Hunting Inflaton at FASER

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We explore a possibility that an inflaton, which drives the cosmological inflation in the early Universe, can be detected by the recently approved FASER at the High-Luminosity LHC (HL-LHC). We consider nonminimal quartic inflation scenario in the minimal $U(1)_X$ extension of the Standard Model (SM) with the classical conformal invariance, where the inflaton is identified with the $U(1)_X$ Higgs field ($\phi$). By virtue of the classical conformal invariance and the radiative $U(1)_X$ symmetry breaking via the Coleman-Weinberg mechanism, the inflationary predictions (in particular, the tensor-to-scalar ratio ($r$)), the $(1)_X$ coupling ($g_X$) and the $(1)_X$ gauge boson mass ($m_{Z'}$), are all determined by only two free parameters, the inflaton mass ($m_\phi$) and its mixing angle ($\theta$) with the SM Higgs field. The FASER can search for the inflaton for the parameter ranges of $0.1 \lesssim m_\phi [\text{GeV}] \lesssim 4$ and $10^{-5} \lesssim \theta \lesssim 10^{-3}$. Because of the direct connection among $r$, $g_X$ and $m_{Z'}$, the $Z'$ boson resonance search at the HL-LHC and the future measurement of the primordial gravitational wave are complementary to the inflaton search at the FASER.

Very recently, the ForwArd Search Experiment (FASER) \cite{FASER} has been approved to search for light, weakly interacting, electrically neutral long-lived particles at the Large Hadron Collider (LHC). Such long-lived particles are included in a variety of new physics models beyond the Standard Model (SM). In the experiment, a detector will be located along the beam trajectory 480 meters downstream from the interaction point within the ATLAS detector at the LHC. This setup is specialized to search for light, long-lived particles with the following advantages: (i) the High-Luminosity upgrade of the LHC (HL-LHC) can produce a huge number of hadrons in the forward region, which could decay into light long-lived particles. Even if such a decay process is extremely rare, the huge number of produced hadrons provides us with a sizable number of events for the long-lived particle production; (ii) such light particles are highly boosted in the beam direction and mostly produced in the forward region; (iii) Because of very weak interactions, such particles can have a decay length of $O(100 \text{ m})$. The displaced vertex signature from such long-lived particles is almost free from the SM backgrounds. In Refs. \cite{Belyaev:2018cvi, Belyaev:2018mpt}, the authors have explored a possibility of detecting a SM singlet scalar ($\phi$) at the FASER and other proposed experiments for the displaced vertex search. The production rate and the lifetime of the particle $\phi$ are controlled by only two parameters, its mass ($m_\phi$) and mixing angle ($\theta$) with the SM Higgs field. Impressively, these experiments are capable of probing extremely small mixing angles, $10^{-7} \lesssim \theta \lesssim 10^{-3}$, for $0.1 \lesssim m_\phi [\text{GeV}] \lesssim 10 \text{ GeV}$.\cite{Belyaev:2018mpt, Belyaev:2018cvi}

In their pioneering work \cite{Belyaev:2018mpt}, the authors have pointed out that the long-lived light scalar can be identified with a light inflaton in the chaotic inflation scenario. Once observed, its mass and mixing with the SM Higgs field can be measured. This measurement provides us with the information of the inflaton lifetime, which is interpreted into the information about the reheating temperature after inflation. However, in the chaotic inflation scenario, there is no direct connection between the light inflaton observation and the inflationary predictions.

In this letter, we consider the nonminimal quartic inflation in a classically conformal $U(1)_X$ extended SM, which the authors of the present paper have proposed with their collaborators \cite{Okada:2017zqz} (see also Ref. \cite{Okada:2016rwa}). By imposing the conformal invariance at the classical level on the minimal $U(1)_X$ extended SM \cite{Okada:2017zqz}, all the mass terms in the Higgs potential is forbidden. As a result, the $(1)_X$ gauge symmetry is radiatively broken by the Coleman-Weinberg (CW) mechanism \cite{Buryakovsky:2017lkl}, which subsequently drives the electroweak symmetry breaking through a mixing quartic coupling between the $(1)_X$ Higgs and the SM Higgs fields \cite{Buryakovsky:2017lkl}. As first pointed out in Ref. \cite{Okada:2017zqz}, the classical conformal invariance could be a clue to solve the gauge hierarchy problem of the SM. In our paper \cite{Okada:2017zqz}, we have identified the $(1)_X$ Higgs field with a nonminimal gravitational coupling as inflaton. Because of the classical conformal invariance, this scenario not only leads to the inflationary predictions consistent with the Planck 2018 results \cite{Ade:2015lrj}, but also provides a direct connection between the inflationary predictions and the LHC search for the $(1)_X$ gauge boson ($Z'$) resonance. The main purpose of this letter is to show that if the inflaton mass and its mixing angle with the SM Higgs field lie in a suitable range, the inflaton can be searched by the FASER with a direct connection to the inflationary predictions.\cite{FASER} Therefore, three independent experiments, namely, the inflaton search at the FASER, the $Z'$ boson resonance search at the HL-LHC and the precision measurement of the inflationary predictions, are complementary to test our inflation scenario.

