Neutrino Mass and Dark Matter from B-L Breaking

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in collaboration with

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Phys. Rev. D **90**, 013001 (2014)

In This Talk,

- We discuss gauged $U(1)_{B-L}$ model.
- It is possible to explain tiny neutrino masses and dark matter (DM) from type-I like seesaw diagram.
- In our model, $U(1)_{B-L}$ is free from anomaly.
- Constraints from neutrino oscillation data, LFV search, DM abundance, and DM direct search can be satisfied.
- New particle masses are in the TeV−scale.

Tiny Neutrino Masses

- The standard model (SM) is successful.
- Neutrinos are massless in SM.
- But! Neutrinos have tiny masses. $m_\nu \simeq 0.1\mathrm{eV}$
- What is the origin of neutrino masses?

Tiny Neutrino Masses

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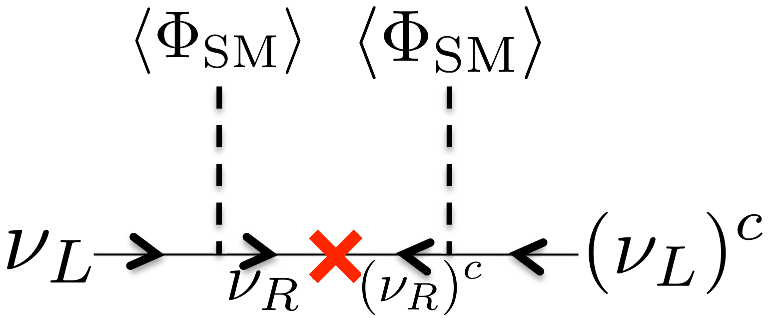
- But! Neutrinos have tiny masses. $m_\nu \simeq 0.1\text{eV}$
- What is the origin of neutrino masses?

Majorana ⇒ Type-I seesaw is not testable.

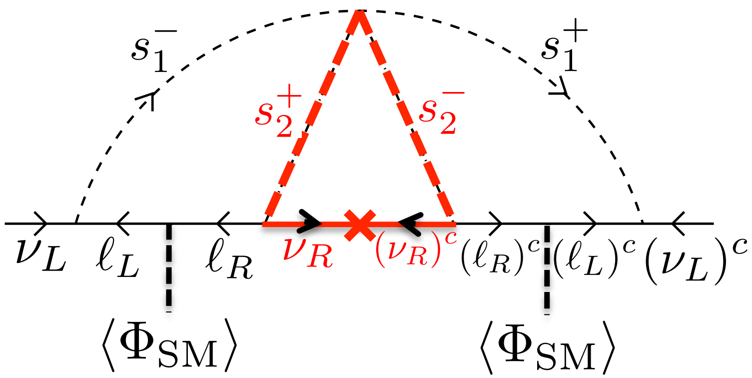


$$m_\nu \simeq \frac{(y_{\text{D}} v)^2}{m_{\nu_R}}$$

$$\rightarrow \quad m_{\nu_R} \simeq 10^{14}\,\text{GeV}$$

TeV-scale Loop Suppression Scenario

$$\mathcal{L}_{\text{eff}} = \left(\frac{c_{ij}}{M_{\text{eff}}}\right) \nu_{\text{L}}^{i} \nu_{\text{L}}^{j} \Phi_{\text{SM}} \Phi_{\text{SM}}$$



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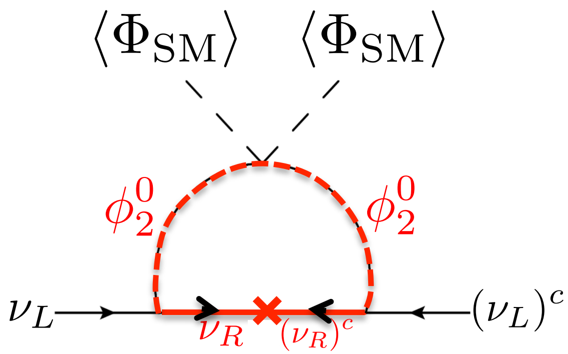

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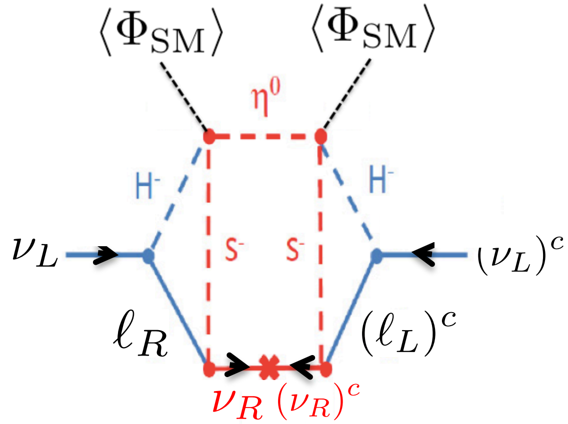

③

Radiative seesaw models with Z_2 symmetry

① L. M. Krauss, S. Nasri, M. Trodden, PRD **67** 085002 (2003)
② E. Ma, PRD **73** 077301 (2006)
③ M. Aoki, S. Kanemura, O. Seto, PRL **102** 051805 (2009)

⇒ We can explain neutrino masses and DM!

