Z'-portal right-handed neutrino dark matter in the minimal $U(1)$ x extended Standard Model

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Ref: NO & S. Okada, PRD 93, 075003 (2016) PRD 95, 035025 (2017)

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Problems of the Standard Model

Although the Standard Model (SM) is the best theory so far, New Physics beyond SM is strongly suggested by both experimental & theoretical points of view

What is missing?

1. Neutrino masses and flavor mixings 2. Dark matter candidate

New Physics must supplement the missing pieces

For neutrino mass

Minimal gauged B-L extension of the Standard Model

- \triangleright B-L is the unique anomaly free global symmetry in the SM
- \triangleright Gauging the global B-L symmetry looks natural
- \triangleright Anomaly free requirement \rightarrow 3 right-handed neutrinos

In terms of LHC physics,

we focus on the B-L model $@$ TeV

Minimal Gauged B-L Extension of the SM

Mohapatra & Marshak; Wetterich; others

The model is based on
$$
SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}
$$

Particle Contents

New Yukawa terms in Lagrangian <u>*New Yukawa terms in Lagrangian* experience the contract of the district of</u> α terms <u>ns</u>

$$
\mathcal{L}_{Yukawa} \supset -\sum_{i,j} Y_D^{ij} \overline{\ell_L^i} H N_R^j - \frac{1}{2} \sum_k Y_N^k \Phi \overline{N_R^k} \overline{C} N_R^k + \text{h.c.}
$$

B-L symmetry breaking via
$$
\left\langle \Phi \right\rangle = \frac{v_{BL}}{\sqrt{2}}
$$

$$
\begin{array}{|c|c|c|c|c|}\n\hline\n\end{array}\n\quad \text{B-L gauge boson (Z' boson) mass} \quad \text{Mass scale is controlled}
$$

$$
m_{Z'} = 2g_{BL}v_{BL}
$$
 Mass scale is controlled
by B-I Sym. Br. scale

Mass scale is controlled $\underline{O}(102) = 29BL^oBL$ ¹ by B-L Sym. Br. scale $\int m_{Z'} = 2g_{BL}v_{BL}$ Mass scale is controlled *Mass scale is controlled*

Heavy Majorana neutrino mass

$$
m_N^k = \frac{Y_N^k}{\sqrt{2}} v_{BL}
$$

B-L sym breaking also *generates RHN mass* v_{BL} **d** $\frac{b}{2}$ ² $\frac{b}{2}$ $\frac{b}{2}$ $\frac{b}{2}$ $\frac{b}{2}$ $\frac{c}{2}$

Seesaw mechanism after EW sym. breaking

DM candidate is still missing in TeV-scale minimal B-L model

There have been many proposal for introduction of DM particles Concise model: no extension of the particle content

Instead, introduce a parity

NO & Seto, PRD 82 (2010) 023507

- \triangleright Assigning odd parity for one RHN
- \triangleright The others are all even

TeV-scale minimal B-L model with RHN DM

3 right-handed neutrinos \rightarrow 2+1

 \triangleright 2 RHNs for the minimal seesaw

King, NPB 576 (2000) 85; Frampton, Glashow & Yanagida, PLB 548 (2002) 119

 \checkmark Neutrino oscillation data with one massless eigenstate

 \triangleright Z₂-odd 1 RHN for thermal Dark Matter

More general gauged U(1) extension of the SM at TeV *x*

 \rightarrow Non-Exotic U(1) extension

PRD 68 (2003) 035012 *A*ppelquist, Dobrescu & Hopper, ^Ω*DMh*² = 0*.*¹¹⁹⁸ *[±]* ⁰*.*0015*.* (1) *U*(1)*^X* = *U*(1)*^Y* ⊕ *U*(1)*^B*−*^L* (3)

$U(1)$ x direction is a linear combination of the SM hypercharge & the gauged B-L directions *x*^{*H* θ + 0 θ +} **x** $\overline{\text{MS}}$

- θ \triangleright Particle contents = the B-L model
- \triangleright Anomaly Free
-

TeV-scale minimal $U(1)x$ model with RHN DM

 \triangleright The minimal B-L model is in the limit of $\boxed{x_H\to 0}$ $x_H \rightarrow 0$

Phenomenology of **Title**

Grid

TeV-scale minimal U(1)x model with RHN DM **50** TeV-scale minimal U(1)x model with RHN DI <u>ith RHN DI</u>

50

(1) Z'-portal RHN DM

RHN DM communicates with the SM particles through Z' boson mediated processes **Export PNG LaTeX Export PNG LaTeX**

