An extended Higgs model for neutrino mass, dark matter, and baryon asymmetry

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Based on

M. Aoki, SK, O. Seto arXiv:0807.0361

M. Aoki, SK, K. Tsumura, K. Yagyu In preparation

16-20. Nov. 2008, LCWS2008, UIC, Chicago

What is discussed

Phenomena of Beyond the SM

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

We discuss a TeV scale model to solve them

- Dim4 Lagrangian whose masses are O(1) TeV or below

Bounds and predictions:

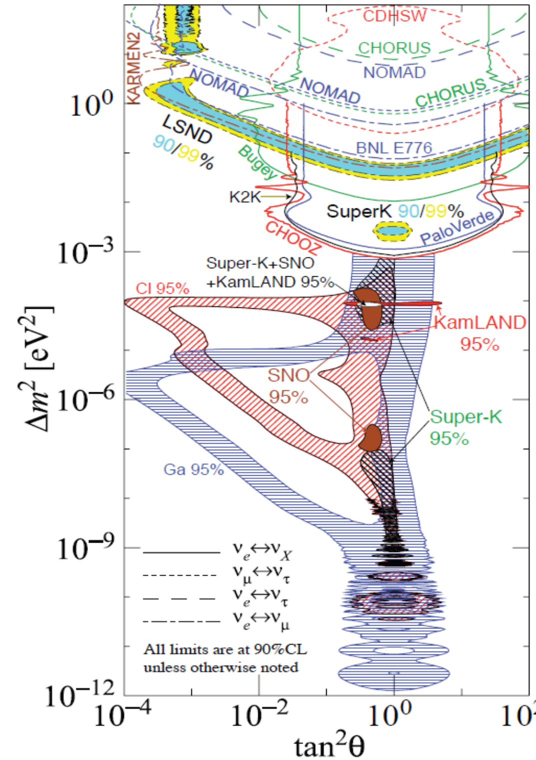
Many interesting phenomena, in particular, in Higgs physics

Phenomena of Beyond-SM

Neutrino Oscillation

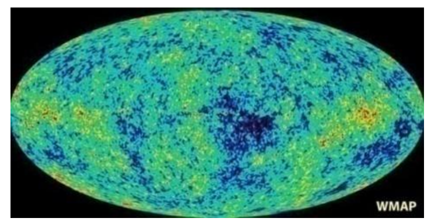
BSM!

$\Delta m_{sol}^2 \sim 8 \times 10^{-5}\,eV^2, \;\; \Delta m_{atm}^2 \sim 0.0021\;\; eV^2$



Dark Matter

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



WIMP : BSM!

Baryon Asymmetry of the Universe

$n_B/s \sim 10^{-10}$

Sakharov's condition

B violation

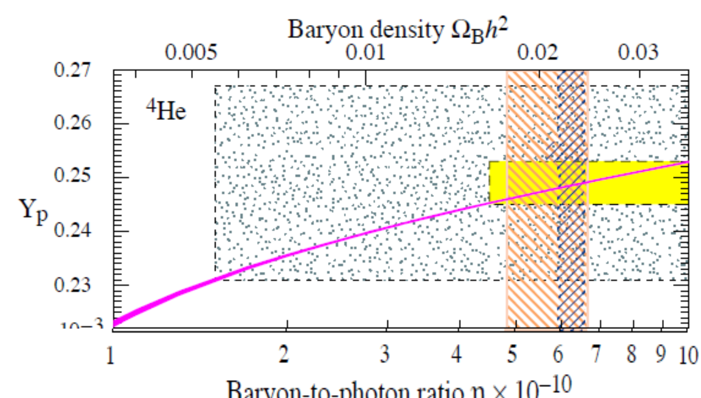
CP violation

Non-equiliblium

Electroweak Baryogenesis

SM is excluded by LEP

BSM!

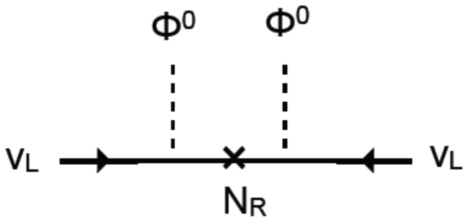


Scenario for ν Mass: Seesaw

Super heavy RH neutrinos ($M_{NR} \sim 10^{13\text{-}16}$GeV)

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

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



νν$\phi\phi$

Minkowski
Yanagida
Gell-Mann et al

– Simple, compatible with GUT etc

– Has the problem really been solved ?

Hierarchy for hierarchy ?

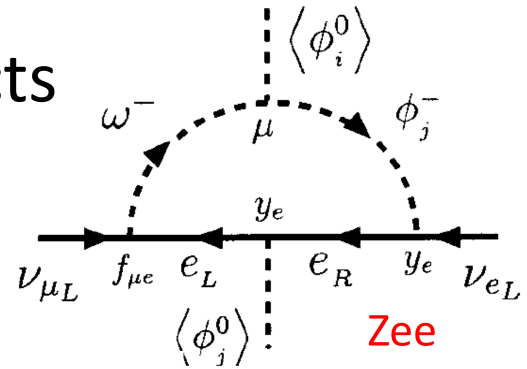
– Introduction of super high scale

= far from experimental reach…

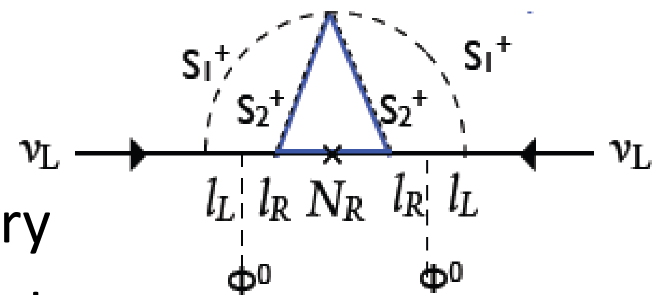
Scenario for ν Mass: Quantum Effects

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
  - Tiny ν masses are radiatively generated.



Zee



Krauss et al

Physics at TeV: Testable at collider experiments

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 (dim-4) field theory of at most TeV scale ?

No large masses in the Lagrangian

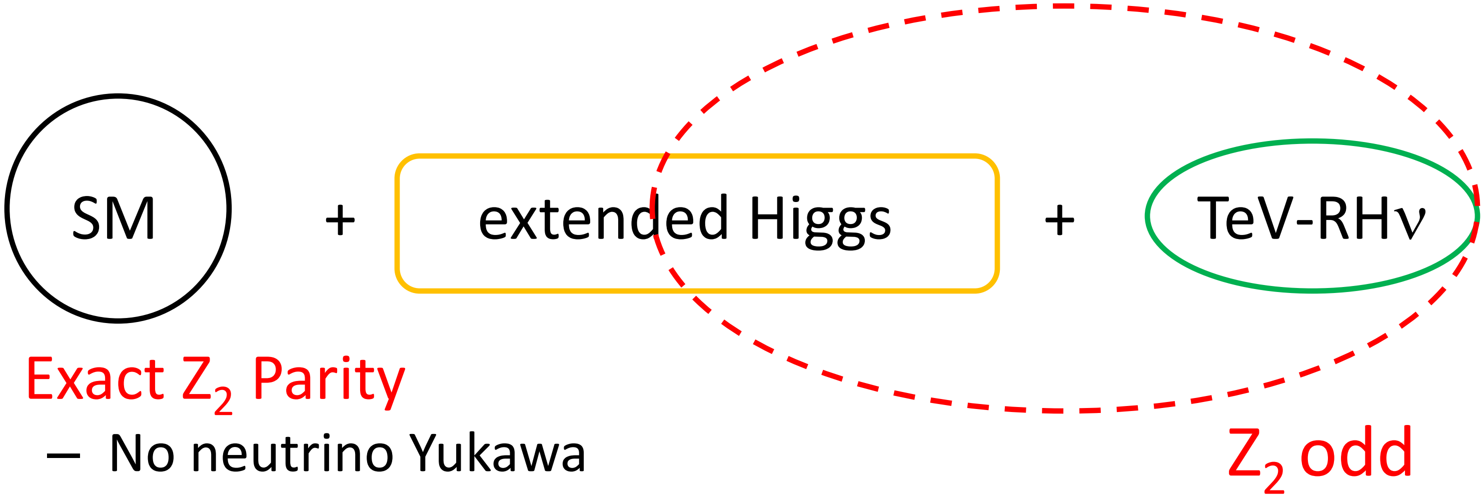
Predictable and testable

We consider such a model and discuss its phenomenology

The Model

SM + extended Higgs + TeV-RHν

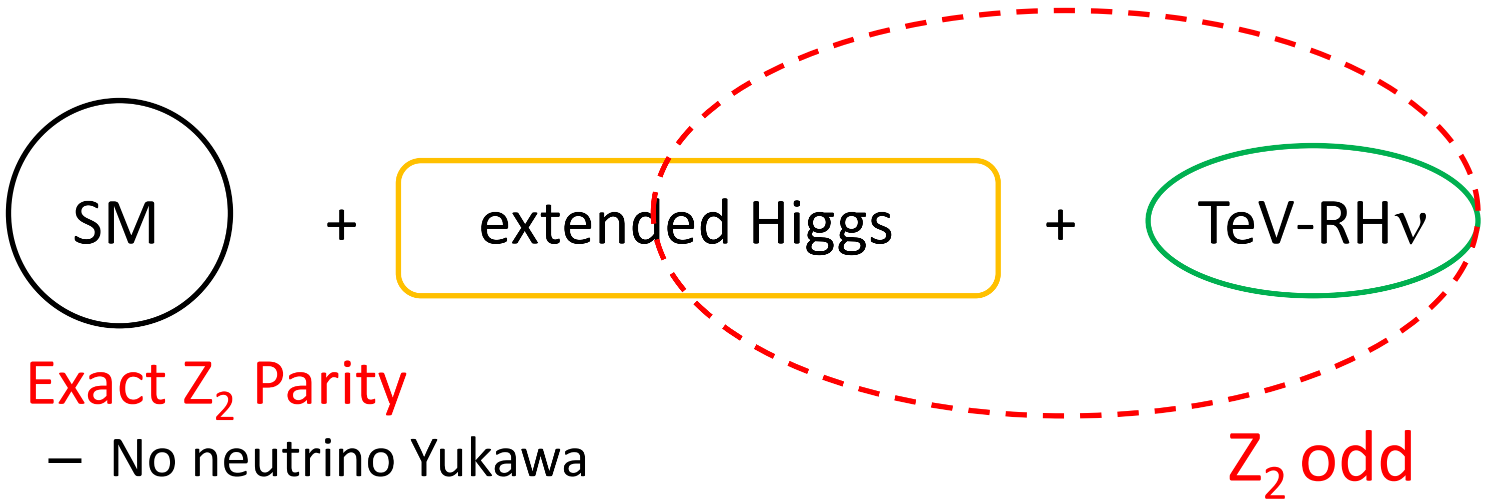
The Model



- 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 (η^0, S^+)
  - Tiny ν-mass: 3-loop (N_R, η^0, S^+, H^+, e_R)
  - DM candidate (η^0)
  - EW Baryogenesis [1st Order PT, Source of CPV] (Extend Higgs)

