Cosmic Inflation, Baryogenesis and Particle Phenomenology in an Extend Higgs Portal model

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and arXiv:1411.xxxx

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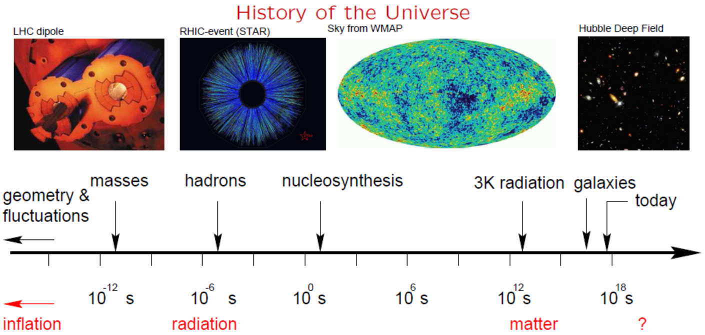
Outline

- Motivation
- Phenomenology of an extended Higgs portal inflation model after Planck 2013
- A brief discussion on the electroweak baryogenesis
- Conclusion

Motivation–Interesting Particle cosmology



- Searching for DM at LHC (F.P.Huang,C.S.Li,et al.PRD87,094018(2013))
- Inflation (F.P.Huang,C.S.Li,et al. Eur.Phys.J. C74 (2014) 2990) :Hitoshi Murayama, John Ellis...
- Baryogenesis(F.P.Huang,C.S.Li,arXiv:1411.xxxx)

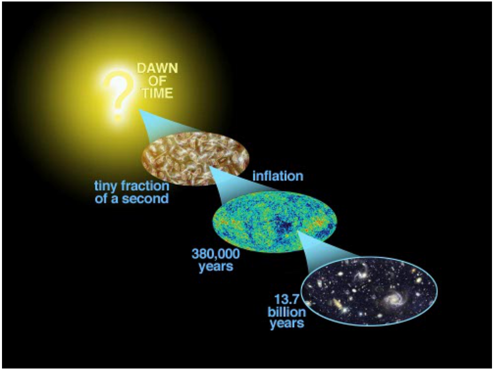
Motivation–Need to reconsider the role of the 125GeV scalar boson in early universe after its discovery

Reconsider the role of the Higgs boson in the early universe

- The 125 Higgs boson–so simple, yet not so natural!
- If nothing but a light Higgs is discovered in LHC, Higgs physics can yield surprises of fundamental significance for cosmology.

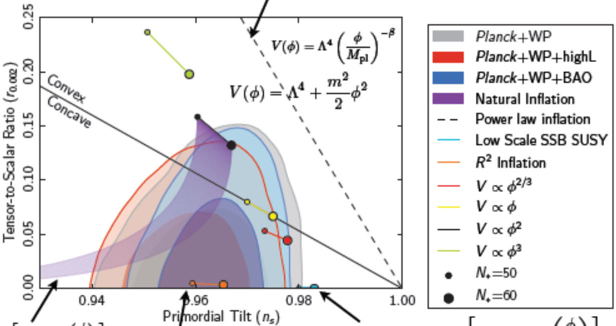
Motivation–Implications on inflation of Planck 2013 results

- Inflation solves the flatness, horizon, the monopole and entropy problems in the SM of cosmology.
- The Planck data impressively confirm the SM of cosmology including the inflation.



Motivation–Implications on inflation of Planck 2013 results

$$V(\phi) = \Lambda^4 \exp\left(-\lambda \frac{\phi}{M_{\rm pl}}\right)$$



$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

$$\mathcal{L} = \frac{M_{\rm pl}^2}{2}\left(R + \frac{R^2}{6M^2}\right)$$

$$V(\phi) = \Lambda^4 \left[1 + \alpha_{\rm h} \ln\left(\frac{\phi}{\mu}\right)\right]$$

$$\mathcal{L} = \frac{M_{\rm pl}^2 + \xi\phi^2}{2} R - \frac{1}{2} g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{\lambda}{4}\left(\phi^2 - \phi_0^2\right)^2$$

$$V(\tilde{\phi}) = \frac{\Lambda^4}{4}\left(1 - e^{-2\tilde{\phi}/\sqrt{6}M_{\rm pl}}\right)^2$$

Motivation–Baryogenesis

A long standing problem in cosmology and particle physics is the origin of baryogenesis, which is quantified by the baryon-to-photon ratio

$$\eta = \frac{n_B}{n_\gamma} = \frac{n_b - b_{\bar{b}}}{n_\gamma} = 6.05(7) \times 10^{-10}(\mathrm{CMB})(\mathit{Planck}2013). \quad (1)$$

The value η can be determined from studies of the power spectrum of the CMB or BBN.

