Higgs as a probe of long-lived particle productions

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Current status of Particle Physics Phenomenology

- Success of the Standard Model

  The best particle physics theory for decades

- Problems of the Standard Model

  Theoretical/conceptual

  - Gauge hierarchy problem
  - The origin of the electroweak symmetry breaking
  - Fermion mass hierarchy
  - Strong CP problem, and more

  Experimental/Observational Evidences

  - Neutrino masses & flavor mixings
  - Dark Matter in the Universe

The main subject of particle physics:

Quest for

New Physics beyond the Standard Model

Current status in the light of LHC

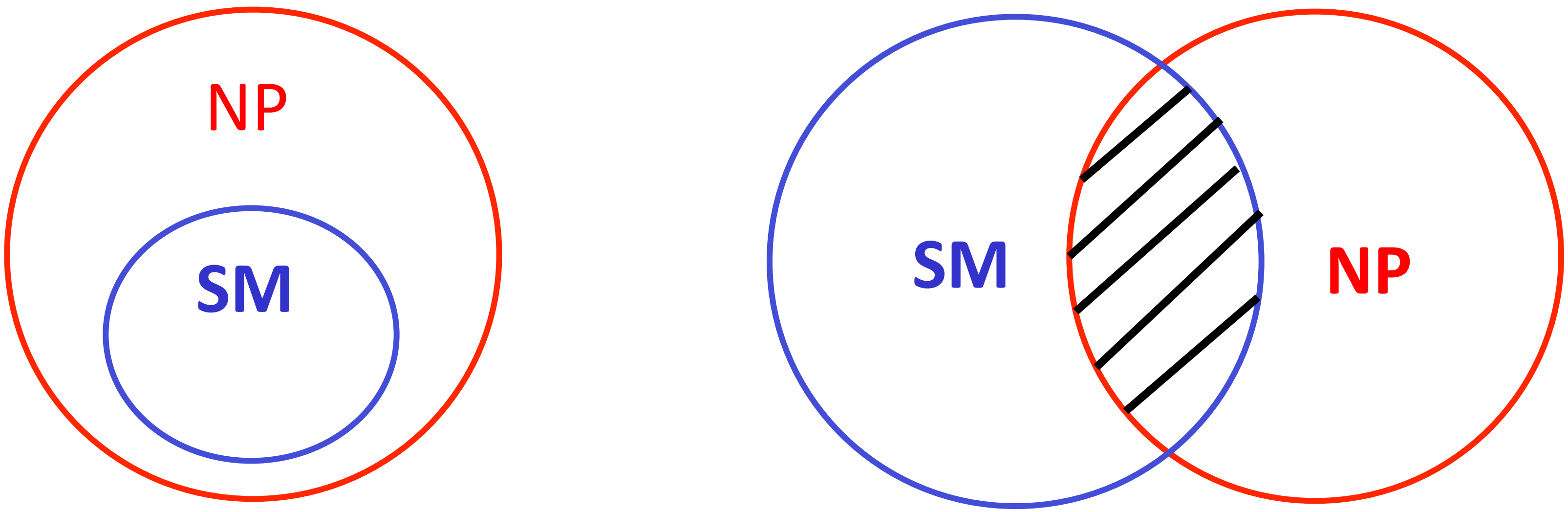
- Success of the Standard Model even at TeV
    - Higgs boson discovery
    - Higgs boson properties consistent with SM predictions
    - SM gauge interactions

- No evidence of NP so far

What is an indication of the LHC results?

Case 1

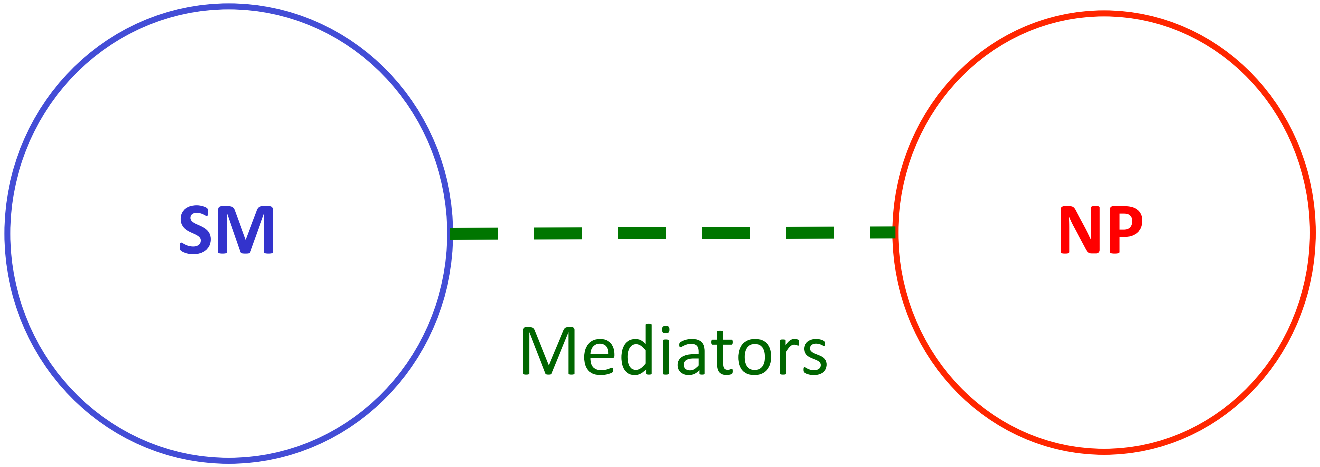
All/part of new particles in the NP sector have the SM gauge charges



LHC data may indicate that new particles are heavy and we need to wait for their discovery some more years/need new machine

Case 2

All new particles in the NP sector are SM gauge singlet



New particles very weakly couple to the SM sector.
It could be very difficult to explore the NP sector.

Hope?

Although new particles are rarely produced, they may be long-lived → displaced vertex signature

What particle is a mediator/portal?

- Structure of the SM: Chiral Gauge Theory

- Assumption: New particles are SM singlet
  Theory is renormalizable

➢ It is most likely Higgs is the portal

$(H^\dagger H)$

Gauge invariant OP
Mass dimension: 2
Lorentz scalar

Higgs as a probe of long-lived particle productions

HL-LHC physics or more future collider physics

1) Higgs boson productions
2) Higgs boson rare decays to long-lived particles
3) Displaced vertex signature of long-lived particle decays

