Gauged U(1) extended Standard Model and long-lived new particle searches

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Quarks-2020 Online Workshops-2021, June 07, 2021

Problems of the Standard Model

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

What is missing?

- Neutrino masses and flavor mixings
- Dark Matter candidate
- Origin of Electroweak symmetry breaking
- Inflaton to drive Inflation
- …….

New Physics must supplement the missing pieces

Status of New Physics (direct) searches

Something must be there, but no indication of New Physics in the current LHC data

Indication?

New particle(s) may be singlet under the SM gauge group & very weakly coupled with the SM particles

If so, new particle(s) are expected to be long-lived

In this talk, I will discuss a new physics model with long-lived particle(s) and discuss the prospect of discovering such particle(s) in the future

How New Particles communicate with the SM sector?

New force?

since new particles are SM singlets

We focus on gauged U(1) extended SM

Well-known example: gauged U(1) B-L extended SM

- B-L (baryon minus lepton number) is in the SM as anomaly-free global symmetry.
- Particle physics history may suggest it natural to gauge it.

Before the construction of the SM,
isospin SU(2) & hyper-charge U(1) were global symmetry,
which are promoted to the gauge symmetry in the SM

Minimal gauged B-L extension of the SM

Marshak & Mohapatra, PLB 91 (1980) 222;Wetterich, NPB 187 (1981) 343
Masiero, Nieves and Yanagida, PLB 116 (1982) 11 + Others

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

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

3 right-handed neutrinos (RHNs)

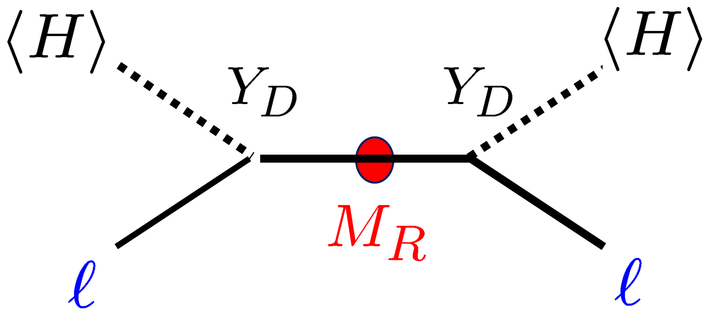
B-L Higgs field for the B-L breaking

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



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

Generalization of the minimal B-L model to the minimal U(1)x

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

3 RHNs

U(1)x Higgs

Appelquist, Dobrescu & Hopper, 2003; Oda, NO & Takahashi, 2015; Das, Oda, NO & Takahashi, 2016

- U(1)x charge: $Q_X = Q_Y x_H + Q_{B-L}$ (xH=0 is the B-L model)
- Free from gauge & mixed gauge-gravitational anomalies
- Seesaw Mechanism is automatically implemented

In gauged U(1) extended SM,

(i) Right-handed neutrino (heavy neutrino)
(ii) U(1) gauge boson (Z')
(iii) U(1) Higgs boson

can be long-lived, depending on the model parameter choice.

