# Radiative Type-I Seesaw Model with Dark Matter via $\mathrm{U(1)_{B-L}}$ Gauge Symmetry Breaking at the ILC

**Hiroaki SUGIYAMA**
**(Univ. of Toyama, Japan)**

Contents

- Introduction
- Our Model - "Radiative Type-I Seesaw" -
- Phenomenology ( $\nu_R$ )
- Summary

based on 'S. Kanemura, T. Nabeshima, HS, PRD**85**, 033004(2012)'
'S. Kanemura, T. Nabeshima, HS, arXiv:1207.7061'

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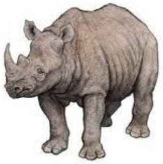
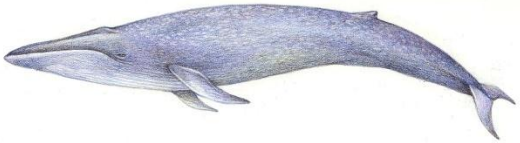
# Introduction

**Neutrino masses** are very different from other fermion masses.

neutrino $\lesssim 1\,\mathrm{eV}$ electron $= 0.5\,\mathrm{MeV}$ tau $= 1.8\,\mathrm{GeV}$ top $= 172\,\mathrm{GeV}$



$1\,\mathrm{MeV}$ "$\simeq$" $1\,\mathrm{kg}$

⟶ neutrino-specific mechanism to generate their masses ?

## Neutrino-specific mass term

Majorana mass : $\frac{1}{2} m\, e^{-i\varphi}\, \overline{(\nu_L)^c}\, \nu_L + \mathrm{h.c.}$

$Q_{\mathrm{EM}}$ : $0 + 0 = 0$ (possible only for $\nu$ )

$Y : (-1/2) + (-1/2) = -1$

$I_3 : \quad 1/2 + 1/2 = 1$

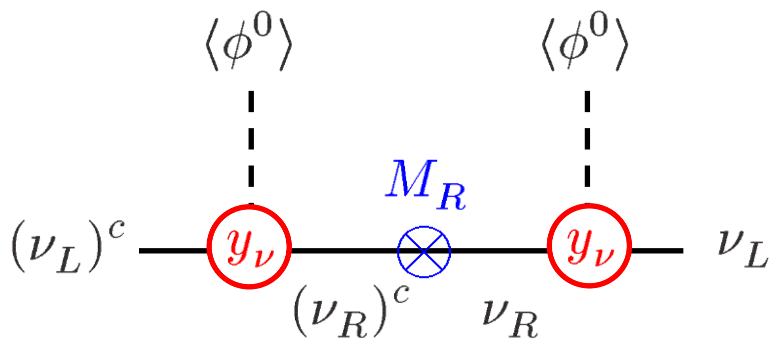
to be compensated by scalar fields

$\Phi = (\phi^+, \phi^0)^T$

Only the SM Higgs boson has vev. $\Longrightarrow \frac{1}{M} \left[\overline{L^c}\, i\sigma_2\, \Phi\right] \left[\Phi^T i\sigma_2 L\right]$ etc.

# Type-I Seesaw

SM + $\nu_R$




$$m_\nu \simeq \frac{y_\nu^2 \langle\phi^0\rangle^2}{M_R} \sim 0.1\,\mathrm{eV} = 10^{-10}\,\mathrm{GeV}$$

$y_\nu \sim 1, \quad M_R \sim 10^{14}\,\mathrm{GeV}$

Far from experimental reach

$y_\nu \lesssim 10^{-6}, \quad M_R \lesssim 10^{3}\,\mathrm{GeV}$

Good for experimental search

Why small ? Radiatively generated?

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# Our Model

**Gauge Group :** $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

No VEV

| | Fermion $(i=1,2)$ | | | Boson | | |
|---|---|---|---|---|---|---|
| | $\nu_{Ri}$ | $\Psi_{Li}$ | $\Psi_{Ri}$ | $\eta$ | $s^0$ | $\sigma^0$ |
| $SU(2)_L$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{2}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ |
| $U(1)_Y$ | $0$ | $0$ | $0$ | $1/2$ | $0$ | $0$ |
| $U(1)_{B-L}$ | $+1$ | $3/2$ | $-1/2$ | $1/2$ | $1/2$ | $2$ |

Broken by $\langle\sigma^0\rangle$

**Not** $-1$

$\Rightarrow \overline{L}\widetilde{\Phi}\,\nu_R$ **is forbidden**

| | $\nu_R$ | $\Psi_L$ | $\Psi_R$ | $\eta$ | $s^0$ | $\sigma^0$ |
|---|---|---|---|---|---|---|
| $\mathrm{SU(2)_L}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{2}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ |
| $\mathrm{U(1)_Y}$ | 0 | 0 | 0 | $1/2$ | 0 | 0 |
| $\mathrm{U(1)_{B-L}}$ | $+1$ | $3/2$ | $-1/2$ | $1/2$ | $1/2$ | 2 |

## $\mathrm{U(1)_{B-L}}$ charges and dark matter

**SM particles +** $\nu_R$ **:** $0,\ \frac{1}{3},\ -1,\ +1$

$\sigma^0$ **:** $2$

} **Integer or 1/3**

**"Red particles" : Half-integer (Interactions :** $\sigma^0\,\overline{\Psi_L}\,\Psi_R$ **etc.)**

$\Downarrow$

$\mathrm{U(1)_{B-L}} \times \mathrm{U(1)_{DM}}$

**Unbroken global U(1)** $_{\mathbf{DM}}$ **as an accidental symmetry**

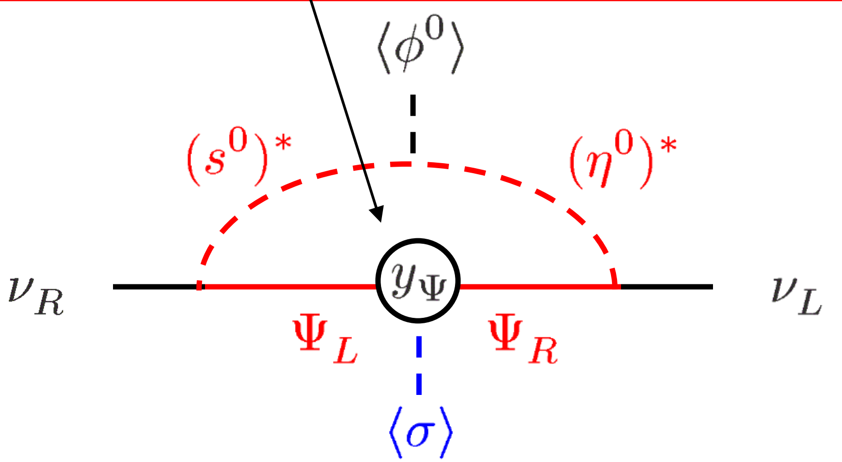
$\Rightarrow$ **The lightest "red particle" is stable (dark matter).**

| | $\nu_R$ | $\Psi_L$ | $\Psi_R$ | $\eta$ | $s^0$ | $\sigma^0$ |
|---|---|---|---|---|---|---|
| $\mathrm{SU(2)_L}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{2}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ |
| $\mathrm{U(1)_Y}$ | 0 | 0 | 0 | 1/2 | 0 | 0 |
| $\mathrm{U(1)_{B-L}}$ | +1 | 3/2 | −1/2 | 1/2 | 1/2 | 2 |