Questions

- What is the origin of the Majorana mass term of right handed neutrinos ν_R?
- What is the origin of the artificial Z_2 symmetry?

⇒ We consider gauged $U(1)_{B\text{-}L}$ model.

Model of $U(1)_{B-L}$ Gauge Symmetry

S. Kanemura, T. Nabeshima, H. Sugiyama, PRD **85** 03304 (2012)

	σ^0	$(\nu_R)_a$	$(\psi_L)_i$	$(\psi_R)_i$	$\eta = \begin{pmatrix}\eta^+ \\ \eta^0\end{pmatrix}$	s^0
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	0	0	0	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	2	1	$3/2$	$-1/2$	$1/2$	$1/2$

$a = 1 - 2$
$i = 1 - 2$

- In previous study, they explain the origin of Majorana masses and DM stability with $U(1)_{B-L}$.
- But, <u>additional new particles</u> are required to cancel anomaly.

⇒We construct an improved anomaly-free model.

Our Model

S. Kanemura, **T. M.** , H. Sugiyama, PRD **90** 013001 (2014)

	σ^0	$(\nu_R)_a$	$(\psi_L)_i$	$(\psi_R)_i$	$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$	s^0
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	0	0	0	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	$\frac{2}{3}$	$-\frac{1}{3}$	$x+\frac{2}{3}$	x	$x+1$	$x+1$

$$a = 1 - N_{\nu_R}$$
$$i = 1 - N_{\psi}$$

- B-L charge assignments x
- Determination of $(N_{\nu R}, N_{\psi})$

} Anomaly free conditions

Our Model

S. Kanemura, **T. M.** , H. Sugiyama, PRD **90** 013001 (2014)

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$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	0	0	0	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{\sqrt{3}+1}{3}$	$\frac{\sqrt{3}-1}{3}$	$\frac{\sqrt{3}+2}{3}$	$\frac{\sqrt{3}+2}{3}$

$a = 1$
$i = 1 - 4$

- B-L charge assignments x
- Determination of $(N_{\nu R}, N_\psi)$

} Anomaly free conditions

→We take $(N_{\nu R}, N_\psi) = (1,4)$ for $x = \frac{\sqrt{3}-1}{3}$ as an example.

Our Model

S. Kanemura, **T. M.** , H. Sugiyama, PRD **90** 013001 (2014)

	σ^0	$(\nu_R)_a$	$(\psi_L)_i$	$(\psi_R)_i$	$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$	s^0
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$U(1)_Y$	0	0	0	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{\sqrt{3}+1}{3}$	$\frac{\sqrt{3}-1}{3}$	$\frac{\sqrt{3}+2}{3}$	$\frac{\sqrt{3}+2}{3}$

$a = 1$
$i = 1 - 4$

- B-L charge assignm...
- Determination of ... ee conditions

Particles of dark side

~~$U(1)_{B-L}$~~ → global $U(1)_{DM}$

→We take $(N_{\nu R}, N_{\psi})=(1,4)$ for $x = \frac{\sqrt{3}-1}{3}$ as an example.

$$(\eta^0, s^0) \xrightarrow{\theta'} (\mathcal{H}_1^0, \mathcal{H}_2^0)$$

⇒ ψ_1 or $\mathcal{H}_1^0$ is DM candidate!

$U(1)_{B\text{-}L}$ Symmetry Breaking

$$v_\sigma = \sqrt{2}\left\langle \sigma^0 \right\rangle$$

- B-L gauge mass is given by characteristic charge.

$$m_{Z'} = \frac{2}{3} g_{\mathrm{B-L}} v_\sigma$$ (←B-L charge of σ: 2/3)

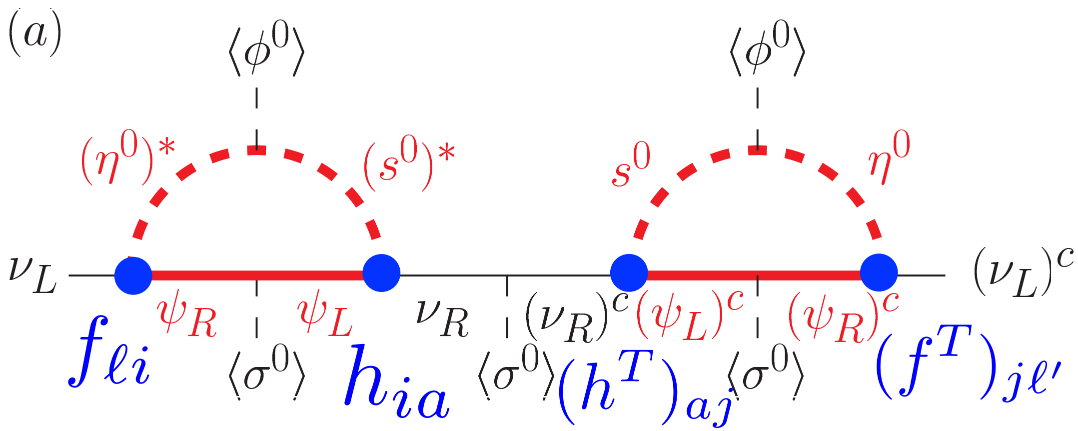
- Yukawa interactions:

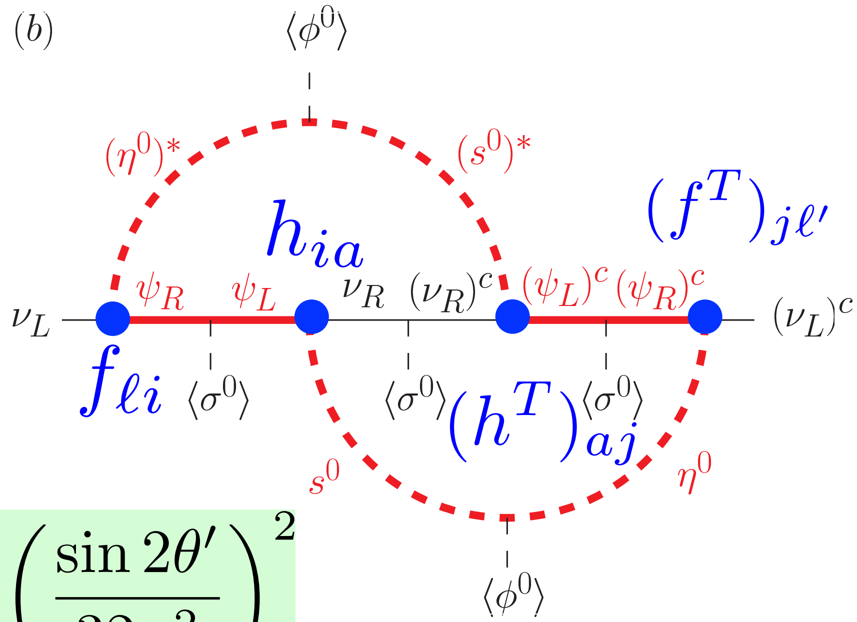
$$\mathcal{L}_{\mathrm{Yukawa}} = \mathcal{L}_{\mathrm{SM\text{-}Yukawa}} - (y_R)_a \overline{(\nu_R)_a} (\nu_R)^c_a (\sigma^0)^* - (y_\psi)_i \overline{(\psi_R)_i} (\psi_L)_i (\sigma^0)^* - h_{ia} \overline{(\psi_L)_i} (\nu_R)_a s^0 - f_{\ell i} \overline{L_\ell} (\psi_R)_i \tilde{\eta} + \mathrm{h.c.}$$

⇒ ~~$U(1)_{B\text{-}L}$~~ explain the origin of masses of a Majarana neutrino ν_R and singlet-fermions ψ_i!

Radiative Type-I Seesaw

- Light Majorana neutrino mass term is generated by the loop suppressed Dirac mass term & TeV-scale ν_R.