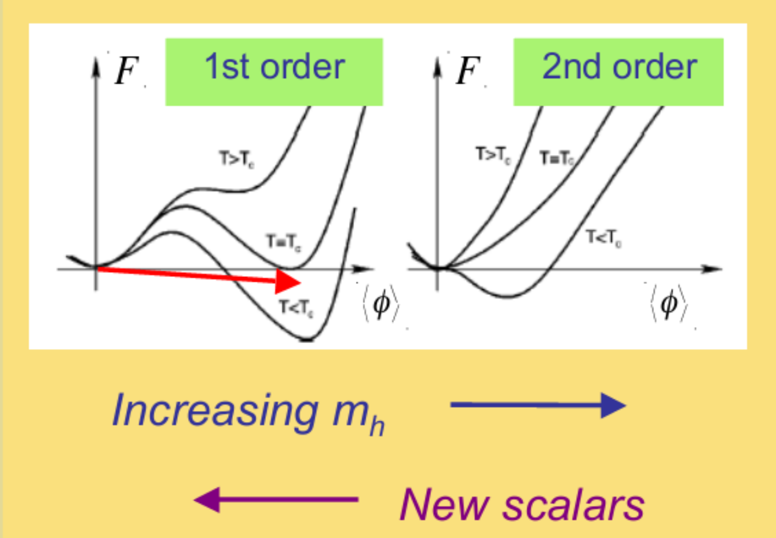
Electroweak baryogenesis

Sakharov Conditions for baryogenesis (1967)

- violation of baryon number–create baryonic charge;
- CP-violation and C violation–distinguish matter from antimatter;
- departure from equilibrium dynamics or CPT violation–provide a time arrow.

An important ingredient for sufficient baryon number generation is the existence of a strong first order electroweak phase transition (SFOPT) in which electroweak symmetry-breaking (EWSB) proceeds via bubble nucleation.

Motivation–Strong First Order Phase Transition



Motivation–Implications on Electroweak baryogenesis for 125 GeV Higgs boson

- With the discovery of the 125 GeV scalar boson, the eletroweak baryogenesis becomes a particularly timely, interesting and testable scenario to explain the baryon asymmetry of our universe.
- However, the 125 GeV is too heavy for eletroweak baryogenesis.
- Any Extension of the Higgs sector is needed to be discussed.

Motivation–Steven Weinberg's new model

Recently, Steven Weinberg proposed a new scalar field $\chi(x)$ to explain the fractional cosmic neutrinos.
The new scalar interact with the particles of the standard model through mixing with the Higgs boson.
(Steven Weinberg,Goldstone Bosons as Fractional Cosmic Neutrinos,Phys. Rev. Lett. 110,241301, 2013.)

Motivation

- The cosmic inflation needs a scalar field, while Weinberg introduces an interesting scalar field
- It is natural to ask the question:
  whether this scalar field can solve the inflationary problem besides the cosmic neutrino problem.
- How is cosmic inflation naturally embedded in the extended SM of particle physics?

Introduction to our extended Higgs portal inflation model

Under the nonminimal coupling assumption of the scalar field χ to the gravity, the generalized action is

$$S = \int \sqrt{-g} d^4x \left(\mathcal{L}_W + \mathcal{L}\text{grav}\right), \tag{2}$$

with

$$\mathcal{L}_W = -\frac{1}{2}\partial_\mu \chi^\dagger \partial^\mu \chi + \frac{1}{2}\mu^2 \chi^\dagger \chi - \frac{\lambda}{4}(\chi^\dagger \chi)^2 - \frac{\mathscr{G}}{4}(\varphi^\dagger \varphi)(\chi^\dagger \chi) + \mathcal{L}_{SM}, \tag{3}$$

and

$$\mathcal{L}_{\text{grav}} = \frac{M_P^2 + \xi \chi^\dagger \chi}{2} R. \tag{4}$$