Classically conformal $U(1)_X$ model: We first define our model with the particle content listed in Table \ref{tb:particle_content} where the $(1)_X$ charge of a particle is defined as a linear combination of its SM hypercharge and its $B - L$ (Baryon minus Lepton) number. The $(1)_X$ charges are determined by a real parameter, $x_H$, and the well-known minimal $U(1)_{B-L}$ model \cite{Goldberg:1983nd} is realized as the limit of $x_H \to 0$. Produces In the presence of the three right-hand neutrinos (RNHs), $\nu_R^{1,2,3}$, this model is free from all the gauge and the mixed gauge-gravitational

\begin{table}[h]
\centering
\caption{Particle content of our model. The $(1)_X$ charge is defined as a linear combination of its SM hypercharge and its $B - L$ (Baryon minus Lepton) number. The $(1)_X$ charges are determined by a real parameter, $x_H$.}
\begin{tabular}{|c|c|c|c|c|}
\hline
Particle & \text{SM Hypercharge} & $B - L$ & $(1)_X$ Charge \hline
$Q$ & 1 & 0 & $(1)_X$ \hline
$e^+$ & 0 & 0 & $-\frac{x_H}{2}$ \hline
$e^-$ & 0 & 0 & $\frac{x_H}{2}$ \hline
$\nu_L$ & $-1$ & 0 & $-\frac{x_H}{2}$ \hline
$\nu_R^{1,2,3}$ & $0$ & 0 & $\frac{x_H}{2}$ \hline
$H^+$ & 0 & 1 & $\frac{x_H}{2}$ \hline
$H^-$ & 0 & -1 & $\frac{x_H}{2}$ \hline
$H_u$ & $+1$ & 0 & $\frac{x_H}{2}$ \hline
$H_d$ & $-1$ & 0 & $\frac{x_H}{2}$ \hline
$h$ & 0 & 0 & 0 \hline
$H'$ & 0 & 0 & 0 \hline
\hline
\end{tabular}
\end{table}
TABLE I. The particle content of the minimal $U(1)_X$ model. $i = 1, 2, 3$ is the generation index.

| SU(3)$_c$, SU(2)$_L$, U(1)$_Y$ | U(1)$_X$ |
|---------------------------------|---------|
| $q^i_L$                         | 3       |
| $u^i_R$                         | 3       |
| $d^i_R$                         | 3       |
| $\ell^i_L$                      | 1       |
| $e^i_R$                         | 1       |
| $H$                             | 1       |
| $N^i_R$                         | 1       |

The stationary condition, $dV/d\phi|_{\phi=v_X} = 0$, leads to

$$\bar{\lambda}_X = \frac{11}{6} \beta_X,$$

where the barred quantities are evaluated at $\langle \phi \rangle = v_X$. The mass of $\phi$ is given by

$$m_\phi^2 = \frac{d^2V}{d\phi^2} \bigg|_{\phi=v_X} = -\beta_X v_X^2,$$

$$= \frac{6}{\pi} m_{Z'}^2 \left( 1 - 2 \left( \frac{m_N}{m_{Z'}} \right)^4 \right),$$

where $\alpha_X = g_X^2/(4\pi)$. The condition for the stability of $U(1)_X$ vacuum, $m_{Z'}^2 > 0$, requires $m_{Z'} > 2^{1/4}m_N$.

The $U(1)_X$ gauge symmetry breaking by $\langle \Phi \rangle = v_X/\sqrt{2}$ induces a negative mass squared for the SM Higgs doublet $(-\lambda_{mix}|\Phi|^2)$ in Eq. (2) and triggers the electroweak symmetry breaking [19]. The SM(-like) Higgs boson mass ($m_h = 125$ GeV) is described as

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

where $v_h = 246$ GeV is the Higgs doublet VEV. From this formula, we can justify our assumption of $\lambda_{mix} \ll 1$ by considering the LEP constraint on $v_X \gtrsim 10$ TeV [15–18].

