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Seesaw from the Loop-Induced Neutrino Dirac Yukawa Coupling

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S.K., T. Nabeshima, H. Sugiyama,PLB703,66(2011)
S.K., T. Nabeshima, H. Sugiyama, arXiv: 1111.0059

Introduction

- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

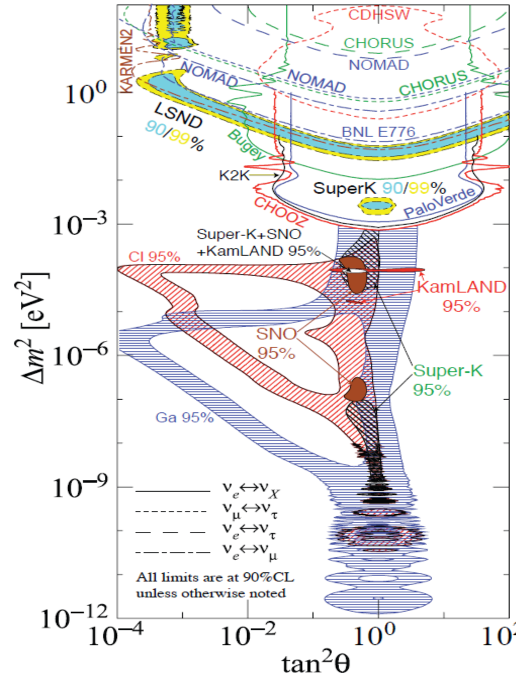
    $\Delta m^2 \sim 8 \times 10^{-5}\, eV^2, \;\; \Delta m^2 \sim 2 \times 10^{-3}\;\; eV^2$

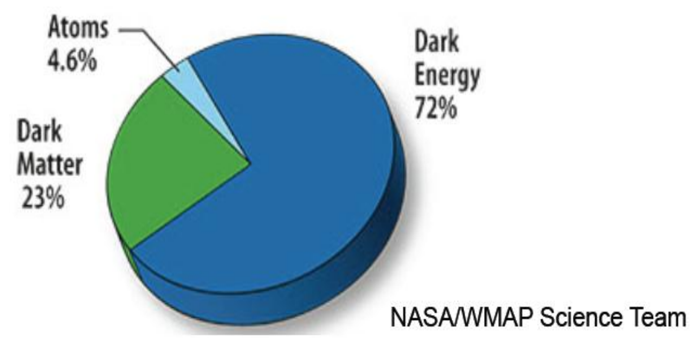
  - Dark Matter

    $\Omega_{DM} h^2 \sim 0.11$

  - Baryon Asymmetry of the Universe

    $n_B/s \;\sim 9 \times 10^{-11}$





To understand these phenomena, we need to go beyond-SM

2 possibilities

1) Scenario dependent on very high scales
   - Maybe compatible with canonical GUTs
   - Large mass hierarchy
   - A direct link to the GUT or Planck Scale?
   - Too high to be tested

2) Scenario due to the TeV scale physics
   - Renormalizable theory at the TeV scale
   - No large hierarchy among mass scales
   - Strong connection to Electroweak Symmetry Breaking
   - Testable at collider experiments

Neutrino Mass

Neutirno Mass Term (= Effective dim-5 operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

$\langle\phi\rangle = v = 246\mathrm{GeV}$

Mechanism for tiny masses:

$$m^\nu{}_{ij} = (c_{ij}/M)\, v^2 \;< 0.1\ \mathrm{eV}$$

<u>Seesaw (tree level)</u>

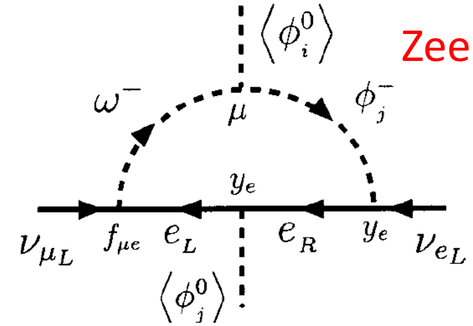
$$m^\nu{}_{ij} = y_i y_j\, v^2/M \qquad (M \gg 1\mathrm{TeV})$$

<u>Quantum Effects</u> N-th order of perturbation theory

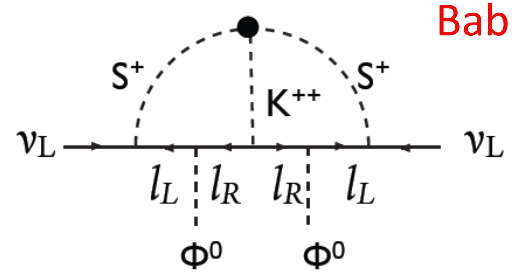
$$m^\nu{}_{ij} = [g^2/(16\pi^2)]^N\, C_{ij}\, v^2/M \qquad (\text{M can be 1 TeV})$$

Scenario of Radiative ννϕϕ generation

- Tiny ν-Masses come from loop effects
  - Zee (1980, 1985)
  - Zee, Babu (1988)
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), ...



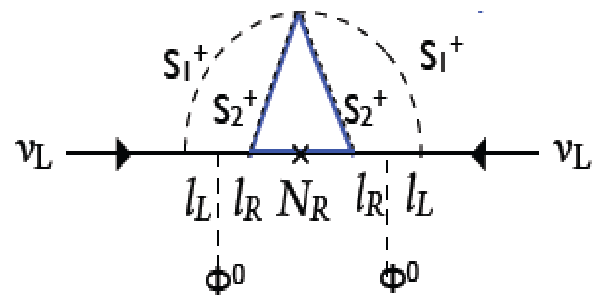
Zee



Babu

- Merit
  - Super heavy particles are not necessary

    Size of tiny m_ν can naturally be deduced from TeV scale by higher order perturbation
  - Physics at TeV: Testable at collider experiments