Eur.Phys.J. C74 (2014) 2990 F.P.Huang C.S.Li,Ding Yu Shao, Jian Wang

Introduction to our extended Higgs portal inflation model

Define

$$\chi(x) = r(x)e^{2i\alpha(x)}, \tag{5}$$

where $r(x)$ is the radial massive field and $\alpha(x)$ is the massless Goldstone boson field (source of the fractional neutrino), Then, the Lagrangian becomes

$$\begin{aligned}\mathcal{L}_{\text{grav}} + \mathcal{L}_W = -\frac{1}{2}\partial_\mu r \partial^\mu r + \frac{1}{2}\mu^2 r^2 - \frac{\lambda}{4} r^4 - 2r^2 \partial_\mu \alpha \partial^\mu \alpha \\ -\frac{\mathscr{G}}{4}(\varphi^\dagger \varphi) r^2 + \frac{M_P^2 + \xi r^2}{2} R + \mathcal{L}_{SM}.\end{aligned} \tag{6}$$

Introduction to our extended Higgs portal inflation model

In unitary gauge, $r(x) = \langle r \rangle + r'(x)$ and $\varphi(x)^T = (0, \langle \varphi \rangle + \varphi'(x))$. The mixing of the radial boson $r(x)$ and the Higgs boson is get through the term

$$-\mathscr{G}\langle r\rangle\langle\varphi\rangle r'\varphi'. \tag{7}$$

After diagonalizing the mass matrix for r' and φ', the mixing angle is approximated by

$$\vartheta \approx \frac{\mathscr{G}\langle\varphi\rangle\langle r\rangle}{2(m_\varphi^2 - m_r^2)}, \tag{8}$$

where $\vartheta \ll 1$ is assumed.

This mixing of the radial boson and the Higgs boson may produce the abundant particle phenomenology.

Cosmic inflation driven by the new scalar field

It is convenient to investigate the cosmic inflation in the Einstein frame by performing the Weyl conformal transformation:

$$g_{\mu\nu} \rightarrow g_{E\mu\nu} = f g_{\mu\nu}\,, \qquad f = 1 + \xi r^2/M_P^2\,. \tag{9}$$

The corresponding potential in the Einstein frame becomes

$$V_E = \frac{V(r)}{f^2}\,, \tag{10}$$

$$\frac{d\sigma}{dr} \equiv \sqrt{\frac{f + 6\xi^2 r^2/M_P^2}{f^2}}. \tag{11}$$

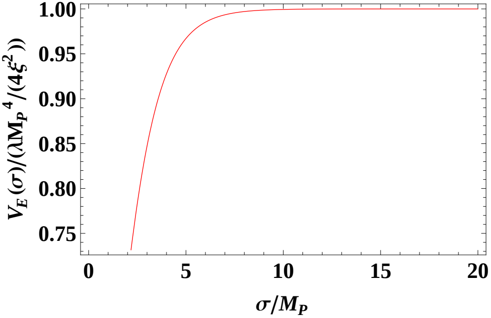
$$S_E = \int d^4x \sqrt{-g_E}\left[\frac{1}{2}M_P^2 R_E - \frac{1}{2}(\partial_E \sigma(r))^2 - V_E(\sigma(r))\right].$$

Cosmic inflation driven by the new scalar field

Thus, for large field $r(x)$ we have

$$V_E(\sigma) \approx \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\sigma}{\sqrt{6}M_P}\right)\right)^{-2}. \qquad (12)$$

This potential is the slow-roll potential, which is needed to drive the cosmic inflation.