Search for Long-Lived particles (LLPs) at future experiments

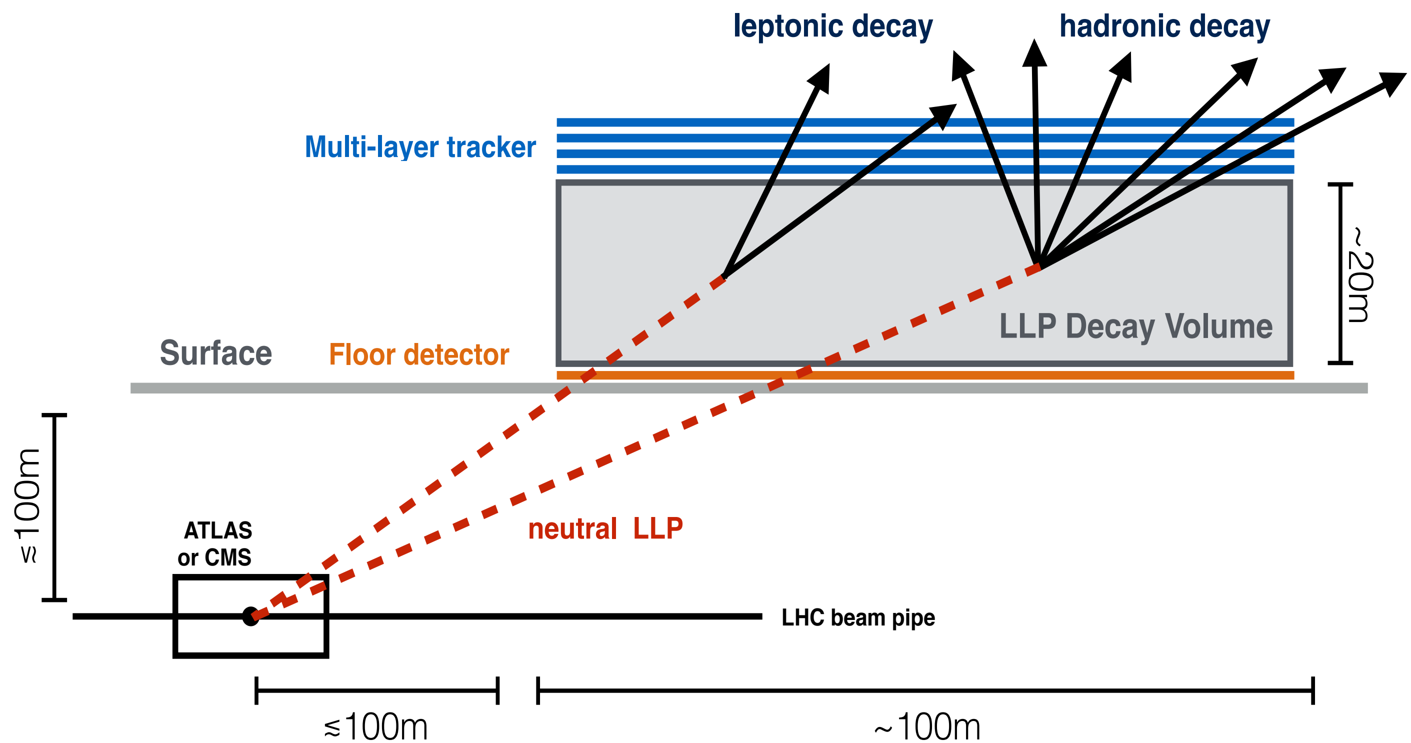
Examples) MTHUSLA & FASER

Recent proposal for a dedicated LLP search

MATHUSLA

arXiv: 1901.04040

$c\tau \gtrsim$ Detector size

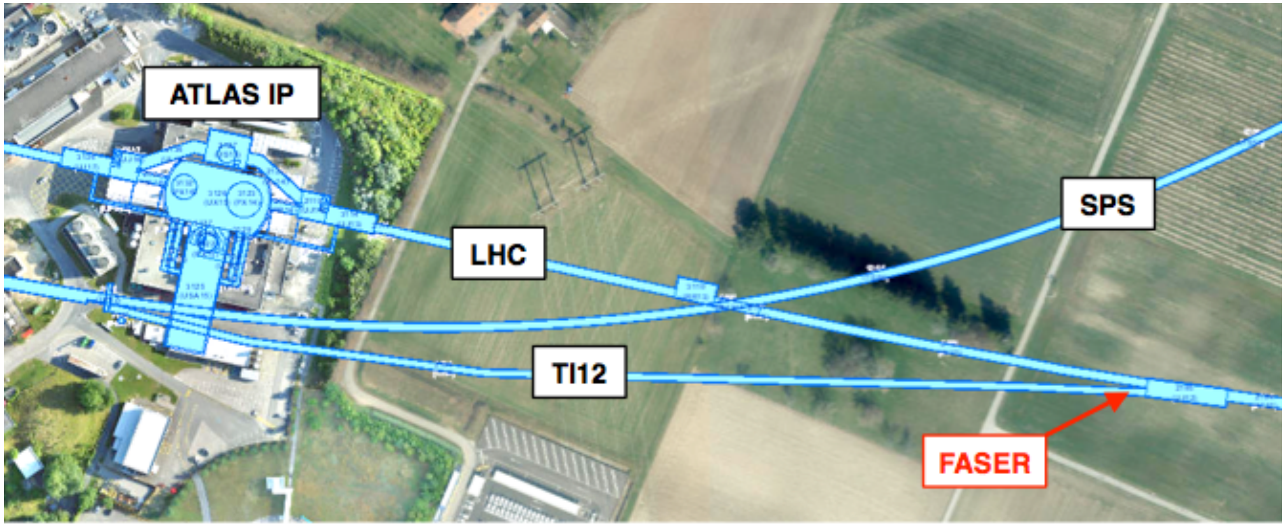


Almost SM background free

FASER

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



(i) Long-Lived right-handed neutrino (heavy neutrino)