FCNC suppression

Softly-broken Z_2 symmetry ($\tilde{Z}_2$)

Glashow -Weinberg

$$\Phi_1 \longrightarrow +\Phi_1$$
$$\Phi_2 \longrightarrow -\Phi_2$$

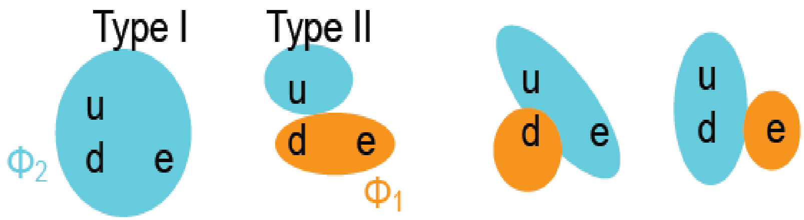
FCNC suppression

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

Softly-broken Z_2 symmetry ($\tilde{Z}_2$)

Glashow -Weinberg

4 Petterns of Yukawa coupling



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

FCNC suppression

Softly-broken Z_2 symmetry ($\tilde{Z}_2$)

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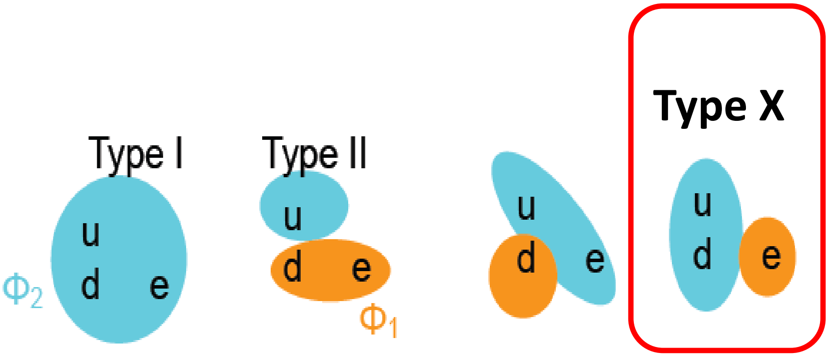
4 Petterns of Yukawa coupling



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In the type-II 2HDM, such a light H^+ is excluded by $b \to s\gamma$ result.

Type-X 2HDM

= Model-IV (Berger et al). Model-II'(Grossmann), ...

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

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks

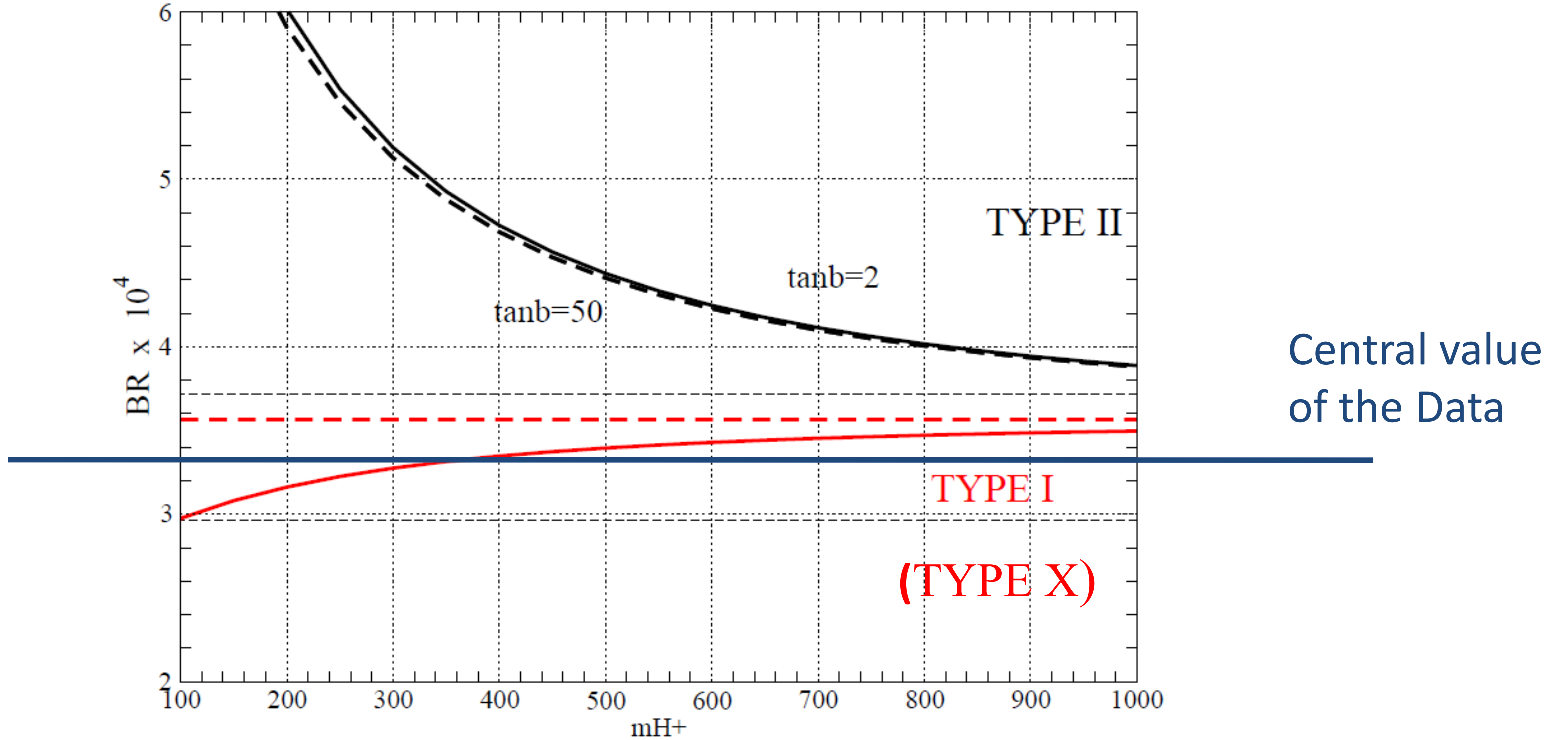
Discriminative Higgs phenomenology from MSSM, type-I, II 2HDM,

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 γ result even m_{H+}=100GeV

Symmetries of 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)	−	+

Rows Q^i through Φ_2: Type-X 2HDM

Lagrangian

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

Z_2 even(2HDM) + Z_2odd(S^+, η^0 , N_R^α)

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

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

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

RH neutrinos

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

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 $\tilde{Z}_2$

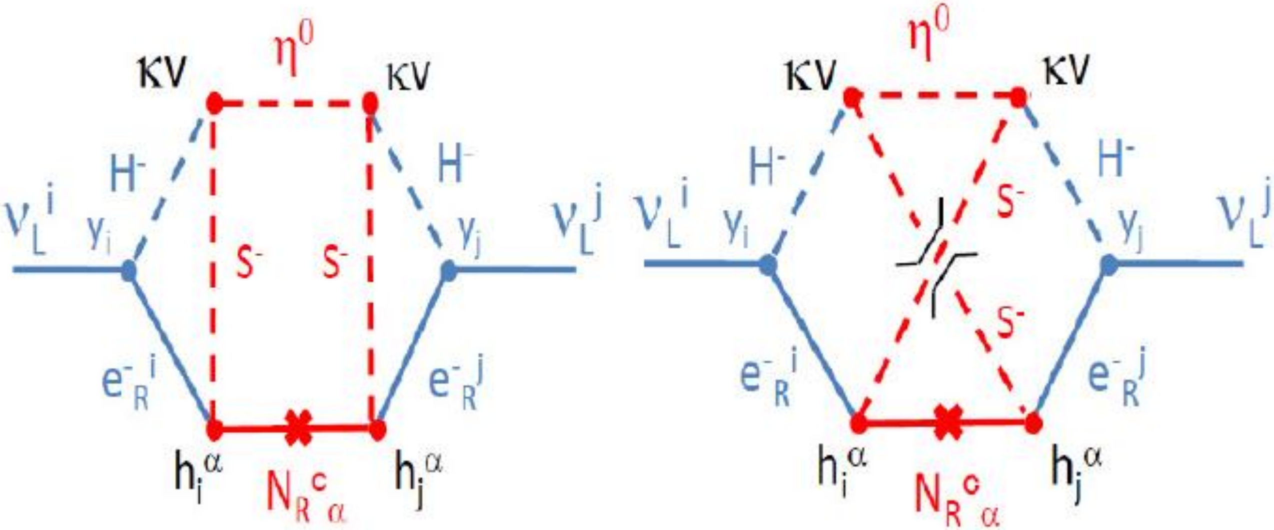
$m_{S+}^2 = \mu_{s+}^2 + O(\rho)\, v^2$

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

Neutrino Mass
(radiative ννϕϕ 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
- η, 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

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

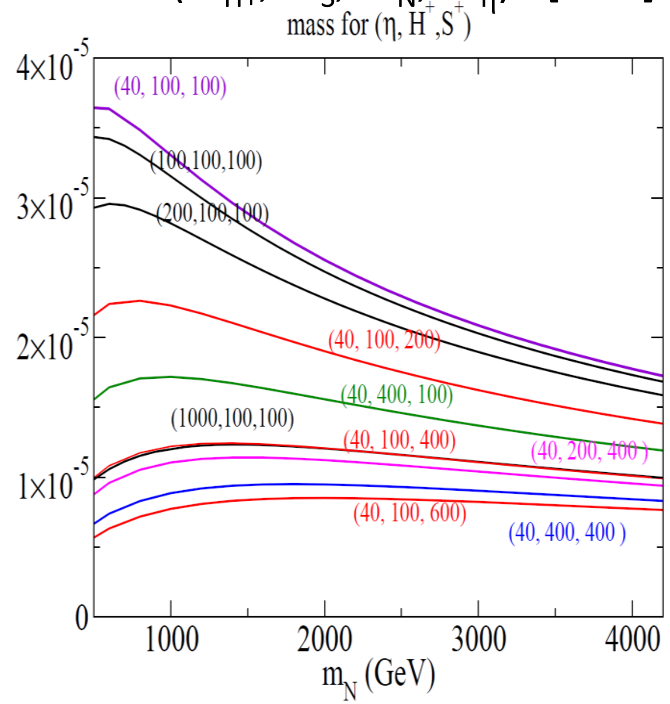
Universal scale is determined by the 3-loop function factor F

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

Mixing Structure is determined by

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

$F(m_{H+}, m_S, m_N, m_\eta)$ [GeV]



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

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

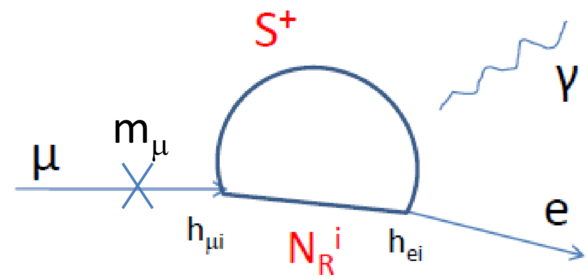
$$m_\nu^{\rm diag} \equiv \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sqrt{\Delta m^2_{\rm solar}} & 0 \\ 0 & 0 & \sqrt{\Delta m^2_{\rm atom}} \end{bmatrix} \quad U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 &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

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

Set	h_e^1	h_e^2	h_μ^1	h_μ^2	h_τ^1	h_τ^2	$B(\mu \to e\gamma)$
A	1.2	1.2	-0.011	0.025	-0.0015	0.00070	5.3×10^{-12}
B	1.2	1.35	0.0037	0.022	-0.00075	0.0012	4.5×10^{-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).

