Freeze-in Dark Matter in U(1) extended Standard Model and Lifetime Frontier Experiments

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Based on collaborations with

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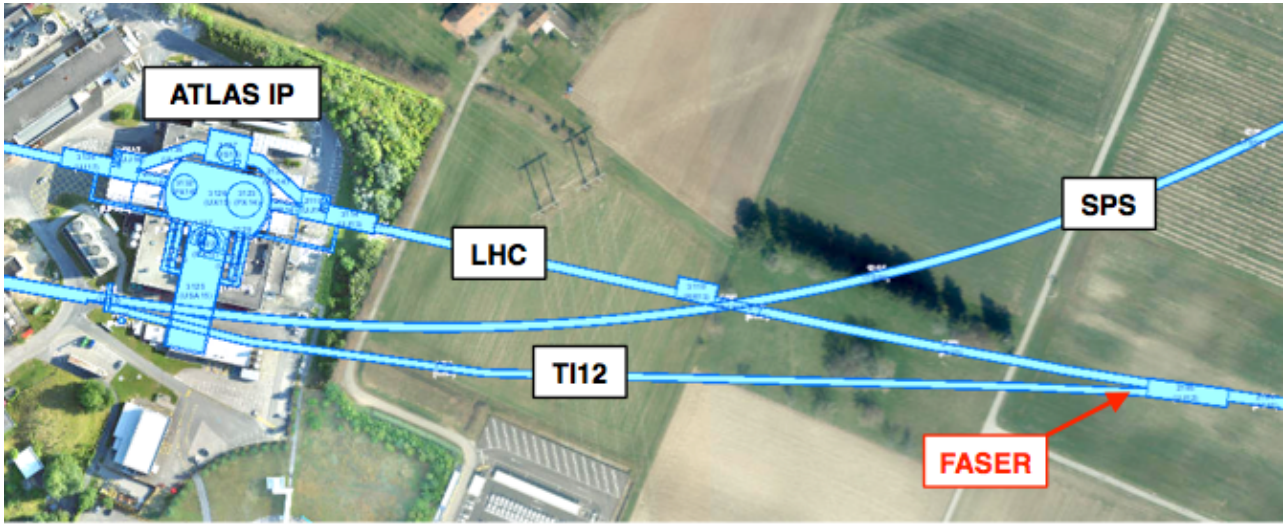
ForwArd Search ExpeRiment (FASER)

- Recently approved (March 2019) new experiment at CERN to look for long-lived charge-neutral particles
- The FASER detector will be installed in a tunnel near the ATLAS detector about 480 m away



FASER Search for a long-lived B-L gauge boson search

Z' boson in the gauged B-L (Baryon-Lepton number) extended Standard Models (Minimal B-L Model) is one of the search targets

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$1/3$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$1/3$
l_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1
N_R^i	$\mathbf{1}$	$\mathbf{1}$	0	-1
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	-1
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
Φ	$\mathbf{1}$	$\mathbf{1}$	0	2

3 right-handed neutrinos (RHNs)

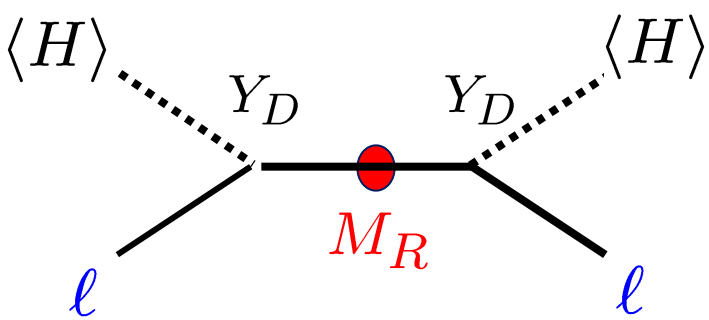
B-L Higgs field for the B-L symmetry breaking

Properties of gauged B-L extended SM

- It is easy (well-motivated) to gauge the global B-L symmetry in the SM
- All the gauge anomalies cancel in the presence of 3 RHNs

- New B-L gauge boson mass & RHNs' Majorana masses are generated by the B-L gauge symmetry breaking
- The seesaw mechanism for generating tiny neutrino masses is implemented automatically.

