Testability of the Higgs inflation scenario in a radiative seesaw model *

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The Higgs inflation scenario is an approach to realize the inflation, in which the Higgs boson plays a role of the inflaton without introducing a new particle. We investigate a Higgs inflation scenario in the so-called radiative seesaw model proposed by E. Ma. We find that a part of parameter regions where additional scalar fields can play a role of an inflaton is compatible with the current LHC results, the current data from neutrino experiments and those of the dark matter abundance as well as the direct search. We show that we can partially test this model by measuring masses of scalar bosons at the International Linear Collider.

I. INTRODUCTION

In 2012, the LHC discovered a new particle with the mass of 126 GeV [2, 3]. The particle is regarded as the Higgs boson predicted in the Standard Model (SM) of elementary particles. The discovery of the Higgs boson means that all the particle contents in the SM are completed. The LHC is now searching for indications of new physics, and is trying to measure the deviation in the coupling from the SM. On the other hand, the cosmic observations such as the experiments at WMAP and Planck have reported the new results [4, 5]. These experiments measure the temperature fluctuation of the cosmic microwave background precisely, by which we can impose constraints on the models of inflation. Cosmic inflation at the early Universe [6], which is a promising candidate to solve cosmological problems such as the horizon problem and the flatness problem, requires an additional scalar boson, the inflaton. We consider the Higgs inflation scenario where the Higgs boson plays a role of the inflaton. In the minimal model of this scenario [7], we do not have to introduce any other particle in addition to the particle contents in the SM to explain an inflation.

However, it would be difficult to realize the Higgs inflation scenario in the minimal model. Assuming the SM with one Higgs doublet, the vacuum stability argument indicates that the model can be well defined only below the energy scale where the running coupling of the Higgs self-coupling becomes zero. For the Higgs boson mass to be 126 GeV with the top quark mass to be 173.1 GeV and for the coupling for the strong force to be $\alpha_s = 0.1184$, the critical energy scale is estimated to be around 10^{10} GeV using the NNLO calculation, although the uncertainty due to the values of the top quark mass and α_s is not small [8]. The vacuum seems to be metastable when we assume that the model holds up to the Planck scale. This kind of analysis gives a strong constraint on the scenario of the Higgs inflation, because the inflation occurs at the energy scale where the vacuum stability is not guaranteed in the SM. Recently, a viable model for the Higgs inflation has been proposed, in which the Higgs sector is extended including an additional scalar field [9, 10]. There is also another problem in the minimal model, which comes from unitarity argument [11, 12].

Extending the Higgs sector from the SM one, we may expect to reveal new physics that can explain phenomena such as neutrino oscillation, existence of dark matter and baryon asymmetry of the Universe. Here, we extend the Higgs inflation model in the framework of a radiative seesaw scenario by E. Ma [1]. The radiative seesaw scenario is a way to explain tiny neutrino masses, where they are radiatively induced at the loop level by introducing Z_2-odd scalar fields and Z_2-odd right-handed neutrinos [13–15]. An interesting characteristic feature in these radiative seesaw models is that dark matter candidates automatically enter into the model because of the Z_2 parity.

In this work, we discuss a simple model to explain inflation, neutrino masses and dark matter simultaneously, which is based on the simplest radiative seesaw model [14]. Both the Higgs boson and neutral components of the Z_2-odd scalar doublet can satisfy conditions on the slow-roll inflation [16] and vacuum stability up to the inflation scale. We find that a part of the parameter region where these scalar fields can play a role of the inflaton is compatible with the current LHC results, the current data from neutrino experiments and those of the dark matter abundance as well as the direct search [17]. A phenomenological consequence of scenario results in a specific mass spectrum of scalar fields, which can be tested at the International Linear Collider (ILC) [18].

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* This proceeding paper is based on Ref. [1].