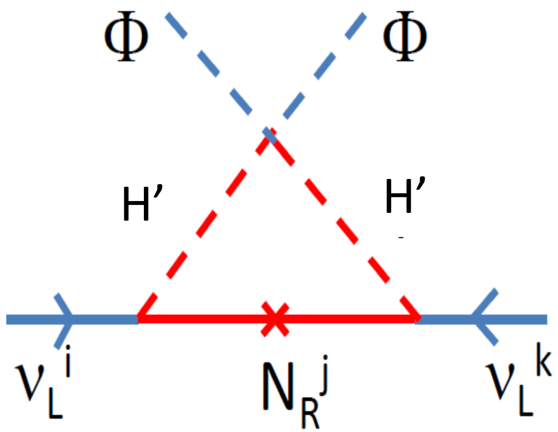


Krauss, Nasri, Trodden

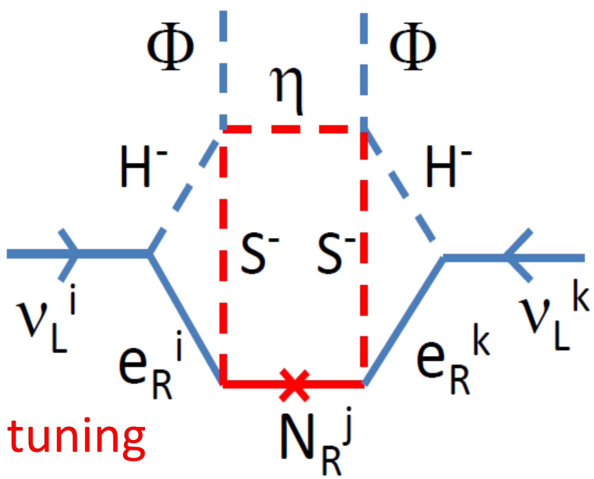
Radiative seesaw with Z_2

Z_2-parity plays roles:
1. No Yukawa coupling (Radiative neutrino mass)
2. Stability of the lightest Z_2 odd particle (DM)

Ex1) 1-loop Ma (2006)
- Simplest model
- SM + N_R + Inert doublet (H')
- DM candidate [H' or NR]



Ex2) 3-loop Aoki-Kanemura-Seto (2008)
- Neutrino mass from O(1) coupling
- 2HDM + η^0 + S^+ + N_R
- DM candidate [η^0 (or NR)]
- Electroweak Baryogenesis



All 3 problems may be solved by TeV physics w/o fine tuning

Questions on Radiative Seesaw with Z_2

- What is the origin of LNV at the TeV scale?
- What is the origin of the DM mass?
- Where the Z_2 parity come from?

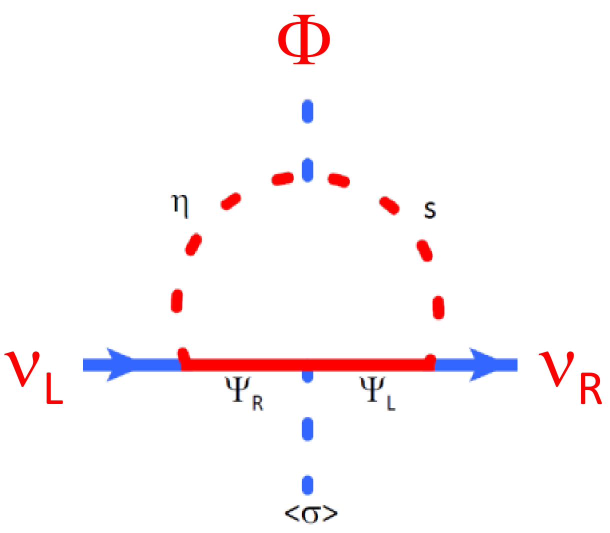
Gauged $U(1)_{B-L}$ would solve these problems

- LNV: SSB of $U(1)_{B-L}$ at the TeV scale
- DM mass: chiral for $U(1)_{B-L}$

  → Dirac fermion after the SSB
- Global $U(1)_{DM}$ as remnant of the SSB of $U(1)_{B-L}$

Phenomenological interest

- It is interesting if mass of ν_R is at TeV
- Seesaw Mechanism:
  - ν_R must be very heavy, if y=O(1)
- Radiative Seesaw:
  - ν_R can be at the TeV scale w/o fine tuning but it is Z_2-odd in many models
- Can we have mechanism to have a TeV scale Z_2-even ν_R w/o finetuning ?
- Loop-induced the Yukawa coupling!
- After the SSB of Lepton Number at the TeV scale, Type-I seesaw happens with TeV-scale ν_R via the loop-induced Dirac Yukawa coupling

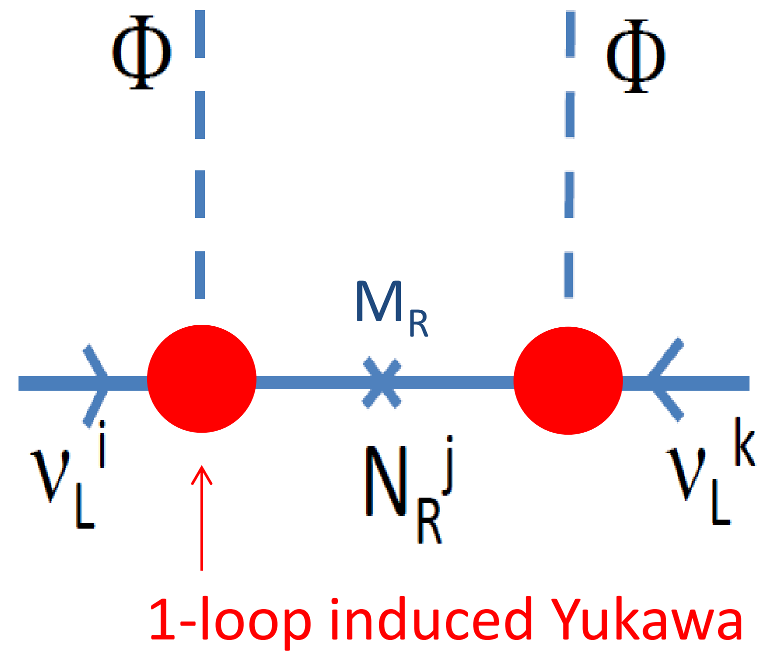


Loop-induced Dirac Yukawa coupling

$L\Phi\nu_R$

Raditative Type-I seesaw model

If Dirac Yukawa couplings are 1-loop induced, M_R can be at TeV scale or below w/o large fine tuning (g~0.1).



