A Radiative type-I seesaw model via TeV scale B-L breaking and its phenomenology.

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S. Kanemura, T.N., H. Sugiyama, Phys. Rev. D85, 033004
S. Kanemura, T.N., H. Sugiyama, **arXiv:1207.7061**

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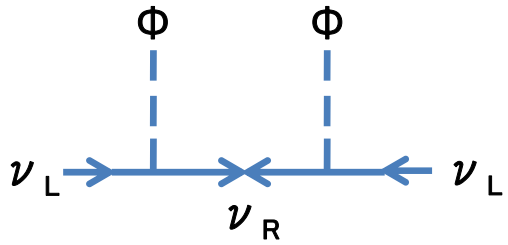
1.Introduction

Neutrino masses

- Tree level

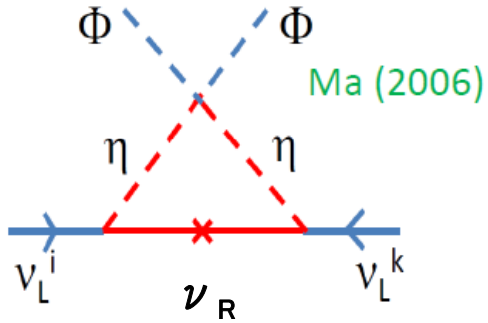


M ～ O(10^{12}) TeV → c ～ O(1)
M ～ O(1) TeV → c ～ O(10^{-6})

This case is very simple.

It would be difficult to test at collider experiments

- Loop level (radiative seesaw)



M ～ O(1) TeV
→ c ～ O(10^{-4})

This case could allow sizable coupling constants.

Dark matter is naturally supplied.

1.Introduction

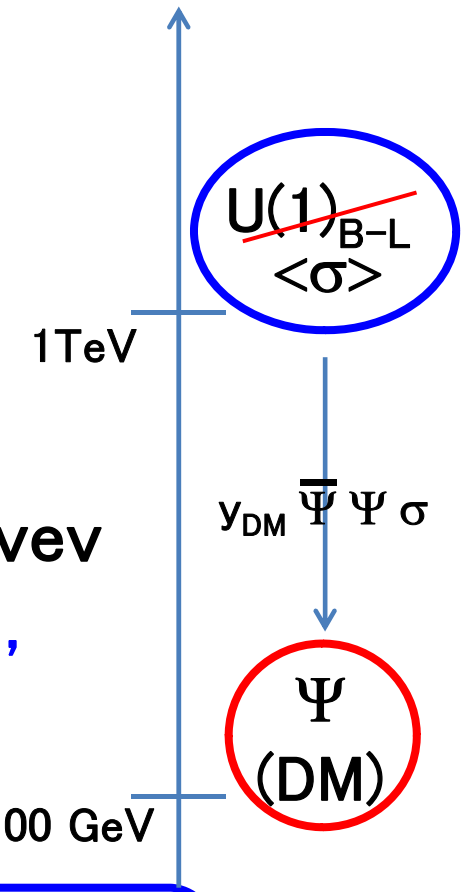
WIMP dark matter

・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 $y_{DM}\,\bar{\Psi}\Psi\sigma$ coupling.



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

2.Model

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

- 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 $\Psi_{R,L}^{1,2}$

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

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

- ν_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, $\eta^\pm$

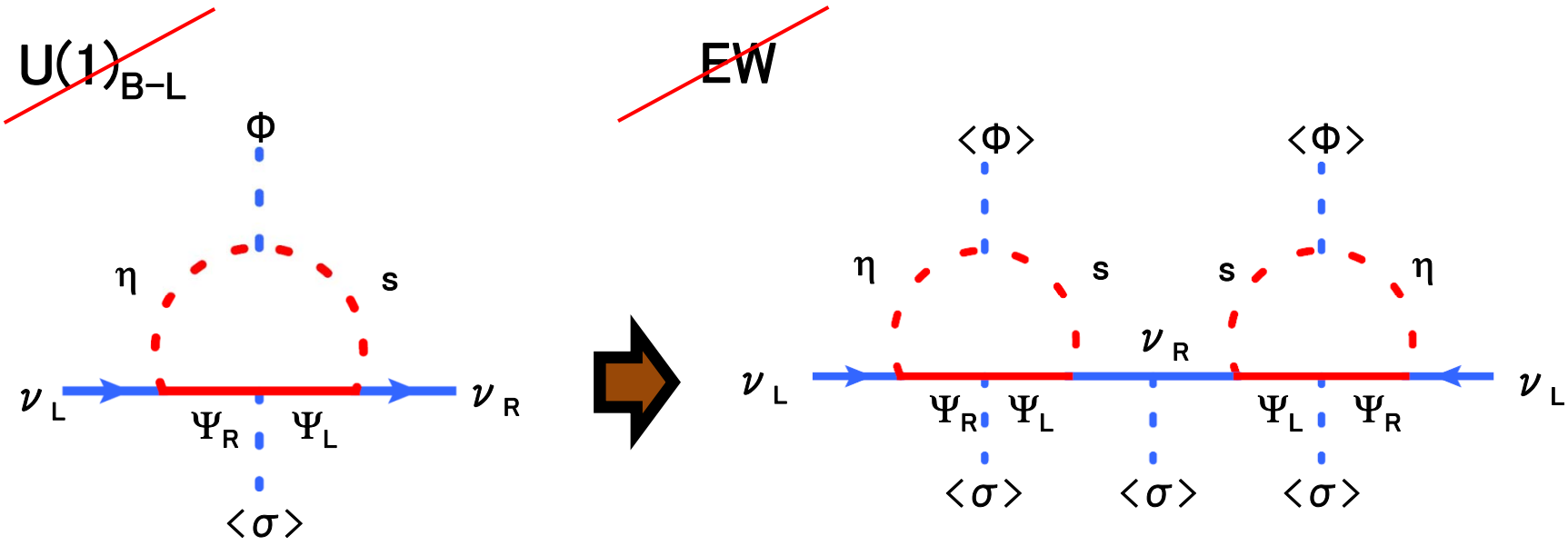
$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_r^0 \\ \sigma_r^0 \end{pmatrix}, \quad \begin{pmatrix} s_1^0 \\ s_2^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta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

