Seesaw model with a loop-induced Dirac mass term and dark matter From $U(1)_{B-L}$ gauge symmetry breaking

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S. Kanemura, T.N., H. Sugiyama, Phys. Lett. B703:66–70
S. Kanemura, T.N., H. Sugiyama, Phys. Rev. D85, 033004

KILC12 25 Apr. 2012

1.Introduction

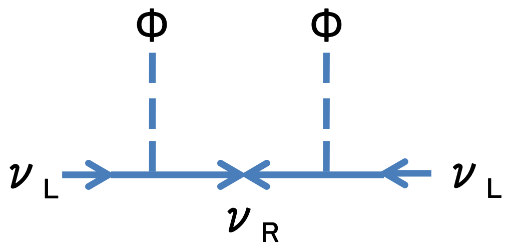
The standard model (SM) is a very successful model
to describe physics below O(100)GeV.
However,
we know the phenomena of the beyond-SM.

1. Neutrino oscillation
2. Dark matter
3. Baryon asymmetry of the Universe

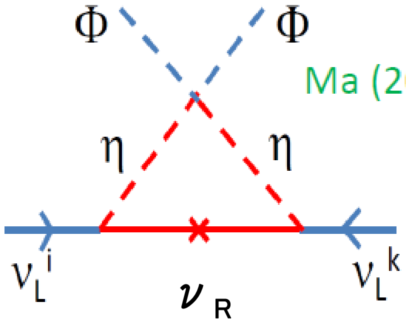
Especially, neutrino oscillation and dark matter would be explained by radiative seesaw models at TeV scale.

1.Introduction

Neutrino masses

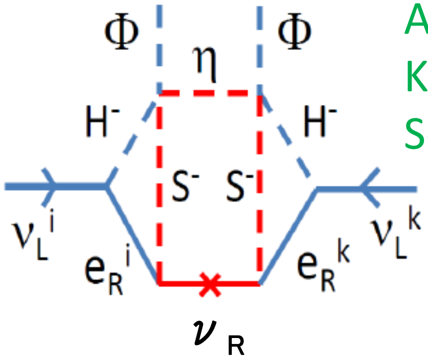


M ∼ O(1) TeV
→ c ∼ $O(10^{-6})$



Ma (2006)

M ∼ O(1) TeV
→ c ∼ $O(10^{-4})$

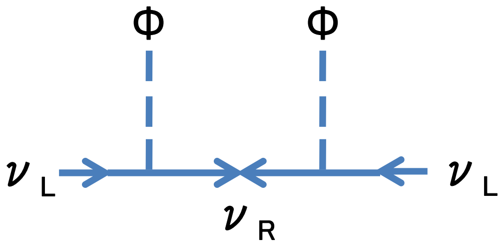


Aoki,
Kanemura,
Seto (2008)

M ∼ O(1) TeV
→ c ∼ O(1)

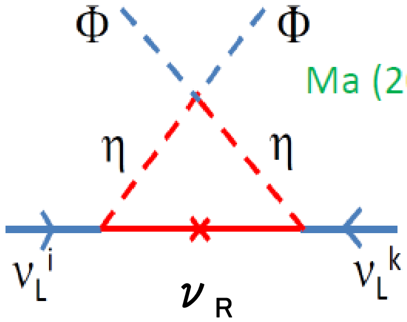
1.Introduction

Neutrino masses



$M \sim O(1)$ TeV

$\to c \sim O(10^{-6})$



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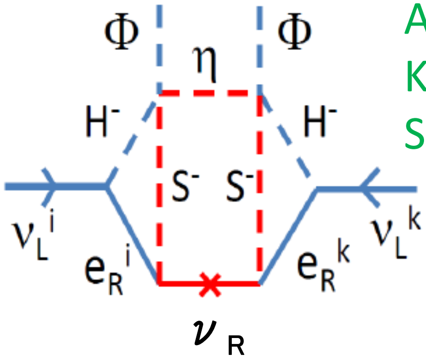

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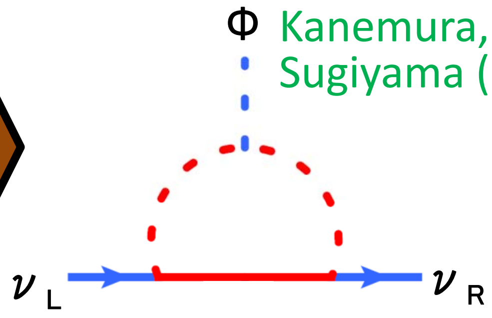
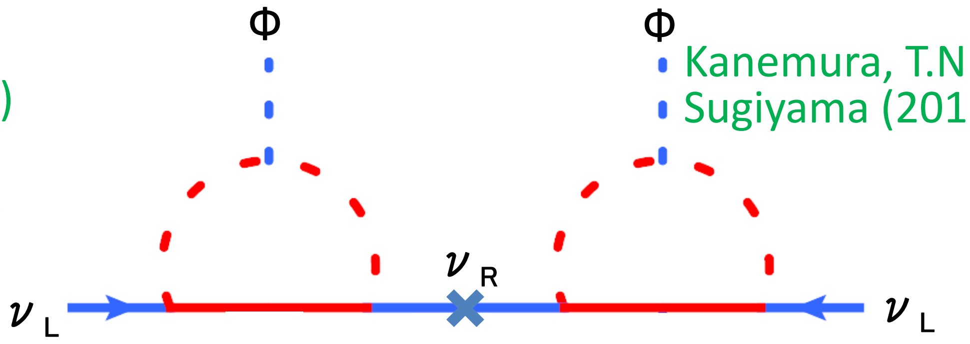


Kanemura, T.N.,
Sugiyama (2011)



Kanemura, T.N.,
Sugiyama (2012)

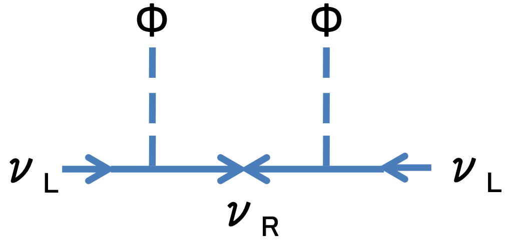
$M \sim O(1)$ TeV

$\to c \sim O(10^{-2}–10^{-1})$

ν_R are not stable.