Cosmic inflation driven by the new scalar field

The detailed conditions of the cosmic inflation are described by the following slow-roll parameters:

$$\epsilon = \frac{M_P^2}{2}\left(\frac{dV_E/d\sigma}{V_E}\right)^2 = \frac{8M_P^4}{\left(M_P^2+\xi(6\xi+1)r^2\right)r^2}, \tag{13}$$

$$\eta = M_P^2\frac{d^2V_E/d\sigma^2}{V_E} = \frac{4M_P^2(\xi(12\xi+1)r^2M_P^2+3M_P^4-2\xi^2(6\xi+1)r^4)}{r^2(M_P^2+\xi(6\xi+1)r^2)^2}. \tag{14}$$

Cosmic inflation driven by the new scalar field

The number N of e-foldings is given by

$$\begin{aligned} N &= \frac{1}{\sqrt{2}M_P}\int_{r_e}^{r_N} \frac{d\tilde{r}}{\sqrt{\varepsilon(\tilde{r})}}\left(\frac{d\sigma}{d\tilde{r}}\right) \\ &= \frac{3}{4}\left[-\ln\frac{M_P^2+\xi r_N^2}{M_P^2+\xi r_e^2}+\left(\xi+\frac{1}{6}\right)(r_N^2-r_e^2)/M_P^2\right], \quad (15) \end{aligned}$$

where r_N is the field value at Hubble exit during inflation.

Cosmic inflation driven by the new scalar field

The amplitude of density perturbations in k-space is defined by the power spectrum:

$$P_s(k) = A_s \left(\frac{k}{k^*}\right)^{n_s-1}, \qquad (16)$$

where A_s is the scalar amplitude at some "pivot point" k^*, which is given by

$$A_s = \left.\frac{V_E}{24\pi^2 M_P^4 \epsilon}\right|_{k^*}, \qquad (17)$$

which can be measured by astrophysical experiments. As a good approximation, the corresponding scalar spectral index n_s is given by

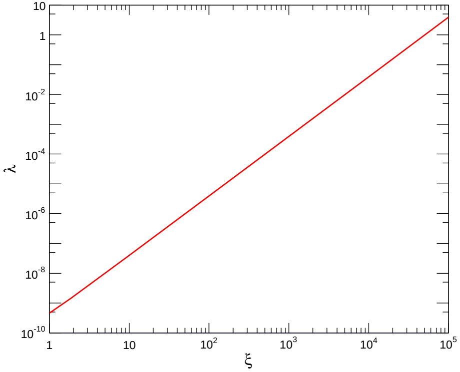
$$n_s = 1 - 6\epsilon + 2\eta\,, \qquad (18)$$

and the tensor-to-scalar ratio r^* at leading order is

$$r^* = 16\epsilon\,. \qquad (19)$$

Cosmic inflation driven by the new scalar field

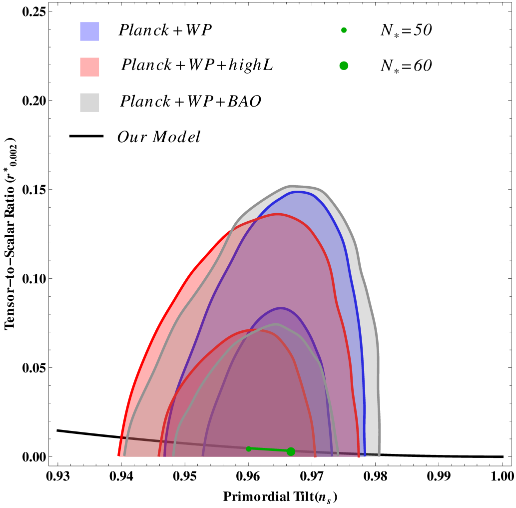
We use the Planck+WP data $\ln(10^{10}A_s) = 3.089^{+0.024}_{-0.027}$ and $n_s = 0.9603^{+0.024}_{-0.027}$ to give the constraints on the relation between ξ and λ needed to drive the inflation.



Cosmic inflation driven by the new scalar field

We fit the the combined experimental results of Planck and other data using our model. Our inflationary model is favored by the astrophysical measurements.