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

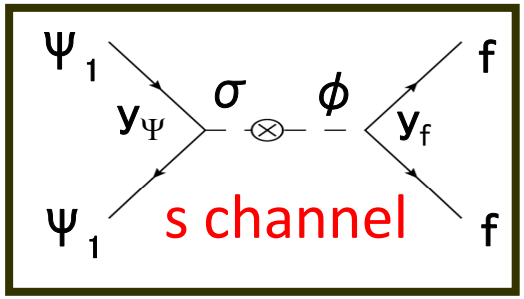
Neutrino masses

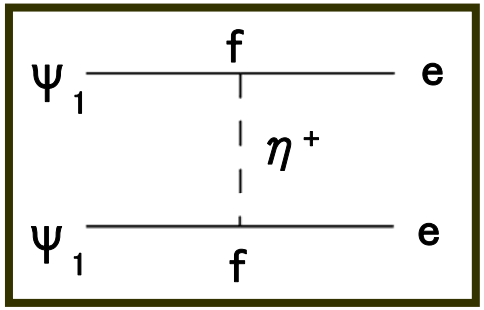


The O(0.1) eV neutrino masses can be naturally deduced from TeV scale physics with O(0.01−0.1) coupling constant

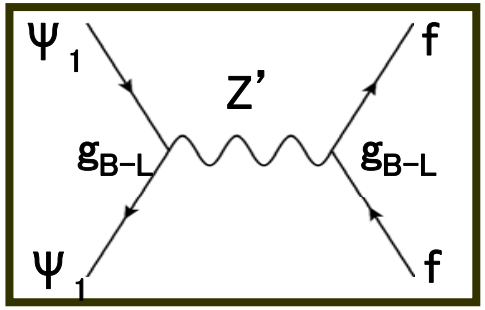
2.Model

Abundance of Ψ_1

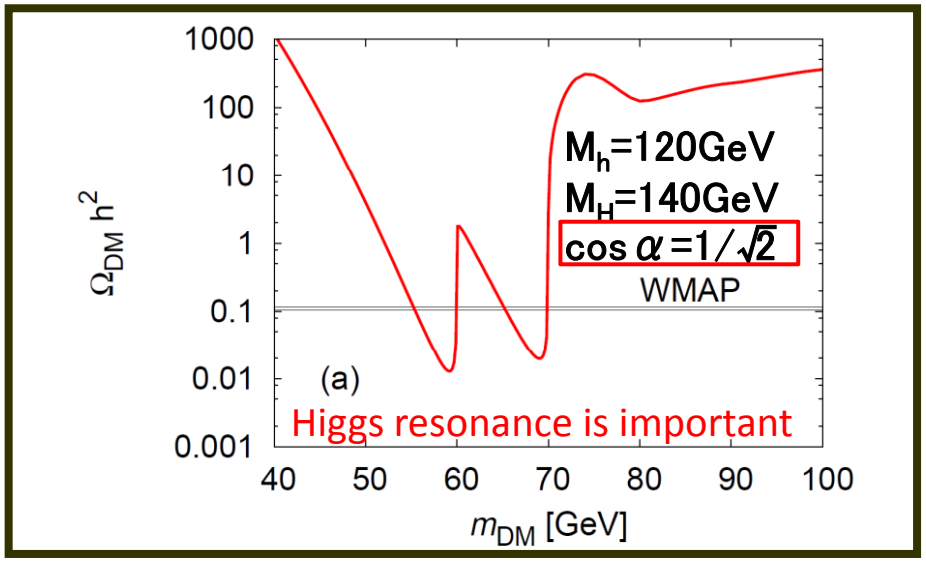




constraint by $\mu \to e\gamma$



Z' is heavy



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

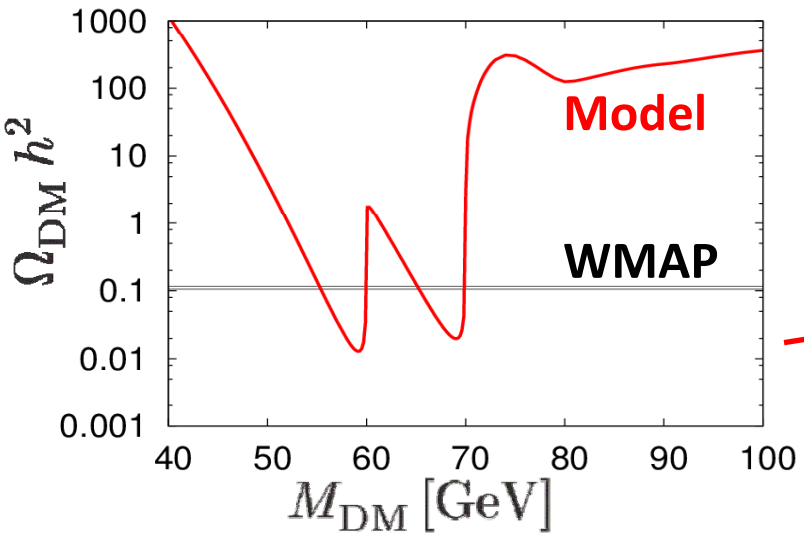
Maximal mixing between σ and ϕ is required!

