拡張ヒッグスセクターの物理

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Plan of Talk

[1] Introduction

[2] Physics of extended Higgs sector

[3] TeV-scale models for tiny neutrino masses
and dark matter without fine tuning

[4] Summary

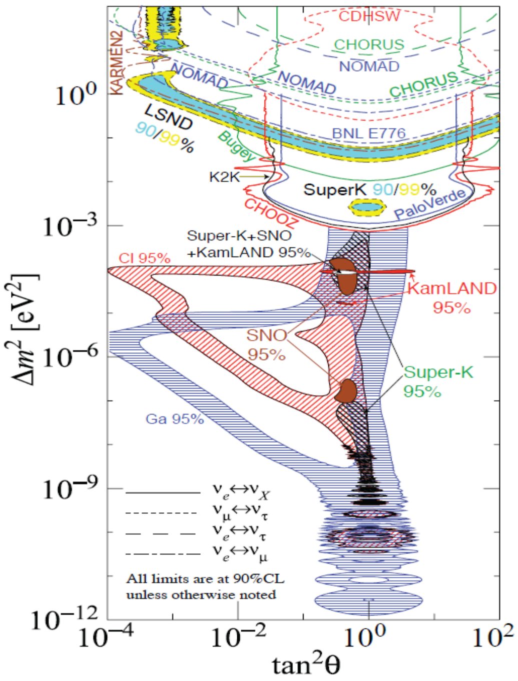
Introduction

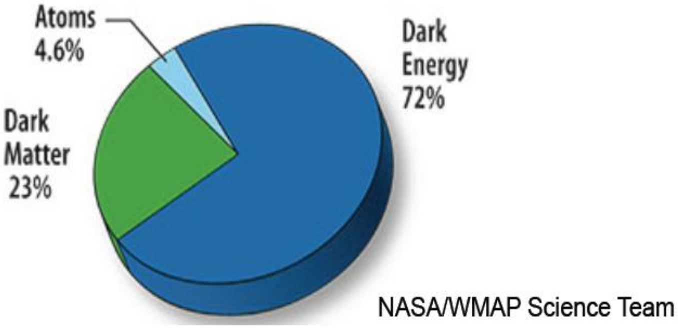
- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

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

    $\Omega_{DM} h^2 \sim 0.1$
  - Baryon Asymmetry of the Universe

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

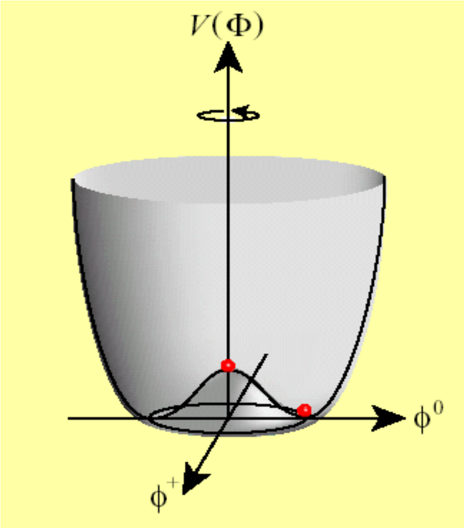




NASA/WMAP Science Team

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

Electroweak Symmetry Breaking



Nothing is known for Higgs sector!

- Anything to trigger EWSB: SU(2) × U(1) → U(1)
- Elementary Scalar? Dynamical?
- Scale of EWSB: 246GeV （Fermi Constant）

Higgs: Origin of Mass？

- Weak Gauge Boson （Higgs Mechanism）
- Quarks and Leptons （Yukawa Interaction）
- Mass of itself （Higgs Potential）
- [Neutrinos (Dirac? Seesaw? Radiative?)]
- [Dark Matter?]

In the SM, only a Higgs doublet field is responsible for all of them!

SM Higgs

Mass is a free parameter

$$\boxed{V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4}$$

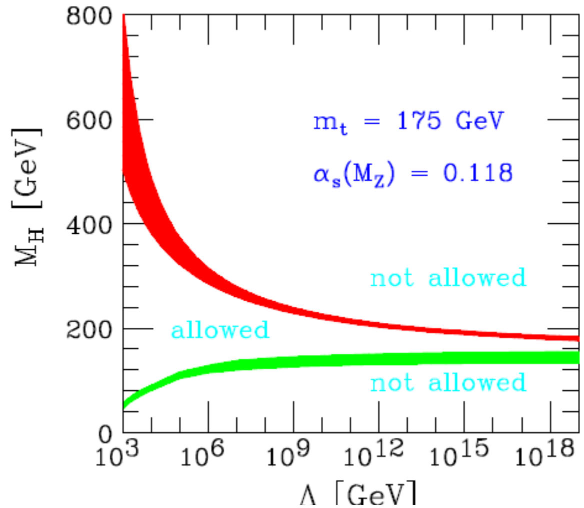
$$m_h^2 = 2\,\lambda\,v^2$$

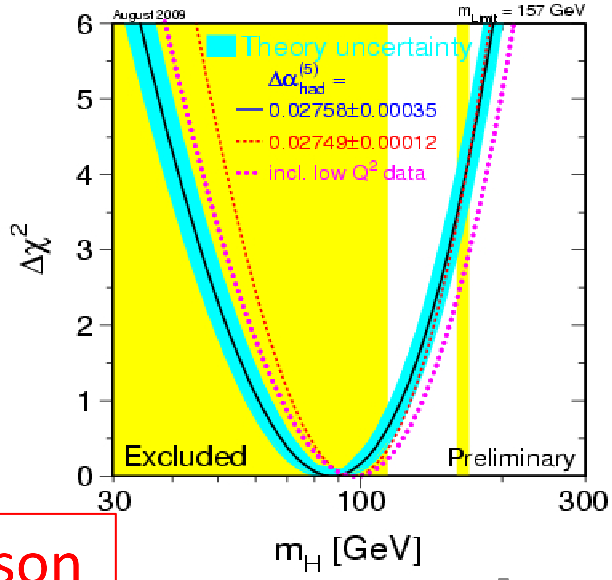
Relation to Λ (RGE)

- Light Higgs (weak : high Λ)
- Heavy Higgs (strong : low Λ)

Constraint from LEP, Tevatron

- 114 GeV < mh < 149 GeV allowed at 95%CL
- 158 GeV < mh < 175 GeV excluded (Tevatron)





Theory and experiment suggest a light Higgs boson

Heavy Higgs is excluded?

No!

A heavy (SM-like) Higgs is not excluded, if there is new physics

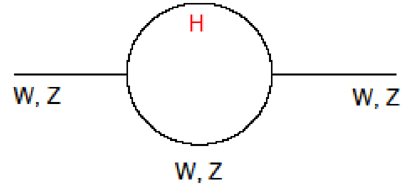
The upper bound comes from the loop effect of m_H.

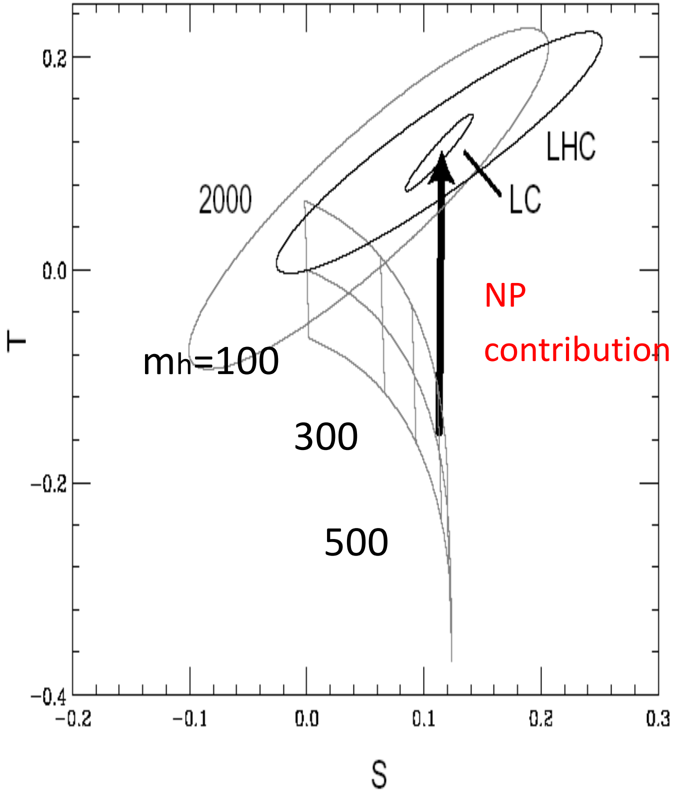
$$\Delta T_{\text{Higgs}} \simeq -\ln \frac{m_H^2}{M_W^2} \quad (\sim 0)$$

A heavy Higgs is possible by additional new physics loop contributions to the T parameter

Heavy Higgs: Signal of New Physics

Oblique Corrections





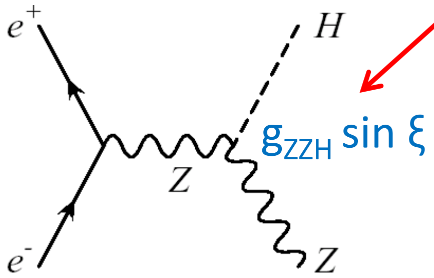
Mass lighter than 114GeV is excluded?

No!

It is always possible to relax the lower bound, if there is the mixing in multi-Higgs models

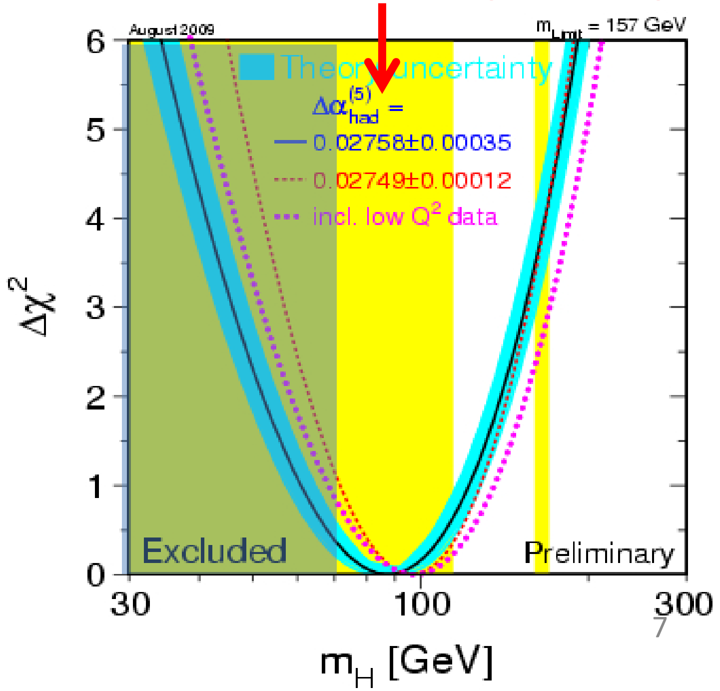
- SM + Singlet Higgs
- 2Higgs doublet model
- MSSM light Higgs scenario
- …

Multi-Higgs may be more natural from phenomenological view?



Coupling smaller by the mixing

Allowed in multi Higgs with Large Mixing



Non-minimal Higgs sector?

Many new physics models predict extended Higgs sectors

- SUSY, DSB, Little Higgs, …
- Extra CPV phases, First order phase transition
- Radiative Seesaw models

Each model has a specific (extended) Higgs sector

Higgs Sector = Window to New Physics

[2] Extended Higgs models

- If the Higgs sector contains more than one scalar bosons, possibility is
  - Extra singlets
  - Extra doublets
  - Extra triplets
  - ….
- What kind of experimental constraint we have?