II. EXTENSION TO A RADIATIVE SEESAW MODEL

We extend the Higgs inflation model in the framework of a radiative seesaw scenario [14]. In this model, there are the Z_2-odd scalar doublet field Φ_2 and right-handed neutrino ν_R in addition to the Z_2-even SM Higgs doublet field Φ_1 due to the invariance under the unbroken discrete Z_2 symmetry [14]. Because Dirac Yukawa couplings of neutrinos are forbidden by the Z_2 symmetry, the Yukawa interaction for leptons is given by $\mathcal{L}_{Yukawa} = Y_\ell \overline{L_L}\Phi_1 \ell_R + Y_\nu \overline{L_L}\Phi_2^c \nu_R + h.c.$ (the superscript c denotes the charge conjugation). The scalar potential is given by [10]

$$\begin{aligned} V &= \frac{M_P^2 R}{2} + (\xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2)R + \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 \\ &+\frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2 + h.c.), \end{aligned} \tag{1}$$

where $M_P(\simeq 10^{19}$ GeV) is the Planck scale, and R is the Ricci scalar. Then, these quartic coupling constants should satisfy the following constraints on the unbounded-from-below conditions at the tree level;

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0, \tag{2}$$

and we impose the conditions of triviality;

$$\lambda_i \lesssim 2\pi. \tag{3}$$

Assuming μ_1^2 <0 and $\mu_2^2 > 0$, Φ_1 obtains the vacuum expectation value (VEV) v $(= \sqrt{-2\mu_1^2/\lambda_1})$, while Φ_2 cannot get the VEV because of the unbroken Z_2 symmetry. The lightest Z_2-odd particle is stabilized by the Z_2 parity, and it can act as the dark matter as long as it is electrically neutral. Mass eigenstates of the scalar bosons are the SM-like Z_2-even Higgs scalar boson (h), the Z_2-odd CP-even scalar boson (H), the Z_2-odd CP-odd scalar boson (A) and Z_2-odd charged scalar bosons ($H^\pm$). Masses of these scalar bosons are given by [14]; $m_h^2 = \lambda_1 v^2$, $m_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2$, $m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2$, $m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$.

III. CONSTRAINTS ON THE PARAMETERS

For the Higgs inflation scenario in our model defined in the previous section, there are nine parameters in the scalar sector; i.e., ξ_1, ξ_2, μ_1^2, μ_2^2, λ_1, λ_2, λ_3, λ_4 and λ_5. They must satisfy the vacuum stability condition on the running of the scalar coupling constants and the constraint from the slow-roll inflation, the dark matter data and the neutrino data. We find that a part of parameter regions is compatible with all constraints. Then, we can get the possible mass spectrum for additional scalar bosons in our model [1].

First, we discuss the constraint from the slow-roll inflation. In order that some of the scalar bosons play a role of the inflaton, we need to impose following conditions [10];

$$\begin{aligned} \lambda_2\xi_1 - (\lambda_3 + \lambda_4)\xi_2 &> 0, \\ \lambda_1\xi_2 - (\lambda_3 + \lambda_4)\xi_1 &> 0, \\ \lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2 &> 0. \end{aligned} \tag{4}$$

Parameters in the scalar potential should satisfy the constraint from the power spectrum [4, 10];

$$\xi_2\sqrt{\frac{2(\lambda_1 + a^2\lambda_2 - 2a(\lambda_3 + \lambda_4))}{\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2}} \simeq 5 \times 10^4, \qquad \frac{\lambda_5}{\xi_2}\frac{a\lambda_2 - (\lambda_3 + \lambda_4)}{\lambda_1 + a^2\lambda_2 - 2a(\lambda_3 + \lambda_4)} \lesssim 4 \times 10^{-12}, \tag{5}$$

where a is given as $a \equiv \xi_1/\xi_2$. When the scalar potential satisfies the conditions in Eqs. (4) and (5), the model could realize the inflation.