2.Model

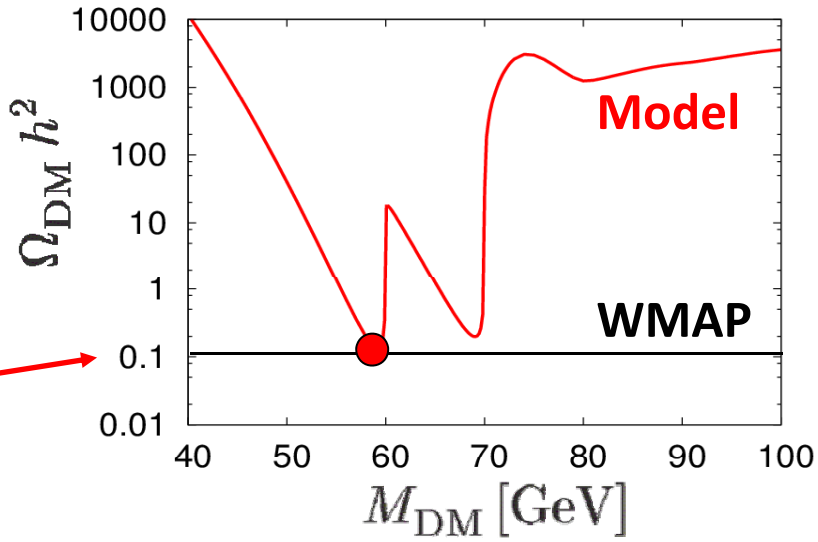
Bound of v_σ

DM Relic Abundance $\propto 1/y_\Psi^2 \propto v_\sigma^2$

$v_\sigma = \sqrt{2}\langle\sigma^0\rangle = 5\,\mathrm{TeV}$ $\xrightarrow{\times\sqrt{10}}$ $v_\sigma = \sqrt{2}\langle\sigma^0\rangle = 5\sqrt{10}\,\mathrm{TeV}$

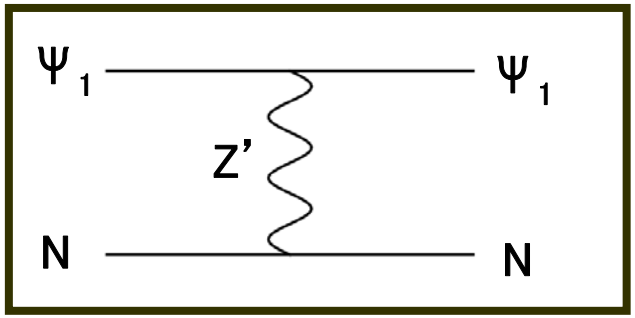


$\times 10$



$v_\sigma \lesssim 5\sqrt{10}\,\mathrm{TeV}$

Marginal



$$\Rightarrow \sigma(\Psi_1 N \to \Psi_1 N) \gtrsim 3\times 10^{-47}\,[\mathrm{cm}^2]$$

Sensitivity in XENON 1T (2017?) :

$$\sigma(\text{'DM'}N \to \text{'DM'}N) \sim 10^{-47}\,[\mathrm{cm}^2]$$

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, $-1/2 \times 14$, $1/3 \times 9$

left hand: $3/2 \times 14$, $-5/3 \times 9$

(B−L charge, # of fields)

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

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 , $M_{\psi 1} = 57.5$ GeV , $M_{\psi 2} = 800$ GeV

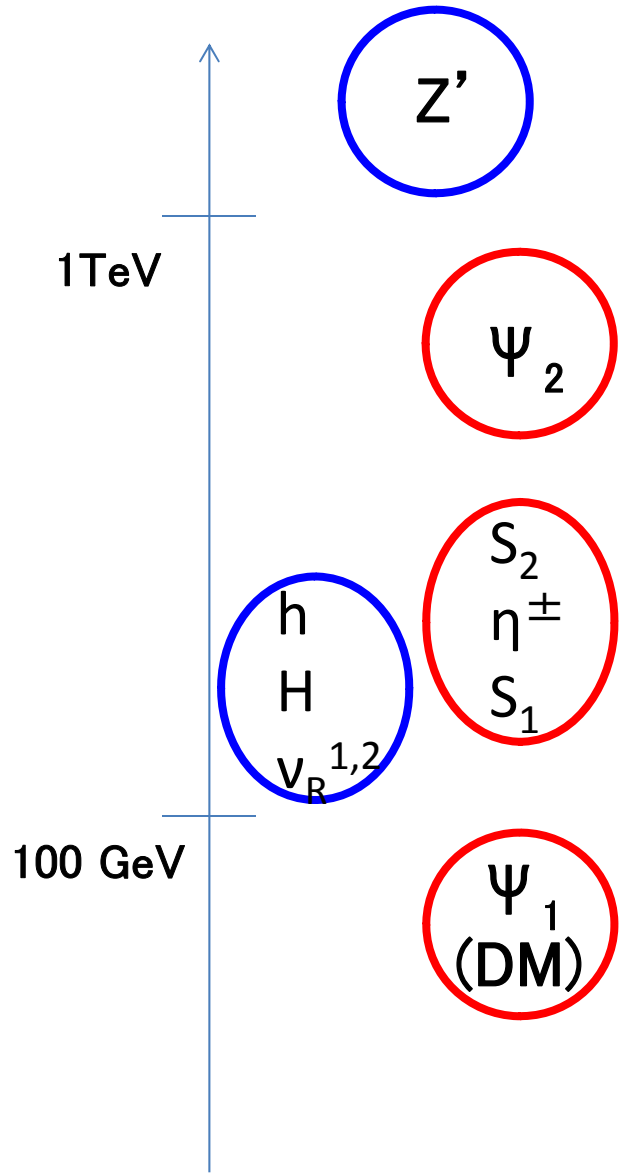
$M_{S1} = 200$ GeV, $M_{S2} = 300$ GeV ,

$M_h = 125$ GeV, $M_H = 130$ GeV,

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

$g_{B-L}=0.4$, $M_{Z'}=4000$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'