**Assumed to be DM**

**Mass of Dirac fermion** $\Psi \equiv \begin{pmatrix} \Psi_R \\ \Psi_L \end{pmatrix}$ **:** $y_\Psi \left[ \langle\sigma\rangle \overline{\Psi_L} \Psi_R \right]$

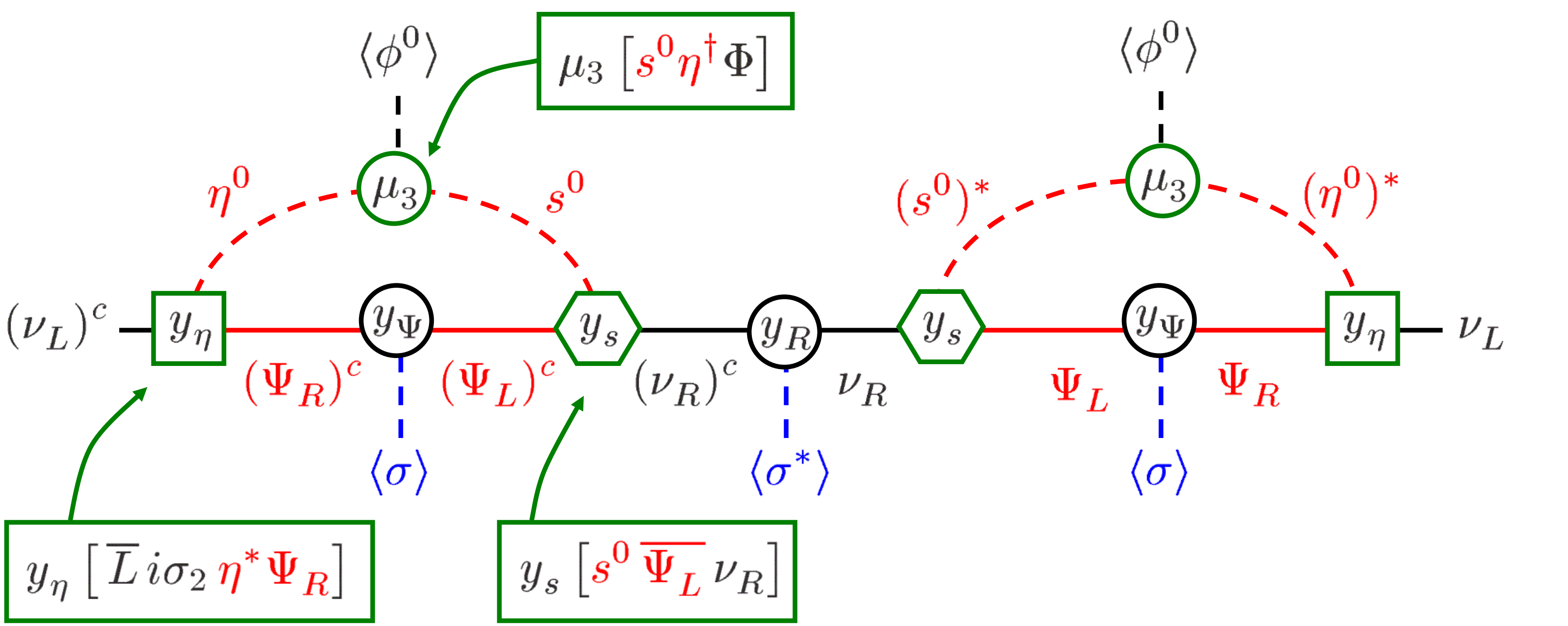
**Dirac mass term of** $\nu$ **:**
**(forbidden at tree level)**
~~L~~#




**Majorana mass of** $\nu_R$ **:** $y_R \left[ \langle\sigma^*\rangle \overline{(\nu_R)^c} \nu_R \right]$

| | $\nu_R$ | $\Psi_L$ | $\Psi_R$ | $\eta$ | $s^0$ | $\sigma^0$ |
|---|---|---|---|---|---|---|
| $SU(2)_L$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{2}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ |
| $U(1)_Y$ | 0 | 0 | 0 | 1/2 | 0 | 0 |
| $U(1)_{B-L}$ | +1 | 3/2 | −1/2 | 1/2 | 1/2 | 2 |

## "Radiative Type-I Seesaw" with DM



| | $\nu_R$ | $\Psi_L$ | $\Psi_R$ | $\eta$ | $s^0$ | $\sigma^0$ |
|---|---|---|---|---|---|---|
| $SU(2)_L$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{2}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ |
| $U(1)_Y$ | 0 | 0 | 0 | 1/2 | 0 | 0 |
| $U(1)_{B-L}$ | +1 | 3/2 | −1/2 | 1/2 | 1/2 | 2 |

## Scalar Mass Eigenstates

$$\left. \begin{matrix} s^0 \\ \eta^0 \end{matrix} \right\} \xrightarrow{\mu_3 \left[ s^0 \eta^\dagger \Phi \right]} \left\{ \begin{matrix} S_1^0 \\ S_2^0 \end{matrix} \right.$$

$$\eta^\pm \longrightarrow \eta^\pm$$

$$\left. \begin{matrix} \mathrm{Re}(\phi^0) \\ \mathrm{Re}(\sigma^0) \end{matrix} \right\} \xrightarrow{\lambda_{\sigma\phi} \left[ |\sigma^0|^2 \, \Phi^\dagger \Phi \right]} \left\{ \begin{matrix} h^0 \\ H^0 \end{matrix} \right.$$