Cosmic inflation driven by the new scalar field



Cosmic inflation driven by the new scalar field

The one-loop correction to the effective potential in the $\overline{MS}$ scheme is given by

$$16\pi^2 V^{(1)}(r) = A_r^2\left(\ln\frac{A_r}{\mu_r^2}-\frac{3}{2}\right)+\frac{1}{4}B_r^2\left(\ln\frac{B_r}{\mu_r^2}-\frac{3}{2}\right), \qquad (20)$$

where

$$A_r = m_\varphi^2+\frac{1}{2}\mathscr{G}r^2, \qquad (21)$$

$$B_r = -\mu^2+3c_r\lambda r^2. \qquad (22)$$

The effective potential at one-loop level in the Einstein frame:

$$V_E=\frac{V^{(1)}+\frac{\lambda}{4}r^4}{f^2}.$$

Constraints from particle physics

We discuss the constraints on the model parameters from the current experimental results in the particle physics due to the mixing of the radial boson and the Higgs boson.
Keep the relation $\mathscr{G}$ and m_r

$$\frac{\mathscr{G}^2 m_\mu^7 M_\mathrm{P}}{m_r^4 m_\varphi^4} \approx 1, \tag{23}$$

which is proposed to explain the cosmic neutrino problems.

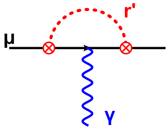
Constraints from particle physics:SM Higgs invisible decay

- Due to the mixing effects between SM Higgs boson and radial field r' the invisible decay channel for SM Higgs boson $\varphi' \to \alpha\alpha$ opens.
- The total decay width of Higgs boson is $\Gamma_{\rm visible} = 4.03\ {\rm MeV}$, and the decay width of $\varphi' \to \alpha\alpha$ can be obtained as

$$\Gamma_{\rm invisible} = \frac{\mathscr{G}^2 \langle\varphi\rangle^2 m_\varphi^3}{16\pi(m_\varphi^2 - m_r^2)^2}. \tag{24}$$

- The upper limit for Higgs invisible decay branching ratio at 2σ is 19% based on a combined fit of ATLAS, CMS and Tevatron results (arXiv:1306.4710).

Constraints from particle physics:Muon anomalous magnetic moment



- At the one-loop level the contribution from the radial boson r'

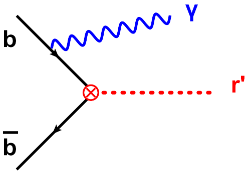
$$\Delta a_\mu^{\rm NP} = \vartheta^2 \frac{G_{\rm F} m_\mu^4}{4\pi^2\sqrt{2}} \int_0^1 \frac{y^2(2-y)}{m_\mu^2 y^2 + m_r^2(1-y)} dy. \qquad (25)$$

- Up to now there is a 4σ derivation between SM predictions and experimental results at BNL E821:

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (31.6 \pm 7.9) \times 10^{-10}. \qquad (26)$$

- Constraints from $\Delta a_\mu^{\rm NP} < \Delta a_\mu$

Constraints from particle physics:Radiative Upsilon decay $\Upsilon(nS) \to \gamma + \not{E}$



The main decay channel of r' is $r' \to \alpha\alpha$, where α is identified as missing energy in the experiments. The branching ratio of $\Upsilon(nS) \to \gamma + r'$ is given by

$$\frac{\mathcal{B}r\left(\Upsilon(nS) \to \gamma + r'\right)}{\mathcal{B}r(\Upsilon(nS) \to \mu^+\mu^-)} = \vartheta^2 \frac{G_F m_b^2 x_n}{\sqrt{2}\pi\alpha}\left[1 - \frac{4\alpha_s}{3\pi} f(x_n)\right] \Theta\left(m_{\Upsilon(nS)} - m_r\right).$$

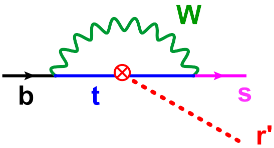
Constraints from particle physics:Radiative Upsilon decay $\Upsilon(nS) \to \gamma + \not{E}$

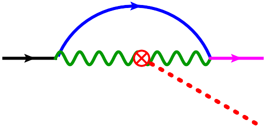
The current experimental results in radiative Upsilon decays $\Upsilon(nS) \to \gamma + \not{E}$ from BaBar are

$$\mathcal{B}r^{\mathrm{BaBar}}(\Upsilon(1S) \to \gamma + \not{E}) < 2 \times 10^{-6}, \tag{27}$$

$$\mathcal{B}r^{\mathrm{BaBar}}(\Upsilon(3S) \to \gamma + \not{E}) < 3 \times 10^{-6}. \tag{28}$$