1.Introduction

Neutrino masses



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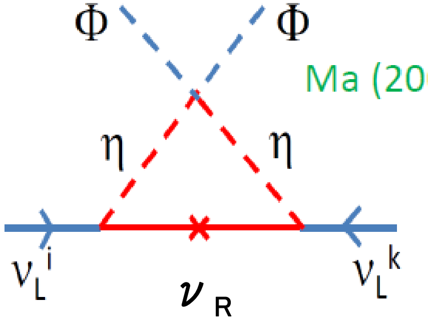
$\rightarrow c \sim O(10^{-6})$



Ma (2006)

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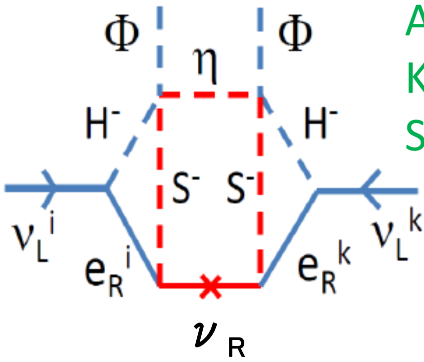

Aoki,
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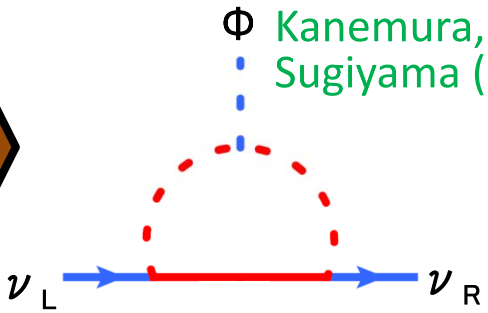
$\rightarrow c \sim O(1)$



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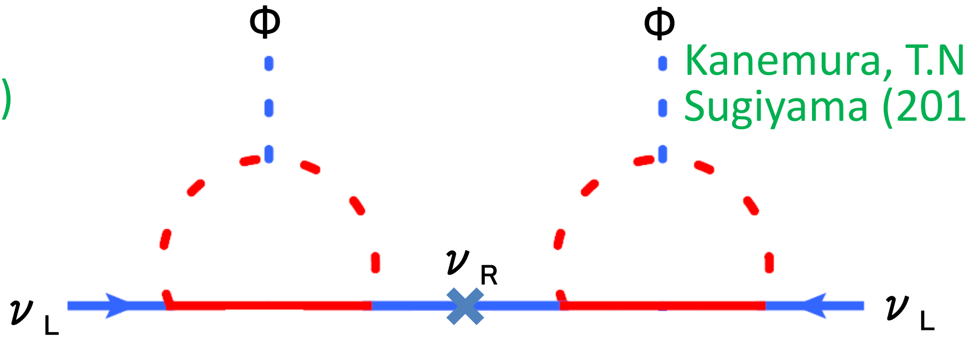


Kanemura, T.N.,
Sugiyama (2012)

$M \sim O(1)$ TeV
$\rightarrow c \sim O(10^{-2}–10^{-1})$

ν_R are not stable.

We consider this case.

1.Introduction

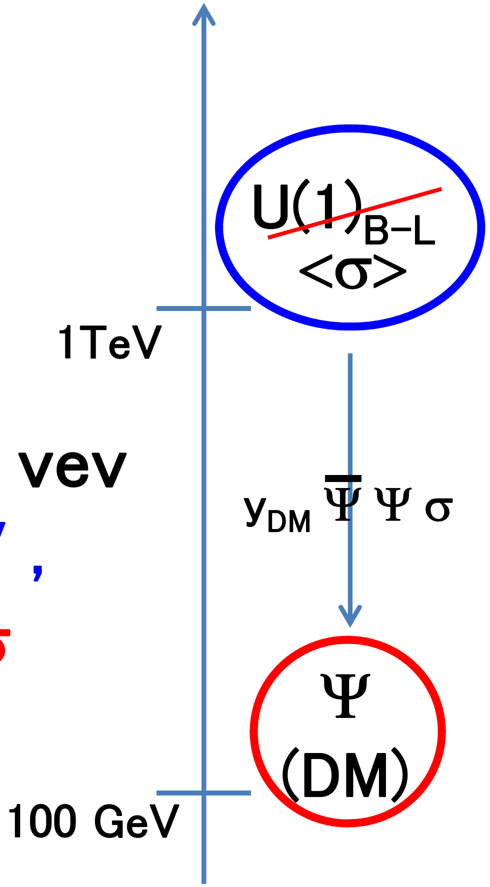
WIMP dark matter

- WIMP dark matter mass:

$$M_{DM} \sim O(100\text{–}1000)\text{GeV}$$

What is the origin of M_{DM}?

If $U(1)_{B-L}$ gauge symmetry is broken by the vev of additional scalar boson σ at O(1–10)TeV , M_{DM} is given by this vev through $y_{DM}\,\overline{\Psi}\,\Psi\,\sigma$ coupling.



1.Introduction

WIMP dark matter

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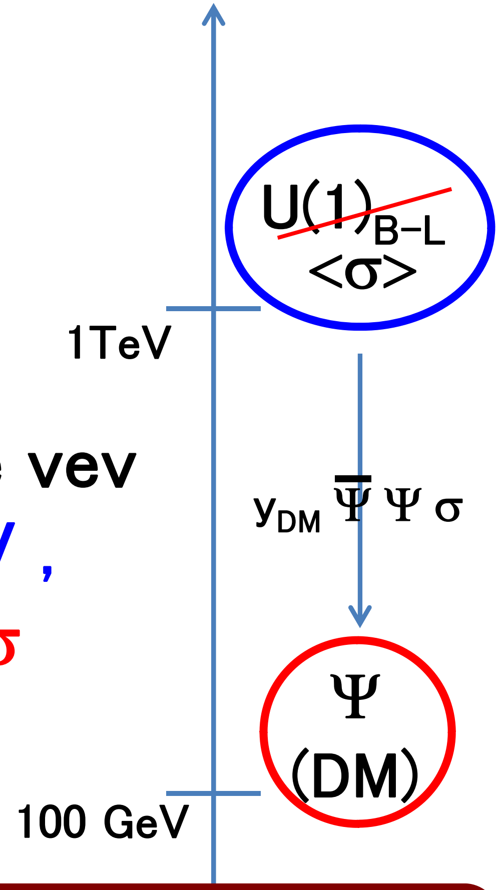
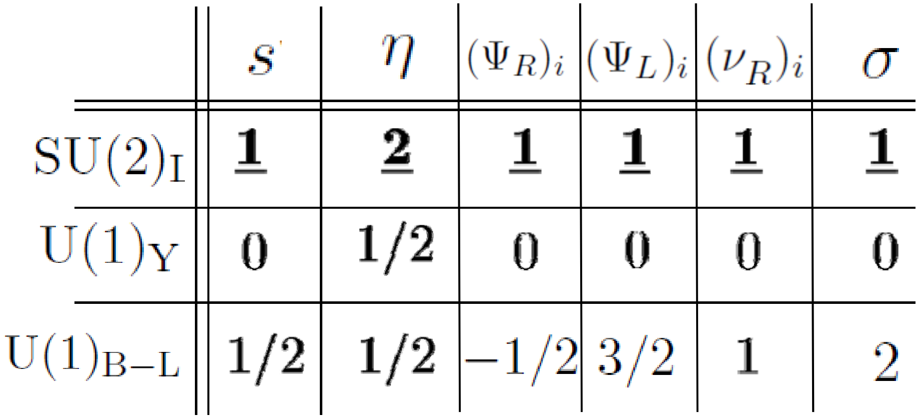