Second, we discuss the constraint from dark matter. We here assume that the CP-odd boson A is the dark matter (the lightest Z_2-odd particle). When λ_5 is very small such as $\mathcal{O}(10^{-7})$, A is difficult to act as the dark matter because the scattering process $AN \to HN$ (N is a nucleon) opens and the cross section cannot be consistent with the current direct search results for dark matter [19–21]. To avoid the process $AN \to HN$ kinematically, we here take $\lambda_5 \simeq 10^{-6}$ and

$$a\lambda_2 - (\lambda_3 + \lambda_4) \simeq 10^{-1} \tag{6}$$

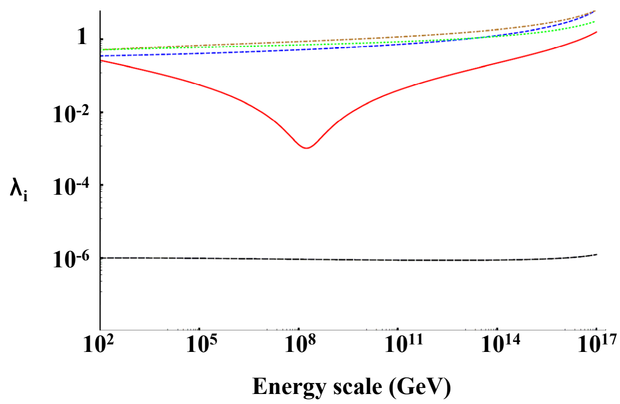

FIG. 1: Running of the scalar coupling constants. Red (solid), blue (dashed), brown (dot-dashed), green (dotted) and black (long-dashed) curves show λ_1, λ_2, λ_3, $-\lambda_4$ and λ_5, respectively.

	λ_1	λ_2	λ_3	λ_4	λ_5
10^2 GeV	0.26	0.35	0.51	-0.51	1.0×10^{-6}
10^{17} GeV	1.6	6.3	6.3	-3.2	1.2×10^{-6}

TABLE I: The possible parameter set which satisfies constraints from the inflation and the dark matter at the scales of $\mathcal{O}(10^2)$ GeV and $\mathcal{O}(10^{17})$ GeV.

at the inflation scale. With this choice, masses of A and H are almost the same value. The co-annihilation process $AH \to XX$ via the Z boson is important to explain the abundance of the dark matter where X is a particle in the SM, because the pair annihilation process $AA \to XX$ via the h boson is suppressed due to the constraint from the inflation. Because the cross section of $AH \to XX$ depends only on the mass of the dark matter, the mass of the dark matter A is constrained from the abundance of the dark matter as 128 GeV $\leq m_A \leq$ 138 GeV, where we have used the nine years WMAP data [4].

Third, we can explain tiny neutrino masses in this model which are generated by the one loop diagram [14]. The neutrino mass is related to λ_5 and masses of scalar bosons (m_H and m_A), which are constrained from the inflation and the dark matter. From the relation $(Y_\nu)_i^k (Y_\nu)_j^k / M_R^k \simeq \mathcal{O}(10^{-11})$ GeV^{-1} where M_R^k is the Majorana mass of ν_R^k (k=1-3) and $(Y_\nu)_i^k$ is neutrino Yukawa coupling constant, the magnitude of tiny neutrino masses can be explained. For example, when M_R^k is $\mathcal{O}(1)$ TeV, $(Y_\nu)_i^k$ is $\mathcal{O}(10^{-2})$.