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

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

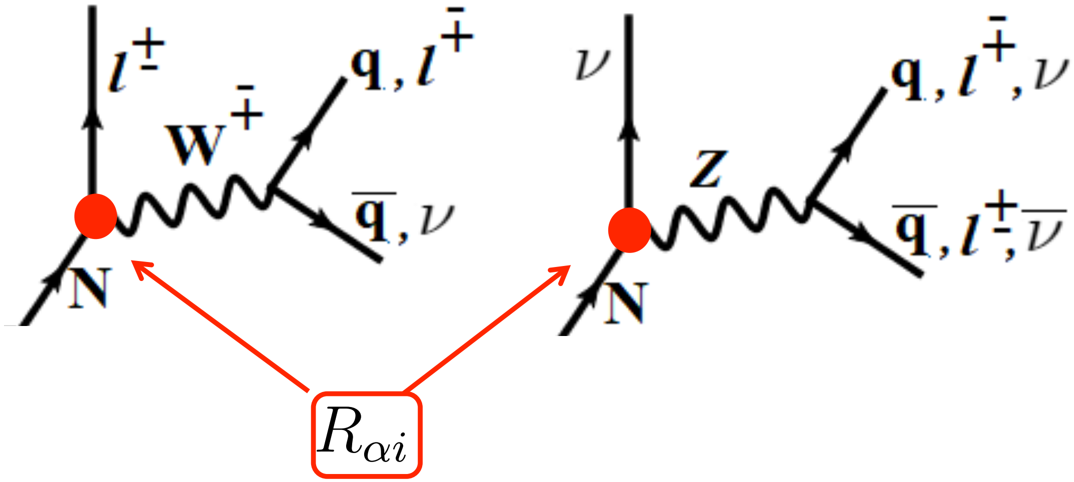
Das & NO, PLB 774 (2017) 32

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

The effective couplings with W/Z are controlled by

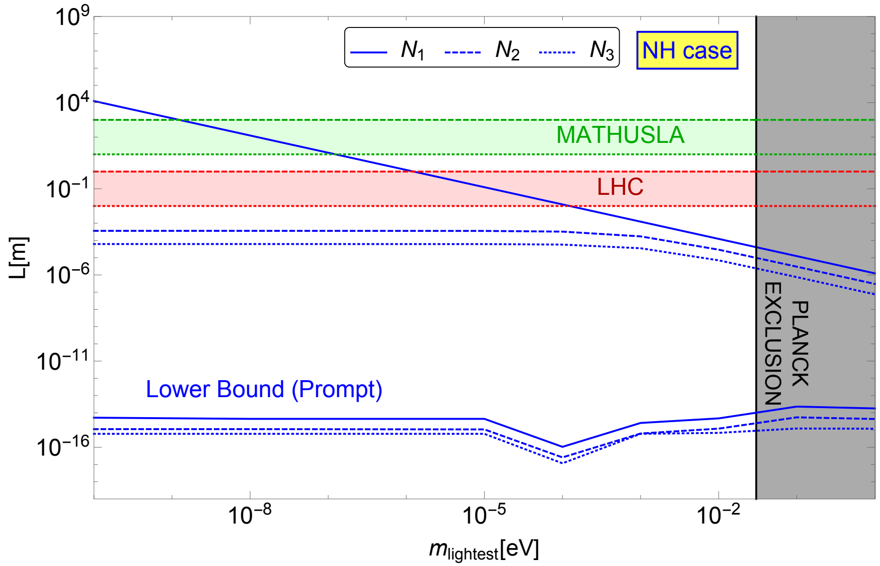
$$R_{\alpha i} = m_D (M_N)^{-1} = U^*_{\mathrm{MNS}} \sqrt{D_\nu}\, O(\sqrt{M_N})^{-1}.$$

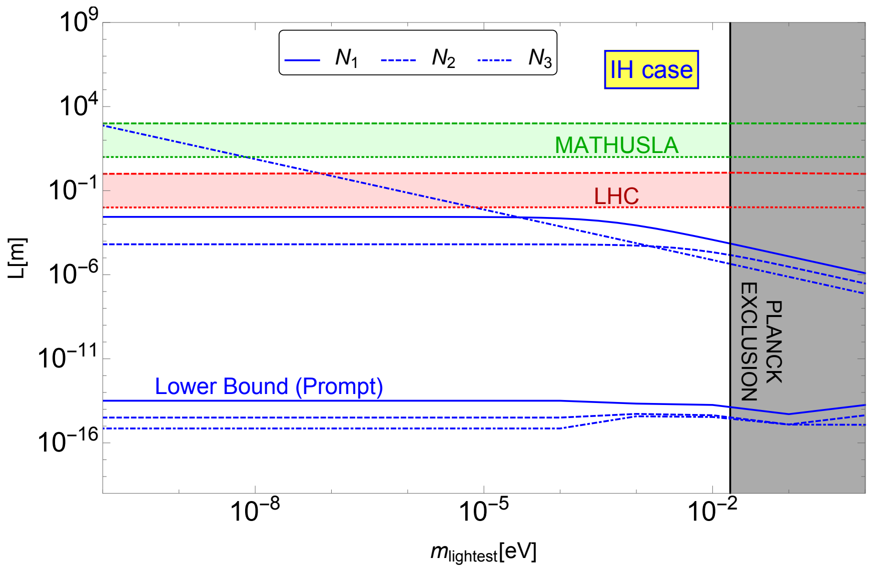
Employing the neutrino oscillation data, we can calculate the N's lifetime.