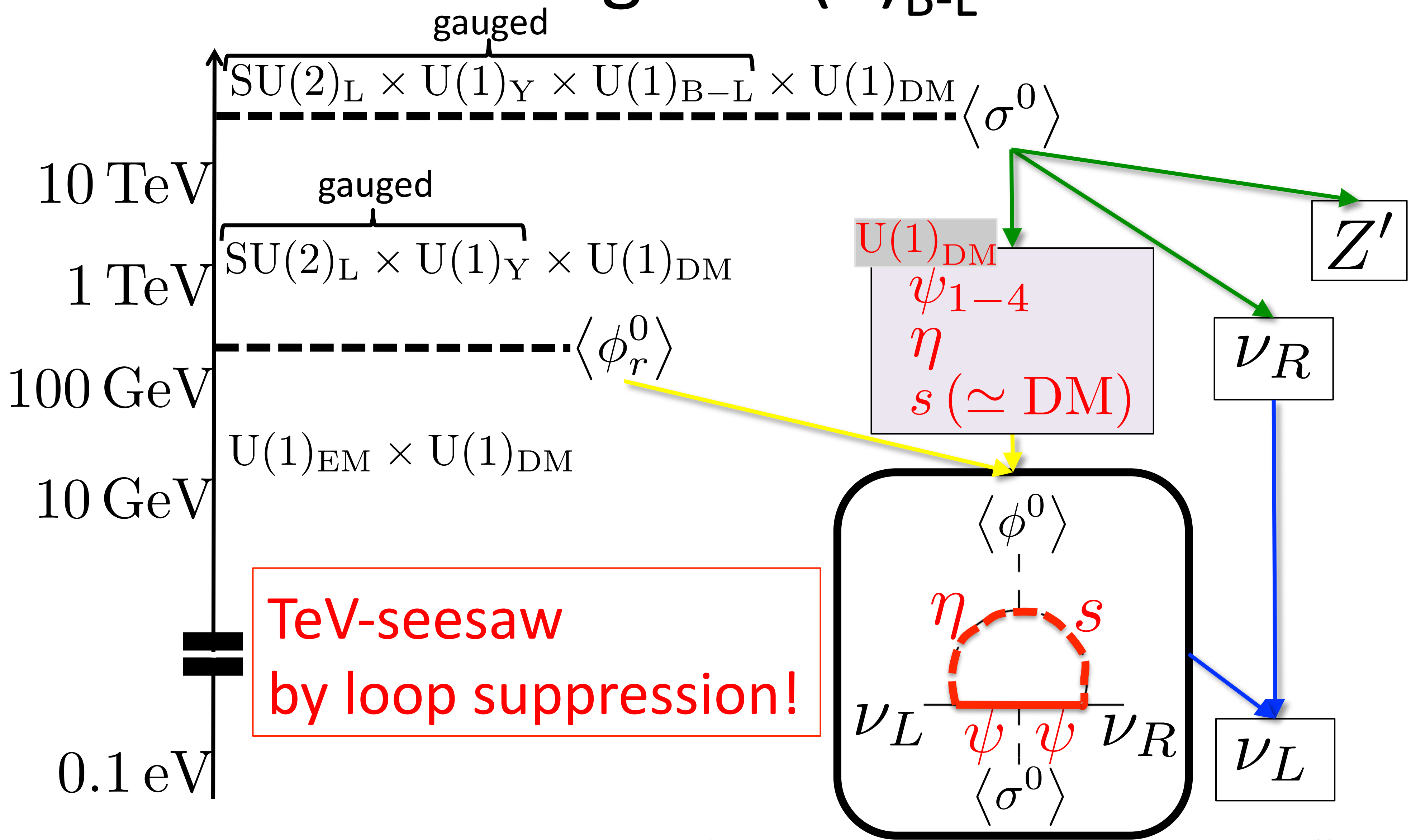




$$(m_\nu)_{\ell\ell'} \simeq f_{\ell i}\, h_{ia}\, (h^T)_{aj}\, (f^T)_{j\ell'} \frac{m_{\Psi_i}\, m_{\Psi_j}}{m_{R_a}} \left(\frac{\sin 2\theta'}{32\pi^2}\right)^2$$

⇒ We can explain tiny neutrino masses!

TeV-scale Gauged $U(1)_{B-L}$ Scenario



Benchmark

- This parameter set satisfy neutrino oscillation data, LFV search, DM abundance, and DM direct search!

$$f_{\ell i} = \begin{pmatrix} 0.0178686 & -0.0248746 & -0.019737 & 0.0255808 \\ -0.0182223 & 0.0110461 & 0.0129624 & -0.00818099 \\ 0.0140402 & -0.00598335 & -0.00904845 & 0.00222417 \end{pmatrix}$$

$$m_R = 250\text{GeV} \qquad h_i = (0.7\ 0.8\ 0.9\ 1)^T$$

$$(m_{\psi_1}, m_{\psi_2}, m_{\psi_3}, m_{\psi_4}) = (650, 750, 850, 950)\text{GeV}$$

$$(m_h, m_H) = (125, 1000)\text{GeV} \quad \cos\theta = 1$$

$$(m_{\mathcal{H}_1}, m_{\mathcal{H}_2}, m_{\eta^\pm}) = (60, 450, 420)\text{GeV} \quad \cos\theta' = 0.05$$

$$\mathcal{H}_1 \simeq s$$

⇒ New particle masses are in the TeV−scale!

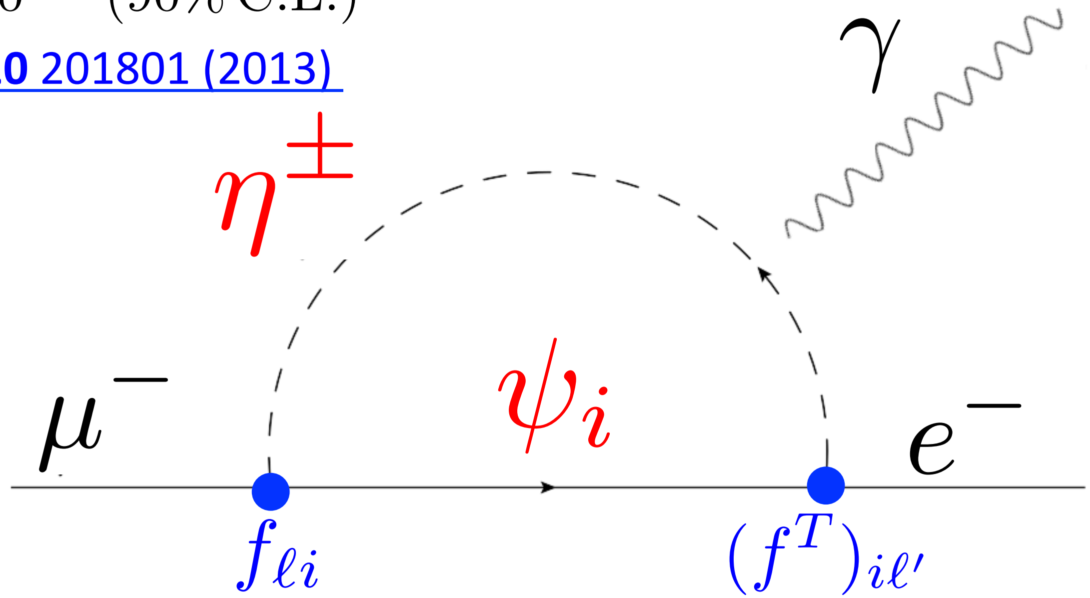
Lepton Flavor Violation

- μ → eγ

$$\mathrm{BR}(\mu \to e\gamma) = 6.07 \times 10^{-14}$$ @benchmark point

$$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13} (90\% \, \mathrm{C.L.})$$