$\phi^\pm \longrightarrow$ **Eaten by $W^\pm$ boson**

$\mathrm{Im}(\phi^0) \longrightarrow$ **Eaten by $Z$ boson**

$\mathrm{Im}(\sigma^0) \longrightarrow$ **Eaten by $Z'$ boson**

# Example Set of Parameter Values

$$y_\eta = \begin{pmatrix} 0.0757 & 0.0445 \\ 0.01 & -0.0123 \\ 0.141 & -0.0101 \end{pmatrix} \quad y_s = \begin{pmatrix} -0.0152 & 0.0152 \\ 0.1 & 0.1 \end{pmatrix}$$

$$M_{R1} = M_{R2} = 250\,\mathrm{GeV}$$

$$\{M_{\Psi_1},\ M_{\Psi_2}\} = \{57.5\,\mathrm{GeV},\ 800\,\mathrm{GeV}\}$$

**DM**

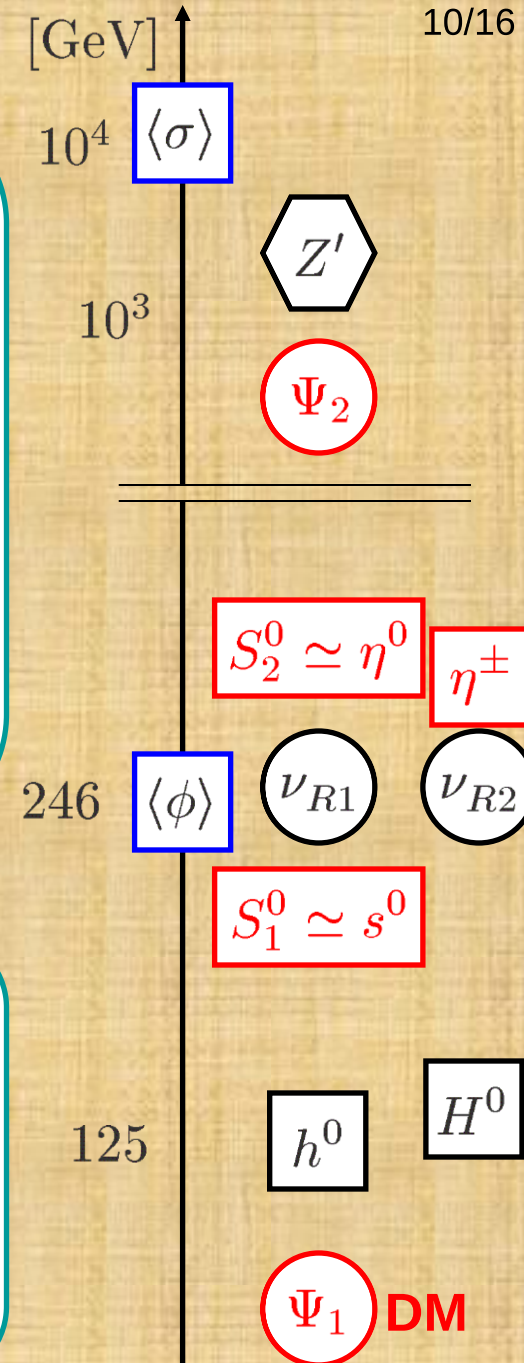
$$\{m_{S_1},\ m_{S_2},\ \cos\theta\} = \{200\,\mathrm{GeV},\ 300\,\mathrm{GeV},\ 0.05\}$$

$$m_{\eta^\pm} = 280\,\mathrm{GeV}$$

$\Downarrow$ **Just an example**

$$\Delta m_{21}^2 = 7.6 \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m_{31}^2 = 2.4 \times 10^{-3}\,\mathrm{eV}^2 \quad U_{\mathrm{MNS}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & -\frac{1}{3} & \frac{1}{2} \end{pmatrix}$$



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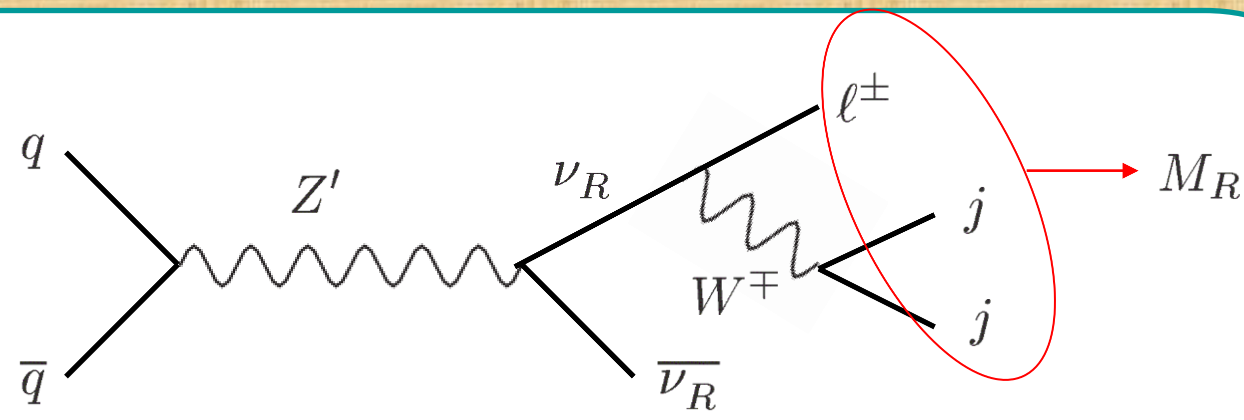
# Phenomenology - $\nu_R$ at LHC -




$\sigma(pp \to Z') \simeq 70\,\mathrm{fb}$ **for** $\sqrt{s} = 14\,\mathrm{TeV},\ m_{Z'} = 2\,\mathrm{TeV},\ g_{\mathrm{B-L}} = 0.2$