Dark matter and neutrino masses could be naturally explain by TeV scale physics with $U(1)_{B-L}$ gauge symmetry.

2.Model

- $SU(3)_C \times SU(2)_I \times U(1)_Y \times U(1)_{B-L}$



	s	η	$(\Psi_R)_i$	$(\Psi_L)_i$	$(\nu_R)_i$	σ
$SU(2)_I$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	0	1/2	0	0	0	0
$U(1)_{B-L}$	1/2	1/2	−1/2	3/2	1	2

- New matter particle:
  - −B−L Higgs scalar σ
  - −Right handed neutrinos $\nu_R^{1,2}$
  - −$SU(2)_I$ singlet scalar s
  - −$SU(2)_I$ doublet scalar η
  - − Chiral fermion $\Psi_{R,L}^{1,2}$

Half unit of $U(1)_{B-L}$ charge
→ $U(1)_{DM}$

$U(1)_{B-L}$ protect: Tree-level $L\phi_{SM}\nu_R$
Majorana mass of ν_R
Dirac mass of Ψ

2.Model

U(1)$_{B-L}$ symmetry breaking

- $\nu_{R,}$ Ψ_R and Ψ_L

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

$$\rightarrow \frac{(M_R)_{ii}}{2} = (y_R)_{ii}\frac{v_\sigma}{\sqrt{2}}, \qquad (M_\Psi)_{ii} = (y_\Psi)_{ii}\frac{v_\sigma}{\sqrt{2}}.$$

← tree level

Electroweak symmetry breaking

- ϕ, σ, s and η → Physical state: h,H,S1,S2, $\eta^{\pm}$

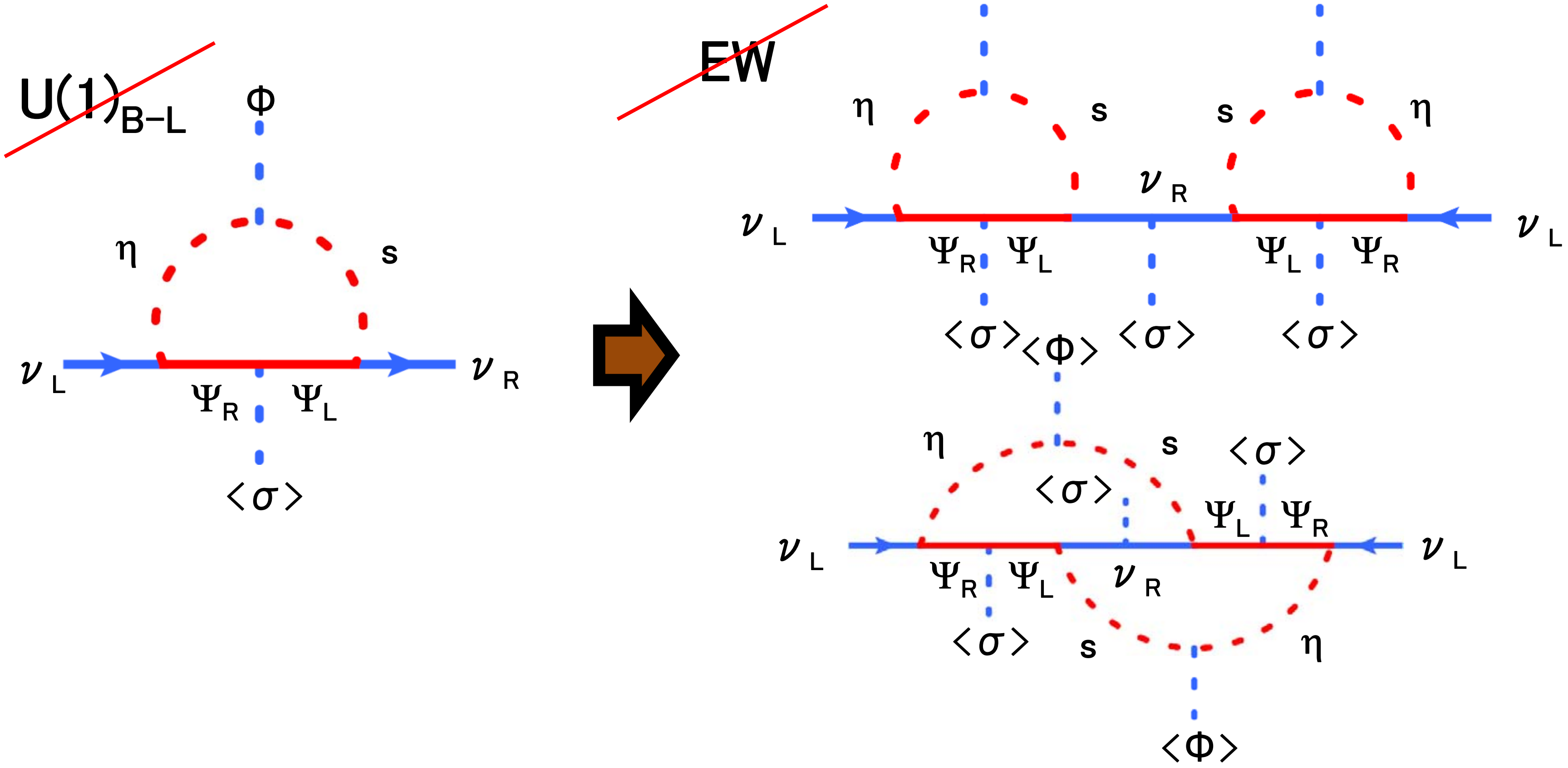
$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_r^0 \\ \sigma_r^0 \end{pmatrix}, \quad \begin{pmatrix} s_1^0 \\ s_2^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \eta^0 \\ s^0 \end{pmatrix}$$

Global U(1)$_{DM}$ remains after U(1)$_{B-L}$ gauge symmetry breaking.
We assume that the Ψ_1 is the lightest U(1)$_{DM}$ particle.