M_{NR} is naturally at TeV scale so that it is testable at LHC

In this model, ν_R is Z_2-even, so that it can decay into SM particles
DM candidate may be in the loop sub-diagram of Yukawa coupling

Our Model

S.K., T. Nabeshima, H. Sugiyama
arXiv: 1111.0059

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

- Z' : B-L gauge boson
- σ^0 : B-L Higgs
- ν_R^i : RH-neutrino (i=1,2)
- $\Psi_{L,R}^i$: chiral (i=1,2)
- s^0 : singlet
- η : doublet

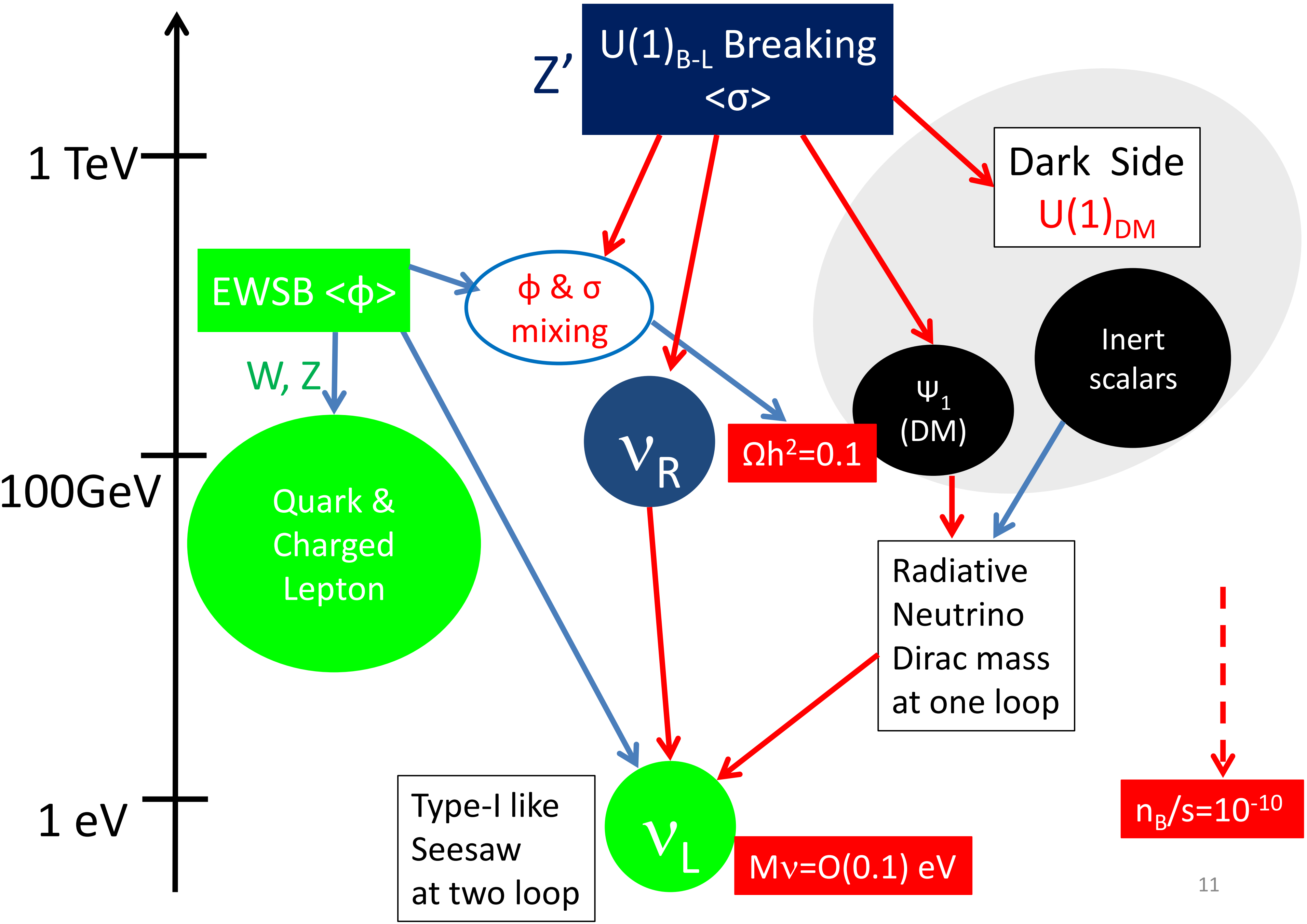
Particles	s^0	η	$(\Psi_R)_i$	$(\Psi_L)_i$	$(\nu_R)_i$	σ^0
$SU(3)_C$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$
$SU(2)_L$	$\underline{1}$	$\underline{2}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$
$U(1)_Y$	0	1/2	0	0	0	0
$U(1)_{B-L}$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

half-unit
B-L charge

Remnant global $U(1)_{DM}$ remains after SSB of B-L

$U(1)_{B-L}$ protects 1. Tree-level Yukawa $L\Phi\nu_R$ and
2. Majorana mass of ν_R
Chirality protects 3. Dirac mass of Ψ

Masses of ν_R and Ψ are generated by SSB of $U(1)_{B-L}$



1 TeV
100GeV
1 eV
Z'
U(1)$_{B-L}$ Breaking
<σ>
Dark Side
U(1)$_{DM}$
EWSB <ϕ>
ϕ & σ
mixing
W, Z
ν$_R$
Ωh^2=0.1
Ψ$_1$
(DM)
Inert
scalars
Quark &
Charged
Lepton
Radiative
Neutrino
Dirac mass
at one loop
Type-I like
Seesaw
at two loop
ν$_L$
Mν=O(0.1) eV
n$_B$/s=10^{-10}

$\cancel{U(1)}_{B\text{-}L}$ ⇒ Masses of Z', ν_R and Ψ

B-L gauge boson Z'

$m_{Z'} = 2 g_{B\text{-}L}\, v_\sigma$ $\quad v_\sigma \; [= \sqrt{2}\langle\sigma^0\rangle]$

LEP bounds: $m_{Z'}/g_{B\text{-}L} = 2\, v_\sigma > 6\text{-}7$ TeV ⇒ $v_\sigma > 3\text{-}3.5$ TeV