LFV



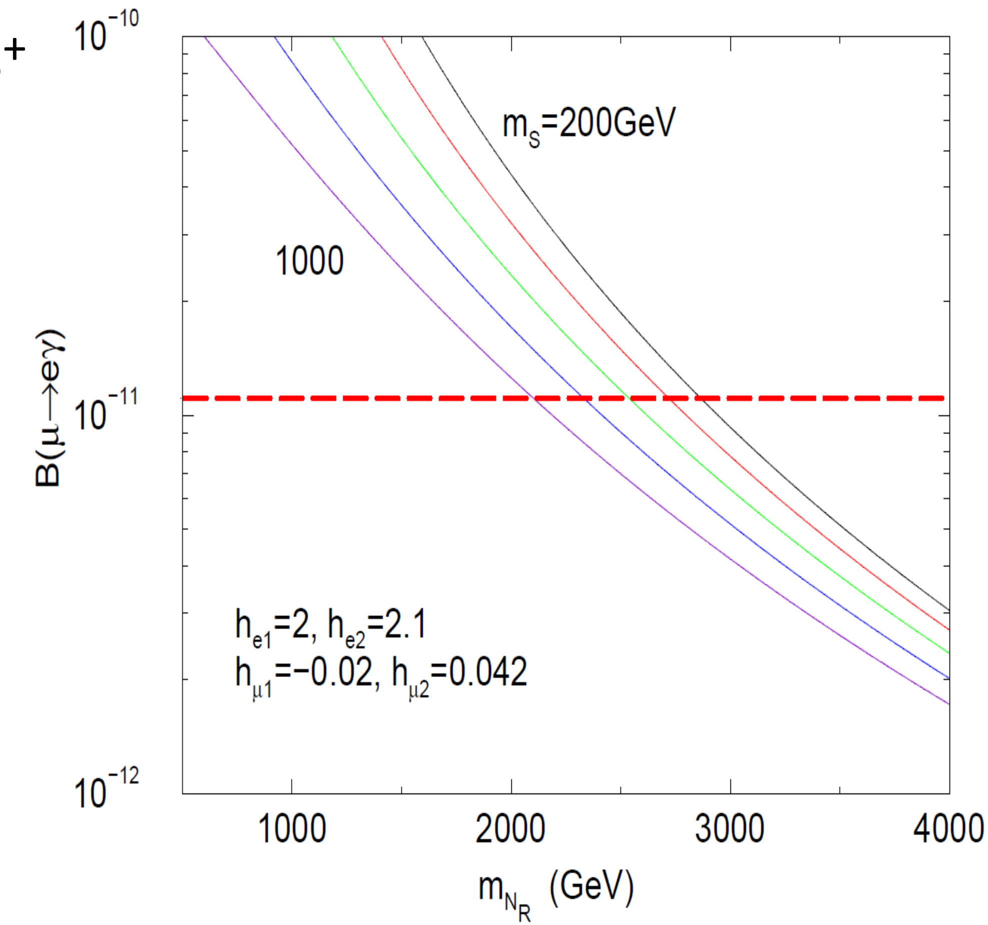
The parameters receive strong bounds from $\mu \to e\gamma$, which prefer heavy N_R and S^+

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

S^+ several times 100 GeV

N_R several times 1 TeV

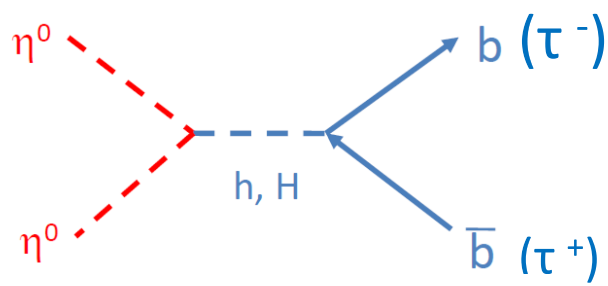
η is DM candidate !

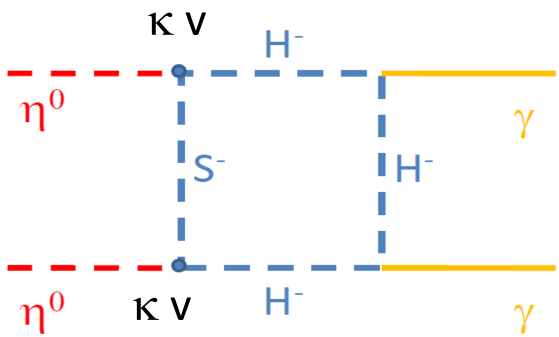


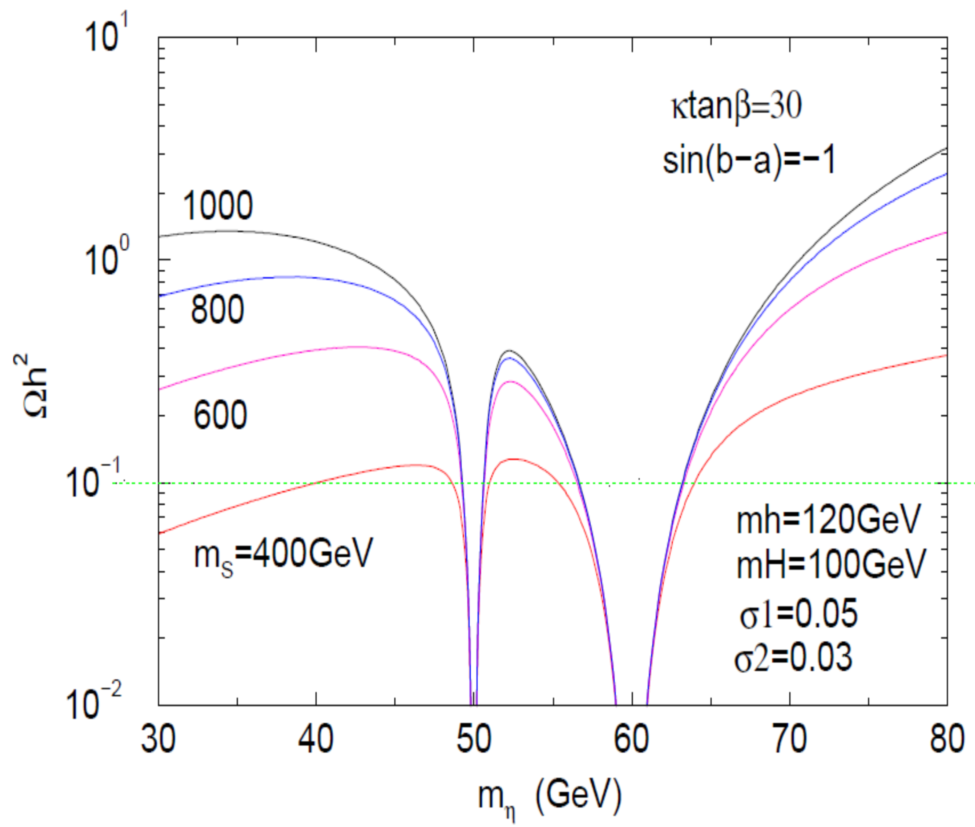
Thermal Relic Abundance of η^0

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

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



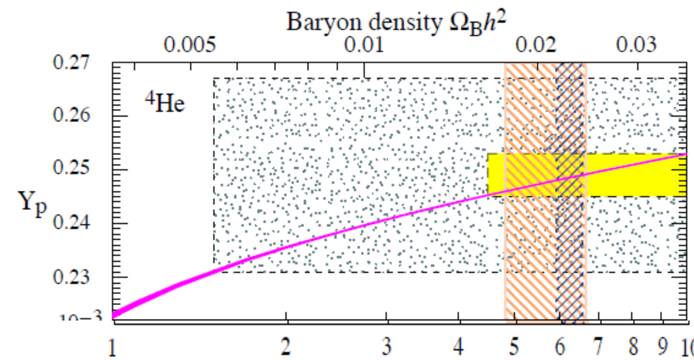




m_η would be around 40-65 GeV for m_S = 400GeV

Electroweak Baryogenesis

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



Sakharov's conditions:

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

Strong 1st Order Phase Transition

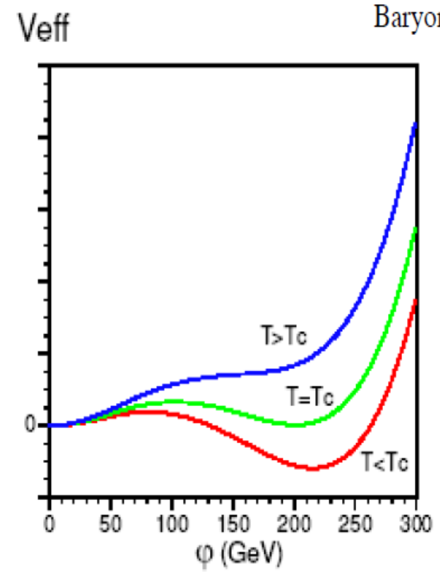
= rapid sphaleron decoupling

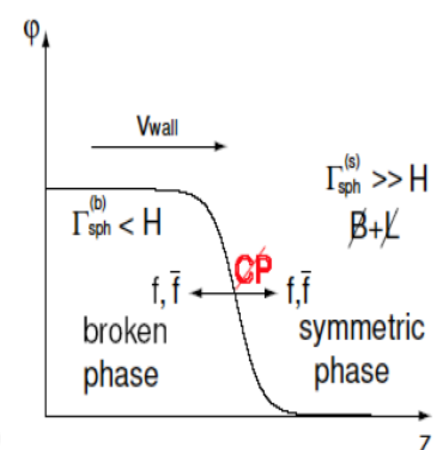
in the broken phase

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

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

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





EW baryogenesis in 2HDM

Cohen, Kaplan, Nelson, 1991, …..
Cline, Kainulainen, Vischer 1996, …..
Fromme, Huber, Seniuch 2006