Parameter scan results (Das, Dev & NO, arXiv: 1906.04132; see also Jana, NO & Raut, arXiv: 1804.06828)

$$m_{N_1} = 500\,\mathrm{GeV}, m_{N_2} = 1\,\mathrm{TeV}\ \&\ m_{N_3} = 2\,\mathrm{TeV}$$





$$L^{\mathrm{NH}}_{\mathrm{max}} \simeq 0.62 \left(\frac{0.001\,\mathrm{eV}}{m_{\mathrm{lighest}}}\right)\left(\frac{1\,\mathrm{TeV}}{m_{N_1}}\right) \quad [\mathrm{mm}]$$

$$L^{\mathrm{IH}}_{\mathrm{max}} \simeq 0.15 \left(\frac{0.001\,\mathrm{eV}}{m_{\mathrm{lighest}}}\right)\left(\frac{1\,\mathrm{TeV}}{m_{N_3}}\right) \quad [\mathrm{mm}]$$

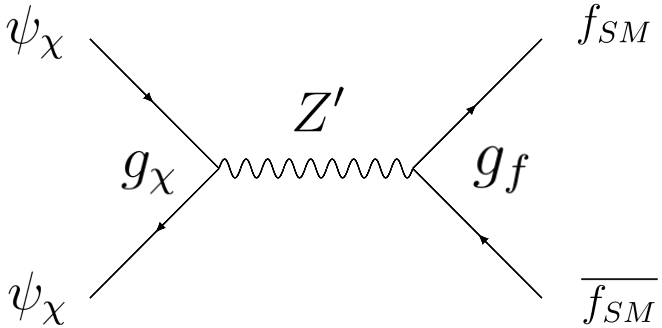
- ➢ Neutrino oscillation data are reproduced
- ➢ Correlations with the lightest neutrino mass eigenvalue
- ➢ N production at LHC through Z’ production

(ii) Long-Lived light Z' boson

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

- Although the minimal U(1)x 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 $m_\chi \gg m_{Z'}$

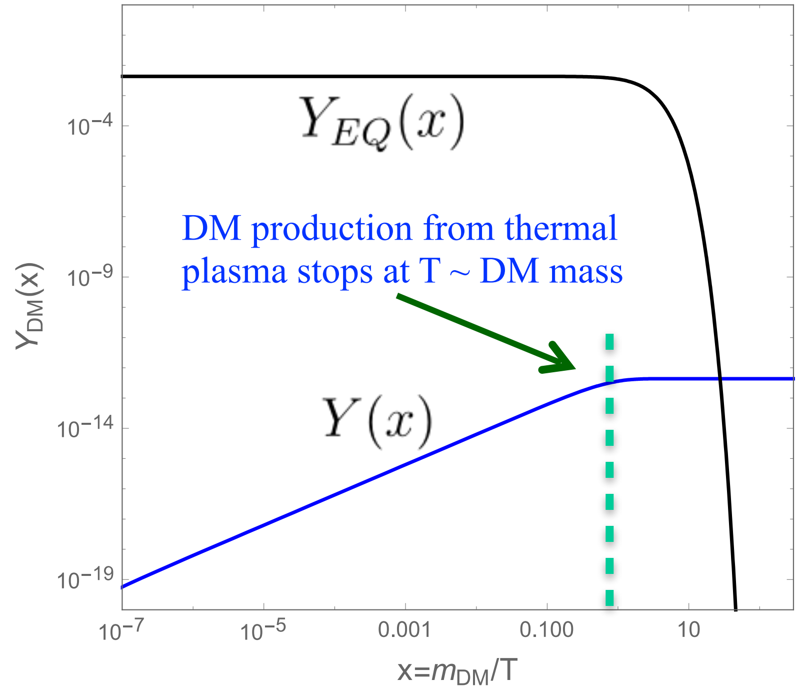
Complementarity between Z' boson searches at FASER & Z'-portal DM scenario

- 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

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

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



Simple Freeze-In DM model

The minimal B-L model + Dirac Fermion Dark Matter

(Mohapatra & NO, 2019)

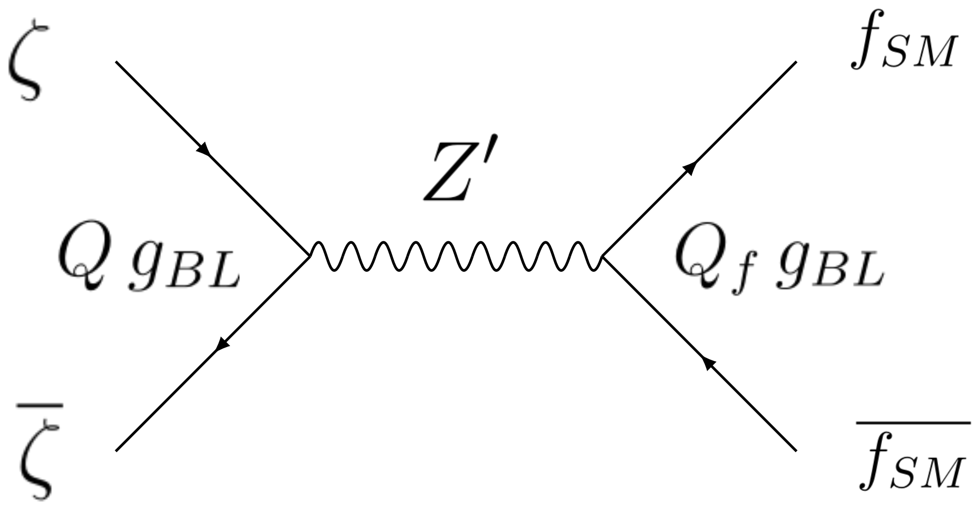
- A simple way to supplement the B-L model with a DM candidate: we introduce an SM singlet Dirac fermion