Weyl fermions ν_R, Ψ_L, Ψ_R

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

$$m_{\nu_R} = \sqrt{2} y_R v_\sigma$$

Majorana mass of ν_R

Ex) $m_{\nu R}$ = 200 GeV for y_R=0.05, v_σ = 3 TeV

$$m_\Psi = y_\Psi \frac{v_\sigma}{\sqrt{2}}$$

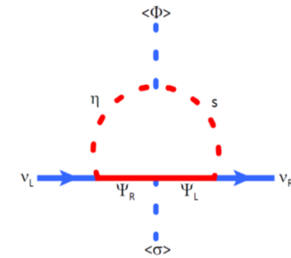
Dirac mass of Ψ

Ex) m_Ψ = 100 GeV for y_Ψ=0.05, v_σ = 3 TeV

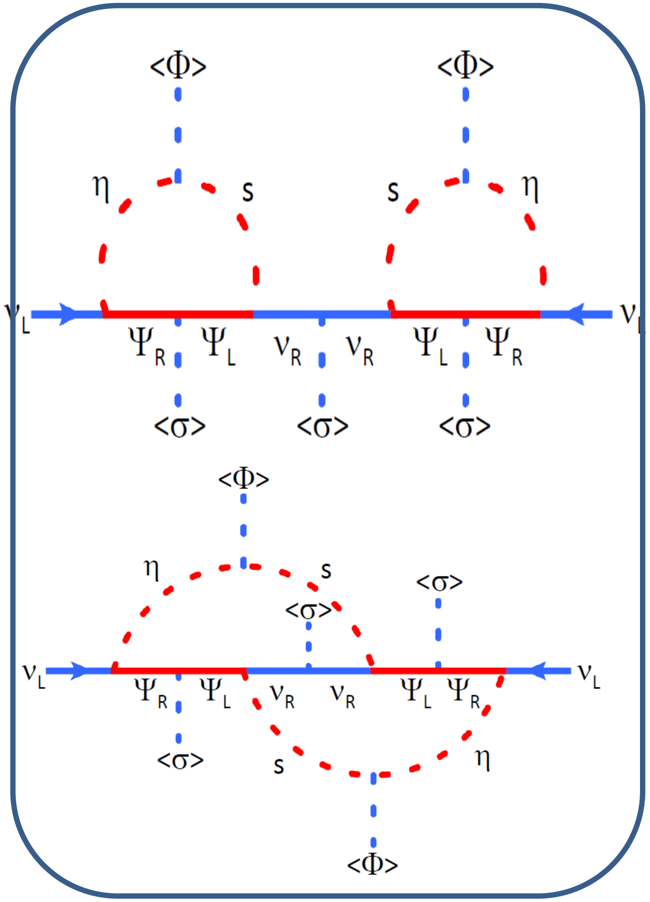
$U(1)_{DM}$ ⇒ Lightest Ψ (Ψ^1) is the DM candidate

~~U(1)~~$_{B-L}$ ⇒ Mass of Neutrinos

- No Yukawa $L\Phi\nu_R$ by the B-L charge assignment
- ~~U(1)~~$_{B-L}$: Source of LNV v_σ → $m_{\nu R}$, m_Ψ
- ~~U(1)~~$_{B-L}$: Remnant $U(1)_{DM}$
- Radiative generation of the operator $L\Phi\nu_R\sigma$
- Seesaw mechanism → Majorana mass of ν_L



$$(m_\nu)_{\ell\ell'} = \left(\frac{1}{16\pi^2}\right)^2 f_{\ell i} h_{ia} (m_R)_a (h^T)_{aj} (f^T)_{j\ell'} \frac{(8\pi^2 \sin 2\theta)^2 m_{\Psi_i} m_{\Psi_j}}{(m_R)_a^2}$$



The correct neutrino mass O(0.1) eV can be deduced from TeV scale physics w/o fine tuning

- All mass parameters = O(0.1 - 1) TeV
- All coupling constants = O(0.1)

Mass structure is similar but not exactly same as the tree-level seesaw scenario.

S.K., T. Nabeshima, H. Sugiyama, arXiv: 1111.0059

A viable parameter set (Set A)

$$s_{23}^2 = \frac{1}{2}, \quad s_{13}^2 = 0, \quad s_{12}^2 = \frac{1}{3},$$
$$\Delta m_{21}^2 = 7.5 \times 10^{-5}\,\mathrm{eV}^2, \quad |\Delta m_{31}^2| = 2.3 \times 10^{-3}\,\mathrm{eV}^2.$$

Coupling constants are all O(0.01 -0.1)

Masses are O(0.1-1) TeV

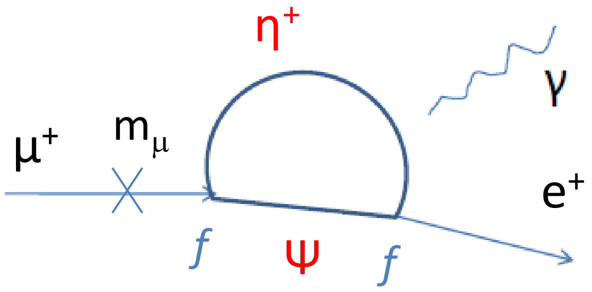
Among Ψ, s^0, η which have $U(1)_{DM}$ charge, Ψ^1 is the DM candidate

$f_{\ell i}$	$\begin{pmatrix} -0.00726 & 0.00667 \\ -0.0523 & 0.0206 \\ -0.0378 & 0.00723 \end{pmatrix}$
h_{ij}	$\begin{pmatrix} -0.119 & 0.150 \\ 0.150 & 0.150 \end{pmatrix}$
$(y_3)_{ij}$	$\begin{pmatrix} 0.0152 & 0.0152 \\ 0.0152 & 0.0152 \end{pmatrix}$
$m_R \equiv (m_R)_1 = (m_R)_2$	250 GeV
$\{m_{\Psi_1},\ m_{\Psi_2}\}$	$\{57.0\,\mathrm{GeV},\ 800\,\mathrm{GeV}\}$
$\{m_{h^0},\ m_{H^0},\ \cos\alpha\}$	$\{120\,\mathrm{GeV},\ 140\,\mathrm{GeV},\ 1/\sqrt{2}\}$
$\{m_{s_1^0},\ m_{s_2^0},\ \cos\theta\}$	$\{200\,\mathrm{GeV},\ 300\,\mathrm{GeV},\ 0.05\}$
$m_{\eta^\pm}$	280 GeV
$g_{\mathrm{B-L}}$	0.2
$m_{Z'}$	2000 GeV

