Higgs inflation scenario in a radiative seesaw model and its testability at the ILC

Toshinori MATSUI (Univ. of Toyama)

in collaboration with

Shinya KANEMURA[1], Takehiro NABESHIMA[2]

[1]Univ. of Toyama, [2]Technische Universität München

Phys. Lett. B **723** (2013) 126,

including some recent developments

In this talk,

- In Higgs inflation scenario, it would be difficult to satisfy perturbative unitarity and vacuum stability.
- These problems can be solved by multi-Higgs models.
- In the framework of a radiative seesaw scenario with multi-Higgs structure, we can explain not only DM, neutrino masses but also inflation.
- We discuss the testability of the characteristic mass spectrum at the collider experiments.

What is inflation?

- Standard cosmology is the very successful model to explain observations.
- Additionally, we need inflation to solve horizon problem & flatness problem.

Guth(1981), Sato(1981)

$$a_\Lambda = \exp\left(\frac{\Lambda}{3}t\right) \quad \Lambda \equiv 8\pi G \rho_\Lambda$$

- But, we do not know the detail of inflation.
- The scenario of slow-roll inflation is explained by a scalar particle (inflaton) ϕ.

Linde(1981)

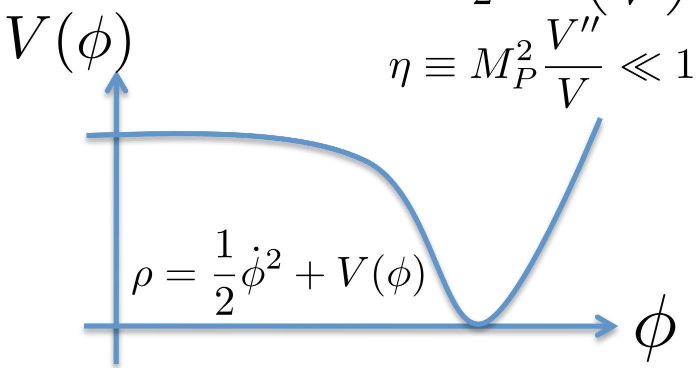
$$\varepsilon \equiv \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta \equiv M_P^2 \frac{V''}{V} \ll 1$$

Observable parameters

$$n_s \equiv 1 - 6\varepsilon + 2\eta$$

$$r \equiv 16\varepsilon$$



↑Typical potential of the slow-roll inflation

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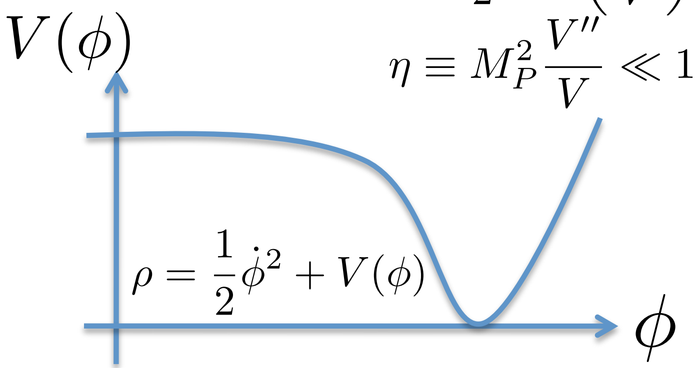

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Observable parameters

$$n_s \equiv 1 - 6\varepsilon + 2\eta$$

$$r \equiv 16\varepsilon$$

We can test inflation models by cosmological experiment!