Two possibilities

$c\tau \lesssim$ Detector size length

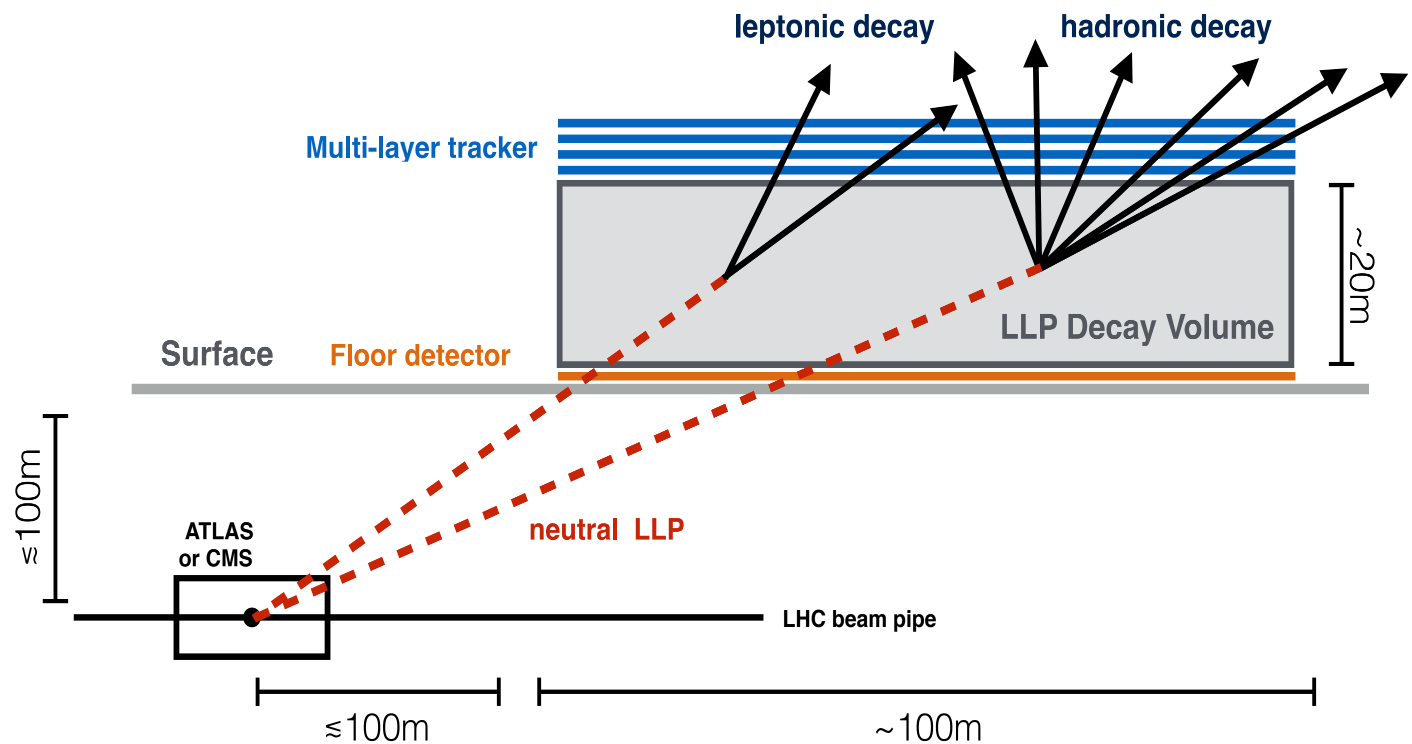
$c\tau \gtrsim$ Detector size length

Recent proposal for a dedicated LLP search

MATHUSLA

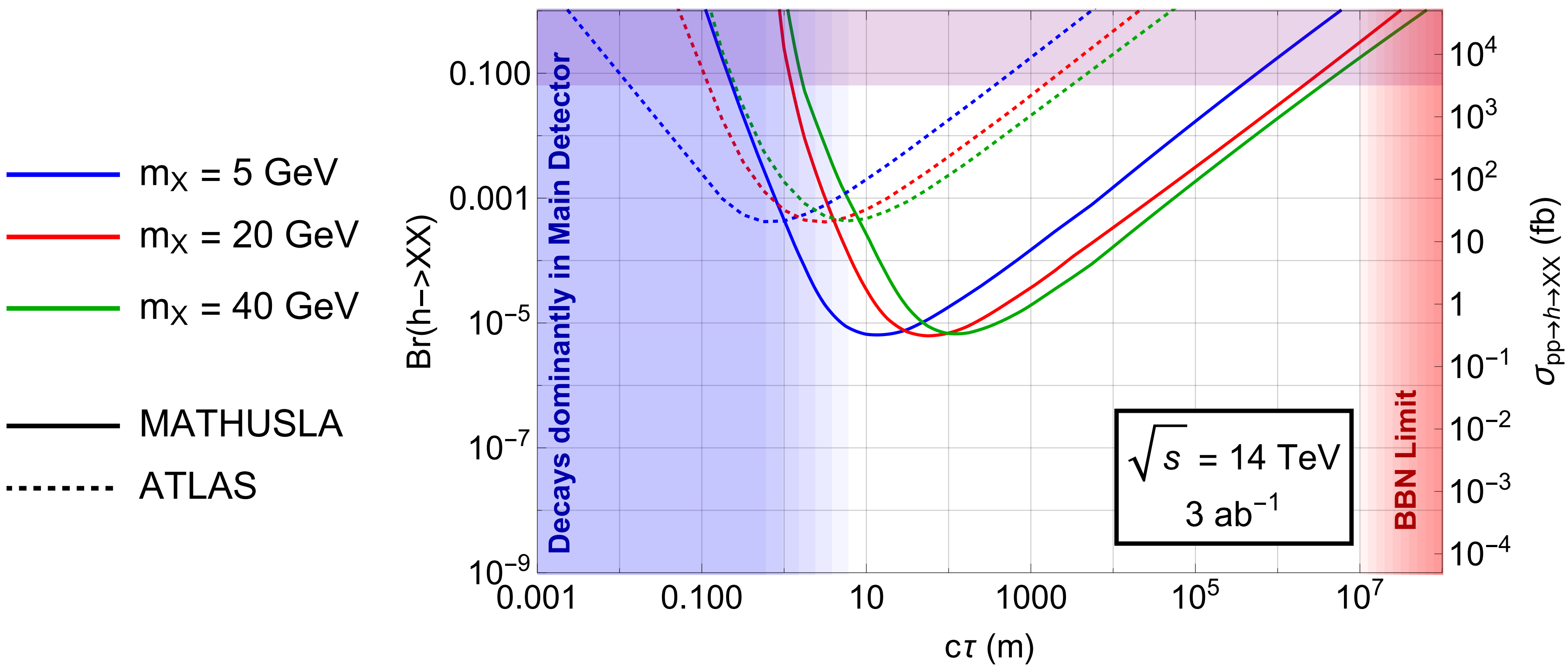
arXiv: 1901.04040

$c\tau \gtrsim$ Detector size



Almost SM background free

MATHUSLA search reach



The best reach for Br(h->XX) is 10^(-5) !

Physics Study with a simple NP model

A simple gauge extension of the SM for neutrino masses

Minimal gauged B-L extension of the Standard Model

- B-L is the unique anomaly free global symmetry in the SM
- Gauging the global B-L symmetry may be natural
- Anomaly free requirement → 3 right-handed neutrinos
- Seesaw mechanism is automatically implemented

In terms of high energy collider physics,
we focus on the gauged U(1) extended 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

i=1,2,3

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
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
New fermions: 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
New scalar: φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$

New particles are all SM singlet

New Yukawa terms in Lagrangian

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i}HN_R^j - \frac{1}{2}\sum_{k=1}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