LFV constraint

Ψ and η (have U(1)$_{DM}$ charge) contribute to μ→eγ process

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm EM}}{64\pi G_F^2}\left|\frac{1}{m_{\eta^\pm}^2} f_{\mu i} F_2\left(\frac{m_{\Psi_i}^2}{m_{\eta^\pm}^2}\right)(f^\dagger)_{ie}\right|^2$$



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

Experimental upper bound

$\mathrm{Br}(\mu \to e\gamma) < 2.4 \times 10^{-12}$

is satisfied

For Set A, it is evaluated as

$\mathrm{Br}(\mu \to e\gamma) = 5.1 \times 10^{-13}$

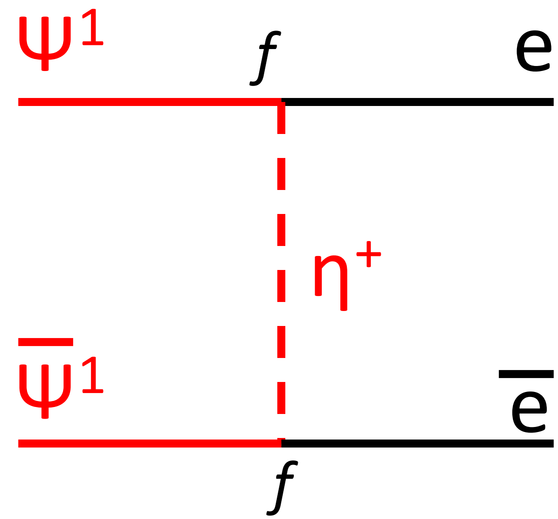
Safe against the current bound but can be future experimental reach

Thermal relic abundance of Ψ^1

Remnant $U(1)_{DM}$ Dirac fermion

Ψ^1 is dark matter candidate

WMAP: $\Omega h^2=0.11$



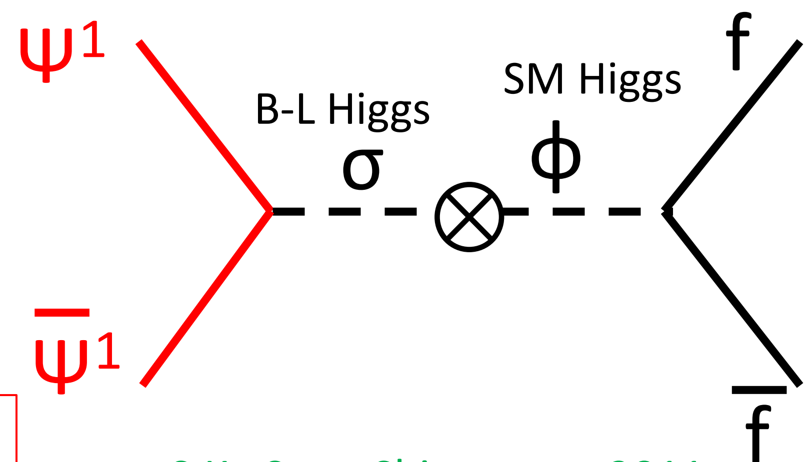
t-channel contributions

Small due to LFV

Annihilation not enough due to TeV scale η and small coupling *f*

s-channel (Higgs portal)

resonance can be used



Mixing between B-L Higgs σ and SM Higgs ϕ is essentially important

S.K., Seto, Shimomura 2011

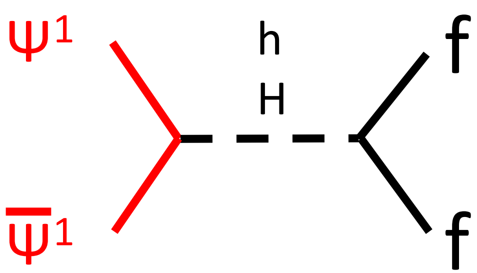
Okada, Seto, 2010

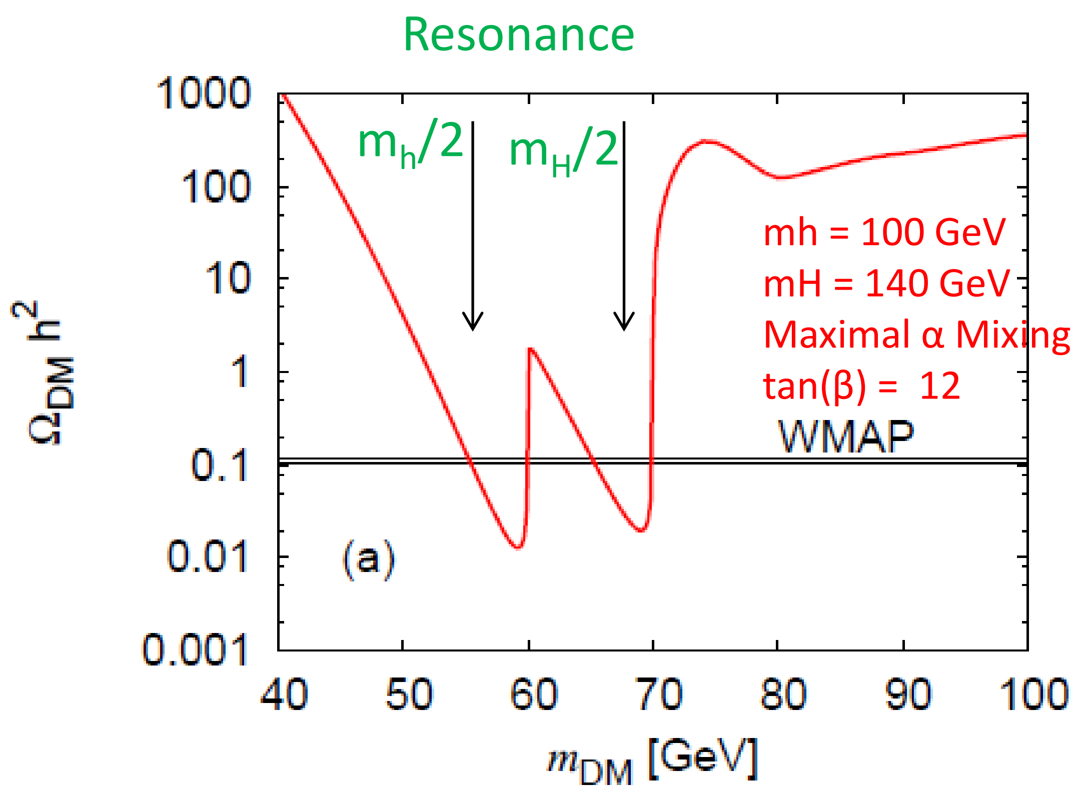
Thermal Relic Abundance of Ψ^1

$$\Omega h^2 \simeq 1.47 \sqrt{\frac{G}{g^*}} \frac{10^9}{\int_0^{\frac{T}{m}} \langle \sigma v \rangle d\left(\frac{T}{m}\right)} \mathrm{GeV}^{-1}$$