  Most important quantities may be
  - Electroweak rho parameter
  - Flavor Changing Neutral Current (FCNC)

Electroweak rho parameter

$\rho_{exp} = 1.0008 ^{+0.0017}_{-0.0007}$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = \frac{\sum_i \left[4T_i(T_i+1) - Y_i^2 \right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

T_i : SU(2)$_L$ isospin

Y_i : hypercharge

v_i : v.e.v.

c_i : 1 for complex representation

1/2 for real representation

Possibility of ρ=1 (tree)

1. SM + doublets (D) + singlets（S）
2. SM + Triplets（T）
   a) $V_T << V_D$
   b) Combination of several representations $v_D \sim v_T$
      [(ex) D+T_0+T_2: Georgi-Machasek model]

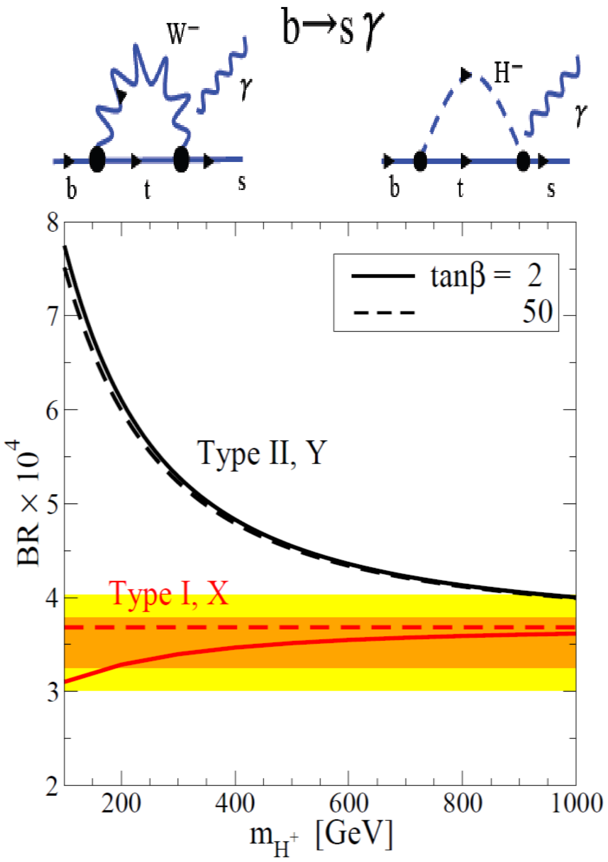
Muliti-doublets (+ singlets) are natural extension

FCNC Suppression

SM: FCNC via Z is suppressed by

GIM mechanism

Multi-Higgs models: FCNC via Higgs



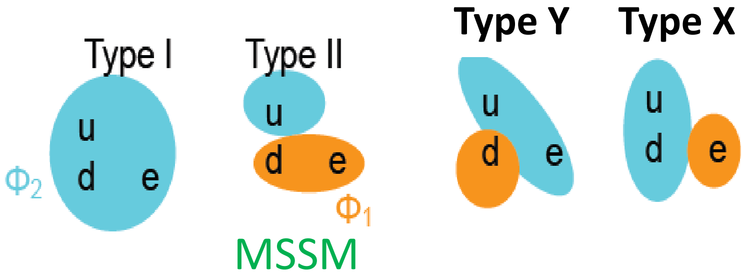
To avoid FCNC, impose a discrete symmetry

2HDM: $\Phi_1 \rightarrow +\Phi_1,$ $\Phi_2 = -\Phi_2$

Each quark or lepton couples only one of the Higgs doublets No FCNC at tree level!

Four types of Yukawa Interaction

$$\boxed{\mathcal{L}^{\rm THDM}_{\rm yukawa} = -\overline{Q}_L Y_u \widetilde{\Phi}_u u_R - \overline{Q}_L Y_d \Phi_d d_R - \overline{L}_L Y_\ell \Phi_\ell \ell_R + {\rm H.c.}}$$



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

2 Higgs doublet model (2HDM)

$$\begin{aligned} V_{\text{THDM}} = &+m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)} \\ &+\frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \\ &+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\text{h.c.})\right] \end{aligned}$$

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

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

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

$$\frac{v_2}{v_1} \equiv \tan\beta$$

Φ_1 and $\Phi_2 \Rightarrow \underline{h, \quad H,} \quad A^0, H^\pm \oplus$ Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

$$\begin{aligned} m_h^2 &= v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2} \sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right), \\ m_H^2 &= M_{\text{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda) \sin^2\beta \cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right), \\ m_{H^\pm}^2 &= M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2, \\ m_A^2 &= M_{\text{soft}}^2 - \lambda_5 v^2. \end{aligned}$$

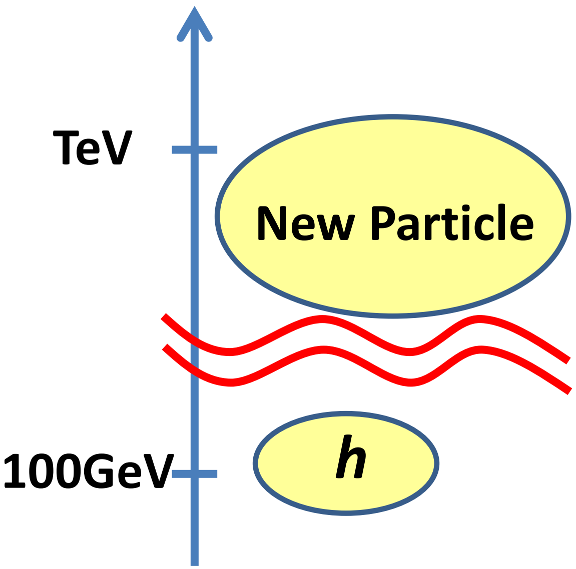
M_{soft}: soft breaking scale

$M_{\text{soft}} \quad \left(= \frac{m_3}{\sqrt{\cos\beta \sin\beta}}\right)$:

soft-breaking scale

of the discrete symm.

Decoupling/Non-decoupling



- Decoupling Theorem

  Appelquist-Carazzone 1975

  New phys. loop effect in observables

  $1/M^n \to 0$ (M→∞ : decouple)

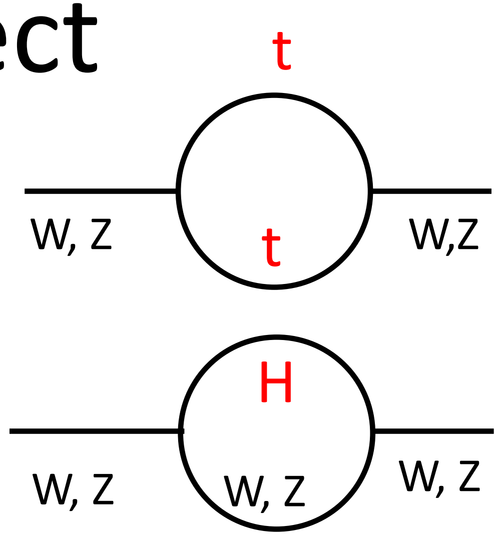
- Violation of the decoupling theorem
  - Chiral fermion loop (ex. top)

    $m_f = y_f v$
  - Boson loop (ex. H^+ in non-SUSY 2HDM)

    $m_\phi{}^2 = \lambda v^2 + M^2$ (only if $\lambda v^2 > M^2$)

  Non-decoupling effect

Non-decoupling effect



Example (Electroweak *T* parameter)

$$\rho = \frac{m_W}{m_Z \cos\theta_W}, \quad \Delta\rho = \rho - 1 = \alpha T$$

Data |*T*| < 0.1

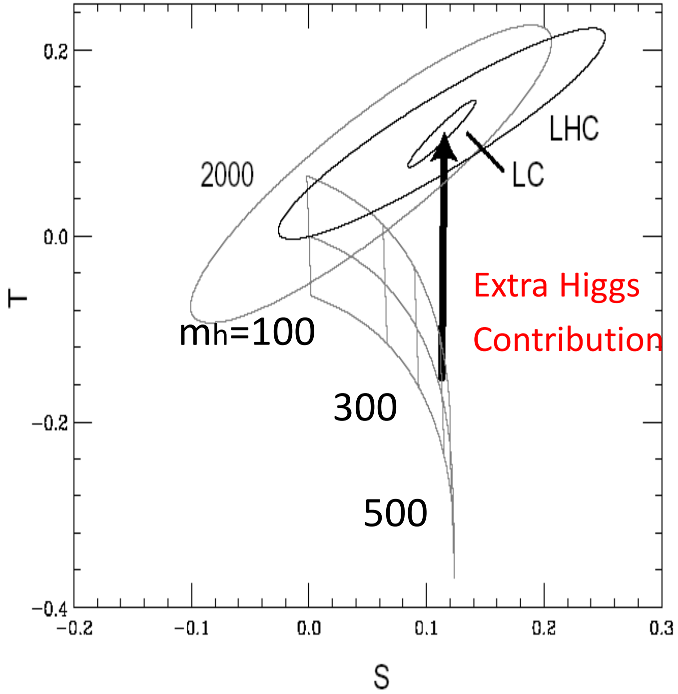
$$\Delta T_{\text{top}} \propto \boxed{\frac{m_t^2}{M_W^2}}$$

$$\Delta T_{\text{Higgs}} \simeq -\ln\frac{m_H^2}{M_W^2} \quad \text{(SM)}$$

$$\Delta T_{\text{Higgs}} \sim -\ln\frac{m_h^2}{M_W^2} + \boxed{\frac{(m_A^2 - m_{H^\pm}^2)^2}{M_W^2 m_A^2}}$$

(2HDM)

Quadratic mass contribution
(non-decoupling effect)



Higgs potential

To understand the essence of EWSB, we must know the self-coupling in addition to the mass independently

$$\boxed{V_{\text{Higgs}} = \frac{1}{2}\underline{m_h^2} h^2 + \frac{1}{3!}\underline{\lambda_{hhh}} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots}$$

Effective potential $V_{\text{eff}}(\varphi) = -\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{4}\varphi^4 + \sum_f \frac{(-1)^{2s_f} N_{C_f} N_{S_f}}{64\pi^2} m_f(\varphi)^4 \left[\ln\frac{m_f(\varphi)^2}{Q^2} - \frac{3}{2}\right]$

Renormalization Conditions

$$\left.\frac{\partial V_{\text{eff}}}{\partial\varphi}\right|_{\varphi=v} = 0, \quad \left.\frac{\partial^2 V_{\text{eff}}}{\partial\varphi^2}\right|_{\varphi=v} = m_h^2, \quad \left.\frac{\partial^3 V_{\text{eff}}}{\partial\varphi^3}\right|_{\varphi=v} = \lambda_{hhh}$$

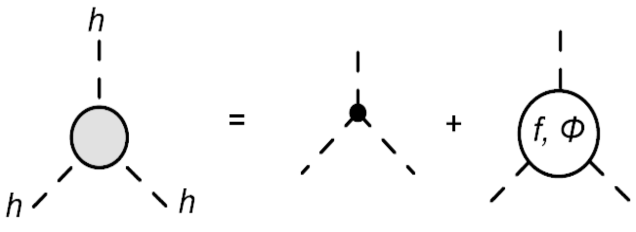
SM Case

$$\boxed{\lambda_{hhh}^{\text{SMloop}} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)}$$

Non-decoupling effect

Case of the non-SUSY 2HDM

- Consider when the lightest *h* is SM-like [sin(β–α)=1]
- At tree, the *hhh* coupling takes the same form as in the SM
- At 1-loop, non-decoupling effect $m_\Phi{}^4$ (If $M < v$)



$\Phi = H, A, H^\pm$

SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

Case of the 2HDM:

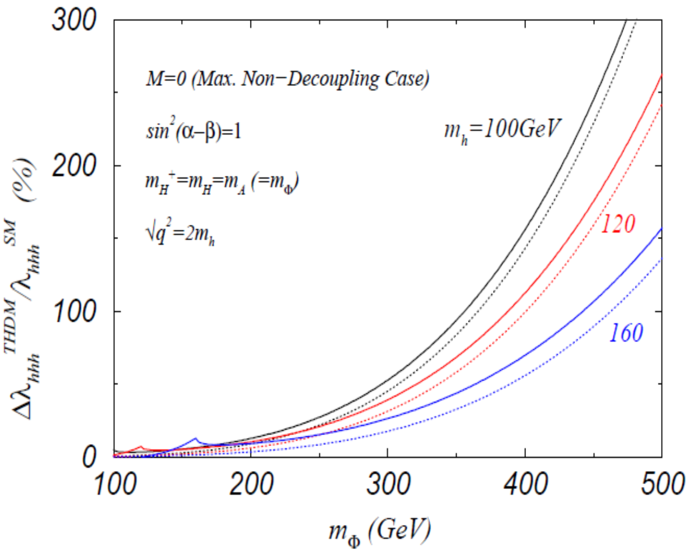
$$\boxed{\lambda^{\mathrm{2HDM}}_{hhh} \simeq \frac{3m_h^2}{v}\left[1+\underline{\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3} - \underline{\frac{m_t^4}{\pi^2 v^2 m_h^2}}\right]}$$

Extra scalar loop **Top loop**

$$m_\Phi^2 = M^2 + \lambda_i v^2$$

$\Phi = H, A, H^\pm$

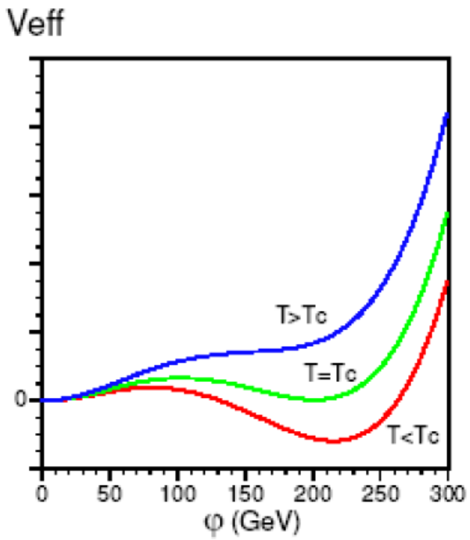
Correction can be huge ∼ 100%

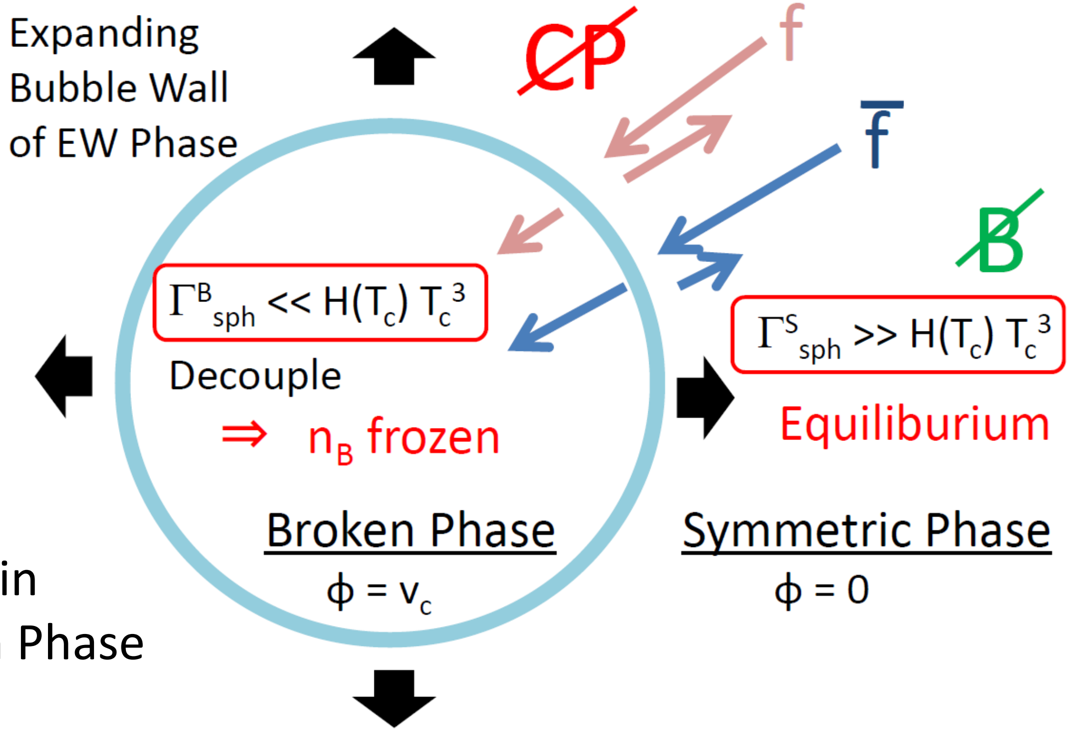


Electroweak Baryogenesis

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




Expanding Bubble Wall of EW Phase

$\cancel{CP}$

f

$\bar{f}$

$\cancel{B}$

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

Decouple

⇒ n_B frozen

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

Equiliburium

Broken Phase

$\phi = v_c$

Symmetric Phase

$\phi = 0$

Quick sphaleron decoupling to retain sufficient baryon number in Broken Phase

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

Electroweak Baryogenesis and the *hhh* coupling

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

$$\phi_c/T_c = 2E/\lambda_{T_c}$$

$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$+ New Phys. Effect

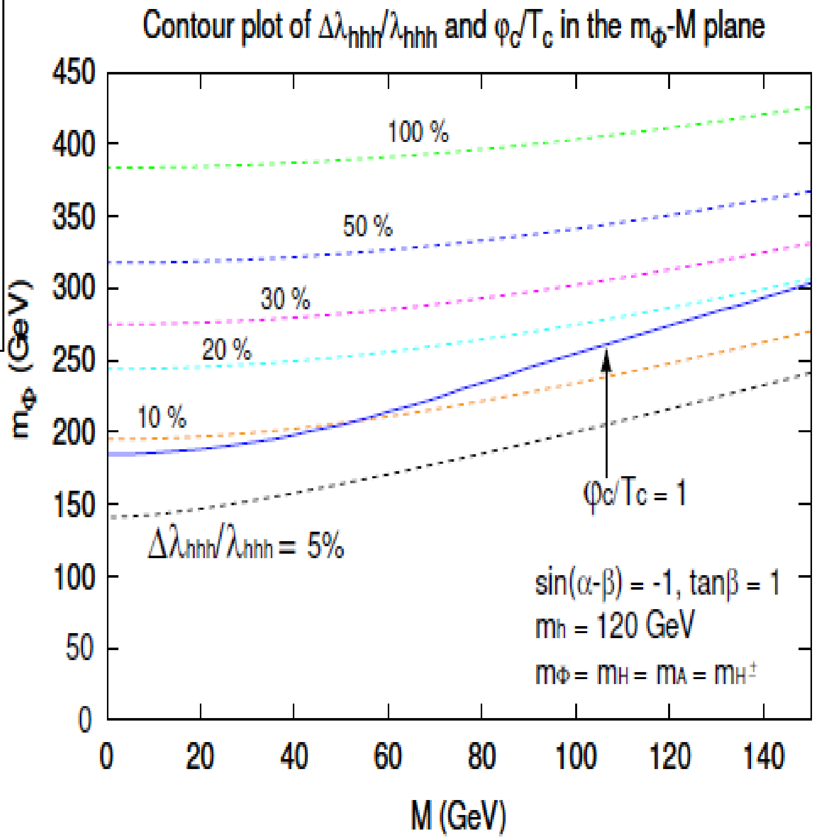
$\lambda_T = m_h^2/2v^2$ + log corrections

$$\boxed{\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1}$$

SM: $m_h < 60$GeV Excluded by LEP

2HDM: m_h =120GeV Possible due non-decoupling effect

Strong 1st OPT ⇔ Large *hhh* coupling



SK, Okada, Senaha (2004)

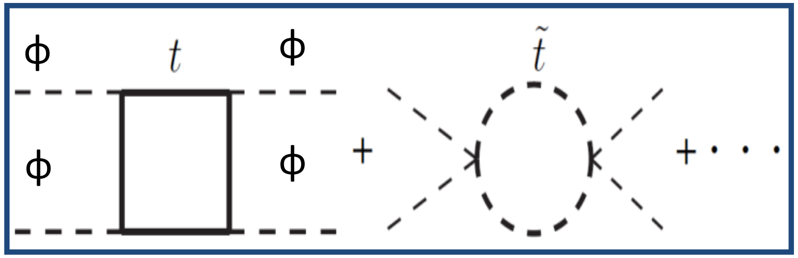
Mass of *h* in the MSSM

MSSM

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta m_{\text{loop}}^2$$

↑

D-term



$$\delta m_{\text{loop}}^2 \simeq \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4} + \frac{3m_t^2 X_t^2 \sin^2\beta}{4\pi^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)} \ln \frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}$$

m_h < 120-130GeV

If no Higgs found below 140 GeV at the LHC?

- At the LHC, the Higgs search is underway.
- If no Higgs is found below 140 GeV, probably we must discard the MSSM.
  - *Q: Shall we abandon the low scale SUSY ?*
  - *A: Maybe No.*

Next-to-MSSM

Two Higgs doublets H_u, H_d and a singlet S

$$\boxed{W = \lambda_{HHS} H_u H_d S - \kappa S^3}$$

μ problem
may be solved

Mass of the lightest h in the NMSSM

$$m_h^2 \simeq m_Z^2 \underset{\substack{\uparrow \\ \text{D-term}}}{\cos^2} 2\beta + \underbrace{(\lambda_{HHS}^2 v^2/2)\sin^2 2\beta}_{\substack{\uparrow \\ \text{F-term}}} + \delta m_{\mathrm{loop}}^2$$

What is the size of λ_{HHS}?

