Neutrino mass, dark matter and baryogenesis from the supersymmetric gauge theory with confinement

Naoki Machida (U. of Toyama)

Collaborators : Shinya Kanemura (U. of Toyama)

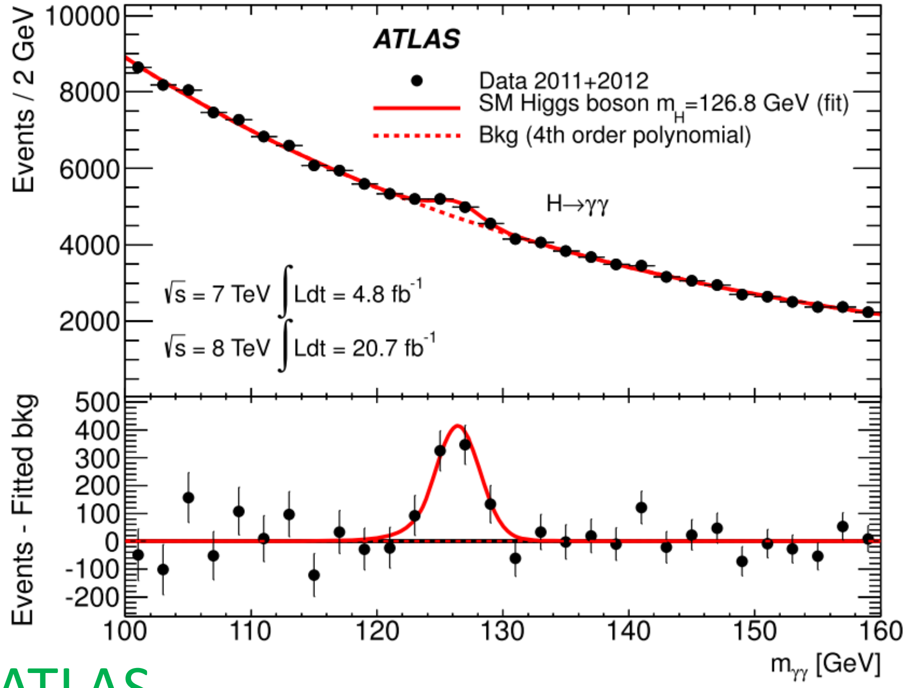
Tetsuo Shindou (Kogakuin U.)

The 37th ILC KEK General Meeting 2014/06/21

Contents

Introduction

The SM-like Higgs boson has been discovered at the LHC.



ATLAS

- The mass is 126 GeV.
- Spin/parity is 0^+ .
- Coupling constants are consistent with the SM.
- No other new particles are found.

The SM is very successful!

Introduction

The SM-like Higgs boson has been discovered at the LHC.

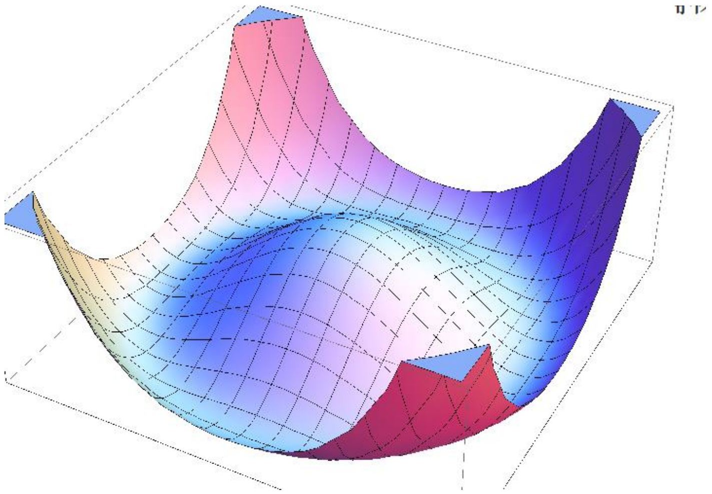
$$V_{\rm SM} = \frac{1}{2}\mu^2|\Phi_{\rm SM}|^2 + \frac{1}{4}\lambda_{\rm SM}|\Phi_{\rm SM}|^4$$

- One Higgs doublet, Minimal form $\Phi_{\rm SM}$ ← No principle

- EWSB by negative mass suare $\mu^2 < 0$
- Higgs force $\lambda_{\rm SM}$

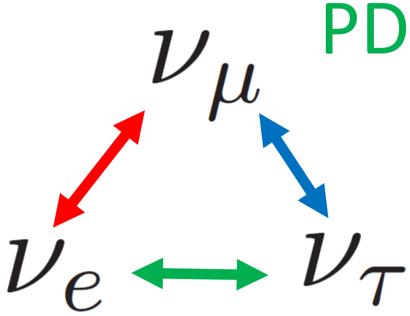
← What is origin?

We do not know the essence of Higgs sector.



Problems in the SM

- Neutrino mass

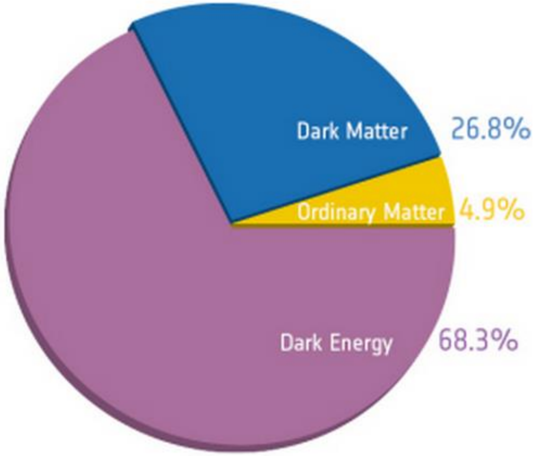


PDG

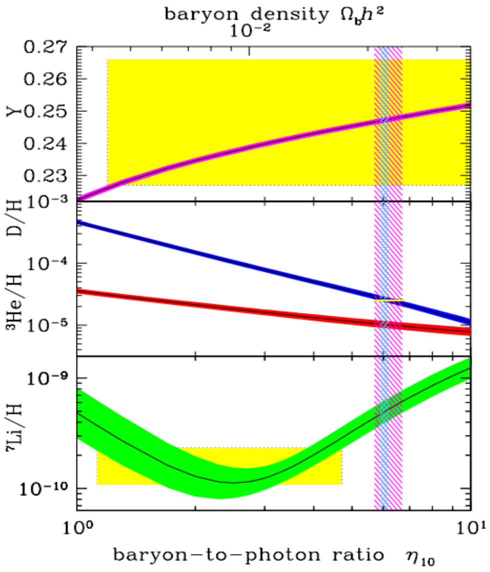
$$7.32 < \frac{\Delta m_{21}^2}{10^{-5}\mathrm{eV}^2} < 7.80,$$
$$2.33 < \frac{|\Delta m_{31}^2|}{10^{-3}\mathrm{eV}^2} < 2.49,$$
$$0.291 < \sin^2\theta_{12} < 0.325,$$
$$0.365 < \sin^2\theta_{23} < 0.410,$$
$$0.0216 < \sin^2\theta_{13} < 0.0266.$$

- Dark matter

Planck



- Baryon asymmetry of the Universe



PDG

These problems can not be explained in the SM.

New physics beyond the SM must exist.

New physics and Extended Higgs sector

Minimal Higgs sector Φ_{SM} ← No principle

Extended Higgs sectors

SM doublet + Singlet
SM doublet + Doublet
SM doublet + Triplet
SM doublet + ,,,,

Extended Higgs sector can explain new physics.

Dark Matter
Baryogenesis
Neutrino mass

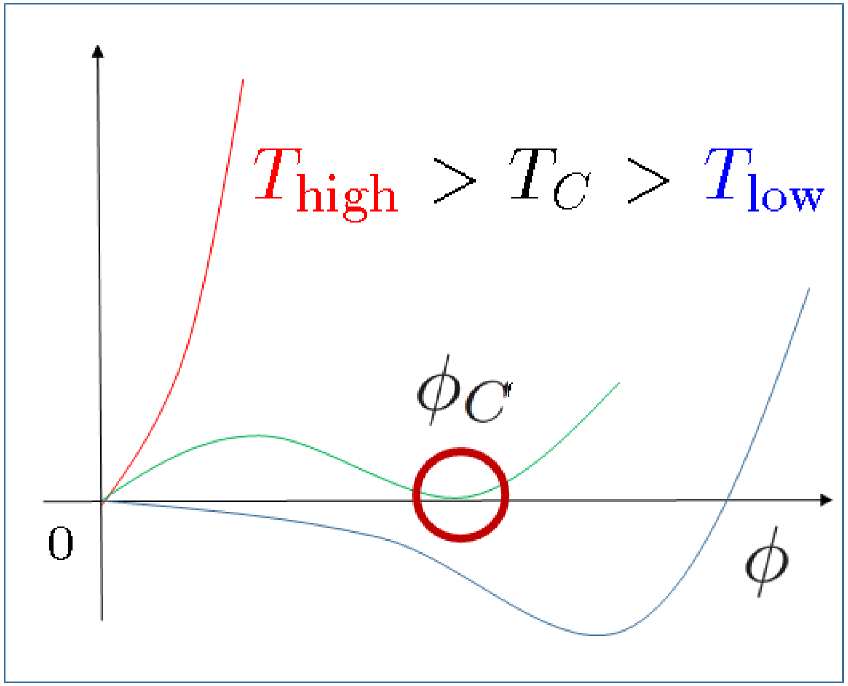
Inert scalar
C and CP violation / 1st order phase transition
Type-II seesaw, Radiative seesaw

Electroweak Baryogenensis : 1st Order Phase Transition

Sakharov's conditions

$$\boxed{\phi_C/T_C \gtrsim 1}$$

1. C and CP violation
2. B-number violation
3. **Departure from thermal equilibrium**



High temperature expansion

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

In the SM,

Conflict!

$$\phi_C/T_C \propto 1/m_h^2 \to m_h < \cancel{50}\,\mathrm{GeV}$$

1st Order Phase Transition and *hhh* coupling in 2HDM

However, two Higgs doublet model can satisfy $\phi_C/T_C \gtrsim 1$.