Constraints from particle physics: B-meson decay $B \to K \not{E}$





The present experimental results for $B \to K \not{E}$ from BaBar are

$$\mathcal{B}r^{\mathrm{BaBar}}(B^- \to K^- \not{E}) < 7.0 \times 10^{-5}. \qquad (29)$$

In our model, the branching ratio is

$$\begin{aligned} \mathrm{Br}\left(B \to K \not{E}\right) &= \frac{9\sqrt{2}\tau_B G_F^3 m_t^4 m_b^2 m_+^2 m_-^2}{1024\pi^5 m_B^3 \left(m_b - m_s\right)^2} \left|V_{tb} V_{ts}^*\right|^2 f_0^2\left(m_r^2\right) \\ &\times \sqrt{\left(m_+^2 - m_r^2\right)\left(m_-^2 - m_r^2\right)}\, \vartheta^2\, \Theta\left(m_- - m_r\right). \end{aligned}$$

Constraints from particle physics:Kaon decay $K \to \pi + \not{E}$

Similar to the case of B-meson decay, for the r' production through Kaon decay $K \to \pi + \not{E}$, the SM predictions are $\mathcal{B}r^{\rm SM}(K^+ \to \pi^+ + \nu\bar{\nu}) = 7.8 \times 10^{-11}$. The current experiments constraints from E787 and E949 are

$$\mathcal{B}r(K^+ \to \pi^+ + \not{E}) < 10^{-10}. \qquad (30)$$

Constraints from particle physics:SM Higgs global signal strength

- It is important to constrain the dimensionless nonminimal coupling ξ by experiments and test the scalar-tensor interaction since the effective operator $\xi r^2 R$ often appears in the quantum gravity theory
- In our model, we try to constrain the nonminimal coupling ξ by the global signal strength of Higgs boson at the LHC using the method (M. Atkins,X. Calmet,Phys.Rev.Lett. 110 (2013) 5, 051301).
- From the mixing term of radial scalar boson and the Higgs boson, an effective interaction can be induced, which is $\kappa\varphi^\dagger\varphi R, \kappa \approx \xi\vartheta^2$.

Constraints from particle physics:SM Higgs global signal strength

The relevant action for Higgs sector is

$$S_{\rm H}=\int d^4x\sqrt{-g}\left[\frac{M_P^2+\kappa\varphi^\dagger\varphi}{2}R-\frac{1}{2}\partial_\mu\varphi^\dagger\partial^\mu\varphi\right]. \qquad (31)$$

Performing the conformal transformation
$g_{\mu\nu}\to\tilde{g}_{\mu\nu}=\Omega^2 g_{\mu\nu}\,, \qquad \Omega^2=1+\kappa\varphi^\dagger\varphi/M_P^2$ the action in the Einstein frame becomes

$$S_{\rm H}^E=\int d^4x\sqrt{-\tilde{g}}\left[\frac{M_P^2}{2}\tilde{R}-\frac{3\kappa^2}{4M_P^2\Omega^4}\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)-\frac{1}{2\Omega^2}\partial_\mu\varphi^\dagger\partial^\mu\varphi\right],$$

Constraints from particle physics:SM Higgs global signal strength

After expanding the Higgs field in the unitary gauge $\varphi(x)^T = (0, \langle\varphi\rangle + \varphi'(x))$ and expanding Ω^2 at leading order, the kinetic term for the Higgs boson is given by

$$\mathcal{L}^{\mathrm{kin}}_{\mathrm{Higgs}} = \frac{1}{2}\rho^2 \frac{\partial_\mu \varphi' \partial^\mu \varphi'}{2}, \tag{32}$$

with

$$\rho^2 = \frac{1}{\Omega_0^2} + \frac{6\kappa^2 \langle\varphi\rangle^2}{M_P^2 \Omega_0^4}, \tag{33}$$