RGE analysis with a cut-off scale Λ

Λ : GUT scale → λ ~ 0.75 (m_h~ 140 GeV)

Λ : TeV scale → λ ~ 2.5 (m_h~ 450 GeV)

Fat Higgs model

Harnik, Kribs, Larson, Murayama

Composite H_1, H_2, N

A UV complete theory

At low energy, a strong NMSSM

$$W = \lambda(N H_1 H_2 - v_0^2)$$

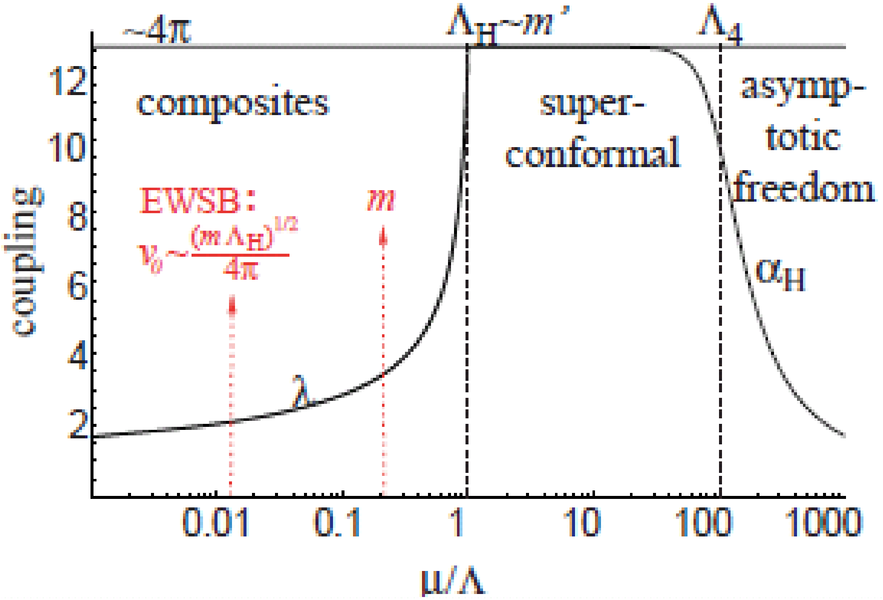
The SM-like Higgs can be heavy

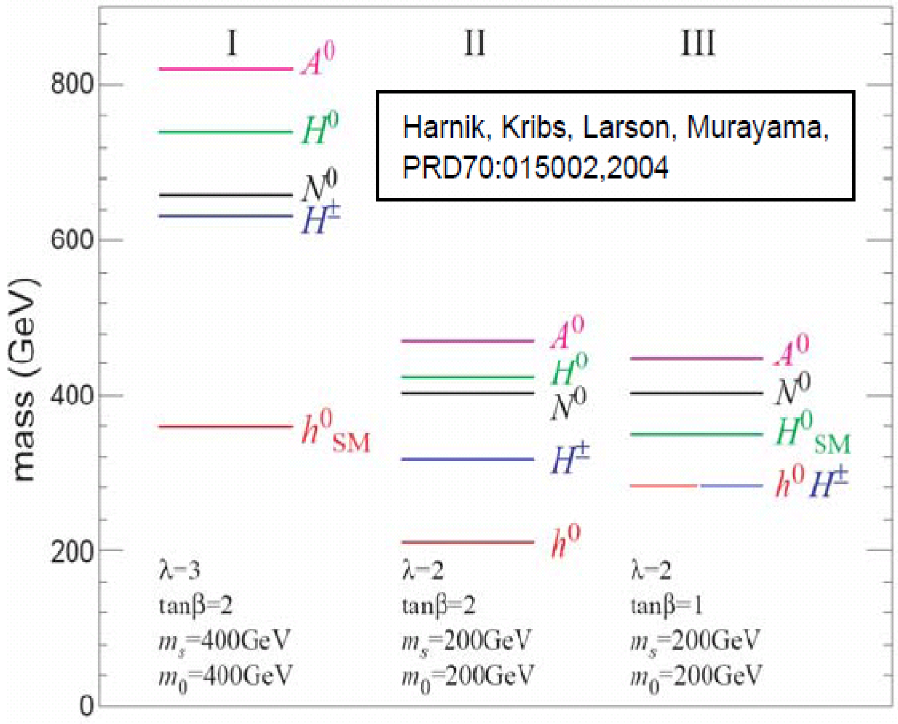
$$m_h^2 \simeq \lambda^2 v^2 + \mathcal{O}(m_Z^2)$$

$$M_{H^\pm}^2 = M_A^2 - \lambda^2 v^2$$

λ can be of O(1)

⇔ $m_h > 200$ GeV



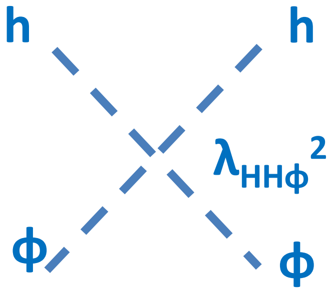

Harnik, Kribs, Larson, Murayama, PRD70:015002,2004

Variation of SUSY Higgs sectors

- The mass of the lightest Higgs boson *h* is a good tool to discriminate the SM, MSSM, NMSSM.
- The *hhh* coupling can also be important
- How about the other possibility of extended SUSY Higgs sectors?
  - MSSM+χ (χ : triplet) [Type-II Seesaw]
  - 4HDM+Ω (Ω: charged singlet) [Super Zee-Model]
- See prediction on m_h and λ_{hhh}

(*h*: Lightest Higgs (SM-like))

F-term contributions to m_h and the hhϕϕ coupling



F-term: $$V_F = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2$$

(ϕ$_i$: Scalar component of
a chiral superfield)

ϕ: Chiral Superfield which generates F-term

$$\boxed{\begin{aligned} &W \supset \lambda_{H_i H_j \phi} H_i H_j \phi, \quad i,j = u,d \\ &\to V_F = \lambda^2_{H_i H_j \phi} |H_i H_j|^2 + \lambda^2_{H_i H_j \phi} |H_i \phi|^2 + \cdots \end{aligned}}$$

Candiate of ϕ: S, $\Omega_\pm$, ξ, $\chi_\pm$

S, ξ, $\chi_\pm$: Both m_h & $\lambda_{hh\phi\phi}$ large

→ **large m_h**

$\Omega_\pm$: Only $\lambda_{hh\phi\phi}$ large

→**non-decoupling hhh**

$$\Delta\lambda^{\rm Model}_{hhh}/\lambda^{\rm SM}_{hhh} \simeq \frac{m_\phi^4}{12\pi^2 v^2 m_h^2}\left(1-\frac{M_\phi^2}{m_\phi^2}\right)^3$$

For doublet-doublet-Ω coupling $H_u \cdot H_{u'}$Ω+

(4 doublets needed, because of $H_u \cdot H_u = 0$)

m_h-$\Delta\lambda_{hhh}$ plot (tanβ = 1-50)

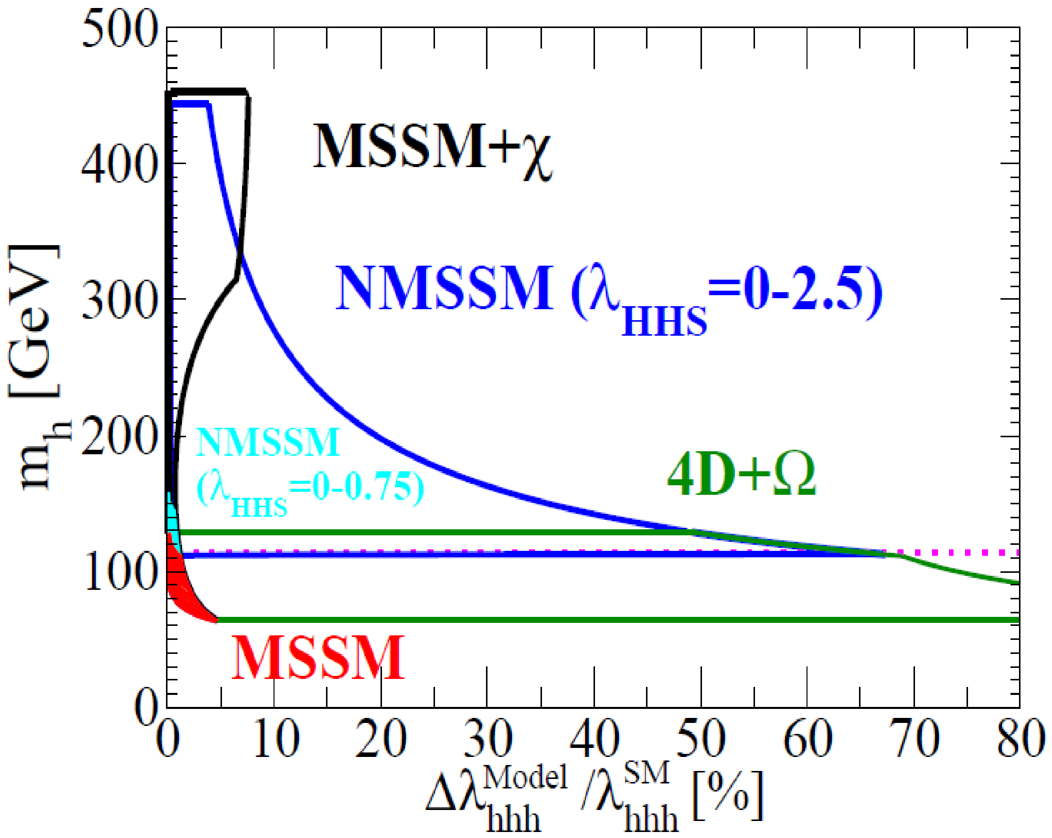
MSSM

NMSSM (Extra Neutral Singlet)

MSSM+χ (Triplet)

4D+Ω (Charged Singlet)

Even when only *h* is found, SUSY Higgs sectors can be tested by measuring the mass of *h* and the *hhh* coupling



SK, Shindou, Yagyu (2010)

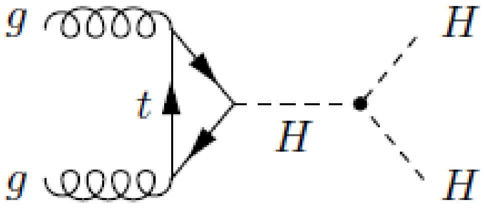
We want O(10) % determination of the *hhh* coupling!

HHH measurement at LHC and ILC

LHC

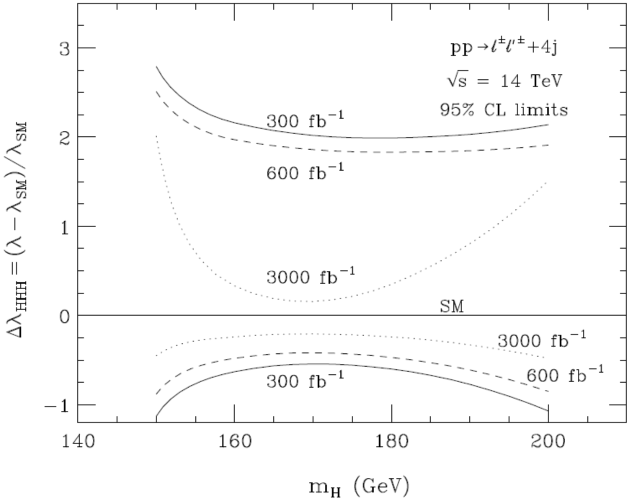
LHC, SLHC (3000fb^{-1})

Hopeless for mH < 140GeV

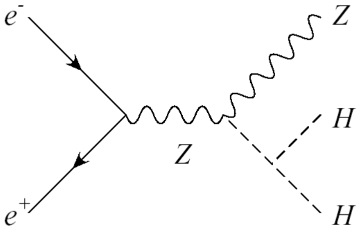


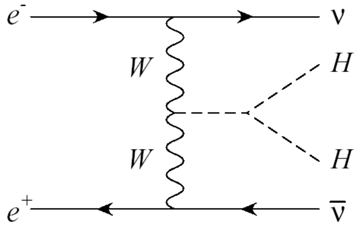
$pp \rightarrow HH \rightarrow W^+W^-W^+W^- \rightarrow l^+l^-\ 4\ j$

Bauer, Plehn, Rainwater 2003

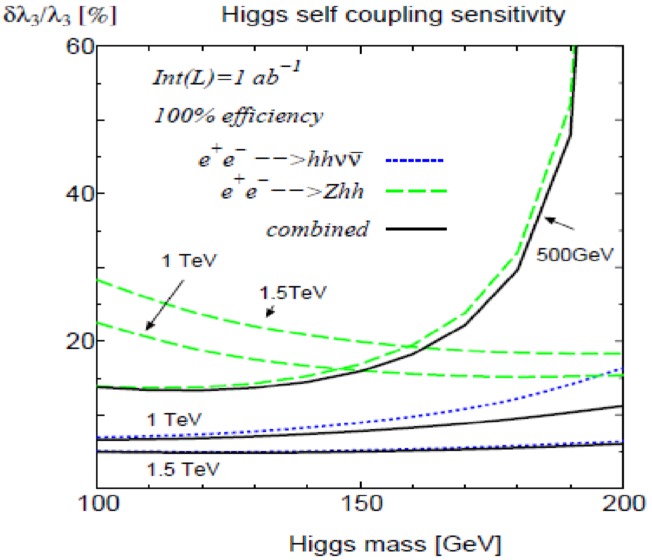


ILC





10-30 % may be expected. Simulation underway



Precision measurement of the *hhh* coupling is business of the ILC.