Extra scalar boson loops enhance ϕ_C/T_C .

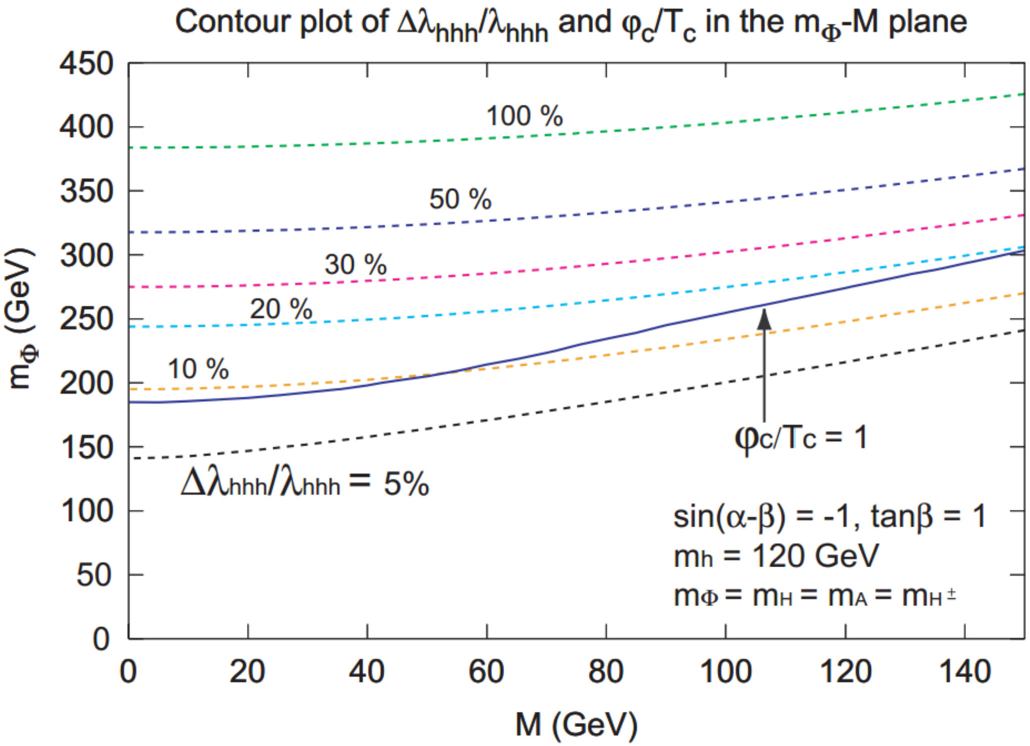
$$\boxed{H, A, H^{\pm}} \quad m_\Phi^2 = M^2 + \lambda_i v^2$$

Kanemura, Okada, Senaha (2005)

Non-decoupling effect deviates *hhh*, O(10) % .

It can be tested.

There are C and CP violation terms.



Neutrino mass : Radiative seesaw scenario

- Inert scalars and Z2-odd right-handed neutrinos are introduced.
- Tiny neutrino masses are generated by loop-level diagram.
- The lightest Z2-odd particle can be DM candidate.

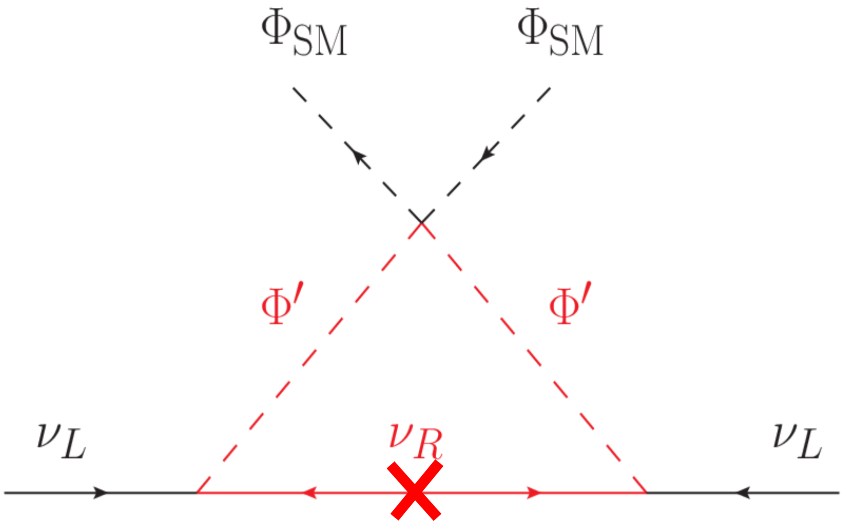
Ma model

Ma (2006)

Φ' : Inert scalar doublet

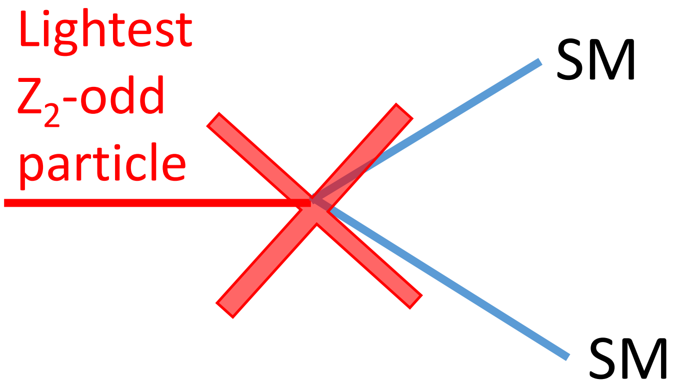
ν_R : Z_2-odd right-handed neutrinos

- Neutrino mass diagram



- Dark matter

Because of unbroken Z_2 symmetry, lightest Z_2-odd particle is a dark matter candidate.



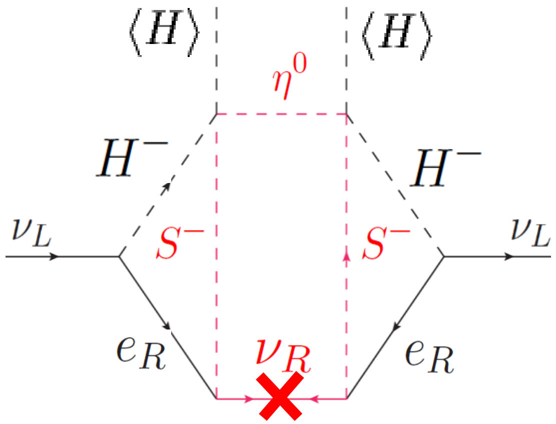
Aoki-Kanemura-Seto model

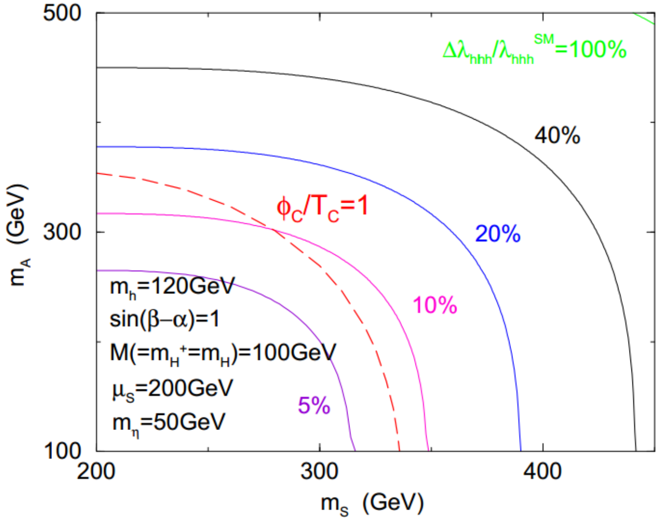
M. Aoki, S. Kanemura, O. Seto
PRL. 102 (2009) 051805

This model can explain neutrino mass, dark matter and baryogenesis.