U(1)$_{B-L}$: Neutrino masses
The dark matter mass
Stability of the dark matter

2.Model

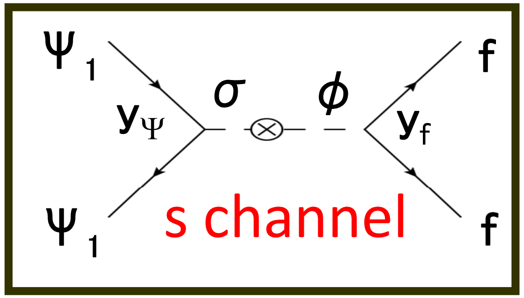
Neutrino masses

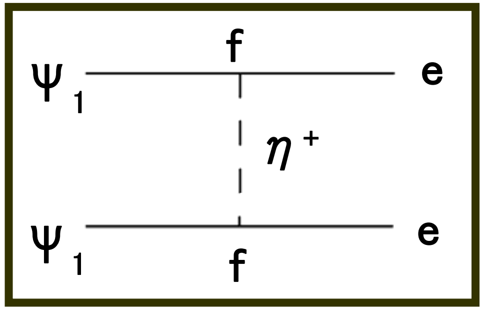


The O(0.1) eV neutrino masses can be naturally deduced from TeV scale physics with O(0.01–0.1) coupling constant

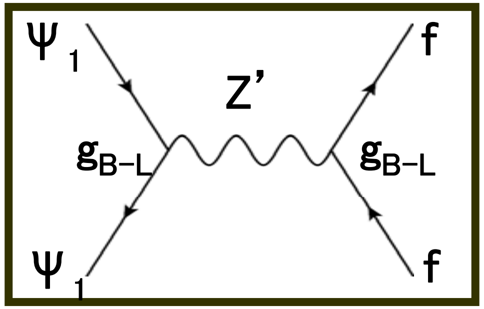
2.Model

Abundance of Ψ^1

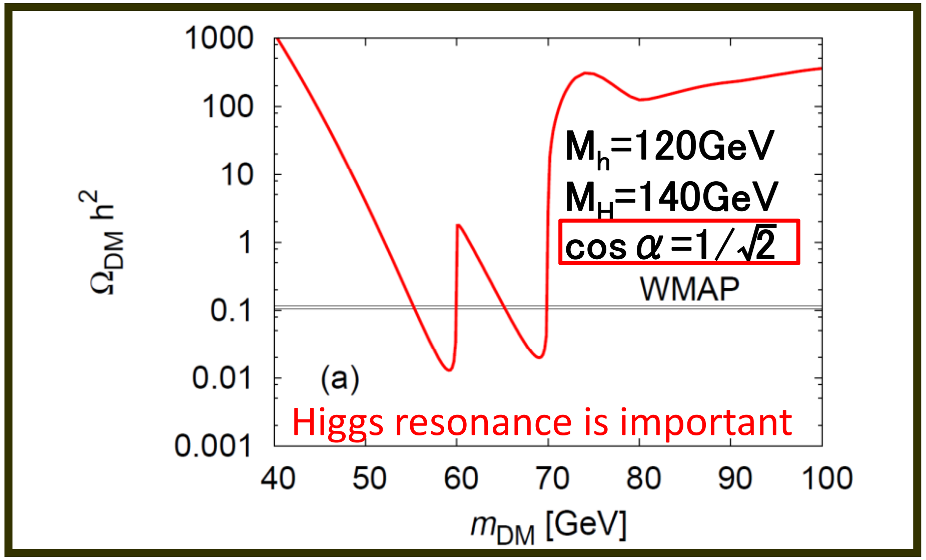




constraint by $\mu \to e\gamma$



Z' is heavy



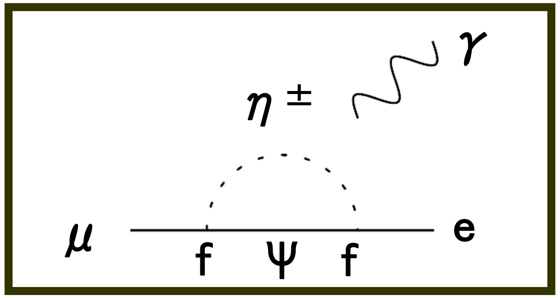
Higgs resonance is important

Okada and Seto (2010)
Kanemura, Seto and Shimomura (2011)

Maximal mixing between σ and ϕ is required!

2.Model

LFV constraint



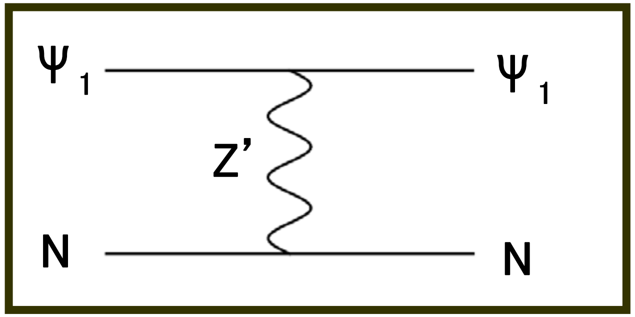
$$BR(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{64\pi G_F^2}\left|\frac{1}{M_{\eta^\pm}^2} f_{\mu i} F_2\left(\frac{(M_\Psi)_i^2}{M_{\eta^\pm}^2}\right)(f^\dagger)_{ie}\right|^2,$$

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

Experimental bound(MEG): $BR(\mu \to e, \gamma) < 2.4\times 10^{-12}$

J. Adam et al.(2011)

Direct detection of Ψ_1



$$\sigma(\Psi_1 N \to \Psi_1 N) \simeq \left(\frac{g_{\rm B-L}}{m_{Z'}}\right)^4 \frac{m_{\Psi_1}^2 m_N^2}{4\pi(m_{\Psi_1}+m_N)^2}$$

Experimental bound(XENON100): $\sigma(\Psi_1 N \to \Psi_1 N) < 8\times 10^{-45}\,\mathrm{cm}^2$

E. Aprile et al. (2011)

Consistent with current experimental bound.