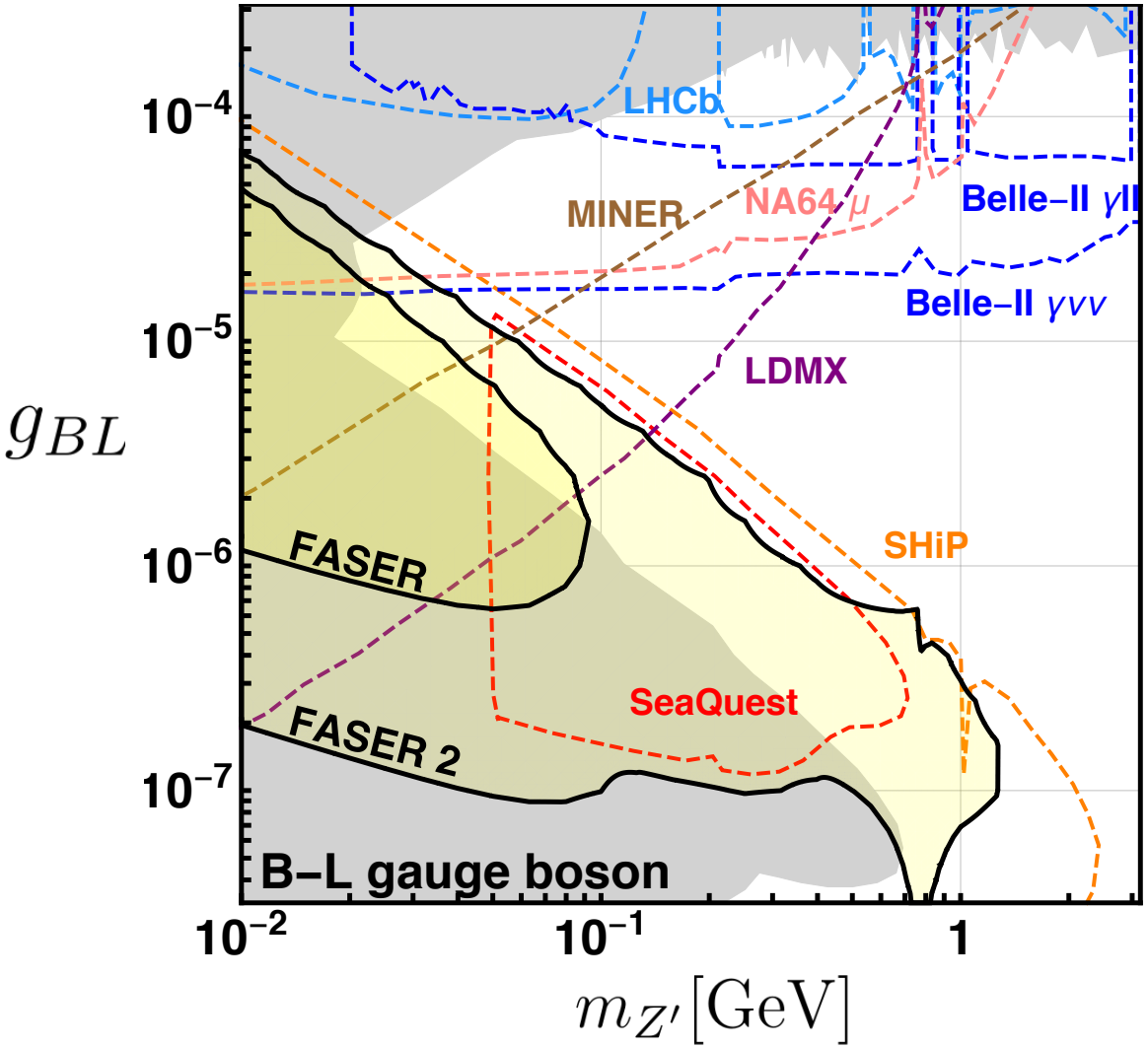
Seesaw mechanism



$$\begin{aligned} m_\nu &= \frac{(Y_D \langle H \rangle)^2}{M_R} \\ &= Y_D \langle H \rangle \left(\frac{Y_D \langle H \rangle}{M_R} \right) \ll Y_D \langle H \rangle \end{aligned}$$