Mass Eigenstates

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_r^0 \\ \sigma_r^0 \end{pmatrix}$$





Ψ can explain Ωh^2=0.11, so that Ψ^1 can be a Dirac DM

Direct searches

Ex) XENON 100 Results

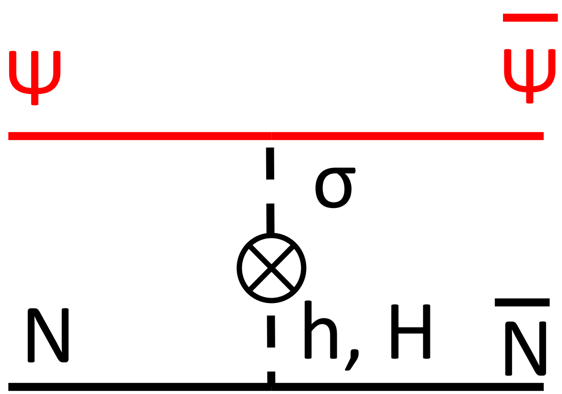
$\sigma(\Psi_1 N \to \Psi_1 N) < 8 \times 10^{-45}\,\mathrm{cm}^2$

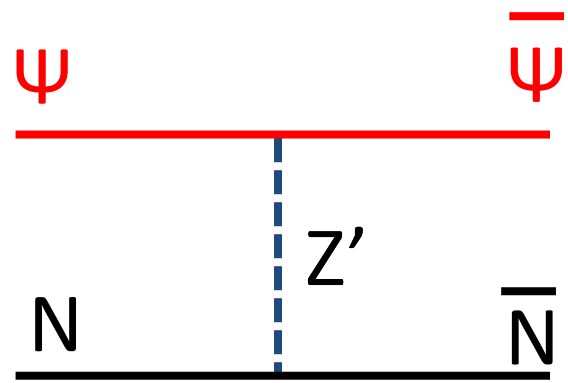
E. Aprile et al, PRL107,131302 (2011)

Prediction in our model for set A

$$\sigma(\Psi_1 N \to \Psi_1 N) = 2.7 \times 10^{-45}\,[\mathrm{cm}^2]$$

Z’ mediation dominant





Testable at ILC and the future direct detection experiments

Parameters

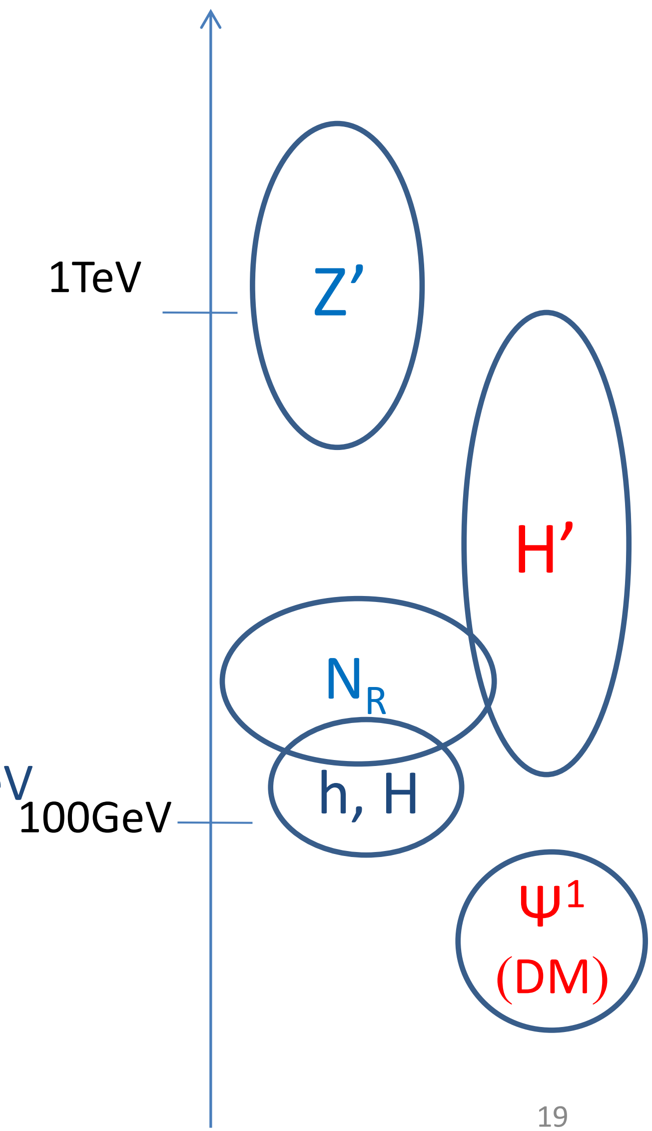
Inputs

- Neutrino mass mixing
- LFV
- DM abundance
- Direct search results
- LEP precision tests
- Z’ search results

Vs =3-4 TeV
V =246 GeV

Mh=O(100) GeV
MH=O(100)GeV
Sinα = 1/Sqrt[2]
tanβ=12-15
MNR=50 GeV
mZ’= 1000-2000 GeV
g=y=λ5=O(0.01-0.1)
Particle mass =O(0.1-1) TeV

Mass Spectrum



Multi Higgs [h and H]

Large Mixing [$\alpha \sim \pi/4$] [$\leftarrow$ $\Omega h^2 = 0.11$]

All the *ffh, ffH* coupling constants are 1/Sqrt[2] of the SM $ff\phi_{SM}$ values.