U(1)B-L symmetry breaking via $\langle\varphi\rangle = v_{BL}/\sqrt{2}$

→ U(1)x gauge boson (Z' boson) mass

$$m_{Z'} = 2\, g_{BL}\, v_{BL}$$

Mass scale is controlled by U(1)B-L Sym. Br. scale

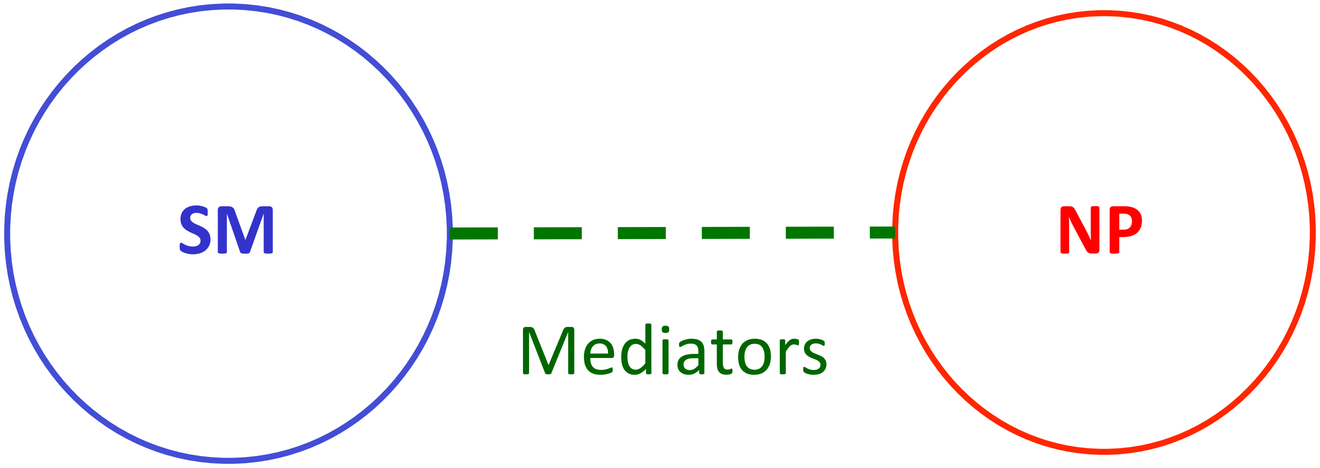
Heavy Majorana neutrino mass

$$M_{N^i} = \frac{Y_N^k}{\sqrt{2}} v_{BL}$$

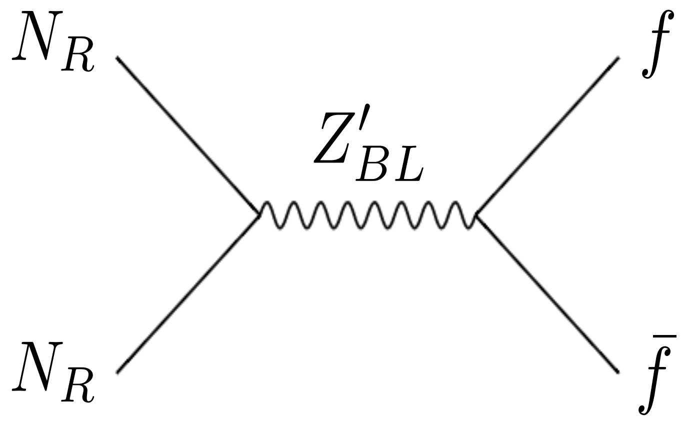
U(1)B-L sym breaking also generates RHN mass

→ Seesaw mechanism after EW sym. breaking

What particle is the portal in the B-L model?

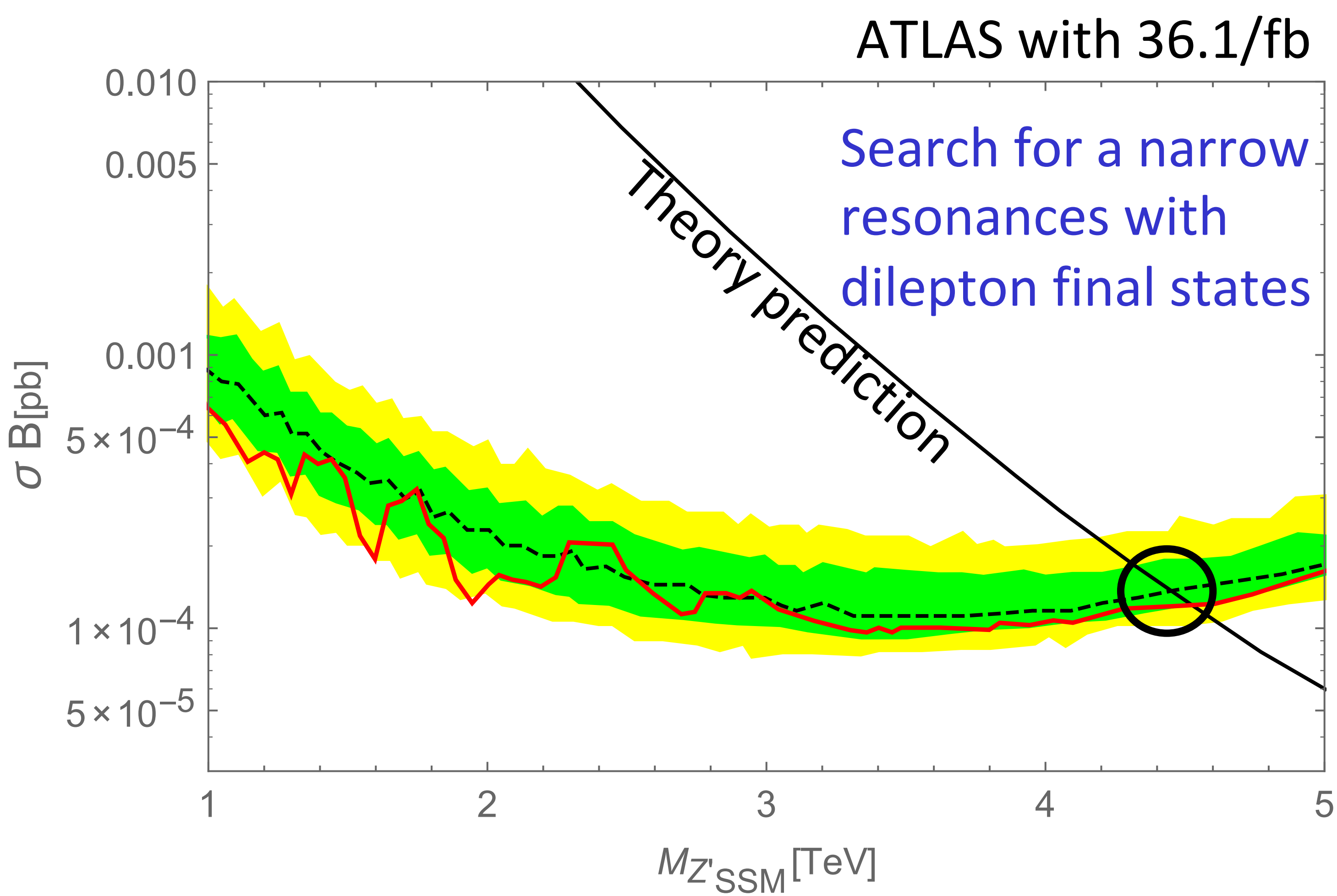


1) B-L gauge boson (Z' boson)



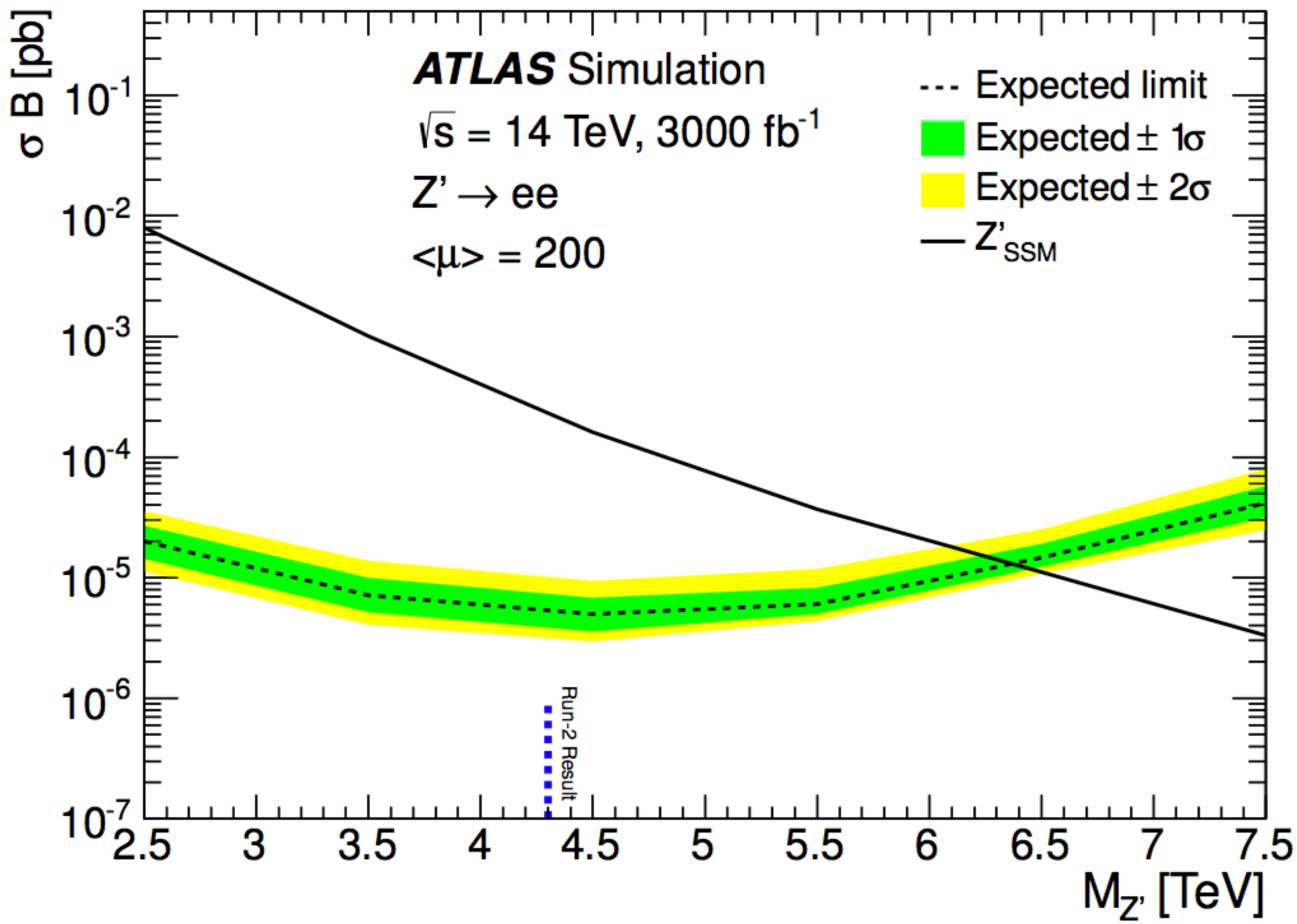
Z' portal case is already very severely constrained by the search at the LHC (Z' resonance search with dilepton)