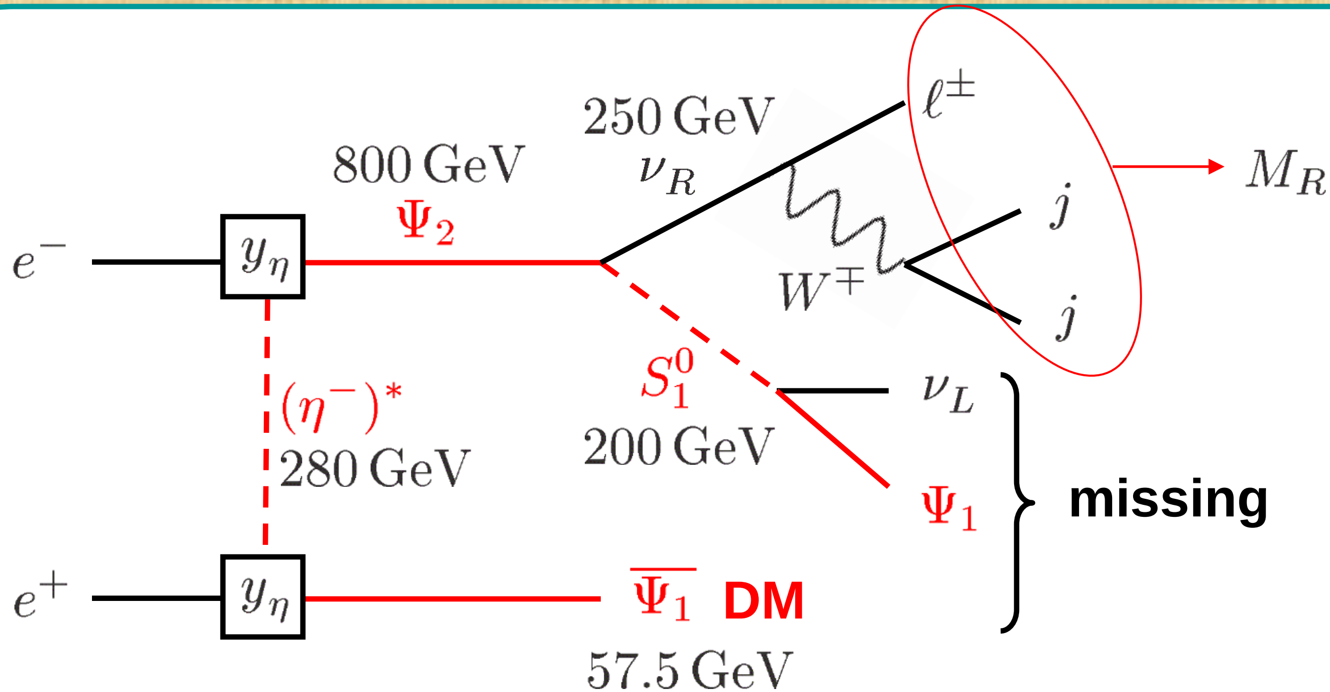
$$\begin{cases} \mathrm{BR}(Z' \to \nu_R \overline{\nu_R}) \simeq 10\,\% \\ \mathrm{BR}(\nu_R \to \ell^- W^+) + \mathrm{BR}(\nu_R \to \ell^+ W^-) \simeq 50\,\% \\ \left(\mathrm{BR}(\nu_R \to \nu_L Z) + \mathrm{BR}(\nu_R \to \nu_L h) + \mathrm{BR}(\nu_R \to \nu_L H) \simeq 50\,\%\right) \\ \mathrm{BR}(W^{\pm} \to \mathrm{hadrons}) \simeq 68\,\% \end{cases}$$

$$\longrightarrow \quad 0.1 \times \left\{1 - (1 - 0.5 \times 0.68)^2\right\} \simeq 0.06$$

$\sigma(\mathrm{signal}) \simeq 70\,\mathrm{fb} \times 0.06 \simeq 4\,\mathrm{fb}$

**Very heavy** $Z'$ $\Longrightarrow$ **ILC**

# Phenomenology - $\nu_R$ at ILC -




$$\begin{cases} \mathrm{BR}(\Psi_2 \to \nu_R\, S_1^0) \simeq 100\,\% \quad \textbf{for} \quad S_1^0 \simeq s^0 (\neq \eta^0) \\ \mathrm{BR}(\nu_R \to \ell^- W^+) + \mathrm{BR}(\nu_R \to \ell^+ W^-) \simeq 50\,\% \\ \mathrm{BR}(W^{\pm} \to \text{hadrons}) \simeq 68\,\% \end{cases}$$

# Kinematical Cuts

$$|\cos\theta_\ell| < 0.95 \qquad E_\ell < 300\,\mathrm{GeV}$$

$$0.9999416 < |\cos\theta_\gamma|$$

$$200\,\mathrm{GeV} < M_{\mathrm{miss}} < 600\,\mathrm{GeV}$$

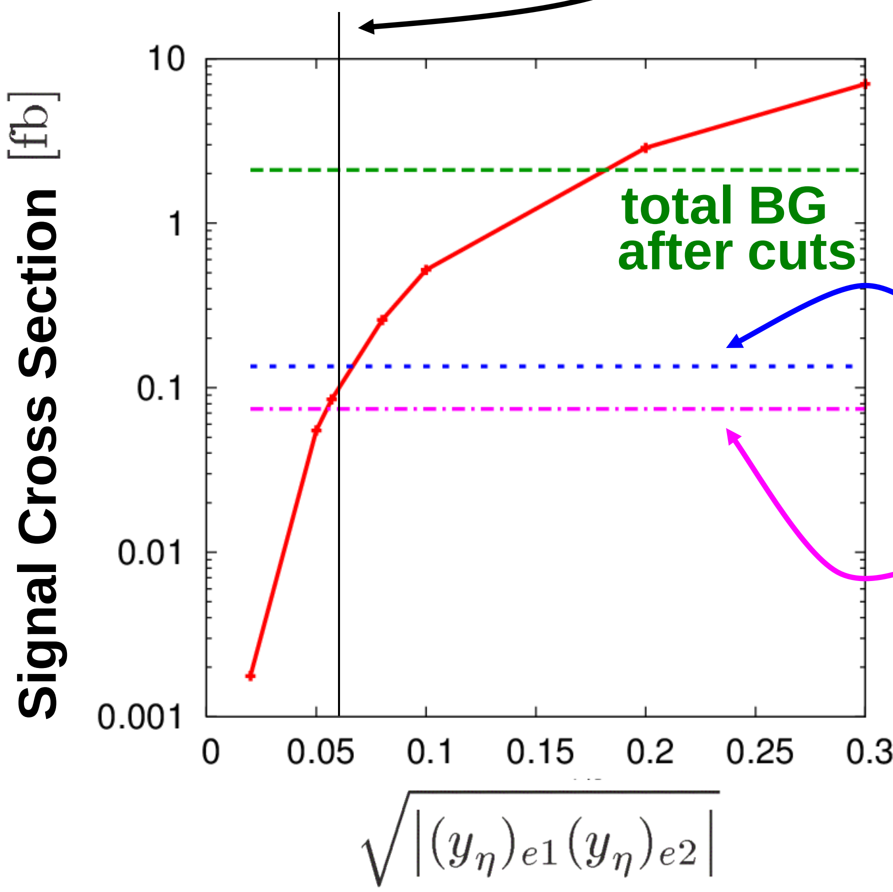
$$240\,\mathrm{GeV} < M_{W\ell} < 260\,\mathrm{GeV}$$

$$300\,\mathrm{GeV} < E_{W\ell} < 600\,\mathrm{GeV}$$

**Example**

$$y_\eta = \begin{pmatrix} 0.0757 & 0.0445 \\ 0.01 & -0.0123 \\ 0.141 & -0.0101 \end{pmatrix}$$

