Seesaw with loop-Induced Dirac mass and dark matter from $U(1)_{B\text{-}L}$ gauge symmetry breaking

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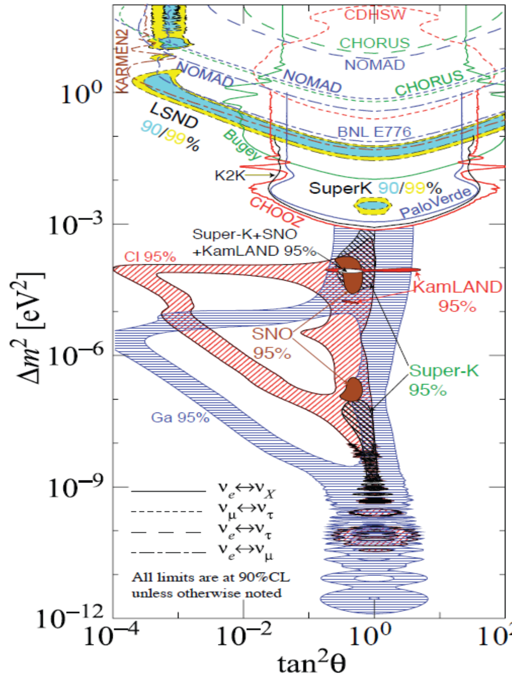
S.K., T. Nabeshima, H. Sugiyama,PLB703,66(2011)
S.K., T. Nabeshima, H. Sugiyama, arXiv: 1111.0059

Seminar at Osaka University, 1 February , 2012

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

$$\boxed{\Delta m^2 \sim 8\times10^{-5}\,\mathrm{eV}^2,\ \ \Delta m^2 \sim 2\times10^{-3}\ \mathrm{eV}^2}$$

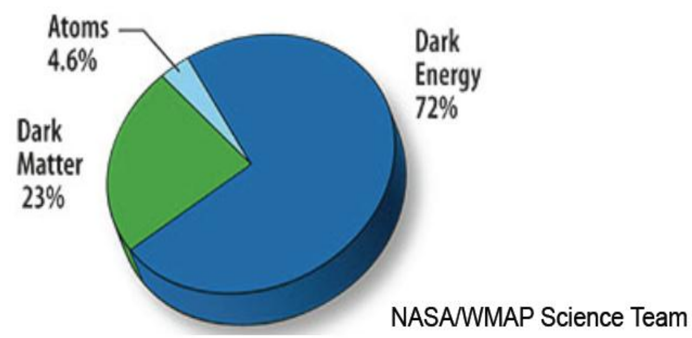


  - Dark Matter

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

  - Baryon Asymmetry of the Universe

$$\boxed{n_B/s \ \sim 9\times10^{-11}}$$

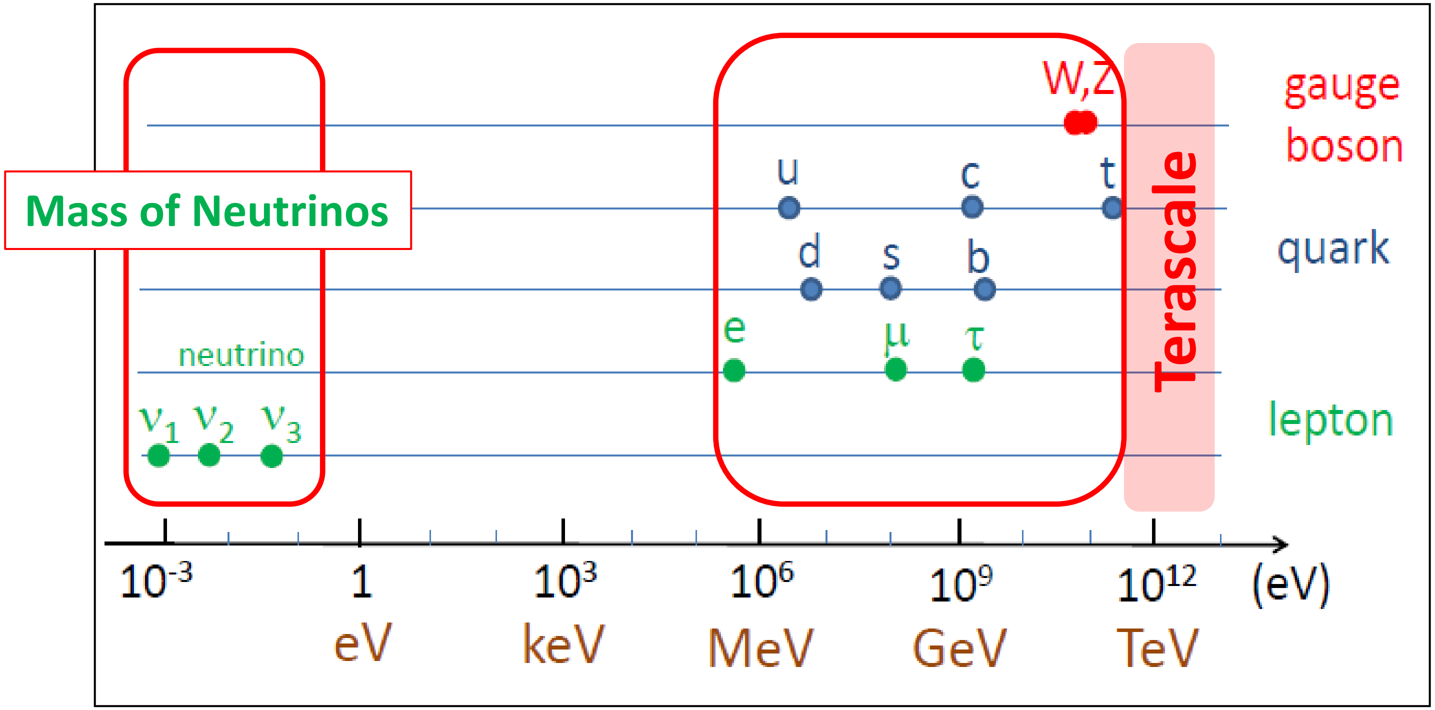


To understand these phenomena, we need to go beyond-SM

Plan of Talk

- Intoroduction
- Physics of Extended Higgs sector
- A new model for neutrino mass and dark matter
- Summary

Masses of elementary particles



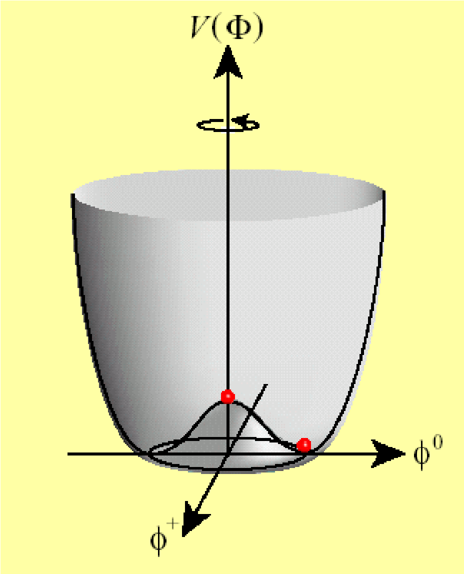
In the SM, all masses are zero in the Lagrangian
Where do they come from?

Electroweak Symmetry Breaking

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!

Higgs potential in the SM

- One doublet field

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

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

- $\lambda\phi^4$ theory→Landau pole

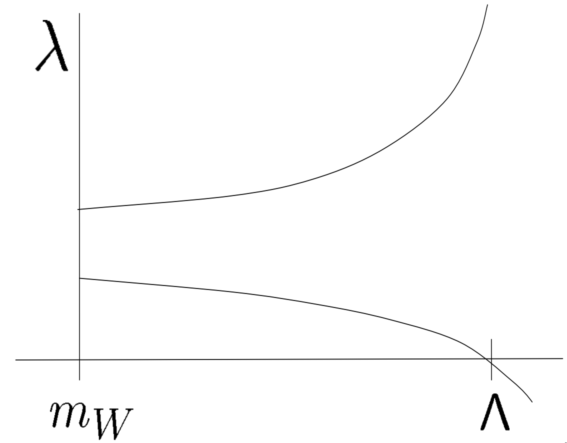
$$16\pi^2\mu\frac{d}{d\mu}\lambda = 24\lambda^2 - 6y_t^4 + \ldots.$$

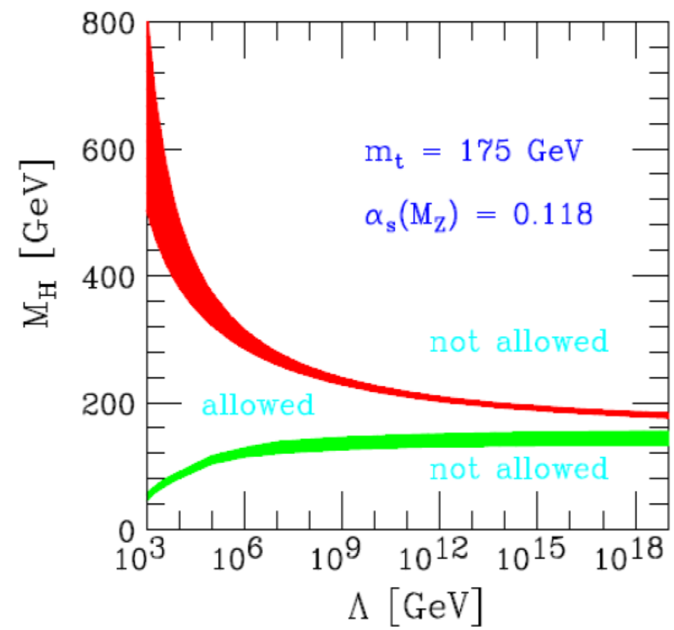
- Custodial symmetry

$$M = (\tilde{\Phi}, \Phi) = \begin{bmatrix} -\phi^0 & \phi^+ \\ \phi^- & \phi^0 \end{bmatrix}$$

$$M \to M' = g_L^\dagger M g_R \quad (g_{L,R} \in SU(2)_{L,R})$$

$$SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V$$



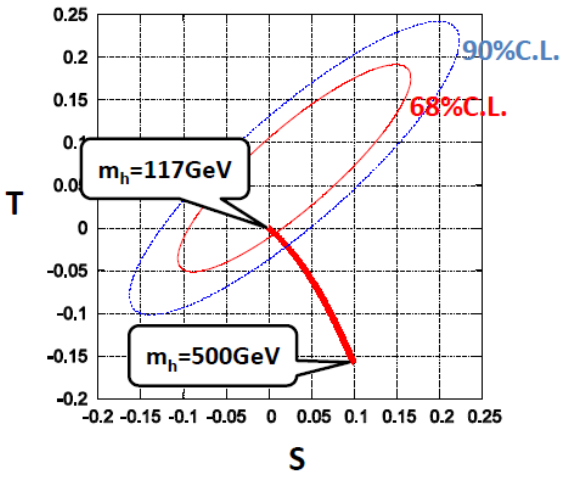


SM Higgs

LEP precision data tells us

Lighter Higgs boson is preferable !

(114 GeV < m_h< 149 GeV at 95 % CL)



Current direct search data at LHC

115 GeV < m_h < 128 GeV

600 GeV < m_h

Data suggest a light Higgs boson

It is expected to detect a light Higgs boson at the LHC in near future

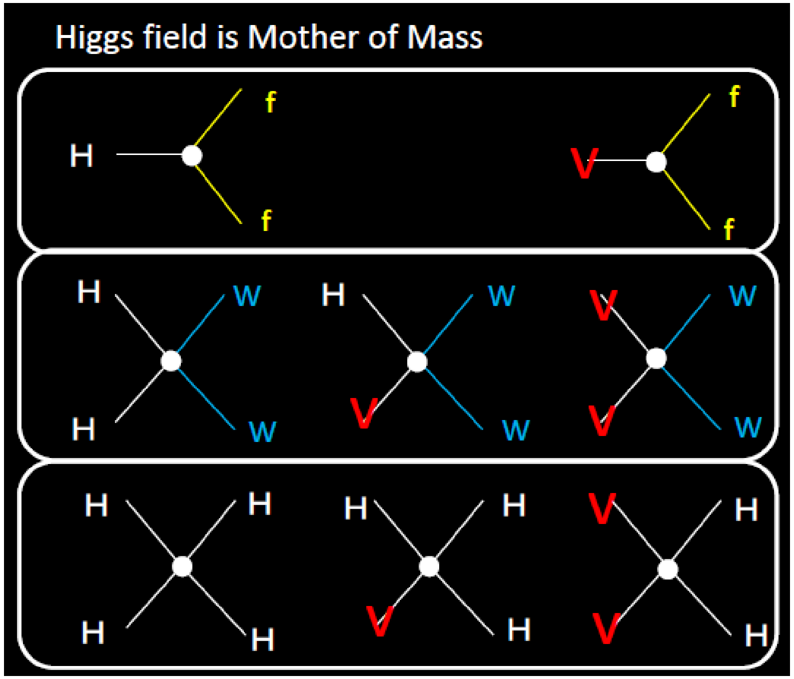
SM Higgs

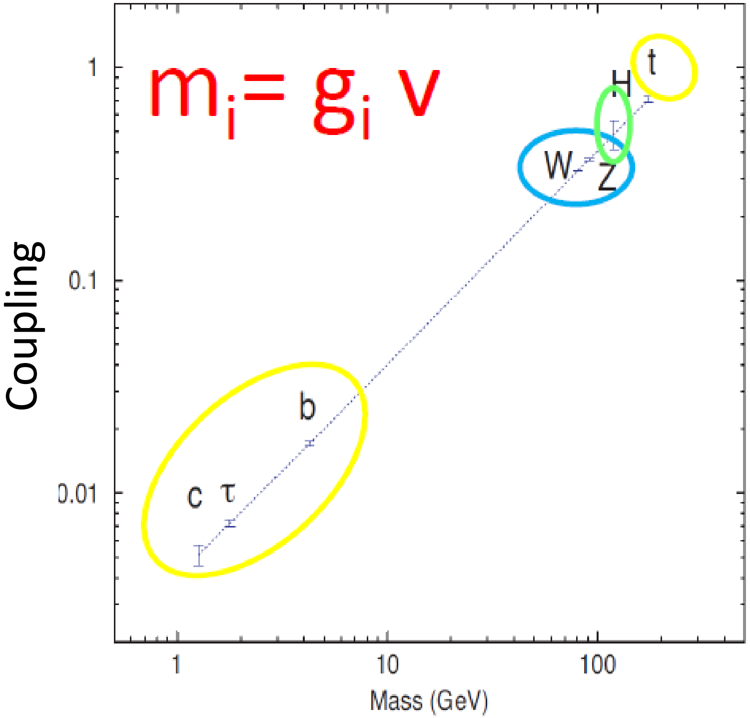
Origin of Mass

Yukawa coupling

Gauge coupling

Self coupling





This relation is important to identify the Higgs boson in the SM

The International Linear Collider is necessary!

Heavy Higgs is really excluded?

No!

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

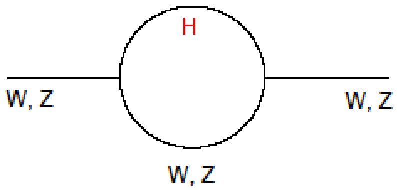
The upper bound comes from the loop effect of m_H.