Search reach by FASER + others for a long-lived B-L gauge boson

FASER collaboration, arXiv: 1811.12522



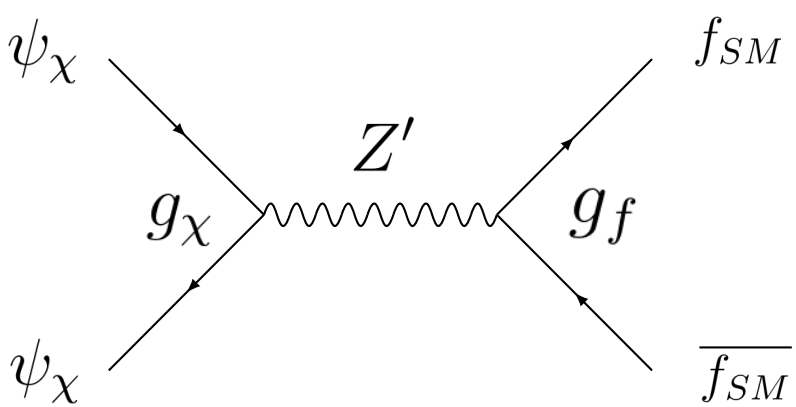
Gray shaded region: current excluded region

Z'-portal Dark Matter in U(1) extended SM

- Although the minimal B-L model is a simple, well-motivated model beyond the SM, a DM candidate is still missing.

- A simple way to supplement the model with a DM candidate: we introduce an SM singlet fermion with a U(1) charge
  "Z'-portal Dark Matter''

  DM particle communicates with the SM particles through new gauge boson Z'



We set $m_\chi \gg m_{Z'}$

Complementarity between Z' boson searches at FASER & Z'-portal DM scenario

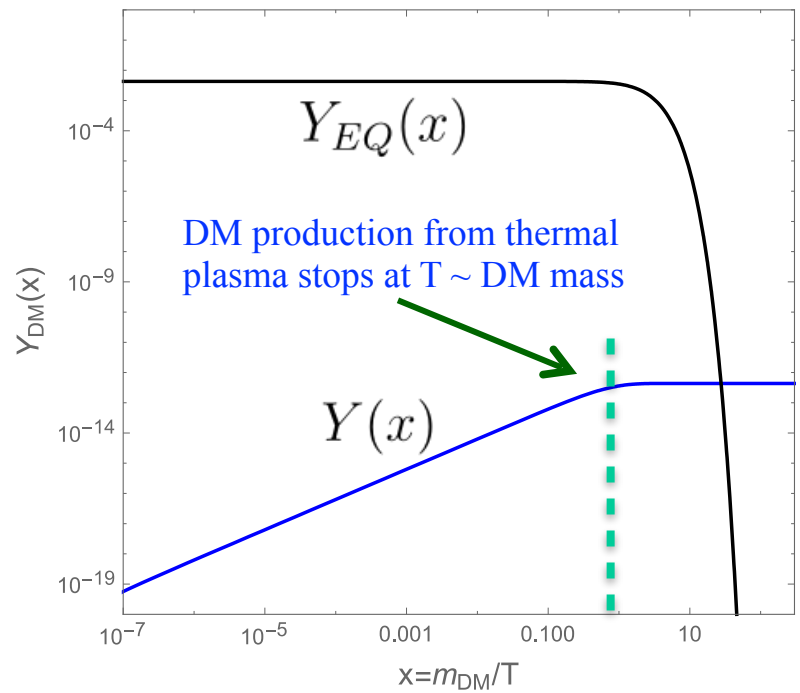
- Z' boson is long-lived: light & very weakly coupled

- Z'-portal DM has never been in thermal equilibrium, and its observed relic density is achieved by "Freeze-In" mechanism

Boltzmann equation

$$\frac{dY}{dx} = -\frac{\langle \sigma v_{rel} \rangle}{x^2} \frac{s(m_\chi)}{H(m_\chi)} \left(Y^2 - Y_{EQ}^2 \right)$$

$$\simeq \frac{\langle \sigma v_{rel} \rangle}{x^2} \frac{s(m_\chi)}{H(m_\chi)} Y_{EQ}^2$$



Two Simple Freeze-In DM models

(i) The minimal B-L model + Dirac Fermion Dark Matter

(R.N. Mohapatra & NO, arXiv: 1908.11325)