2.Model

Parameter set

- ・neutrino oscillation ・LFV ・LEP
- ・DM abundance ・DM direct detection

Normal Hierarchy, Tri-bi maximal

(Our results are not sensitive to value of θ_{13})

$$f_{ij} = \begin{pmatrix} 0.0757 & 0.0445 \\ 0.01 & -0.0123 \\ -0.141 & -0.0723 \end{pmatrix} \qquad h_{ij} = \begin{pmatrix} -0.131 & 0.1 \\ 0.1 & 0.1 \end{pmatrix}$$

$M_R = 250$ GeV , $M_{\psi 1} = 57.0$ GeV , $M_{\psi 2} = 800$ GeV

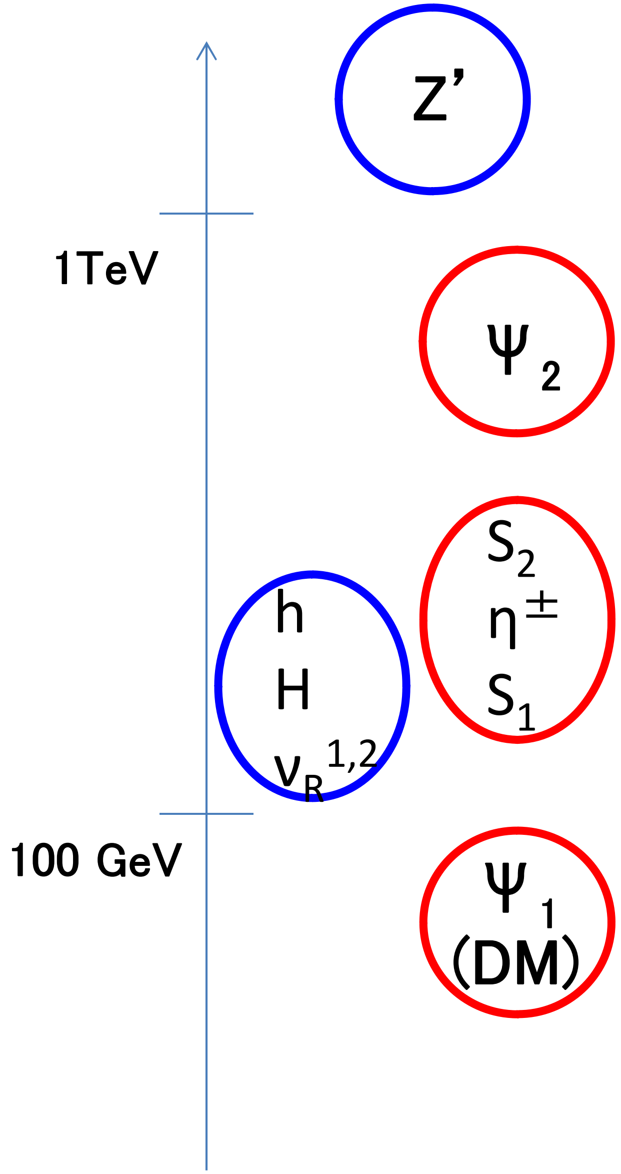
$M_{S1} = 200$ GeV, $M_{S2} = 300$ GeV ,

$M_h = 120$ GeV, $M_H = 140$ GeV,

$M_{\eta^\pm} = 280$ GeV, $\cos\theta = 0.05$, $\cos\alpha = 1/\sqrt{2}$,

$g_{B-L} = 0.2$, $M_{Z'} = 2000$GeV, $v_\phi = 246$ GeV, $v_\sigma = 5$ TeV

All coupling constant are O(0.01-0.1) and all masses are O(100-1000) GeV.



3. Physics at the LHC

Physics of Z’

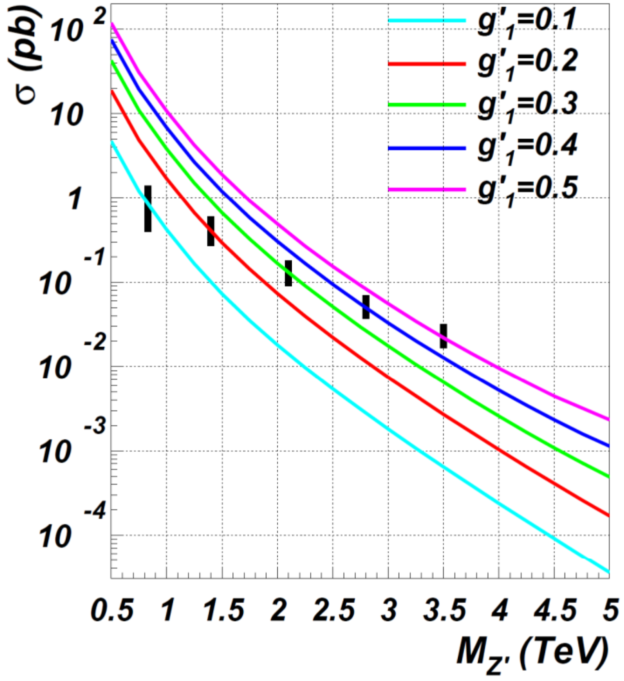
Z’ mass: O(1–10)TeV

$\Gamma(Z' \to XX) \propto (B\text{–}L \text{ charge})^2$

Z’ decay into

invisible about 30%

Z’ production cross section is 70 pb at the LHC for $\sqrt{s} = 14$ TeV , $M_{Z'} = 2000$ GeV and $g_{B-L} = 0.2$



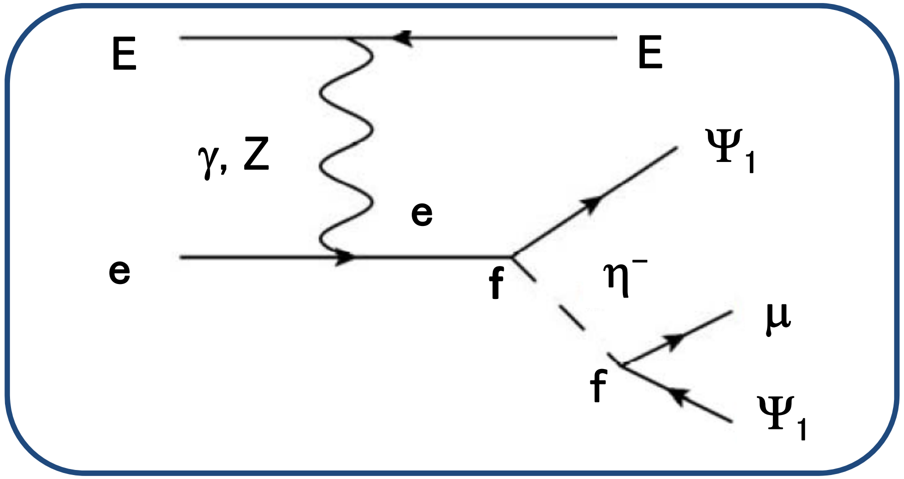
L. Basso, A. Belyaev, S.Moretti and C. H. Shepherd-Themistocleous (2009); L.Basso (2011)

Our model could be tested by measuring decay of the Z’ at the LHC.