Strong 1st Order Phase Transition

- Sphaleron decoupling condition at the broken phase

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

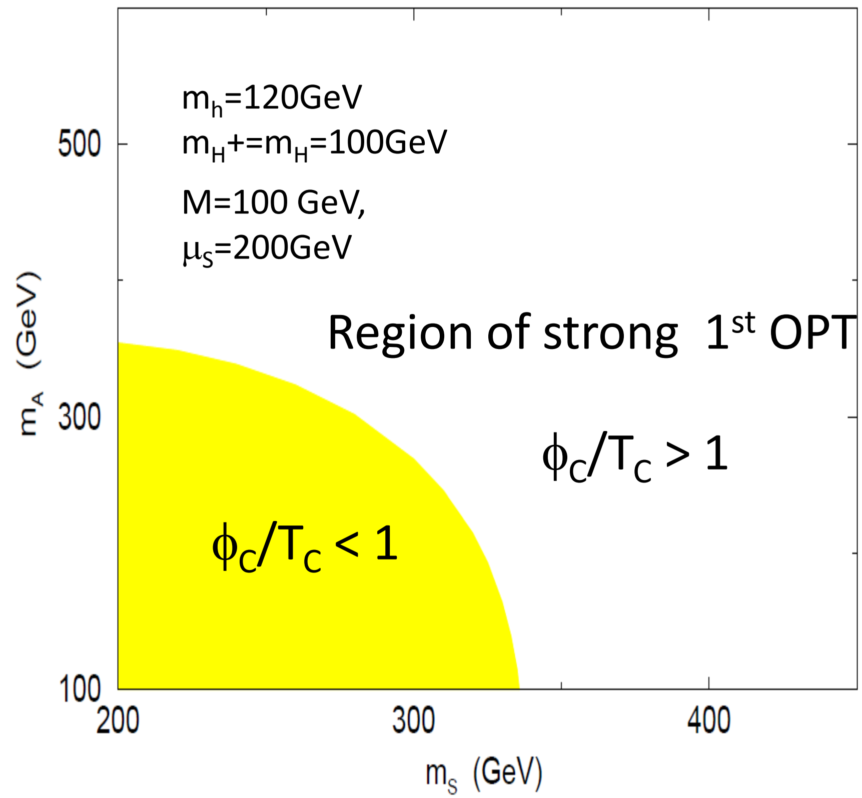
$m_A^2 = M^2 + (\lambda_4 - \lambda_5)v^2/2 \qquad m_S^2 = \mu_S^2 + \lambda_S v^2$

When M^2, μ_S^2 (invariant masses) << $\lambda_i v^2$

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

SM only for a too light h (Excluded!)

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



Mass difference bet. A and H^+ or heavy S^+ (m_S > 300 GeV)

Mass Spectrum

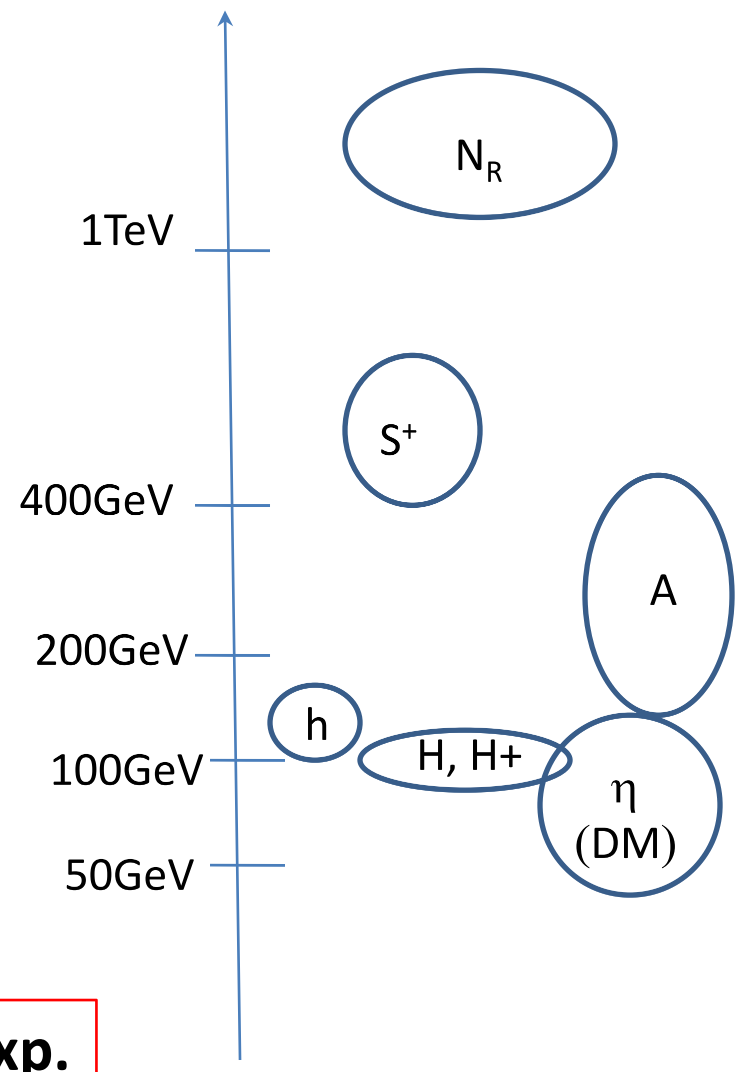
The current data and requirement for

- Neutrino oscillation data
- DM abundances
- Strong 1st order EW phase transition
- LEP bounds (direct , ρ parameter, ...)
- $b \to s\gamma$, $B \to \tau\nu$
- LFV ($\mu \to e\,\gamma$), g-2 , tau leptonic decay
- Tevatron bounds (H^+ from the t decay)
- Perturbative unitarity and vacuum stability

They give constraints on the masses

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

Testable @ Collider Exp.



DM physics

Physics of η

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

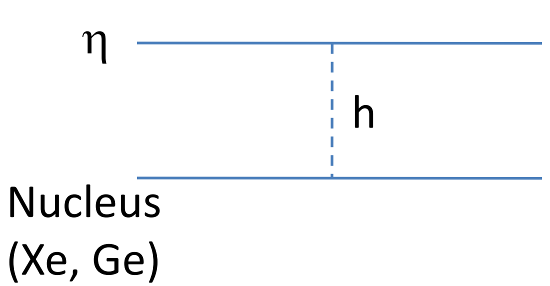
$B(h \rightarrow \eta\eta) = 50 \quad (37) \quad \%$

for $m_\eta = 48 \quad (57)$ GeV

Testable via the invisible Higgs decay at LHC and ILC

η from the halo can basically be detected

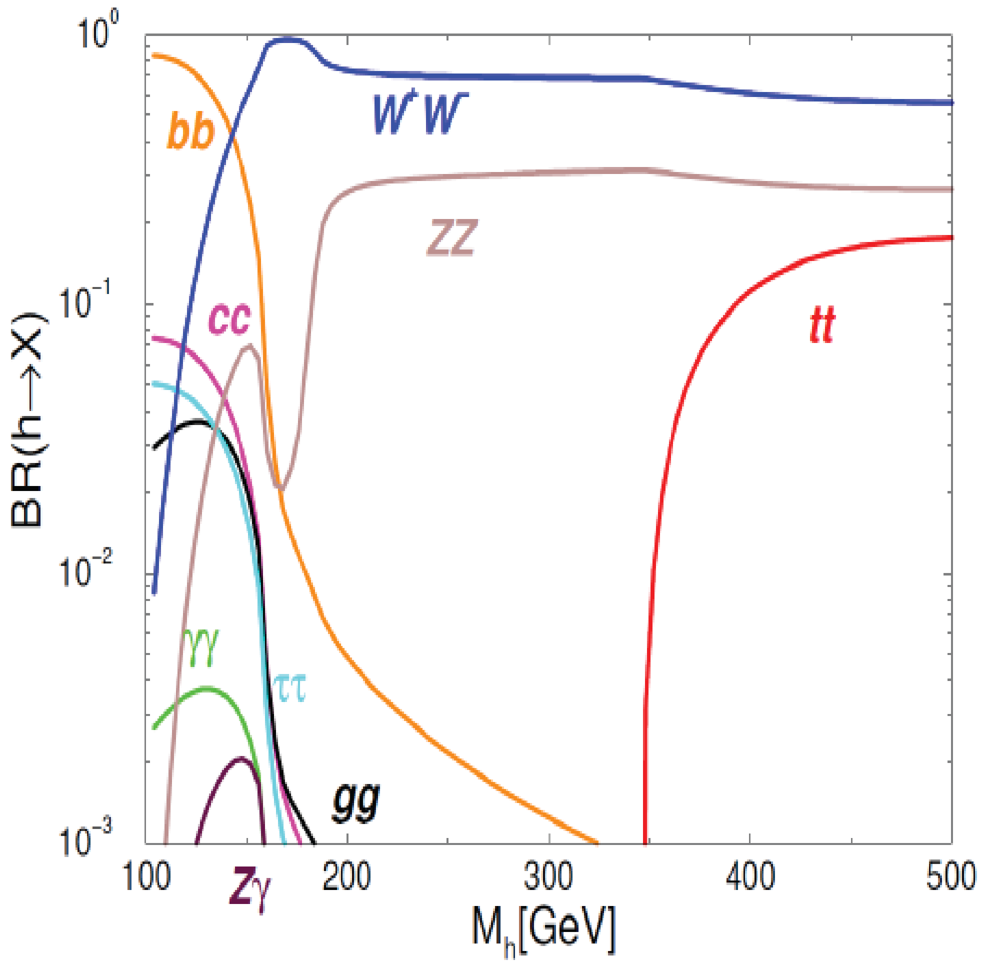
at the direct DM search (CDMS, XMASS)