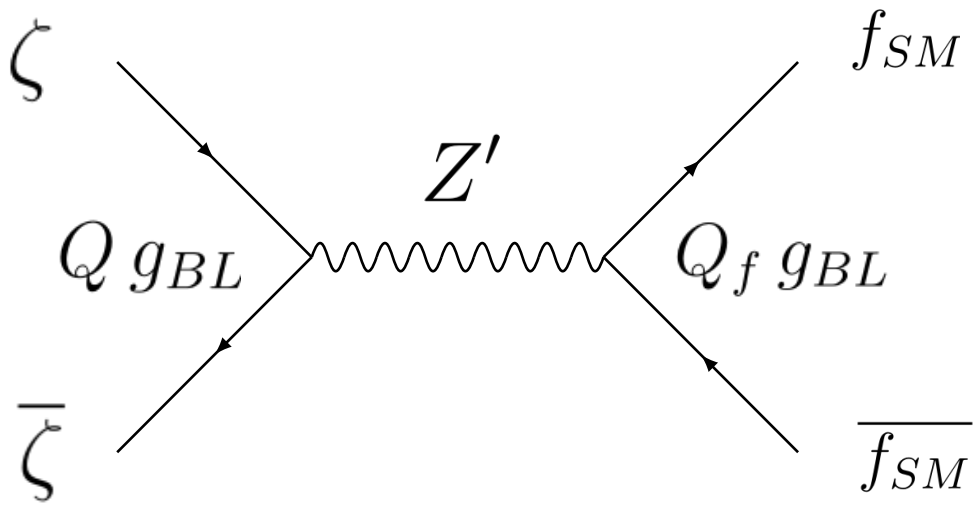
- A simple way to supplement the B-L model with a DM candidate: we introduce an SM singlet Dirac fermion

	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-L}$
$\zeta = \zeta_L + \zeta_R$	$\mathbf{1}$	$\mathbf{1}$	0	Q

- Arbitrary $\boxed{|Q| \neq 1, 3}$ → stability is ensured

B-L Z'-portal Dirac Fermion DM $(\; m_\zeta \gg m_{Z'} \;)$

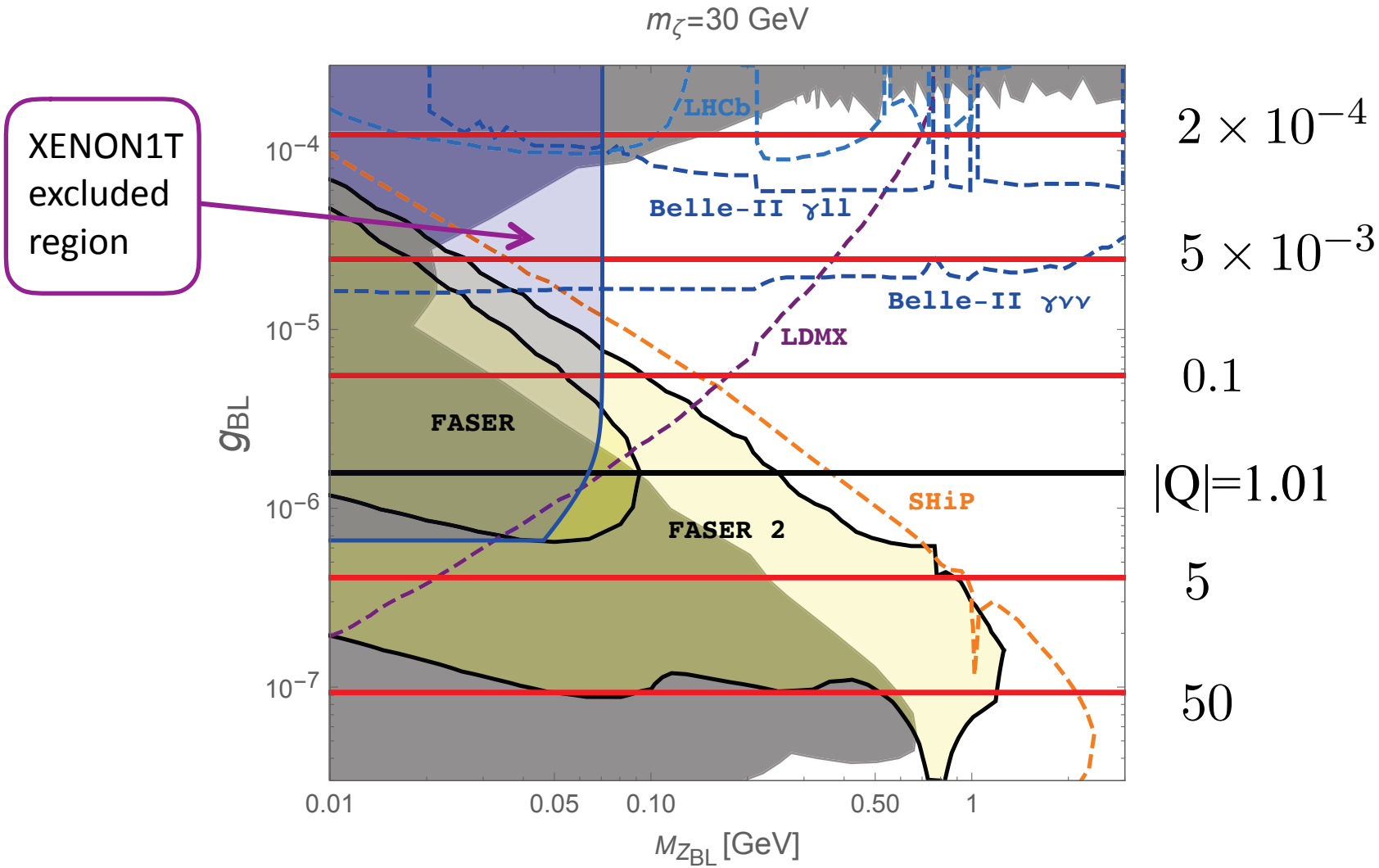
DM particle communicates with the SM particles through the B-L gauge boson Z'