(2) Z' boson search at the LHC Run-2 I 7' hoson soarch at the

Search for a narrow resonance with the di-lepton final state at ATLAS and CMS with LHC Run-2 $\frac{1}{3}$: removed extensive extensive from canvas $\frac{1}{3}$ \overline{a} Search for a narrow re \overline{M} : \overline{M} $\overline{1}$: moved that $\overline{1}$

An Example Feynman Example Feynman Example Feynman Example Feynman Example Feynman

An Example Feynman

(3) We will discuss a complementarity **between DM physics and LHC physics Select element:** Left click **Select multiple elements:** Drag on

(1) Z'-portal RHN dark matter An Example Feynman Diagram

Select element: Left click

52 : moved text

51 : moved text

49 : moved text

54 : Added a text field to the canvas

 \triangleright The RHN dark matter **communicate with the SM** particles through its $U(1)$ x gauge $\overline{\text{interaction}}$

Z' B-L case: NO & S. Okada, <u>Prediction</u> **Definition**es **Definition** ^Ω*DMh*² = 0*.*¹¹⁹⁸ *[±]* ⁰*.*0015*.* (1) *<u><i>x*</u> **p** = 2222 NO 8 C Okede $V = \text{Y} = \$ *U* D **L** Case: NO & 3. Okada,
PRD 93 (2016) 075003

*m*DM (10)

*m*DM (10)

*m*DM (10)

4π

► For Dark Matter physics, only 4 free parameters are involved **and the set of the set** *x*^H → ∞ (5) → *Z*^{*Z*} (*6)* (α*^X* = *<u>Inly 4 free parameter</u>* e p

X

4π

- $\mathbf{5}$: removed element from canvas $\mathbf{5}$ \cdot U(1)X gauge coupling: $\alpha_X =$ g_X^2 4π α*^X* = $x =$ $\alpha_X = \frac{1}{4\pi}$ *m* $\alpha_X = \frac{g_X}{g}$
- 50 : Added a text field to the canvas • Z' boson mass: $m_{Z'}$ (8) 4π (8)
	- SM Higgs $U(1)x$ charge: x_H *m^Z*′ (8) *x^H* (9) m_{DM} x *H* (9) $\frac{1}{2}$ ^{*x*} (9) $\frac{1}{2}$ (9) $\frac{1}{$
	- RHN DM mass: n m_{DM}

Note that the RHN DM has U(1)x charge -1

Cosmological constraint on Z' portal DM C_{source} above is measured at $7'$ montal D_{A} <u>cosifiological constraint on zi portal bivi</u> Cosmological constraint on Z' portal DM

$$
\text{Observed Relic Abundance: } \Omega_{DM} h^2 = 0.1198 \pm 0.0015
$$

Planck 2015 (68% CL) the yield of the dark matter particle in the thermal equilibrium, and *D*
Thermal average in the thermal average in the thermal average in the thermal average in the thermal average in the of the dark matter and the data matter and the data section of the second velocity. \Box *Planck 2015 (68% CL) i* (68% CL)

Thermal DM relic abundance is determined by the Boltzmann eq: Thermal DM relic abundance is nce s det *xH*(*mDM*) *x*(*Telic difficultualite*) determined by the Boltzmann *mDM*

Thermal DIVTEIC abundance is determined by the Boltzmann eq.
\n
$$
\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{EQ}^2)
$$
\n
$$
n(T) = \sqrt{\frac{8\pi \rho}{3} \frac{\rho}{M_{Pl}^2}} = \sqrt{\frac{4\pi^3}{45} g_\star} \frac{T^2}{M_{Pl}}
$$
\n
$$
n(T) = sY_{EQ} = \frac{g_{DM}}{2\pi^2} \frac{m_{DM}^3}{x} K_2(x), \text{ where } x = \frac{m_{DM}}{T}
$$
\n
$$
s = \frac{2\pi^2}{45} g_\star \frac{m_{DM}^3}{x^3}
$$
\n**Thermally averaged**
\n
$$
\langle \sigma v \rangle = \sum_{N}^{N} \frac{z_N}{N} \sum_{f_S}^{f_S}
$$
\n**Thermally averaged**
\nannihilation cross section

Relic abundance for various α_X for fixed x_H and $m_{Z'}$ *g*2 *X* $\frac{11}{4}$ $\textsf{undance} \text{ for various } \alpha_X \text{ for fixed } x_H \text{ and } m_{Z'} \quad \textcolor{red}{\bigcup}$ *m*DM (10) *f*SM *f*SM (2) $m_{Z'}$ |