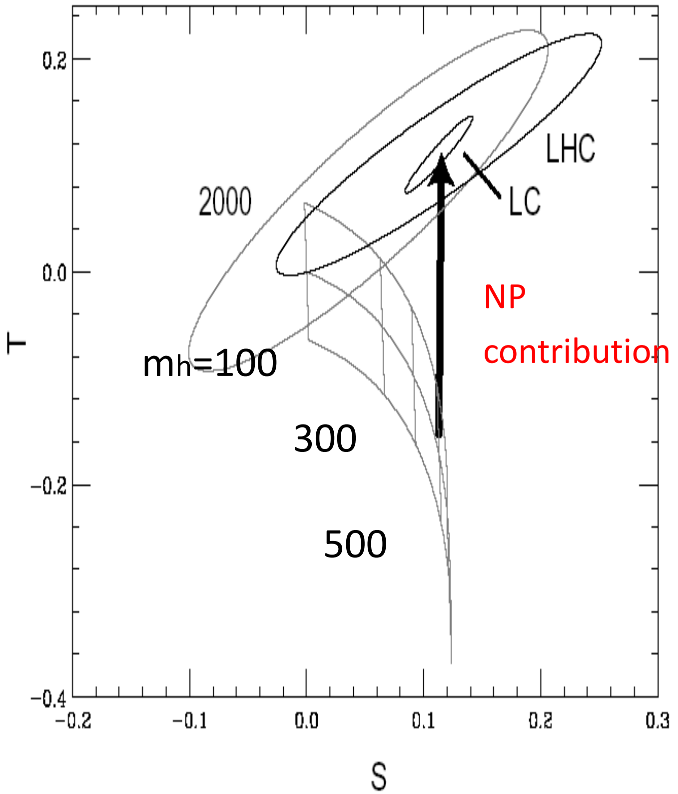
$$\Delta T_{\text{Higgs}} \simeq -\ln \frac{m_H^2}{M_W^2} \quad (\sim 0)$$

A heavy Higgs is possible by additional new physics loop contributions to the T parameter (violation of custodial SU(2))

Heavy Higgs: Signal of New Physics

Oblique Corrections





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

$\boxed{\text{Higgs Sector = Window to New Physics}}$

[2] Extended Higgs models

- If the Higgs sector contains more than one scalar bosons, possibility would be
  - Extra singlets (NMSSM, B-L Higgs, ...)
  - Extra doublets (SUSY, CPV, ...)
  - Extra triplets (Type II seesaw, ...)
  - ....
- Basic experimental quantities:
  - Electroweak rho parameter
  - Flavor Changing Neutral Current (FCNC)

Electroweak rho parameter

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

Q=I_3 + Y/2

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

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]

Naively muliti-doublets (+ singlets) are natural extension

2 Higgs doublet model (2HDM)

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

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

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

$\uparrow \quad \uparrow \quad \uparrow$charged

CPeven CPodd

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

M_{soft}: soft breaking scale

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

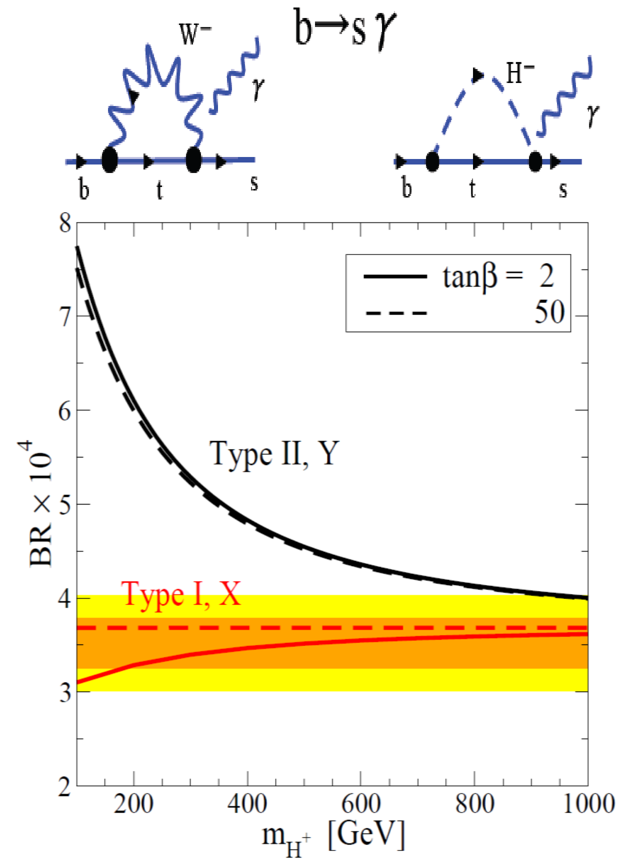
soft-breaking scale
of the discrete symm.

FCNC Suppression

SM: FCNC via Z is suppressed by

GIM mechanism

Multi-Higgs models: FCNC via Higgs



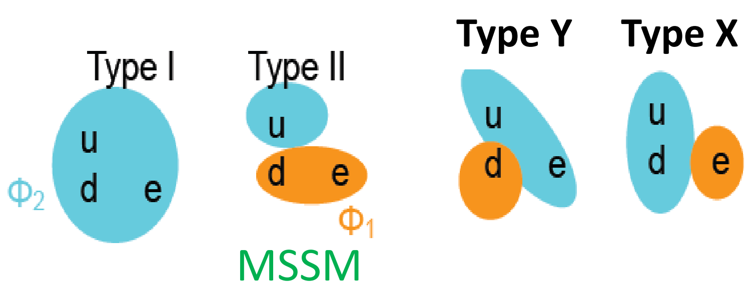
To avoid FCNC, impose a discrete symmetry

2HDM: $\Phi_1 \to +\Phi_1, \qquad \Phi_2 = -\Phi_2$

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

Four types of Yukawa Interaction

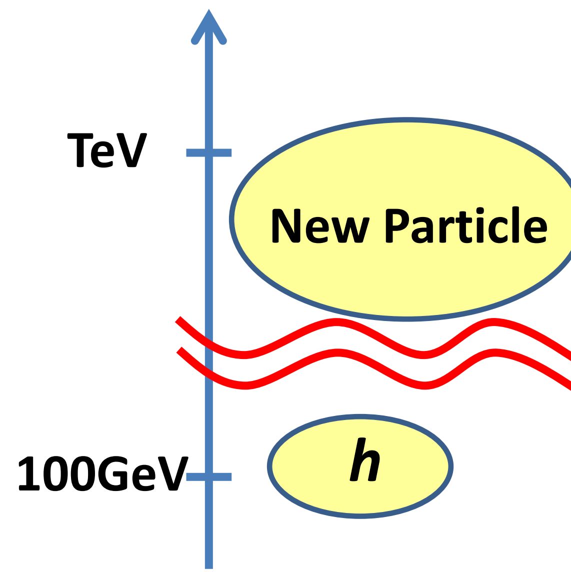
$$\boxed{\mathcal{L}_{\rm yukawa}^{\rm THDM} = -\overline{Q}_L Y_u \widetilde{\Phi}_u u_R - \overline{Q}_L Y_d \Phi_d d_R - \overline{L}_L Y_\ell \Phi_\ell \ell_R + \mathrm{H.c.}}$$



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

Decoupling/Non-decoupling

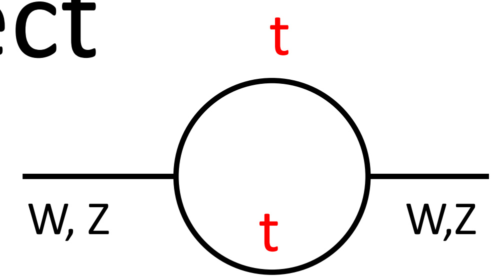
Precision measurements on Higgs sector
Calculation with radiative corrections
→ Determination of deteils of Higgs sector

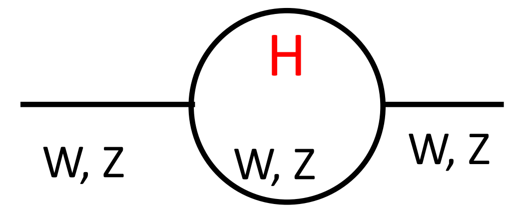


- Decoupling Theorem
  Appelquist-Carazzone 1975
  New phys. loop effect in observables
  $1/M^n \to 0$ (M→∞ : decouple)
- Violation of the decoupling theorem
  - Chiral fermion loop (ex. top)
    $m_f = y_f\, v$
  - Boson loop (ex. H^+ in non-SUSY 2HDM) Non-decoupling effect
    $m_\phi{}^2 = \lambda\, v^2 + M^2$ (only if $\lambda v^2 > M^2$)

Non-decoupling effect

Example (Electroweak *T* parameter)





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

$\boxed{\text{Data } |T| < 0.1}$

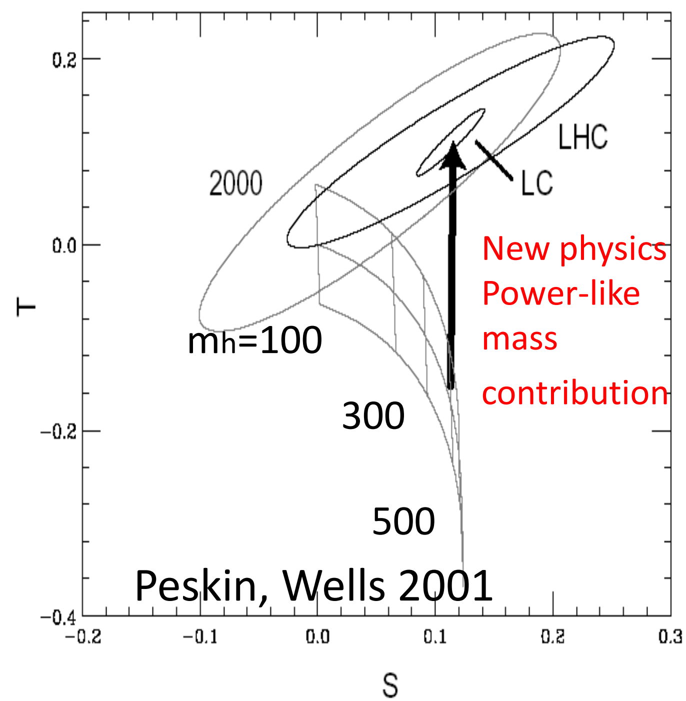
$$\Delta T_{\text{top}} \propto \frac{m_t^2}{M_W^2}$$

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

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

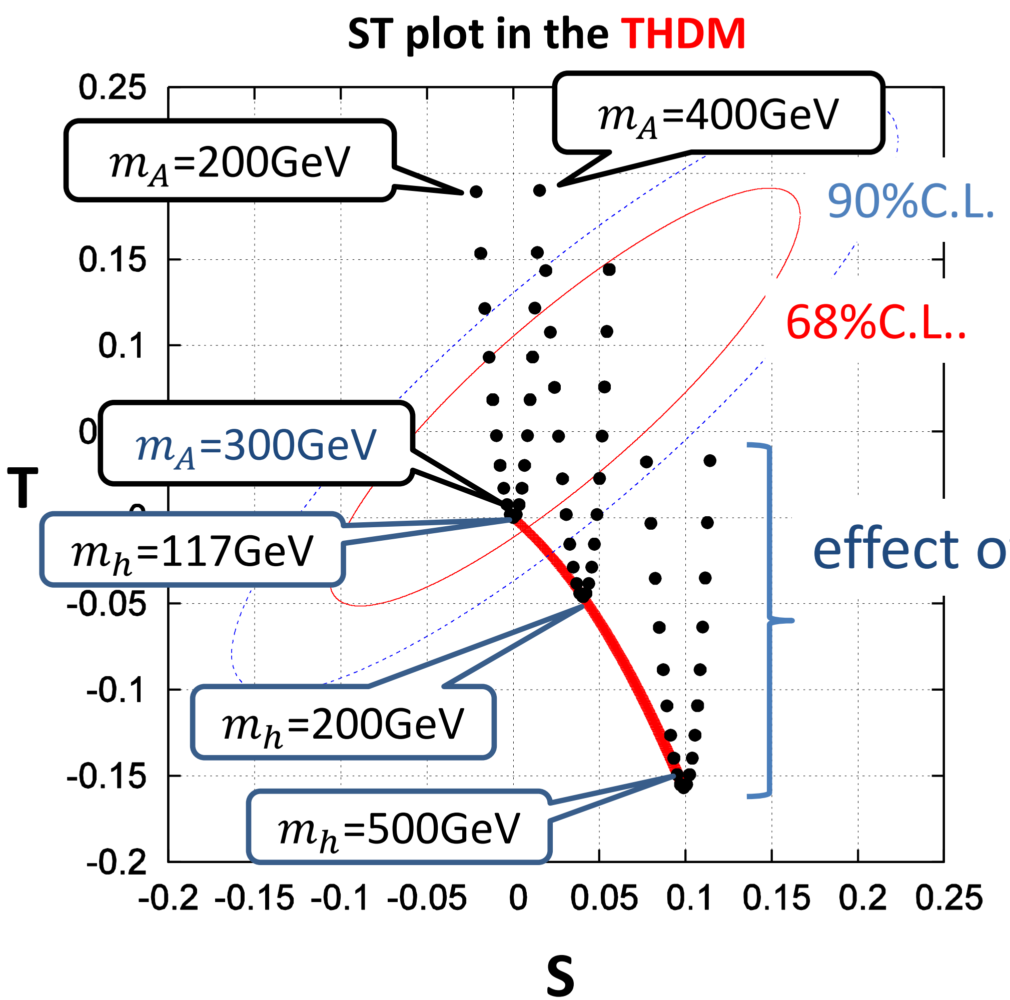
(2HDM)

Quadratic mass contribution
(non-decoupling effect)



2HDM

SK, Okada, Tsumura, Taniguchi, 2011



$$S_\Phi \approx -\frac{1}{12\pi}\ln\frac{m_{H^\pm}^2}{m_A^2},$$

$$\boxed{T_\Phi \approx \frac{\sqrt{2}G_F}{12\pi^2\alpha_{EM}}\left(m_A - m_{H^\pm}\right)^2}$$

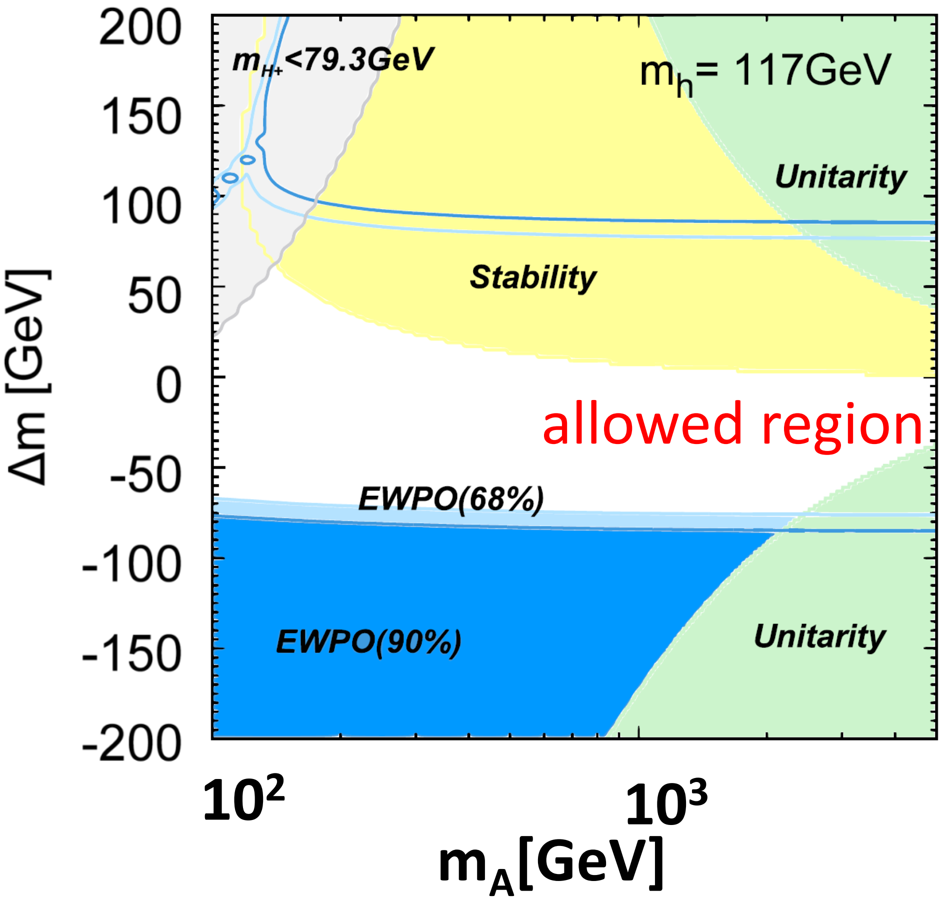
$$m_H = m_A, \sin(\beta-\alpha) = 1$$

$m_{H^\pm}$=300GeV, m_A is varied from 200 to 400 GeV by the 10 GeV step（black dots）.