[3] Neutrino mass, DM, Baryon asymmetry and EWSB

Phenomena which cannot be explained in SM

- Neutrino Mass
- Dark Matter
- Baryon Asymmetry of Universe

How we can explain these problems?

2 possibilities

1) Scenario dependent on very high scales
    - Maybe compatible with canonical GUTs
    - Large mass hierarchy
    - A direct link to the GUT or Planck Scale?
    - Too high to be tested

2) Scenario due to the TeV scale physics
    - Renormalizable theory at the TeV scale
    - No large hierarchy among mass scales
    - Strong connection to EWSB
    - Testable at collider experiments

BSM: Neutrino Mass

Neutirno Mass Term (= Effective Dim-5 Operator)

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

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

Mechanism for tiny masses: $m^{\nu}{}_{ij} = (c_{ij}/M)\ v^2 < 0.1\ \mathrm{eV}$

Seesaw (tree level)

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

Quantum Effects

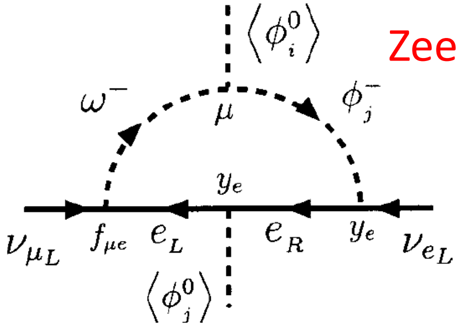
$m^{\nu}{}_{ij} = C_{ij}\ [1/(16\pi^2)]^m\ v^2/M$ loop suppression

Higher dim operator (dim 5+2N)

$m^{\nu}{}_{ij} = C_{ij}\ [v/M]^{2n}\ v^2/M$ $[v/M]^2$ suppression

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

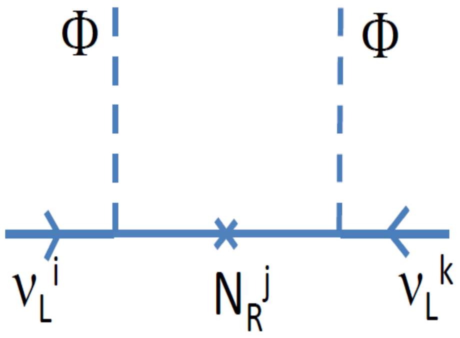
- Tiny ν-Masses come from loop effects
  - Zee (1980)
  - Zee, Babu (1988)
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), …..



- Merit
  - Super heavy particles are not necessary

    Size of tiny m_ν can naturally be deduced

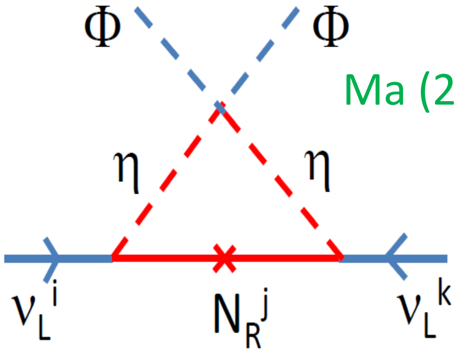
    from TeV scale by higher order perturbation
  - Physics at TeV: Testable at collider experiments



Yanagida;
Gell-Mann;
Minkowski

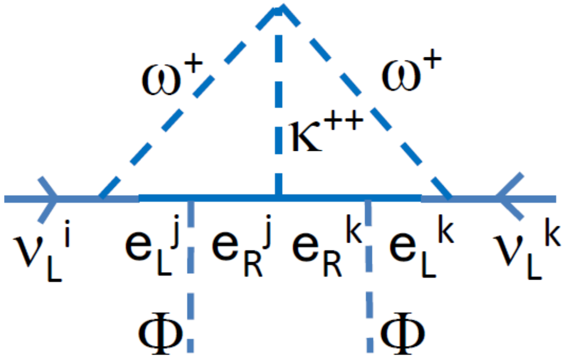
(*m*, *n*)=(0, 0)

Ma (2006)



(1, 0)

Zee; Babu

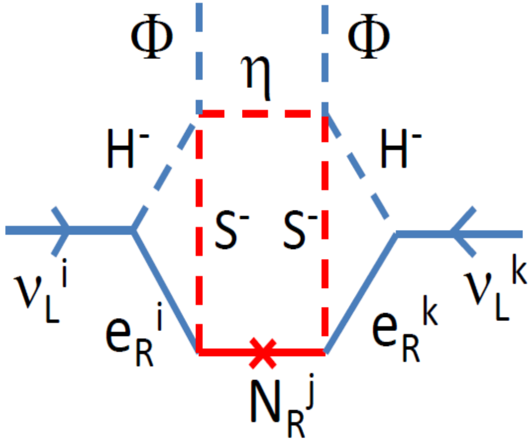


(2, 0)

$$m_\nu \sim c' \left(\frac{1}{16\pi^2}\right)^m \left(\frac{v}{\Lambda}\right)^{2n+1} v.$$

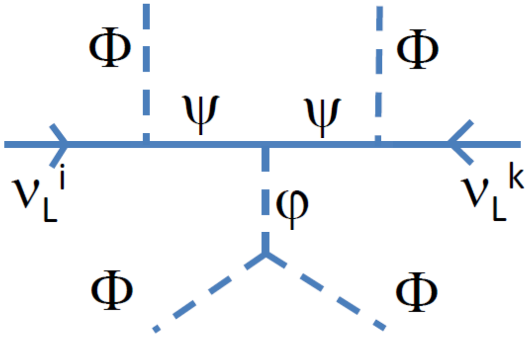
Dim 5+2*n* Operator
m-loop induced

Aoki, SK,
Seto (2008)



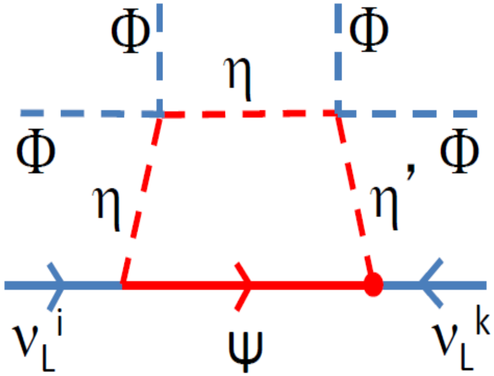
(3, 0)

Bonnet, et al. (2009)



(0, 1)

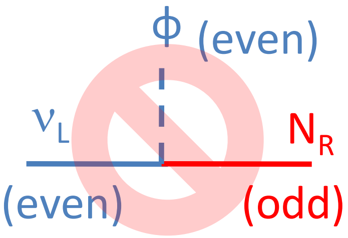
SK, Ota (2010)

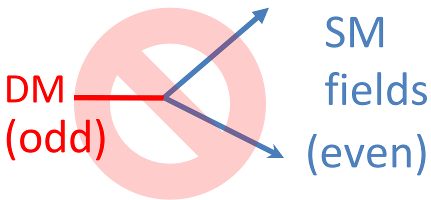


(1, 1)

Radiative Seesaw with Z_2

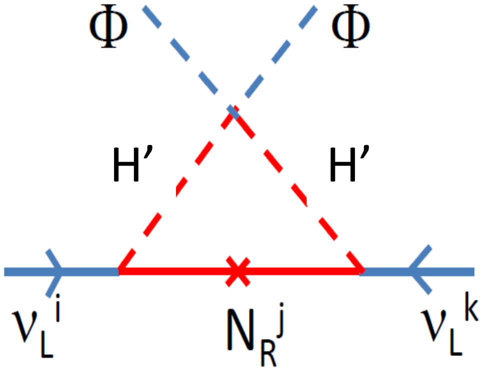
To forbid the tree neutrino Yukawa coupling, a Z_2 parity is imposed.
Lightest Z_2-odd particle is stable (DM)





Ex) 1-loop Ma (2006)

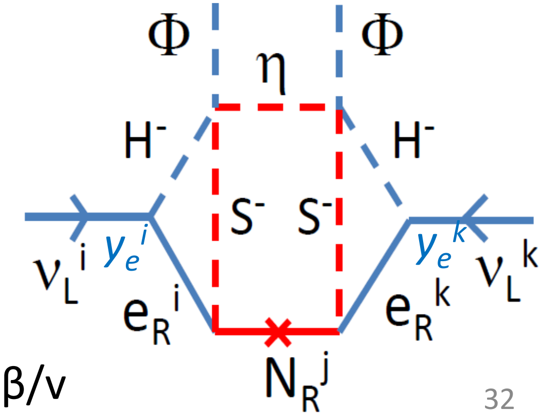
- Simplest model
- SM + NR + Inert doublet (H’)
- DM candidate [H’ or NR]
  - H’ case
  - N_R (LFV and Ωh^2 not compatible)



Ex) 3-loop Aoki, SK, Seto PRL 102, 051805 (2009)

Neutrino mass from O(1) coupling.

- 2HDM + η^0 + S^+ + N_R
- Electroweak Baryogenesis
- DM candidate [η^0 (or NR)]



$y_e^i = m_e^i \tan\beta / v$

Non-decoupling effect

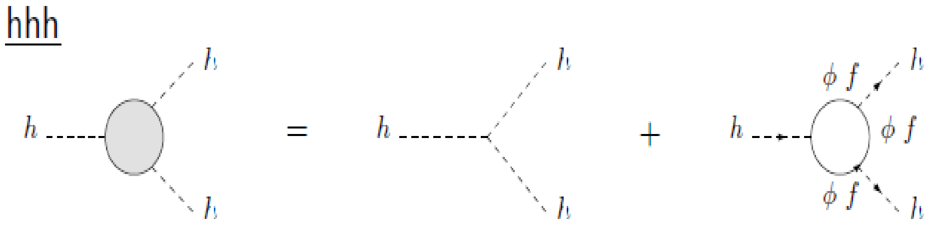
Successful EWBG requires

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

SK, Okada, Senaha 2005

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

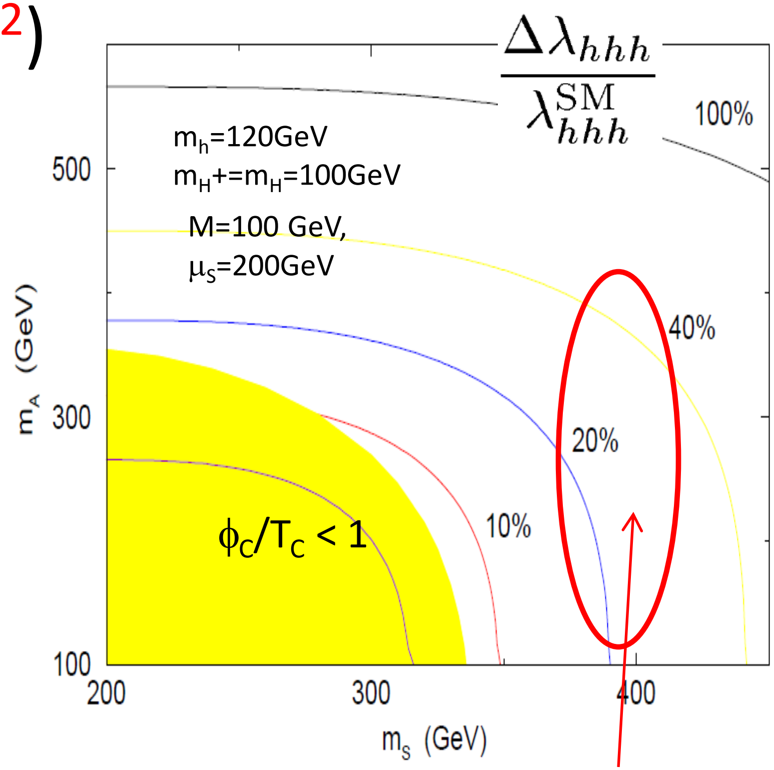
Deviation in the hhh coupling



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

A New Model

TeV-Scale Spontaneous $U(1)_{B-L}$ Breaking:
Mother of Mass of DM and Neutrino

S. Kanemura, O. Seto, T. Shimomura

arXiv: 1101.XXXX (coming soon!)