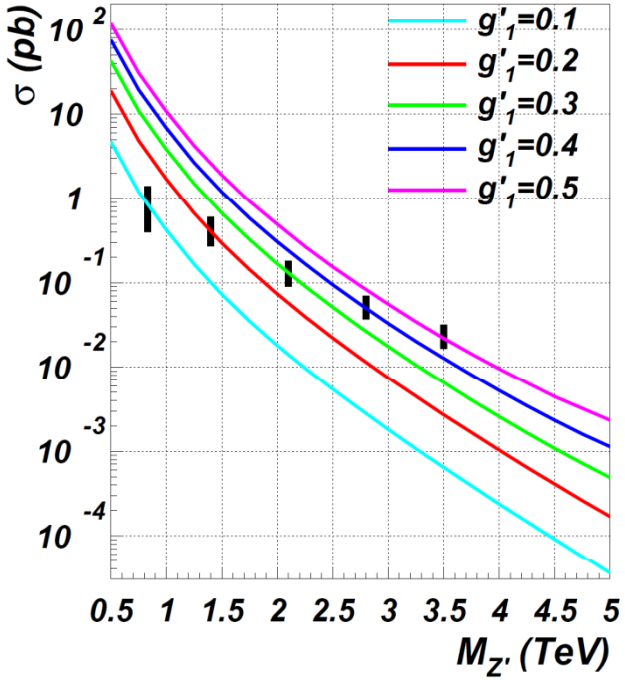
Z' mass: O(1−10)TeV

$\Gamma(Z' \rightarrow XX) \propto$ (B−L charge)^2

Z' decay into

invisible about 30%

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



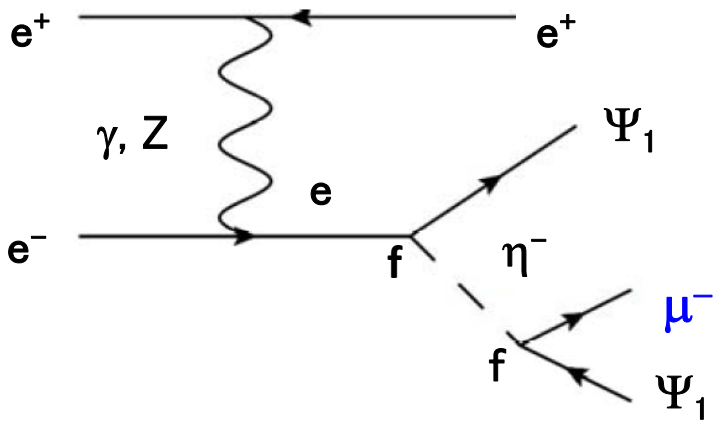
L. Basso, A. Belyaev, S.Moretti and C. H. Shepherd-Themistocleous (2009); L.Basso (2011)

$U(1)_{B-L}$ symmetry could be tested by **measuring decay of the Z'** at the LHC.

However, if we detect only Z' boson, our model cannot be **distinguished other $U(1)_{B-L}$ models**.

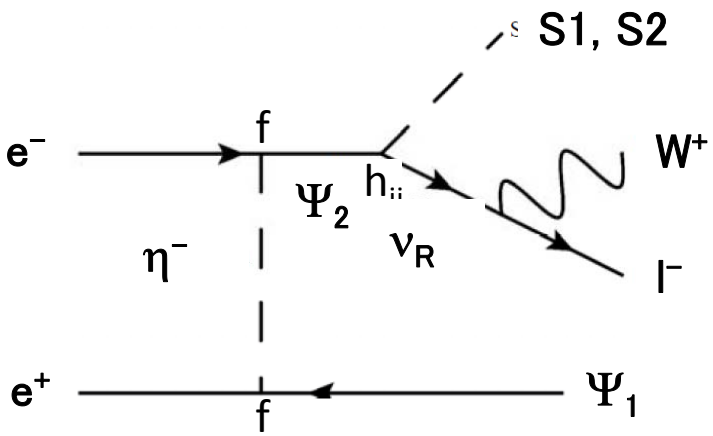
4. Physics at the ILC

Dark matter &
right handed neutrino



We focus on
$e^+, e^- \rightarrow e^+, \mu^- + \not{E}$ processes.

If this cross section is large,
dark matter would be directly coupled to charged lepton.



We focus on
$e^-, e^+ \rightarrow e^- (\text{or } \mu^-), W^+ + \not{E}$ processes.

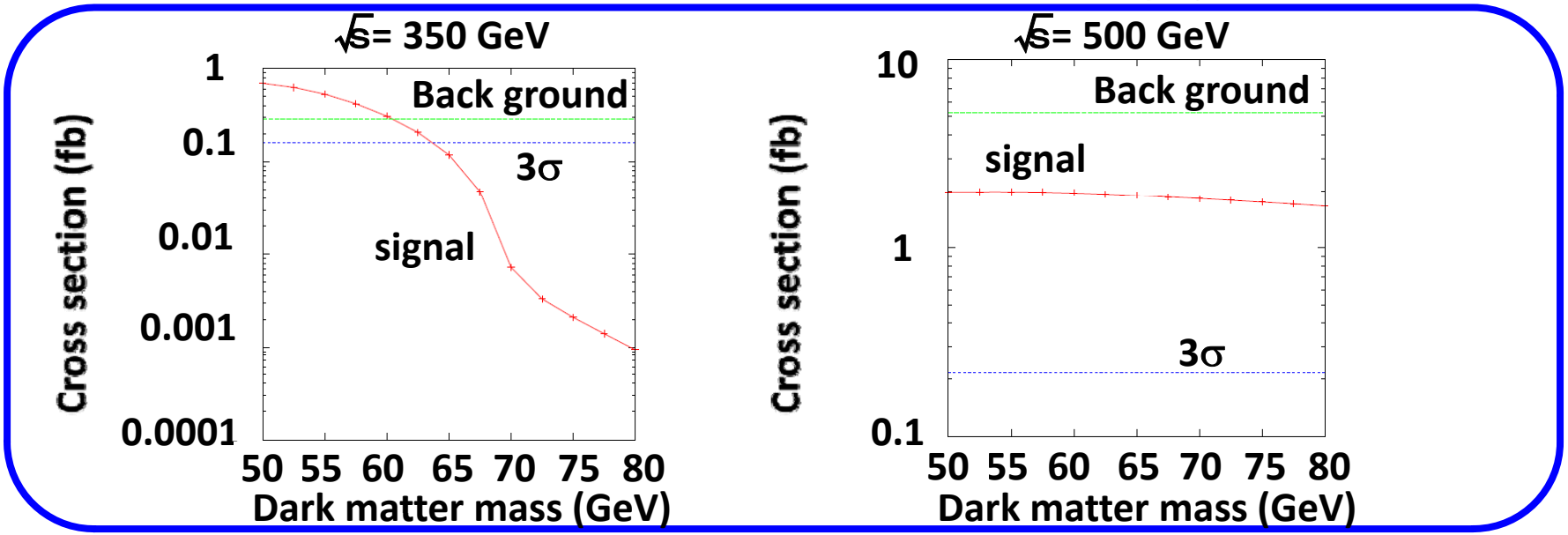
If this cross section is large,
non-stable right handed neutrino exists at O(100) GeV.