Even in the SM Higgs is heavy, the data can be satisfied by the mass splitting between $H^\pm$ and A (by breaking of custodial SU(2)v).

m_h=117GeV

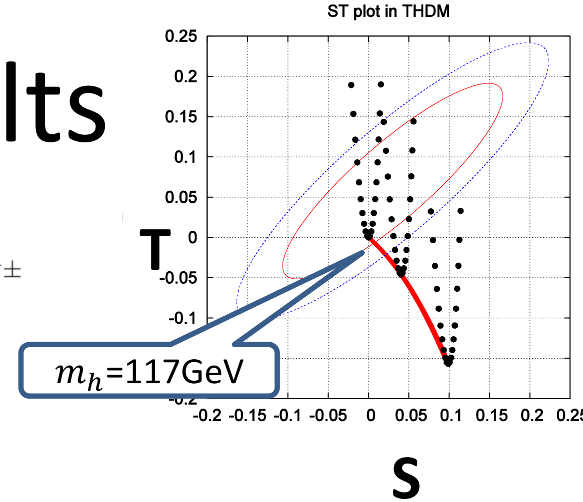
Combined results



$$\Delta m = m_A - m_{H^\pm}$$

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

$$m_A^2 = m_H^2 = M^2$$



The precision measurement data constrain mass splitting
Unitarity restricts a large lambda
Stability restricts a sign of lambda
Direct search constrain $m_{H^\pm}$

the colored region is excluded

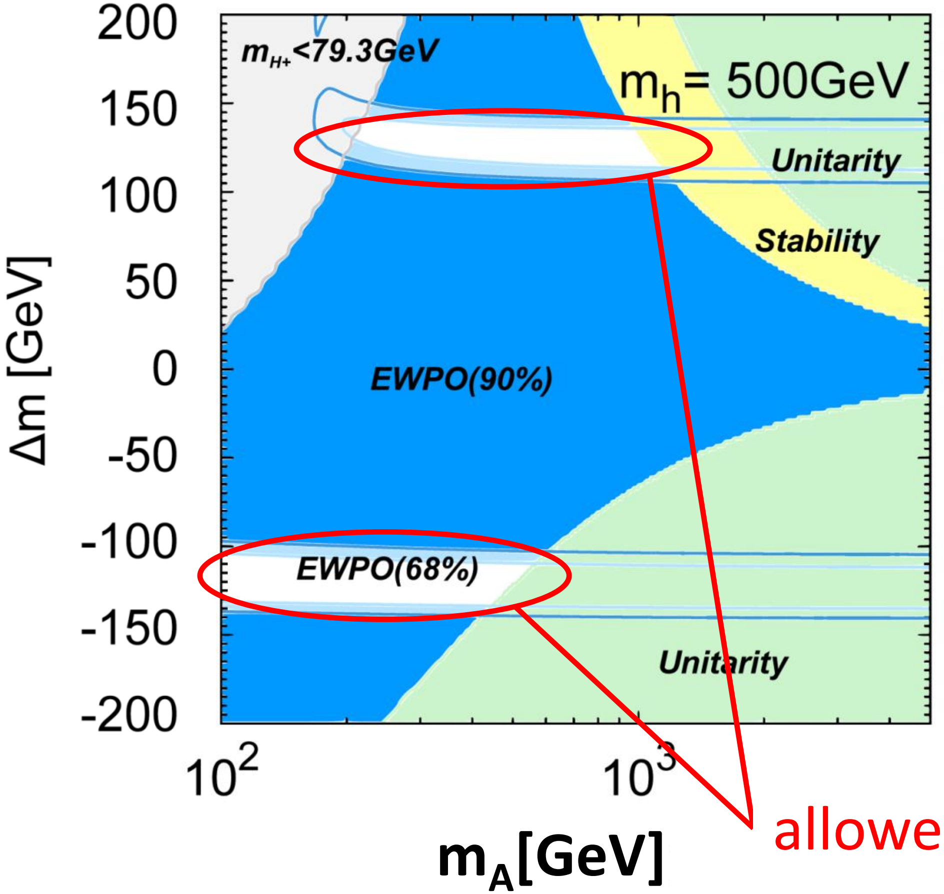
SK, Okada, Taniguchi, Tsumura, 2011

the light SM-like Higgs boson

- The mass splitting is required to be small

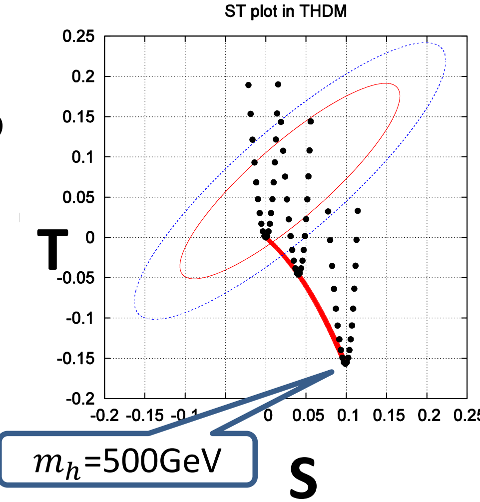
m_h=500GeV

Combined results



allowed region

$$\Delta m = m_A - m_{H^\pm}$$
$$\sin(\beta - \alpha) = 1$$
$$m_A^2 = m_H^2 = M^2$$



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SK, Okada, Taniguchi, Tsumura, 2011

the heavy SM-like Higgs boson

- The large mass splitting is required by EWPO.
- The upper bound of m_A is 1 TeV.

Model without ρ = 1 at tree level

Model with ρ=1: SM, 2HDM, MSSM, ... 3 inputs (α_{EM}, G_F, m_Z)
with $\cos\theta_W = m_W/m_Z$

- $\delta\rho = \rho - 1$ measures the violation of SU(2)v in the loop dynamics

ex) $\delta\rho \propto (m_t - m_b)^2/v^2$ quark-loop

or $(m_{H+} - m_A)^2/v^2$ scalar-loop

Model without ρ=1: models with tripletes 4 inputs (α_{EM}, G_F, m_Z, $\sin^2\theta w$)

- Renormalization of additional EW parameter $\sin^2\theta w$ absorbs the violation of the custodial SU(2)v symmetry

$$1 - 4\hat{s}_W^2(m_Z) = \frac{\mathrm{Re}(v_e)}{\mathrm{Re}(a_e)}$$

v_e (a_e): vector (axial) part of the Zee vertex

- No quadratic mass dependences in $\Delta\rho$!

ex) $\delta\rho \propto \ln(m_t/m_b)$ quark-loop

Higgs Triplet Model (HTM)

Neutrino mass via Type-II Seesaw mechanism

$$\Phi = \left[\begin{array}{c} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + v_\Phi + i\chi) \end{array} \right], \quad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

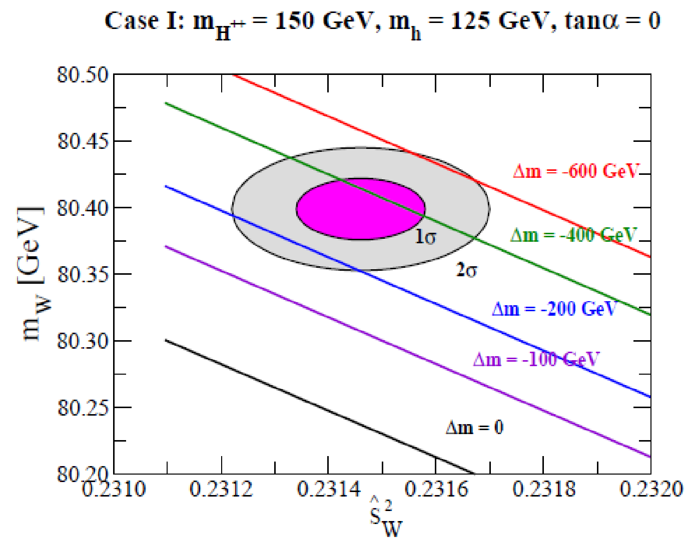
- Tree level

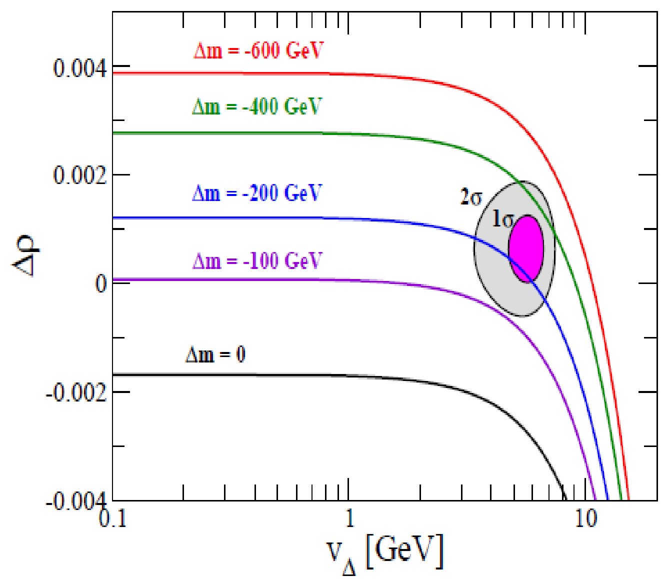
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{1 + \frac{2v_\Delta^2}{v_\Phi^2}}{1 + \frac{4v_\Delta^2}{v_\Phi^2}}$$

- Loop level

$$m_W^2 = \frac{\pi\alpha_{\rm em}}{\sqrt{2}G_F \hat{s}_W^2}(1 + \Delta r),$$

$$\rho = \frac{\pi\alpha_{\rm em}}{\sqrt{2}G_F m_Z^2 \hat{s}_W^2 \hat{c}_W^2}(1 + \Delta r)$$





S. Kanemura, K. Yagyu, arXiv:1201.6287

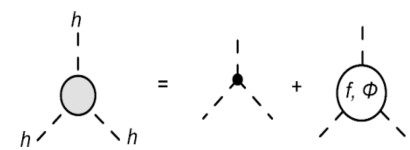
Higgs potential

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

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

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

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



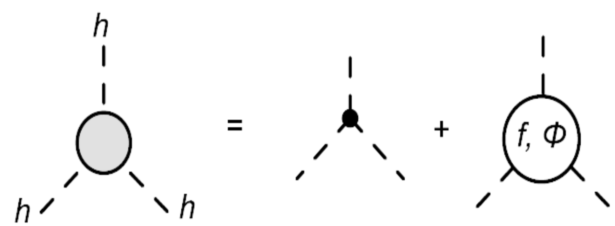
SM Case

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

Non-decoupling effect

Case of 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 $M < v$)



Φ = H, A, $H^\pm$

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

$$\boxed{\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\underbrace{\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3}_{\text{Extra scalar loop}}-\underbrace{\frac{m_t^4}{\pi^2 v^2 m_h^2}}_{\text{Top loop}}\right]}$$

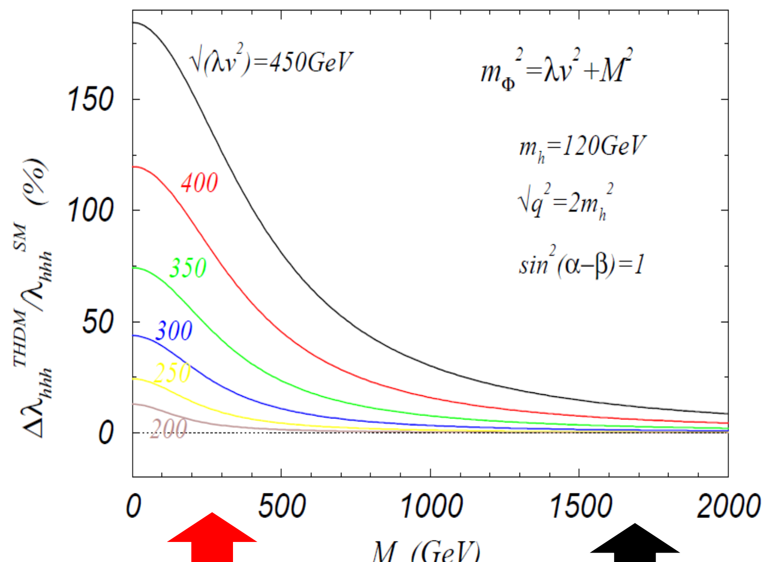
Extra scalar loop

Top loop

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

(Φ = *H, A, H*$^\pm$)

Correction can be huge ∼ 100%



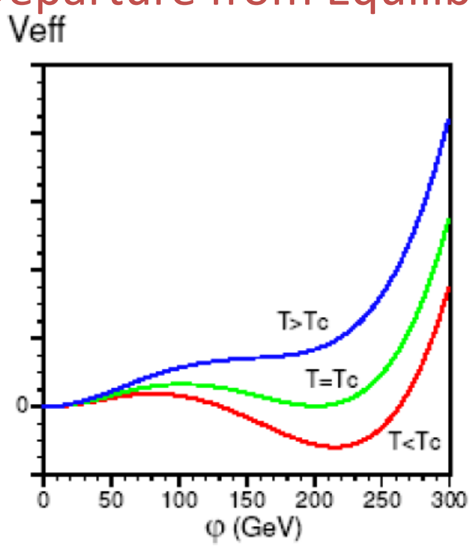
Non-decoupling effect

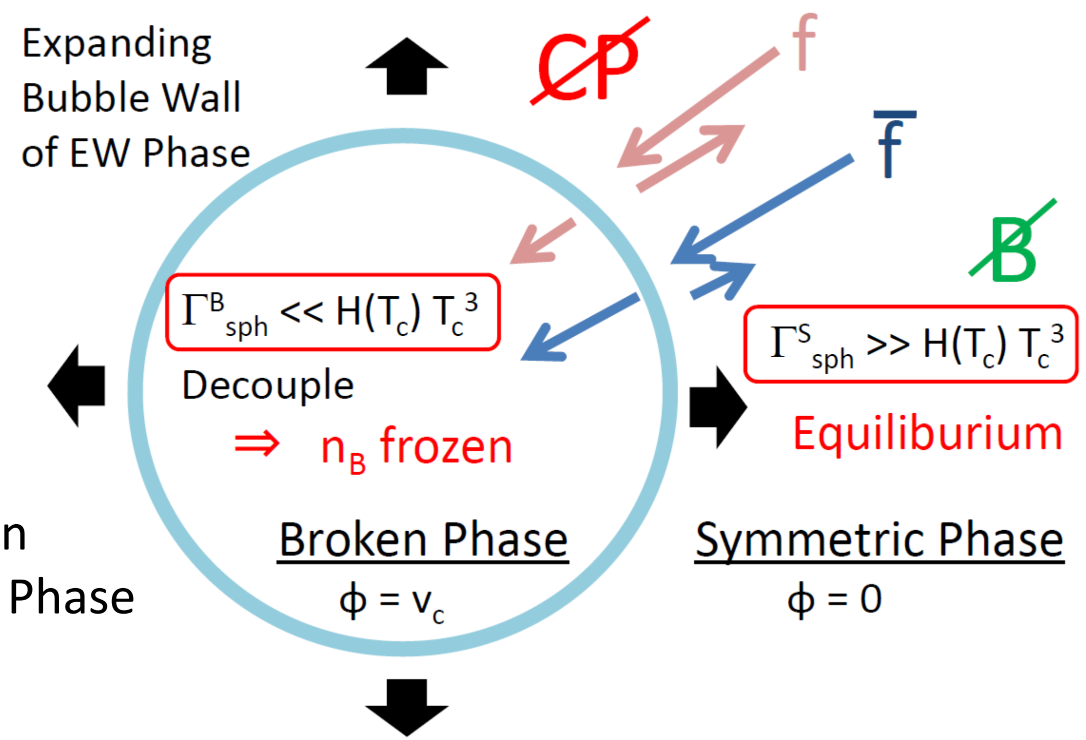
Decoupling

Relation to electroweak baryogenesis

Sakharov's conditions:

- B Violation → Sphaleron transition at high T
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1st Order EW Phase Transition





Quick sphaleron decoupling to retain sufficient baryon number in Broken Phase

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

EW baryogenesis and the *hhh* coupling

Finite temperature potenital

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

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

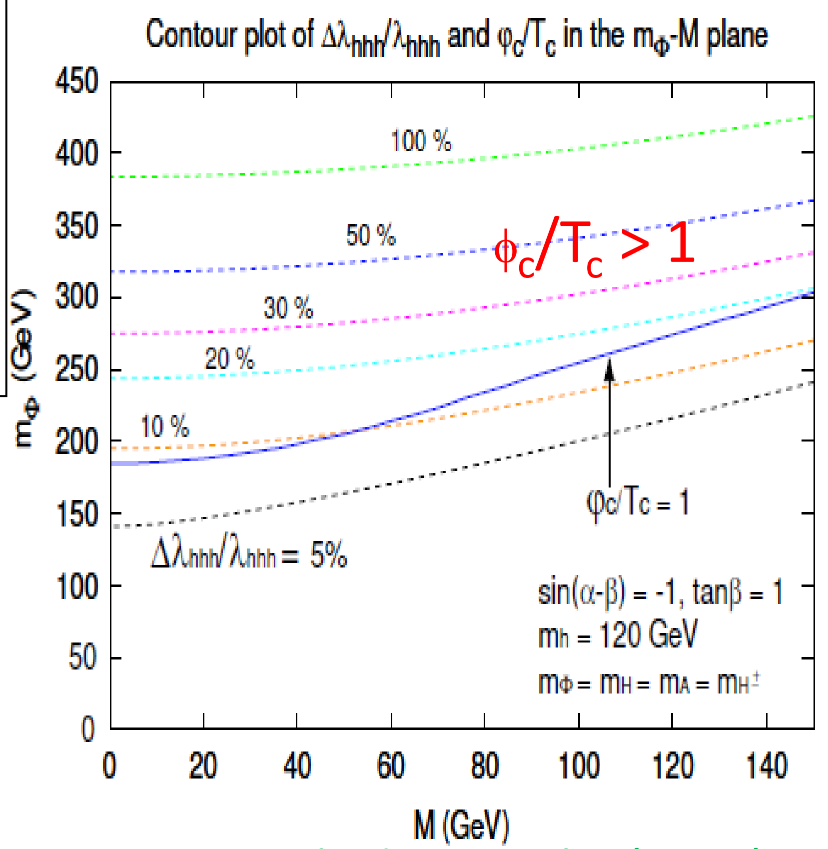
$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) + \text{New Phys. Effect}$$

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

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

SM: $m_h < 60$GeV Excluded by LEP

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



SK, Okada, Senaha (2005)

Strong 1st OPT ⇔ Large *hhh* coupling

What kind of SUSY Higgs sectors give strong 1st OPT ? (large deviation in the *hhh* coupling?)

Case of Non-SUSY THDM

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

1. MSSM: only D term [+ (F-term top Yukawa at loop)] determines m_h, *hhh* etc.

2. General SUSY Higgs sector

$V_{int} = |D|^2 + |F|^2 +$ Soft-breaking

F-term contributions: appear with additional singlets, triplets

$W = \lambda \quad H_u.H_d\,\varphi, \quad \lambda\, H_u\, \Delta\, H_u, \ldots$

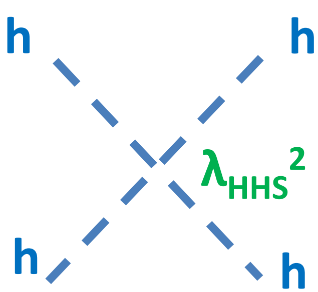
Large non-decoupling effects can appear in observables via F-term

NMSSM (MSSM＋S)

Chiral Superfield: **S (singlet)**
which generates F-term interaction

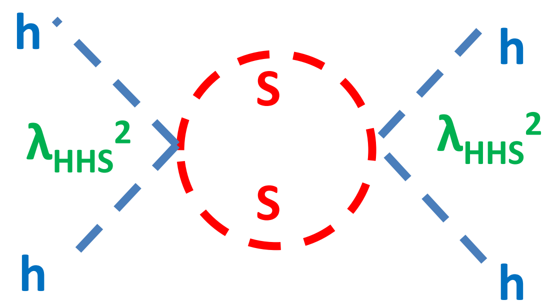
$$\boxed{W = \lambda_{HHS}\ H_u H_d S}$$

$$V_F = \lambda_{HHS}{}^2\ |H_u H_d|^2 + \lambda_{HHS}{}^2\ |H_u S|^2 + \lambda_{HH\phi}{}^2\ |H_d S|^2$$



Tree level
Contribution
To the mass

One-loop
Contribution to
The *hhh* coupling



Same coupling makes both m_h and the *hhh* coupling large

$\boxed{m_h \text{ is large, but the deviation in } hhh \text{ coupling not large}}$

Fat Higgs model

Harnik, Kribs, Larson, Murayama

Composite H_1, H_2, N

A UV complete theory

At low energy, a strong NMSSM

$$W = \lambda(NH_1H_2 - v_0^2)$$

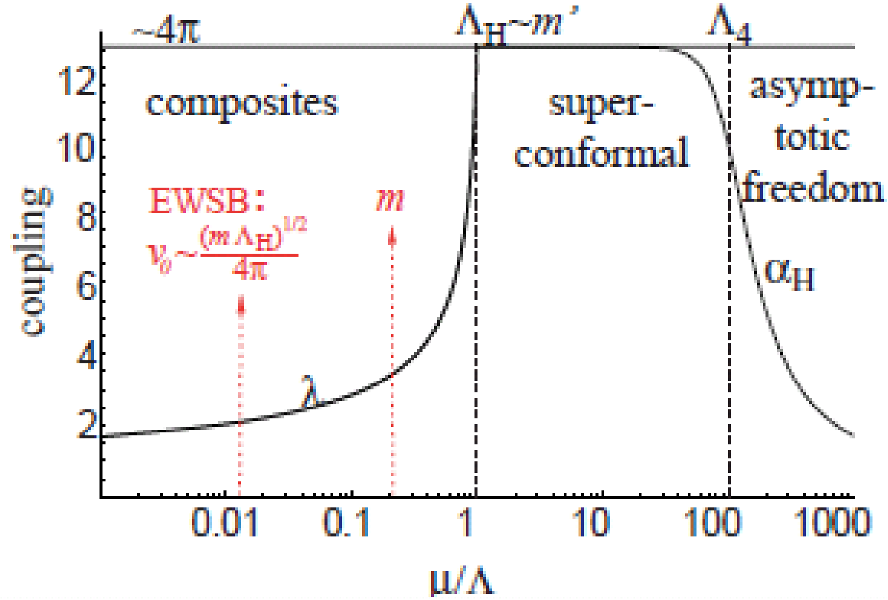
The SM-like Higgs can be heavy

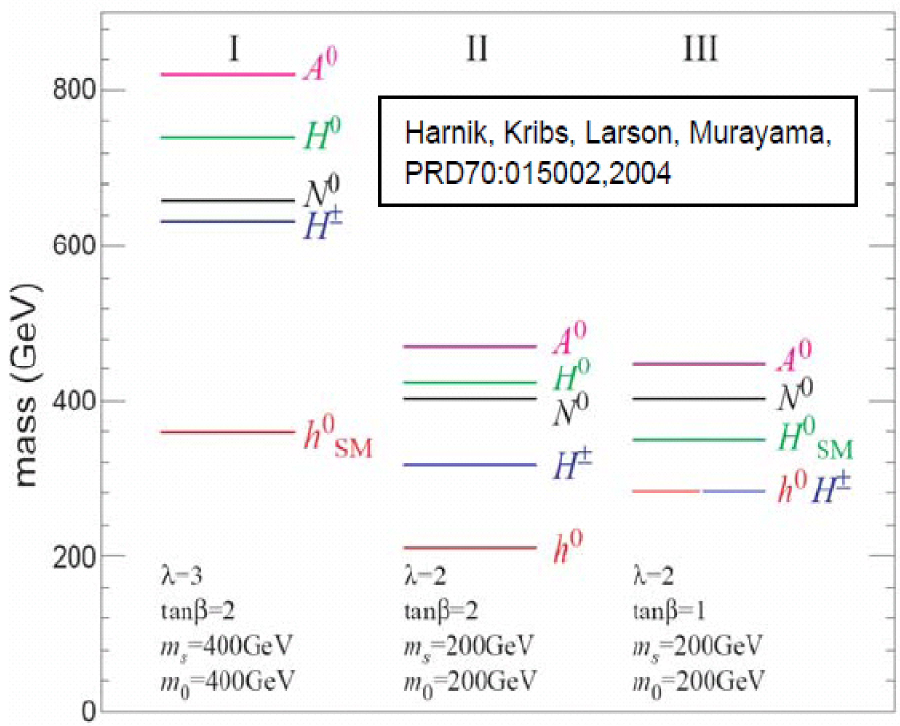
$$m_h^2 \simeq \lambda^2 v^2 + \mathcal{O}(m_Z^2)$$

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

λ can be of O(1)

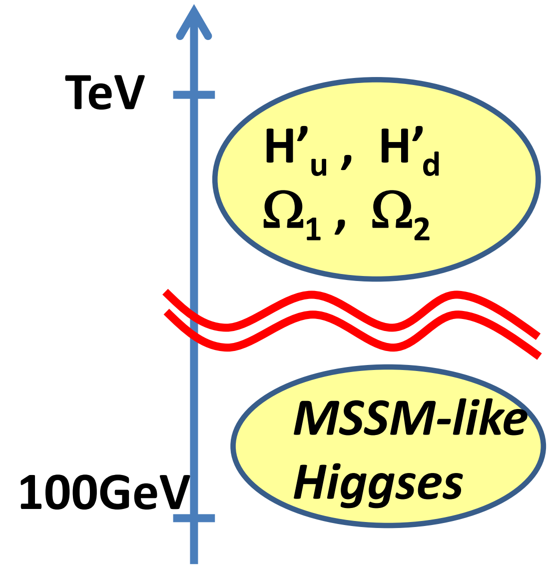
⇔ m_h > 200 GeV





4HDM + charged singlets $\Omega_{1,2}$

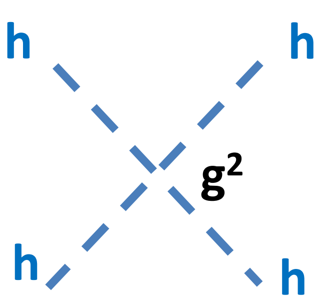
$H'_{u,d}$: extra doublets, $\Omega_{1,2}$: charged singlets



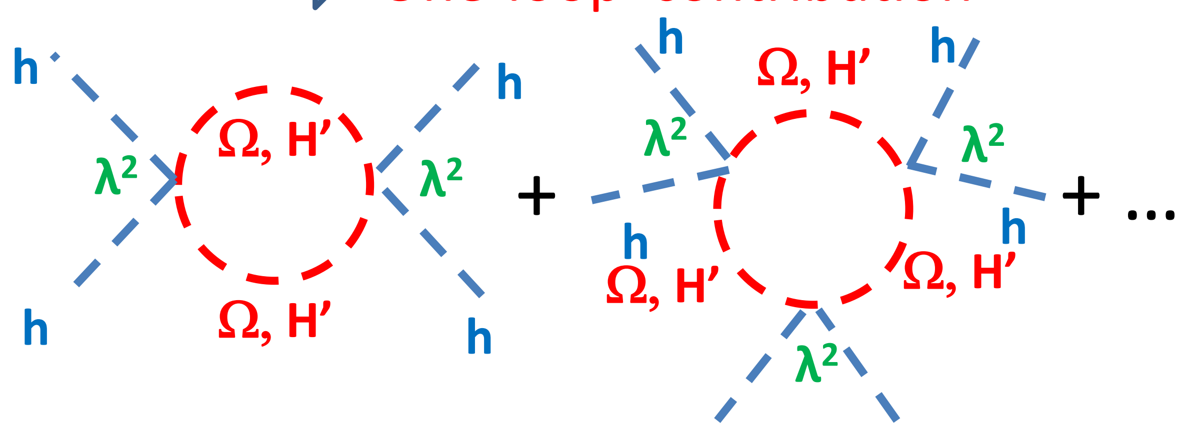
$$W = \lambda_1\ H_u\, H_u'\Omega_1 + \lambda_2\ H_d\, H_d'\Omega_2$$

$$V_F = \lambda_1^{\,2}\ |H_u H_u'|^2 + \lambda_1^{\,2}\ |H_u \Omega_1|^2 + \lambda_1^{2}\ |H_u H_u'|^2$$
$$+\lambda_2^{\,2}\ |H_d H_d'|^2 + \lambda_2^{\,2}\ |H_d \Omega_2|^2 + \lambda_2^{\,2}\ |H_d\ H_d'|^2$$

No tree level contribution to the mass of *h*



One-loop contribution



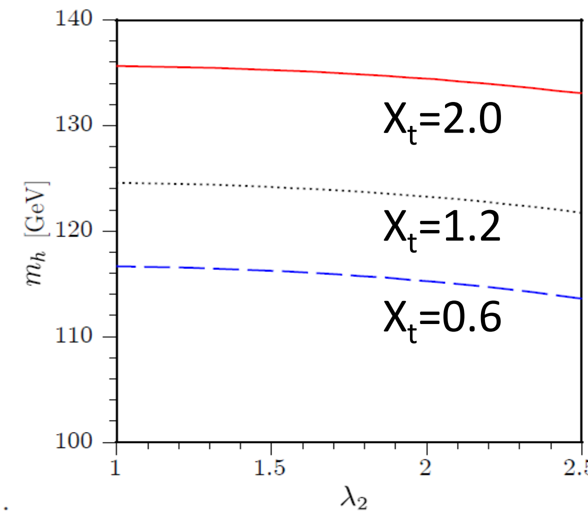
Non-decoupling effect (λ^4/g^2)
appears in the *hhh* coupling after renormalization

Non-decoupling effects

SM-like Higgs mass

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + (\text{MSSM-loop}) + \frac{\lambda_1^4 v^2 c_\beta^4}{16\pi^2} \ln \frac{m^2_{\Omega_2^\pm} m^2_{\Phi_2'^\pm}}{m^4_{\bar{\chi}_2^\pm}} + \frac{\lambda_2^4 v^2 s_\beta^4}{16\pi^2} \ln \frac{m^2_{\Omega_1^\pm} m^2_{\Phi_1'^\pm}}{m^4_{\bar{\chi}_1^\pm}}$$

m_h cannot be very large: 114-135 GeV



The hhh coupling

$$\lambda_{hhh}^{\text{Model}} \simeq \lambda_{hhh}^{\text{SM}} \left[1 + \sum_{1,2} \frac{m^4_{\Omega_i}}{6\pi^2 v^2 m_h^2} \left(1 - \frac{\overline{m}_i^2}{m^2_{\Omega_i}} \right)^3 + \cdots \right]$$

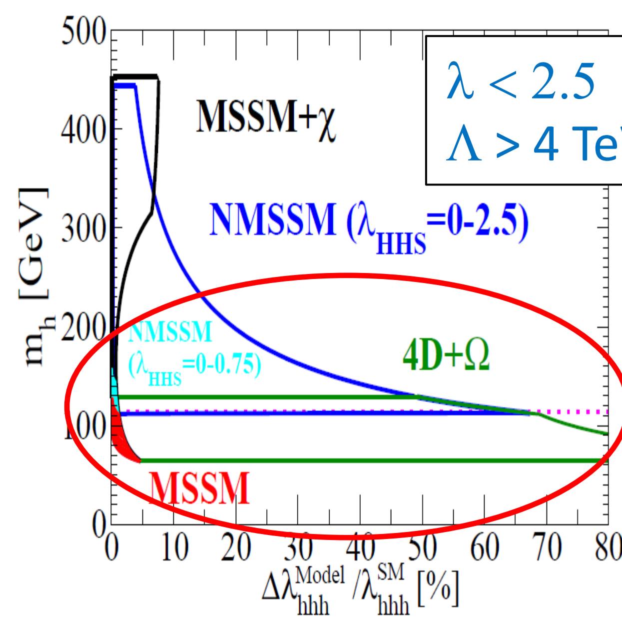
$$m^2_{\Omega_1} \simeq \overline{m}_1^2 + \frac{\lambda_1^2 \sin^2\beta}{2} v^2$$

$$m^2_{\Omega_2} \simeq \overline{m}_2^2 + \frac{\lambda_2^2 \cos^2\beta}{2} v^2$$

Deviation can be large when

$$m_{\Omega_i} \gg m_h$$
$$m_{\Omega_i} \gg \overline{m}_i$$

20-70% !