**ILC with** $\sqrt{s} = 1\,\mathrm{TeV}$




**Main BG**

$e^+e^- \to W^-\ell^+\nu\gamma$

$N_S/\sqrt{N_{BG}} = 3$ **with** $10^3\,\mathrm{fb}^{-1}$

$N_S/\sqrt{N_{BG}} = 3$ **with** $3 \times 10^3\,\mathrm{fb}^{-1}$

# Summary



## $\mathrm{U(1)_{B-L}}$ symmetry

**Symmetry breaking**

$\longrightarrow M_R,\ m_D,\ M_{\mathrm{DM}} \longrightarrow$ { **Radiative Type-I Seesaw** / **TeV-scale $\nu_R$** }

**Charge assignments**

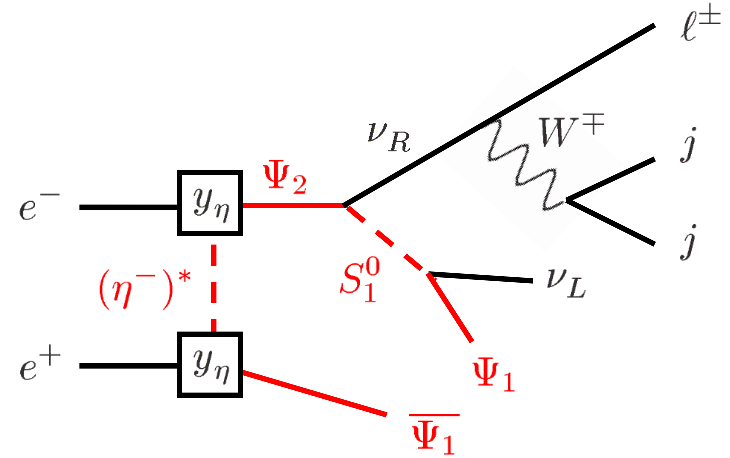
$\longrightarrow$ **Unbroken global $\mathrm{U(1)_{DM}}$** $\longrightarrow$ **Stability of DM**

## $\nu_R$ signal : $\nu_R \to \ell^\pm jj$

$\mathcal{O}(1)\,\mathrm{fb}$ **@14TeV LHC (light $Z'$ )**

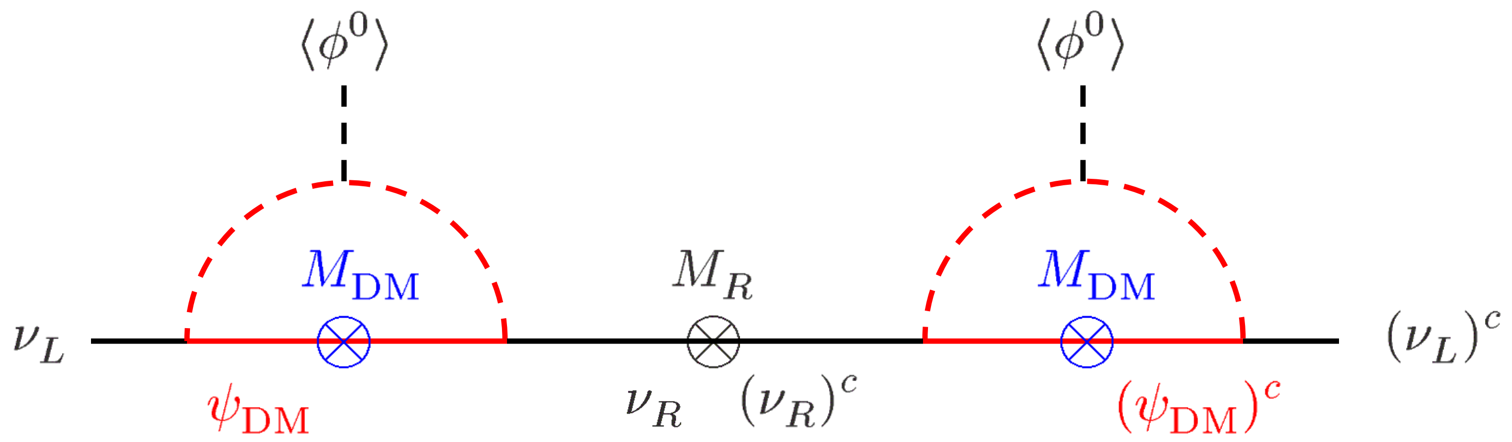
$\mathcal{O}(0.1)\,\mathrm{fb}$ **@ 1TeV ILC (heavy $Z'$)**

$N_S/\sqrt{N_{BG}} = 3$ **w/** $\mathcal{O}(10^3)\,\mathrm{fb}^{-1}$



# backup

# “Radiative Type-I Seesaw” with Dark Matter




**Closed pass (loop)**

$\Rightarrow$ **Some conserved charge (U(1), Z2, etc.) ?**

$\Rightarrow$ $\psi_{\rm DM}$ **can be fermionic dark matter**

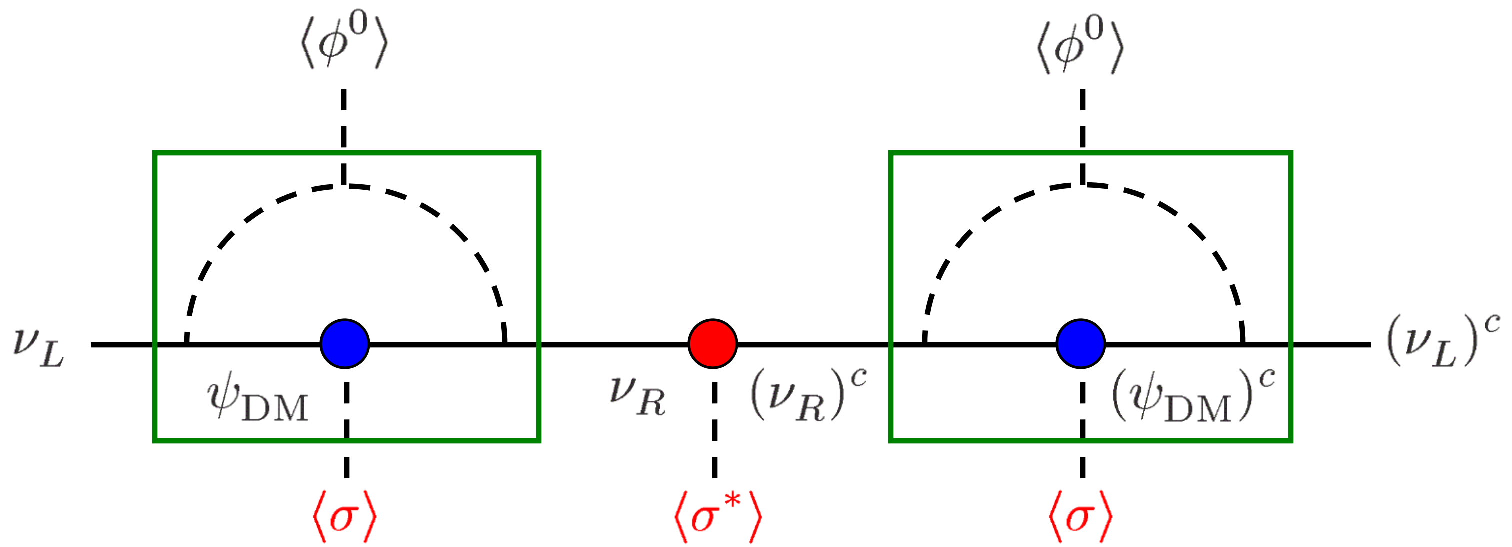
$\langle \phi^0 \rangle \overline{\nu_L} \nu_R$ **: Forbidden**