Higgs sector $\Phi_{SM} + \Phi_2 + S^{\pm} + \eta^0 + \nu_R$ Z_2-odd

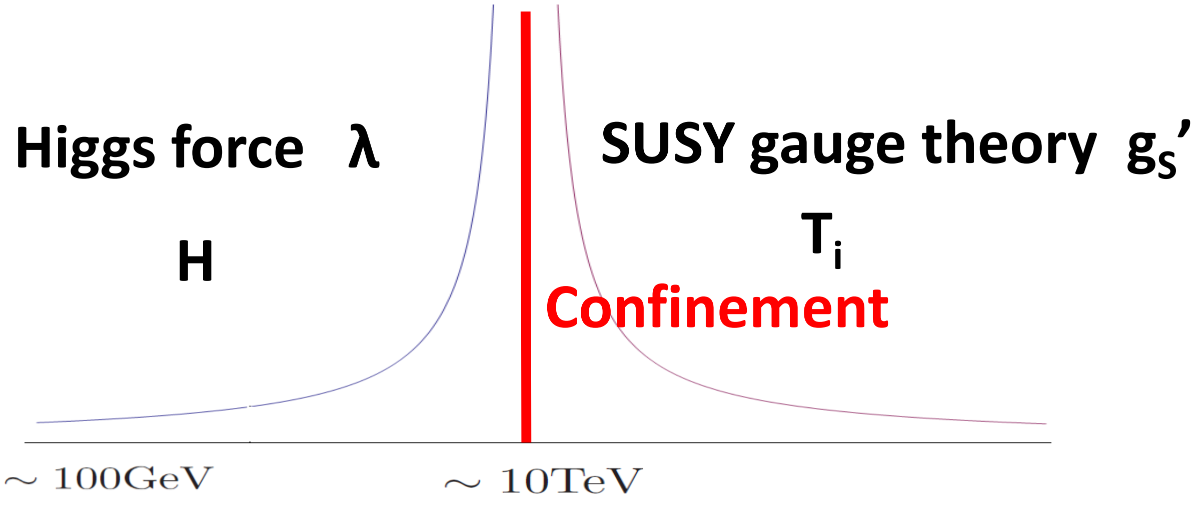
- Neutrino mass and dark matter are similar to the Ma model.
  - ◆Tiny neutrino mass is generated by three loop diagram.
  - ◆Unbroken Z_2 symmetry guarantees DM stability.
- Electroweak baryogenesis
  - ◆Extra boson loops enhance ϕ_C/T_C , so that $\phi_C/T_C \gtrsim 1$ can be satisfied.
  - ◆This model contains 2 doublets so that there are C and CP violation source.





What is a fundamental theory?

- Electroweak baryogensis requires strong coupling constant in the Higgs sector. This leads Landau pole at O(10)TeV.
- Origin of the Higgs force is SUSY gauge theory with confinement above Landau pole.
- Higgs sector at low energy scale is composite states which is formed by fundamental fields. $H_{ij} \sim T_i T_j$



Higgs force **λ**

H

SUSY gauge theory **g_S’**

T_i

Confinement

SUSY SU(2)$_H$ gauge theory

Intriligator, Seiberg
Nucl.Phys.Proc.Sup
pl.45BC:1-28,1996

SUSY QCD : $\boxed{N_f = N_C + 1}$ → Confinement

$\boxed{N_f = 3,\ \ N_c = 2}$

Kanemura, Shindou, Yamada,
PRD86 055023

Harnik, Kribs, Larson, Murayama,
PRD70 015002

UV picture Fundamental fields

Field	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	$\mathbf{2}$	0	$+$
T_3	$\mathbf{1}$	$+1/2$	$+$
T_4	$\mathbf{1}$	$-1/2$	$+$
T_5	$\mathbf{1}$	$+1/2$	$-$
T_6	$\mathbf{1}$	$-1/2$	$-$

T$_i$: SU(2)$_H$ doublet

IR picture Composite fields

MSSM doublets

Exotic fields

Field	$SU(2)_L$	$U(1)_Y$	Z_2
H_u	2	$+1/2$	$+$
H_d	2	$-1/2$	$+$
Φ_u	2	$+1/2$	$-$
Φ_d	2	$-1/2$	$-$
Ω^+	1	$+1$	$-$
Ω^-	1	-1	$-$
$N,\ N_\Phi,\ N_\Omega$	1	0	$+$
$\zeta,\ \eta$	1	0	$-$

$$H_{ij} \sim T_i T_j$$

We introduce Z$_2$-symmetry and Z$_2$-odd RH-neutrino to realize radiative seesaw scenario.

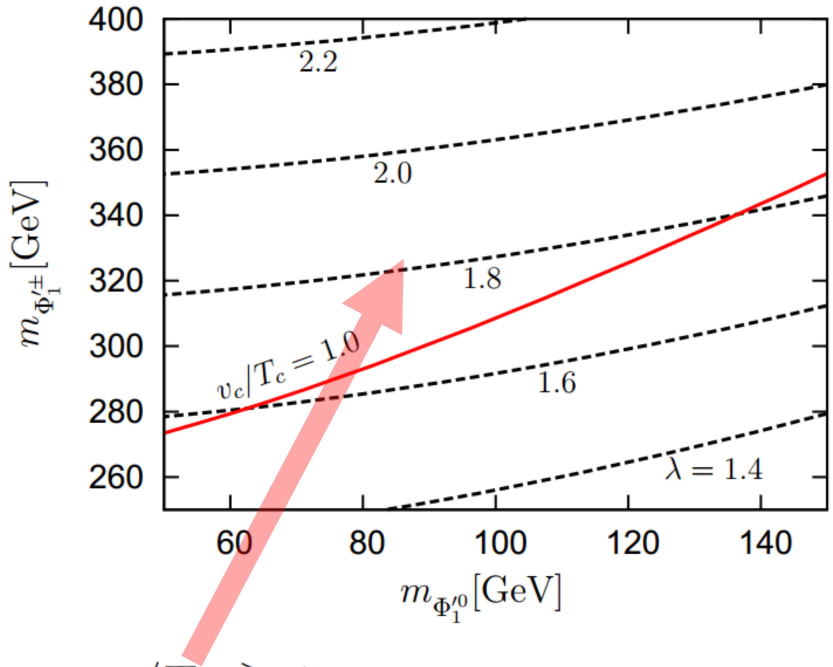
In the Fat Higgs model, Hu, Hd and N are light. Other fields are decoupled by introducing additional fields.

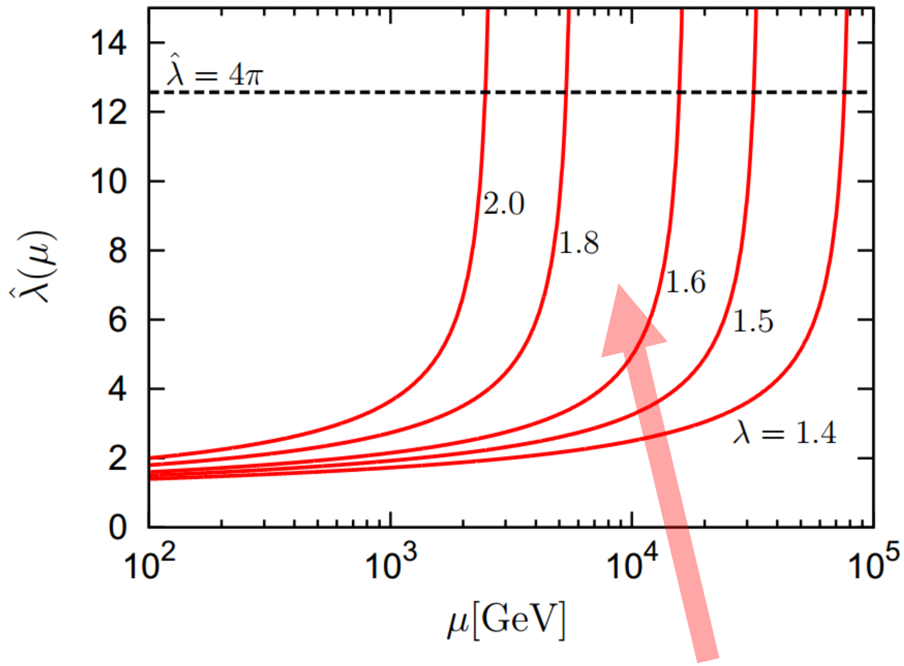
Effective superpotential & Electroweak Baryogenesis

$$W_{\rm dyn} = -\frac{1}{\Lambda^3}\epsilon^{ijklmn}H'_{ij}H'_{kl}H'_{mn} \qquad H'_{ij} = T_i T_j$$

