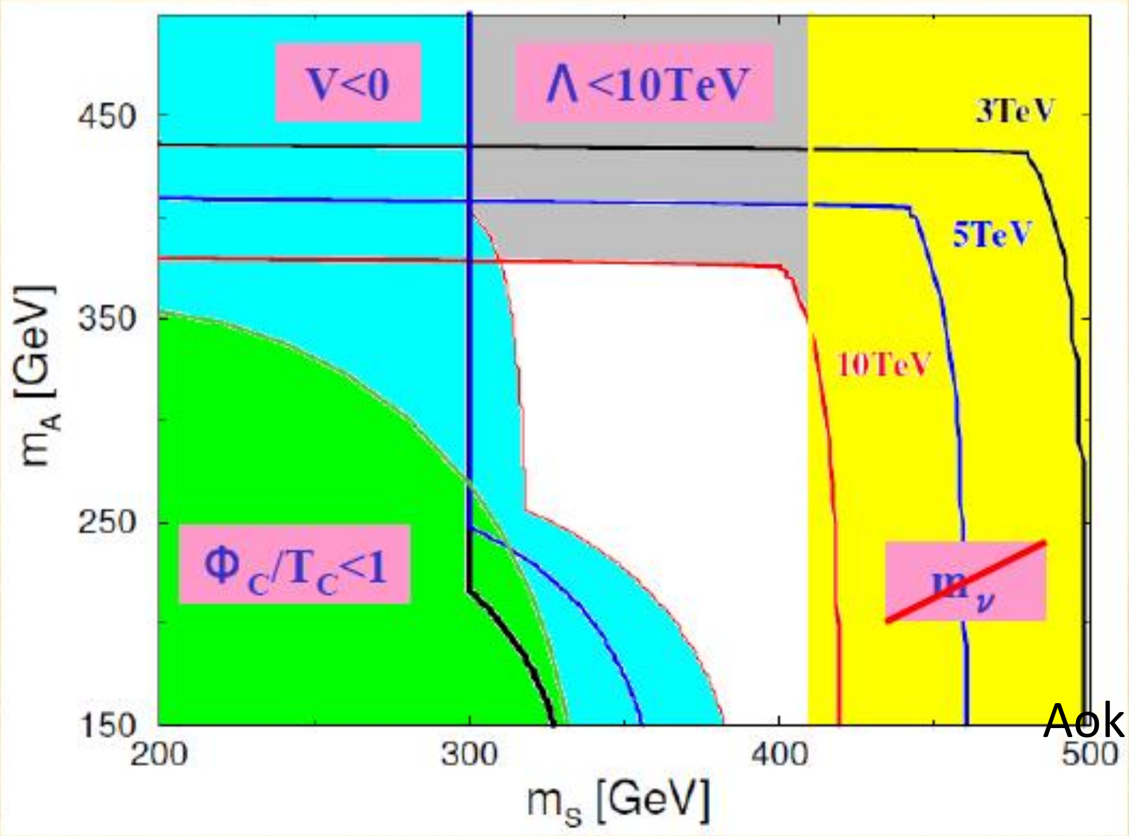
$M = m_{H+} = m_H = 100\text{GeV}$

$\mu_S = 200\text{GeV}$

許されるパラメータ領域では

10TeV以上まで理論が生き残る部分が存在する

Allowed regions from Vacuum Stability+ 1st-OPT+ DM abundance+Neutrino mass



$\sin(\beta - \alpha) = 1$
$\tan\beta = 25$
$\kappa = 1.2$
$\xi = 5.0$
$m_h = 120\mathrm{GeV}$
$M = m_{H+} = m_H = 100\mathrm{GeV}$
$\mu_S = 200\mathrm{GeV}$