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

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

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

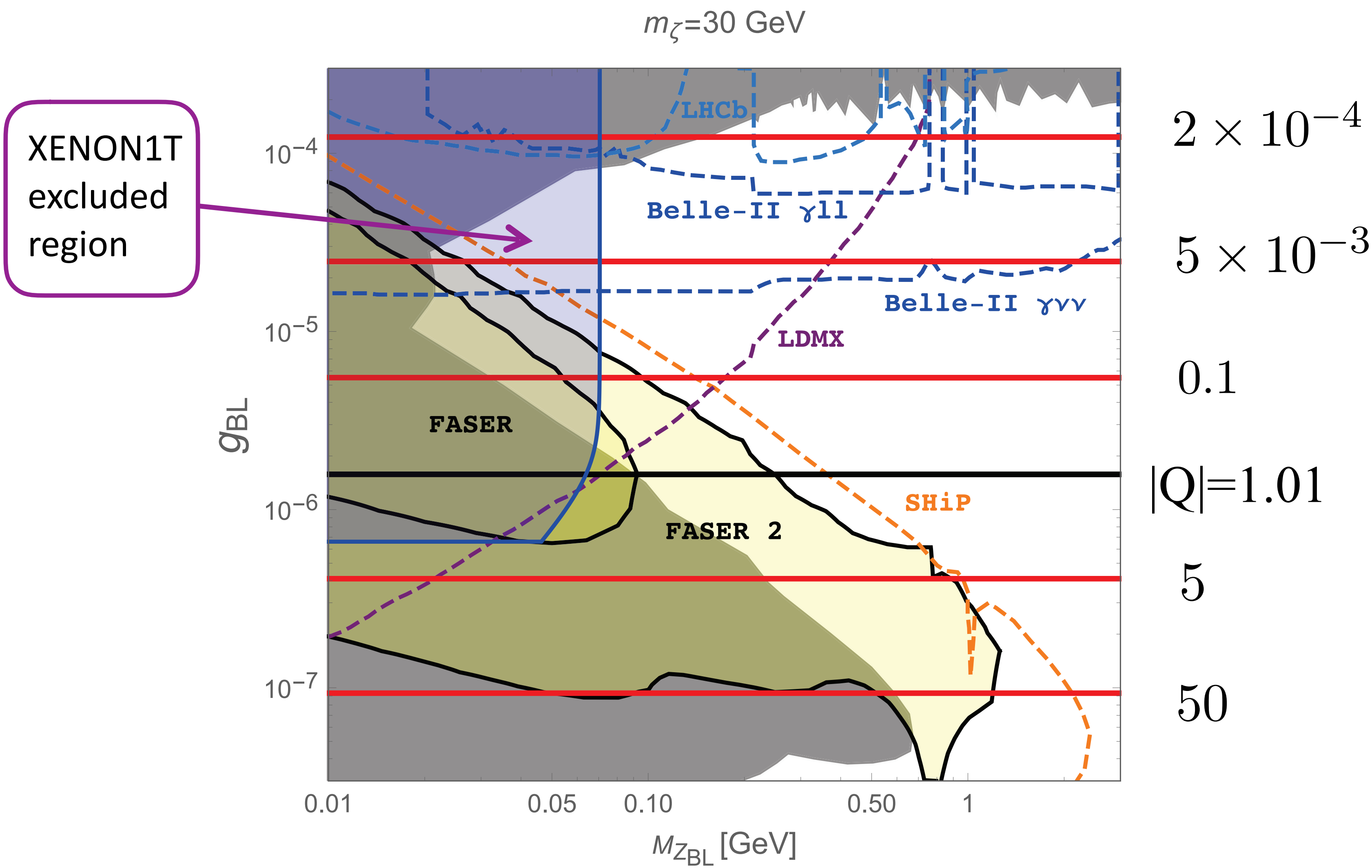
DM particle communicates with the SM particles through the B-L gauge boson Z'



By solving the Boltzmann equation, we find

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

Testing the scenario by Lifetime Frontier Experiments



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

(iii) Long-Lived U(1) Higgs as inflaton

Classically Conformal U(1)x extended SM

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

3 RHNs

U(1)x Higgs

Iso, NO &Orikasa, arXiv: 0902.4050

Oda, NO & Takahashi, arXiv: 1504.06291

Higgs sector with classical conformal invariance

Iso, NO & Orikasa, arXiv: 0902.4050
Oda, NO & Takahashi, arXiv: 1504.06291

$$V = \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 - \lambda_{\rm mix} (H^\dagger H)(\Phi^\dagger \Phi)$$