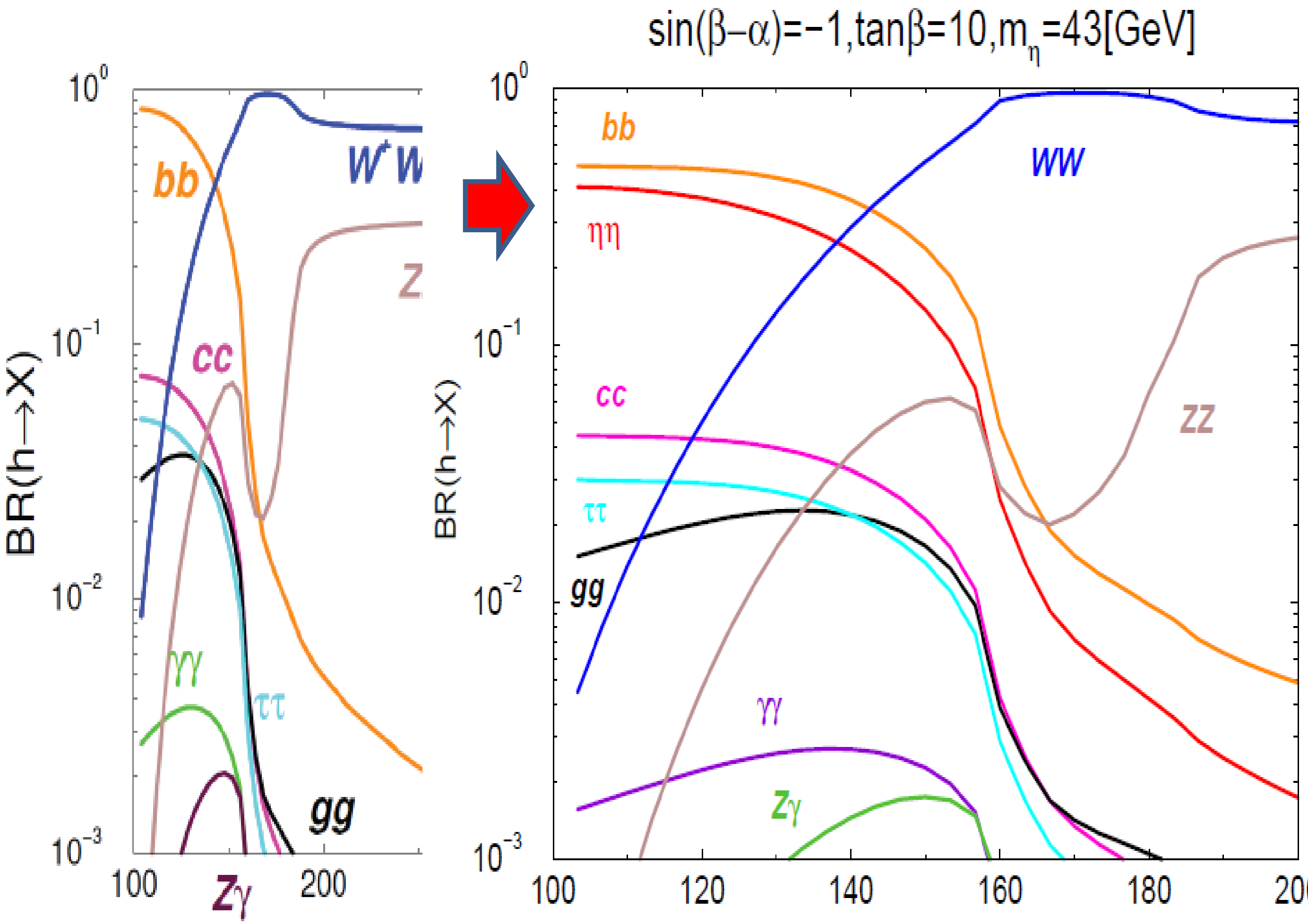
Observing the release energy

Branching ratios of the SM-lile Higgs boson h

SM



Branching ratios of the SM-lile Higgs boson h



Several times 10 % of invisible decay (h→ηη)

Non-Decoupling Property

Strong 1st OPT = non-decoupling prop.

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

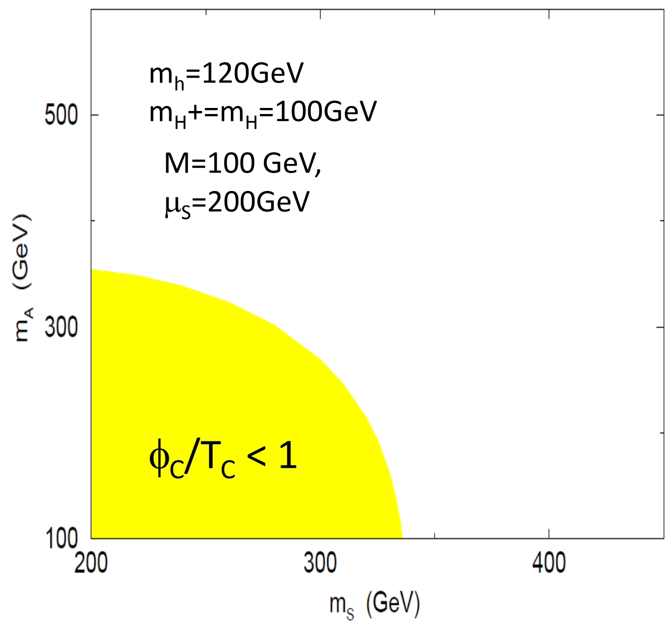
$m_A^2=M^2+(\lambda_4-\lambda_5)v^2/2$

$m_S^2=\mu_S^2+\lambda_S v^2$

When M^2, μ_S^2 (invariant masses) << $\lambda_i v^2$

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

DM abundances require $m_S > 400$GeV



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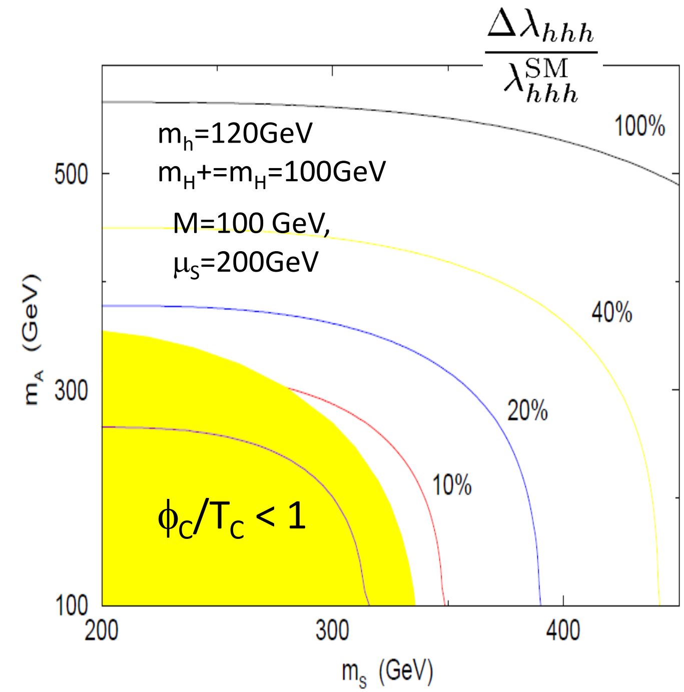
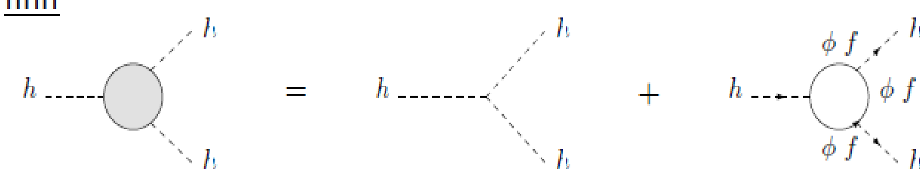
Large deviation in hhh coupling (> 20 %).



SK, Okada, Senaha

hhh



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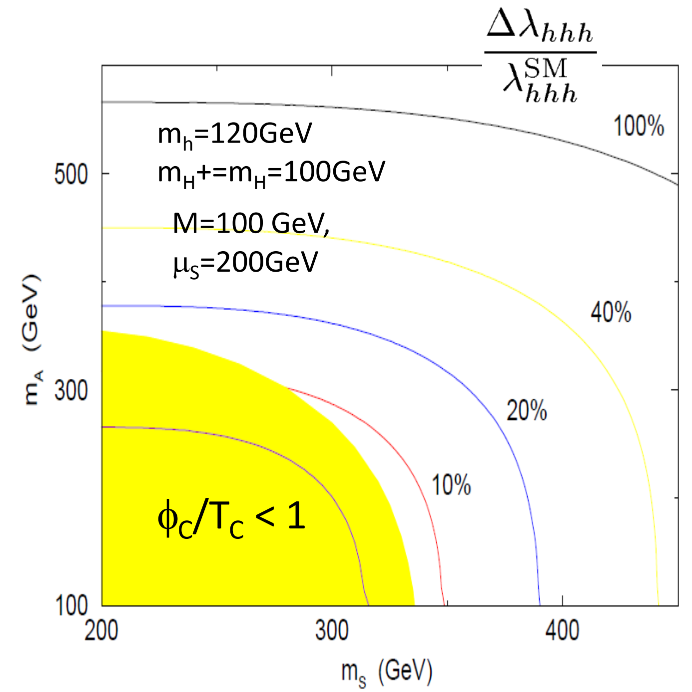
$$\frac{\varphi_c}{T_c}\left(=\frac{2E}{\lambda_{T_c}}\right) \gtrsim 1$$

$m_A^2 = M^2 + (\lambda_4 - \lambda_5)v^2/2$
$m_S^2 = \mu_S^2 + \lambda_S v^2$

When M^2, μ_S^2 (invariant masses) << $\lambda_i v^2$

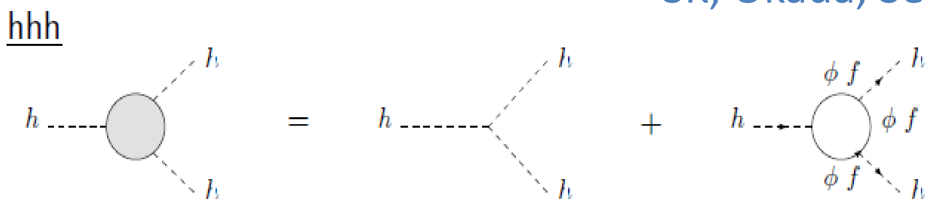
$$E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_A^3 + 2m_{S\pm}^3)$$

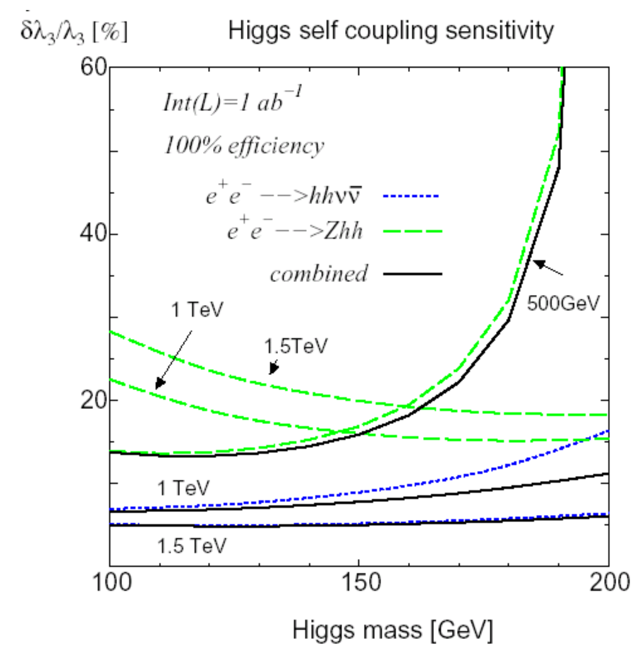
DM abundances require m_S > 400GeV



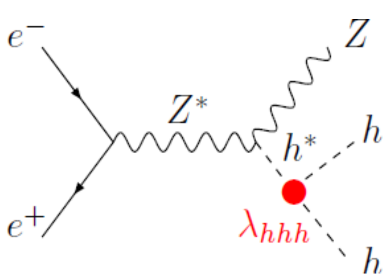
Large deviation in hhh coupling (> 20 %).