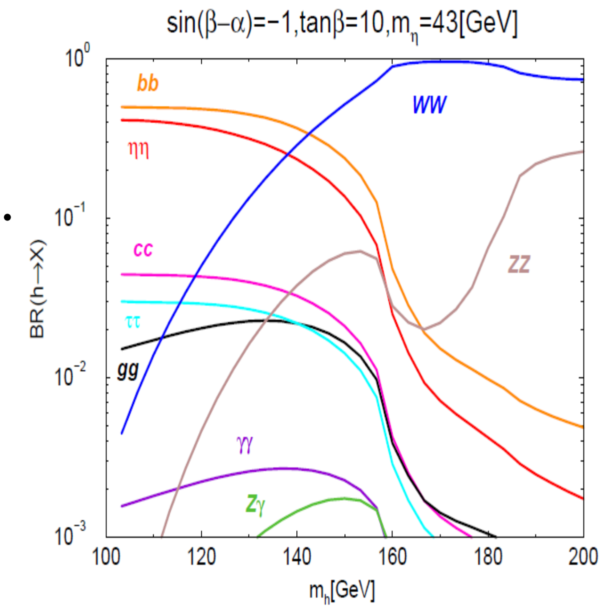
Aoki, SK, Yagyu, in preparation

許されるパラメータ領域では
10TeV以上まで理論が生き残る部分が存在する

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.

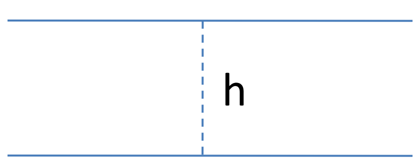
$B(h \to \eta\eta)$ = 36 (34) % for m_η=48 (55) GeV

Testable via the invisible Higgs decay at LHC

Direct Search

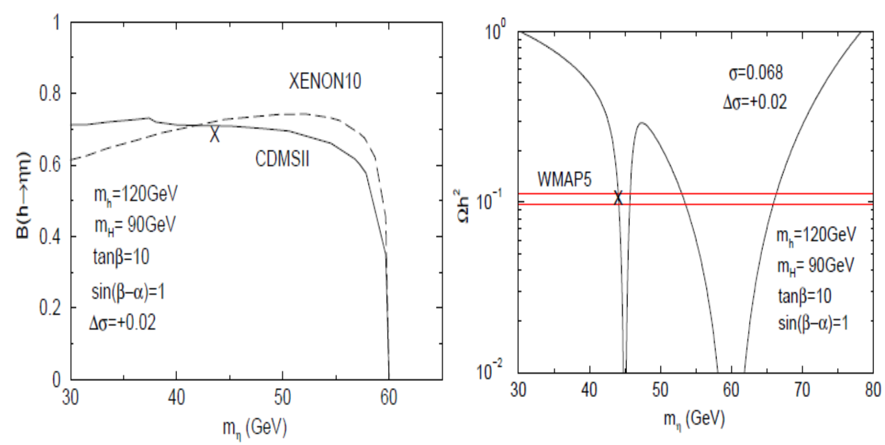
η from the halo can basically be detected at the direct DM search (CDMS, XMASS)

η



Nucleus (Xe, Ge)

Observing the release energy



Aoki, SK, Seto, 2010

Predictions of Type X 2HDM

Aoki, SK, Tsumura, Yagyu, Phys. Rev. D80,015017 (2009)

Decays:

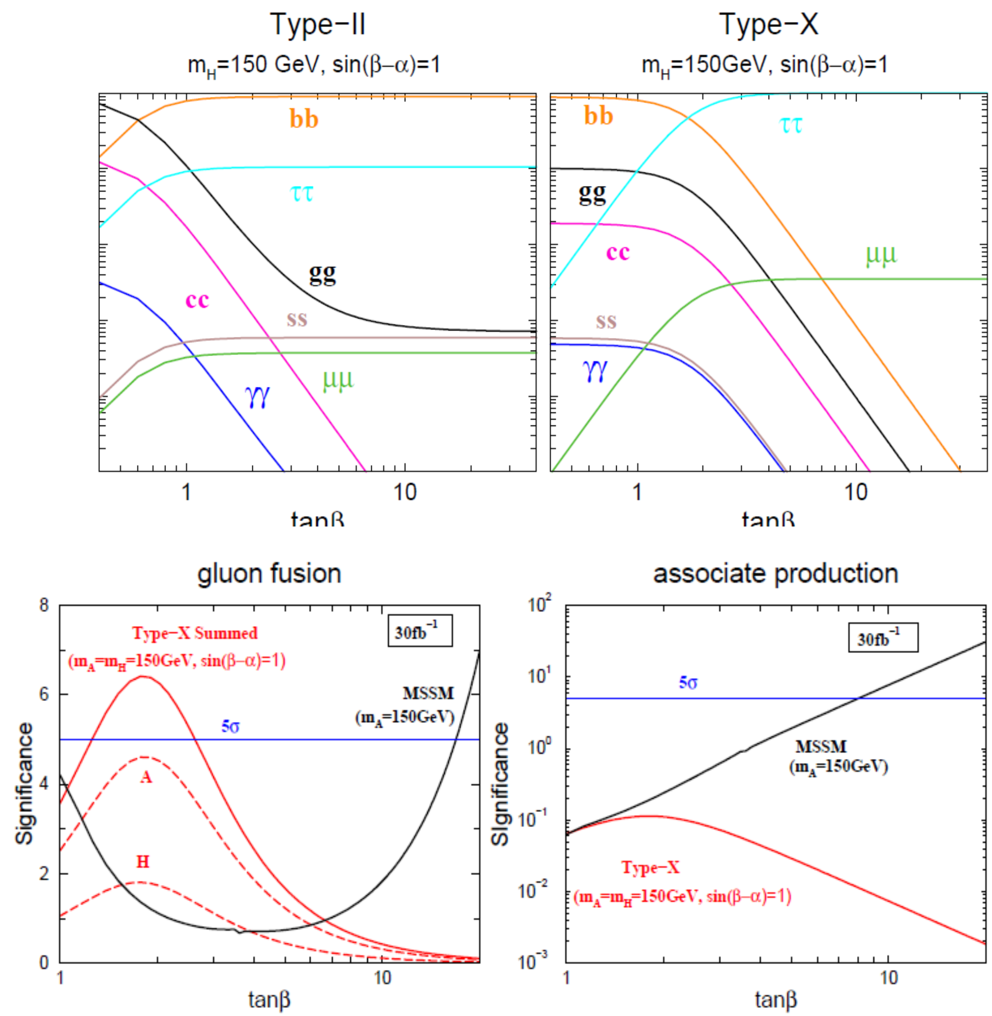
H, A decay into $\tau\tau$, not bb.