Kanemura, Senaha, Shindou, Yamada, PRD86 055023

$$W_{\rm eff} = -\lambda N(H_u H_d + v_0^2) - \mu_\Phi \Phi_u \Phi_d - \mu_\Omega(\Omega^+\Omega^- - \zeta\eta)$$
$$+\lambda\{H_d\Phi_u\zeta + H_u\Phi_d\eta - H_u\Phi_u\Omega^- - H_d\Phi_d\Omega^+\}$$



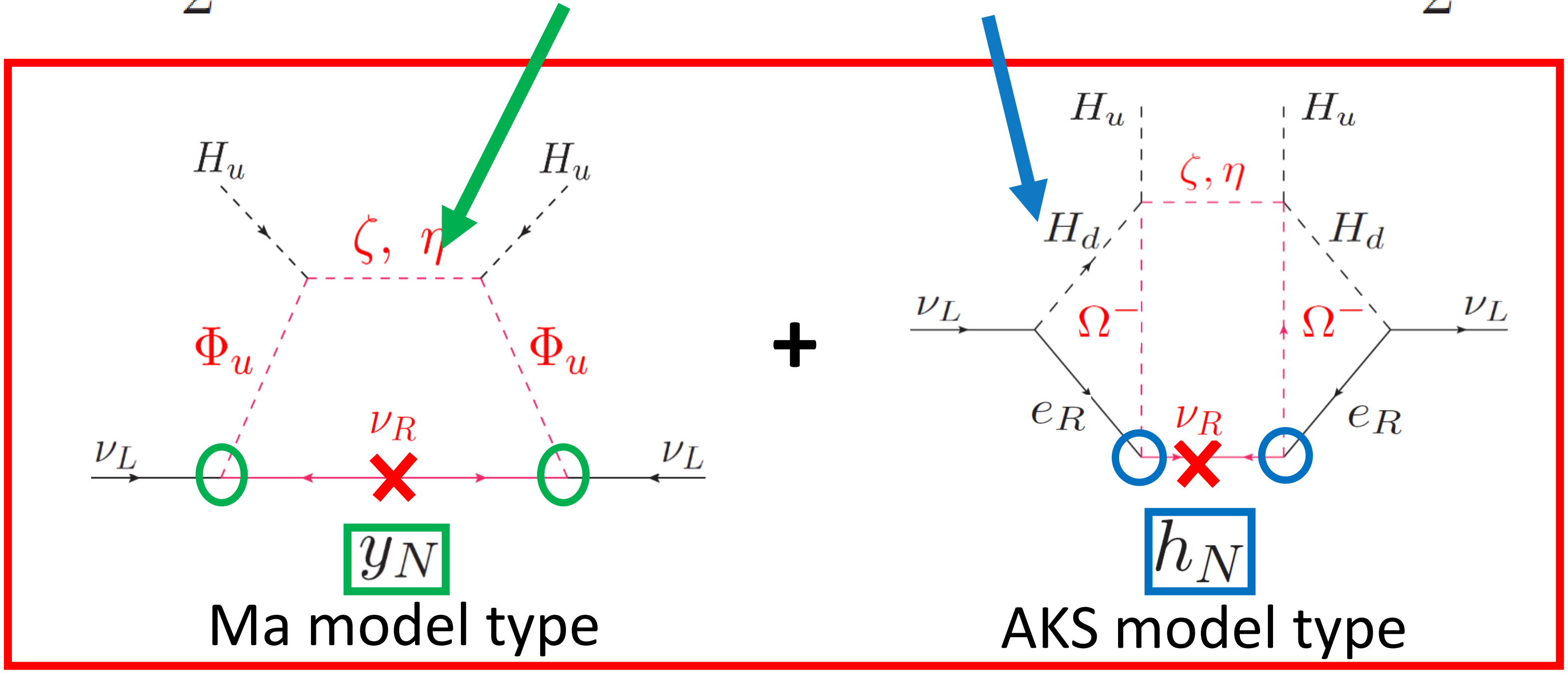


◆ $v_C/T_C \gtrsim 1$ requires $\lambda > 1.6$.

◆Landau pole exists around 10 TeV .

Hybrid radiative seesaw with one RH-neutrino ν_R

$$W_{\rm eff}^N = \frac{\kappa}{2} N \nu_R^c \nu_R^c + y_N^i \nu_R^c L_i \Phi_u + h_N^i \nu_R E_i^c \Omega^- + \frac{M}{2} \nu_R^c \nu_R^c$$



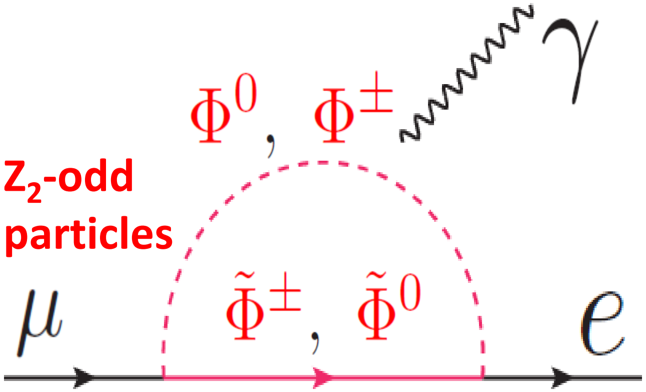
Ma model type

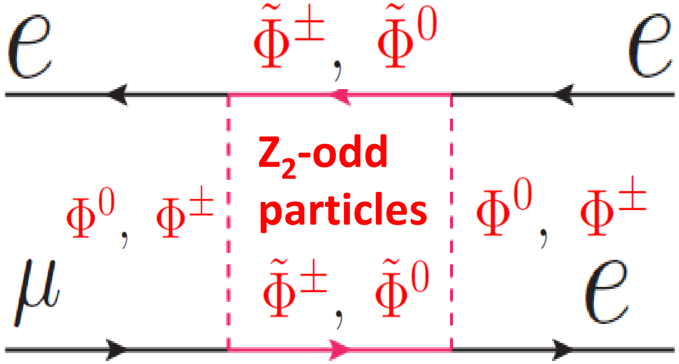
AKS model type

Two diagrams are naturally induced.
All scalars contribute to neutrino mass.

Lepton Falvour Violation

Z_2-odd particles contribute to LFV processes.





Current experimental bounds

$$\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

$$\mathrm{Br}(\mu \to 3e) < 1.0 \times 10^{-12}$$

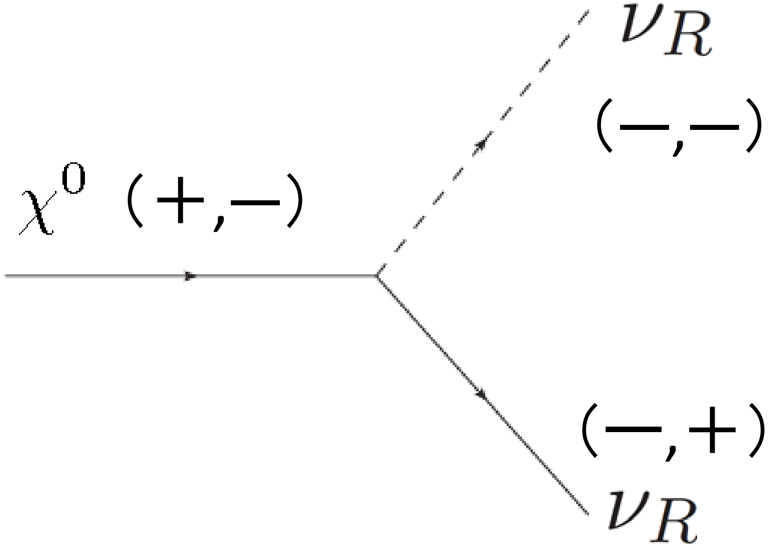
MEG:arXiv:1303.0754v2 [hep-ex] 23 Apr 2013
PDG, Phys. Rev. D**86**, 010001 (2012)

Multi-component dark matter

In general, there are three DM candidates,
(Z2,R)~(+,−),(−,+),(−,−).

$$\Omega_{\rm DM}h^2 = \sum_i \Omega_{\rm DM_i}h^2 \simeq 0.12$$

In benchmark scenario, the lightest neutralino is not DM.



The lightest neutralino decay into RH-neutrino and RH-sneutrino.

$$m_{\chi^0} > m_{\tilde{\nu}_R} + m_{\nu_R}$$

RH-neutrino and RH-sneutrino are DM candidates.