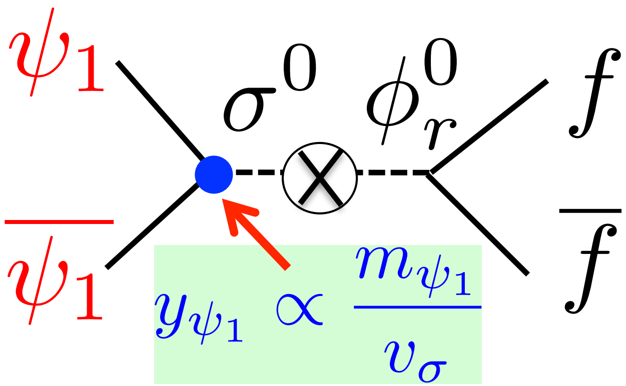
MEG, PRL **110** 201801 (2013)



⇒ Yukawa coupling $f_{\ell i}$ can satisfy LFV constraints!

Fermion DM scenario is excluded!

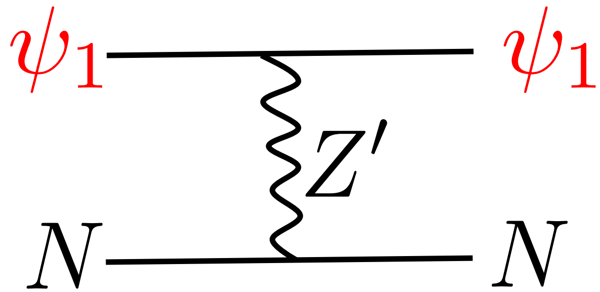
Relic abundance



$$\Omega_{\psi_1} h^2 \propto v_\sigma^2$$

$$\rightarrow v_\sigma \lesssim 10\,\mathrm{TeV}$$

Direct search



$$\sigma_{\rm SI} \simeq \left(\frac{3}{2v_\sigma}\right)^4 \frac{m_\psi^2 m_N^2}{3\,\pi\,(m_\psi + m_N)^2}$$

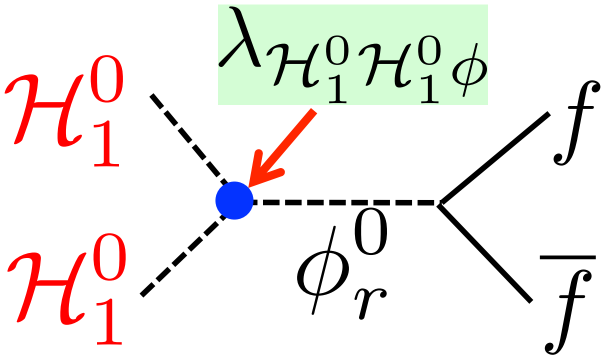
$$\rightarrow 30\,\mathrm{TeV} \lesssim v_\sigma$$

⇒ There is no value of v_σ satisfying two constraints.

$U(1)_{B-L}$ charged scalar should be DM!

(↑Singlet field under the SM gauge group)

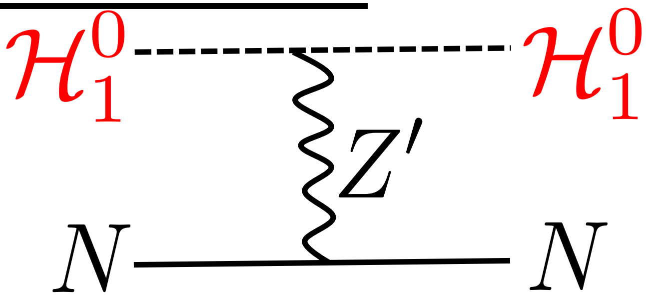
- Relic abundance → Coupling is independent of v_σ .



$$\Omega_c h^2 = 0.1199 \pm 0.0027$$

Planck, arXiv: 1303.5076

- Direct search



$$\sigma_{\rm SI} = \left(\frac{\sqrt{3}+2}{3}\right)^2 \left(\frac{3}{2v_\sigma}\right)^4 \frac{m_{\mathcal{H}_1}^2 m_N^2}{\pi\,(m_{\mathcal{H}_1}+m_N)^2}$$

$$\sigma_{\rm exp} = 9.2 \times 10^{-46}\ {\rm cm}^2$$

LUX, PRL **112** 091303 (2014)

⇒ To satisfy direct search, we need $v_\sigma > 31\ {\rm TeV}$.