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

$pp \to A\ (H) \to \tau\tau$

and bb associate (H)A production

$pp \to bbA\ (bbH)$



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

Light Higgs scenario: Production at the LHC

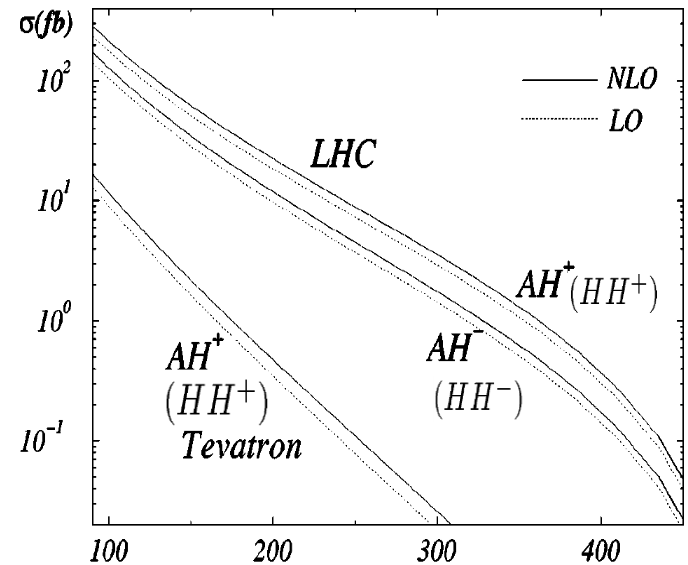
SK, Yuan
Cao, SK, Yuan
Baryaev et al

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

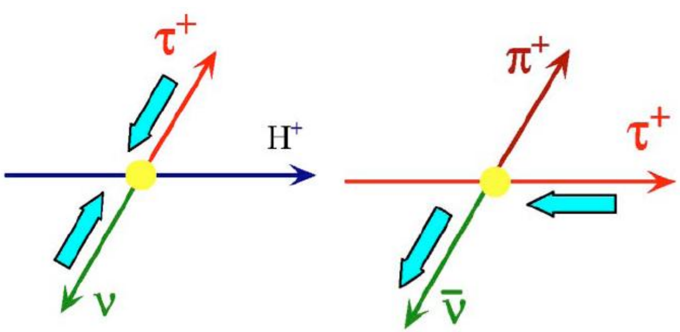
$$HH^{+} \to (\tau\tau)(\tau\nu)$$

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

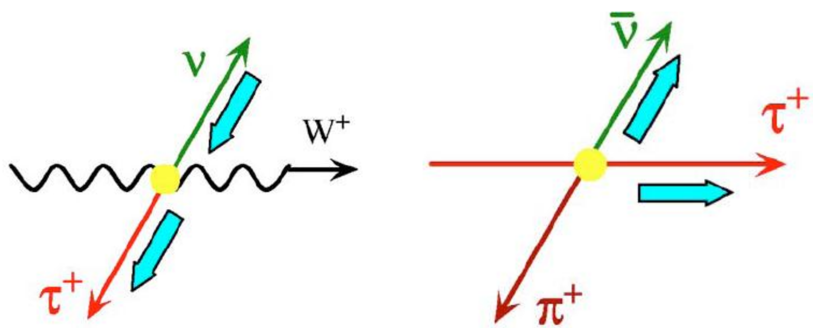
(MSSM) $pp \to AH^{+} \to (b\bar{b})\tau^{+}\nu \to (b\bar{b})(\pi^{+}\bar{\nu}\nu)$



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



High energy pions



low energy pions

Bullock, Hagiwara, Martin

Light Higgs scenario: Production at the ILC

$e^+e^- \rightarrow AH \rightarrow \tau\tau\tau\tau\ (\tau\tau\mu\mu)\ \ (m_A<m_H+m_Z)$

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

Leptonic decay dominance of H, A, H^+

Type-X Yukawa

$B(A\rightarrow\tau\tau)$, $B(H\rightarrow\tau\tau)$ ~ 100 %

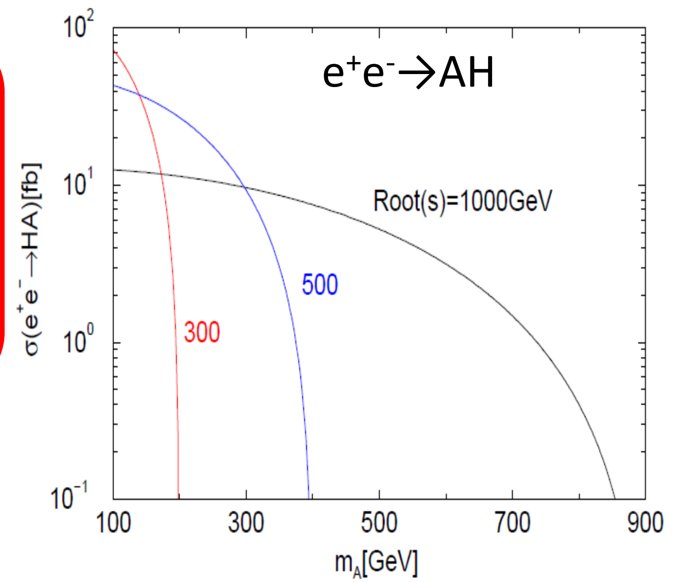
$B(A\rightarrow\mu\mu)$, $B(H\rightarrow\mu\mu)$ ~ 0.3%