Finally, we calculate the running of the coupling constants using the renormalization group equations [22]. As shown in Fig 1, for the contribution of additional scalar bosons, this model can be stable up to the inflation scale from the electroweak scale [23]. As numerical input parameters, we take the VEV ($v = 246$ GeV), SM-like Higgs mass ($m_h = 126$ GeV) and the allowed value for the dark matter mass ($m_A = 130$ GeV). Further numerical input parameter comes from the perturbativity of λ_2 up to the inflation scale; i.e., $\lambda_2(\mu_{\rm inf}) = 2\pi$, where $\mu_{\rm inf}$ is the inflation scale 10^{17} GeV. The parameter set in Table I can be consistent with these numerical inputs and the constraints are given in Eqs. (2)-(6). Consequently, we can obtain the mass spectrum of the scalar bosons in our model as

$$m_h \simeq 126 \text{ GeV}, \quad m_{H^\pm} \simeq 173 \text{ GeV}, \quad m_H \simeq 130 \text{ GeV}, \quad m_A \simeq 130 \text{ GeV}, \tag{7}$$

where the mass difference between A and H is about 500 KeV. The mass spectrum is not largely changed even if m_A is varied with in its allowed region. In the next section, we consider the constraints on our model from the existing experiments and the way to test the characteristic mass spectrum in this model at the future collider experiment.

IV. PHENOMENOLOGY

The LEP experiment constrains masses of the Z_2-odd scalar bosons. The mass of charged scalar bosons $m_{H^\pm}$ should be lager than 70-90 GeV by the LEP [24, 25]. This constraint is satisfied in our model ($m_{H^\pm} \simeq 173$ GeV). Furthermore, $m_H + m_A$ should be larger than m_Z, and the combination of m_H and m_A is bounded by HA production by the LEP date [24, 26]. However, when $m_H - m_A < 8$ GeV, masses of neutral Z_2-odd scalar boson loop diagrams are not really constrained by the LEP [24, 26]. On the other hand, the contributions to the electroweak parameters [27] from additional scalar bosons loops which are given by [28, 29] are also consistent with the electroweak precision data with 90% Confidence Level (C.L.) [29].

Next, we consider the way to test at the LHC. According to Refs. [30–32], they conclude that it could be difficult to test $pp \to AH^+/HH^+/H^+H^-$ processes because the cross sections of the background processes are

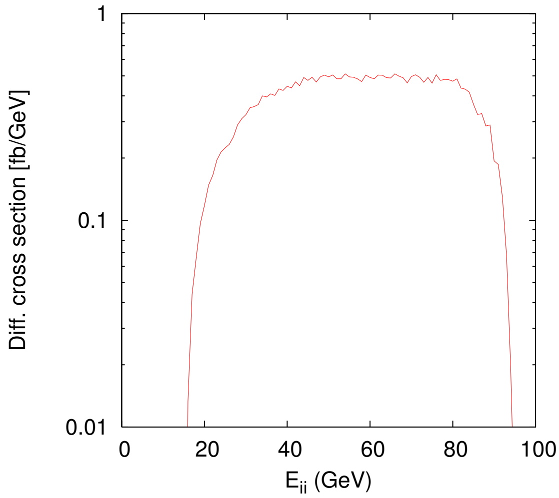

FIG. 2: The distribution of E_{jj} for the differential cross section for $e^+e^- \to H^+H^- \to W^{+(*)}W^{-(*)}AA \to jj\ell\nu AA$. In our parameter set, the endpoint of E_{jj} is estimated at 15 GeV $< E_{jj} <$ 94 GeV.

very large. The process of $pp \to AH$ could be tested with about the 3σ C.L. with the various benchmark points for m_A and m_H. However, it would be difficult to test $pp \to AH$ in our scenario, because m_H and m_A are almost degenerate in our scenario, and the event number of $pp \to AH$ is negligibly small after imposing the basic cuts [30–32]. Furthermore, as the total decay width of H is about 10^{-29} GeV, H would pass through the detector. Therefore, this signal is also difficult to be detected at the LHC.