However, if Z’ mass is heavy, our model would be difficult to be tested at the LHC.

4. Physics at the ILC

Physics of Ψ_1



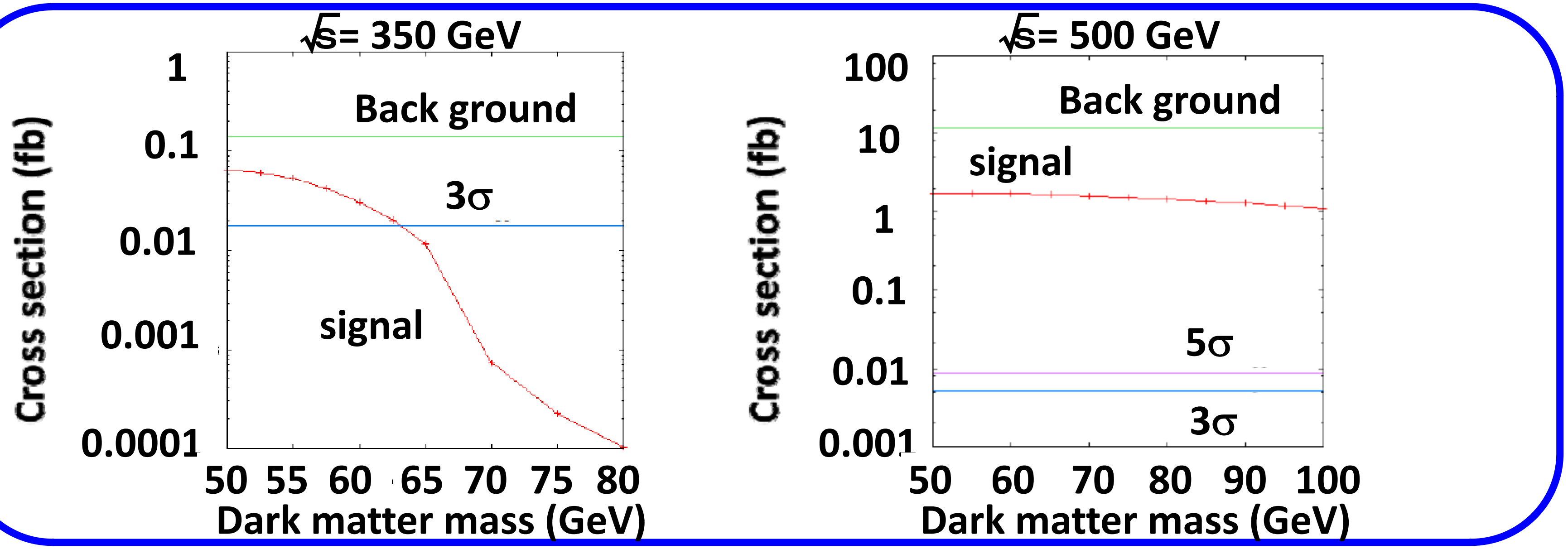
1. In our model, dark matter and electron are coupled via the $L\psi\eta$ coupling (f).
2. The energy momentum conservation is used to detect the dark matter.
3. Background are $e, E \to e, \mu, \not{p}$ processes.

4. Physics at the ILC

The cross section of the signal is very low in this case.
The kinematical cuts to reduce B.G.

$$-0.8 < \cos(\mu) < 0.8, \quad E_\mu > 80GeV,$$

$$E_e < 120GeV, \quad M_{miss} > 120GeV, \quad -0.8 < \cos(e\mu) < 0.8.$$

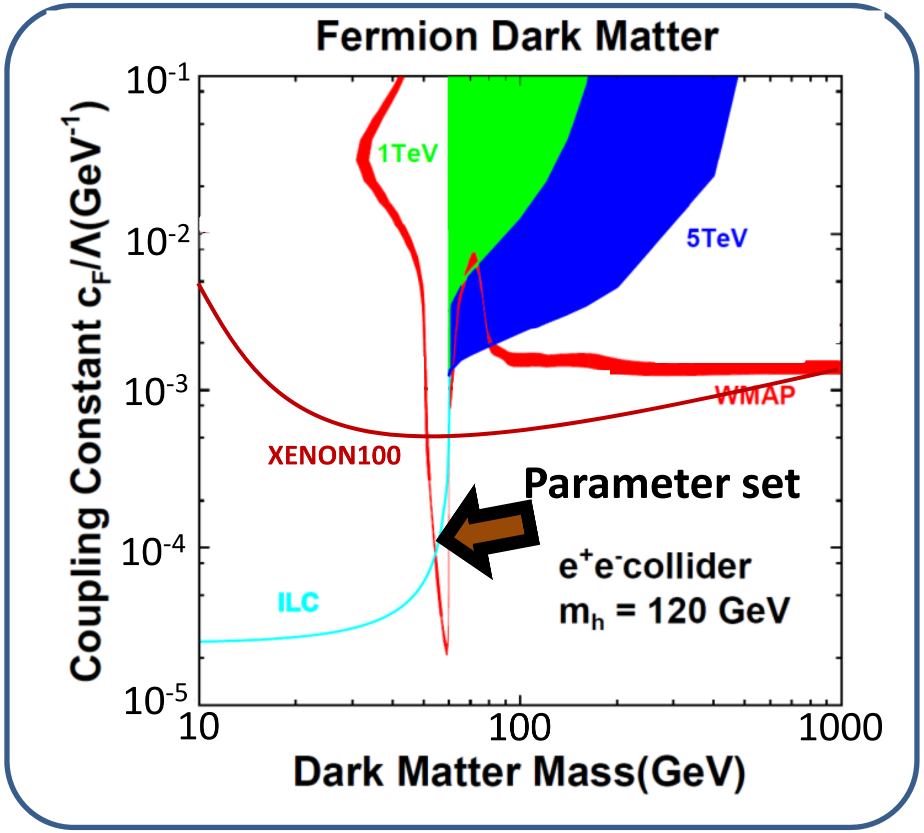


Dark matter can be tested with $1ab^{-1}$ data:

at the $\sqrt{s}$ = 350GeV collider for $M_{DM} \lesssim 63$ GeV at 3σ C.L.

at the $\sqrt{s}$ = 500GeV collider at 5σ C.L.