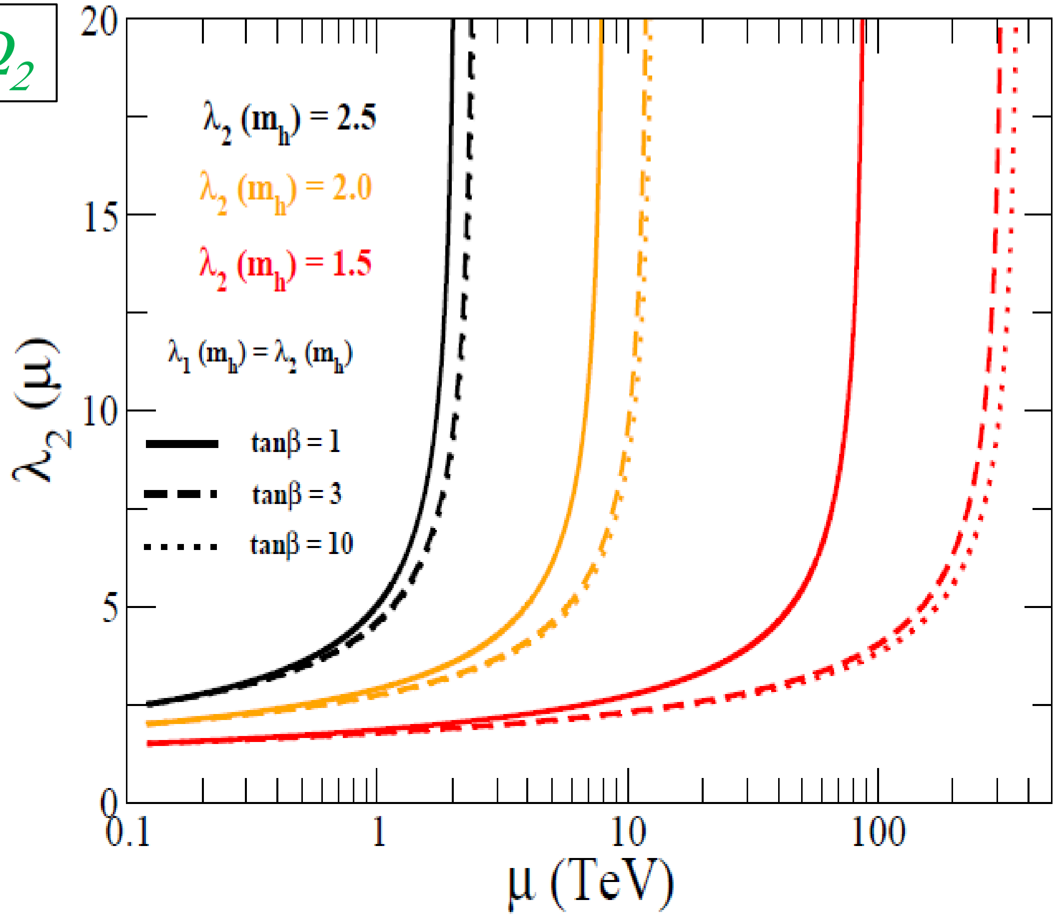


$\lambda < 2.5$
$\Lambda > 4$ TeV

RGE analysis in 4HDM+Ω

$$W = \lambda_1\ H_u H_u'\Omega_1 + \lambda_2\ H_d H_d'\Omega_2$$

λ_2	Λ_{cutoff}
2.5	2 TeV
2.0	10 TeV
1.5	100 TeV



S.K., T. Shindou, K. Yagyu, 2010

EW Phase Transition in 4HDM+Ω

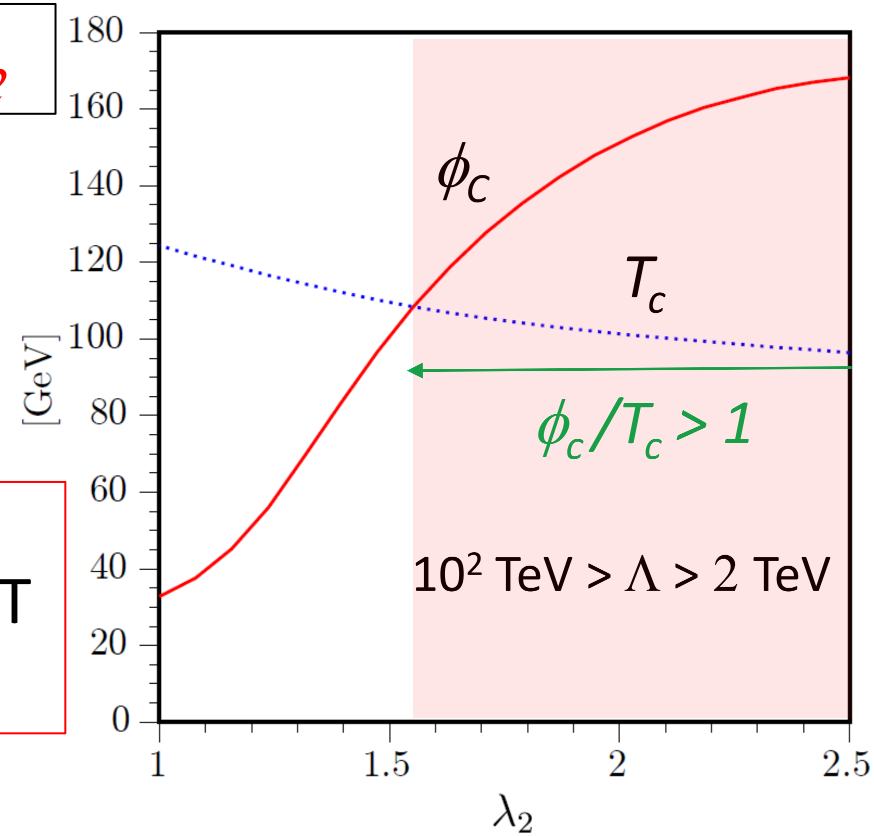
S.K., E. Senaha, T. Shindou arXiv:1109.5226

$$W = \lambda_1\ H_u H_u'\Omega_1 + \lambda_2\ H_d H_d'\Omega_2$$

For relatively large λ_1, λ_2 couplings,

Sphaleron condition is satisfied

4HDM+Ω is a new viable model which can give the strong 1st OPT easily. (2 TeV < Λ_{cutoff} < 10^2 TeV)



In this case, deviations in the *hhh* coupling = 15% - 70 %

Large *hhh* coupling ⇔ Strong 1st OPT

Testable at ILC !

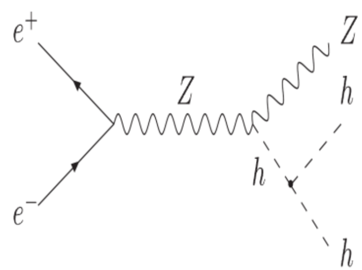
Higgs self-coupling at ILC

The nature of EWSB $V(\phi)=-\mu^2|\phi|^2+\lambda|\phi|^4$

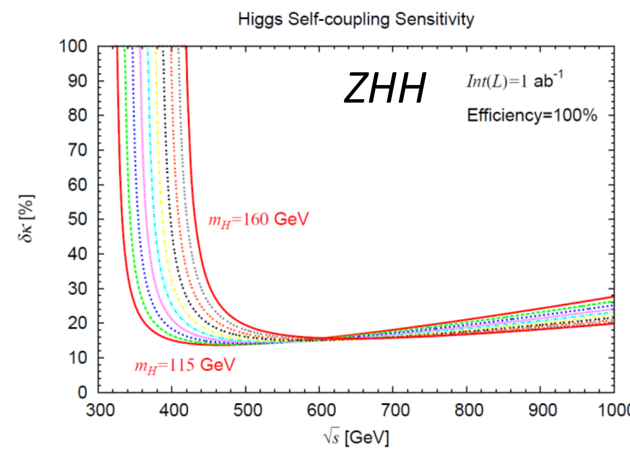
- LHC: Difficult for a light Higgs (< 140 GeV)
- ILC: Testable
  - Simulation study underway

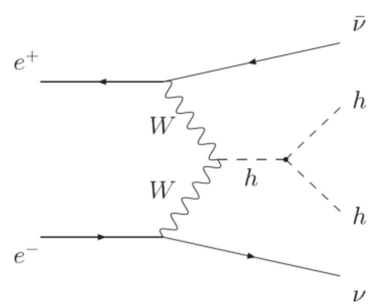
    Suehara-san's talk

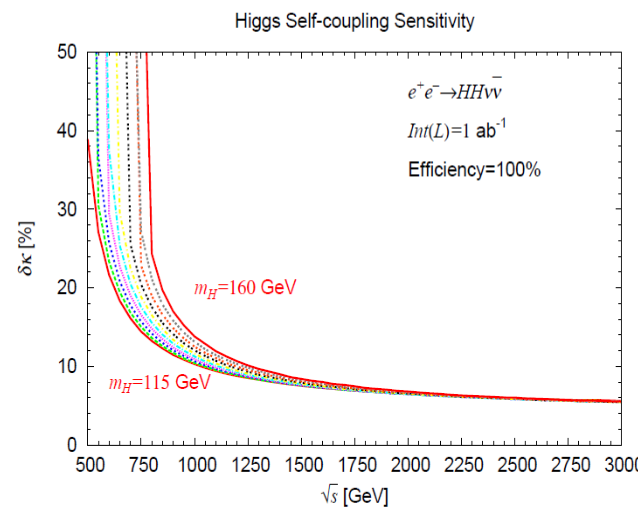
It is important to determine the hhh coupling by O(20) %



Higs self-coupling sensitivity







D. Harada 2010

LC Physics!

Summary

- There are many possibilities for the Higgs sector
- New physics scenarios ⇔ Extended Higgs sector
- The scale of new physics cannot be predicted, so that it is not guaranteed to directly find evidence of new physics at collider experiments
- But at the LHC, we definitely obtain information for the Higgs sector
- New physics can be explored via the detailed study of extended Higgs sectors

A TeV scale model to explain tiny neutrino masses, the WIMP dark matter mass and its stability

Seesaw with loop-Induced Dirac mass and dark matter from $U(1)_{B\text{-}L}$ gauge symmetry breaking

Shinya KANEMURA

University of TOYAMA

富山大学理学部

S.K., T. Nabeshima, H. Sugiyama,PLB703,66(2011)
S.K., T. Nabeshima, H. Sugiyama, arXiv: 1111.0059

Seminar at Osaka University, 1 February , 2012

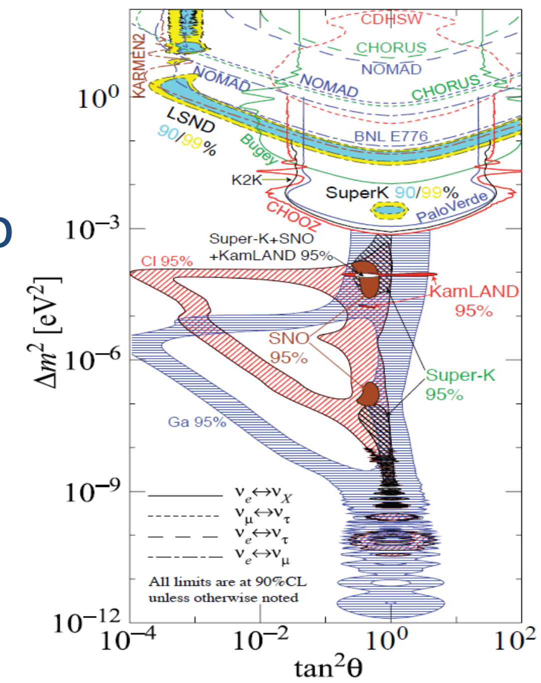
Introduction

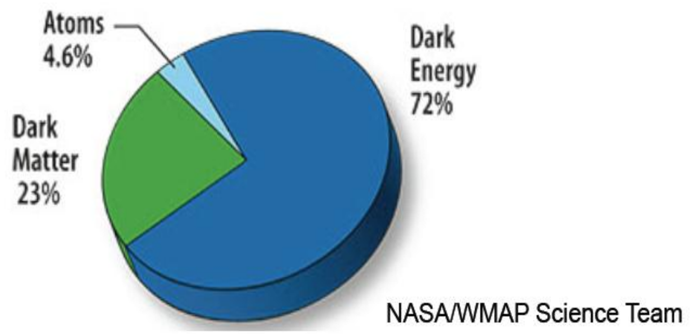
- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

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

WIMP Hypothesis

- Neutral, Non-relativistic , Stable

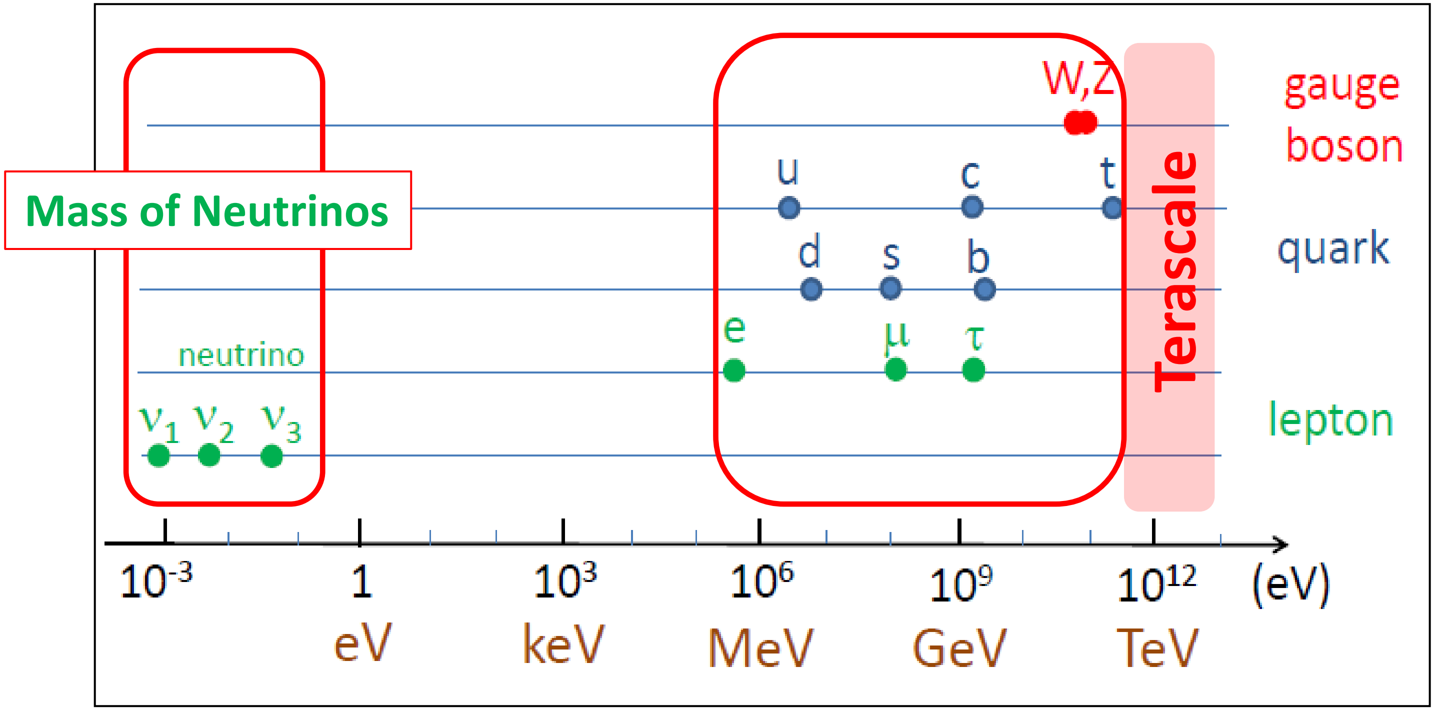
- Mass = 10-1000 GeV (WMAP)

$$\Omega h^2 = 0.1 \Rightarrow \sigma(DD \rightarrow XX) = O(1)\ \text{pb} \Rightarrow M_{DM} = 10\text{-}1000\text{GeV}$$

- Basic Questions
  - Which particle is DM?
  - What is the origin of the DM mass?
  - Why is M_{DM} similar to the scale of EWSB?
  - What is the origin of stability of DM?