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 for $M_{DM} \lesssim 64$ GeV at 3σ C.L.
at the $\sqrt{s}$ = 500GeV at 5σ C.L.

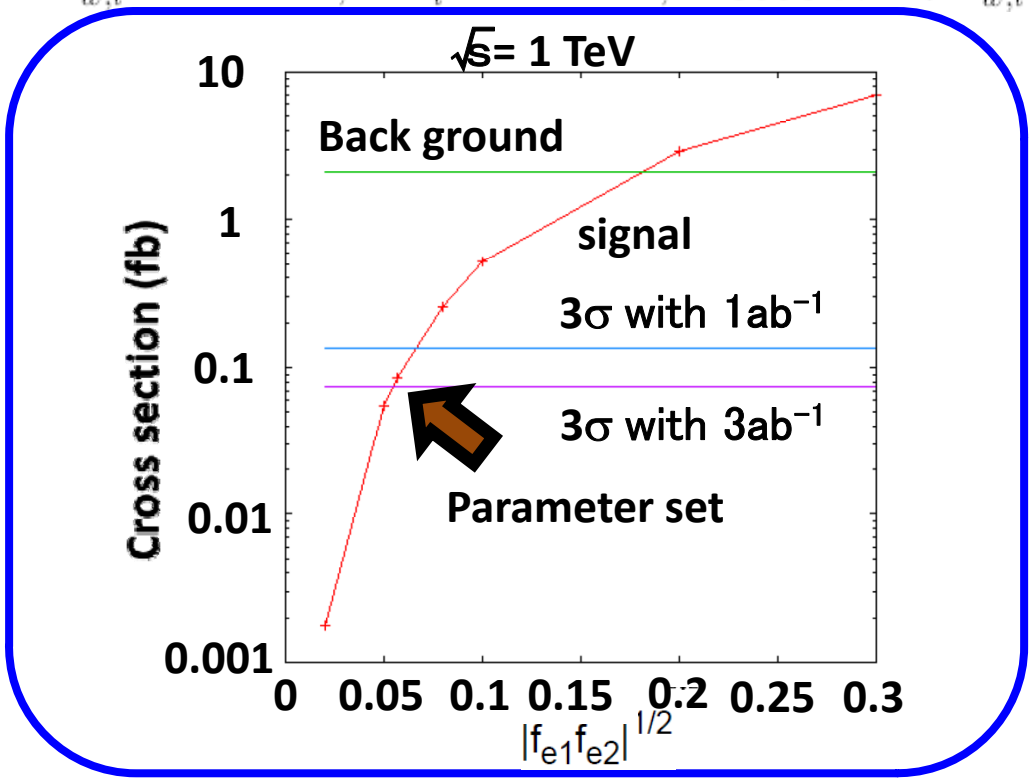
4. Physics at the ILC

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 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, $\mu(\tau)$ with missing momentum

  → Dark matter which is directly coupled to charged leptons.

- 1 TeV

  e, W with Missing momentum

  → O(100) GeV right handed neutrino

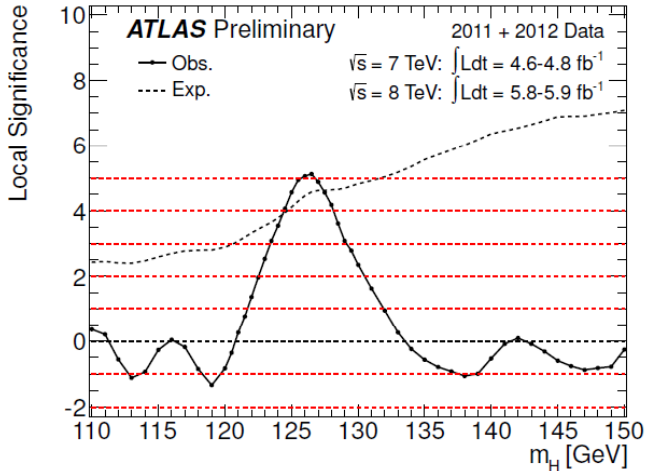
Radiative seesaw model with B−L gauge symmetry which include non stable right handed neutrino exist at TeV scale

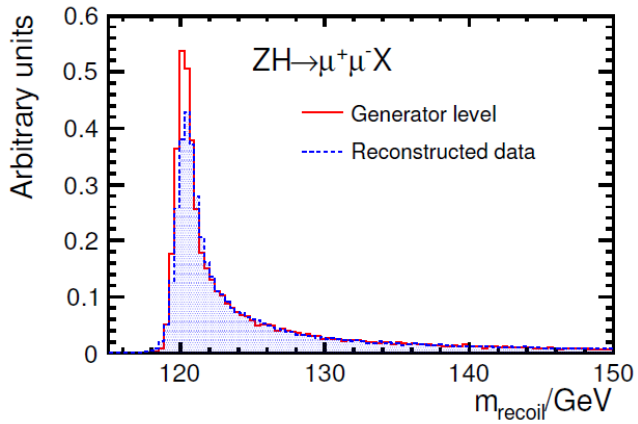
4. Physics at the ILC

SM-like Higgs bosons

Our model predict two SM-like Higgs bosons at O(100)GeV.

One SM-like Higgs boson detected at the LHC ?





Two SM-like Higgs bosons would be separated at the ILC if these mass difference is about more than 50 MeV.