The mass matrix for the Higgs bosons, $\phi$ and $h$, is given by

$$\mathcal{L} \supset -\frac{1}{2} \left( h \phi \right) \begin{bmatrix} m_h^2 & \lambda_{mix} v_h \sqrt{2} & m_h^2 \\ \lambda_{mix} v_h \sqrt{2} & m_{\phi}^2 & m_h^2 \\ m_h^2 & m_h^2 & m_{\phi}^2 \end{bmatrix} \begin{bmatrix} h \\ \phi \\ h \end{bmatrix},$$

where $h$ and $\phi$ are the mass eigenstates, and the mixing angle $\theta$ is determined by

$$2v_X v_h \lambda_{mix} = (m_h^2 - m_{\phi}^2) \tan 2\theta.$$

Since we are interested in the case with $m_{\phi}^2 \ll m_h^2$ and $\lambda_{mix} \ll 1$, we find

$$\theta \simeq \frac{v_h}{v_X} = \sqrt{\frac{16\pi^2 \beta_X}{m_{Z'}}} \ll 1.$$

The mass eigenvalues are given by

$$m_{\phi}^2 = m_h^2 + (m_{\phi}^2 - m_h^2) \frac{\sin^2 \theta}{1 - 2\sin^2 \theta} \simeq m_{\phi}^2 - m_h^2 \theta^2,$$

$$m_h^2 = m_h^2 - (m_{\phi}^2 - m_h^2) \frac{\sin^2 \theta}{1 - 2\sin^2 \theta} \simeq m_h^2.$$

For the parameter region which will be searched by the FASER, we find $m_{\phi,h} \simeq m_{\phi,h}$ and $\phi, h \simeq \phi, h$. For notational simplicity, we will refer to the mass eigenstates without using tilde in the rest of this letter. Note that for a fixed value of $m_N/m_{Z'}$, the inflaton mass ($m_{\phi}$) and its mixing angle with the Higgs field ($\theta$) are uniquely determined by $\alpha_X$ and $m_{Z'}$ with Eqs. (6) and (11).

**Nonminimal quartic inflation:** We here give a brief review on nonminimal quartic inflation with the action in the Jordan frame:

$$S_J = \int d^4 x \sqrt{-g} \left[ -\frac{1}{2} f(\phi) \Box \phi + \frac{1}{2} g_{\mu\nu} \left( \partial_\mu \phi \right) \left( \partial_\nu \phi \right) - V_f(\phi) \right],$$

where

$$f(\phi) = \frac{1}{2} \left( 1 - \frac{1}{2} \beta_X v_X^2 \right) + \frac{1}{2} \beta_X v_X^2 \phi \phi + \frac{1}{2} \beta_X v_X^2 \phi^2 + \frac{1}{2} \beta_X v_X^2 \phi^3,$$

with $g_{\mu\nu}$ the metric and $V_f(\phi)$ the quartic potential.
where $\phi$ is a real scalar field (inflaton), $f(\phi) = (1 + \xi \phi^2)$ with a real parameter $\xi > 0$, $V_{ij}(\phi) = \lambda \phi^4 / 4$ is the inflaton quartic potential, and the reduced Planck mass of $M_P = 2.44 \times 10^{18}$ GeV is set to be 1 (Planck unit). Using the transformation of $f(\phi)g_{\mu\nu} = g_{E\mu\nu}$, the action in the Einstein frame is described as

$$S_E = \int d^4x \sqrt{-g_E} \left[-\frac{1}{2} R_E + \frac{1}{2} g_E^{\mu\nu}(\partial_\mu \sigma)(\partial_\nu \sigma) - V_E(\phi(\sigma))\right], \quad (14)$$

where $V_E(\phi(\sigma)) = \sqrt{g_{E\mu\nu}}(\partial_\mu \sigma)(\partial_\nu \sigma)$, and $\sigma$ is a canonically normalized scalar field (inflaton in the Einstein frame) which is related to the original field $\phi$ by

$$\left(\frac{d\sigma}{d\phi}\right)^2 = 1 + \xi(6\xi + 1)\phi^2 \left(1 + \xi\phi^2\right)^2. \quad (15)$$