4. Physics at the ILC

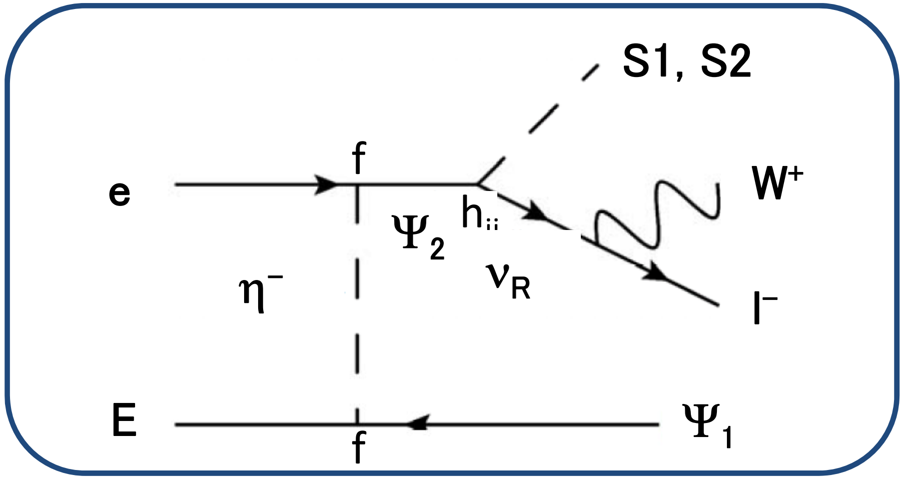


S.Kanemura, S.Matsumoto, TN, H.Taniguchi (2011).

Ψ_1 would be tested by invisible decay of h at $\sqrt{s}$=350 GeV with 500fb^{-1} at 3σ C.L.

4. Physics at the ILC

Physics of ν_R



1. In our parameter set, $\nu_R \to W^\pm,\ l^\mp$ is main decay mode.
2. We consider W→jet, jet process.
3. Background are e, E → e (or μ), W, $\not{p}$ processes.

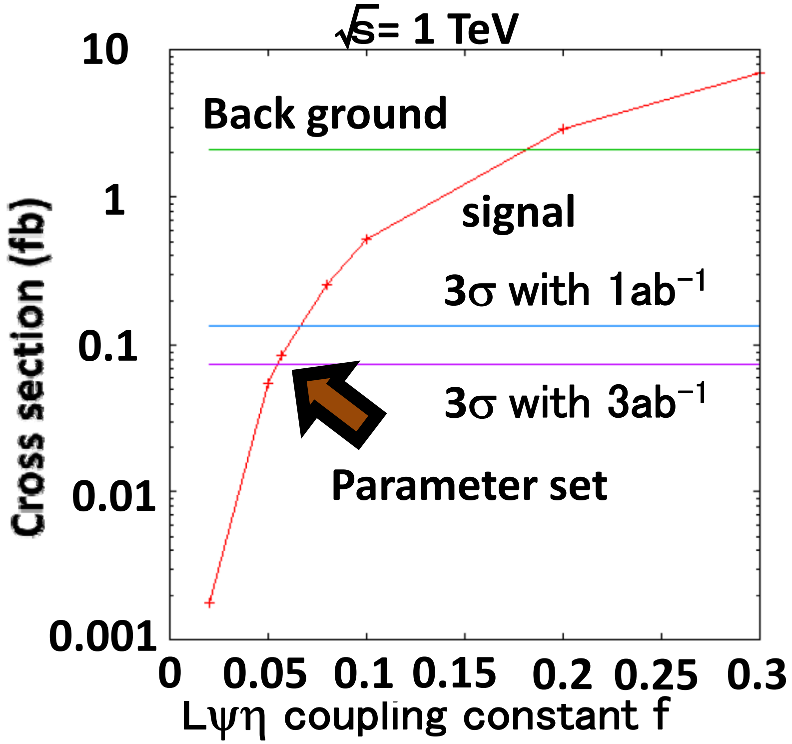
4. Physics at the ILC

The cross section of the signal is very low in this case.

The kinematical cuts to reduce B.G.

$$-0.95 < \cos(l) < 0.95, \quad 200GeV < M_{miss} < 600GeV,$$

$$240GeV < M_{w,l} < 260GeV, \quad E_l < 300GeV, \quad 300GeV < E_{w,l} < 600GeV.$$



Right handed neutrino can be tested at 3σ C.L. at the $\sqrt{s}$ = 1 TeV collider with $3ab^{-1}$ data.

Most optimistic case

LHC Z'_{B-L} is detected at the LHC

ILC

- 350 GeV – 500 GeV (also 1 TeV)
  e, μ with missing momentum
  → Dark matter which is directly coupled
  to charged lepton is detected.
- 1 TeV
  e, W with Missing momentum
  → O(100) GeV right handed neutrino is detected.

Radiative seesaw model with B–L gauge symmetry which include unstable right handed neutrino exist at TeV scale.

5.Conclusion

① **We consider possibility of testing the TeV-scale seesaw model in which U(1)$_{B-L}$ gauge symmetry is the common origin of neutrino masses, the dark matter mass, and stability of the dark matter.**

② Z’ boson could be tested at the LHC.

③ Dark matter Ψ_1 can be tested with 1 ab^{-1}data:
at $\sqrt{s}$ = 350 GeV ILC with $M_{DM} \lesssim$ 63 GeV at 3σ C.L.
at $\sqrt{s}$ = 500 GeV ILC at 5σ C.L.

⑤ Right handed neutrino could be tested at 3σ C.L.
at $\sqrt{s}$ = 1 TeV ILC with 3 ab^{-1}data.

⑥ **ILC have potential to distinguish U(1)$_{B\text{-}L}$ models.**

Back up

2.Model

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

Our model focus to explain TeV scale physics.

$U(1)_{B-L}$ anomaly would be resolved by some heavy singlet fermions with appropriate B-L charge.