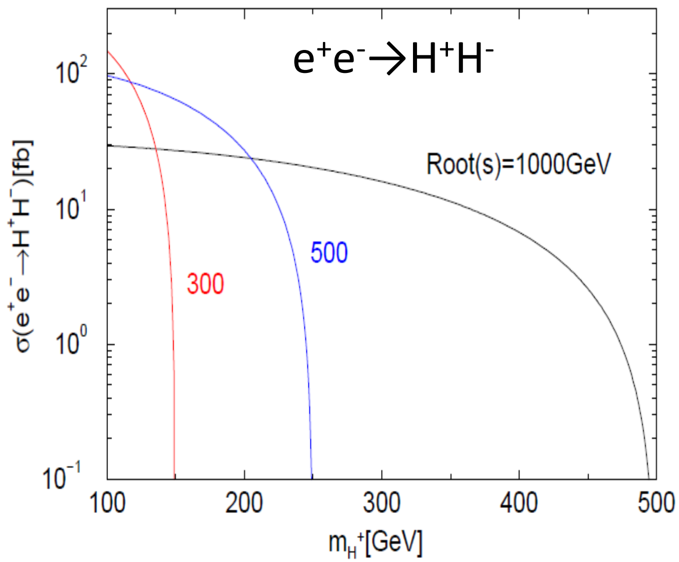
For $m_{H+}=m_H=100$ GeV with $\sin(\beta-\alpha)=1$, tanb=10
$m_A=150$GeV, $E_{cm}=500$GeV, $L=500fb^{-1}$

18000 ττττ events
112 ττμμ events
0 μμμμ events
40000 τντν events
128 τνμν events
0 μνμν events

Testable at ILC?

Simulation study is necessary





Non-decoupling effect

Successful EWBG requires

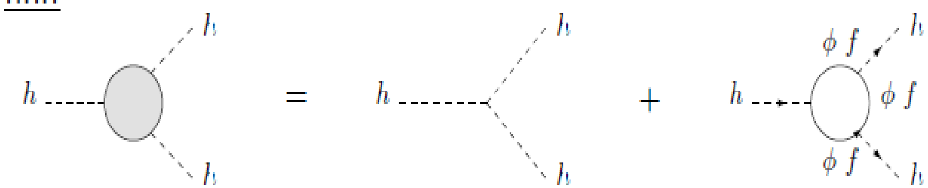
Non-decoupling property for S^+ (or A)