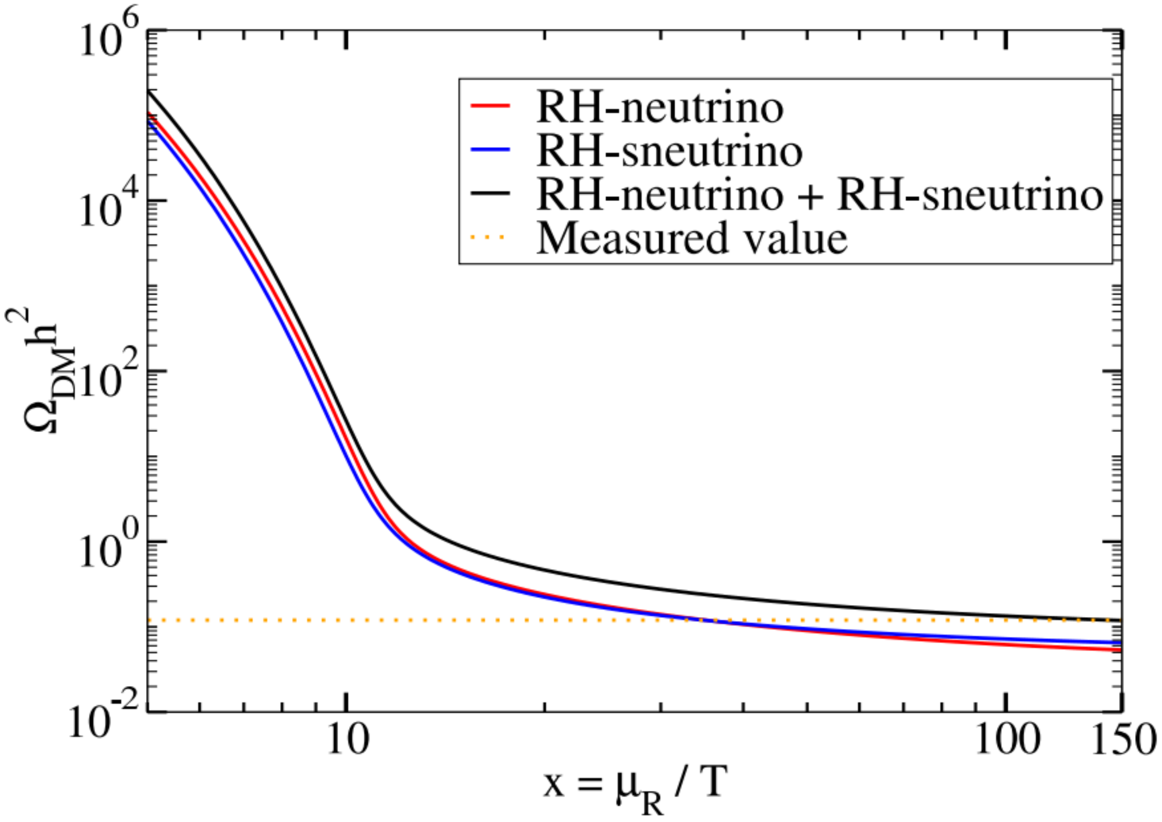
Boltzmann-equation

Annihilation

Conversion

$$\frac{dY}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right) \times \left\{ \boxed{-\langle\sigma_\nu v\rangle \left(Y^2 - Y_{\rm eq}^2\right)} \boxed{- \langle\sigma_{\nu\tilde{\nu}} v\rangle \left(Y^2 - \tilde{Y}^2 \frac{Y_{\rm eq}^2}{\tilde{Y}_{\rm eq}^2}\right) + \langle\sigma_{\tilde{\nu}\nu} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right)} \right\}$$

$$\frac{d\tilde{Y}}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right) \times \left\{ \boxed{-\langle\sigma_{\tilde{\nu}} v\rangle \left(\tilde{Y}^2 - \tilde{Y}_{\rm eq}^2\right)} \boxed{- \langle\sigma_{\tilde{\nu}\nu} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) + \langle\sigma_{\nu\tilde{\nu}} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right)} \right\}$$



$$x = \frac{\mu_R}{T}$$

$$\mu_R^{-1} = m_{\nu_R}^{-1} + m_{\tilde{\nu}_R}^{-1}$$

$$m_{\nu_R} = 63\text{GeV}$$

$$m_{\tilde{\nu}_R} = 65\text{GeV}$$

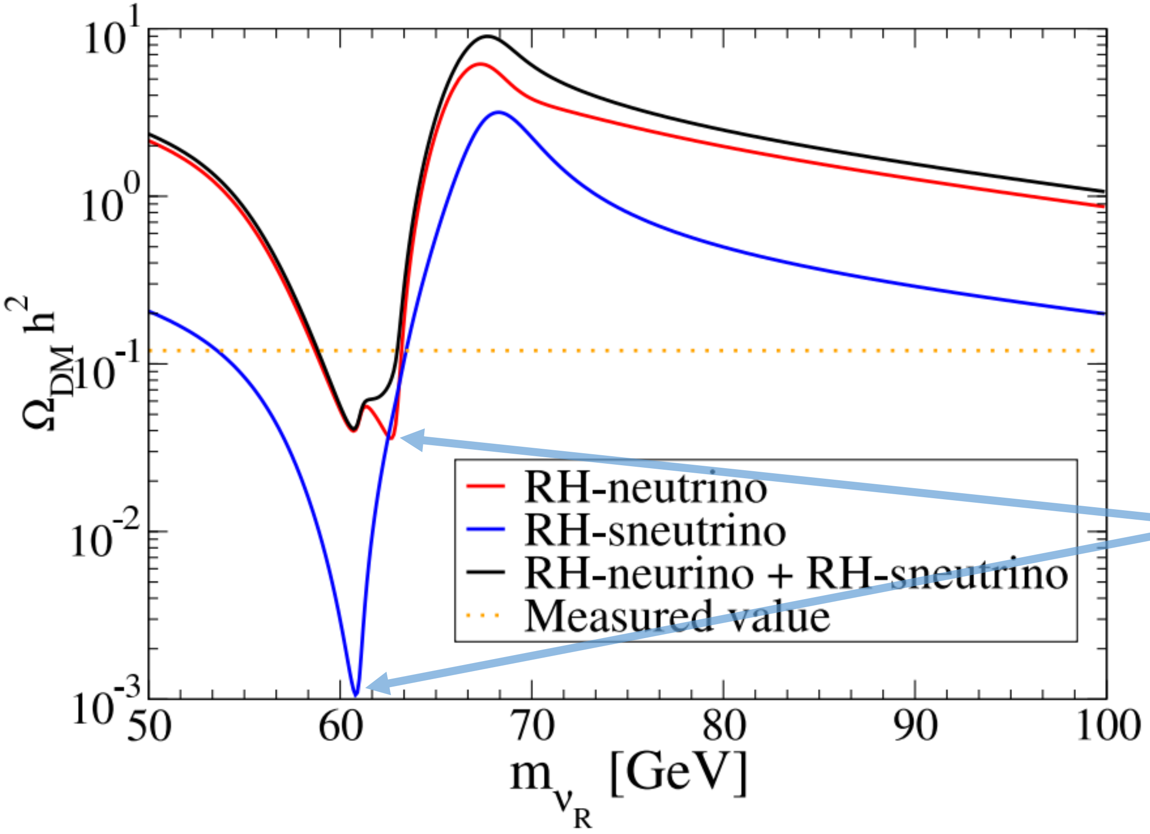
Boltzmann-equation

Annihilation

Conversion

$$\frac{dY}{dx} = 0.264 g_*^{1/2}\left(\frac{\mu_R M_P}{x^2}\right)\times\left\{\boxed{-\langle\sigma_\nu v\rangle\left(Y^2 - Y_{\rm eq}^2\right)}\ \boxed{-\langle\sigma_{\nu\tilde\nu}v\rangle\left(Y^2 - \tilde Y^2 \frac{Y_{\rm eq}^2}{\tilde Y_{\rm eq}^2}\right) + \langle\sigma_{\tilde\nu\nu}v\rangle\left(\tilde Y^2 - Y^2\frac{\tilde Y_{\rm eq}^2}{Y_{\rm eq}^2}\right)}\right\}$$

$$\frac{d\tilde Y}{dx} = 0.264 g_*^{1/2}\left(\frac{\mu_R M_P}{x^2}\right)\times\left\{\boxed{-\langle\sigma_{\tilde\nu} v\rangle\left(\tilde Y^2 - \tilde Y_{\rm eq}^2\right)}\ \boxed{-\langle\sigma_{\tilde\nu\nu}v\rangle\left(\tilde Y^2 - Y^2 \frac{\tilde Y_{\rm eq}^2}{Y_{\rm eq}^2}\right) + \langle\sigma_{\nu\tilde\nu}v\rangle\left(\tilde Y^2 - Y^2\frac{\tilde Y_{\rm eq}^2}{Y_{\rm eq}^2}\right)}\right\}$$