For example;
Right hand: 1×9, -1/2×14, 1/3×9
left hand: 3/2×14, -5/3×9

$U(1)_{B-L}$ anomaly is not serious

Lagrangian

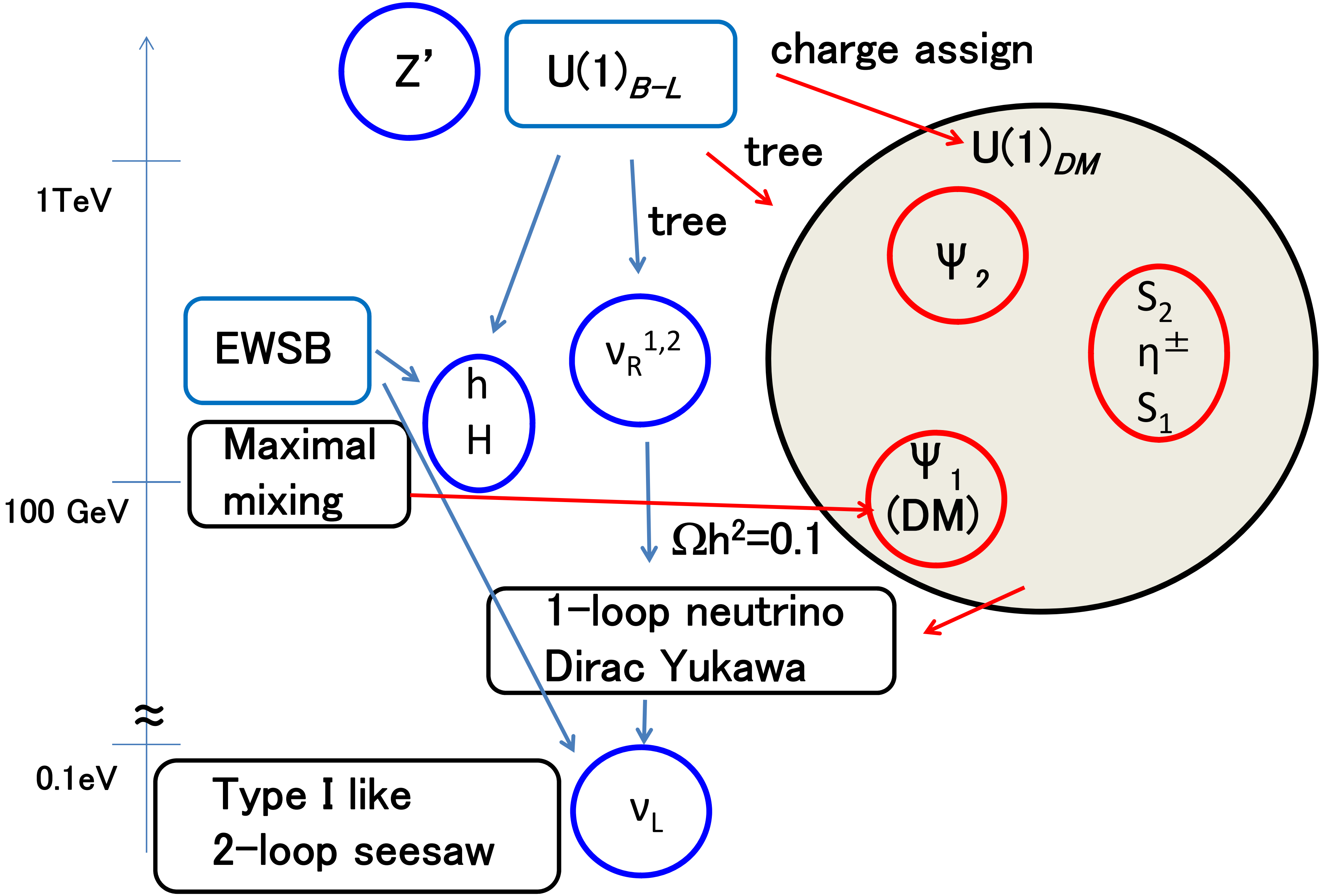
U(1)$_{B-L}$ breaking

$$\begin{aligned}\mathcal{L}_{\rm int} = \;& \mathcal{L}_{\rm SMYukawa} - \{(y_R)_{ij}(\overline{\nu^c_R})_i(\nu_R)_i\sigma + h.c.\} - \{(y_\Psi)_i(\overline{\Psi}_R)_i(\Psi_L)_i\sigma + h.c.\} \\ & - \left(h_{ij}(\overline{\Psi}_L)_i(\nu_R)_j s + h.c.\right) - \left(f_{ij}(\overline{L_L})_i(\Psi_R)_j\eta^c + h.c.\right) - \left\{(y_3)_{ij}\,(\overline{\nu^c_R})_i(\Psi_R)_j s^* + h.c.\right\} \\ & -\mu^2_\phi\Phi^\dagger\Phi + \mu^2_s s^\dagger s + \mu^2_\eta\eta^\dagger\eta - \mu^2_\sigma\sigma^\dagger\sigma + \lambda\left(\Phi^\dagger\Phi\right)^2 + \lambda_1\left(s^\dagger s\right)^2 + \lambda_2\left(\eta^\dagger\eta\right)^2 + \lambda_3(\sigma^\dagger\sigma)^2 \\ & +\lambda_4 s^\dagger s\eta^\dagger\eta + \lambda_5 s^\dagger s\Phi^\dagger\Phi + \lambda_6\eta^\dagger\eta\Phi^\dagger\Phi + \lambda_7\eta^\dagger\Phi\Phi^\dagger\eta \\ & +\lambda_8 s^\dagger s\sigma^\dagger\sigma + \lambda_9\eta^\dagger\eta\sigma^\dagger\sigma + \lambda_{10}\Phi^\dagger\Phi\sigma^\dagger\sigma + \left(\mu s\eta^\dagger\Phi + h.c.\right).\end{aligned}$$

$\cancel{U(1)_{B-L}}$

$$\frac{(M_R)_{ii}}{2} = (y_R)_{ii}\frac{v_\sigma}{\sqrt{2}}, \qquad (M_\Psi)_{ii} = (y_\Psi)_{ii}\frac{v_\sigma}{\sqrt{2}}, \qquad M^2_{Z'} = 4g^2_{B-L}v^2_\sigma$$

Remnant global U(1)$_{DM}$ remains on half unit of U(1)$_{B-L}$ charged particles after SSB of U(1)$_{B-L}$.
U(1)$_{DM}$ guarantee stability of dark matter.
We consider that the Ψ^1 is lightest U(1)$_{DM}$ particle case.



Z'

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

charge assign

tree

$U(1)_{DM}$

tree

1TeV

Ψ_2

S_2

$\eta^{\pm}$

S_1

EWSB

h

H

$\nu_R^{1,2}$

Maximal mixing

100 GeV

Ψ_1 (DM)

$\Omega h^2=0.1$

1-loop neutrino Dirac Yukawa

$\approx$

0.1eV

Type I like 2-loop seesaw

ν_L