$\Rightarrow$ $\Gamma(h,H \rightarrow ff) \sim (1/2)\ \Gamma(\phi_{SM} \rightarrow ff)$

$\Gamma(h,H \rightarrow VV) \sim (1/2)\ \Gamma(\phi_{SM} \rightarrow VV)$

$\sigma(pp \rightarrow h,H) \sim (1/2)\ \sigma(pp \rightarrow \phi_{SM})$

But , $B(h \rightarrow X) \sim B(H \rightarrow X) \sim B(\phi_{SM} \rightarrow X)$

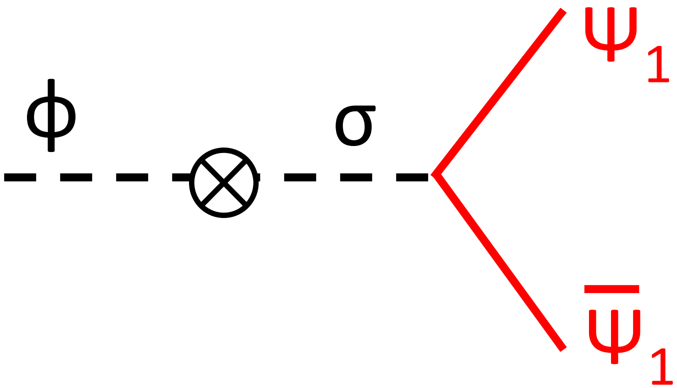
Two SM-like light Higgs bosons with about a half width

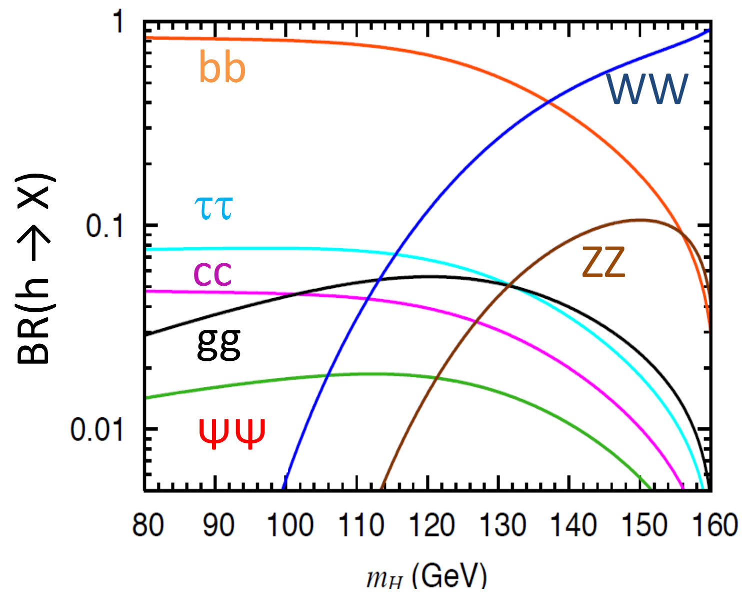
Similar to Type I 2HDM, but no charged Higgs states H^+, H^-.

Easily testable at the LHC and the ILC

Invisible Higgs decays

Higgs decays into $\Psi_1\overline{\Psi}_1$ via the same coupling as the DM annihilation





$\Gamma(h \to \text{invisible})$	~	1 - 2 %
$\Gamma(H \to \text{invisible})$	~	3- 4 %

ILC may be able to test the Higgs invisible decay at the 1 %level

Physics of Z'

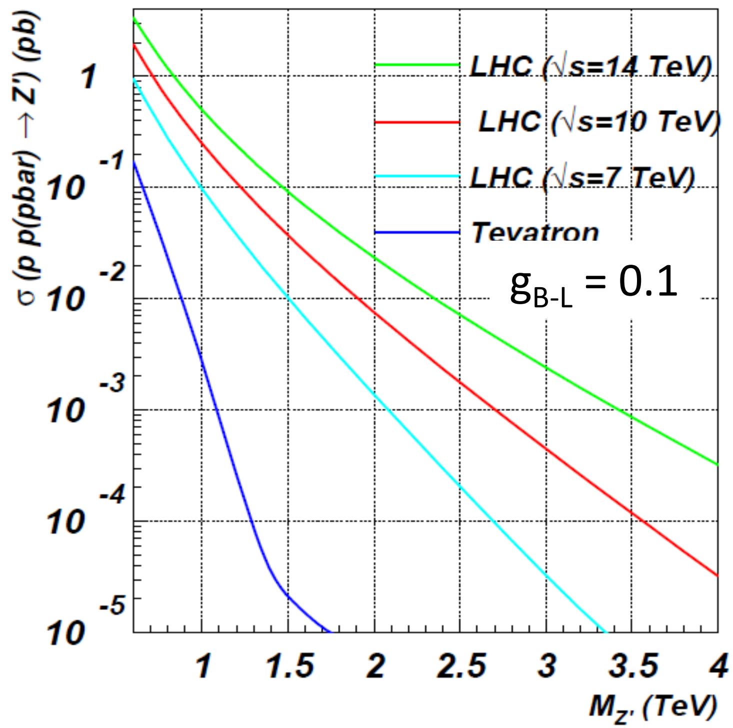
Z' Mass: 500GeV – a few TeV

$\Gamma(Z' \to XX) \propto$ (B-L charge)^2

Decay rates determined by B-L charges

Invisible decay = 40 %

$Z' \to \nu_L \nu_L$	0.15
$Z' \to \Psi_1 \Psi_1$	0.13
$Z' \to \Psi_2 \Psi_2 \to \nu_L \nu_L \Psi_1 \Psi_1$ etc	0.12



Basso, et al (2009)

Production Cross section at the LHC:

For v_S = 3.5 TeV and m_Z'=2TeV, we have g_{B-L}=0.2, then

$\sigma(pp \to Z')$ = 70 fb

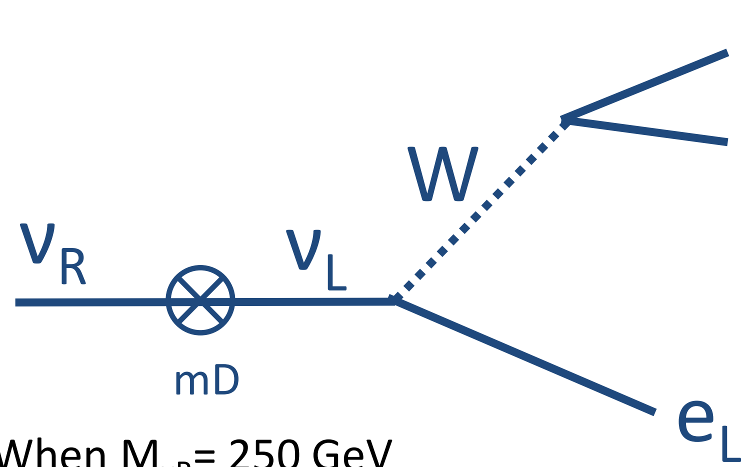
Model can be tested by measuring (invisible) decays of the Z' boson