$$x = \frac{\mu_R}{T}$$

$$\mu_R^{-1} = m_{\nu_R}^{-1} + m_{\tilde\nu_R}^{-1}$$

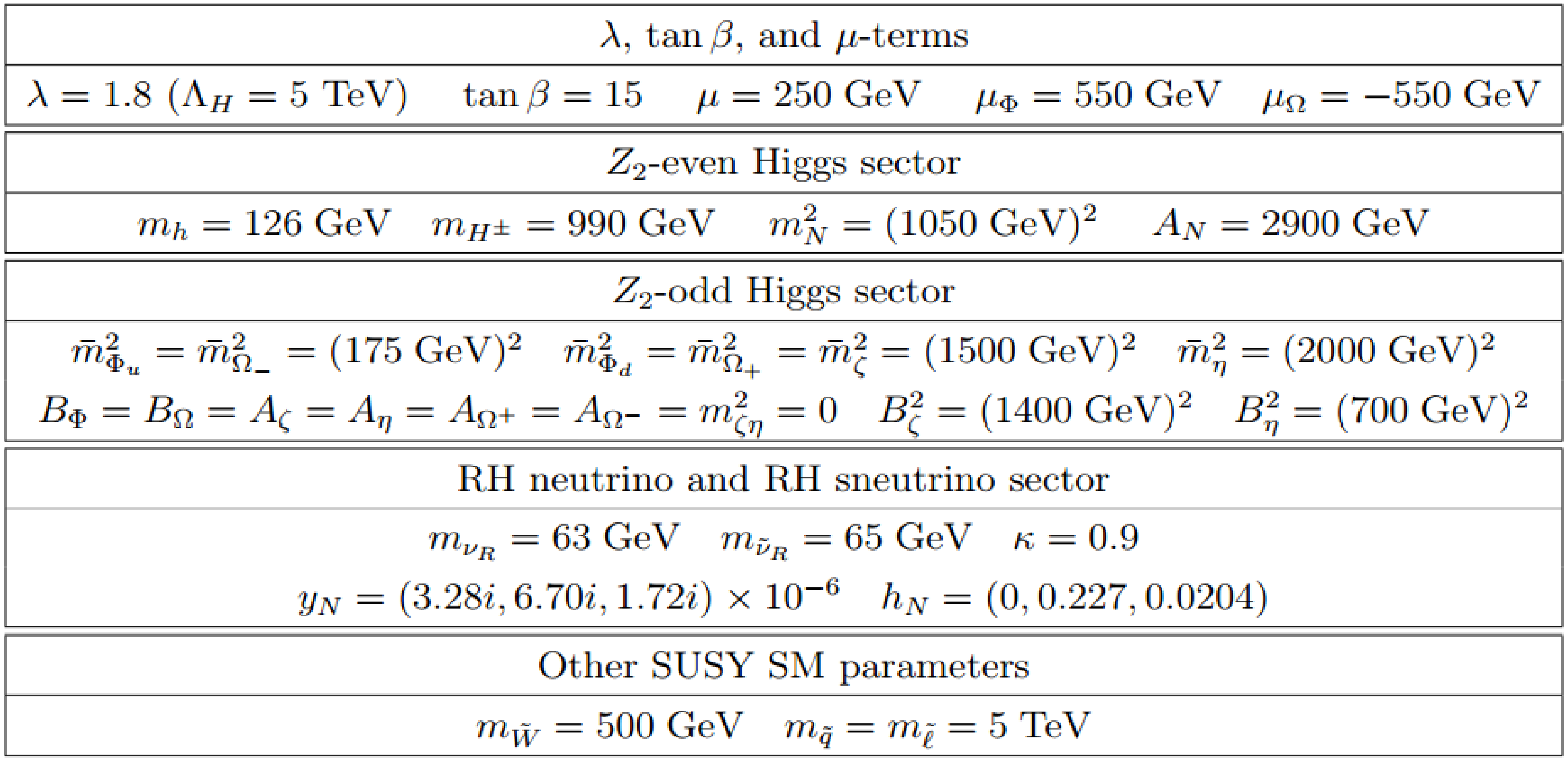
We assume

$$m_{\tilde\nu_R} = m_{\nu_R} + 2\mathrm{GeV}$$

The SM-like Higgs boson resonance ~ 63 GeV

Benchmark

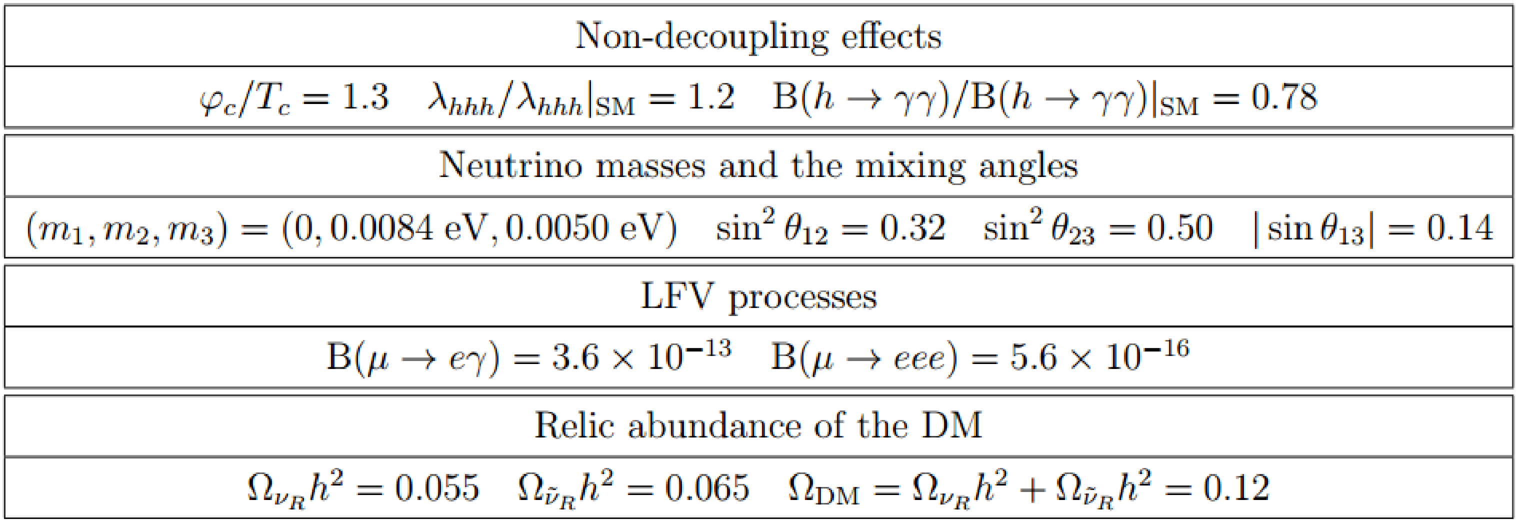
Input parameters



λ, $\tan\beta$, and μ-terms
$\lambda = 1.8$ ($\Lambda_H = 5$ TeV) $\quad \tan\beta = 15 \quad \mu = 250$ GeV $\quad \mu_\Phi = 550$ GeV $\quad \mu_\Omega = -550$ GeV
Z_2-even Higgs sector
$m_h = 126$ GeV $\quad m_{H^\pm} = 990$ GeV $\quad m_N^2 = (1050\text{ GeV})^2 \quad A_N = 2900$ GeV
Z_2-odd Higgs sector
$\bar{m}^2_{\Phi_u} = \bar{m}^2_{\Omega_-} = (175\text{ GeV})^2 \quad \bar{m}^2_{\Phi_d} = \bar{m}^2_{\Omega_+} = \bar{m}^2_\zeta = (1500\text{ GeV})^2 \quad \bar{m}^2_\eta = (2000\text{ GeV})^2$ $B_\Phi = B_\Omega = A_\zeta = A_\eta = A_{\Omega+} = A_{\Omega-} = m^2_{\zeta\eta} = 0 \quad B^2_\zeta = (1400\text{ GeV})^2 \quad B^2_\eta = (700\text{ GeV})^2$
RH neutrino and RH sneutrino sector
$m_{\nu_R} = 63$ GeV $\quad m_{\tilde{\nu}_R} = 65$ GeV $\quad \kappa = 0.9$ $y_N = (3.28i, 6.70i, 1.72i) \times 10^{-6} \quad h_N = (0, 0.227, 0.0204)$
Other SUSY SM parameters
$m_{\tilde{W}} = 500$ GeV $\quad m_{\tilde{q}} = m_{\tilde{\ell}} = 5$ TeV