Neutrino Mass

Majorana (instead of Dirac)

- Different scale from EWSB
- Large flavor mixing

Majorana = Lepton Number Violation (LNV).

What is the source of LNV?

- Seesaw scenario: RHν ← Source of LNV

If source of LNV comes from spontaneous symmetry breaking, it may be of the $U(1)_{B\text{-}L}$ symmetry (anomaly free)

What is the scale of the B-L breaking?

WIMP Dark Matter

Weakly Interacting Massive Particle (WIMP)

- What is the candidate?

WMAP $\Omega_h{}^2$=0.1

- DM Mass = 10-1000 GeV

Why is it similar to Scale of the EWSB?

Maybe, the mass can be spontaneously generated at the scale JUST above EWSB, if it is given at the tree level.

Economical Scenario

- Source of LNV = SSB of the $U(1)_{B-L}$ at TeV
- RH neutrino obtains the mass at the EW scale by the $U(1)_{B-L}$ breaking
- The lightest RH neutrino is the WIMP DM
- Stability? ⇒ Z_2-odd RHN ⇒ No tree Yukawa

  ⇒ Radiative Seesaw
- LH neutrino obtains the Majorana mass via 1-loop of Z_2-odd particles (RHN and extra scalar doublet) .

Minimal Model

Symmetry: $SU(3)_C \times SU(2)_l \times U(1)_Y \times U(1)_{B\text{-}L} \times Z_2$

- (*B*-*L*) gauge boson Z’

New Matter Particles

- Singlet scalar (*B*-*L* Higgs) S
- Z_2 odd RH neutrinos $N_R^{1,2,3}$
- Z_2 odd iso-doublet η

	Q^i	d_R^i	u_R^i	L^i	e_R^i	Φ	η	S	N_R^α
$SU(3)_C$	3	3	3	1	1	1	1	1	1
$SU(2)_W$	2	1	1	2	1	2	2	1	1
$U(1)_Y$	1/6	−1/3	+2/3	1/2	−1	1/2	1/2	0	0
$U(1)_{B-L}$	1/3	1/3	1/3	−1	−1	0	0	+2	−1
Z_2	+	+	+	+	+	+	−	+	−

Higgs potential

$$V(\Phi,\eta,S) = -\mu_1^2|\Phi|^2 + \mu_2^2|\eta|^2 - \mu_S^2|S|^2 + \lambda_1|\Phi|^4$$
$$+\lambda_2|\eta|^4 + \lambda_3|\Phi|^2|\eta|^2 + \lambda_4|\Phi^\dagger\eta|^2 + \frac{\lambda_5}{2}\left[(\Phi^\dagger\eta)^2 + \mathrm{h.c.}\right]$$
$$+\lambda_S|S|^4 + \tilde{\lambda}|\Phi|^2|S|^2 + \lambda|\eta|^2|S|^2,$$

Spontaneous Breaking of $U(1)_{B-L}$ and EWSB

3 mass parameters $\mu_1^2, \mu_2^2, \mu_3^3 \Rightarrow v, v_S, \mu_3^2$

Φ, S $\quad \tan\beta = \frac{v_S}{v}$ $\quad \begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \phi_S \end{pmatrix}$

η $\quad \eta = \begin{pmatrix} H'^+ \\ \frac{1}{\sqrt{2}}(H' + iA') \end{pmatrix}$

Physical States : *h*, *H*, *H′*, *A′*, *H′+*

$\cancel{U(1)}_{B\text{-}L} \Rightarrow$ Mass of $N_R^{\,i}$

B-L gauge boson Z’

$$m_{Z'} = 2 g_{B\text{-}L}\, v_s$$

LEP bounds

$$m_{Z'}/g_{B\text{-}L} = 2\, v_s > 6\text{-}7\ \text{TeV} \Rightarrow v_s > 3\text{-}3.5\ \text{TeV}$$

$$\mathcal{L}_{\text{yukawa}} = \sum_{\alpha=1}^{3}\left(\sum_{i=1}^{3} g_{i\alpha}\overline{L}^{i}\tilde{\eta}N_R^{\alpha} - \frac{y_R^{\alpha}}{2}\overline{N}_R^{\alpha} S N_R^{\alpha} + \text{h.c.}\right)$$

$$\boxed{m_{N_R^{\alpha}} = -y_R^{\alpha}\frac{v_S}{\sqrt{2}}}$$

$y_R = 0.02$ for $M_{NR} =$ 50 GeV

v_S = 3000 GeV

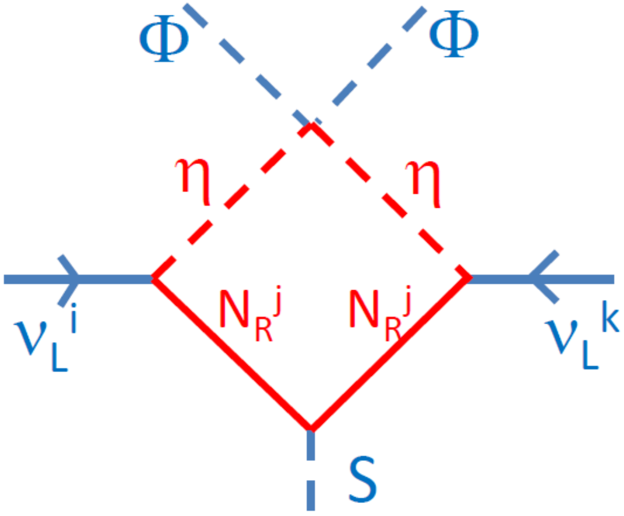
N_R: Z_2-odd ⇒ Lightest N_R is the DM candidate

$\cancel{U(1)}_{B\text{-}L}$ ⇒ Mass of Neutrinos

- $\cancel{U(1)}_{B\text{-}L}$: Source of LNV v_S
- Z_2 : No Yukawa Coupling $L\Phi N$ but $L\eta N$
- Radiative generation from Dim-6 operator $LL\phi\phi S$

$$m_{N_R^\alpha} = -y_R^\alpha \frac{v_S}{\sqrt{2}}$$

$$M_{\nu_L}^{ij} \simeq \frac{\lambda_5}{8\pi^2}\left(\sum_{\alpha=1}^{3} g_{i\alpha} y_R^\alpha g_{\alpha j}^T\right)\left(\frac{v}{m_{\phi'}}\right)^2 v_S$$



The correct neutrino mass O(0.1) eV can be deduced

- $m_{N_{R1}}$=50 GeV $M_{H'}$ = O(1) TeV
- All coupling constants O(10^{-2})

Mass structure is the same as the usual seesaw scenario.

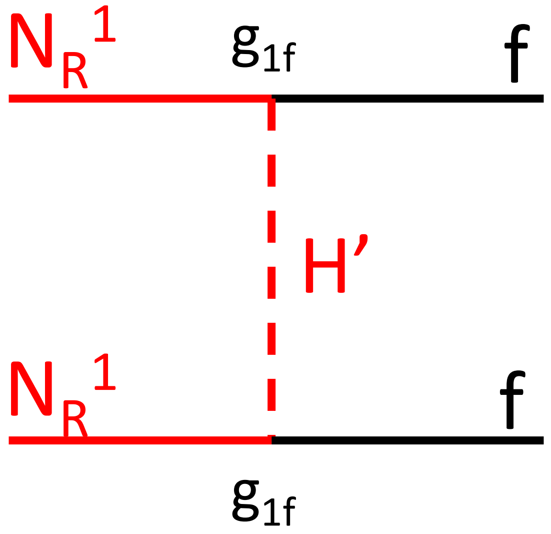
Safe from bounds from Lepton Flavor Violation

Thermal relic abundance of N_R^1

Similarity to the Ma model

t-channel

Strong bound from LFV



Annihilation not enough due to TeV scale inert H’ and small coupling g_{1f}

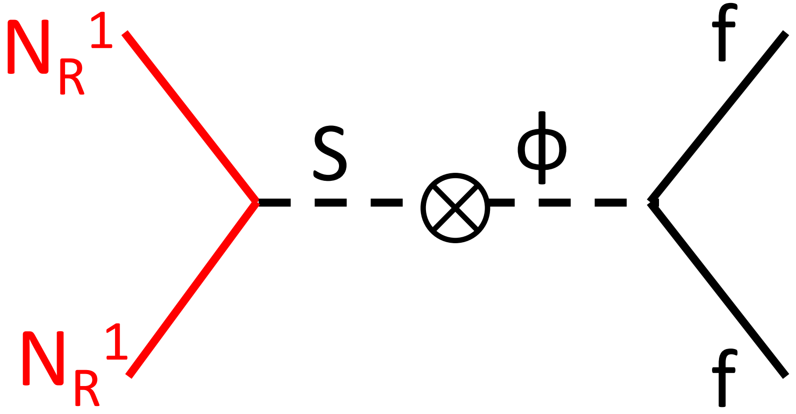
[Extension: ex) Suematsu, Toma]

New contribution in our model

s-channel (Higgs portal)