5.Conclusion

① **We consider possibility of testing the radiative type-I 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.**

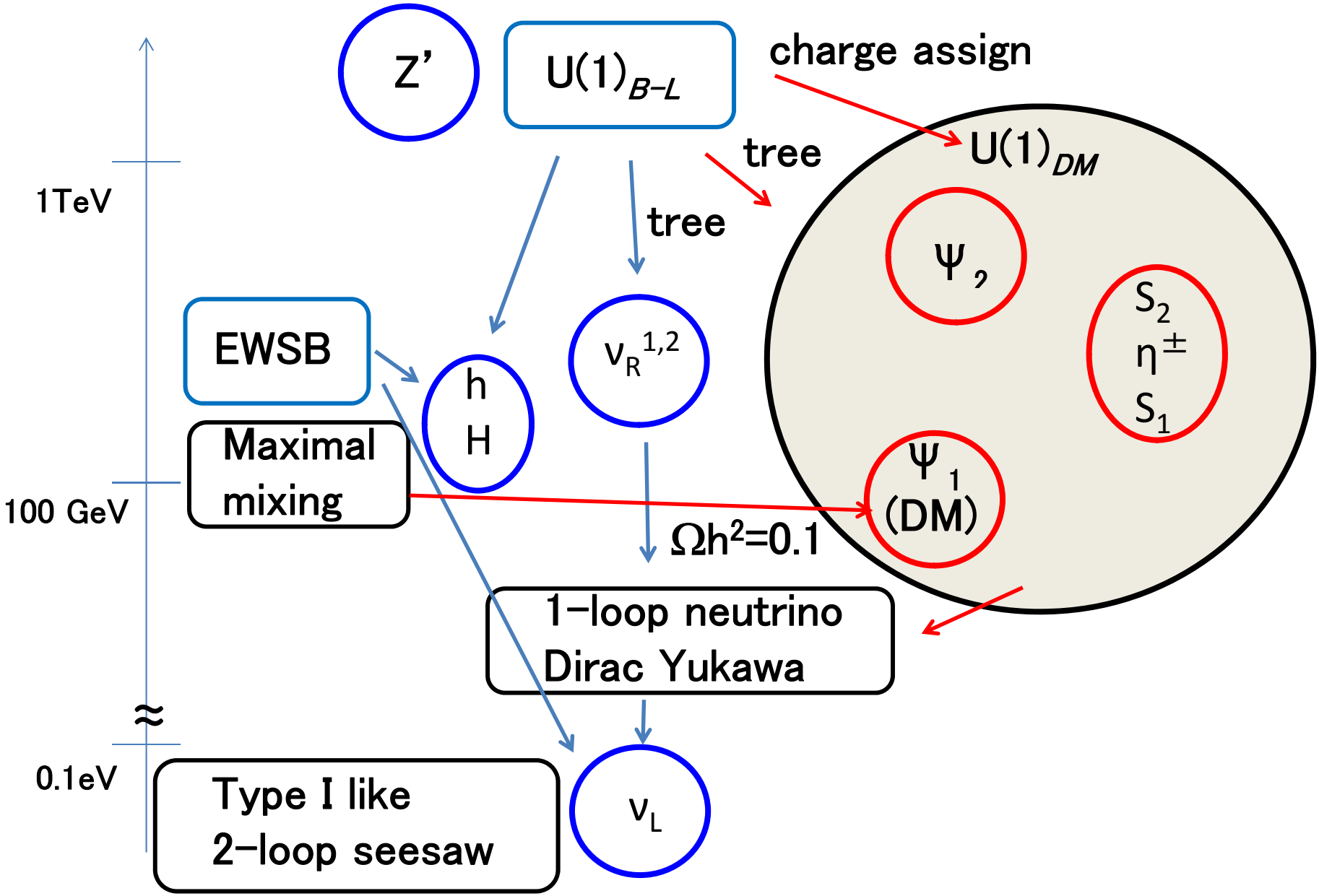
② Z' boson could be tested at the LHC.

③ Dark matter Ψ_1 can be tested with 1 ab^{-1}data:
at $\sqrt{s}$ = 350 GeV with $M_{DM} \lesssim 64$ GeV at 3σ C.L..
at $\sqrt{s}$ = 500 GeV at 5σ C.L. .

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

⑥ **ILC have potential which distinguish our model.**

Back up


Z'
U(1)$_{B-L}$
charge assign
U(1)$_{DM}$
tree
tree
1TeV
EWSB
h
H
$\nu_R^{1,2}$
Ψ_2
S_2
$\eta^{\pm}$
S_1
Maximal mixing
100 GeV
Ψ_1
(DM)
Ωh^2=0.1
1-loop neutrino Dirac Yukawa
≈
0.1eV
Type I like 2-loop seesaw
ν_L

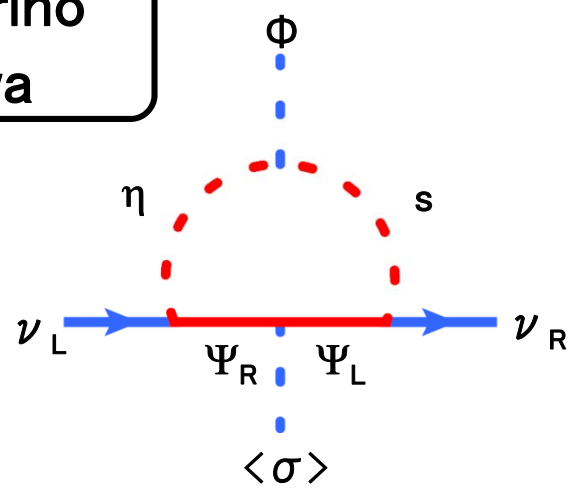
$U(1)_{B-L}$ $\xrightarrow{\text{charge assign}}$ $U(1)_{DM}$

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

1-loop neutrino Dirac Yukawa

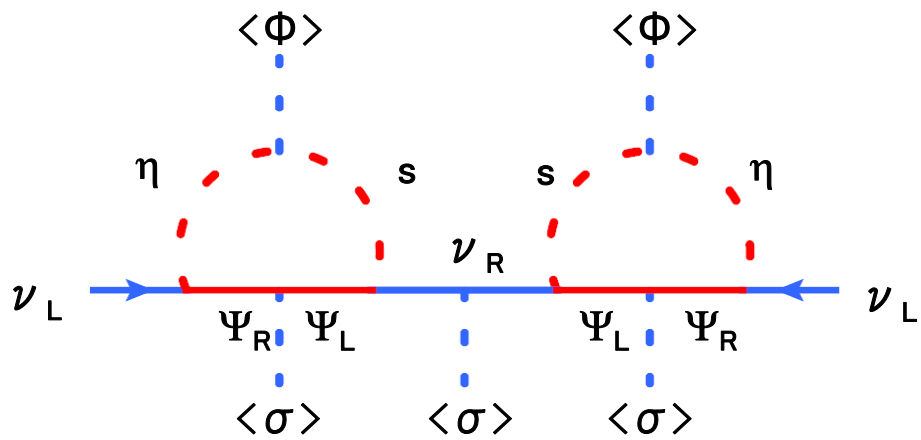
- Majorana mass of ν_R,
- Dirac mass of Ψ