Benchmark

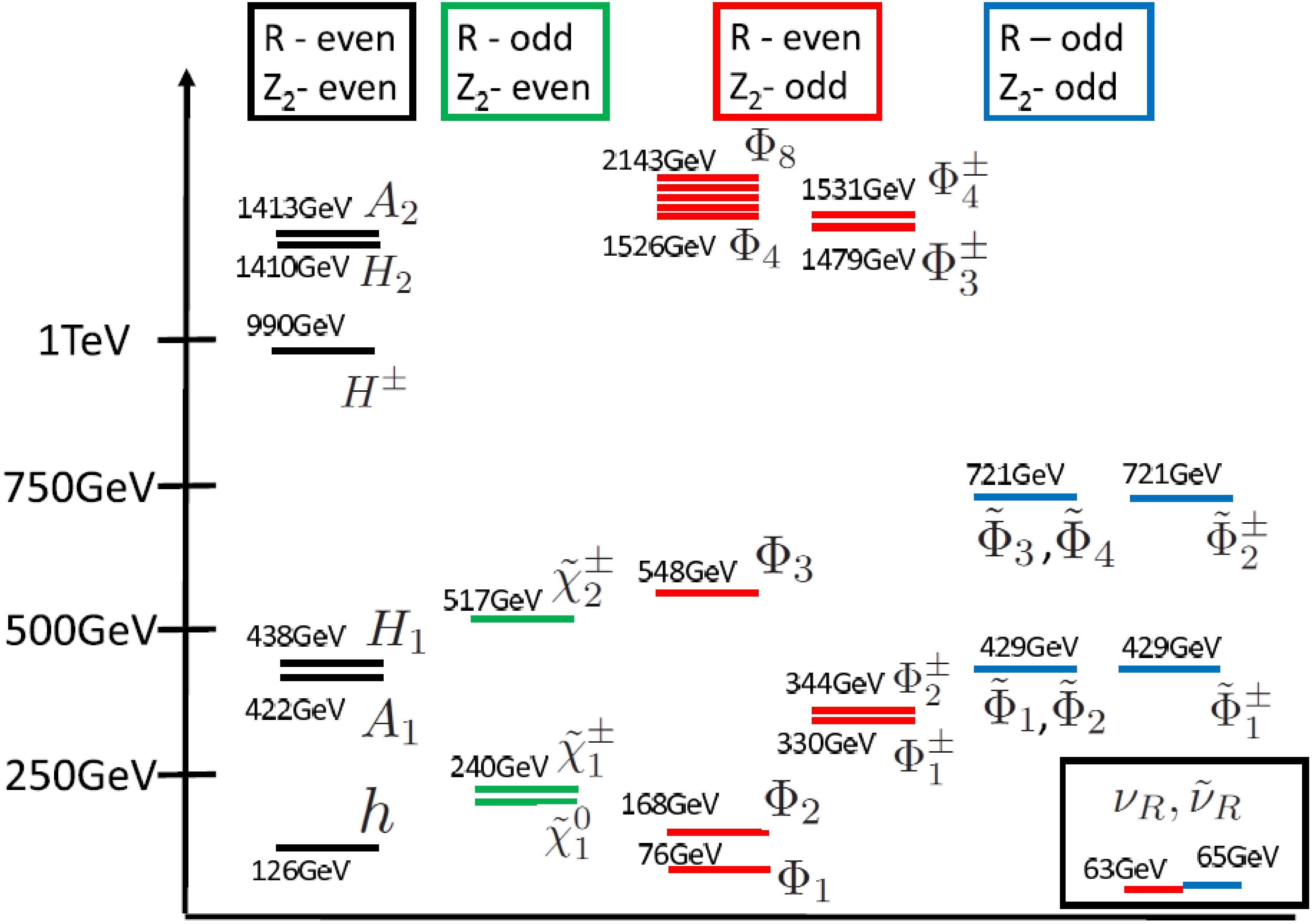
Output parameters



Non-decoupling effects
$\varphi_c/T_c = 1.3 \quad \lambda_{hhh}/\lambda_{hhh}\vert_{\rm SM} = 1.2 \quad {\rm B}(h \to \gamma\gamma)/{\rm B}(h \to \gamma\gamma)\vert_{\rm SM} = 0.78$
Neutrino masses and the mixing angles
$(m_1, m_2, m_3) = (0, 0.0084\ {\rm eV}, 0.0050\ {\rm eV}) \quad \sin^2\theta_{12} = 0.32 \quad \sin^2\theta_{23} = 0.50 \quad \vert\sin\theta_{13}\vert = 0.14$
LFV processes
${\rm B}(\mu \to e\gamma) = 3.6 \times 10^{-13} \quad {\rm B}(\mu \to eee) = 5.6 \times 10^{-16}$
Relic abundance of the DM
$\Omega_{\nu_R} h^2 = 0.055 \quad \Omega_{\tilde{\nu}_R} h^2 = 0.065 \quad \Omega_{\rm DM} = \Omega_{\nu_R} h^2 + \Omega_{\tilde{\nu}_R} h^2 = 0.12$

All experimental constrains are satisfied.

- Neutrino mass, mixing angles,
- Lepton flavour violation
- First order EWPT
- DM abundance

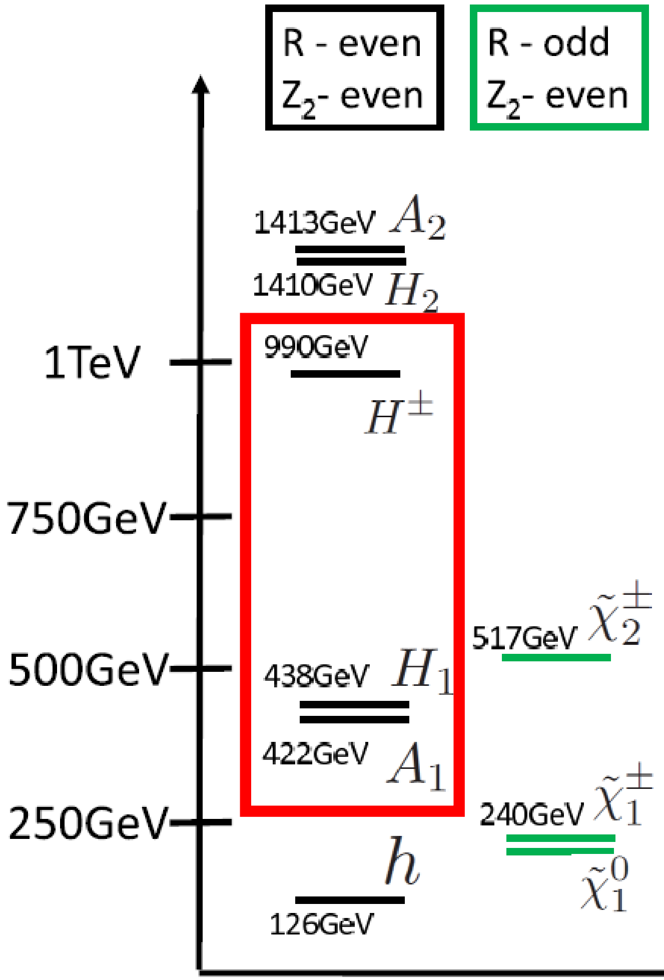

R - even
Z2- even
R - odd
Z2- even
R - even
Z2- odd
R – odd
Z2- odd
1TeV
750GeV
500GeV
250GeV
1413GeV A_2
1410GeV H_2
990GeV
$H^\pm$
438GeV H_1
422GeV A_1
h
126GeV
517GeV $\tilde{\chi}_2^\pm$
240GeV $\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
2143GeV Φ_8
1526GeV Φ_4
1531GeV $\Phi_4^\pm$
1479GeV $\Phi_3^\pm$
548GeV Φ_3
344GeV $\Phi_2^\pm$
330GeV $\Phi_1^\pm$
168GeV Φ_2
76GeV Φ_1
721GeV
721GeV
$\tilde{\Phi}_3, \tilde{\Phi}_4$
$\tilde{\Phi}_2^\pm$
429GeV
429GeV
$\tilde{\Phi}_1, \tilde{\Phi}_2$
$\tilde{\Phi}_1^\pm$
$\nu_R, \tilde{\nu}_R$
63GeV
65GeV

Collider Phenomenology

Tree-level

κ_W	κ_Z	κ_u	κ_d	κ_ℓ	κ_γ	$\lambda_{hhh}/\lambda_{hhh}^{\rm SM}$
0.990	0.990	0.990	0.978	0.978	0.88	1.2

$$\kappa_\phi \equiv g_{h\phi\phi}/g_{h\phi\phi}^{\rm SM}$$



Z_2-even Higgs sector is NMSSM-like.

We can distinguish from the MSSM.

$$m_{H^\pm} > m_{H_1}, m_{A_1}$$

Mixing effect between H_d and N causes this mass splitting.