SK, Okada, Senaha 2005

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

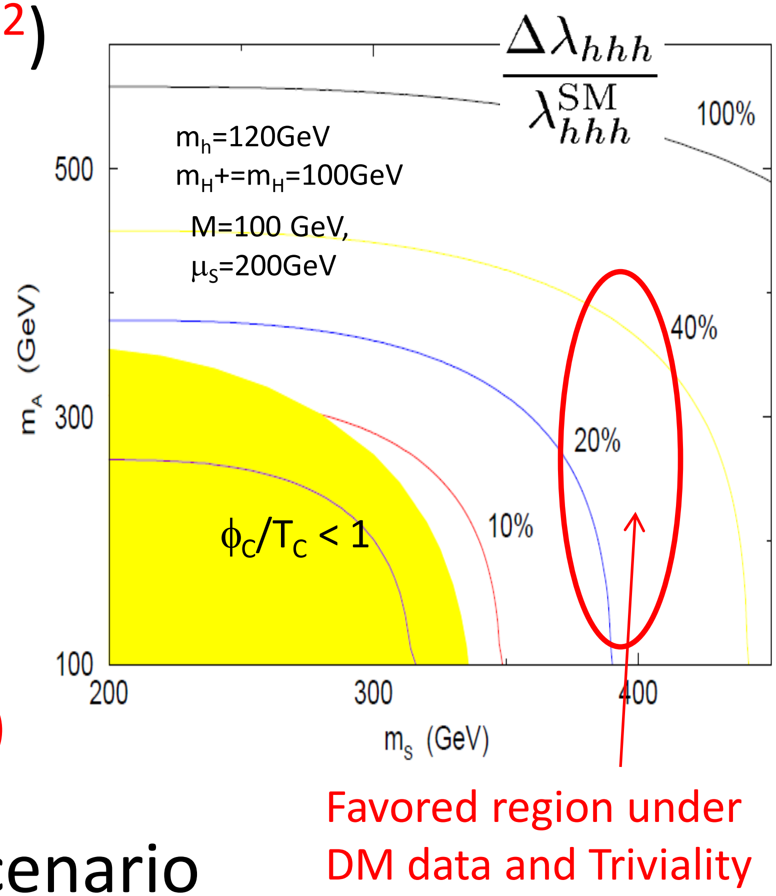
Deviation in the hhh coupling

hhh



Strong 1st OPT

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



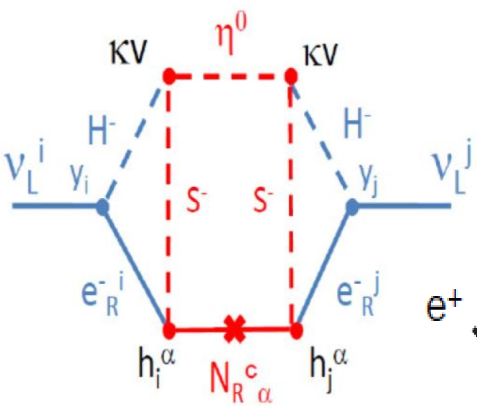
Testable at ILC (e^+e^- and PLC)

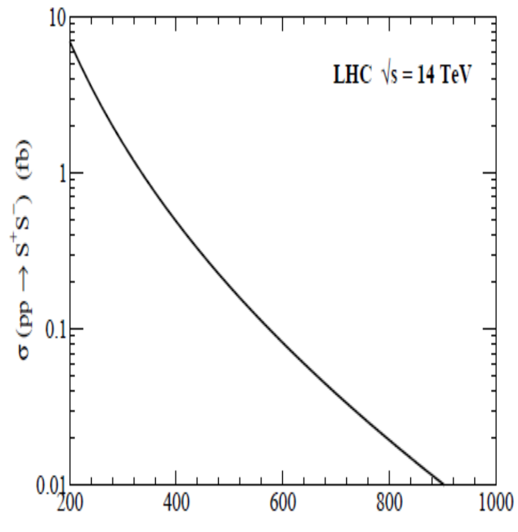
Important Test for our EWBG scenario

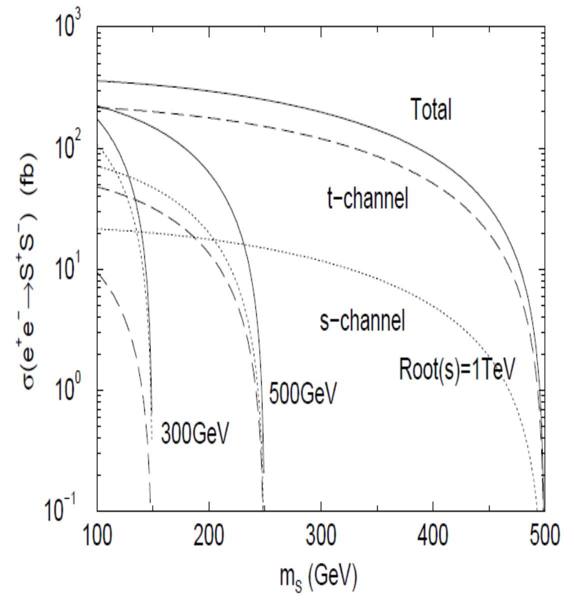
Physics of S^+

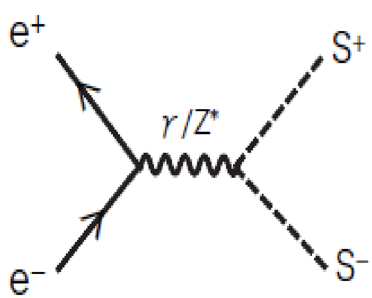
3-loop induced ν-masses

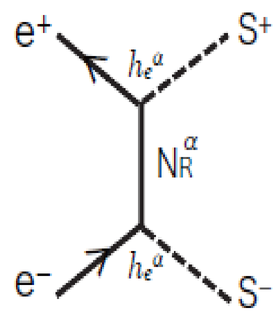
- Z2-odd TeV scale N_R.
- Large couplings $h_e^\alpha = O(1)$