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

BSM phenomenon: tiny neutrino mass



Why neutrino masses are tiny?

What is the origin of neutrino mass?

Dirac? Majorana?

BSM Phenomenon: Neutrino Mass

Neutirno Mass Term (= Effective dim-5 operator)

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

$\langle\phi\rangle = v = 246\text{GeV}$

Mechanism for tiny masses:

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

Seesaw (tree level)

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

$(M \gg 1\text{TeV})$

Quantum Effects   N-th order of perturbation theory

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

(M can be 1 TeV)

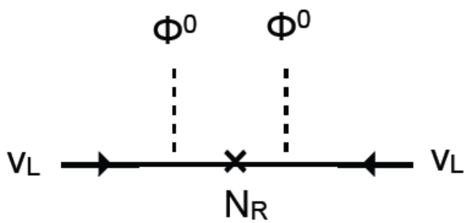
Seesaw Mechanism?

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

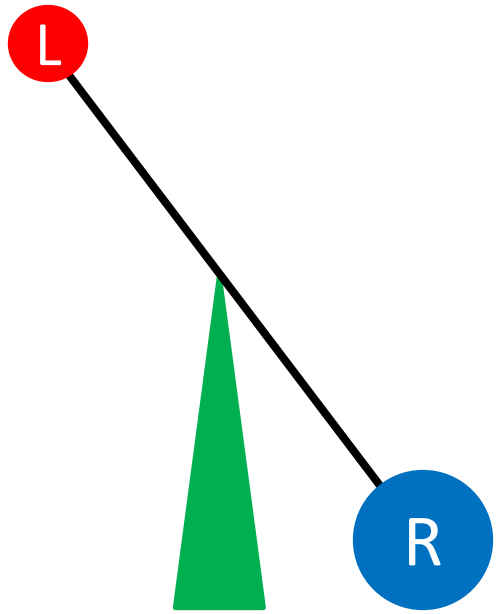
- Hierarchy between M_{NR} and m_D generates that between m_D and tiny m_ν ($m_D \sim 100$ GeV)

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

$\nu\nu\phi\phi$



Minkowski
Yanagida
Gell-Mann et al



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

Hierarchy for hierarchy!

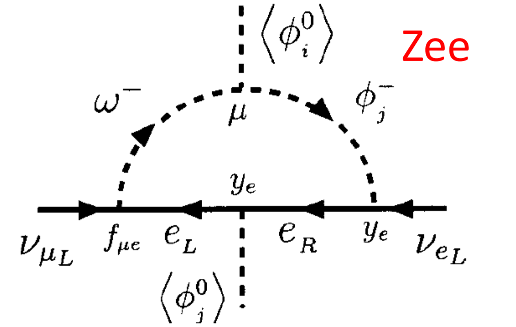
Far from experimental reach...

2 possibilities

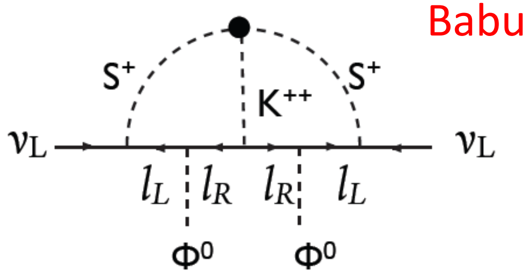
1) Scenario dependent on very high scales
   - Maybe compatible with canonical GUTs
   - Large mass hierarchy
   - A direct link to the GUT or Planck Scale?
   - Too high to be tested

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

Scenario of Radiative $\nu\nu\phi\phi$ generation

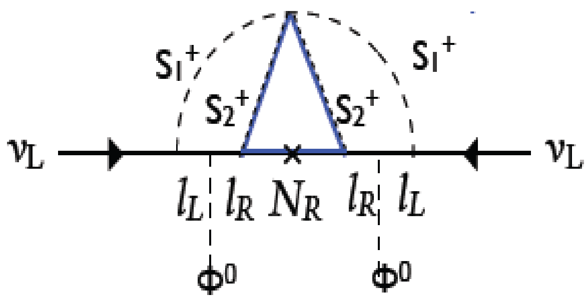


- Tiny ν-Masses come from loop effects
  - Zee (1980, 1985)
  - Zee, Babu (1988)
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), ...



- 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

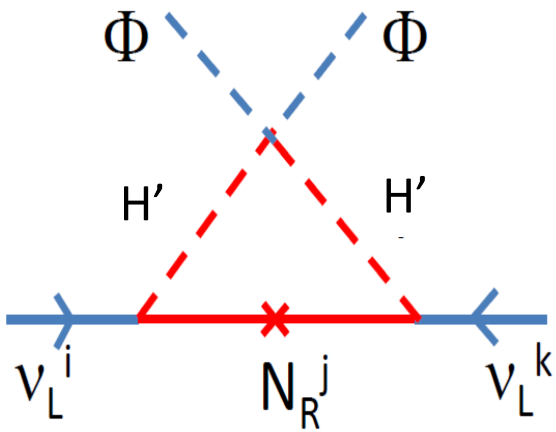


Krauss, Nasri, Trodden

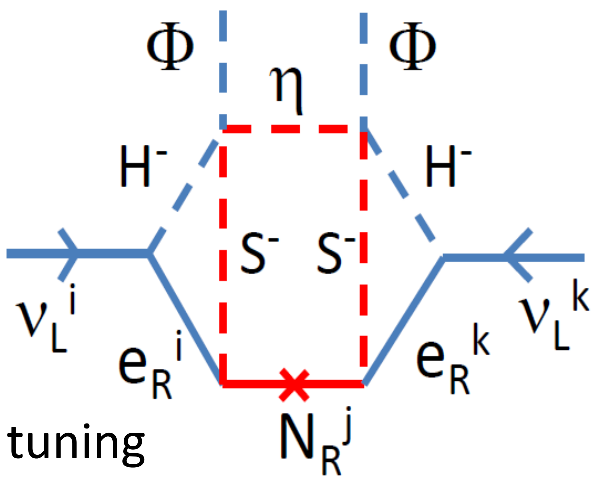
Radiative seesaw with Z_2

Z_2-parity plays roles:
1. No Yukawa coupling (Radiative neutrino mass)
2. Stability of the lightest Z_2 odd particle (DM)

Ex1) 1-loop Ma (2006)
- Simplest model
- SM + N_R + Inert doublet (H')
- DM candidate [H' or NR]



Ex2) 3-loop Aoki-Kanemura-Seto (2008)
- Neutrino mass from O(1) coupling
- 2HDM + η^0 + S^+ + N_R
- DM candidate [η^0 (or NR)]
- Electroweak Baryogenesis



All 3 problems may be solved by TeV physics w/o fine tuning

Questions on Radiative Seesaw with Z_2

- What is the origin of LNV at the TeV scale?
- What is the origin of the DM mass?
- Where the Z_2 parity come from?

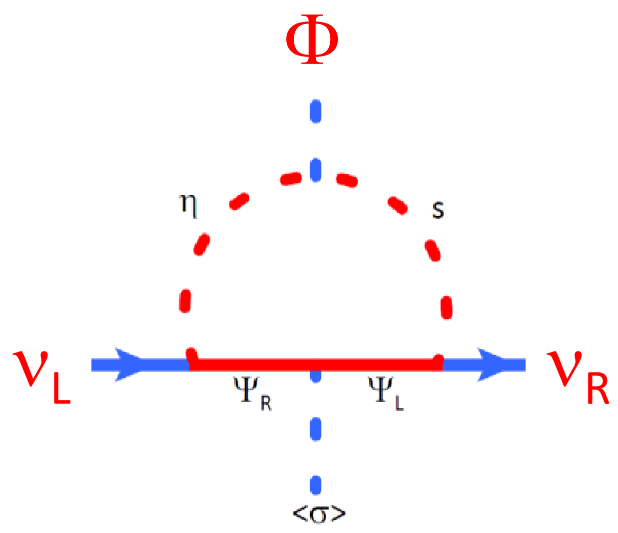
Gauged $U(1)_{B-L}$ would solve these problems

- LNV: SSB of $U(1)_{B-L}$ at the TeV scale
- DM mass: chiral for $U(1)_{B-L}$

  $\rightarrow$ Dirac fermion after the SSB
- Global $U(1)_{DM}$ as remnant of the SSB of $U(1)_{B-L}$

Phenomenological interest

- It is interesting if mass of ν_R is at TeV
- Seesaw Mechanism:
  - ν_R must be very heavy, if y=O(1)
- Radiative Seesaw:
  - ν_R can be at the TeV scale w/o fine tuning but it is Z_2-odd in many models
- Can we have mechanism to have a TeV scale Z_2-even ν_R w/o fine tuning ?
- Loop-induced Yukawa coupling!
- After the SSB of Lepton Number at the TeV scale, Type-I seesaw mechanism occurs with TeV-scale ν_R via the loop-induced Dirac Yukawa coupling

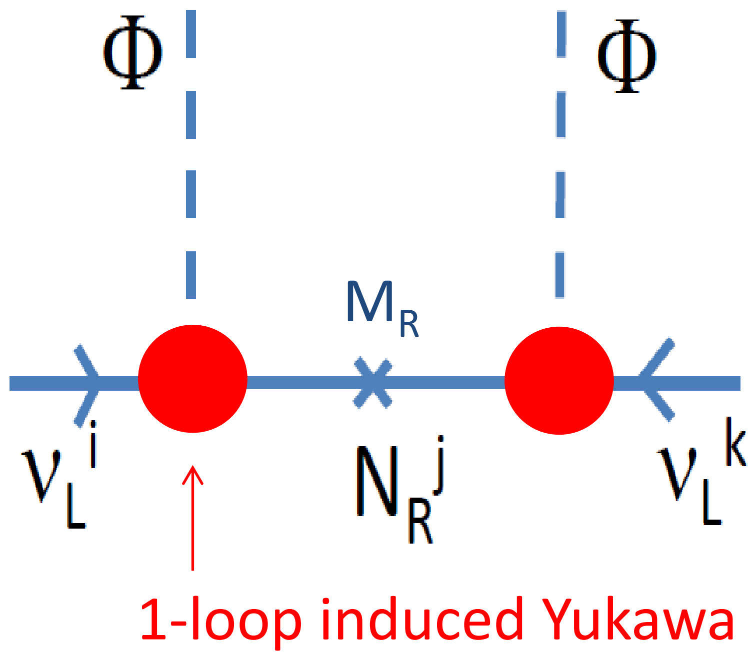


Loop-induced Dirac Yukawa coupling

$L\Phi\nu_R$

Raditative Type-I seesaw model

If Dirac Yukawa couplings are 1-loop induced, M_R can be at TeV scale or below w/o large fine tuning (g~0.1).



M_{NR} is naturally at TeV scale so that it is testable at LHC

In this model, ν_R is Z_2-even, so that it can decay into SM particles
DM candidate may be in the loop sub-diagram of Yukawa coupling

Our Model

S.K., T. Nabeshima, H. Sugiyama
arXiv: 1111.0059

$SU(3)_C$ X $SU(2)_l$ X $U(1)_Y$ X $U(1)_{B-L}$

- Z' : B-L gauge boson
- σ^0 : B-L Higgs
- $\nu_R{}^i$: RH-neutrino (i=1,2)
- $\Psi_{L,R}{}^i$: chiral (i=1,2)
- s^0 : singlet
- η : doublet

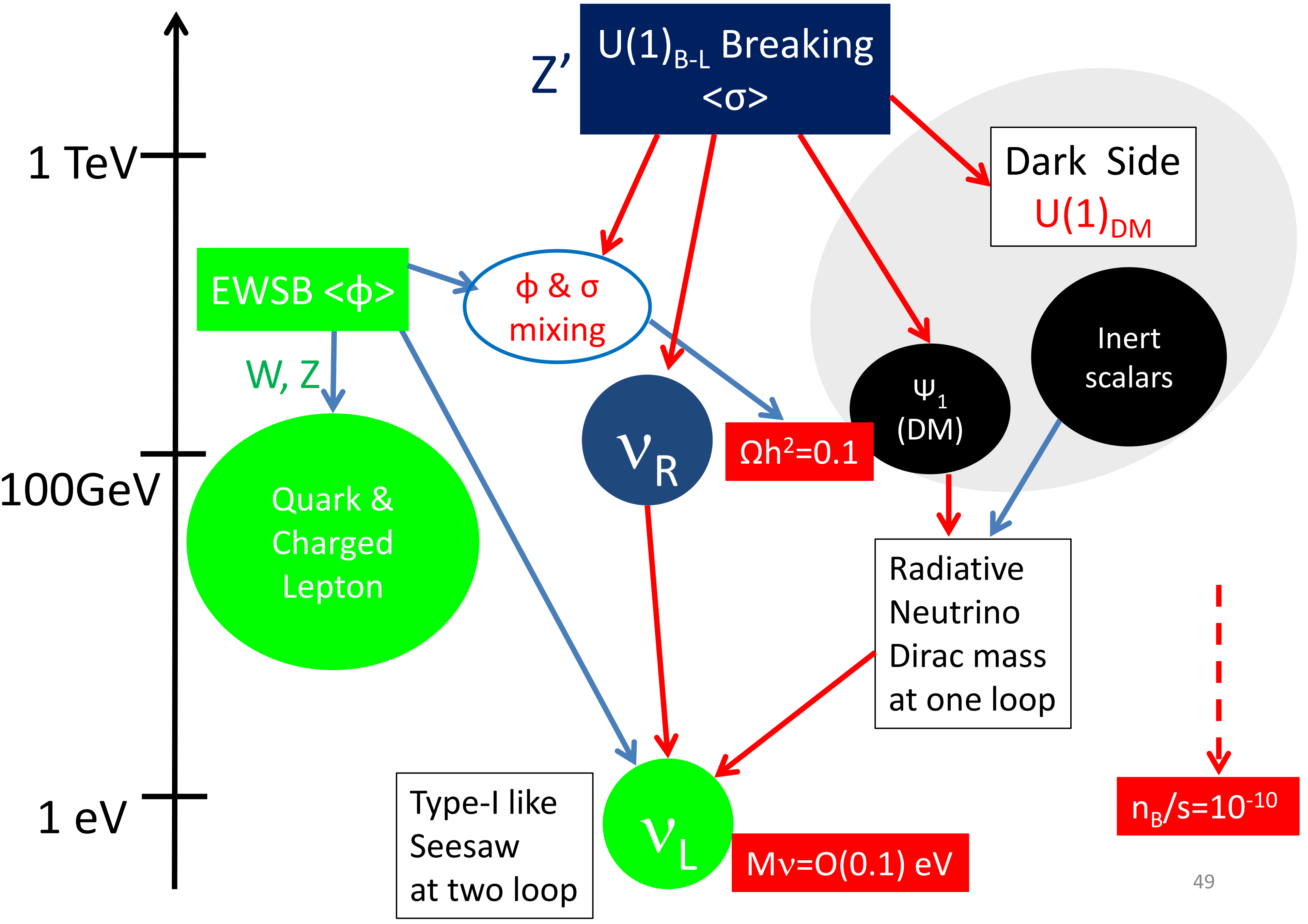
Particles	s^0	η	$(\Psi_R)_i$	$(\Psi_L)_i$	$(\nu_R)_i$	σ^0
$SU(3)_C$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$
$SU(2)_L$	$\underline{1}$	$\underline{2}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$
$U(1)_Y$	0	1/2	0	0	0	0
$U(1)_{B-L}$	1/2	1/2	−1/2	3/2	1	2

half-unit
B-L charge

Remnant global $U(1)_{DM}$ remains after SSB of B-L

$U(1)_{B-L}$ protects 1. Tree-level Yukawa $L\Phi\nu_R$ and
2. Majorana mass of ν_R
Chirality protects 3. Dirac mass of Ψ