$\frac{M_{\rm DM}}{\Lambda} \langle \phi^0 \rangle \overline{\nu_L} \nu_R$ **: Allowed**

$\Rightarrow$ $M_{\rm DM}$ **breaks some symmetry (New VEV ?)**

# A New VEV and New Fermion Masses






$\langle\phi^0\rangle \longrightarrow$ **Fermion masses in the SM**

$\langle\sigma\rangle \longrightarrow$ **Fermion masses beyond the SM**

- ● **Majorana mass of** $\nu_R$
- □ **Dirac mass term of** $\nu$
- ● **Mass of** $\psi_{\rm DM}$

(Majorana mass of $\nu_R$ and Dirac mass term of $\nu$) } **TeV-scale Type-I seesaw**

(Mass of $\psi_{\rm DM}$) **Radiative geneartion**

| | $\nu_R$ | $\Psi_L$ | $\Psi_R$ | $\eta$ | $s^0$ | $\sigma^0$ |
|---|---|---|---|---|---|---|
| $\mathrm{SU(2)_L}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{2}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{1}}$ |
| $\mathrm{U(1)_Y}$ | 0 | 0 | 0 | 1/2 | 0 | 0 |
| $\mathrm{U(1)_{B-L}}$ | +1 | 3/2 | −1/2 | 1/2 | 1/2 | 2 |

## $\mathrm{U(1)_{B-L}}$ charges and dark matter

**Nontrivial interactions of "red particles"**

$$\sigma^0\,\overline{\Psi_L}\,\Psi_R \qquad s^0\,\overline{\Psi_L}\,\nu_R \qquad \overline{L}\,i\sigma_2\,\eta^*\Psi_R \qquad s^0\eta^\dagger\Phi$$

$$\mathrm{B-L}: \quad 2-\frac{3}{2}-\frac{1}{2} \qquad \frac{1}{2}-\frac{3}{2}+1 \qquad 1-\frac{1}{2}-\frac{1}{2} \qquad \frac{1}{2}-\frac{1}{2}+0$$

$\Rightarrow$ **Pairs of particle and antiparticle**

$\Rightarrow$ **Unbroken global $\mathrm{U(1)_{DM}}$ (Conservation of # of "red particles")**

$\mathrm{U(1)_{B-L}} \times \mathrm{U(1)_{DM}}$

$\Rightarrow$ **The lightest "red particle" is stable (dark matter).**

# Heavier Fermions for Anomaly Cancelation



| | SM gauge singlet fermion<br>$M \lesssim \langle\sigma\rangle$<br>(B−L charge, # of fields) | | |
|---|---|---|---|
| **Right-handed** | $(1,\ 9)$ | $(-1/2,\ 14)$ | $(1/3,\ 14)$ |
| **Left-handed** | | $(3/2,\ 14)$ | $(-5/3,\ 14)$ |

# Lepton Flavor Violation

$$y_\eta = \begin{pmatrix} 0.0757 & 0.0445 \\ 0.01 & -0.0123 \\ 0.141 & -0.0101 \end{pmatrix}$$

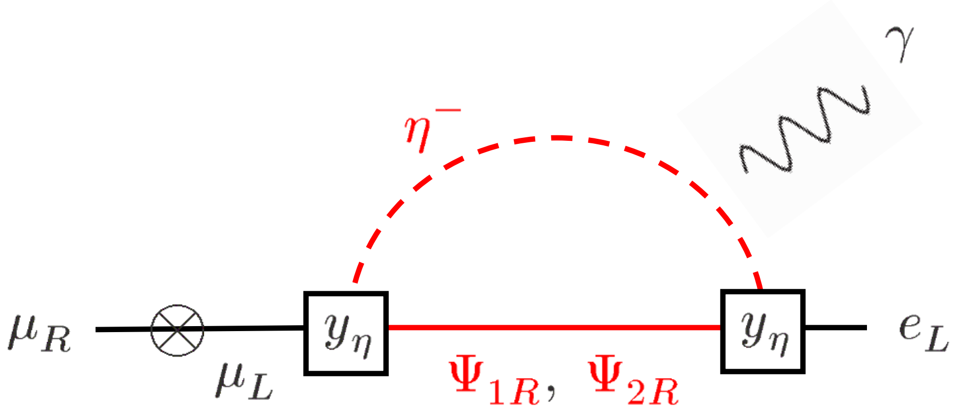
$$\{M_{\Psi_1},\ M_{\Psi_2}\} = \{57.5\,\text{GeV},\ 800\,\text{GeV}\}$$