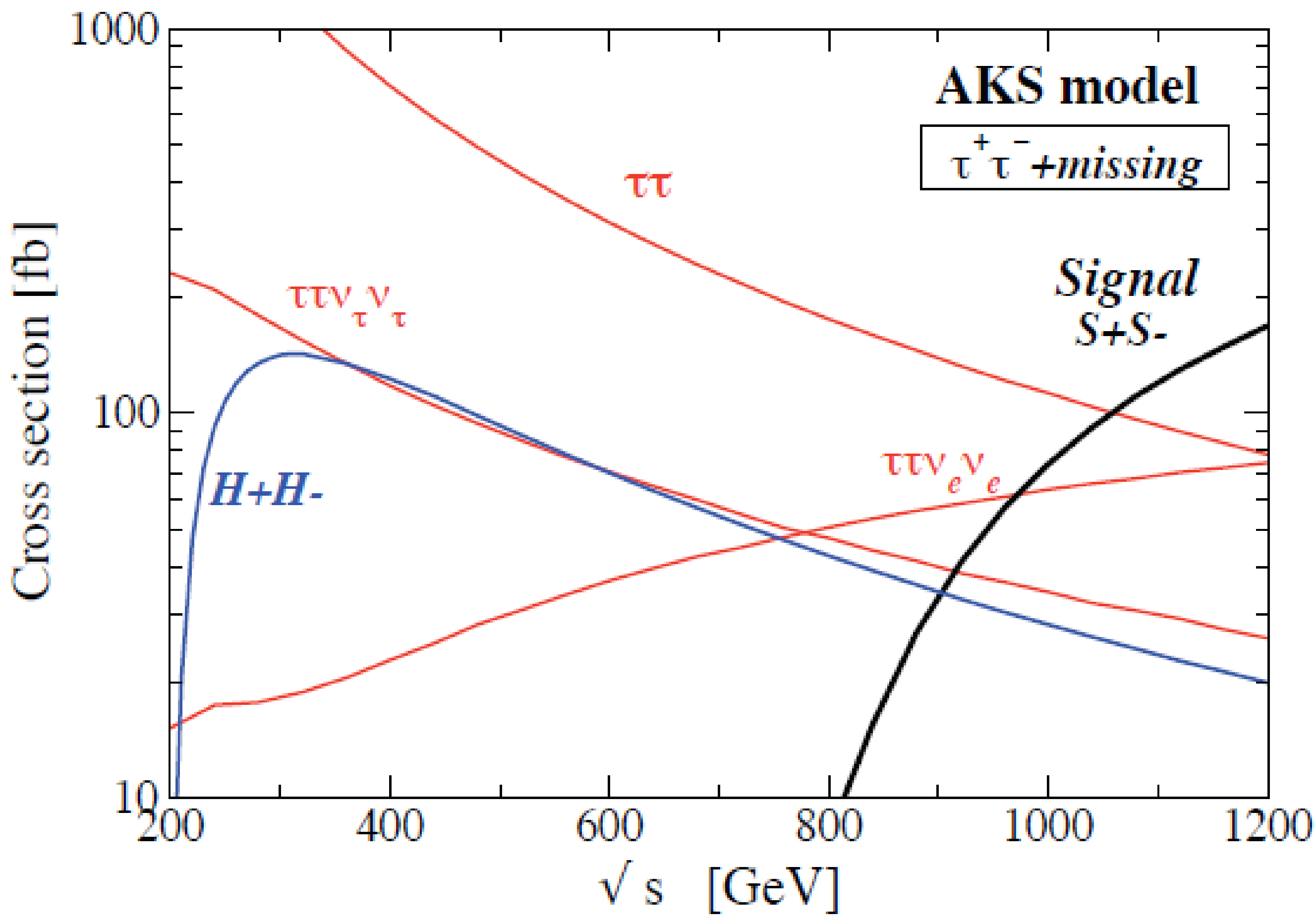


$\sigma(e^+e^- \to S^+S^-) = 100\text{fb}!$

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

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

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



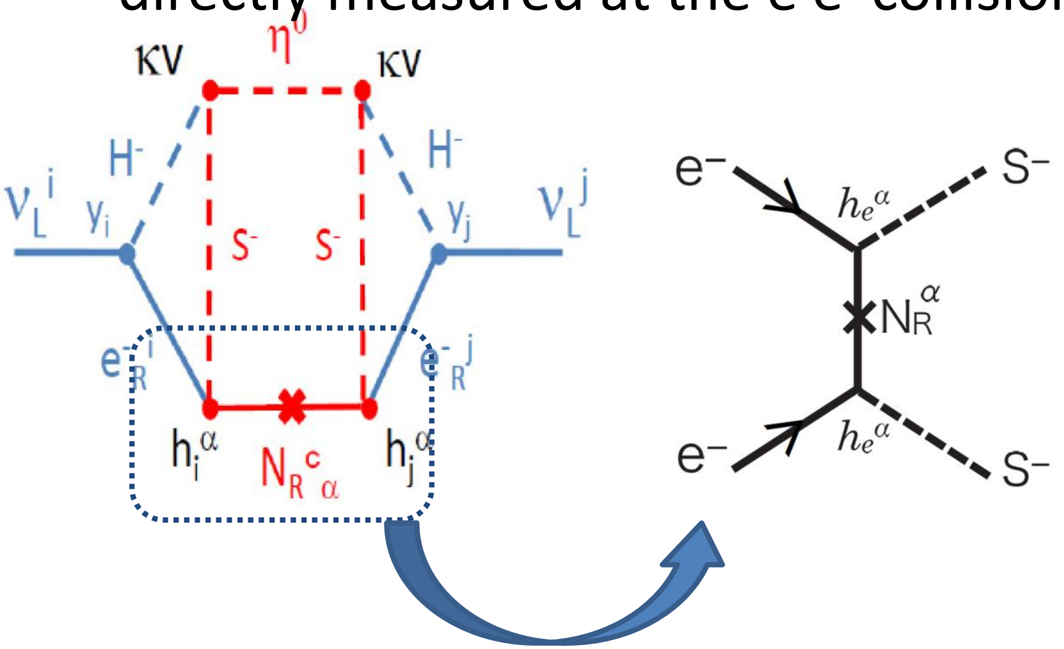
$e^+e^- \rightarrow S^+S^- \rightarrow (H^+\eta)(H^-\eta) \rightarrow (\tau^+\nu\eta)(\tau^-\nu\eta)$

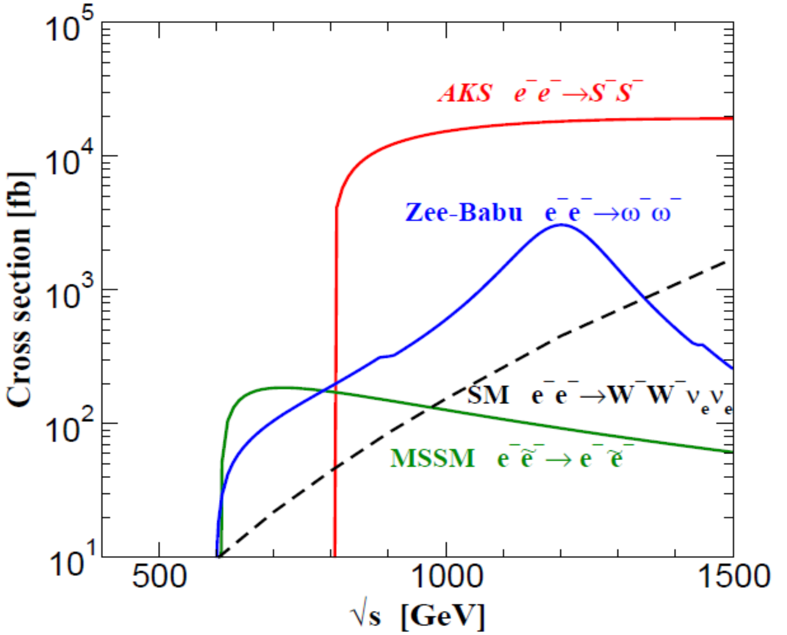
Signal: energitic $\tau^+\tau^-$ with large missing E

Test the Majorana Nature at ILC

Aoki, SK, Seto, PRD80, 033007(2009)
Aoki, SK, PLB689,21 (2010)

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





$h_e^\alpha = O(1)$

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

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

Combined study of pp, e^+e^- and e^-e^- process is useful to test this model

Summary

We discussed a concrete (successful) model which includes

Neutrino Mass --- 3 loop induced

Dark Matter --- Z_2 odd neutral scalar boson

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 , CLIC

The model can be tested at future experiments