0.12

 $\overline{}$ abundance is measured at the 68% limit as $\overline{}$

 $xH = 0$ fixed \triangleright xH=0 fixed *P* xH=0 fixed *x* $\frac{1}{2}$

m^Z′ (8)

- abundance becomes lower *x^H* → 0 (4) *x*
X DM mass $\frac{2}{3}$ /2 is *g*e coupling is
DM *x^H* → 0 (5) *m*
- solution)M !
.
. *x^H* → 0 (4) assent and the ∞ ed to find the *<i>x* find the
- **100** small gauge
100 small gauge **EXAL TOO SMALL BAUGE
COUDLING BO SOLL** *y*n
<mark>mall</mark> ng, no solu<mark>ti</mark>on **z** all gauge **a** *z* auge

dY ⁼ [−] *^s*⟨σ*v*⟩ where the universe is normalized by the universe is normalized by the mass of the mass of the right-handed neu Lower bound on α_X for fixed α_H and $\alpha_{Z'}$ Lower bound on α_X for fixed x_H and n $\frac{1}{1}$ *xer* bound d α_X for fixed x_H and $m_{Z'}$ $m_{Z'}$

(2) LHC Run-2 phenomenology

 $\frac{1}{2}$ bp \Rightarrow Z' +X \Rightarrow II +X $pp \rightarrow Z' + X \rightarrow II + X$

 \triangleright The ATLAS and CMS collaborations have been searching for Z' boson resonance with a dilepton final state at the LHC Run-2

4π

 \triangleright Upper bounds on the cross section for the sequential Z' model have been obtained S S section for the **<u>sequential Z' model</u>** *x*^{*H*} → ∞ ∞ ∞ (6)

Sequential Z': heavy vector boson with the SM Z coupling *x*Here western with the SM ≥ coupling *<u>¹</u> LITE JIV

² g*2 *X* $coupling$

We interpret the ATLAS & the CMS X-sec bounds into $U(1)$ _X Z' $\Bigl)$

Upper bound on α_X for fixed x_H and n *g*2 *X* $\frac{1}{\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac$ x_H and $m_{Z'}$ $m_{Z'}$ (3) Complementarity between Cosmological & LHC bounds

For Z' boson mass =4 TeV

ATLAS update (April, 2017)

ATLAS-CONF-2017-027 36.1/fb

Summary

- Ø We have considered the minimal U(1)_X extension of the ^Ω*DMh*² = 0*.*¹¹⁹⁸ *[±]* ⁰*.*0015*.* (1) *x*^Φ = 1 (2) **Standard Model with right-handed neutrino dark matter** *U*(1)*B*−*L D*(1)*B*−*L* (3)*B*−*L* (3)*B x* = 1 (2) *x* = 1 (2) *x*
	- Minimal seesaw with 2 RHNs for the neutrino
 oscillation data oscillation data *x*
x^H → 0 (4) +
	- 1 RHN serves as DM DM
- \triangleright The RHN DM communicates with the SM particles through the Z'-boson exchange (Z'-portal DM) $x^2 + b$ + b o c M particles through the *M* λ ^{*H*} λ *H* $\frac{1}{2}$ $\frac{1}{2}$ *Z*′ (6) ates with the SM particles through the

Phenomenology is controlled by *<u>Z* (6)</u> *Z***^{** α **} (6) ***Z* (6) *Z* (7) *Z* (7) *Z* α*^X* = *X* \overline{p}

- U(1)X gauge coupling: $\alpha_X =$ α*^X* = $x =$ *n* $\alpha_X = \frac{g_X}{g}$
- Z' boson mass: $m_{Z'}$ $m_{Z'}$ ⁴⁷⁷
- SM Higgs $U(1)x$ charge: x_H *x^H* (9) m_{DM} x_H $\mathbf{r} \mathbf{v} \mathbf{z}$ ^{*x*} (9)
- RHN DM mass: $m_{\rm DM}$ $m_{\rm DM}$

$$
\alpha_X = \frac{g_X^2}{4\pi}
$$

Summary (cont'd)

 \triangleright We have considered phenomenological constraints

- The observed DM relic abundance
- LHC Run-2 constraints from Z' resonance search

and identified an allowed parameter region.

These constraints are complementary with each other to narrow the model parameter space

!*ank y*" *for y*"*r a*\$*ention! for y*"*r a*\$*ention!*