Masses of ν_R and Ψ are generated by SSB of $U(1)_{B-L}$



U(1)$_{B-L}$ Breaking
<σ>
Z'
1 TeV
Dark Side
U(1)$_{DM}$
EWSB <ϕ>
ϕ & σ
mixing
W, Z
Inert
scalars
Ψ$_1$
(DM)
ν$_R$
Ωh^2=0.1
100GeV
Quark &
Charged
Lepton
Radiative
Neutrino
Dirac mass
at one loop
1 eV
Type-I like
Seesaw
at two loop
ν$_L$
n$_B$/s=10^{-10}
Mν=O(0.1) eV

$\cancel{U(1)}_{B\text{-}L}$ ⇒ Masses of Z', ν_R and Ψ

B-L gauge boson Z'

$m_{Z'} = 2g_{B\text{-}L}\, v_\sigma$ $\quad v_\sigma \;[= \sqrt{2}\langle\sigma^0\rangle]$

LEP bounds: $m_{Z'}/g_{B\text{-}L} = 2\, v_\sigma$ > 6-7 TeV ⇒ v_σ > 3-3.5 TeV

Weyl fermions ν_R, Ψ_L, Ψ_R

$$\mathcal{L}_{\rm Yukawa} = -\,(y_R)_i\,\overline{(\nu_R)_i^c}\,(\nu_R)_i\,(\sigma^0)^* - (y_\Psi)_i\,\overline{(\Psi_R)_i}\,(\Psi_L)_i\,(\sigma^0)^*$$

$$\boxed{m_{\nu_R} = \sqrt{2}\,y_R v_\sigma}$$

Majorana mass of ν_R

Ex) $m_{\nu R}$ = 200 GeV for y_R=0.05, v_σ = 3 TeV

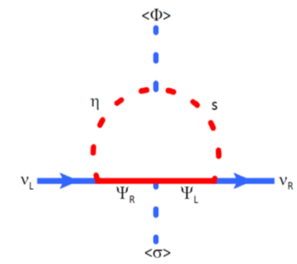
$$\boxed{m_\Psi = y_\Psi \frac{v_\sigma}{\sqrt{2}}}$$

Dirac mass of Ψ

Ex) m_ψ = 100 GeV for y_Ψ=0.05, v_σ = 3 TeV

$U(1)_{DM}$ ⇒ Lightest Ψ (Ψ^1) is the DM candidate

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



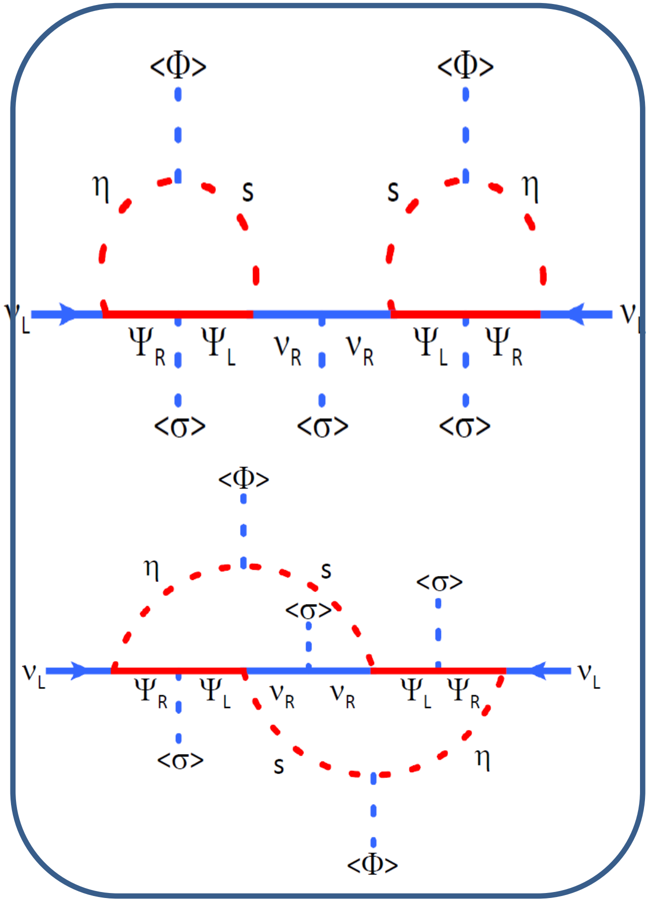
- No Yukawa $L\Phi\nu_R$ by the B-L charge assignment
- $\cancel{U(1)}_{B\text{-}L}$: Source of LNV v_σ → $m_{\nu R}$, m_Ψ
- $\cancel{U(1)}_{B\text{-}L}$: Remnant $U(1)_{DM}$
- Radiative generation of the operator $L\Phi\nu_R\sigma$
- Seesaw mechanism → Majorana mass of ν_L

$$\boxed{(m_\nu)_{\ell\ell'} = \left(\frac{1}{16\pi^2}\right)^2 f_{\ell i} h_{ia} (m_R)_a (h^T)_{aj} (f^T)_{j\ell'} \frac{(8\pi^2 \sin 2\theta)^2 m_{\Psi_i} m_{\Psi_j}}{(m_R)_a^2}}$$

The correct neutrino mass O(0.1) eV can be deduced from TeV scale physics w/o fine tuning

- All mass parameters = O(0.1 - 1) TeV
- All coupling constants = O(0.1)

Mass structure is similar but not exactly same as the tree-level seesaw scenario.



S.K., T. Nabeshima, H. Sugiyama, arXiv: 1111.0059

A viable parameter set (Set A)

$$s_{23}^2 = \frac{1}{2}, \quad s_{13}^2 = 0, \quad s_{12}^2 = \frac{1}{3},$$
$$\Delta m_{21}^2 = 7.5 \times 10^{-5}\,\mathrm{eV}^2, \quad |\Delta m_{31}^2| = 2.3 \times 10^{-3}\,\mathrm{eV}^2.$$

Coupling constants are all O(0.01 -0.1)

Masses are O(0.1-1) TeV

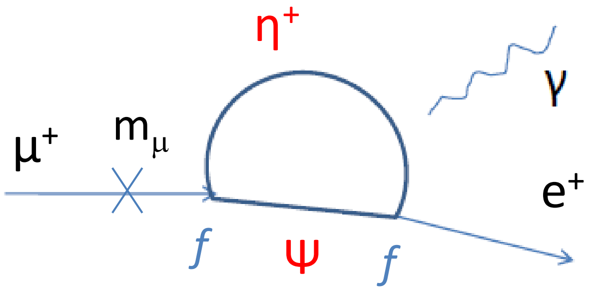
Among Ψ, s^0, η which have $U(1)_{DM}$ charge, Ψ^1 is the DM candidate

$f_{\ell i}$	$\begin{pmatrix} -0.00726 & 0.00667 \\ -0.0523 & 0.0206 \\ -0.0378 & 0.00723 \end{pmatrix}$
h_{ij}	$\begin{pmatrix} -0.119 & 0.150 \\ 0.150 & 0.150 \end{pmatrix}$
$(y_3)_{ij}$	$\begin{pmatrix} 0.0152 & 0.0152 \\ 0.0152 & 0.0152 \end{pmatrix}$
$m_R \equiv (m_R)_1 = (m_R)_2$	$250\,\mathrm{GeV}$
$\{m_{\Psi_1},\ m_{\Psi_2}\}$	$\{57.0\,\mathrm{GeV},\ 800\,\mathrm{GeV}\}$
$\{m_{h^0},\ m_{H^0},\ \cos\alpha\}$	$\{120\,\mathrm{GeV},\ 140\,\mathrm{GeV},\ 1/\sqrt{2}\}$
$\{m_{s_1^0},\ m_{s_2^0},\ \cos\theta\}$	$\{200\,\mathrm{GeV},\ 300\,\mathrm{GeV},\ 0.05\}$
$m_{\eta^\pm}$	$280\,\mathrm{GeV}$
$g_{\mathrm{B-L}}$	0.2
$m_{Z'}$	$2000\,\mathrm{GeV}$

LFV constraint

Ψ and η (have U(1)$_{DM}$ charge) contribute to μ→eγ process

$$\boxed{\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\mathrm{EM}}}{64\pi G_F^2}\left|\frac{1}{m_{\eta^\pm}^2} f_{\mu i} F_2\left(\frac{m_{\Psi_i}^2}{m_{\eta^\pm}^2}\right)(f^\dagger)_{ie}\right|^2}$$



Experimental upper bound

Br(μ→eγ) < 2.4 × 10^{-12}

is satisfied

$$F_2(a) \equiv \frac{1 - 6a + 3a^2 + 2a^3 - 6a^2 \ln(a)}{6(1-a)^4}$$

For Set A, it is evaluated as

Br(μ→eγ) = 5.1 × 10^{-13}

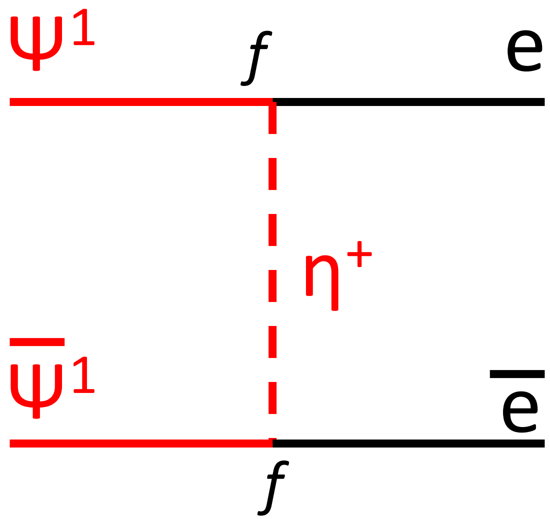
Safe against the current bound but can be future experimental reach

Thermal relic abundance of Ψ^1

Remnant $U(1)_{DM}$ Dirac fermion

Ψ^1 is dark matter candidate

$\boxed{\text{WMAP: } \Omega h^2=0.11}$



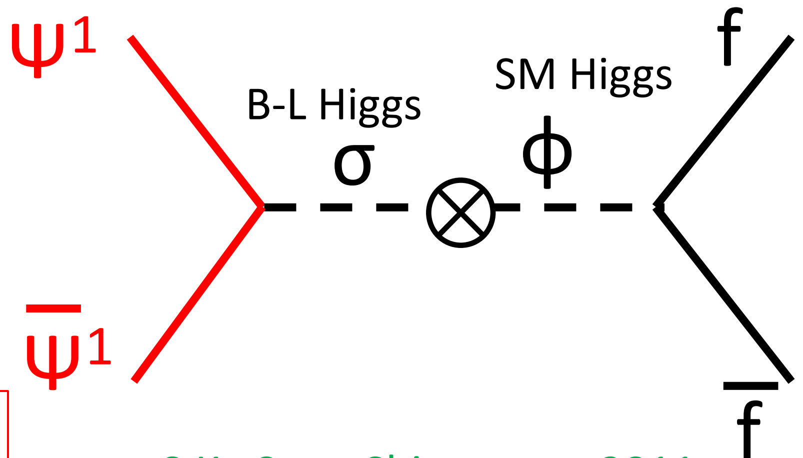
t-channel contributions

Small due to LFV

Annihilation not enough due to TeV scale η and small coupling f

s-channel (Higgs portal)

resonance can be used



Mixing between B-L Higgs σ and SM Higgs ϕ is essentially important

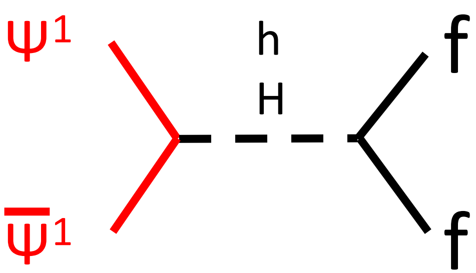
S.K., Seto, Shimomura 2011
Okada, Seto, 2010

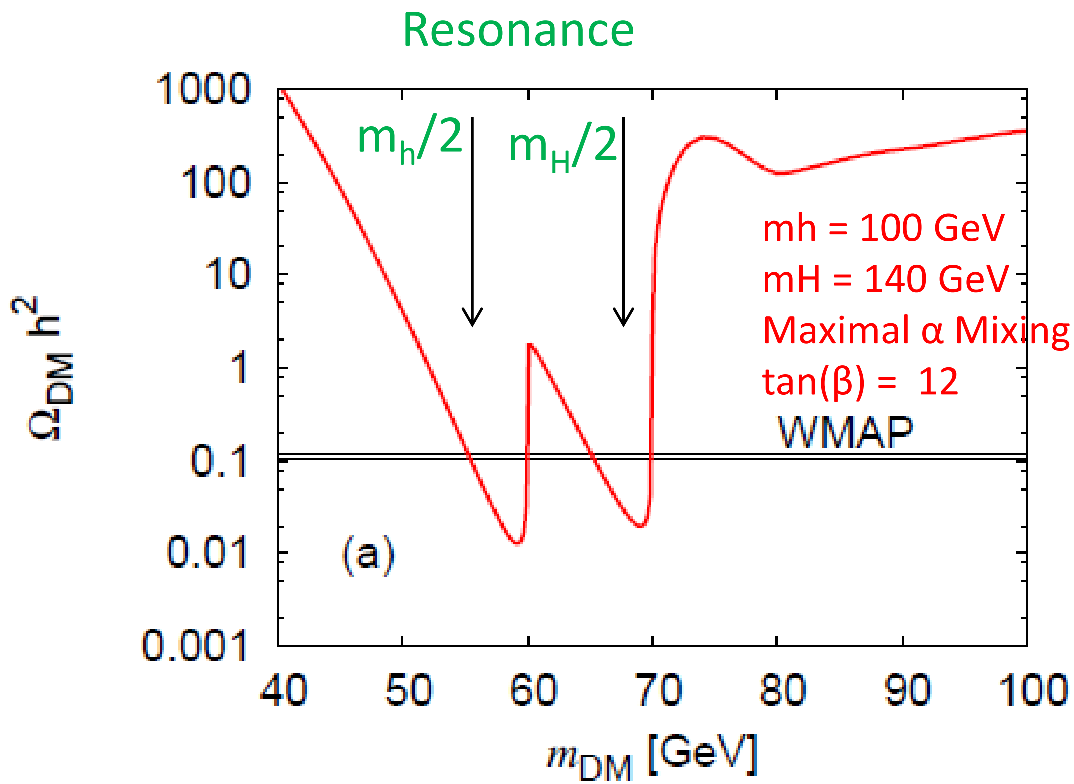
Thermal Relic Abundance of Ψ^1

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

Mass Eigenstates

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \phi_r^0 \\ \sigma_r^0 \end{pmatrix}$$





Ψ can explain Ωh^2=0.11, so that Ψ^1 can be a Dirac DM

Direct searches

Ex) XENON 100 Results

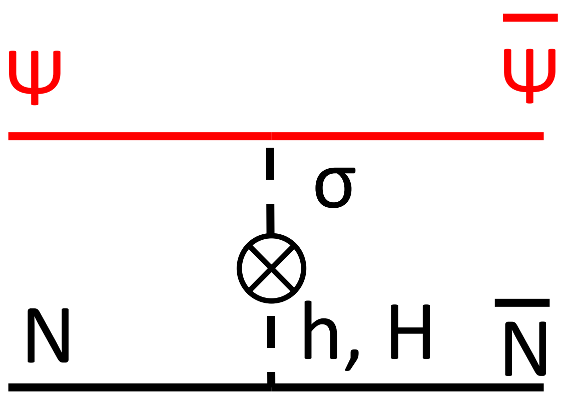
$$\boxed{\sigma(\Psi_1 N \to \Psi_1 N) < 8 \times 10^{-45}\,\mathrm{cm}^2}$$