Finally, we discuss the signals of H, A and $H^\pm$ at the ILC with $\sqrt{s} = 500$ GeV. In the following, we use Calchep 2.5.6 for numerical evaluation [33]. We focus on the $H^\pm$ pair production process: $e^+e^- \to Z^*(\gamma^*) \to H^+H^- \to W^{+(*)}W^{-(*)}AA \to jj\ell\nu AA$ (j denotes a hadron jet) [34]. Because of the kinematical reason, the energy of the two-jet system E_{jj} satisfies the following equation;

$$\frac{m_{H^\pm}^2 - m_A^2}{\sqrt{s} + 2\sqrt{s/4 - m_{H^\pm}^2}} < E_{jj} < \frac{m_{H^\pm}^2 - m_A^2}{\sqrt{s} - 2\sqrt{s/4 - m_{H^\pm}^2}}. \tag{8}$$

In our parameter set, the distribution of E_{jj} for the differential cross section in this process is shown in Fig. 2. The important background processes against this process, which are $e^+e^- \to W^+W^- \to jj\ell\overline{\nu}$ and $e^+e^- \to Z(\gamma)Z \to jj\ell\overline{\ell}$ with a missing $\overline{\ell}$ event, could be well reduced by imposing an appropriate kinematic cuts. Then, we expect that $m_{H^\pm}$ and m_A can be measured by using the endpoints of E_{jj} at the ILC after the background reduction.

On the other hand, we consider HA production: $e^+e^- \to Z^* \to HA \to AAZ^* \to AAjj$ at the ILC. If the mass difference between m_A and m_H is sizable, it could also be detected by using the endpoint of E_{jj}. However, m_A and m_H are almost degenerate in our scenario. When we detect $H^\pm$ but we cannot detect the clue of this process at the ILC, it seems that m_A and m_H are almost same value.

V. CONCLUSION

We have studied the Higgs inflation model in the framework of a radiative seesaw scenario. In our model, we may be able to explain inflation, neutrino masses and dark matter simultaneously. We find that a part of parameter regions is compatible with all constraints which come from the conditions of the slow-roll inflation, the current LHC results, the current data from neutrino experiments and those of the dark matter abundance as well as the direct search results. We can test this scenario by measuring masses of scalar bosons at the ILC with $\sqrt{s} = 500$ GeV.