Using Eq. (15), we can express the slow-roll inflation parameters in the Einstein frame as

$$\epsilon(\phi) = \frac{1}{2} \left(\frac{V_E'}{V_E}\right)^2,$$
$$\eta(\phi) = \frac{V_E''}{V_E} \left(\frac{V_E'}{V_E}\right)^2,$$
$$\zeta(\phi) = \left(\frac{V_E'}{V_E}\right)^3 - 3 \frac{V_E''}{V_E} \left(\frac{V_E'}{V_E}\right)^2,$$

$$+3 \frac{V_E'''}{V_E} \left(\frac{V_E'}{V_E}\right)^2 - \frac{V_E'''}{V_E} \left(\frac{V_E'}{V_E}\right)^4,$$ \quad (16)

where a prime denotes a derivative with respect to $\phi$. The slow-roll inflation takes place when $\epsilon, |\eta|, \zeta < 1$. The amplitude of the curvature perturbation,

$$\Delta_R^2 = \frac{V_E(\phi)}{24\pi^2 \epsilon(\phi)} \bigg|_{k_0}, \quad (17)$$

should satisfy $\Delta_R^2 = 2.099 \times 10^{-9}$ from the Planck 2018 result [11] for the pivot scale $k_0 = 0.05$ Mpc$^{-1}$. The number of e-folds is evaluated by

$$N_0 = \frac{1}{\sqrt{2}} \int_{\phi_0}^{\phi} d\phi \frac{\sigma'}{\sqrt{\epsilon(\phi)}},$$ \quad (18)

where $\phi_0$ is the inflaton value at the horizon exit of the scale corresponding to $k_0$, and $\phi_e$ is the inflaton value at the end of inflation, which is defined by $\epsilon(\phi_e) = 1$. In our analysis, we fix $N_0 = 60$ to solve the horizon and flatness problems.

The inflationary predictions for the scalar spectral index ($n_s$), the tensor-to-scalar ratio ($r$), and the running of the spectral index ($\alpha = \frac{dn_s}{d\ln k}$), are given by

$$n_s = 1 - 6\epsilon + 2\eta, \quad r = 16\epsilon, \quad \alpha = 16\epsilon\eta - 24\epsilon^2 - 2\zeta,$$ \quad (19)

which are evaluated at $\phi = \phi_0$. Using $\Delta_R^2 = 2.099 \times 10^{-9}$ and $N_0 = 60$, the inflationary predictions, $\lambda, \phi_0$, and $\phi_e$ are determined as a function of the nonminimal gravitational coupling $\xi$. Based on unitarity arguments [19], we only consider $\xi < 10$. Our results are summarized in Table II.

**Table II.** Inflationary predictions for various $\xi$ values and $N_0 = 60$. The region $\xi < 0.00642$ ($r > 0.064$) is excluded by the Planck 2018 result.

| $\xi$    | $\phi_0/M_P$ | $\phi_e/M_P$ | $n_s$ | $r$ | $\alpha(10^{-4})$ | $\lambda$   |
|---------|-------------|--------------|-------|-----|-------------------|-------------|
| 0       | 22.1        | 2.83         | 0.951 | 0.262 | -8.06             | 1.23 × 10^{-13} |
| 0.00333 | 22.00       | 2.79         | 0.961 | 0.1  | -7.03             | 3.79 × 10^{-13} |
| 0.00642 | 21.85       | 2.76         | 0.963 | 0.064 | -7.50             | 3.79 × 10^{-13} |
| 0.0689  | 18.9        | 2.30         | 0.967 | 0.01  | -5.44             | 6.69 × 10^{-12} |
| 1       | 8.52        | 1.00         | 0.968 | 0.00346 | -5.25             | 4.62 × 10^{-10} |
| 10      | 2.89        | 0.337        | 0.968 | 0.00301 | -5.24             | 4.01 × 10^{-8} |

### Nonminimal U(1)$_X$ Higgs inflaton

By introducing the nonminimal gravitational coupling of $-\xi(\Phi^4)$, we identify the U(1)$_X$ Higgs field with the inflaton field in Eq. (13). Since $\phi > v_X$ during inflation, we approximate the Higgs potential by its quartic potential in the following inflationary analysis.