} tree level



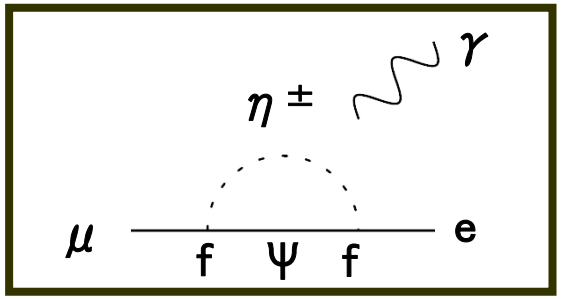
~~EW~~

Type I like
2-loop seesaw



2.Model

LFV constraint



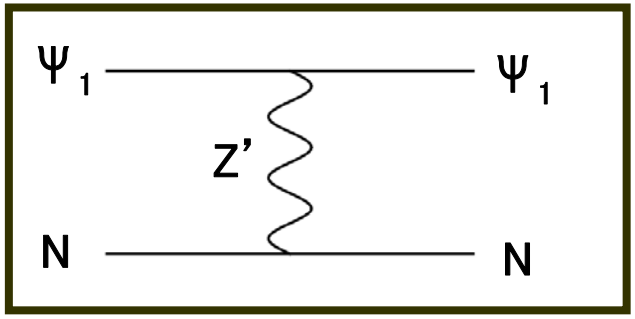
$$BR(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{64\pi G_F^2}\left|\frac{1}{M_{\eta^\pm}^2} f_{\mu i} F_2\left(\frac{(M_\Psi)_i^2}{M_{\eta^\pm}^2}\right)(f^\dagger)_{ie}\right|^2,$$

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

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

J. Adam et al.(2011)

Direct detection of Ψ_1



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

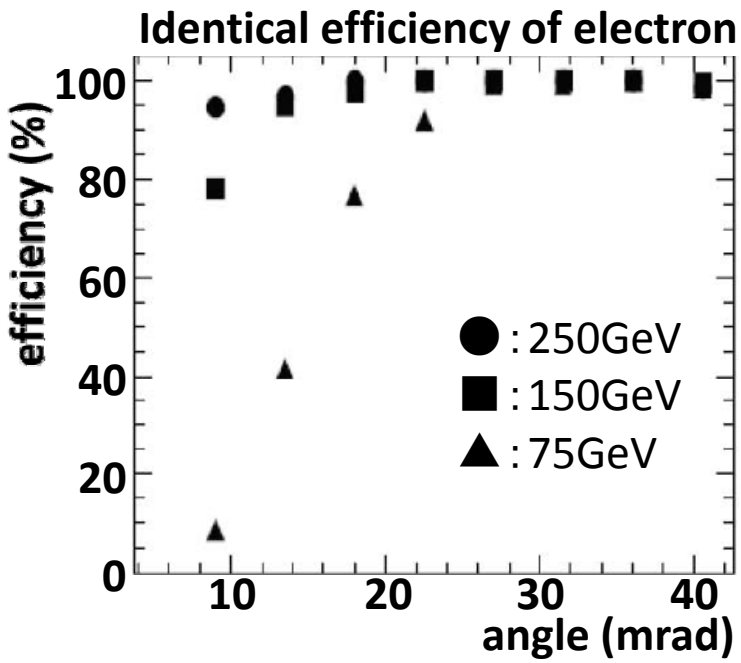
Experimental bound(XENON100): $\sigma(\Psi_1 N \to \Psi_1 N) < 2 \times 10^{-45}\,\mathrm{cm}^2$

XENON collaboration (2012)

Consistent with current experimental bound.

4. Physics at the ILC

Electron efficiency

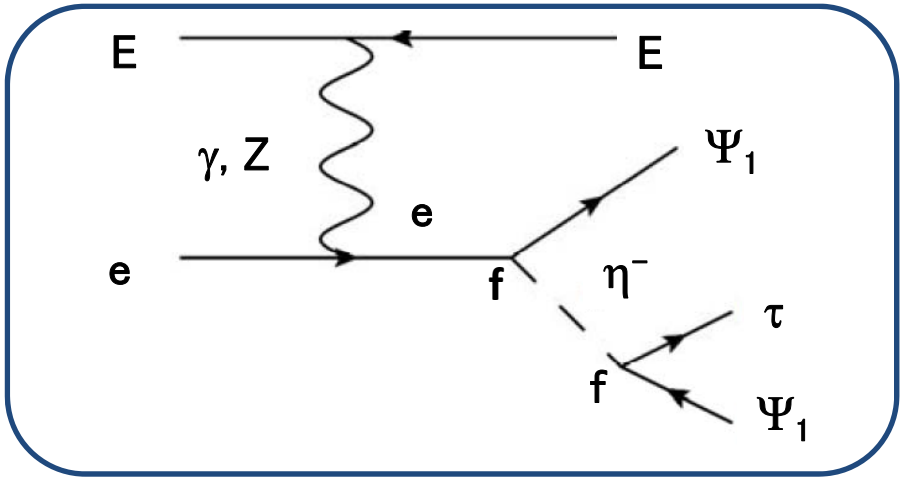


I.Bozovic-Jelisavcic [on behalf of the FCAL Collaboration], (2011)

1. In the signal processes, Electron tend to be emitted forward region.
2. We assume detectable area of electron 30 mrad and 20 mrad for 350 GeV and 500 GeV collider respectively