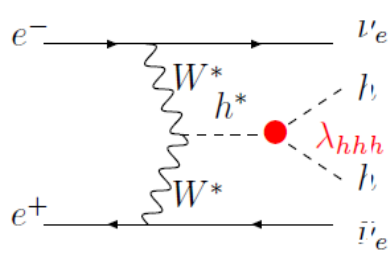
SK, Okada, Senaha





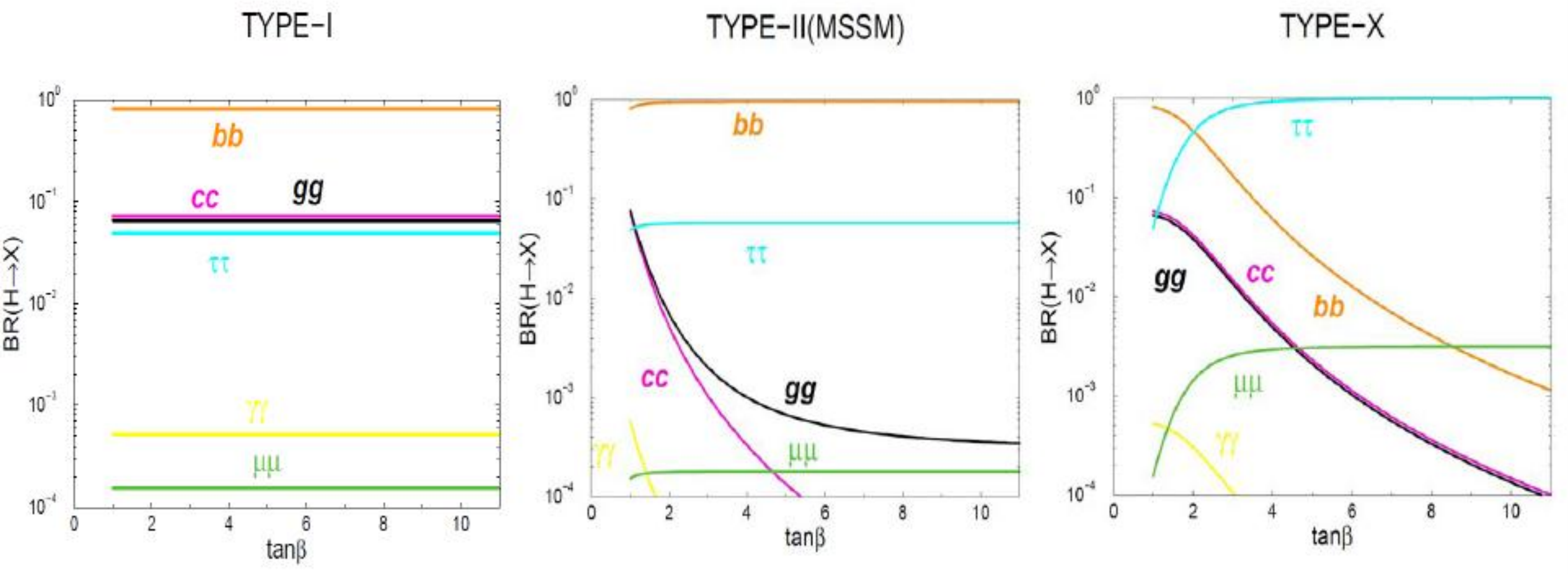
Testable at ILC?





H^0 (extra Higgs) decay

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks

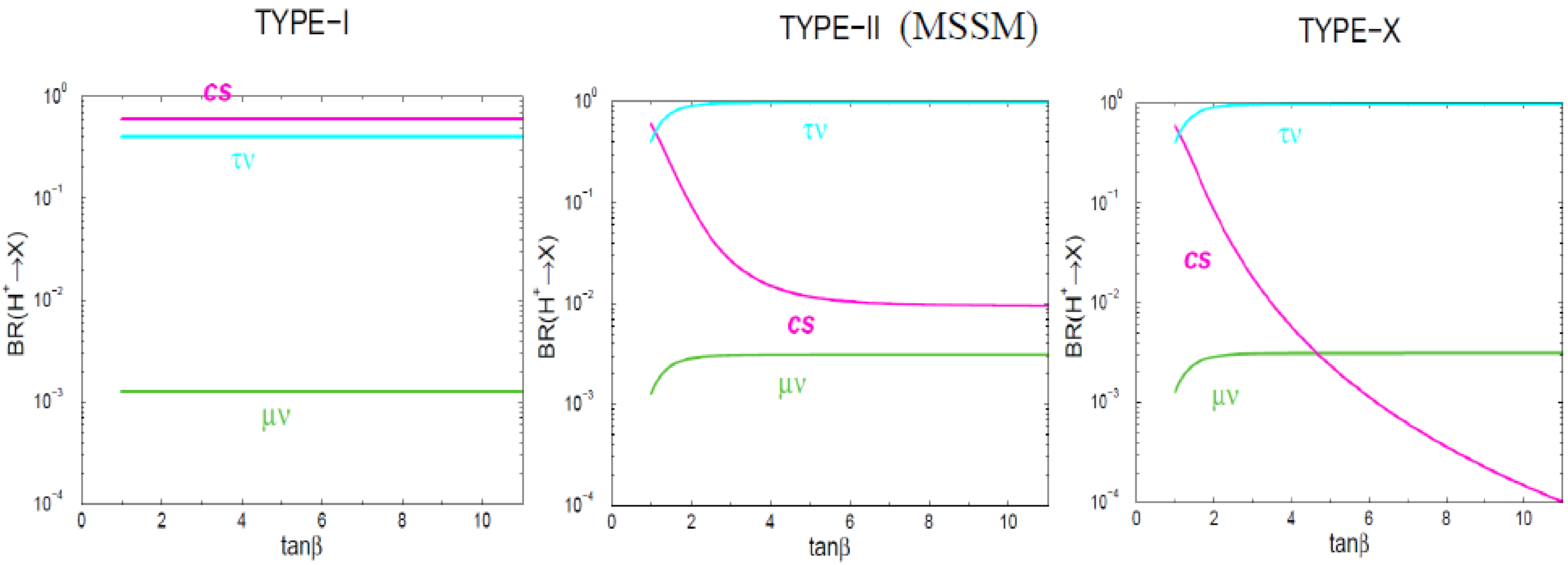


$M_H = M_{H+} = 130GeV$

H^+ (extra Higgs) decay

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks

$$M_H = M_{H+} = 130\text{GeV}$$



Light Higgs scenario: Production at the LHC

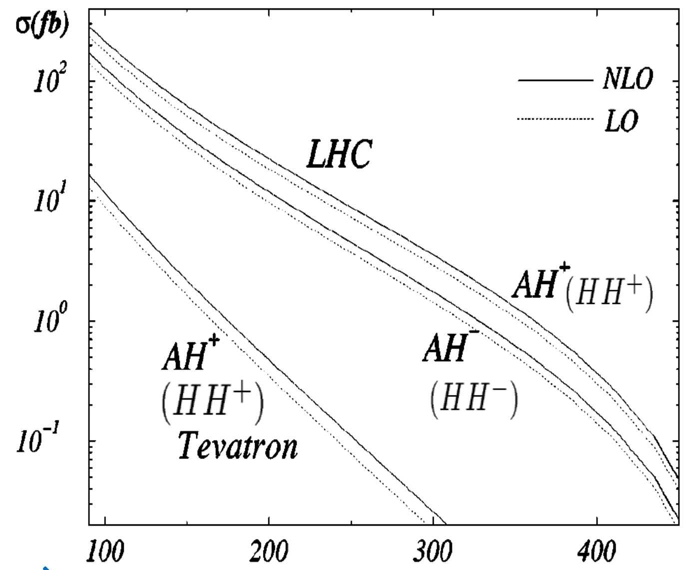
SK, Yuan
Cao, SK, Yuan
Baryaev et al

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

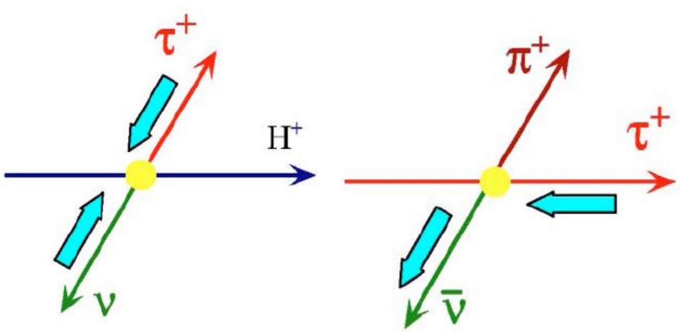
$$HH^{+} \to (\tau\tau)(\tau\nu)$$

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

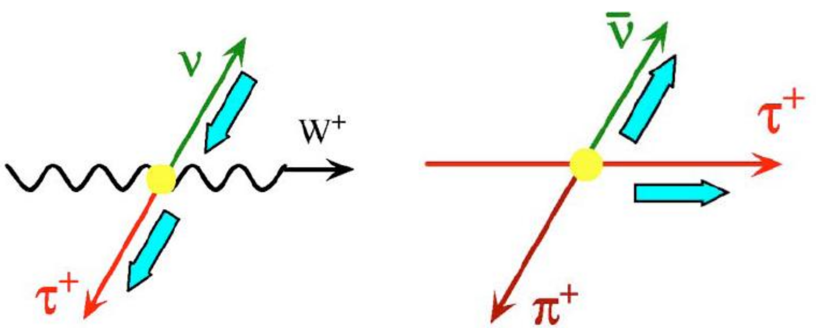
(MSSM) $pp \to AH^{+} \to (b\bar{b})\tau^{+}\nu \to (b\bar{b})(\pi^{+}\bar{\nu}\nu)$