By solving the Boltzmann equation, we find

$$\boxed{\Omega_{DM} h^2 = 0.12 \rightarrow Q\, g_{BL}^2 \simeq 10^{-11}}$$

Testing the scenario by Lifetime Frontier Experiments



- DM mass independent
- The result shifts downward as Q becomes larger

(ii) Minimal U(1)X model with RHN DM

(NO, S. Okada & Q. Shafi, arXiv: 2003.02898)

- Generalization of the minimal U(1) B-L model
- Same particle contents, but $Q_X = x_H Q_Y + Q_{B-L}$
- Basics structure is the same as the minimal B-L model
- We impose **Z**2 symmetry

Particle contents

$$Q_X = x_H Q_Y + Q_{B-L}$$

B-L model limit:
$x_H \to 0$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
q_L^i	**3**	**2**	$\frac{1}{6}$	$\frac{1}{6}x_H + \frac{1}{3}$	$+$
u_R^i	**3**	**1**	$\frac{2}{3}$	$\frac{2}{3}x_H + \frac{1}{3}$	$+$
d_R^i	**3**	**1**	$-\frac{1}{3}$	$-\frac{1}{3}x_H + \frac{1}{3}$	$+$
ℓ_L^i	**1**	**2**	$-\frac{1}{2}$	$-\frac{1}{2}x_H + (-1)$	$+$
e_R^i	**1**	**1**	-1	$-x_H + (-1)$	$+$
H	**1**	**2**	$-\frac{1}{2}$	$-\frac{1}{2}x_H$	$+$
N_R^j	**1**	**1**	0	-1	$+$
N_R	**1**	**1**	0	-1	$-$
Φ	**1**	**1**	0	$+2$	$+$