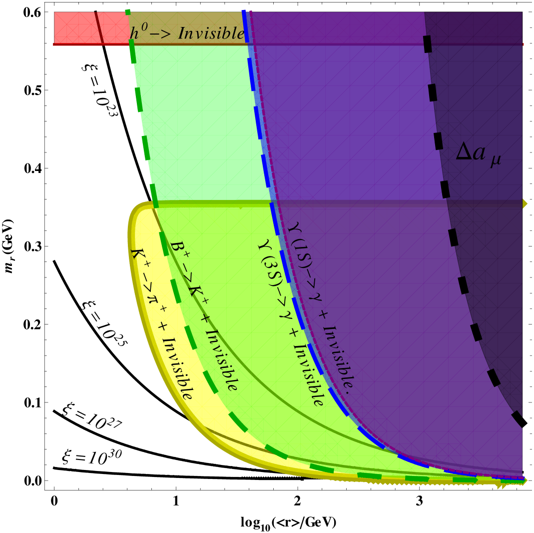
where

$$\Omega_0^2 = \frac{M_P^2 + \kappa\langle\varphi\rangle^2}{M_P^2}. \tag{34}$$

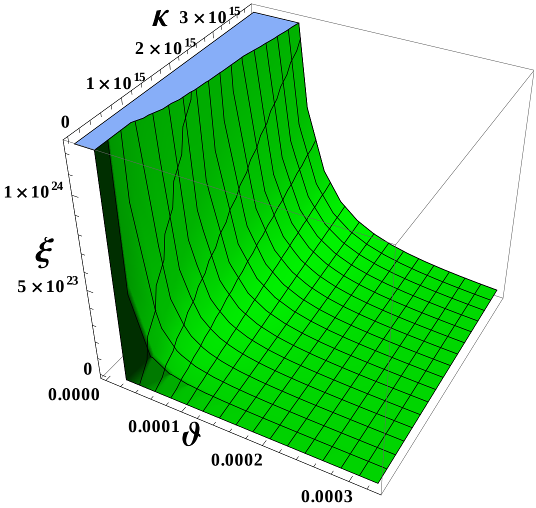
Constraints from particle physics:SM Higgs global signal strength

- To get the canonical kinetic term, all the Higgs couplings to the SM particles should be scaled by $1/\rho$.
- Using the narrow width approximation, we can obtain the global signal strength $\mu_s = \sigma/\sigma_{SM} = 1/\rho^2$.
- Considering the best-fit signal strength $\mu_s = 0.80 \pm 0.14$ from CMS (CMS-PAS-HIG-13-005) for all channels combined, $\kappa > 3.9 \times 10^{15}$ is excluded at 95% C.L. The upper bounds of ξ for given mixing angle which depends on m_r and $< r >$ can be obtained.

Constraints from particle physics:Combined results



Constraints from particle physics:Combined results



Baryogenesis production after cosmic inflation

The condition of the strong first order phase transition(SFOPT) which is a necessary condition for the baryogenesis is

$$\frac{v(T_c)}{T_c} > 1 \tag{35}$$

By observing the vacuum structure of the Higgs sector at zero temperature, we find that
$\mu^2 = \mu_{SM}^2 \frac{\mathscr{G}}{2\lambda_{SM}}(1+\delta_{\mu^2}), \lambda = (\frac{\mathscr{G}}{2\lambda_{SM}})^2 \lambda_{SM}(1+\delta_\lambda)$ will produce SFOPT.
This work on baryogenesis (1411.xxxx) is in preparation with C.S. Li.

Baryogenesis production after cosmic inflation

In this model, the phase transition critical temperature is

$$T_c \approx \frac{m_H\sqrt{\delta_\lambda - 2\delta_{\mu^2}}}{2\sqrt{D_h - D_\sigma}}, \tag{36}$$

and the washout parameter is given by

$$\frac{v(T_c)}{T_c} \approx \frac{2\sqrt{D_H - D_\sigma}v}{m_H\sqrt{\delta_\lambda - 2\delta_{\mu^2}}} \tag{37}$$

Baryogenesis production after cosmic inflation

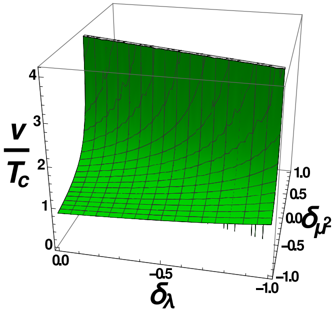
The coefficients D_H, D_σ is obtained from one-loop effective potential with thermal effects by using the effective temperature field theory.