7000 of Z' are produced for 100fb^{-1}

light RH neutrinos

- light RH neutrinos are a good feature of the scenario of radiative Dirac masses
- RH neutrinos are produced from Z’
- It decays via Dirac mass term
- Reconstructing jje or jjμ, RH neutrino can be tested at the LHC/ILC/CLIC

$\mathrm{BR}(\nu_R \to XY)$			
$W^{\pm}\ell^{\mp}$	$Z\nu_L$	$h^0\nu_L$	$H^0\nu_L$
0.53	0.28	0.10	0.09



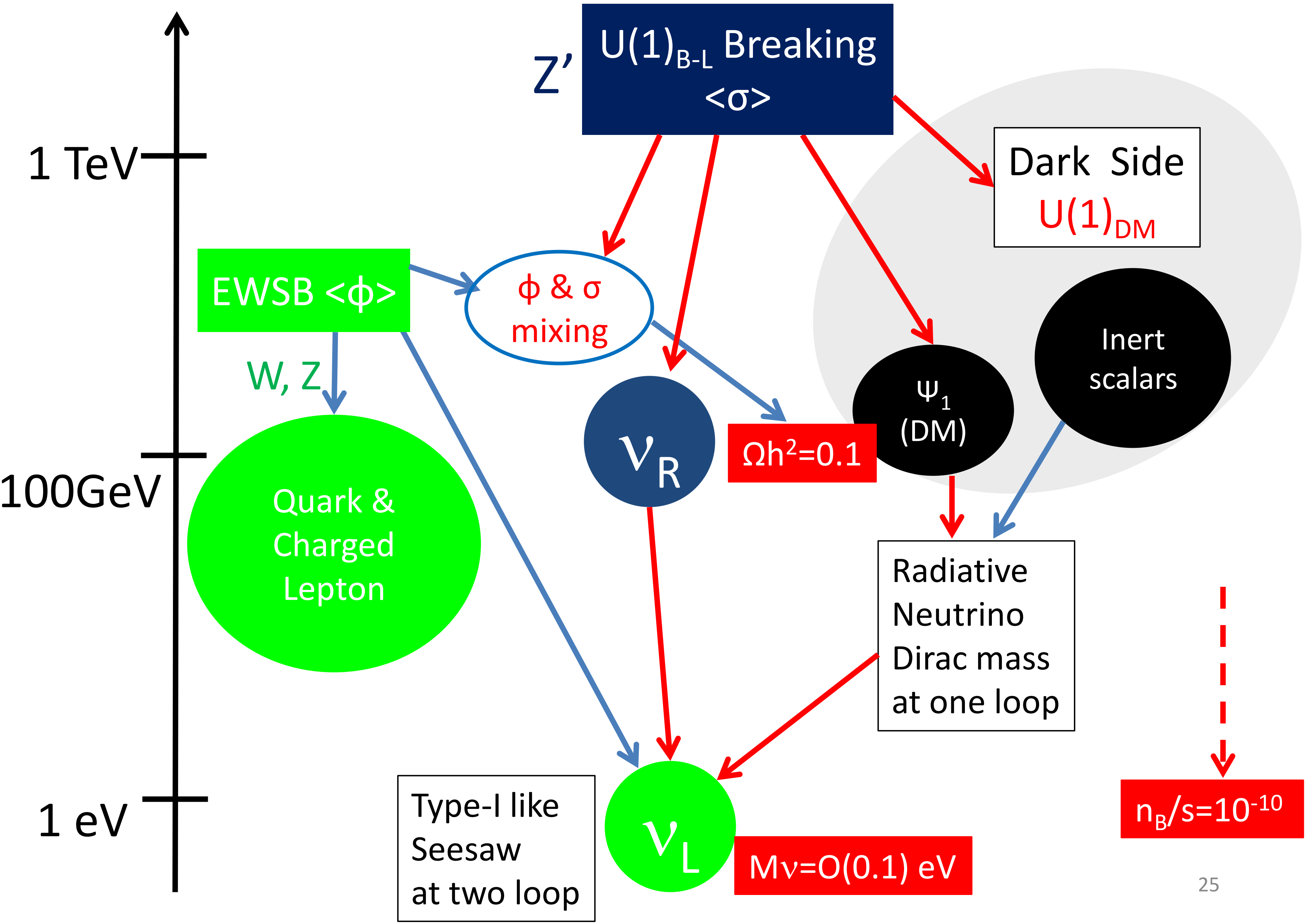
When $M_{\nu R}$= 250 GeV
1200 pairs of ν_R from 7000 Z’
at LHC with 14 TeV/70 fb^{-1}

The process $pp \to W^{+*} \to e^+e^+jj$ can also be useful

Summary

- Radiative seesaw scenario is interesting:

  Testability and strong connection with EWSB
- A model with gauged $U(1)_{B-L}$ (SSB at the TeV scale)
- A remnant global $U(1)_{DM}$ remains after the SSB, which forbids tree-level Yukawa coupling and also guarantees stability of DM
- The SSB also gives Dirac mass of Ψ^1 (DM) as well as Majorana mass of ν_R at tree level
- Dirac Yukawa coupling is also induced at one-loop level after SSB.
- Type-I seesaw mechanism occurs at two-loop level, and tiny neutrino masses can be explaind w/o excessive fine tuning
- A light ν_R (O(100)GeV) is predicted: testable at the LHC
- A unique Higgs sector is predicted (two SM-like Higgs bosons)
- Invisible decay of Z' can also be used to test the model



1 TeV
100GeV
1 eV
Z'
U(1)B-L Breaking
<σ>
Dark Side
U(1)DM
EWSB <ϕ>
ϕ & σ
mixing
W, Z
Quark &
Charged
Lepton
νR
Ωh2=0.1
Ψ1
(DM)
Inert
scalars
Radiative
Neutrino
Dirac mass
at one loop
νL
Mν=O(0.1) eV
nB/s=10-10
Type-I like
Seesaw
at two loop