- No mass term
- We set $\lambda_{H,\Phi,{\rm mix}} > 0$
- No symmetry breaking at the tree-level

Assuming a small mixing quartic coupling, the symmetry breaking occurs in the following way………

Symmetry Breaking

1st: Radiative U(1) breaking by Coleman-Weinberg mechanism

$$V(\phi) = \frac{\lambda_\Phi}{4}\phi^4 + \frac{12 g_X^4}{16\pi^2}\phi^4 \left(\ln\left[\frac{\phi^2}{v_X^2}\right] - \frac{25}{6} \right) \qquad \phi = \sqrt{2}\mathrm{Re}\left[\Phi\right]$$

$$\langle \Phi \rangle = \frac{v_X}{\sqrt{2}}$$

2nd: Electroweak symmetry breaking is triggered

$$V \supset -\lambda_{\rm mix}\left(\Phi^\dagger \Phi\right)\left(H^\dagger H\right) + \lambda_H \left(H^\dagger H\right)^2$$
$$\to -\lambda_{\rm mix}\langle \Phi^\dagger \Phi \rangle \left(H^\dagger H\right) + \lambda_H \left(H^\dagger H\right)^2$$

Haba, Kitazawa & NO, hep-ph/0504279

Iso, NO &Orikasa, arXiv: 0902.4050

Negative mass squared generated!

Relations among parameters

CW mechanism:

$$\lambda_\Phi = \frac{11}{\pi^2} g_X^4$$

$$m_\phi = \sqrt{\frac{3}{2\pi^2}}\, g_X\, m_{Z'} = \sqrt{\frac{6}{\pi^2}}\, g_X^2\, v_X$$

Higgs mass relations:

$$m_h^2 = \lambda_{\rm mix} v_X^2 = 2\lambda_H v_h^2$$

Mixing between Higgs bosons:

$$\mathcal{L} \supset -\frac{1}{2} \begin{bmatrix} h & \phi \end{bmatrix} \begin{bmatrix} m_h^2 & \lambda_{\rm mix} v_X v_h \\ \lambda_{\rm mix} v_X v_h & m_\phi^2 \end{bmatrix} \begin{bmatrix} h \\ \phi \end{bmatrix}$$

$$\theta \simeq \frac{v_h}{v_X}$$

Fixing m_h=125 GeV & v_h=246 GeV, we have only 2 free parameters:

m_ϕ & θ

If $0.3 \lesssim m_\phi[\mathrm{GeV}] \lesssim 3$ & $10^{-5} \lesssim \theta \lesssim 10^{-3}$,

this U(1) Higgs boson will be searched by FASER!

Inflationary Universe

- Standard paradigm in modern cosmology
  - Solving Horizon & Flatness problems
  - Generating primordial density fluctuations

- Slow-roll inflation
  - A simple model
  - A scalar field (``inflaton'') with a flat potential
  - Constraints from CMB data (Planck 2018)

Non-minimal Quartic Inflation

simple & successful slow-roll inflation scenario

Action in Jordan Frame

See, for example,
NO, Rehman & Shafi, PRD 82 (2010) 04352

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

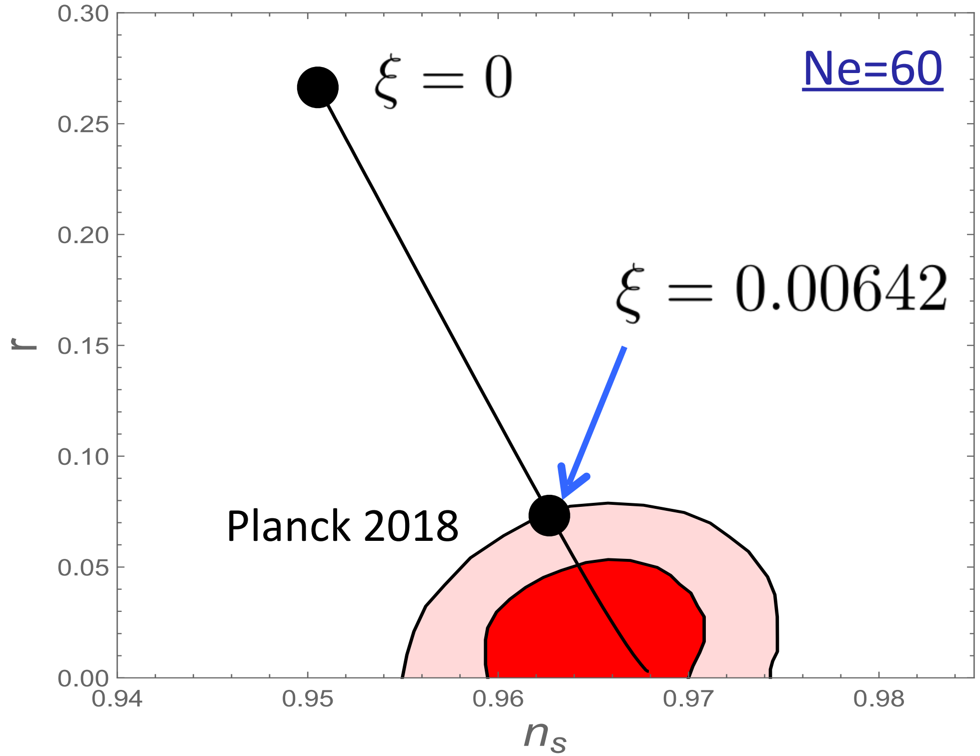
- Non-minimal gravitational coupling (Planck units)