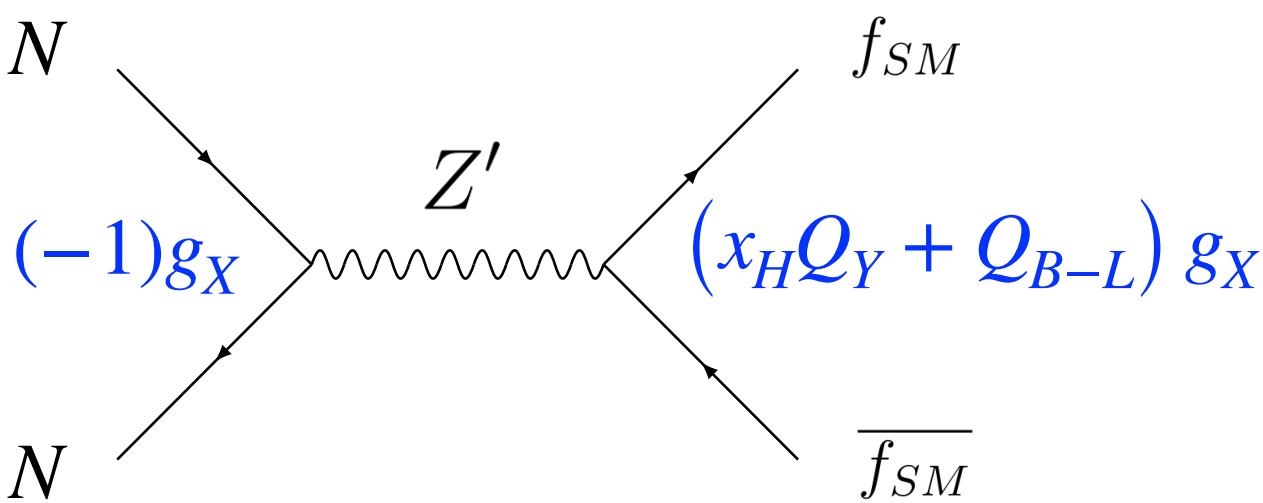
Stable

3 RHNs = 2 RHNs for the Minimal Seesaw
+ 1 RHN for DM

NO & O.Seto, arXiv: 1002.2525

Z'-portal RHN DM

RHN DM communicates with the SM particles through the U(1)x gauge boson Z'



Here we consider Freeze-In RHN DM

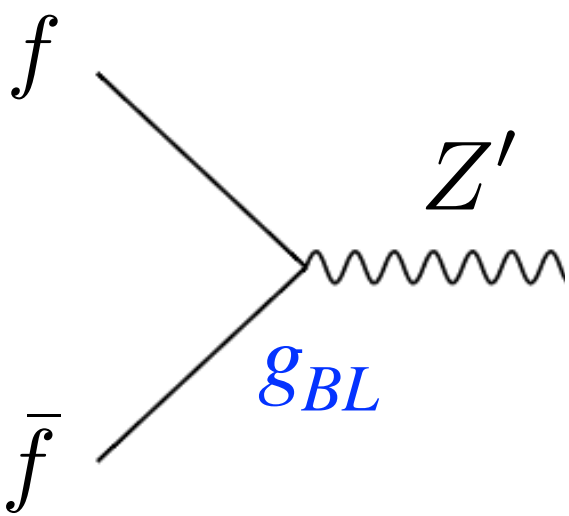
*For Freeze-out Z'-portal RHN DM,
see NO & S. Okada, arXiv: 1601.07526 & arXiv: 1611:02672

Testing the scenario by Lifetime Frontier Experiments

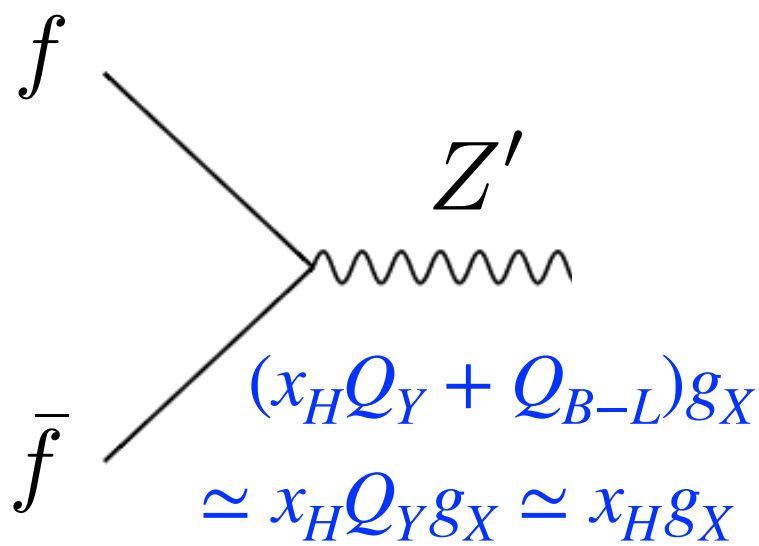
For a large $|x_H|$ value, we can infer a corresponding B-L gauge coupling by