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

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

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

Leptonic decay dominance of H, A, H^+

Type-X Yukawa

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

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

For $m_{H+} = m_H = 100$ GeV with $\sin(\beta - \alpha) = 1$, tanb=10

$m_A = 150$GeV, $E_{cm} = 500$GeV, $L = 500 fb^{-1}$

18000 $\tau\tau\tau\tau$ events

112 $\tau\tau\mu\mu$ events

0 $\mu\mu\mu\mu$ events

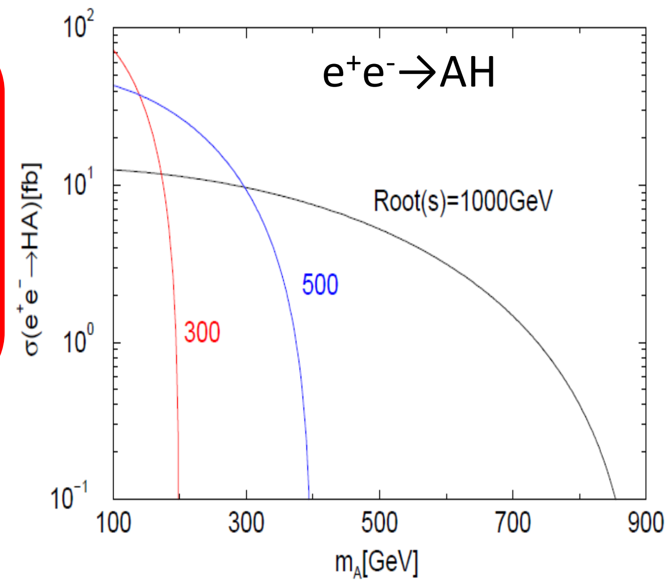
40000 $\tau\nu\tau\nu$ events

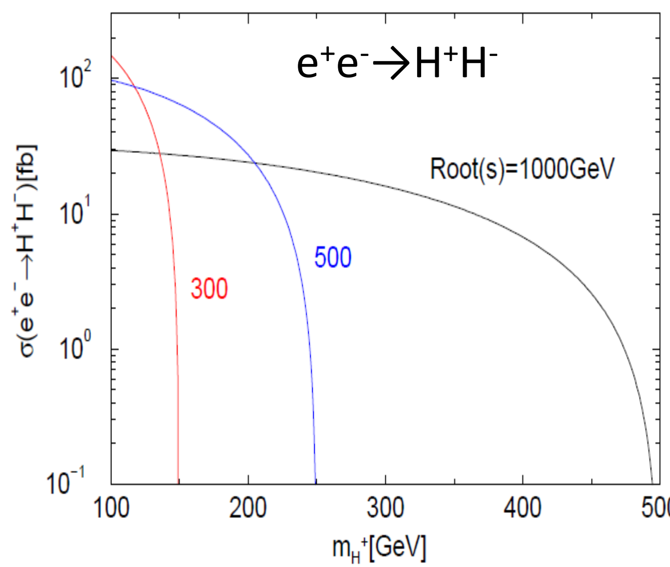
128 $\tau\nu\mu\nu$ events

0 $\mu\nu\mu\nu$ events

Testable at ILC?

Simulation study is necessary

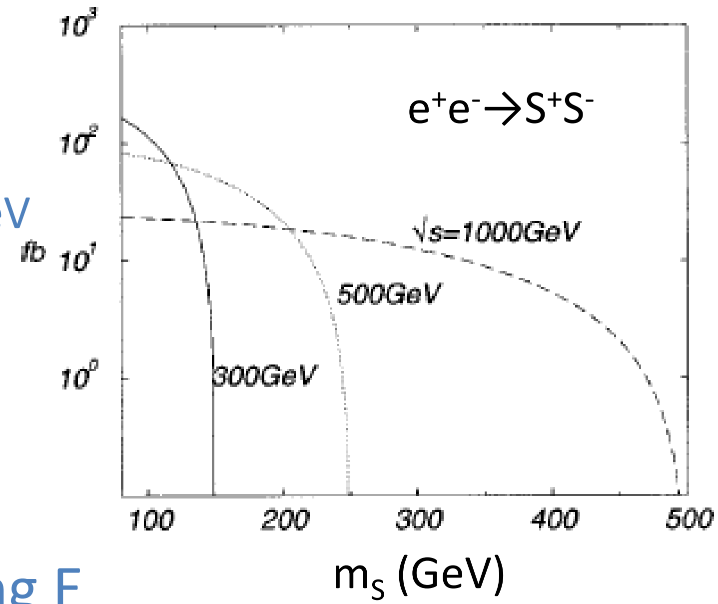




Z_2-odd charged scalar S^+

Produced in Pair

5fb for m_S=400GeV
at ILC 1000

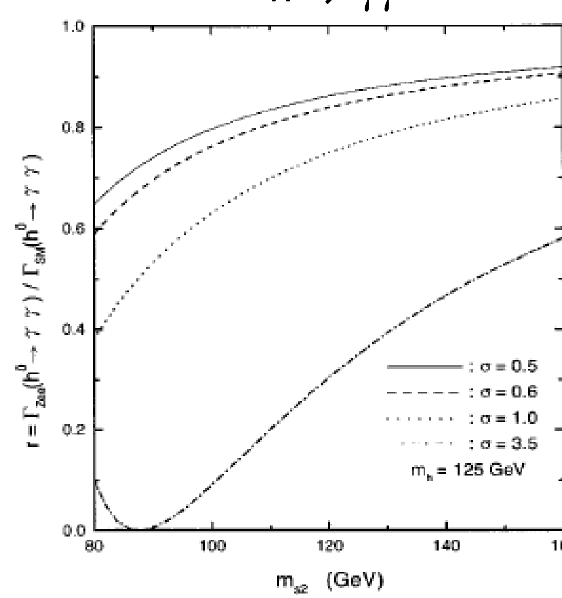


$$e^+e^- \to S^+S^-$$

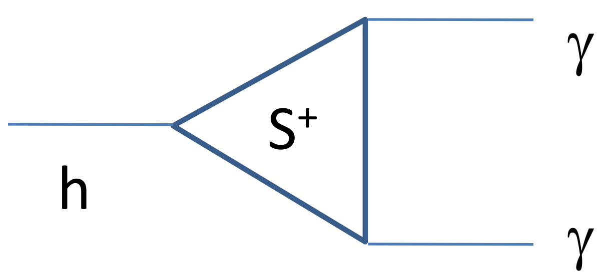
Signal be hard hadrons+ large missing E

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

h → γγ



Indirect quantum effect can be significant (hhh, hγγ)



SK, Lin, Kasai, Okada, Yuan

Summary for phenomena at ILC

- Invisible decay of the SM-like Higgs h.
- Mass spectrum

  Light H^+ (m_{H+} = 100 GeV), $m_{H+} = m_H$, sin(b-a)=1, etc
- Large deviation in the hhh coupling
- Enhanced 4 lepton events

  $e^+e^- \to AH \to \tau\tau\tau\tau$ ($\tau\tau\mu\mu$)
- Physics of Z_2-odd S^+

  Pair production and decay with large missing E

  Quantum effect on the $h\gamma\gamma$, hhh couplings

Summary

Phenomena of BSM

- Neutrino oscillation
- Dark Matter
- Baryon Asymmetry of the Universe (EWPT)

We proposed a model to solve them by

TeV-scale physics

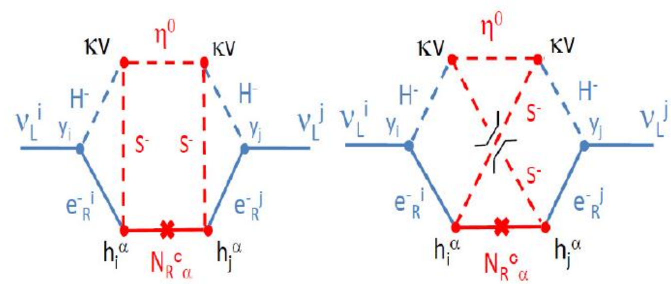
$\Phi_1, \Phi_2, \eta, S^+, N_R$

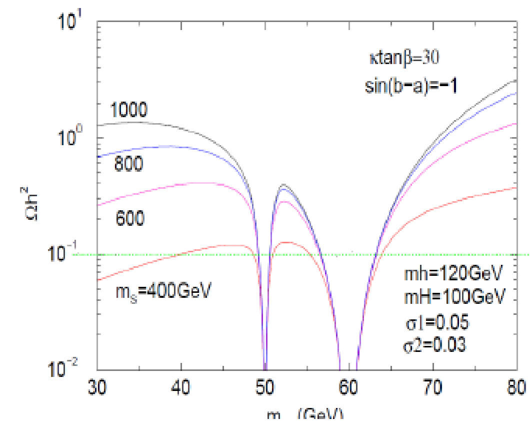
Predictions in Higgs physics and DM physics

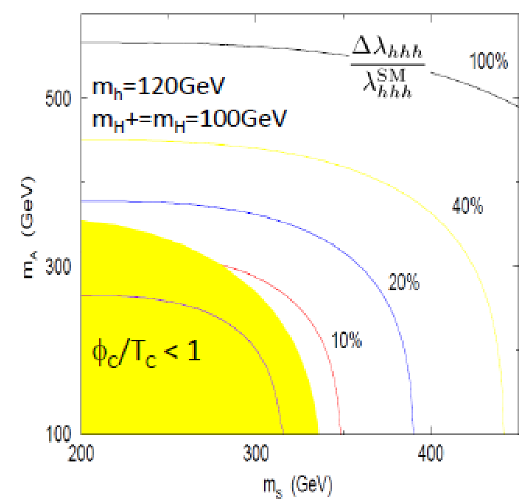
- Invisible decay of h
- Type-X Yukawa coupling
- Light H+ (H, S) scenario
- Non-decoupling property

Testable at experiments (LHC, ILC)

Further phenomenological study underway



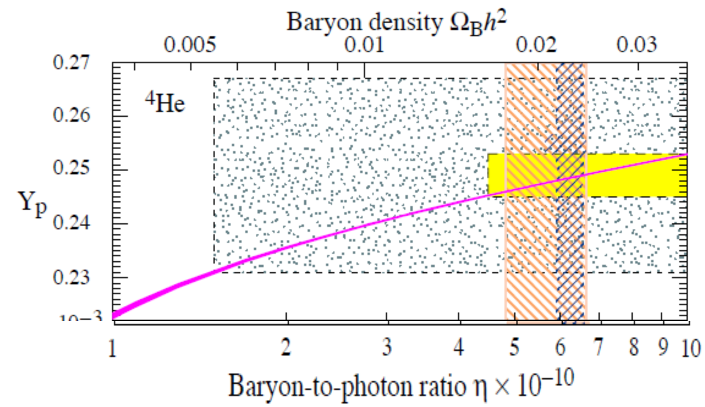




Back up slides

Electroweak Baryogenesis

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



Sakharov's conditions:

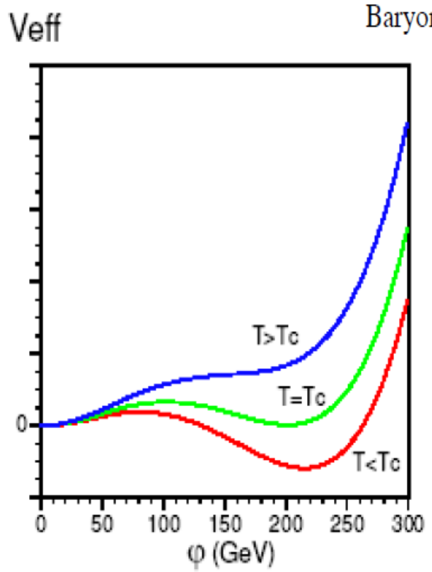
- Baryon number violation
- C, and CP violation
- Departure from thermal equilibrium