Benchmark model: sequential SM Z' boson

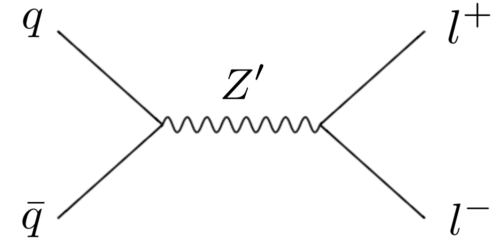


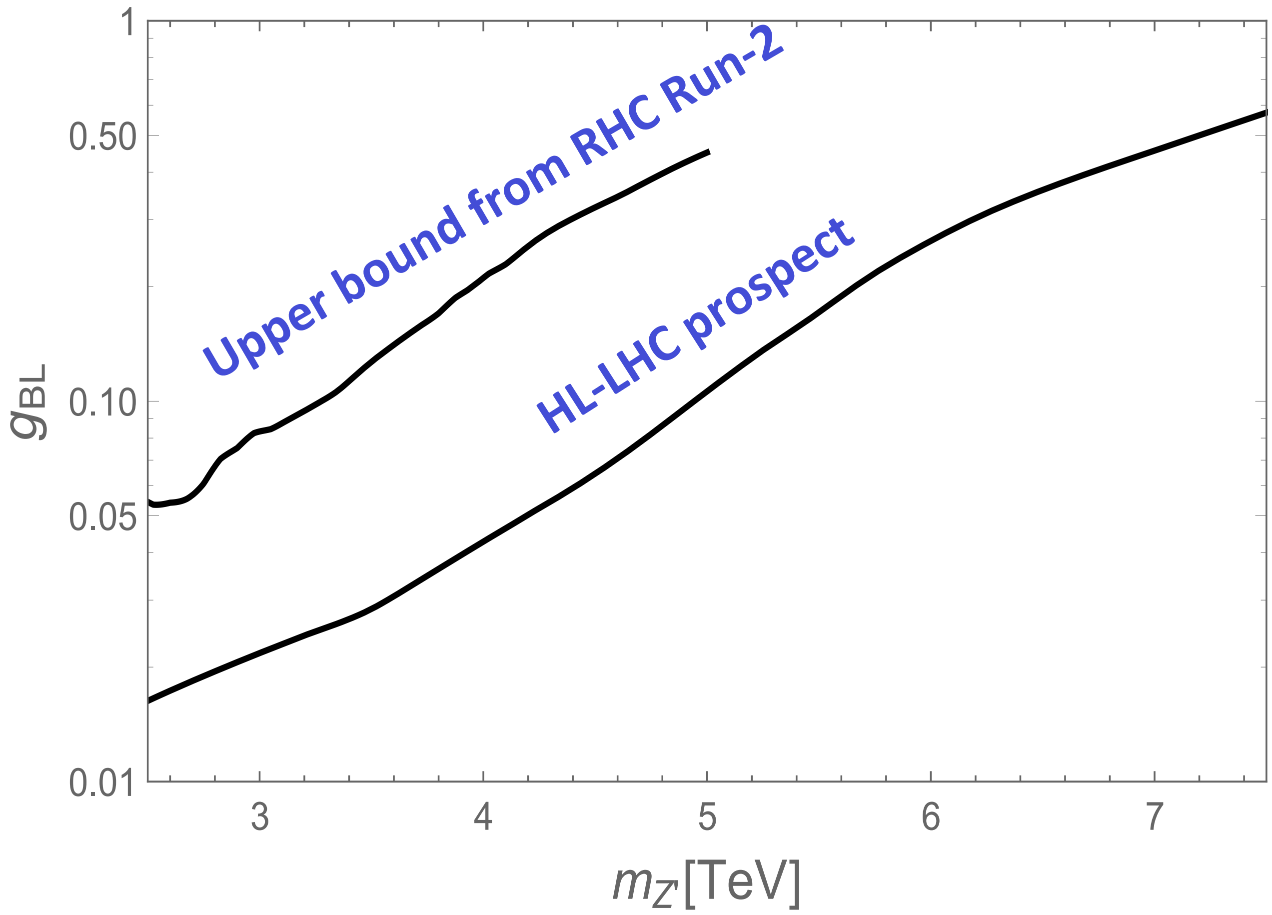
Future prospect on Z' boson bound from HL-LHC

ATLAS TDR



Interpretations of the LHC Run-2 constraints & HL-LHC prospects for the B-L Z' boson





N.O & Okada, PRD 95 (2017) 035025; Das, NO, Okada & Raut, arXiv: 1812.11931

Since LHC constraints are very severe, we set the B-L gauge coupling <<1

(2) Higgs portal

Higgs potential:

$$V(|H|,|\varphi|) = \lambda \left(|\varphi|^2 - \frac{v_{BL}^2}{2} \right)^2 + \lambda_H \left(|H|^2 - \frac{v_{SM}^2}{2} \right)^2 + \lambda' \left(|H|^2 - \frac{v_{SM}^2}{2} \right) \left(|\varphi|^2 - \frac{v_{BL}^2}{2} \right)$$

Mass eigenstates:

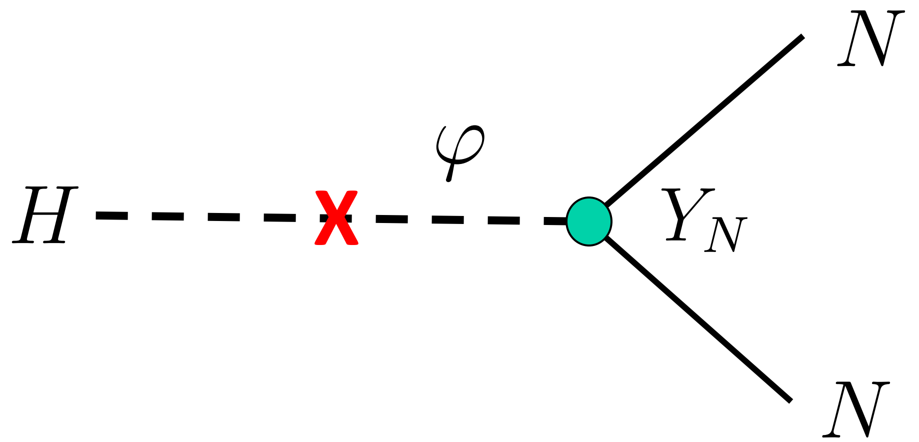
$$\mathcal{L} \supset -\frac{1}{2} \begin{bmatrix} \phi_{SM} & \phi_{BL} \end{bmatrix} \begin{bmatrix} m_H^2 & \lambda' v_{BL} v_{SM} \\ \lambda' v_{BL} v_{SM} & m_\varphi^2 \end{bmatrix} \begin{bmatrix} \phi_{SM} \\ \phi_{BL} \end{bmatrix}$$

$$\begin{bmatrix} \phi_{SM} \\ \phi_{BL} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} h \\ \phi \end{bmatrix}$$

$$2 v_{BL} v_{SM} \lambda' = (m_H^2 - m_\varphi^2) \tan 2\theta,$$
$$m_h^2 = m_H^2 - \left(m_\varphi^2 - m_H^2 \right) \frac{\sin^2\theta}{1-2\sin^2\theta},$$
$$m_\phi^2 = m_\varphi^2 + \left(m_\varphi^2 - m_H^2 \right) \frac{\sin^2\theta}{1-2\sin^2\theta} .$$

(i) Higgs portal production of Heavy Majorana Neutrinos

Since the Higgs boson properties measured at LHC are consistent with the SM predictions, we assume the mixing between Higgses is small < 0.1



Benchmark

$$m_N = 20\,\mathrm{GeV},\ m_h = 125\,\mathrm{GeV},\ m_\phi = 70\,\mathrm{GeV}.$$

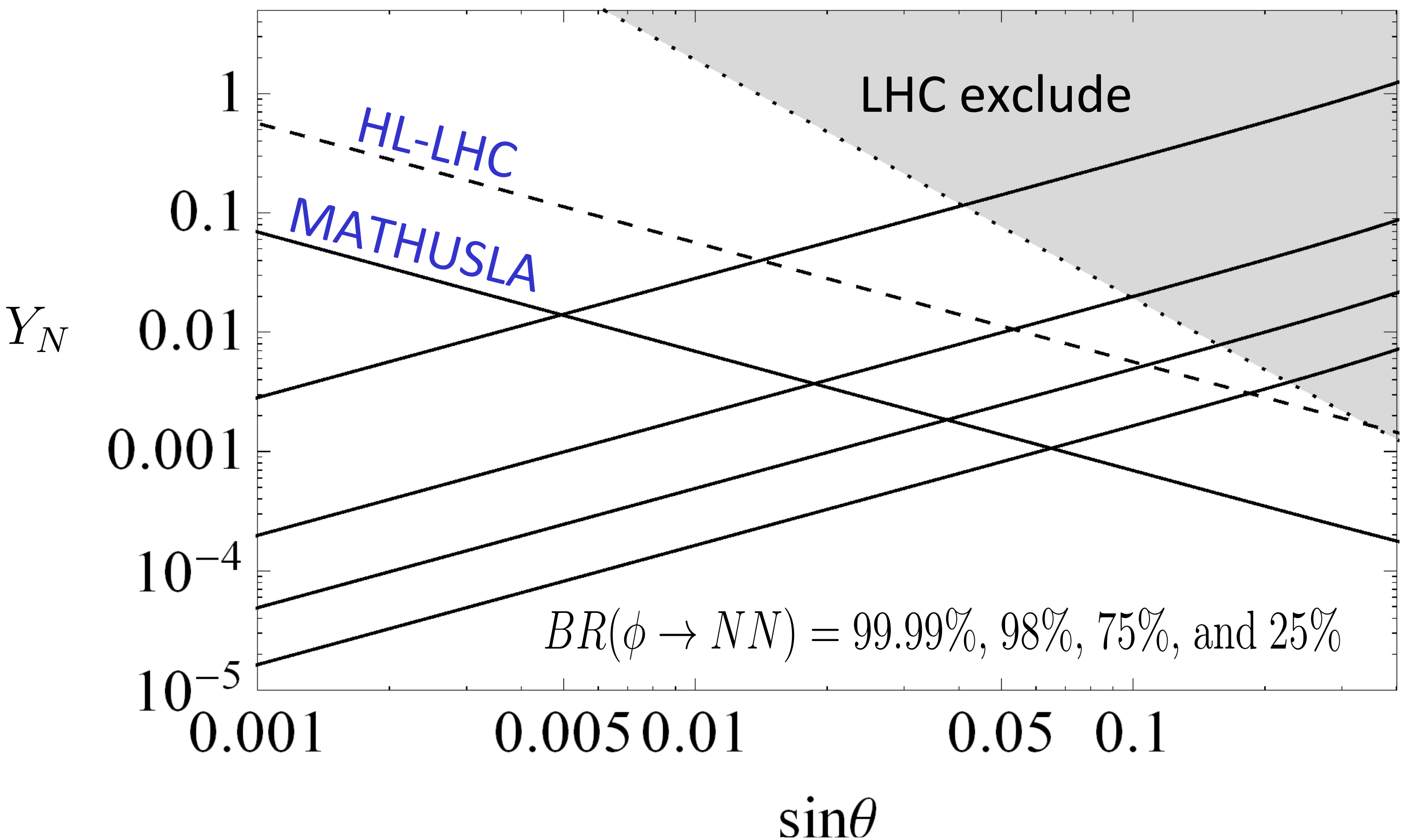
Two free parameters: $\begin{cases} \sin\theta \\ Y_N \end{cases}$

Assuming the N's lifetime to yield the best reach

$$\mathrm{Br}(h \to NN) \simeq 4.3 \times 10^{-4}$$ (HL-LHC)

$$\mathrm{Br}(h \to NN) \simeq 7.0 \times 10^{-6}$$ (MATHUSLA)

Jana, NO & Raut,
PRD 98 (2018) 035023



Is the N's lifetime is adjustable?

Seesaw formula: $m_\nu \simeq m_D (M_N)^{-1} m_D^T.$

General parameterization (Casas-Ibarra):

$$m_D = U^*_{\rm MNS}\sqrt{D_\nu}\, O \sqrt{M_N},$$

where
$$\sqrt{M_N} \equiv {\rm diag}(\sqrt{m_{N^1}}, \sqrt{m_{N^2}}, \sqrt{m_{N^3}})$$
$$\sqrt{D_\nu} \equiv {\rm diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$$

O: general orthogonal matrix

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu \overline{\ell_\alpha}\gamma^\mu P_L \left(\mathcal{N}_{\alpha i}\nu^i_m + \mathcal{R}_{\alpha i} N^i_m\right) + {\rm h.c.},$$

$$\mathcal{L}_{NC} = -\frac{g}{2\cos\theta_{\rm W}} Z_\mu \Big[\overline{\nu^i_m}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{N})_{ij}\nu^j_m + \overline{N^i_m}\gamma^\mu P_L(\mathcal{R}^\dagger\mathcal{R})_{ij} N^j_m + \left\{\overline{\nu^i_m}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{R})_{ij} N^j_m + {\rm H.c.}\right\}\Big], \qquad \mathcal{N} \simeq U_{\rm MNS}$$