DM

$$m_{\eta^\pm} = 280\,\text{GeV}$$

$$\Rightarrow \text{BR}(\mu \to e\gamma) = 1.4 \times 10^{-12}$$

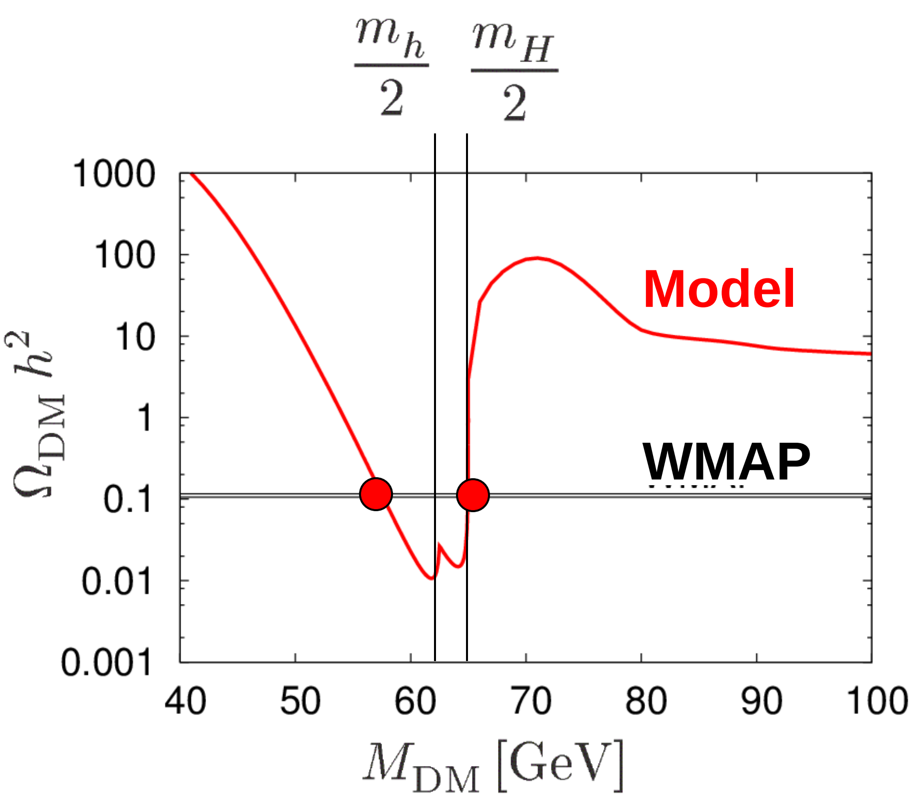
**(MEG :** $< 2.4 \times 10^{-12}$ **at 90% CL)**

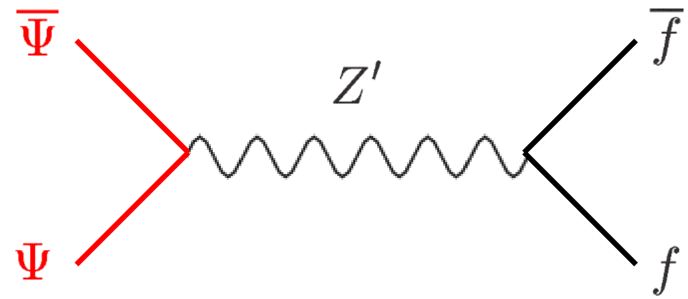


# Phenomenology - Dark Matter -

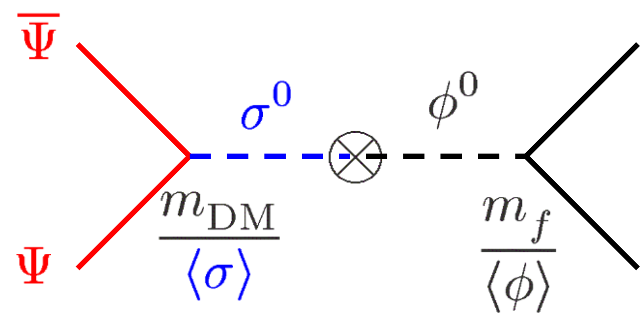
## DM relic abundance

$$\left\{ \begin{array}{l} v_\sigma = \sqrt{2}\langle\sigma\rangle = 5\,\mathrm{TeV} \\ \textbf{Maximal } \sigma^0\text{-}\phi^0 \textbf{ mixing} \end{array} \right.$$




**Not sufficient annihilation**




**Sufficient Annihilation**

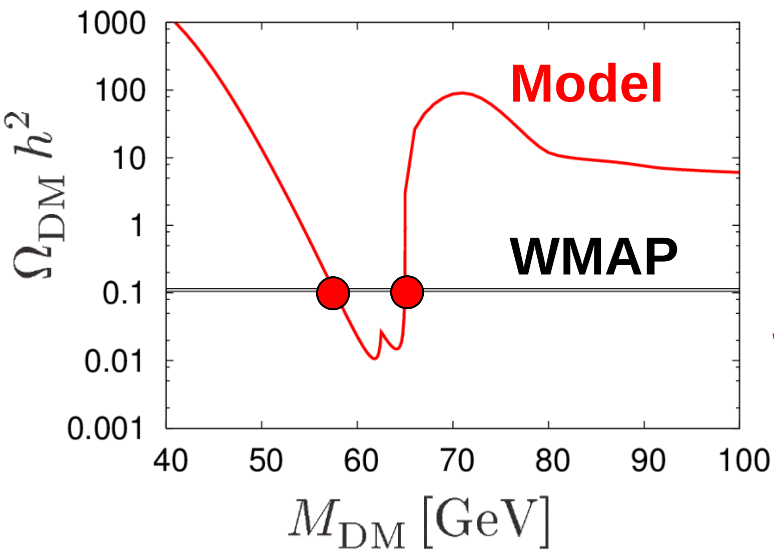
$\Leftrightarrow$ **Large mixing** $\otimes$

$\Leftrightarrow$ $m_h \simeq m_H$

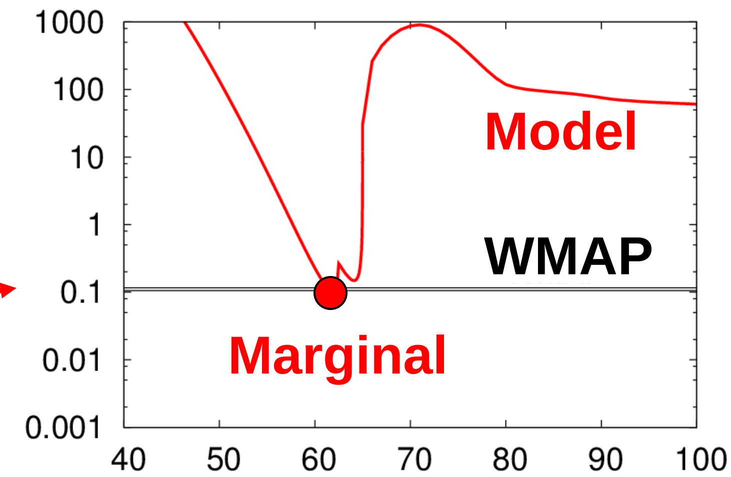
"$h^0 + H^0$" **looks like** $h^0_{\rm SM}$

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

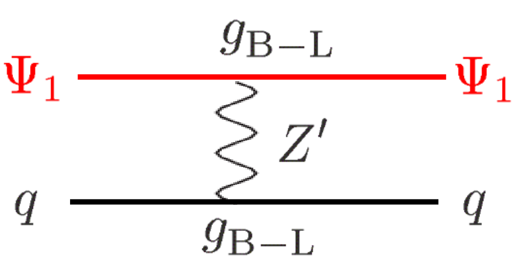
$$v_\sigma = \sqrt{2}\langle\sigma^0\rangle = 5\,\mathrm{TeV} \xrightarrow{\times\sqrt{10}} v_\sigma = \sqrt{2}\langle\sigma^0\rangle = 5\sqrt{10}\,\mathrm{TeV}$$