Collider Phenomenology

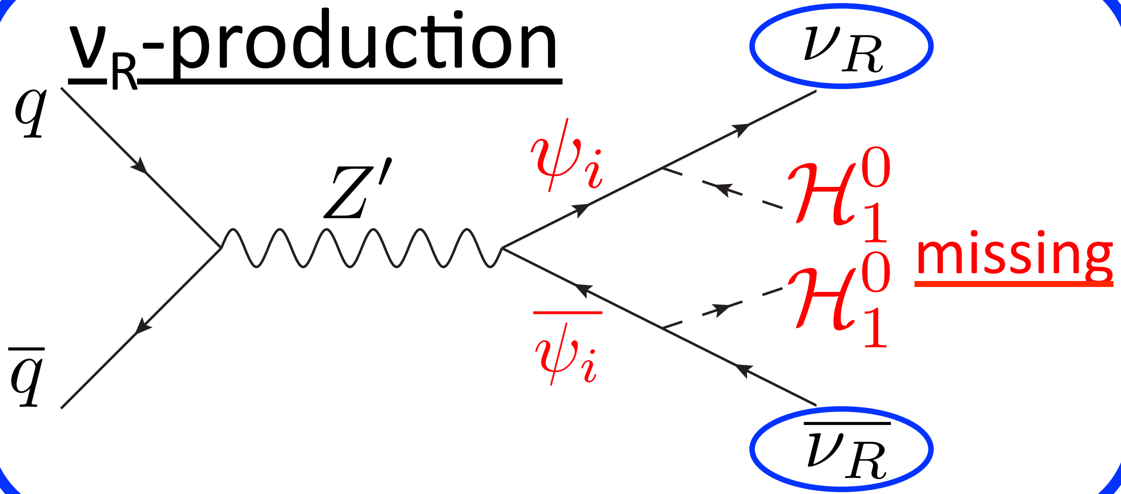
Z'-production

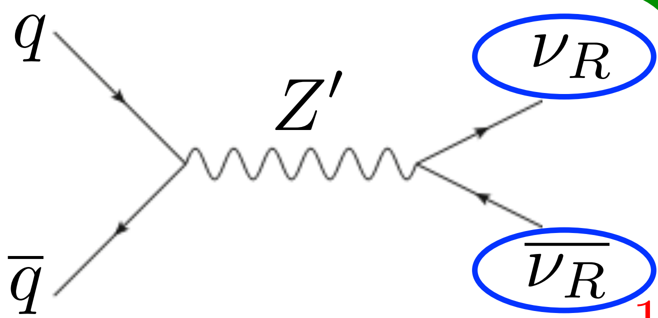
$\sigma = 0.3\ \mathrm{fb}$ @14TeV-LHC L. Basso, arXiv: 1106.4462

$v_\sigma = 60\ \mathrm{TeV}$

$m_{Z'} = 4\ \mathrm{TeV}$

ν_R-production





Suppressed by $q_{\mathrm{B-L}}^{\nu_R} = -\frac{1}{3}$

⇒ We can distinguish our model from others!

Conclusions

- $U(1)_{B\text{-}L}$ model can explain tiny neutrino masses and dark matter by gauge symmetry breaking w/o artificial Z_2 symmetry.
- Additionally, the origin of Majorana mass term can be explained.
- We construct an anomaly-free model at the TeV-scale.
- In our model, fermion DM is excluded.
- We can distinguish our model from others by observing ν_R.

Back Up

Anomaly Cancelation of $U(1)_{B-L}$

- We want to construct radiative type-I like seesaw model.

	σ^0	$(\nu_R)_i$	$(\psi_L)_i$	$(\psi_R)_i$	$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$	s^0
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	0	0	0	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	$\frac{2}{3}$	$-\frac{1}{3}$	$x+\frac{2}{3}$	x	$x+1$	$x+1$

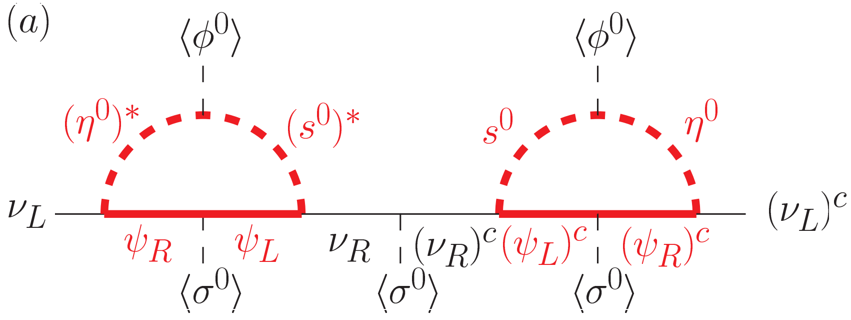
$\overline{\nu_L}(\nu_L)^c(\sigma^*)^3$

$(\sigma)^*\overline{\nu_R}(\nu_R)^c$

$\overline{(\psi_R)_i}(\sigma^0)^*(\psi_L)_i$

- We know B-L of SM is $(B\text{-}L)_{SM} = 3$, $(B\text{-}L)_{SM}^3 = 3$.
- We can get anomaly cancelation conditions from these constraints.

(a)



Neutrino Masses

- When we write $(m_\nu)_{\ell\ell'} = f_{\ell i}\, I_{ij}\, (f^T)_{j\ell'}$,

I_{ij} can be diagonalized by U_{ij} .