$$g_{BL} \leftrightarrow g_X |x_H|$$

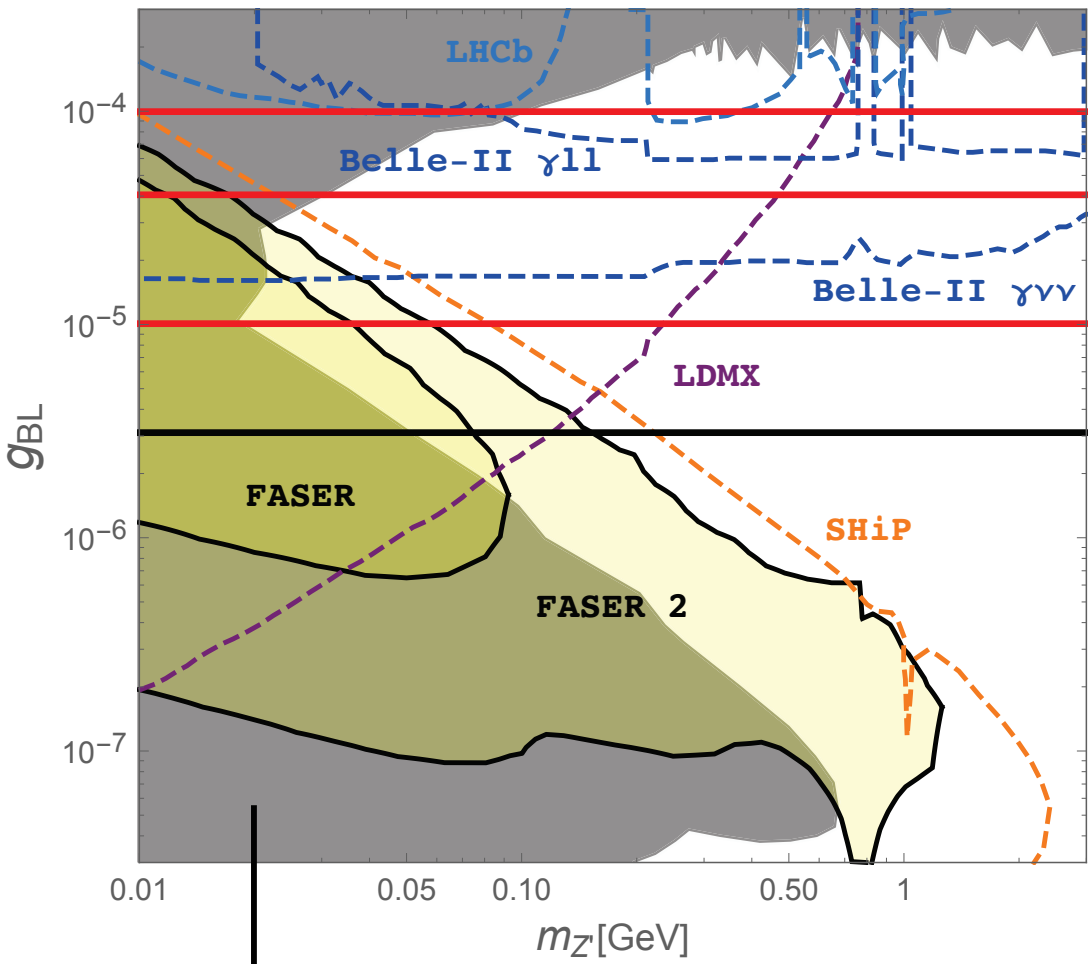
B-L model



U(1)x model



Testing the scenario by Lifetime Frontier Experiments



$|x_H| = 900$

100

10

0 (B − L limit)

Inferred g_{BL} value shifts upward as $|x_H|$ increases

Current excluded region

- Searches for long-lived particle
- Anomalous neutrino interactions

Summary

- The U(1) extended SM is a well-motivated New Physics model beyond the SM.
- If it is light and long-lived, Z'-boson can be searched by FASER and other Lifetime Frontier experiments.
- Two example models supplementing the U(1) extended SM with a Fermion Dark Matter have been considered: Z'-portal Freeze-In DM.
- The models can be tested by future Lifetime Frontier experiments: complementarity between DM physics and Lifetime Frontier experiments.