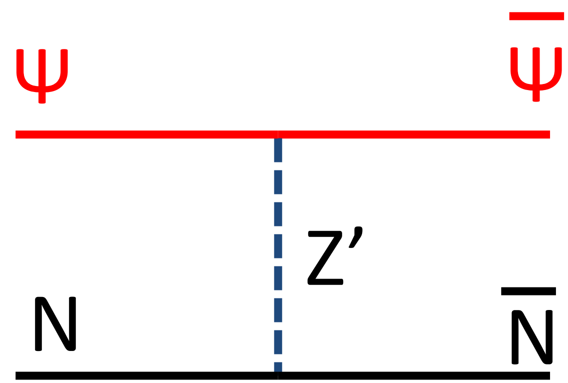
E. Aprile et al, PRL107,131302 (2011)

Prediction in our model for set A

$$\sigma(\Psi_1 N \to \Psi_1 N) = 2.7 \times 10^{-45}\,[\mathrm{cm}^2]$$

Z' mediation dominant





Testable at ILC and the future direct detection experiments

Parameters

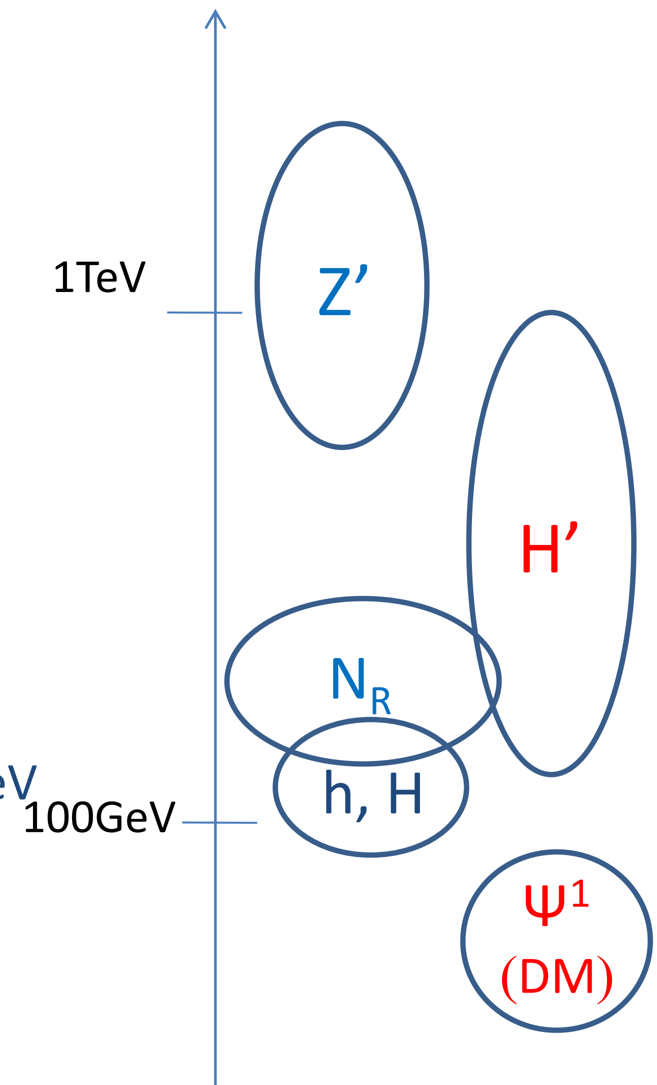
Mass Spectrum

Inputs

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

Vs =3-4 TeV
V =246 GeV

Mh=O(100) GeV
MH=O(100)GeV
Sinα = 1/Sqrt[2]
tanβ=12-15
MNR=50 GeV
mZ'= 1000-2000 GeV
g=y=λ5=O(0.01-0.1)
Particle mass =O(0.1-1) TeV



Multi Higgs [h and H]

Large Mixing [$\alpha \sim \pi/4$] [$\leftarrow$ $\Omega h^2 = 0.11$]

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

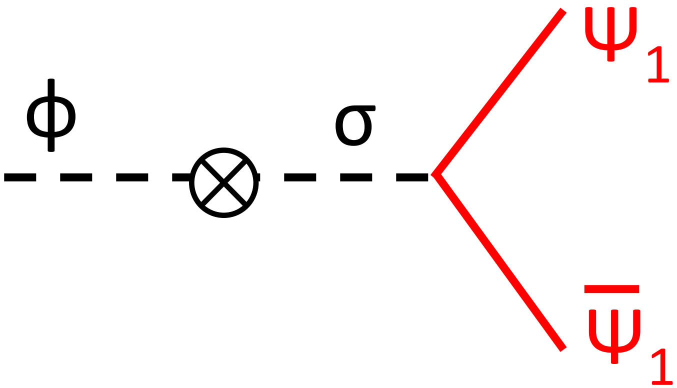
Two SM-like light Higgs bosons with about a half width

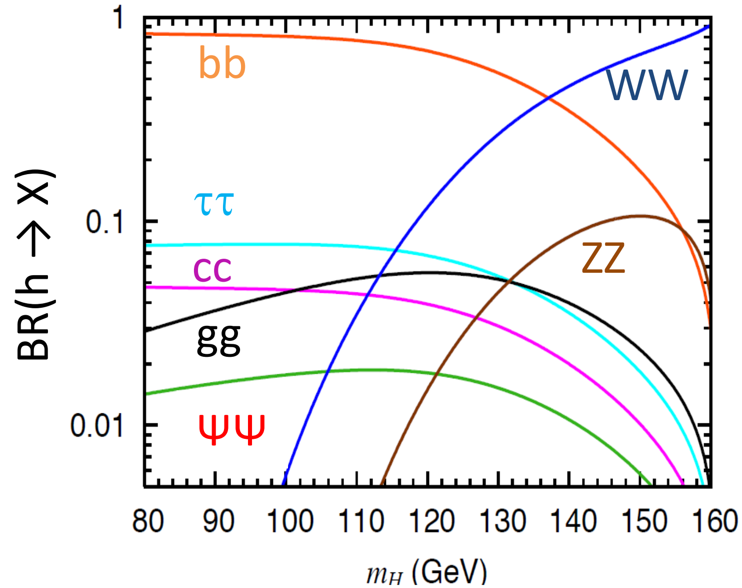
Similar to Type I 2HDM, but no charged Higgs states H^+, H^-.

Easily testable at the LHC and the ILC

Invisible Higgs decays

Higgs decays into $\Psi_1\overline{\Psi}_1$ via the same coupling as the DM annihilation





$\Gamma(h \rightarrow \text{invisible}) \sim 1 - 2\ \%$

$\Gamma(H \rightarrow \text{invisible}) \sim 3 - 4\ \%$

ILC may be able to test the Higgs invisible decay at the 1 %level

Physics of Z'

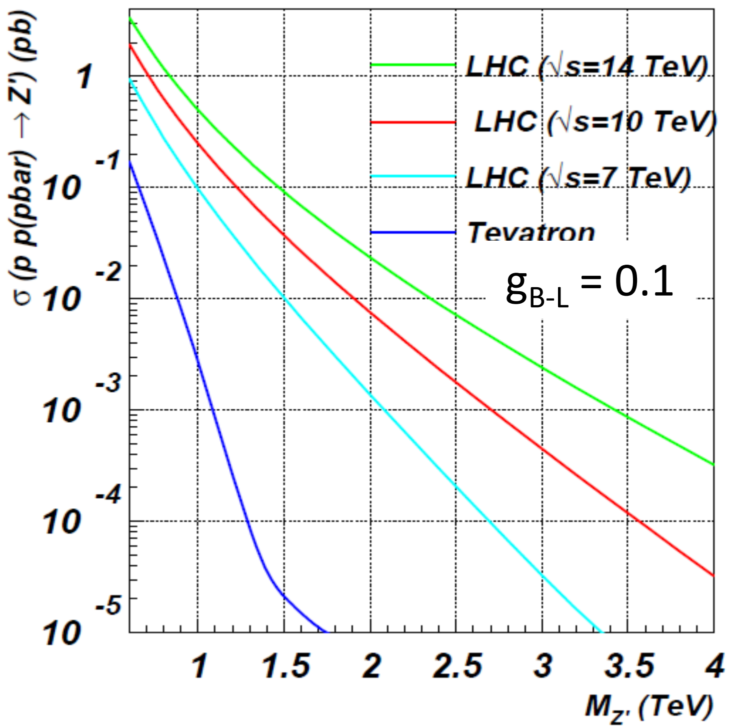
Z' Mass: 500GeV – a few TeV

$\Gamma(Z' \to XX) \propto$ (B-L charge)^2

Decay rates determined by B-L charges

Invisible decay = 40 %

$Z' \to \nu_L \nu_L$	0.15
$Z' \to \Psi_1 \Psi_1$	0.13
$Z' \to \Psi_2 \Psi_2 \to \nu_L \nu_L \Psi_1 \Psi_1$ etc	0.12



Basso, et al (2009)

Production Cross section at the LHC:

For v_S = 3.5 TeV and m_Z'=2TeV, we have g_{B-L}=0.2, then

$\sigma(pp \to Z')$ = 70 fb

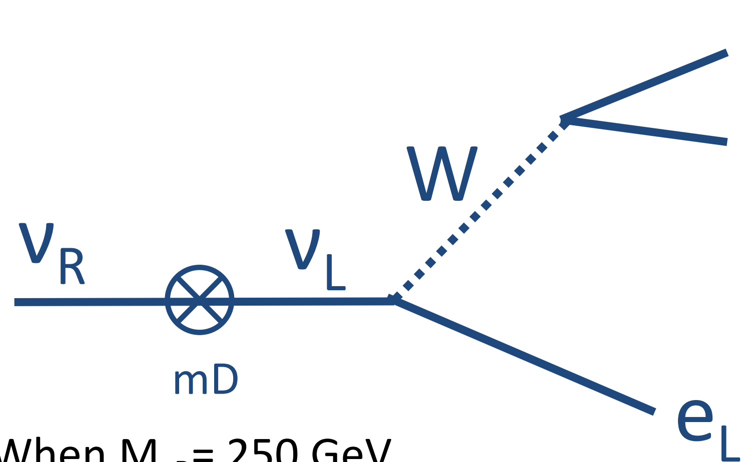
Model can be tested by measuring (invisible) decays of the Z' boson

7000 of Z' are produced for $100 fb^{-1}$

light RH neutrinos

- light RH neutrinos are a good feature of the scenario of radiative Dirac masses
- RH neutrinos are produced from Z’
- It decays via Dirac mass term
- Reconstructing jje or jjμ, RH neutrino can be tested at the LHC/ILC/CLIC

$\mathrm{BR}(\nu_R \to XY)$			
$W^{\pm}\ell^{\mp}$	$Z\nu_L$	$h^0\nu_L$	$H^0\nu_L$
0.53	0.28	0.10	0.09



When $M_{\nu R}$= 250 GeV
1200 pairs of ν_R from 7000 Z’
at LHC with 14 TeV/70 fb^{-1}

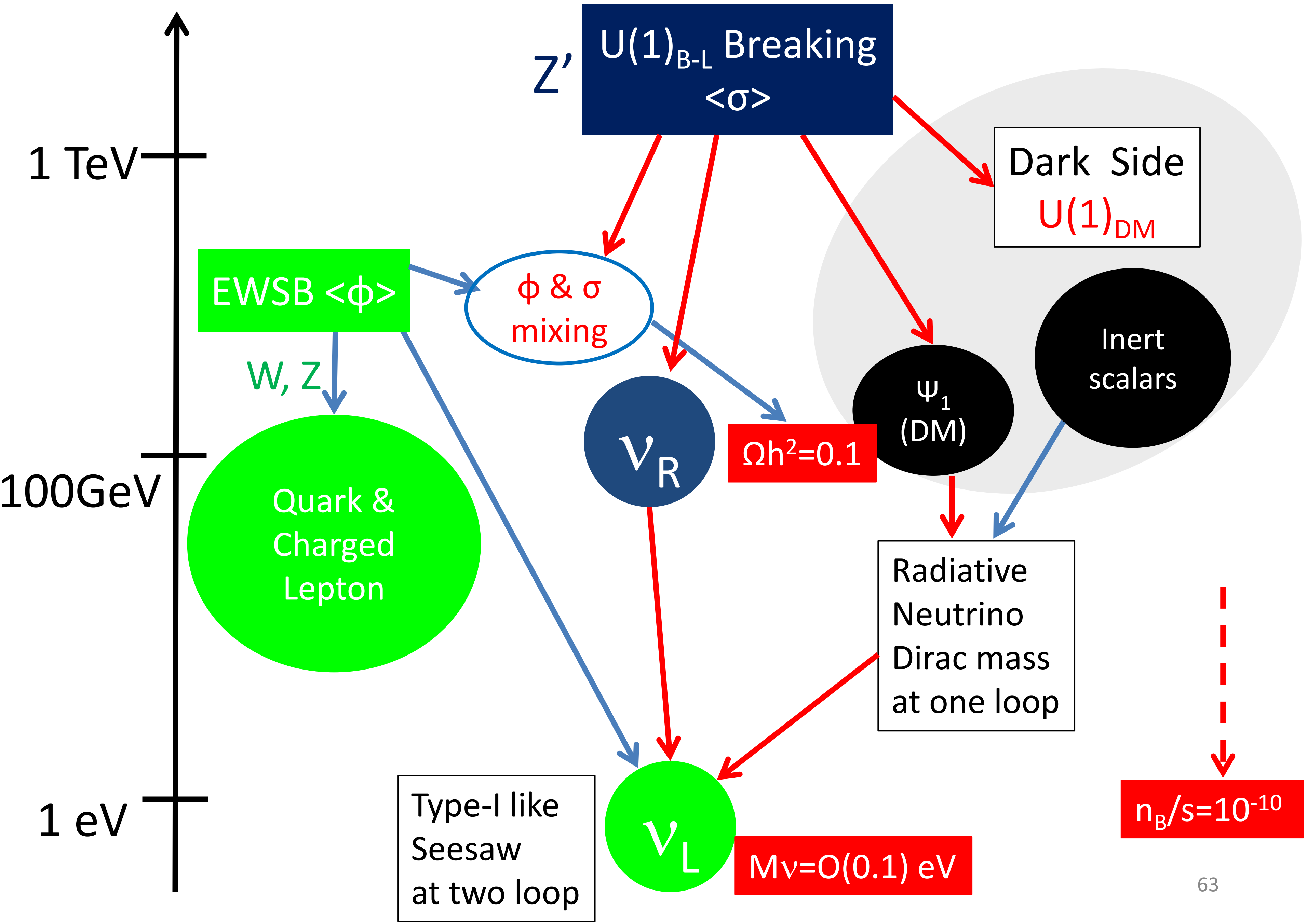
The process $pp \to W^{+*} \to e^+e^+jj$
can also be useful

Summary

- Radiative seesaw scenario is interesting:

  Natural scale of neutrino mass, dark matter

  Testability and strong connection with EWSB
- A model with the gauged $U(1)_{B\text{-}L}$ (SSB at the multi TeV scale)
- After the SSB of B-L , a remnant global $U(1)_{DM}$ forbids neutrino Yukawa couplings at tree and also guarantees stability of DM.
- The SSB also gives Dirac mass of Ψ^1 (DM) as well as Majorana mass of ν_R at tree level, Dirac Yukawa coupling is also induced at one-loop
- Type-I seesaw occurs at two-loop level, and tiny neutrino masses can be explaind w/o excessive fine tuning
- A light ν_R (O(100)GeV) , unique Higgs sector (two SM-like Higgs bosons) and Z' physics are predicted (testable at colliders)



1 TeV
100GeV
1 eV
Z'
U(1)$_{B-L}$ Breaking
<σ>
Dark Side
U(1)$_{DM}$
EWSB <ϕ>
ϕ & σ mixing
W, Z
ν_R
Ωh²=0.1
Ψ_1 (DM)
Inert scalars
Quark & Charged Lepton
Radiative Neutrino Dirac mass at one loop
Type-I like Seesaw at two loop
ν_L
Mν=O(0.1) eV
$n_B/s=10^{-10}$