For the inflation analysis, we employ the renormalization group (RG) improved effective potential of the form [20],

$$V(\phi) = \frac{1}{4} \lambda_\phi(\phi)\phi^4,$$ \quad (20)

where $\lambda_\phi(\phi)$ is the solution to the following RG equations at the 1-loop level:

$$\frac{d\lambda_\phi}{d\ln \phi} = \beta_\lambda \approx 96\alpha_X^2 - 3\alpha_Y^2,$$
$$\frac{d\alpha_X}{d\ln \phi} = \beta_\alpha = \frac{72 + 64x_H + 41x_H^2}{12\pi} \alpha_X,$$
$$\frac{d\alpha_Y}{d\ln \phi} = \beta_Y = \frac{1}{2\pi} \alpha_Y \left(\frac{5}{2} \alpha_Y - 6\alpha_X\right).$$ \quad (21)

Here, $\alpha_Y = Y^2_{/M} (4\pi)$ and we have identified $\phi$ with the renormalization scale along the inflation trajectory.

Since $\lambda_\phi \ll 1$, the stationary condition in Eq. (5) implies that $g_X, Y_M \ll 1$. Hence, the RG evolutions of $\alpha_X$ and $\alpha_Y$ can be approximated as

$$\alpha_X, Y(\phi) \approx \alpha_X, Y(0) + \beta_{\alpha_X, Y} \ln \left[\frac{\phi}{v_X}\right],$$ \quad (22)

and accordingly,

$$\beta_\lambda(\phi) \approx \beta_{\lambda} + 2 \left(96 \alpha_X^2 \beta_y - 3 \alpha_Y^2 \beta_Y\right) \ln \left[\frac{\phi}{v_X}\right].$$ \quad (23)

We now approximate the evolution of the quartic coupling by

$$\lambda_{\phi}(\phi) \approx \left(\frac{11}{6} + \ln \left[\frac{\phi}{v_X}\right]\right) \beta_\lambda$$

$$+ \left(96 \alpha_X^2 \beta_y - 3 \alpha_Y^2 \beta_Y\right) \left(\ln \left[\frac{\phi}{v_X}\right]\right)^2.$$ \quad (24)

In the following analysis, we fix $m_N = m_{ZZ}/3$ (or equivalently, $\alpha_Y = 62\alpha_X/9$) to satisfy the vacuum stability condition. Using Eq. (24), the quartic coupling is determined.
as a function of $\phi$, $\alpha_X$, $m_{Z'}$, and $x_H$. On the other hand, in the inflation analysis, the inflationary predictions are controlled by only one parameter $\xi$. Once we fix a $\xi$ value, $\phi_0$ and $\lambda_{\phi}(\phi_0)$ are completely fixed as listed in Table I. Hence, by using Eq. (24) we can express $\alpha_X$ as a function of $m_{Z'}$ and $x_H$ for a fixed value of $\xi$. In fact, for $\xi \gtrapprox 10$, we find that $\alpha_X$ is almost independent of $x_H$, so that the $x_H$ dependence for inflationary predictions effectively drops off. Therefore, the inflationary predictions, $\alpha_X$, $m_{Z'}$, $m_\phi$ and $\theta$ are directly related with each other through Eqs. (6), (11) and (24).

![FIG. 1. The upper bounds on $g_X$ from the ATLAS result for $x_H = -0.8$, 0 and 10 (the diagonal lines from top to bottom), respectively.](image)

The ATLAS and the CMS collaborations have been searching for a narrow resonance at the LHC, and the most severe constraint on the $Z'$ boson of our model has been obtained by the search with dilepton final states. The ATLAS collaboration has recently reported their final result of the LHC Run-2 with a $139 \text{ fb}^{-1}$ integrated luminosity [21]. Following the analysis in Ref. [22], we interpret the ATLAS result into an upper bound on $g_X$ as a function of $m_{Z'}$ for a fixed $x_H$ value. In Fig. 1 we show our results for $x_H = -0.8$, 0, and 10 (the solid diagonal lines from top to bottom). The upper bounds depend on $x_H$ values and roughly scale as $g_X/|x_H|$ for $|x_H| \gtrapprox 3$, while we find the LHC bound becomes weak for $x_H \sim -1$ [23]. In the figure, we also plot the contours for fixed $\xi$ values. For $x_H = 0$, the horizontal solid lines from top to bottom correspond to $\xi = 10$, 1.0, $6.9 \times 10^{-2}$, and $6.4 \times 10^{-3}$ or equivalently, $r = 0.1$, 0.01, $3.4 \times 10^{-3}$, and $3.0 \times 10^{-3}$, respectively. The cyan shaded region is excluded by the Planck 2018 measurement $r > 0.064$. As discussed above, the inflationary predictions are almost independent of $x_H$ for $|x_H| < 10$ and the horizontal lines represent the results for any values of $x_H$ for $|x_H| < 10$. Fig. 1 indicates a complementarity between the LHC search for the $Z'$ boson resonance and the inflationary predictions.