Enough annihilation

Mixing between S and ϕ is essentially important

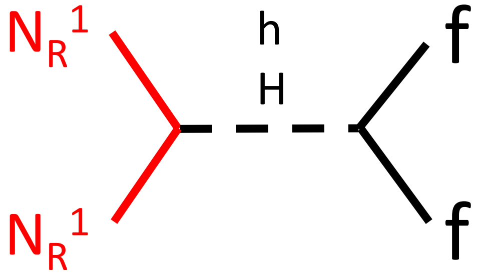


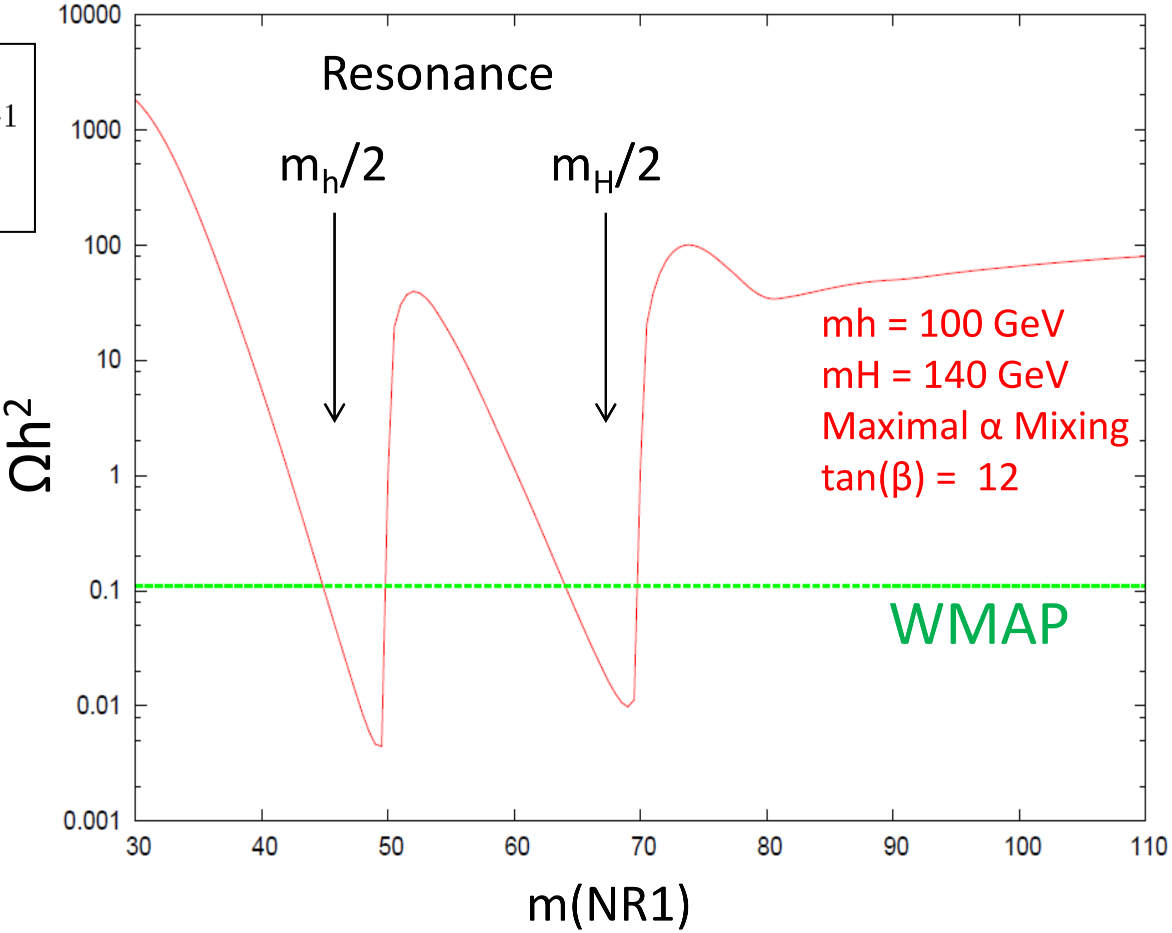
Thermal relic abundance of N_R^1

$$\Omega h^2 \simeq 1.47 \sqrt{\frac{G}{g^*}} \frac{10^9}{\int_0^{\frac{T}{m}} \langle \sigma v \rangle d\left(\frac{T}{m}\right)} \mathrm{GeV}^{-1}$$

Mass Eigenstates

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \phi_S \end{pmatrix}$$





N_R^1 can explain Ωh^2=0.11, so that N_R^1 can be DM

Successful Scenario

Inputs

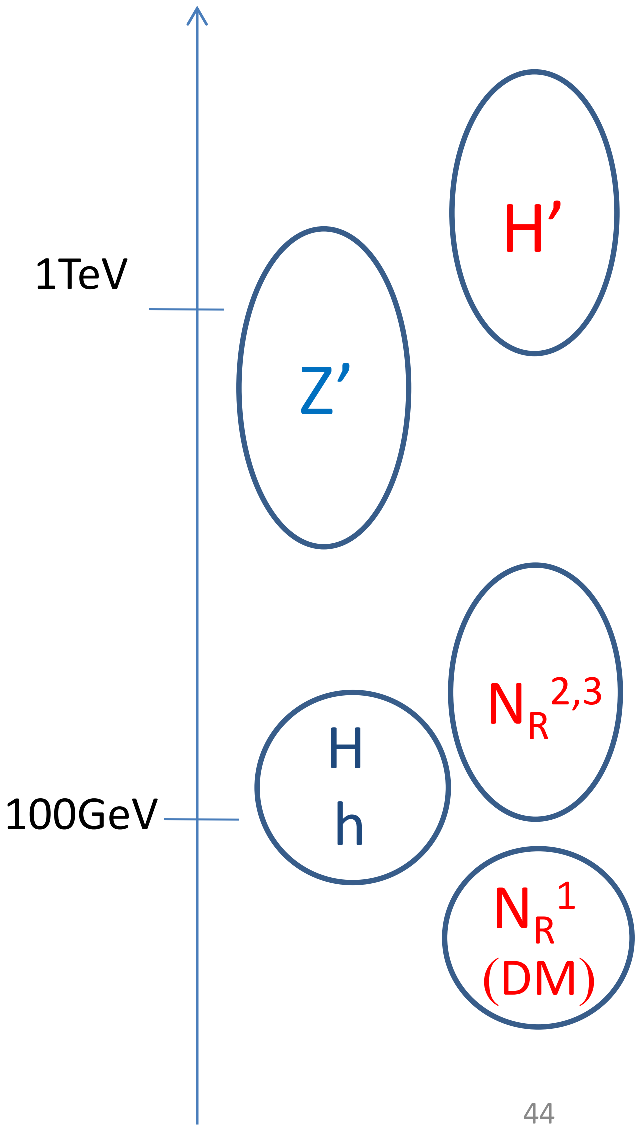
- Neutrino mass
- LFV
- DM abundance
- LEP precision tests
- Z' search results

- Perturbative Unitairty
- Vacuum Stability

Vs =3-4 TeV
V =246 GeV
MH'= O(1) TeV

Mh=100 GeV
MH=140GeV
Sinα = 1/Sqrt[2]
Tanβ=12-15
MNR=45 GeV
mZ'= 600-700 GeV
g=y=λ5=O(0.01)
$mH'=mA'=mH'^{+}=O(1)$ TeV

Mass Spectrum



Predictions

- 2 light-neutral Higgs bosons with large mixing
  - LEP and Tevatron bounds OK
  - Type-I like 2HDM (2 bosons with SM-like decay)
- Invisible decays of Higgs bosons
- Invisible decays of Z' (unique!) $Z' \rightarrow N_R^1 N_R^1$
- Lepton Flavor Violation $\mu \rightarrow e\, \gamma$
- Inert scalar physics $H'\ A'\ H^{+\prime}, H^{-\prime}$
- Production of $N_R^{2,3}$ and decay $N_R^{2,3} \rightarrow \mu^+\mu^-\ N_R^1$

Prediction 1: Multi Higgs [h and H]

Large Mixing [$\alpha=\pi/4$] [← $\Omega h^2 = 0.1$]

All the *ffh, ffH* coupling constants are 1/Sqrt[2] of the SM $ff\phi_{SM}$ values.

$$\Rightarrow \quad \Gamma(h,H \to ff) \sim (1/2)\ \Gamma(\phi_{SM} \to ff)$$

$$\Gamma(h,H \to VV) \sim (1/2)\ \Gamma(\phi_{SM} \to VV)$$

$$\sigma(pp \to h,H) \sim (1/2)\ \sigma(pp \to \phi_{SM})$$

But , $B(h \to X) \sim B(H \to X) \sim B(\phi_{SM} \to X)$

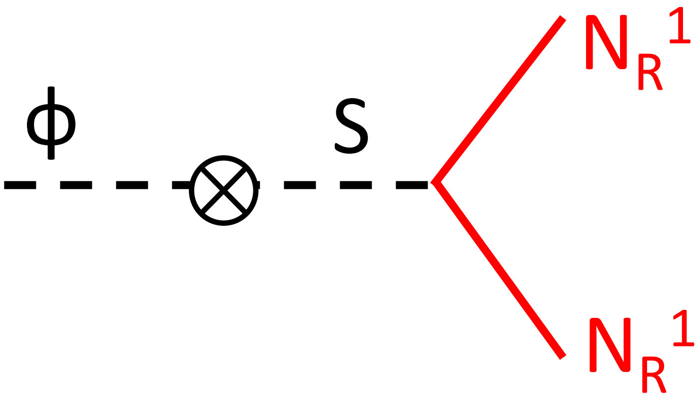
Two SM-like light Higgs bosons with about a half width

Similar to Type I 2HDM, but no charged Higgs states H^+, H^-.

Easily testable at the LHC and the ILC

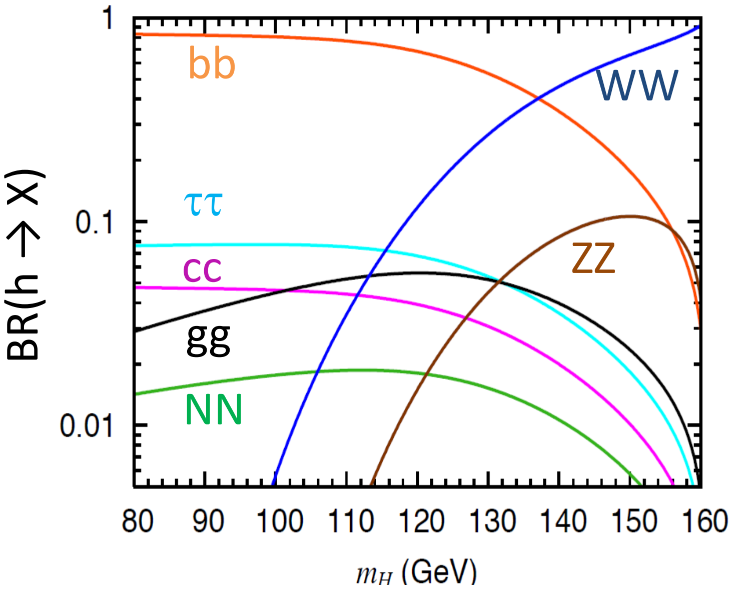
Prediction 2: Invisible Higgs decays

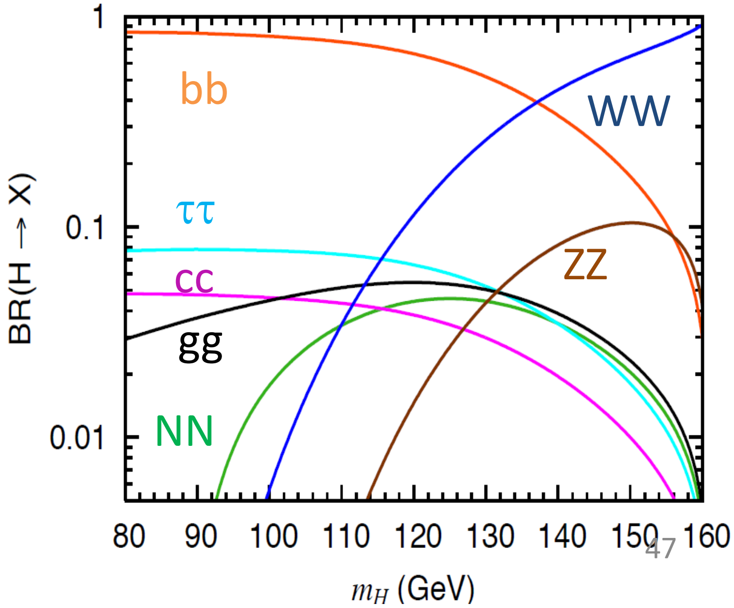
Higgs decays into NN via the same coupling as the DM annihilation



$\Gamma(h \rightarrow inv)$ ~ 1 - 2 %
$\Gamma(H \rightarrow inv)$ ~ 3- 4 %

ILC can test the Higgs invisible decay at the 1 %level





Higgs portal dark matter

N_R^1 (DM) couples to SM particles mainly via Higgs boson (h and H)