$$D_H = \frac{1}{32}(8\lambda + g'^2 + 3g^2 + 4\tilde{y}_t^2 + 2\mathscr{G})$$

$$D_\sigma = \frac{1}{24}(2\mathscr{G} + 5\lambda + 6g_2^2)$$

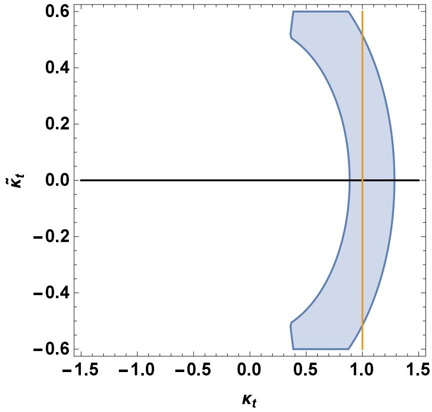
Baryogenesis production after cosmic inflation

As long as $\delta_\lambda - 2\delta_{\mu^2} << 1$, $v(T_c)/T_c > 1$ and the SFOPT can be realized.



Baryogenesis production after cosmic inflation

SFOPT is realized, the next piece is new CP violation source. Current LHC experiments still leave large room for the CP-violation top Yukawa coupling $-\frac{\sqrt{2}m_t}{v}\Phi\left(\kappa_t\,\bar{t}t + i\tilde{\kappa}_t\,\bar{t}\gamma_5 t\right)$.

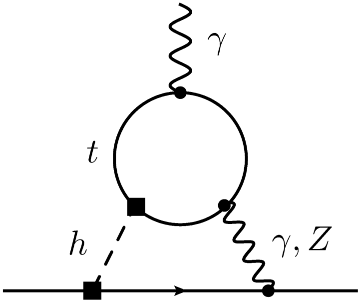


Baryogenesis production after cosmic inflation

The recent eletron EDM gives the constraint

$$|\tilde{\kappa}_t| < 0.01\,, \tag{38}$$

We use the approximated formula $\frac{n_B}{s} \sim \kappa_W^4 \alpha \delta_{CP} F$ to calculate the ratio of baryon number density to entropy. The current cosmological data gives the constraints of CP violation top Yukawa coupling as $\tilde{\kappa}_f > 0.0001$.



Future collider signature

Precise measurement of the following channels are needed to test this scenario:

- Higgs invisible decay
- $t\bar{t}H, Ht, H\bar{t}$ production with CP-violation top Yukawa coupling:crosssecion, polarization...

Conclusion

- An extended Higgs portal inflation model is proposed.
- The relation between the nonminimal coupling ξ and the self coupling λ is obtained using Planck data.
- Our inflationary model is favored by the combined results of Planck and the relevant astrophysical data.
- Constraints on the model parameters from experiments of particle physics are discussed.
- It is interesting to discuss the baryogenesis in this model.

Thanks!

Backup Slides:Cosmic Inflation

INFLATION and THE INFLATON

Inflation (accelerated expansion in the early universe) is attained if the energy density is dominated by the potential energy of a scalar field (the inflaton)

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \Longrightarrow p_\phi \simeq -\rho_\phi$$

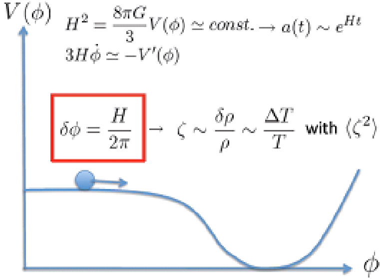
The inflaton is *slowly rolling along* a flat potential: $\phi(t) \approx const\,,\quad \epsilon \ll 1 \qquad |\eta| \ll 1$

$$\epsilon = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \quad \eta = \frac{m_{\rm Pl}^2}{4\pi}\left(\frac{V''}{V}\right)$$

$$H^2 = \frac{8\pi G}{3}V(\phi) \simeq const. \to a(t) \sim e^{Ht}$$

$$3H\dot{\phi} \simeq -V'(\phi)$$

$$\boxed{\delta\phi = \frac{H}{2\pi}} \to \zeta \sim \frac{\delta\rho}{\rho} \sim \frac{\Delta T}{T} \text{ with } \langle\zeta^2\rangle \sim \frac{H^2}{\epsilon M_{\rm Pl}^2}$$



Backup Slides: Higgs portal model