**Searching for the inflaton at the FASER:** We are now ready to discuss the inflaton search at the FASER and its complementarity to the cosmological constraints on the inflationary predictions. For a fixed $\xi$ value, the inflationary predictions are fixed and $\alpha_X$ is determined as a function of $m_{Z'}$, independently of $x_H$ for $|x_H| < 10$. As a result, both the mass of inflaton ($m_\phi$) and its mixing angle with the SM Higgs field ($\theta$) are uniquely determined by the CW relations in Eqs. (6) and (11), respectively.

In Fig. 2 we show our results in $(m_\phi, \theta)$-plane, together with the FASER search reach, the search reach of other planned/proposed experiments (contours with the names of experiments indicated), and the current excluded region (gray shaded) from CHARM [24], Belle [25] and LHCb [26] experiments, as shown in Ref. [3]. The diagonal dashed lines correspond to $\xi = 0.00642$ ($r = 0.064$) and $\xi = 0.00689$ ($r = 0.01$), respectively, from left to right. The cyan shaded region ($r > 0.064$) is excluded by the Planck 2018 results. We find that the parameter region corresponding to the inflationary prediction $r \sim 0.01$ can be searched by the FASER 2 in the future, a part of which is already excluded the Planck 2018 result. For a fixed $m_{Z'}$, we can obtain a relation between $m_\phi$ and $\theta$ through $\alpha_X$ (recall, again, that this relation is almost independent of $x_H$ for $|x_H| < 10$). In Fig. 2, the diagonal solid lines correspond to $m_{Z'}[\text{TeV}] = 0.7$, 1.0, 1.3, 2.6, 5.0, and 10, from top to bottom. A point on a solid line corresponds to a fixed value of $\xi$, or equivalently, $r$. Along each line, the $\xi$ ($r$) value increases (decreases) from left to right. In Table I for various $m_{Z'}$ values, we have listed the range of the predicted tensor-to-scalar ratio ($r$) which will be covered by the FASER. The blue shaded region (labeled ATLAS) is excluded by the ATLAS result of the $Z'$ boson search for $x_H = 10$, corresponding to the bottom solid line in Fig. 1. The excluded regions for $x_H = -0.8$ and $x_H = 0$ (the $B-L$ model limit) correspond to $\theta > 10^{-3}$, and thus they are cov-
The range covered by FASER is rendered by the gray shaded region.

| \( m_\phi \) [GeV] | The range covered by FASER |
|-----------------|-----------------------------|
| 0.7 | \( 5.7 \times 10^{-3} \leq r \leq 6.0 \times 10^{-2} \) |
| 1.0 | \( 5.3 \times 10^{-3} \leq r \leq 1.0 \times 10^{-2} \) |
| 1.3 | \( 6.1 \times 10^{-3} \leq r \leq 1.4 \times 10^{-2} \) |
| 2.6 | \( 7.7 \times 10^{-3} \leq r \leq 6.4 \times 10^{-2} \) |
| 5.0 | \( 4.7 \times 10^{-3} \leq r \leq 6.4 \times 10^{-2} \) |
| 10 | \( 7.0 \times 10^{-3} \leq r \leq 6.4 \times 10^{-2} \) |

TABLE III. The ranges of \( r \) which will be covered by the FASER.

In conclusion, we have considered the nonminimal quartic inflation scenario in the minimal \( U(1)_X \) model with classical conformal invariance, where the inflaton is identified with the \( U(1)_X \) Higgs field. The FASER can search for the inflaton when its mass and mixing angle with the SM Higgs field are in the range of \( 0.1 \lesssim m_\phi [\text{GeV}] \lesssim 4 \) and \( 10^{-5} \lesssim \theta \lesssim 10^{-3} \). By virtue of the classical conformal invariance and the radiative \( U(1)_X \) symmetry breaking via the Coleman-Weinberg mechanism, the inflaton search by the FASER, the \( Z' \) boson resonance search at the LHC, and the future measurement of \( r \) are complementary to test our inflationary scenario.

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