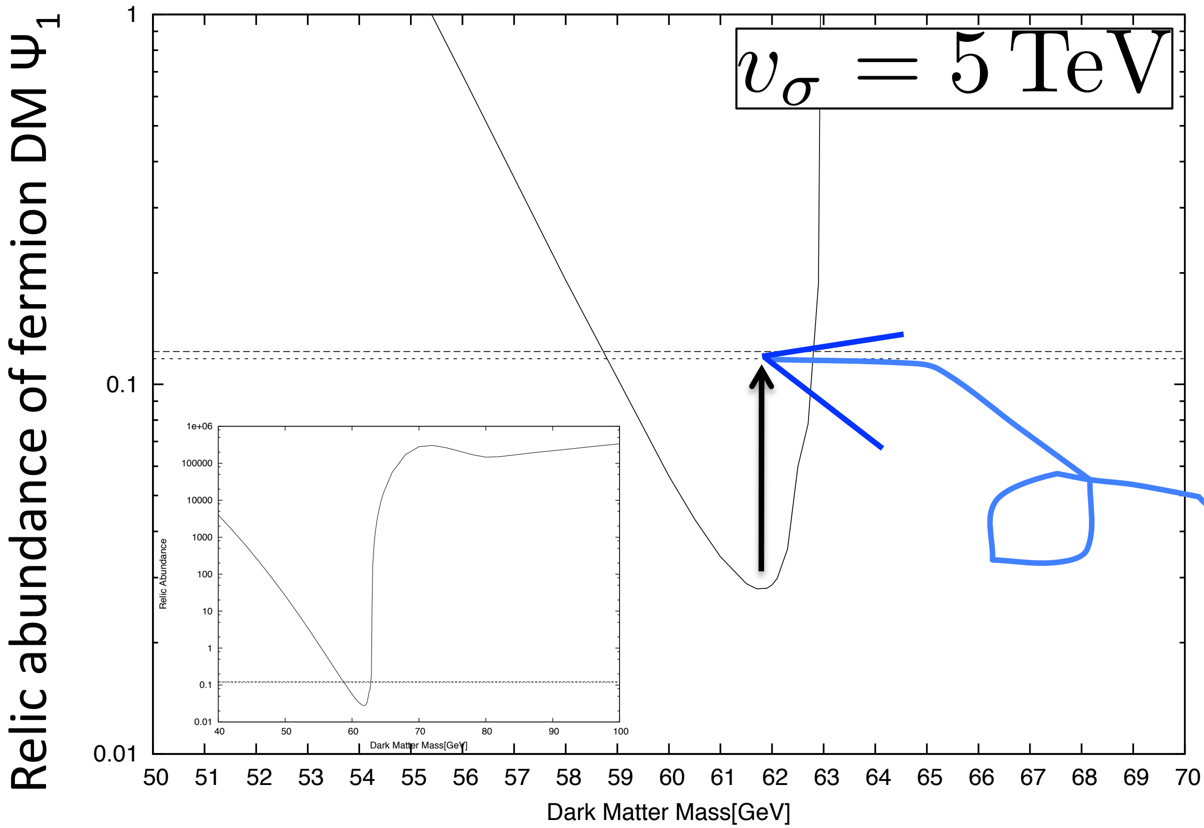
$$U^{-1} I (U^T)^{-1} = \mathrm{diag}(X_1, X_2, X_3, X_4)$$

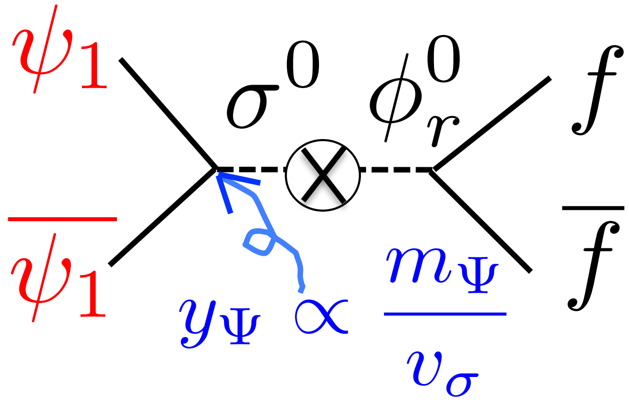
- Then, Yukawa matrix $f_{\ell\, i}$ can be associated with values of neutrino oscillation!

$$(m_\nu)_{\ell\,\ell'} = U^*_{\mathrm{MNS}} m_\nu^{\mathrm{diag}} U^\dagger_{\mathrm{MNS}} = (f\,U) I^{\mathrm{diag}} (f\,U)^T$$

$$f = U^*_{\mathrm{MNS}} \begin{pmatrix} \sqrt{\frac{m_1}{X_1}} & 0 & 0 & 0 \\ 0 & \sqrt{\frac{m_2}{X_2}} & 0 & 0 \\ 0 & 0 & \sqrt{\frac{m_3}{X_3}} & 0 \end{pmatrix} U^{-1}$$

Fermion DM scenario is excluded!





$$\Omega_\psi h^2 (\propto \sigma^{-1}) \propto v_\sigma^2$$

$$v_\sigma = 10\,\mathrm{TeV}$$

Upper bound from Ωh^2

$$\sigma_{\mathrm{SI}} \simeq \left(\frac{3}{2 v_\sigma}\right)^4 \frac{m_\psi^2 m_N^2}{3\pi (m_\psi + m_N)^2}$$