$$f(\phi) = \left(1+\xi\phi^2\right)$$ with a real parameter $\xi > 0$,

- Quartic coupling dominates during inflation

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

Inflationary Predictions VS Planck 2018 results



$$\Delta^2_{\mathcal{R}} = 2.099 \times 10^{-9}$$

$$k_0 = 0.05 \text{ Mpc}^{-1}$$

Spectral index: n_s

Tensor-to-scalar ratio: r

Non-minimal quartic inflation

- Controlled by only one free parameter $\xi \leftrightarrow \lambda$
- Consistent with Planck 2018 data for $\xi \geq 0.00642$
- Any scalar with a quartic potential term can be "inflaton"

Search for Inflaton at FASER

Let us now identify the U(1)x Higgs as inflaton
in non-minimal Inflation

★ We have a connection among FASER search region,
Inflationary predictions & Z'-boson search at LHC

FASER Search: m_ϕ, θ

↕

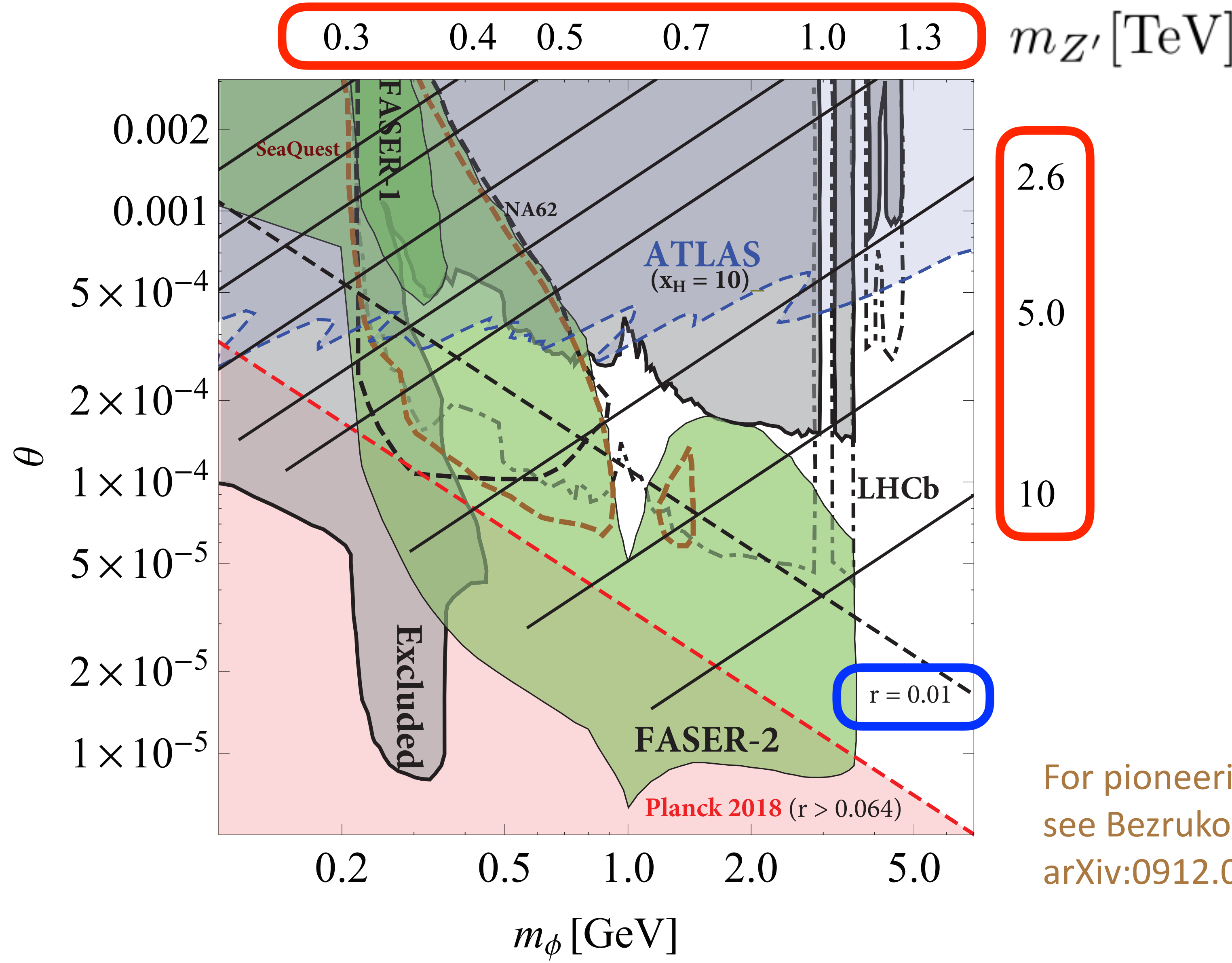
Inflationary predictions: $\xi(m_\phi, \theta)$