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[1] S. Kanemura, T. Matsui, T. Nabeshima and , arXiv:1211.4448 [hep-ph].
[2] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1.
[3] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30.
[4] D. Larson *et al.*, Astrophys. J. Suppl. **192** (2011) 16, G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolta and M. Halpern *et al.*, arXiv:1212.5226 [astro-ph.CO].
[5] P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1303.5062 [astro-ph.CO].
[6] A. H. Guth, Phys. Rev. D **23** (1981) 347; K. Sato, Mon. Not. Roy. Astron. Soc. **195** (1981) 467.
[7] F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659** (2008) 703.
[8] A. De Simone, M. P. Hertzberg and F. Wilczek, Phys. Lett. B **678** (2009) 1; F. Bezrukov and M. Shaposhnikov, JHEP **0907** (2009) 089; J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto and A. Strumia, Phys. Lett. B **709** (2012) 222; G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia, JHEP **1208** (2012) 098.
[9] R. N. Lerner and J. McDonald, Phys. Rev. D **80** (2009) 123507,R. N. Lerner and J. McDonald, Phys. Rev. D **83** (2011) 123522,R. N. Lerner and J. McDonald, JCAP **1211** (2012) 019,C. Arina, J. -O. Gong and N. Sahu, Nucl. Phys. B **865** (2012) 430.
[10] J. -O. Gong, H. M. Lee and S. K. Kang, JHEP **1204** (2012) 128.
[11] C. P. Burgess, H. M. Lee and M. Trott, JHEP **0909** (2009) 103; JHEP **1007** (2010) 007; J. L. F. Barbon and J. R. Espinosa, Phys. Rev. D **79** (2009) 081302; M. P. Hertzberg, JHEP **1011** (2010) 023.
[12] G. F. Giudice and H. M. Lee, Phys. Lett. B **694** (2011) 294.
[13] L. M. Krauss, S. Nasri and M. Trodden, Phys. Rev. D **67** (2003) 085002; K. Cheung and O. Seto, Phys. Rev. D **69** (2004) 113009.
[14] E. Ma, Phys. Rev. D **73** (2006) 077301; Phys. Lett. B **662** (2008) 49; T. Hambye, K. Kannike, E. Ma and M. Raidal, Phys. Rev. D **75** (2007) 095003; E. Ma and D. Suematsu, Mod. Phys. Lett. A **24** (2009) 583.
[15] M. Aoki, S. Kanemura and O. Seto, Phys. Rev. Lett. **102** (2009) 051805; Phys. Rev. D **80** (2009) 033007; M. Aoki, S. Kanemura and K. Yagyu, Phys. Rev. D **83** (2011) 075016; Phys. Lett. B **702** (2011) 355.
[16] A. D. Linde, Phys. Lett. B **108** (1982) 389; A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett. **48** (1982) 1220.
[17] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **109** (2012) 181301.
[18] J. Brau, (Ed.) *et al.* [ILC Collaboration], arXiv:0712.1950 [physics.acc-ph]; G. Aarons *et al.* [ILC Collaboration], arXiv:0709.1893 [hep-ph]; N. Phinney, N. Toge and N. Walker, arXiv:0712.2361 [physics.acc-ph]; T. Behnke, (Ed.) *et al.* [ILC Collaboration], arXiv:0712.2356 [physics.ins-det]; H. Baer, *et al.* "Physics at the International Linear Collider", *Physics Chapter of the ILC Detailed Baseline Design Report*: http://lcsim.org/papers/DBDPhysics.pdf.
[19] Y. Cui, D. E. Morrissey, D. Poland and L. Randall, JHEP **0905** (2009) 076; C. Arina, F. -S. Ling and M. H. G. Tytgat, JCAP **0910** (2009) 018.
[20] S. Kashiwase and D. Suematsu, Phys. Rev. D **86** (2012) 053001.
[21] L. Lopez Honorez, E. Nezri, J. F. Oliver and M. H. G. Tytgat, JCAP **0702** (2007) 028.
[22] K. Inoue, A. Kakuto and Y. Nakano, Prog. Theor. Phys. **63** (1980) 234; H. Komatsu, Prog. Theor. Phys. **67** (1982) 1177.
[23] S. Nie and M. Sher, Phys. Lett. B **449** (1999) 89; S. Kanemura, T. Kasai and Y. Okada, Phys. Lett. B **471** (1999) 182.
[24] G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **35** (2004) 1; Eur. Phys. J. C **32** (2004) 453.
[25] A. Pierce and J. Thaler, JHEP **0708** (2007) 026.
[26] E. Lundstrom, M. Gustafsson and J. Edsjo, Phys. Rev. D **79** (2009) 035013.
[27] M. E. Peskin and T. Takeuchi, Phys. Rev. Lett. **65** (1990) 964; Phys. Rev. D **46** (1992) 381.
[28] D. Toussaint, Phys. Rev. D **18** (1978) 1626; M. E. Peskin and J. D. Wells, Phys. Rev. D **64** (2001) 093003.
[29] S. Kanemura, Y. Okada, H. Taniguchi and K. Tsumura, Phys. Lett. B **704** (2011) 303; M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Ludwig, K. Moenig, M. Schott and J. Stelzer, Eur. Phys. J. C **72** (2012) 2003.
[30] R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D **74** (2006) 015007 [hep-ph/0603188].
[31] Q. -H. Cao, E. Ma and G. Rajasekaran, Phys. Rev. D **76** (2007) 095011.
[32] E. Dolle, X. Miao, S. Su and B. Thomas, Phys. Rev. D **81** (2010) 035003
[33] A. Pukhov, hep-ph/0412191.
[34] M. Aoki, S. Kanemura and H. Yokoya, arXiv:1303.6191 [hep-ph]; M. Aoki and S. Kanemura, Phys. Lett. B **689** (2010) 28.