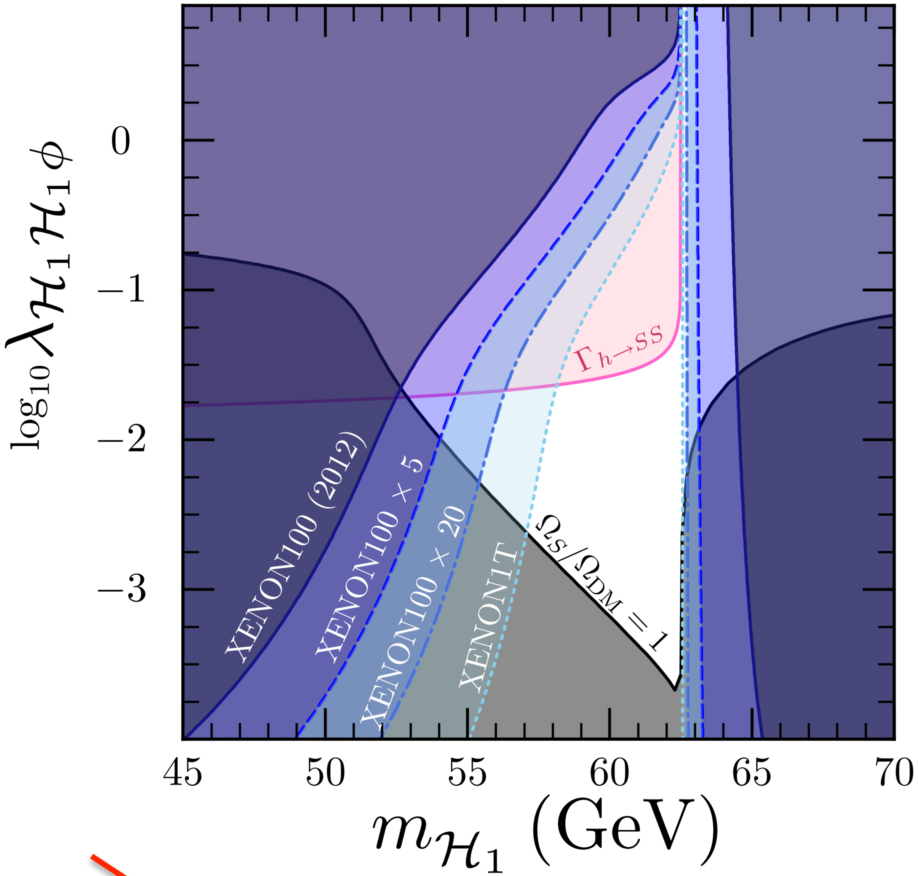
$$\sigma_{\mathrm{SI}} = 1.4 \times 10^{-44}\,\mathrm{cm}^2$$

$$\sigma_{\mathrm{exp}} = 9.2 \times 10^{-46}\,\mathrm{cm}^2$$

LUX, PRL **112** 091303 (2014)

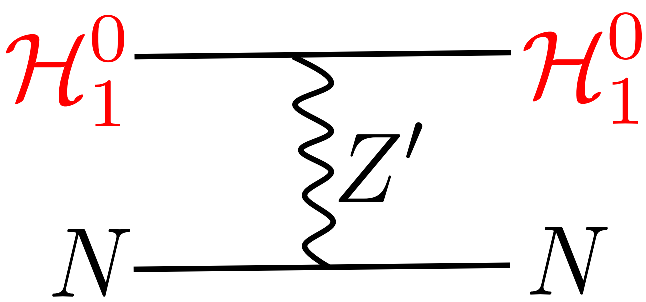
Constraints on Scalar DM $\mathcal{H}_1^0$

J.M.Cline et al, PRD, **88** 055025 (2013)



1. $\lambda_{\mathcal{H}_1\mathcal{H}_1\phi}$ depends on relic abundance. (←)

2. Z' propagating is dominant.
We need vσ > 31TeV. (↓)



$$\sigma_{\rm SI} = \frac{\lambda^2_{\mathcal{H}_1\mathcal{H}_1\phi}}{m_\phi^4}\frac{m_N^2}{4\pi(m_{\mathcal{H}_1}+m_N)^2}f_N^2 + \left(\frac{\sqrt{3}+2}{3}\right)^2\left(\frac{3}{2v_\sigma}\right)^4\frac{m^2_{\mathcal{H}_1}m_N^2}{\pi(m_{\mathcal{H}_1}+m_N)^2}$$

Constraints from Collider Experiments

- LEP-II bound: $v_\sigma \gtrsim 10.5\,\mathrm{TeV}$ PRD, **74** 033011 (2006)
- Z' search bound: $m_{Z'} \gtrsim 2.86\,\mathrm{TeV}$ ATLAS-CONF-2013-017

Predictions of Branching Ratio

- Branching ratios of Z' decays:

$\mathrm{BR}(Z' \to \psi\overline{\psi_i}) = 0.18$

$q\bar{q}$	$\ell\bar{\ell}$	$\nu_L\overline{\nu_L}$	$\nu_R\overline{\nu_R}$	$\Psi_1\overline{\Psi_1}$	$\Psi_2\overline{\Psi_2}$	$\Psi_3\overline{\Psi_3}$	$\Psi_4\overline{\Psi_4}$	$s_1^0(s_1^0)^*$	$s_2^0(s_2^0)^*$	$\eta^+\eta^-$
0.21	0.32	0.16	0.0059	0.046	0.045	0.044	0.043	0.041	0.038	0.039

- Branching ratios of ν_R decays:

$W^+\ell^- + W^-\ell^+$	$Z\nu_L + Z\overline{\nu_L}$	$h^0\nu_L + h^0\overline{\nu_L}$	$H^0\nu_L + H^0\overline{\nu_L}$
0.56	0.28	0.16	0