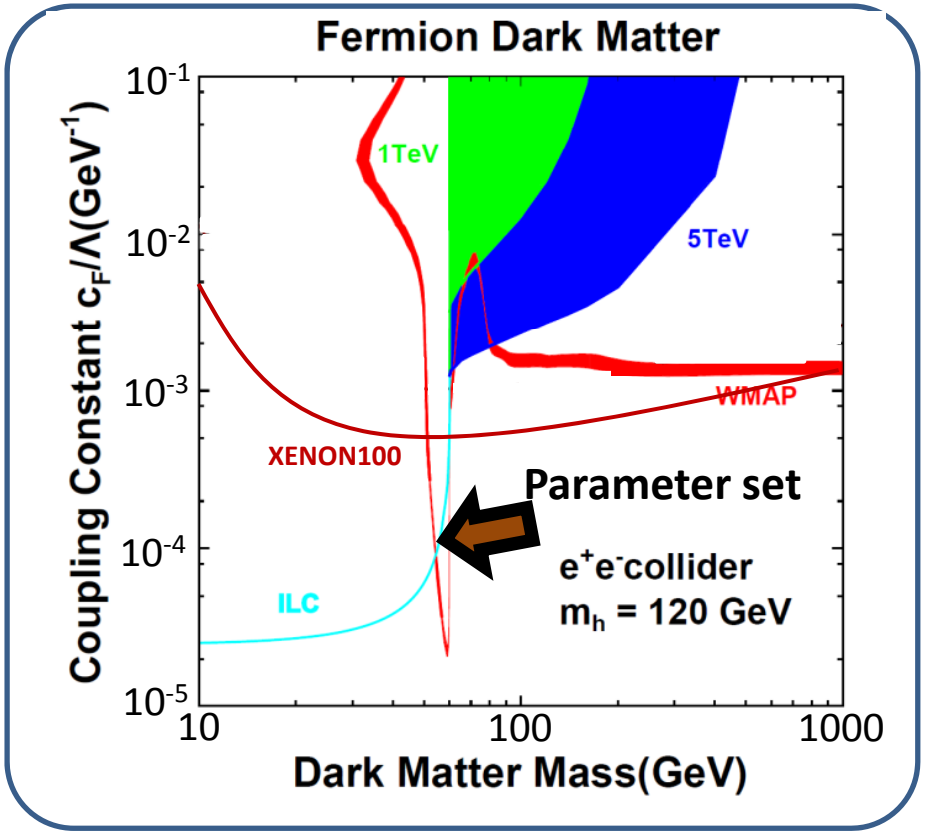
4. Physics at the ILC

e, E → e, τ, ∅ processes



1. In our model, $f_{\tau j}$ coupling can take larger value than $f_{\mu j}$ coupling.
2. Signal cross section increase about 100 times more than e, E → e, μ, ∅ processes in our parameter set.
3. Background are same value to e, E → e, μ, ∅ processes.

4. Physics at the ILC

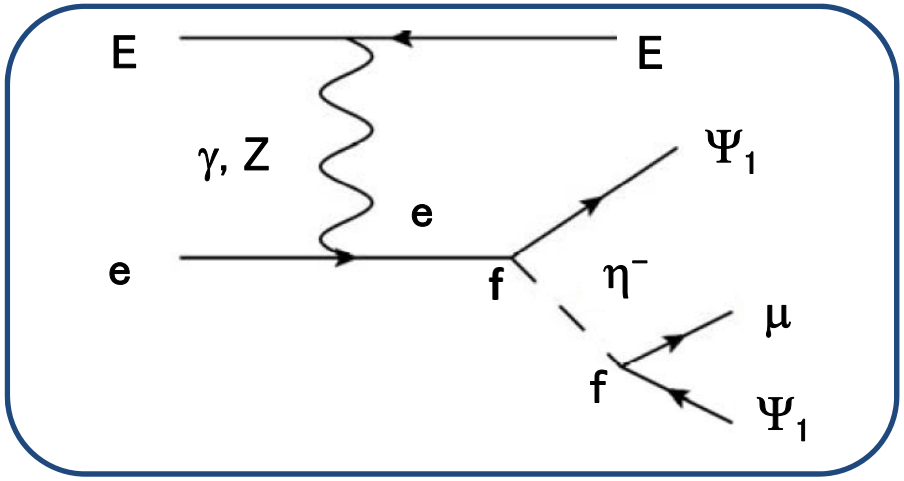


S.Kanemura, S.Matsumoto, TN, H.Taniguchi (2011).

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

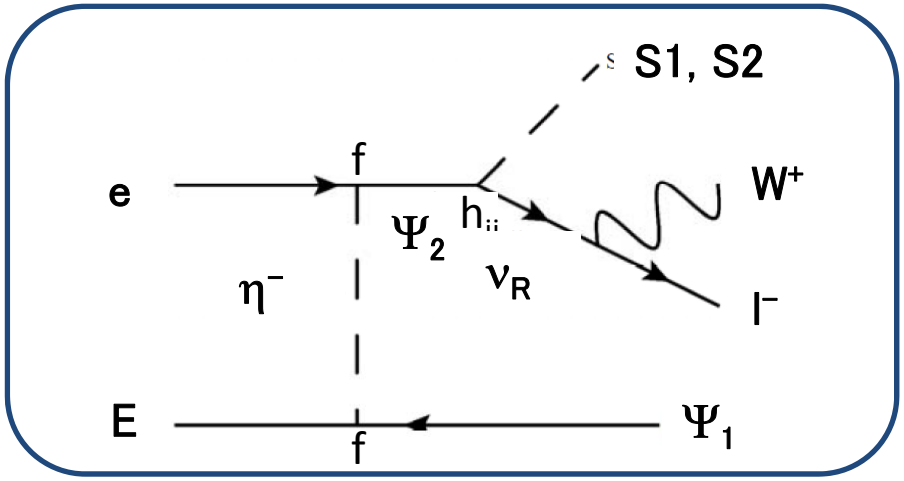
Physics of Ψ_1



1. In our model, dark matter and electron are coupled via the $L\psi\eta$ coupling
2. The energy momentum conservation is used to detect the dark matter.
3. If this cross section is large, dark matter would be directly coupled to charged lepton.

4. Physics at the ILC

Physics of ν_R



1. In our parameter set, $\nu_R \rightarrow W^{\pm}$, $l^{\mp}$ is main decay mode.
2. We consider W→jet, jet process.
3. If this cross section is large, non-stable right handed neutrino exist at O(100) GeV.