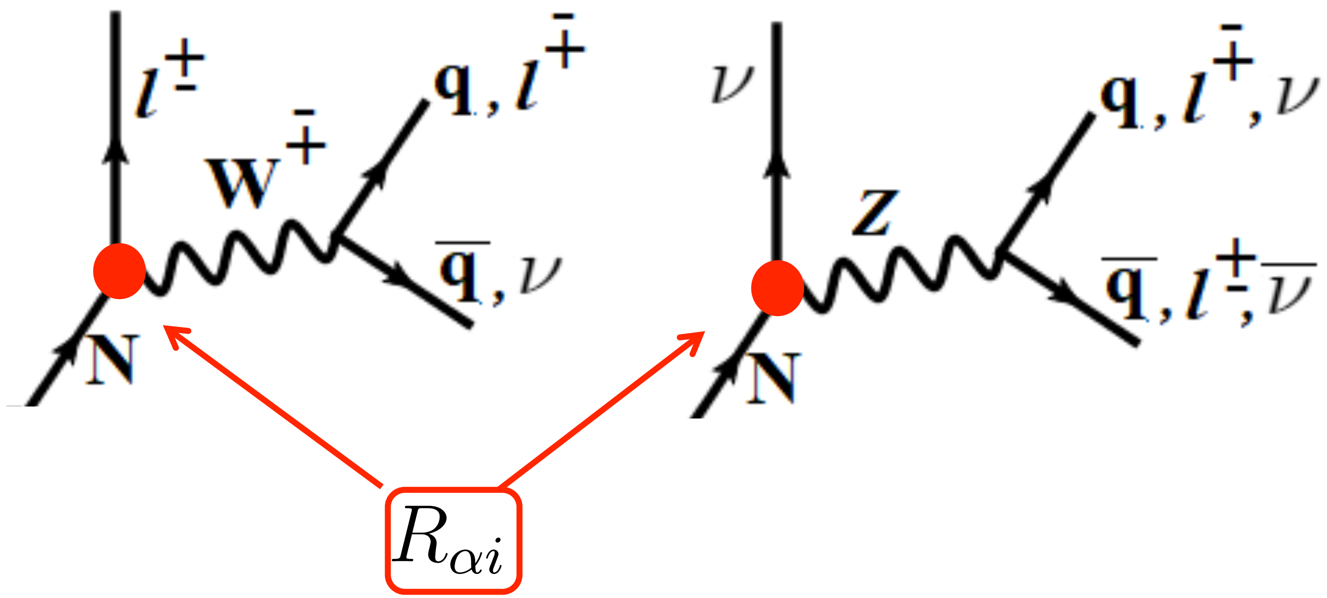
Das & NO, PLB 774 (2017) 32

The effective couplings with W/Z are controlled by

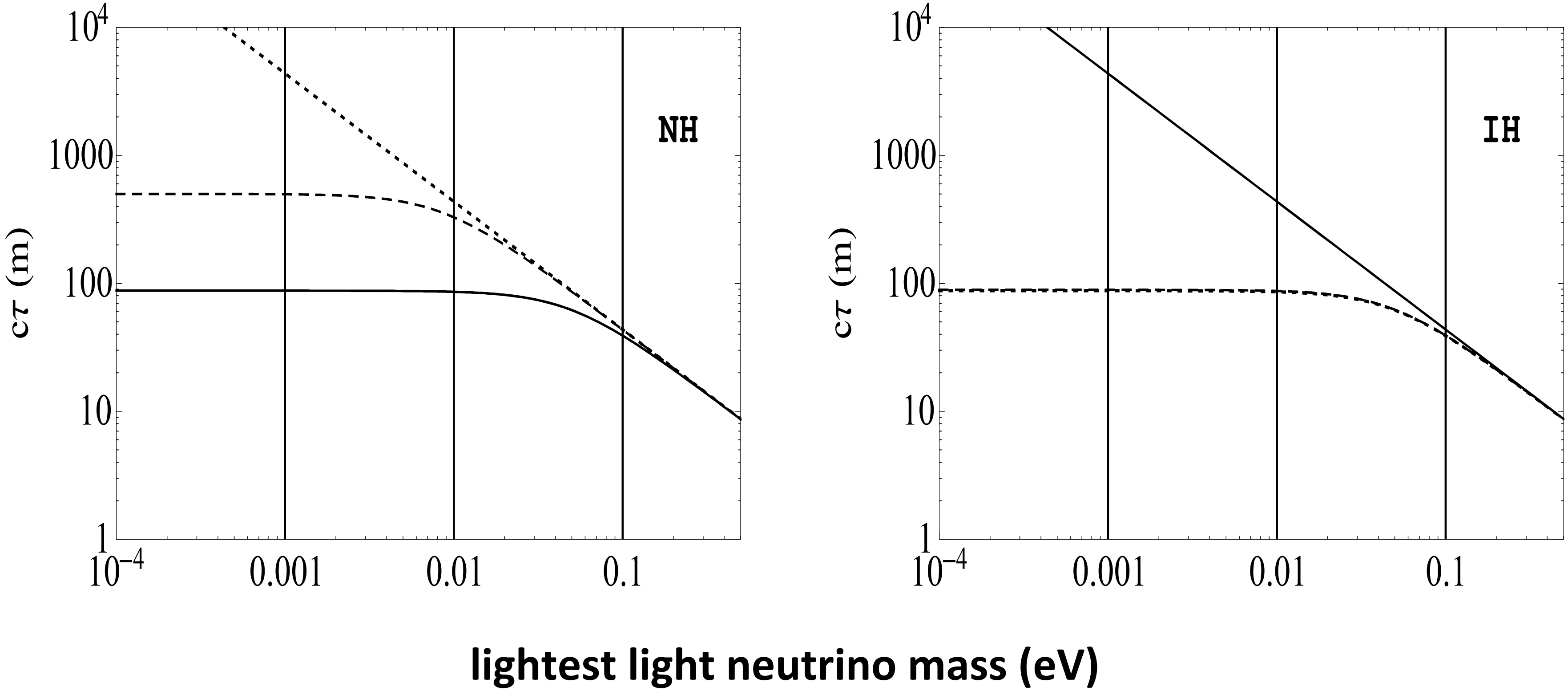
$$R_{\alpha i} = m_D (M_N)^{-1} = U^*_{\rm MNS} \sqrt{D_\nu}\, O(\sqrt{M_N})^{-1}.$$

Employing the neutrino oscillation data, we can calculate the N's lifetime.

Example) degenerate Ns (20 GeV) and O= Id



Example) degenerate Ns (20 GeV) and O= Id



*Lightest light neutrino mass → 0, one N_R becomes a DM candidate (NO & Seto, PRD 89 (2010) 023507)

General case: *O* is a general orthogonal matrix

Ex) 2 by 2 case

$$\mathcal{O} = \begin{bmatrix} \cos(\alpha + i\beta) & \sin(\alpha + i\beta) \\ -\sin(\alpha + i\beta) & \cos(\alpha + i\beta) \end{bmatrix}$$

For $\beta \gg 1$, $\mathcal{O} \propto e^{\beta}$

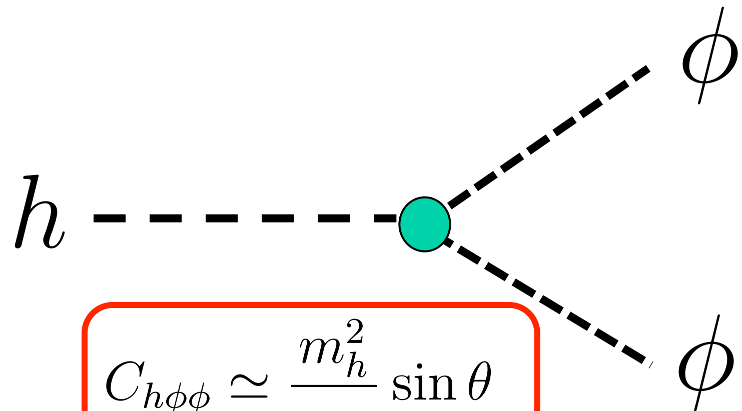
Choosing a suitable beta value, we can adjust the N's lifetime