$\times 10$




## DM - Nucleon Cross Section $\propto v_\sigma^{-4}$




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

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

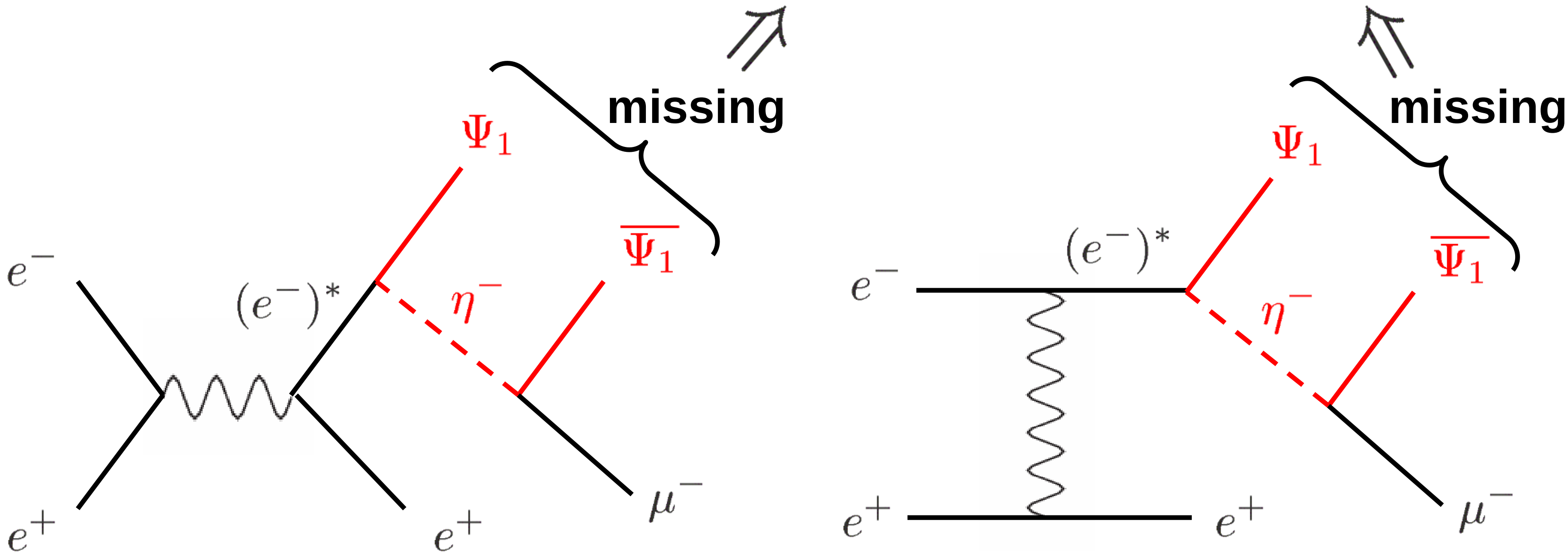
**Sensitivity in XENON 1T (2017?) :**

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

**(Scalar med. : Negligible)**

# Phenomenology - Dark Matter at ILC-

**Compare $M_{\Psi_1}$ with $M_{\rm DM}$ in XENON 1T**




$\Rightarrow$ **DM – lepton interaction**

$\Rightarrow$ **DM might contribute to neutrino mass generation mechanism**

# Kinematical Cuts

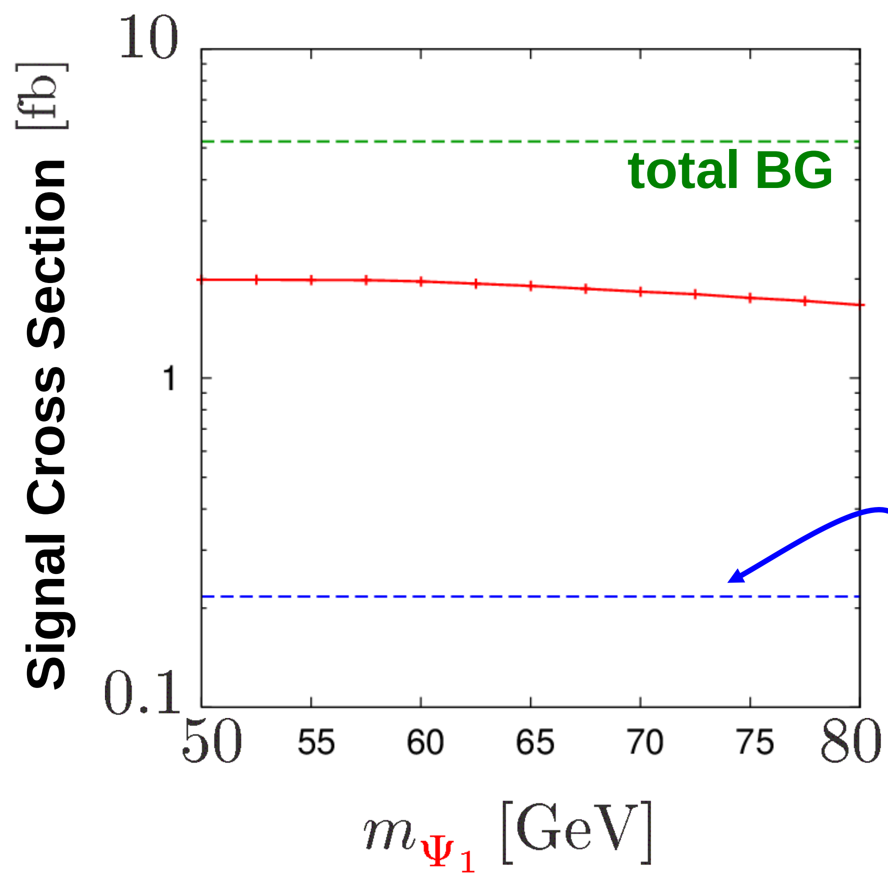
$$0.98 < |\cos\theta_e| < 0.99998 \qquad E_e < 120\,\mathrm{GeV}$$

$$|\cos\theta_\mu| < 0.8 \qquad 80\,\mathrm{GeV} < E_\mu$$

$$|\cos\theta_{e\mu}| < 0.8$$

$$120\,\mathrm{GeV} < M_{\mathrm{miss}}$$

**ILC with $\sqrt{s} = 500\,\mathrm{GeV}$**




**Main BG**

$e^+e^- \to e^+\mu^-\nu_e\overline{\nu_\mu}$

$N_S/\sqrt{N_{BG}} = 3$

**with** $10^3\,\mathrm{fb}^{-1}$

**Around** $\frac{m_h}{2}$

## DM - Nucleon Cross Section