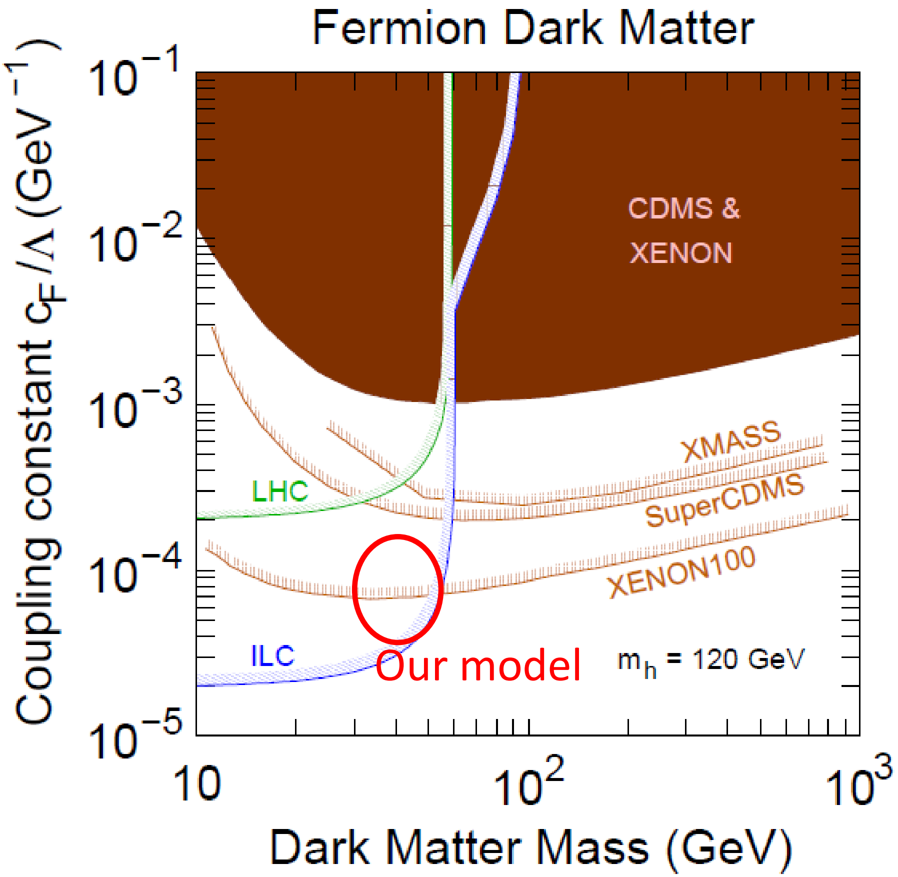
(Multi-)Higgs portal DM!

Aoki, SK, Seto (2010)

Experiments

- Direct Search (CDMS, XENON, …)
- Invisible Decay (LHC, ILC)

Testable at ILC and the future direct detection experiments



SK, Matsumoto, Okada, Nabeshima (2010)

Prediction 3: Z' Physics

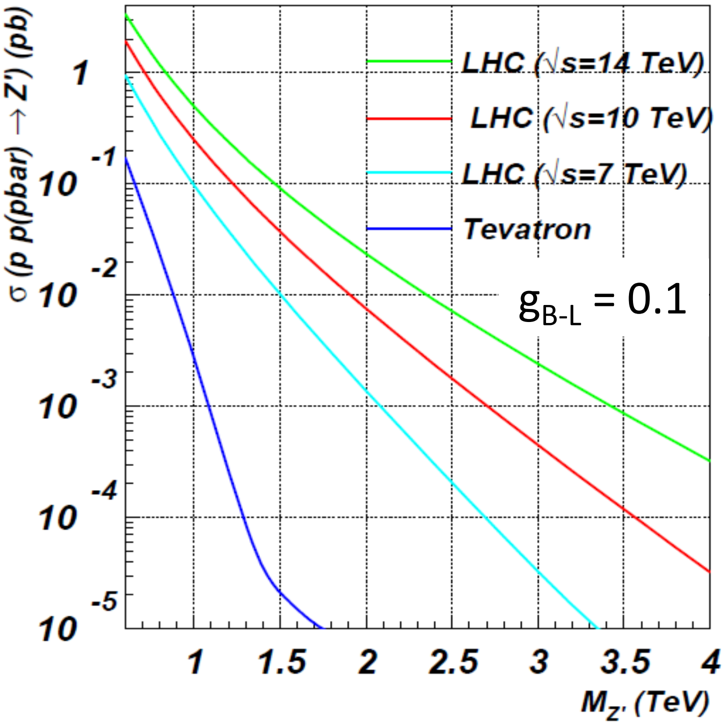
Z' Mass: 500GeV – a few TeV

$\Gamma(Z' \rightarrow XX) \propto (\text{Charge})^2$

Decay rates determined by B-L charges

Invisible decay = 22.5 %

$Z' \rightarrow \nu_L \nu_L$	3/20
$Z' \rightarrow N_R^{2,3} N_R^{2,3} \rightarrow \nu_L \nu_L N_R^1 N_R^1$	1/40
$Z' \rightarrow N_R^1 N_R^1$	1/20



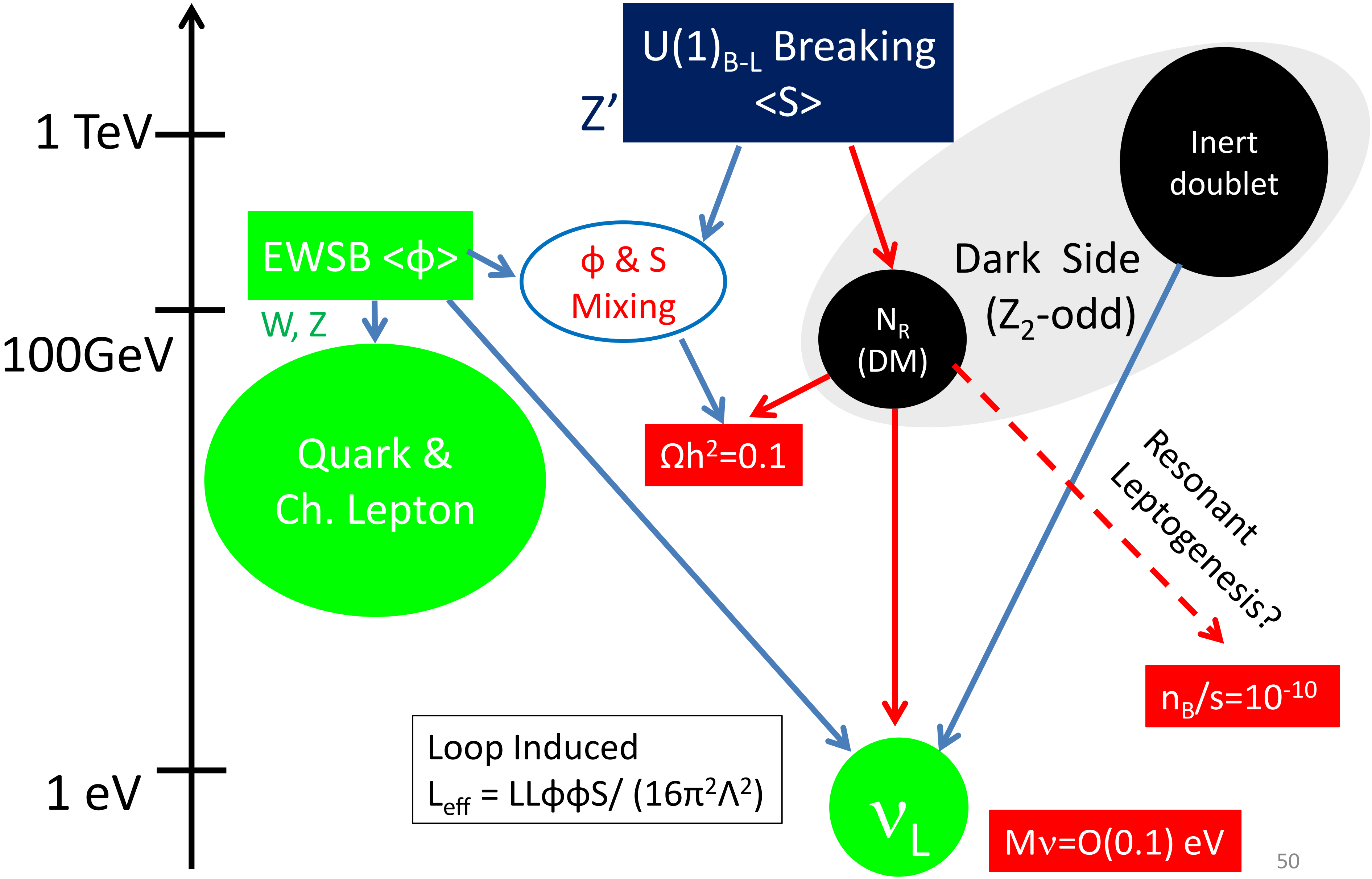
Basso, et al (2009)

Production Cross Section of Z'

For v_S = 3.5 TeV and m_Z'=700GeV,
we have g_{B-L}=0.1, then

$\sigma(pp \rightarrow Z') = O(1)$ pb

Model can be tested by measuring (invisible) decays of the Z' boson



1 TeV

100GeV

1 eV

$U(1)_{B-L}$ Breaking

<S>

Z’

EWSB <ϕ>

W, Z

ϕ & S

Mixing

Quark &

Ch. Lepton

$\Omega h^2=0.1$

Inert

doublet

Dark Side

(Z_2-odd)

N_R

(DM)

Resonant

Leptogenesis?

$n_B/s=10^{-10}$

Loop Induced

$L_{eff} = LL\phi\phi S/ (16\pi^2\Lambda^2)$

ν_L

$M\nu=O(0.1)$ eV

[4] Summary

- Higgs sector is unknown
  - Higgs searches at the LHC and the Tevatron
  - Higgs ID is important not only to confirm the SM, but also to obtain information for new physics.
- Various extended Higgs models have been discussed
  - Mixing, Non-decoupling effects
  - Mass and the hhh coupling in SUSY/non-SUSY models
- TeV-scale models for BSM phenomena (neutrino mass, dark matter, baryogenesis) have also been discussed
  - Extended Higgs sectors
  - Neutrino mass via radiative seesaw with Z_2
  - WIMP DM

Summary (cont.)

Model with 3-loop neutrino mass generation

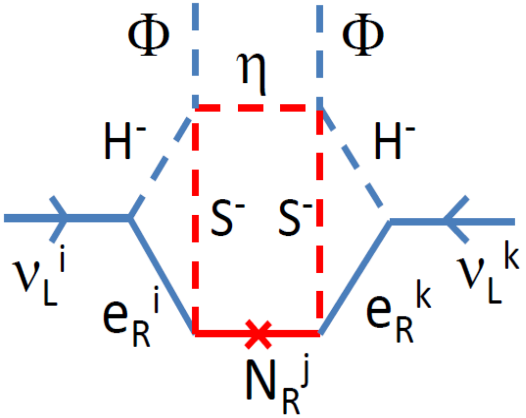
- M_ν (3-loop)
- DM (Z_2-odd real scalar boson)
- BAU (Electroweak Baryogenesis)

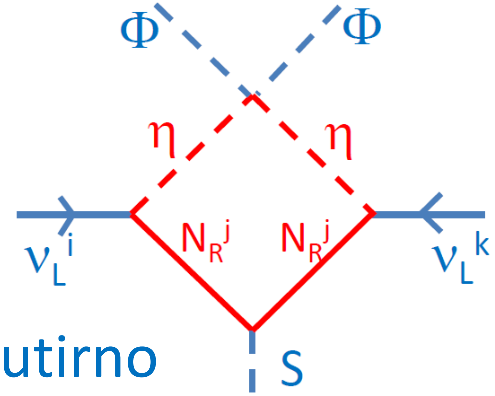
Model with TeV scale $U(1)_{B-L}$ breaking

- Neutrino Mass (1-loop)
- DM (Z_2-odd RH-neutrino)
- [BAU (TeV Leptogenesis? EWBG?)]

B-L Breaking : Mother of Masses of DM and Neutirno

Aoki, SK, Seto PRL 102, 051805 (2009)





SK, Seto, Shimomura, in preparation

These models can be tested at collider experiments via Higgs phenomenology, LFV and direct/indirect search of DM