(ii) Higgs portal production of BL-like Higgs bosons

Benchmark

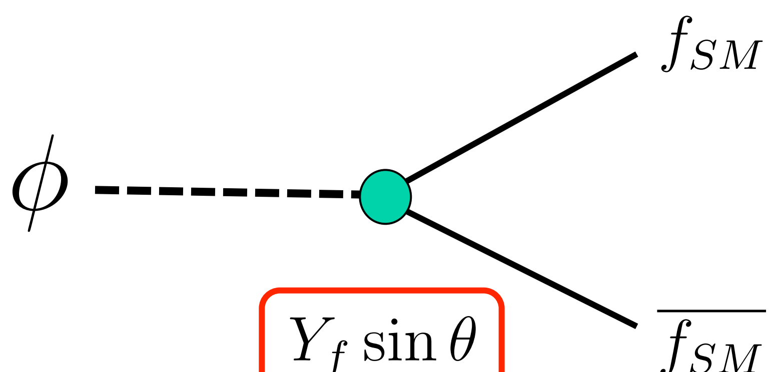
$$m_h = 125\,\mathrm{GeV},\; m_N \gg m_\phi$$

Production from rare h decay:



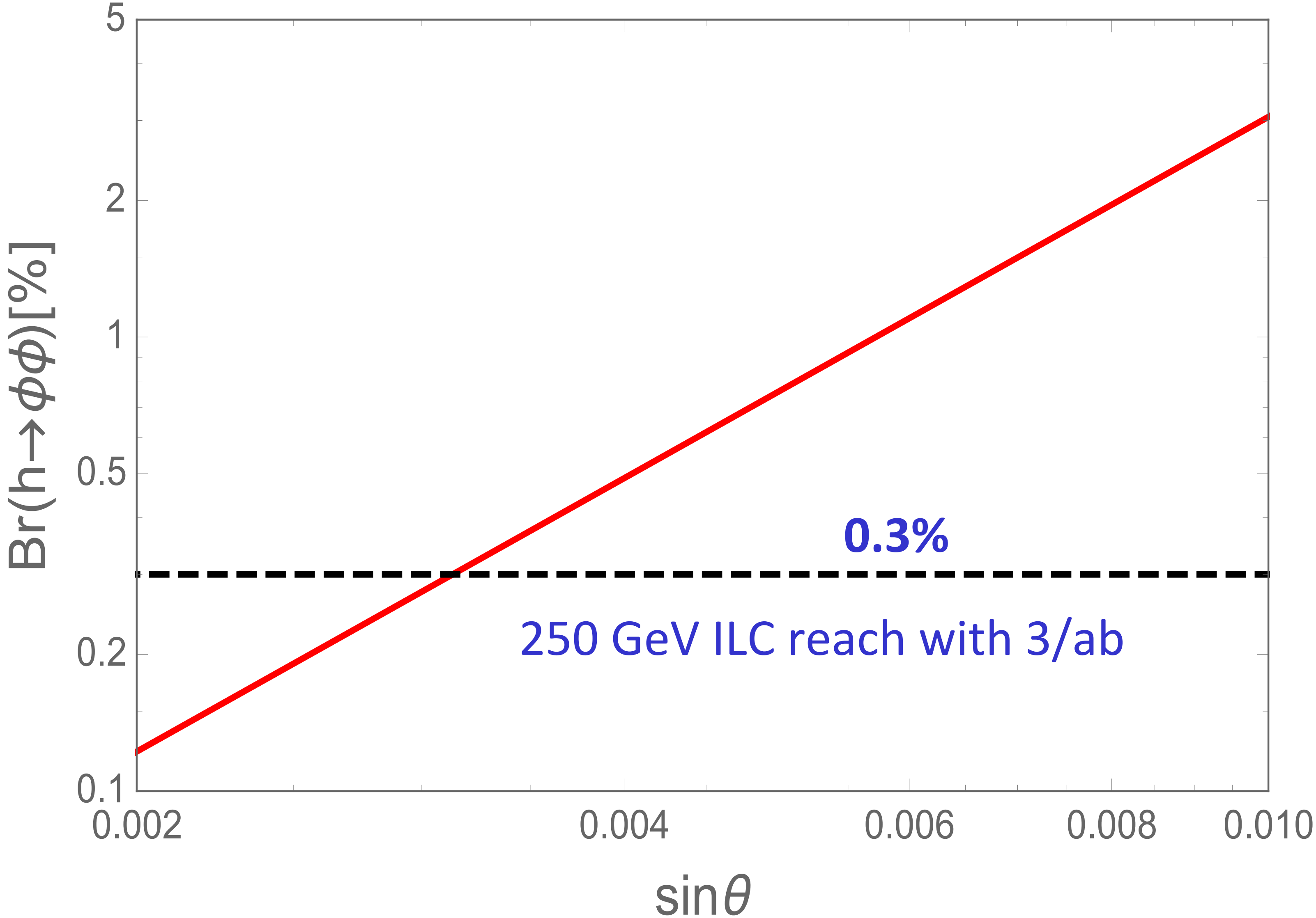
$$C_{h\phi\phi} \simeq \frac{m_h^2}{v_{BL}} \sin\theta$$

Decay into SM fermions:

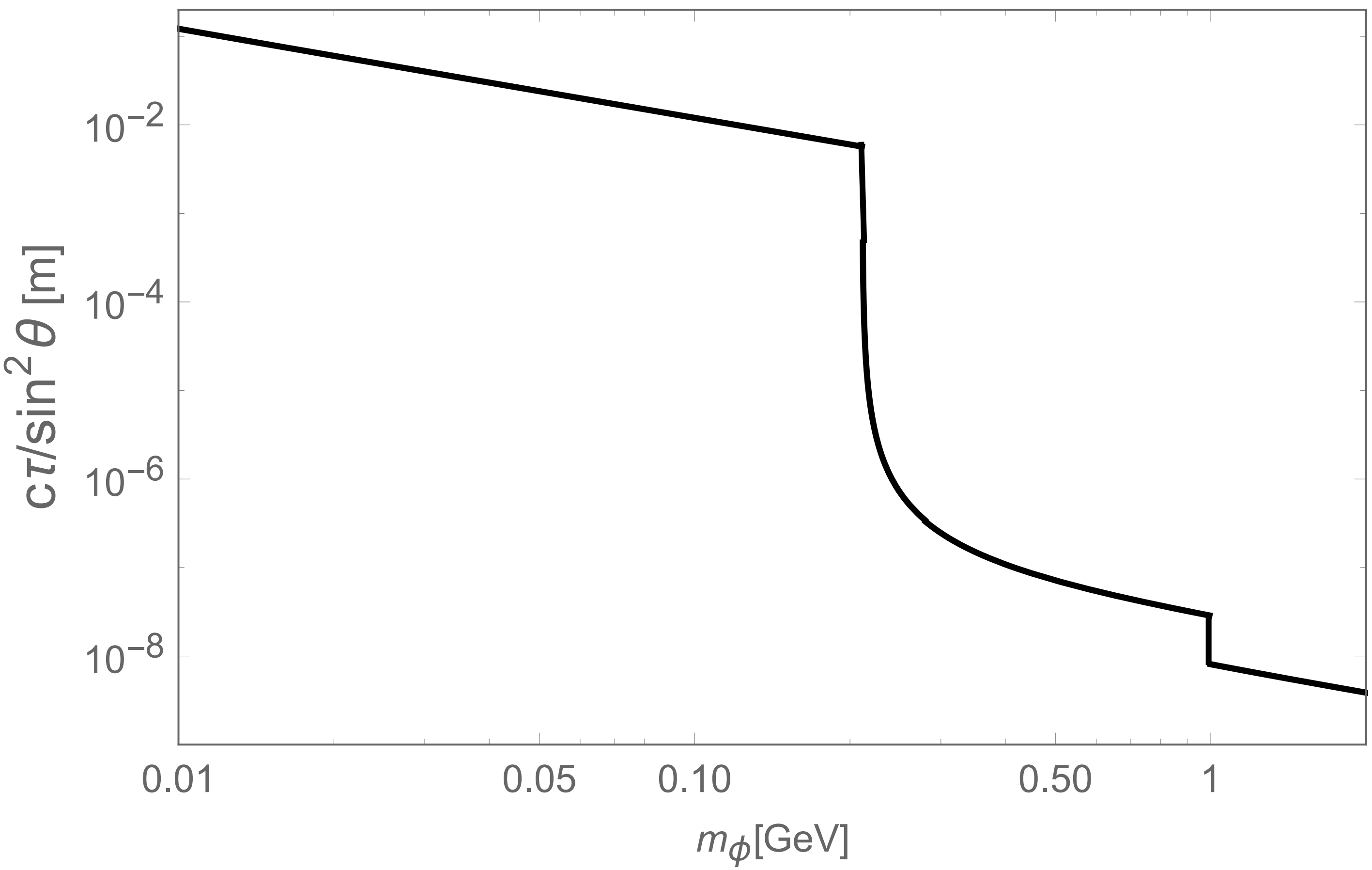


$$Y_f \sin\theta$$

Higgs Branch ($v_{BL} = 100\,\mathrm{GeV}$)