Collider Phenomenology

Tree-level

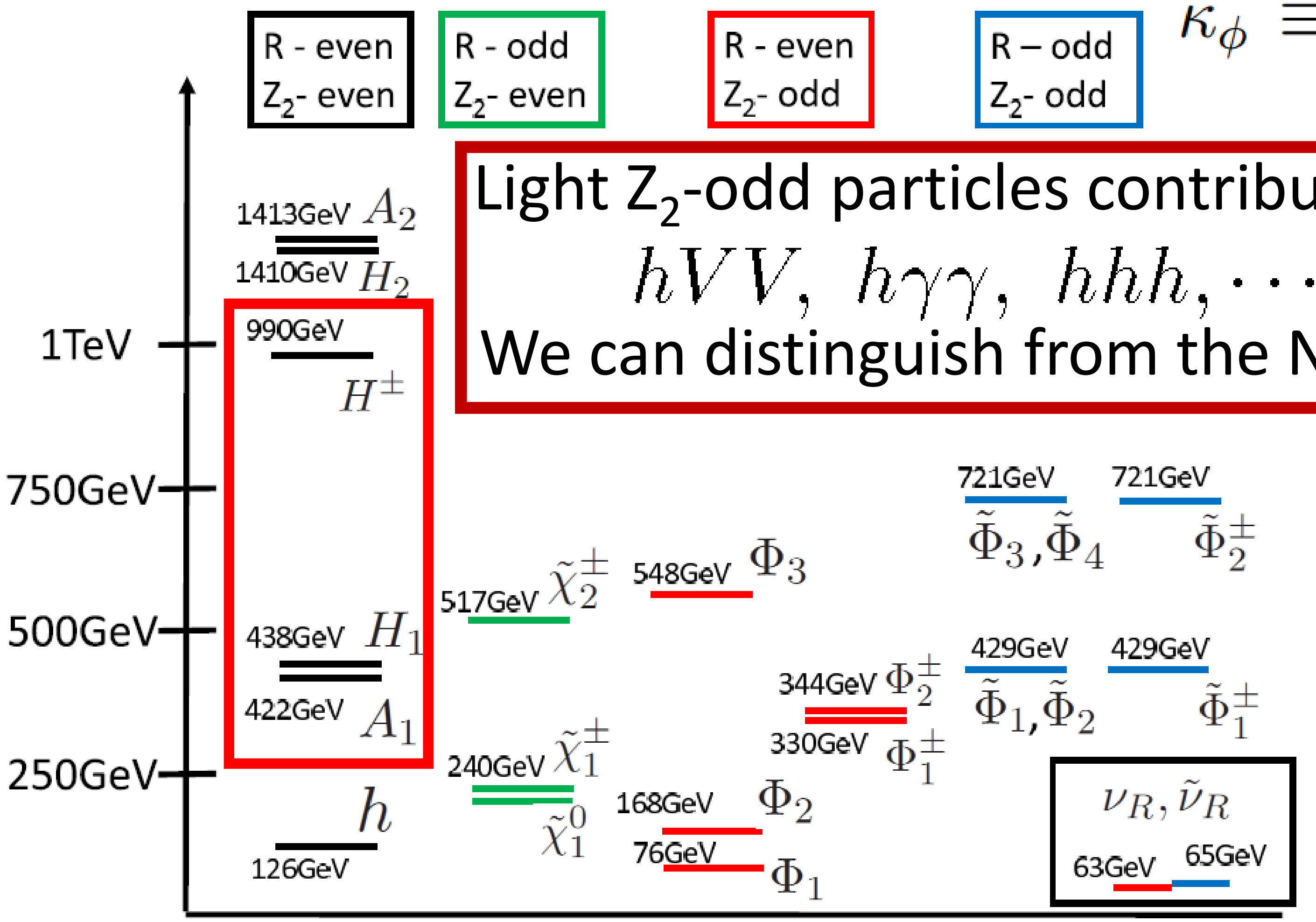
κ_W	κ_Z	κ_u	κ_d	κ_ℓ	κ_γ	$\lambda_{hhh}/\lambda_{hhh}^{\rm SM}$
0.990	0.990	0.990	0.978	0.978	0.88	1.2

$$\kappa_\phi \equiv g_{h\phi\phi}/g_{h\phi\phi}^{\rm SM}$$

Light Z_2-odd particles contribute to

$$hVV,\ h\gamma\gamma,\ hhh,\cdots$$

We can distinguish from the NMSSM.



Collider Phenomenology

Z_2-odd particles characterize this model.

(A) Light Inert Doublet
(B) Light Singlet-like Charged particle

(A) Light Inert Doublet

Aoki, Kanemura, Yokoya, PLB725 (2013)

$$e^+e^- \to HA \to ZHH$$

$$e^+e^- \to H^+H^- \to W^+W^-HH$$

Mass can be determined with a few percent accuracy.

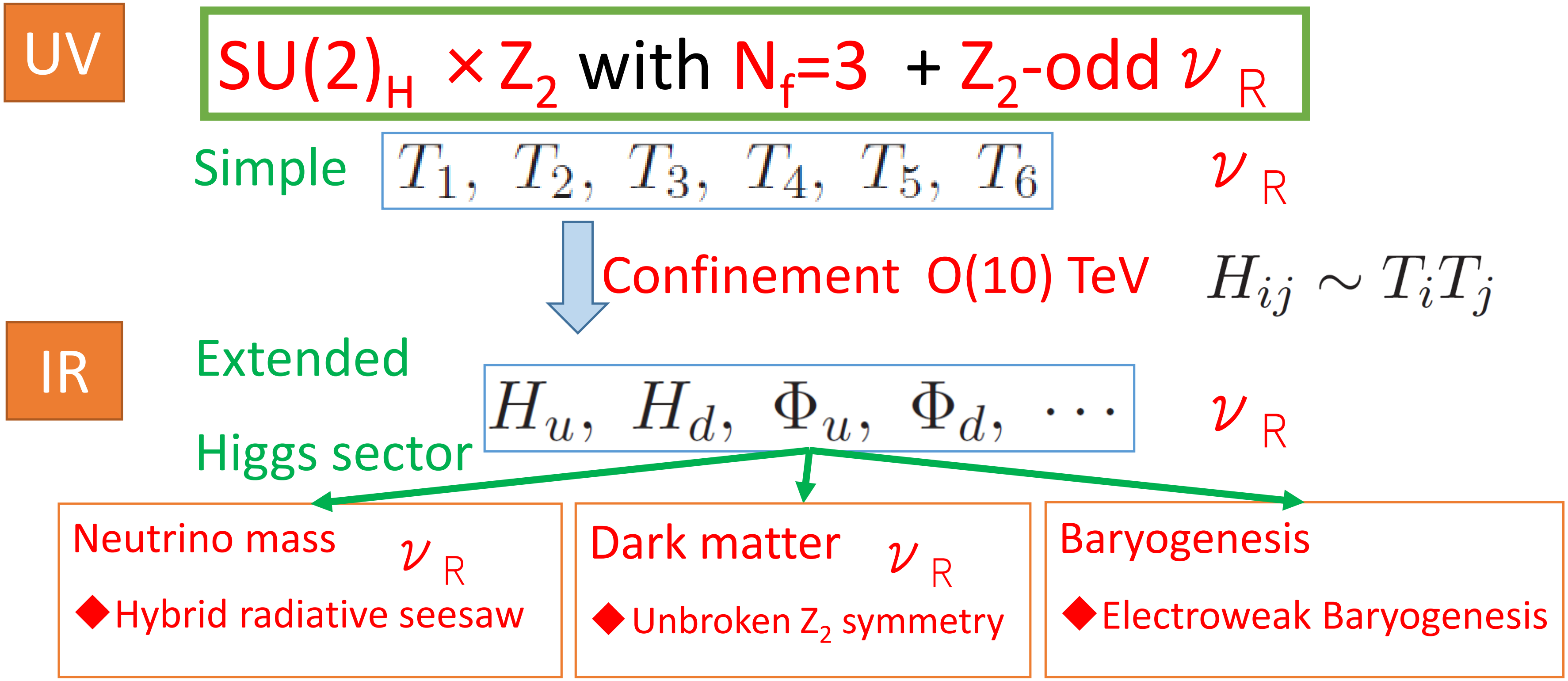
(B) Light Singlet-like Charged particle

$$e^+e^- \to \Omega^+\Omega^-, e^-e^- \to \Omega^-\Omega^-$$

Aoki, Kanemura, PLB689,28   Aoki, Kanemura, Seto, PRD80,033007

Summary

- We propose a UV complete model which can explain neutrino mass, dark matter and baryogensis with confinement.



UV

$SU(2)_H \times Z_2$ with $N_f=3$ + Z_2-odd ν_R

Simple $T_1,\ T_2,\ T_3,\ T_4,\ T_5,\ T_6$ ν_R

Confinement O(10) TeV $H_{ij} \sim T_i T_j$

IR

Extended Higgs sector $H_u,\ H_d,\ \Phi_u,\ \Phi_d,\ \cdots$ ν_R

Neutrino mass ν_R

◆Hybrid radiative seesaw

Dark matter ν_R

◆Unbroken Z_2 symmetry

Baryogenesis

◆Electroweak Baryogenesis

Rich structure

- Phenomenology
  - ➢ Mass spectrum ➢Multi-component DM ➢Corrections to *hhh*, *hγγ*, …

Future works.