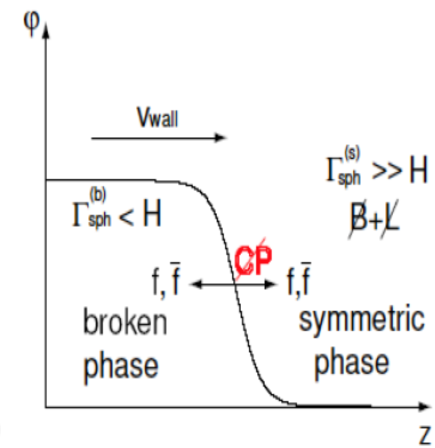
Strong 1st Order Phase Transition

= rapid sphaleron decoupling

in the broken phase

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





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

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

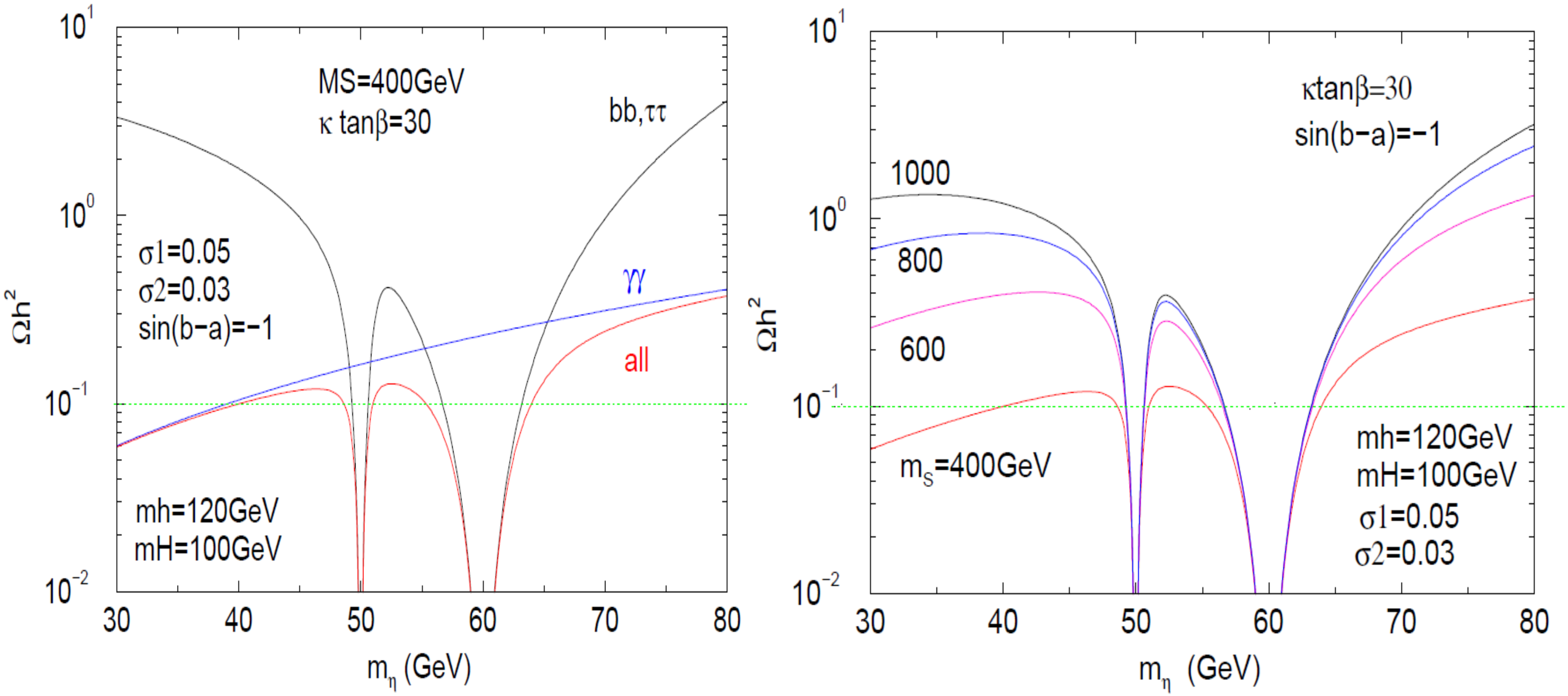
EW baryogenesis in 2HDM

Cohen, Kaplan, Nelson, 1991, ...

Cline, Kainulainen, Vischer 1996, ...

Fromme, Huber, Seniuch 2006

Thermal Relic Abundance of η^0



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

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.

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

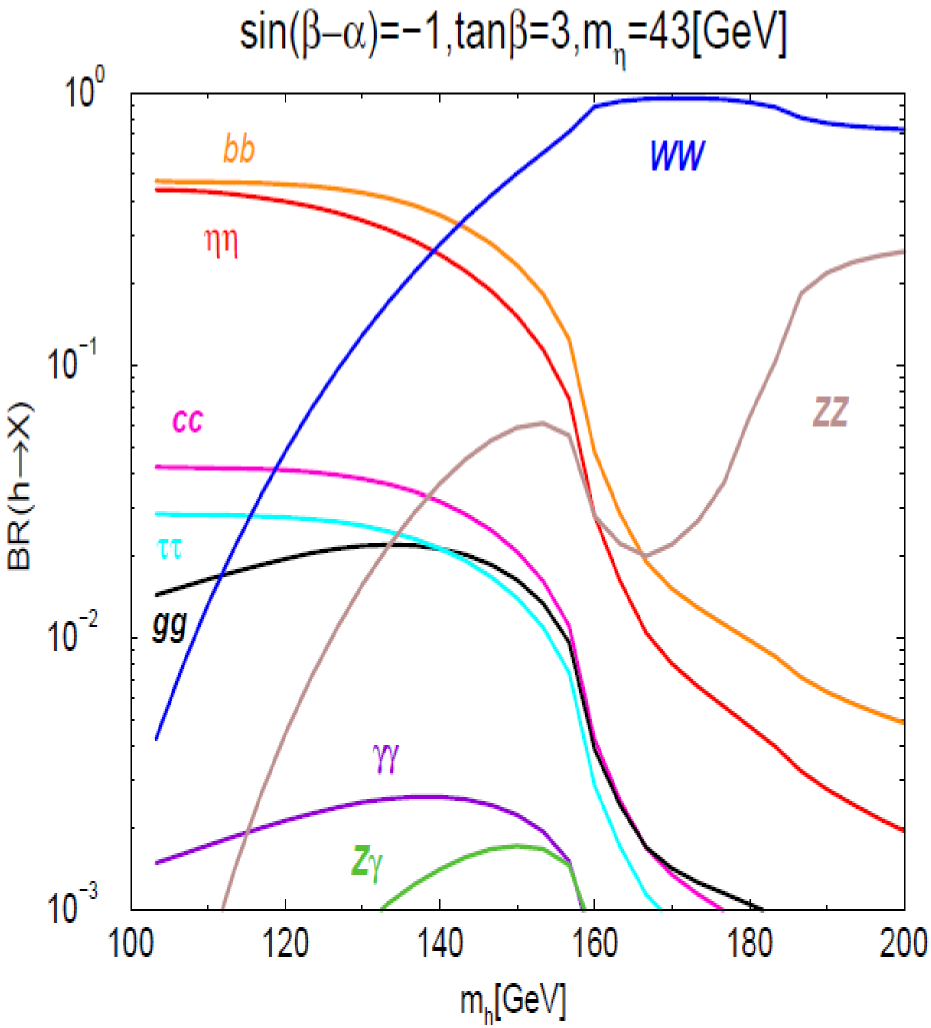
$$\begin{bmatrix} w_1^{\pm} \\ w_2^{\pm} \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^{\pm} \\ H^{\pm} \end{bmatrix}$$

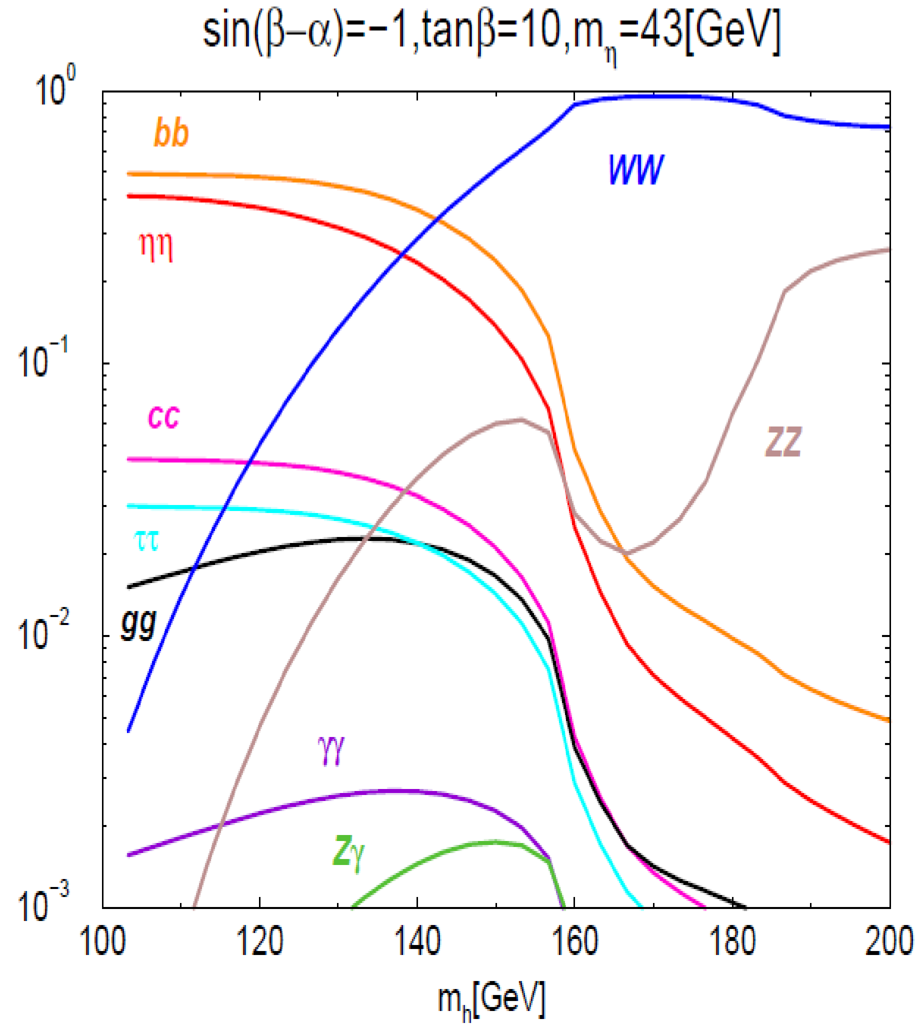
$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} \quad \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix}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

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

  Z_2-odd states
  - η, S^+, N_R^{α}

Branchin ratio of the SM-lile Higgs boson h





Numerical Evaluation

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