Lifetime of BL-like Higgs



Sample) $m_\phi = 10\,\mathrm{MeV}$ $\quad c\tau \sim 10\,\mathrm{km}$

$\sin\theta = 0.0034$ $\quad \mathrm{Br}(h \to \phi\phi) \simeq 0.35\,\%$

Any motivation for such a light scalar?

$$m_\phi = 10\,\text{MeV}$$
$$v_{BL} = 100\,\text{GeV}$$

→ Extremely small self-coupling

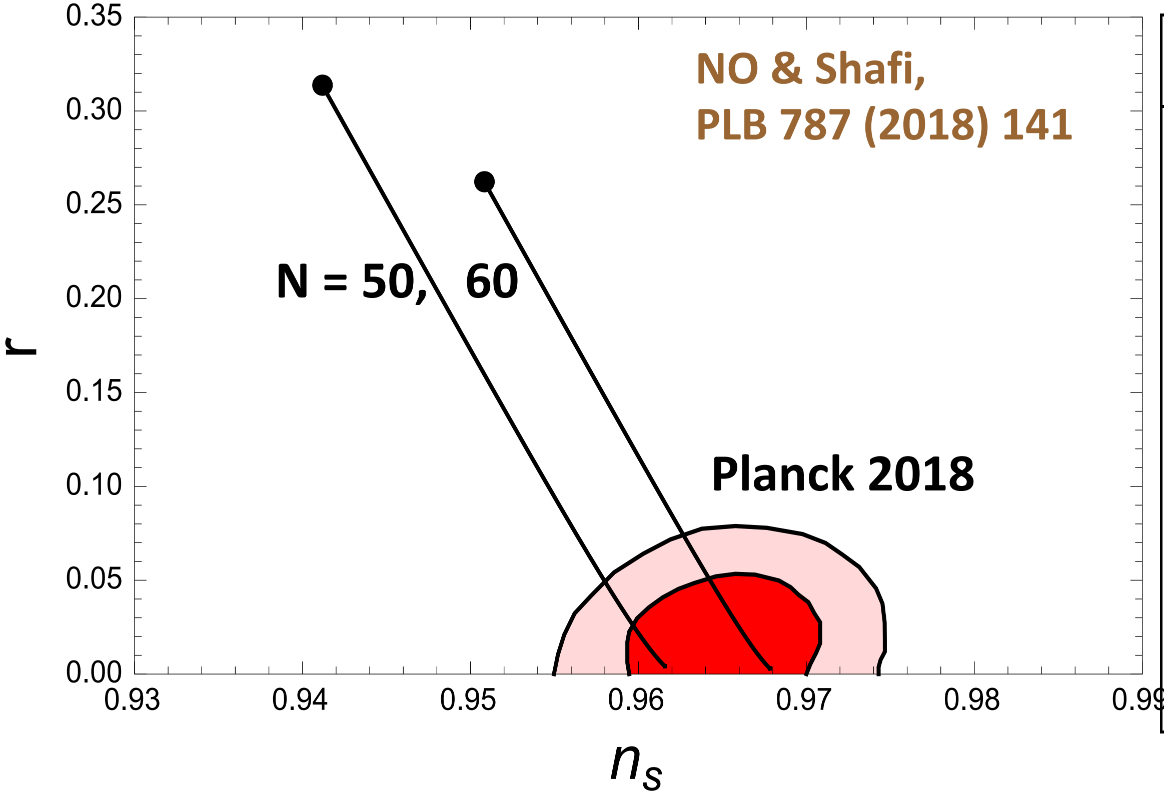
$$\lambda \simeq 10^{-9}$$

This scalar can be infalton in Non-Minimal Quartic Inflation

$$\mathcal{S}_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}f(\phi)\mathcal{R} + \frac{1}{2}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - V_J(\phi)\right]$$

$$f(\phi) = (1+\xi\phi^2)$$

$$V_J = \frac{1}{4}\lambda\phi^4$$



N = 60

ξ	r	λ
0	0.262	1.43×10^{-13}
0.00333	0.1	3.79×10^{-13}
0.0689	0.01	6.69×10^{-12}
1	0.00346	4.62×10^{-10}
10	0.00301	4.01×10^{-8}
100	0.00297	3.95×10^{-6}
1000	0.00296	3.94×10^{-4}

$$\lambda \simeq 10^{-9} \to \xi \sim \mathcal{O}(1)$$

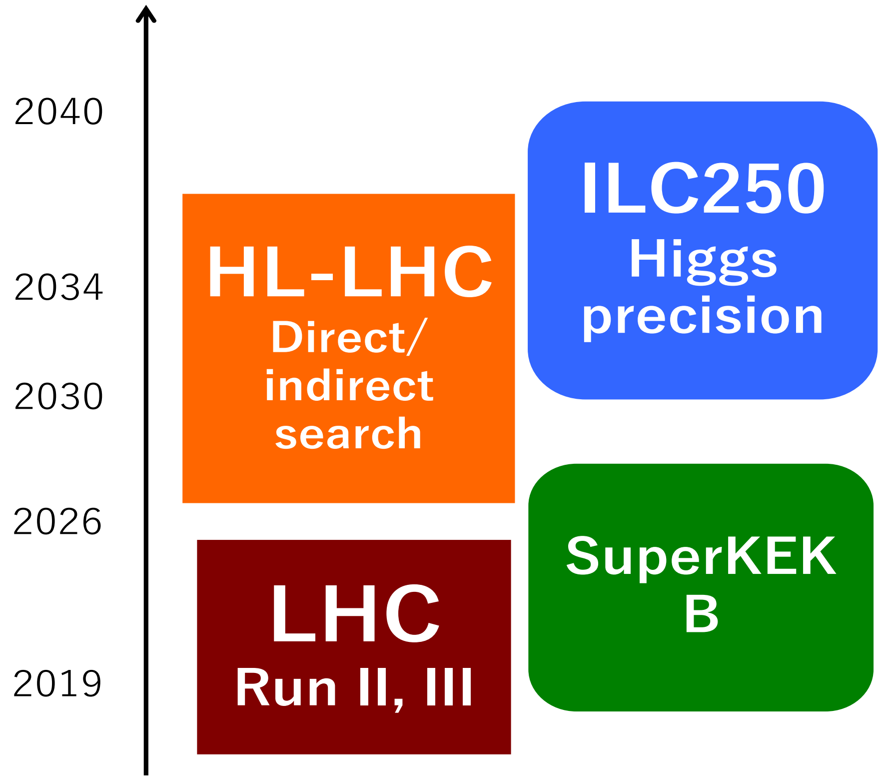
Inflationary predictions are consistent with Planck 2018 data
Non-minimal parameter is O(1) → no unitarity issue

Inflaton production from Higgs decay

Summary

- New Physics sector may be the SM gauge singlet and their couplings with the SM sector may be very weak
- In such a scenario, the Higgs boson is most likely the portal to this "dark sector"
- Promising signature would be a displaced vertex of a long-lived particle produced from the Higgs decay.

- Long-lived particle can be discovered at future collider experiments



Near/Far future?

To discover a long-lived particle,

We have to be long-lived!

Thank you

for your attention!