↕

Z' boson resonance search: $g_X(m_\phi, \theta), m_{Z'}(m_\phi, \theta)$

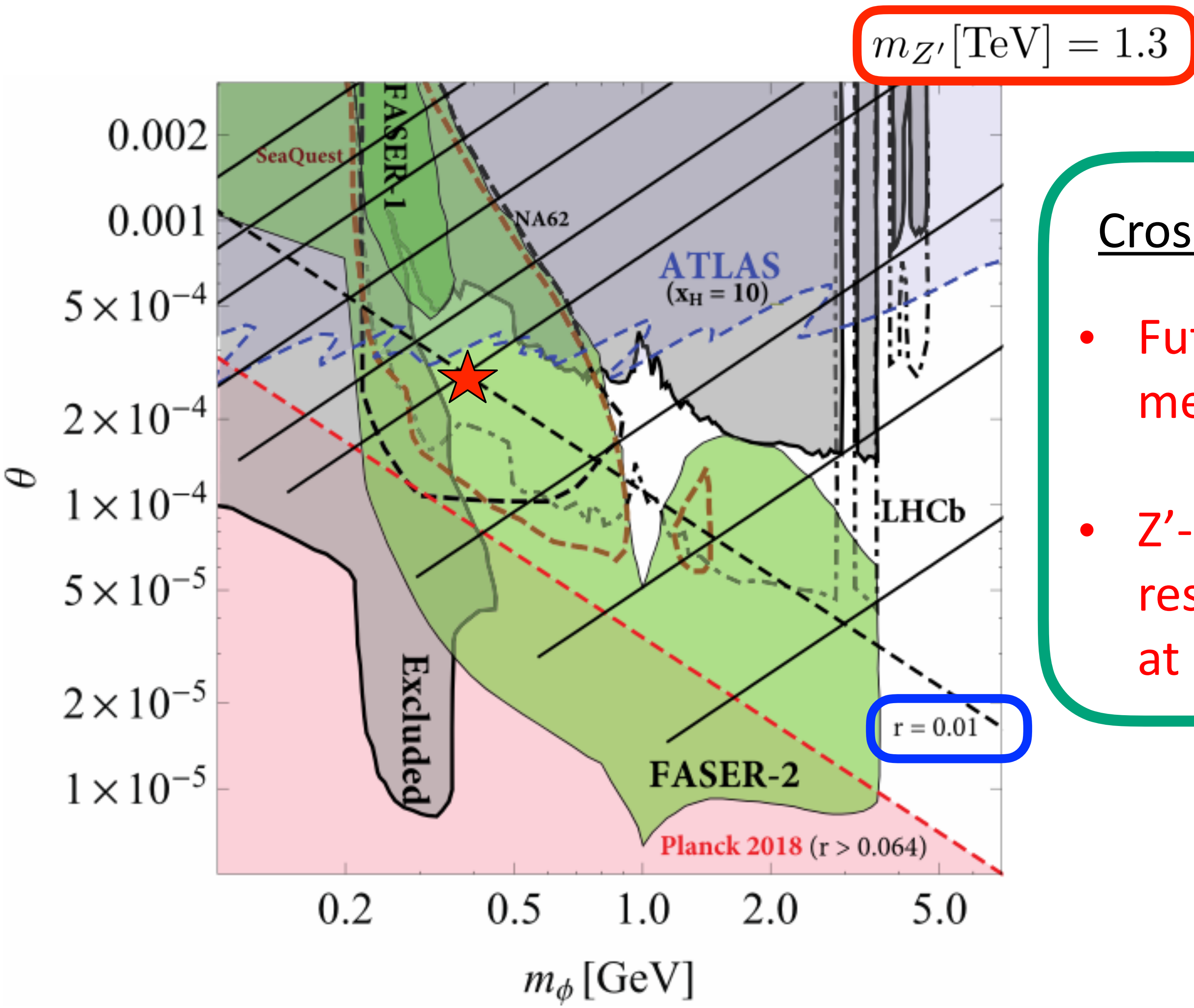
Hunting Inflaton at FASER

(NO & Raut, arXiv: 1910.09663)



For pioneering work, see Bezrukov & Gorbunov, arXiv:0912.0390

If a Dark Scalar (U(1) Higgs) was discovered by FASER,……



Cross checked by

- Future CMB measurements
- Z'-boson resonance search at HL-LHC

Summary

- The U(1) extended SM is a well-motivated New Physics model beyond the SM for neutrino mass regeneration, dark matter & inflation.
- Depending on the model parameter choice, heavy neutrino/Z’ boson/U(1) Higgs (inflaton) can be long-lived.
- They can be searched in the future experiments.