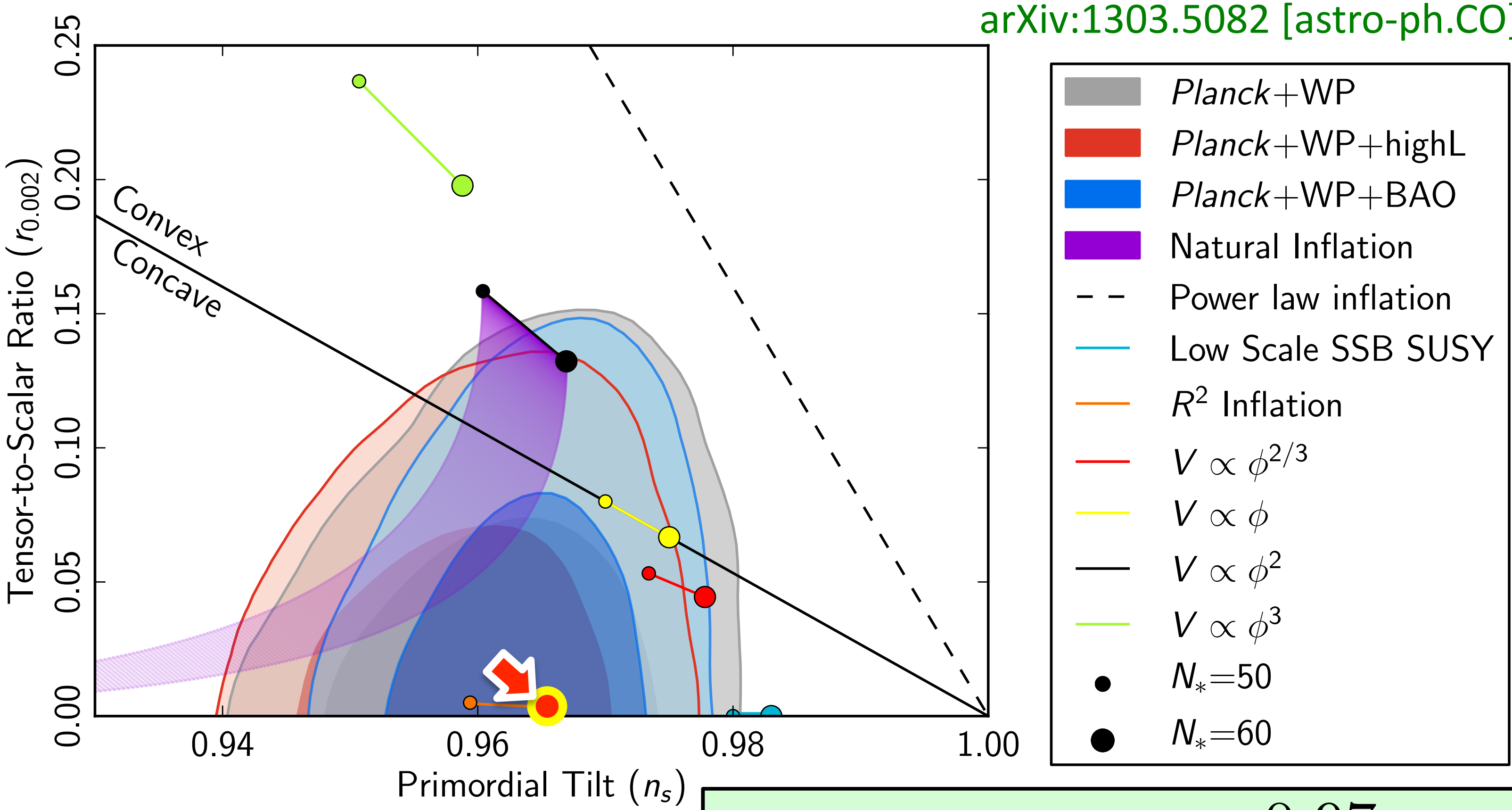
Planck 2013: 1303.5076

$$n_s = 0.9585 \pm 0.070 (68\%\text{C.L.})$$

$$r < 0.11 (95\%\text{C.L.})$$

The result of Planck

arXiv:1303.5082 [astro-ph.CO]



Higgs inflation model: $n_s \simeq 0.97 \; r \simeq 0.0033$

Planck data support to Higgs inflation model.

Higgs inflation scenario

Inflaton = Higgs boson

Simplest model "The Standard Model Higgs boson as the inflaton"

F. L. Bezrukov, M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008)

→We introduce to the coupling term of the Higgs field to gravity.

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \mathcal{L}_{\rm SM} - \frac{1}{2}M_P^2 R - \underline{\xi H^\dagger H R}$$

M_P : Planck mass, R : Ricci scalar

⇒ $\xi \simeq 49000\sqrt{\lambda}$ $n_s \simeq 0.97$ $r \simeq 0.0033$ (Predictions)

- ξ is too large from curvature power spectrum: $\mathcal{P}_R = 2.198 \pm 0.056 \times 10^{-9}$
- Slow-roll parameters agree with Planck date.
- Inflation scale is $\Lambda_{\rm I} = \dfrac{M_P}{\sqrt{\xi}}$.

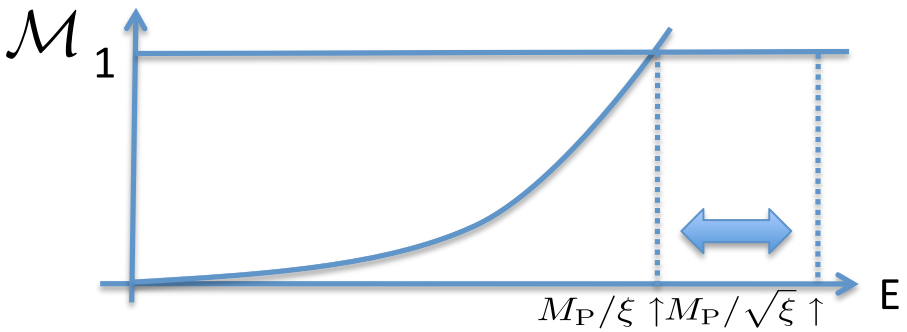
Constraints of slow-roll inflation can be satisfied!

(Ⅰ)Problem of perturbative unitarity

C.P.Burgess, H.M.Lee, M.Trott, JHEP **1007**, 007(2010)

- Perturbative unitarity is violated at high energy (which scale is $\Lambda_{\rm U} \equiv \frac{M_P}{\xi}$) by the Higgs-gauge scattering processes.

$$\mathcal{M}(W_L\,\chi_h \to W_L\,\chi_h) = \mathcal{M}(W_L\,h \to W_L\,h) + a\,\frac{E^2}{\Lambda_U^2} + b$$



χ_h is Higgs boson in Einstein frame.

Cannot reach to the inflation scale! $\Lambda_{\rm I} = \frac{M_P}{\sqrt{\xi}}$

(I)Solution of unitarity problem by singlet scalar field (σ)

G.F.Giudice, H.M.Lee, Phys.Lett.B **694**, 294(2011)

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = |D_\mu H| + \frac{1}{2}(\partial_\mu \sigma)^2 - V - \frac{1}{2}(M_P^2 + 2\xi H^\dagger H + \zeta\sigma^2)\mathcal{R}$$

$$\frac{\lambda_h\lambda_\sigma - \lambda_{h\sigma}^2/4}{\lambda_h\zeta^2 + \lambda_\sigma\xi^2 - \zeta\xi\lambda_{h\sigma}} \equiv \frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2} \simeq (10^4)^{-2}$$

By the coupling ζ between singlet scalar (σ) and Ricci scalar (R), it is possible to choose $\zeta \simeq 10^4$, $\xi < 10^2$.

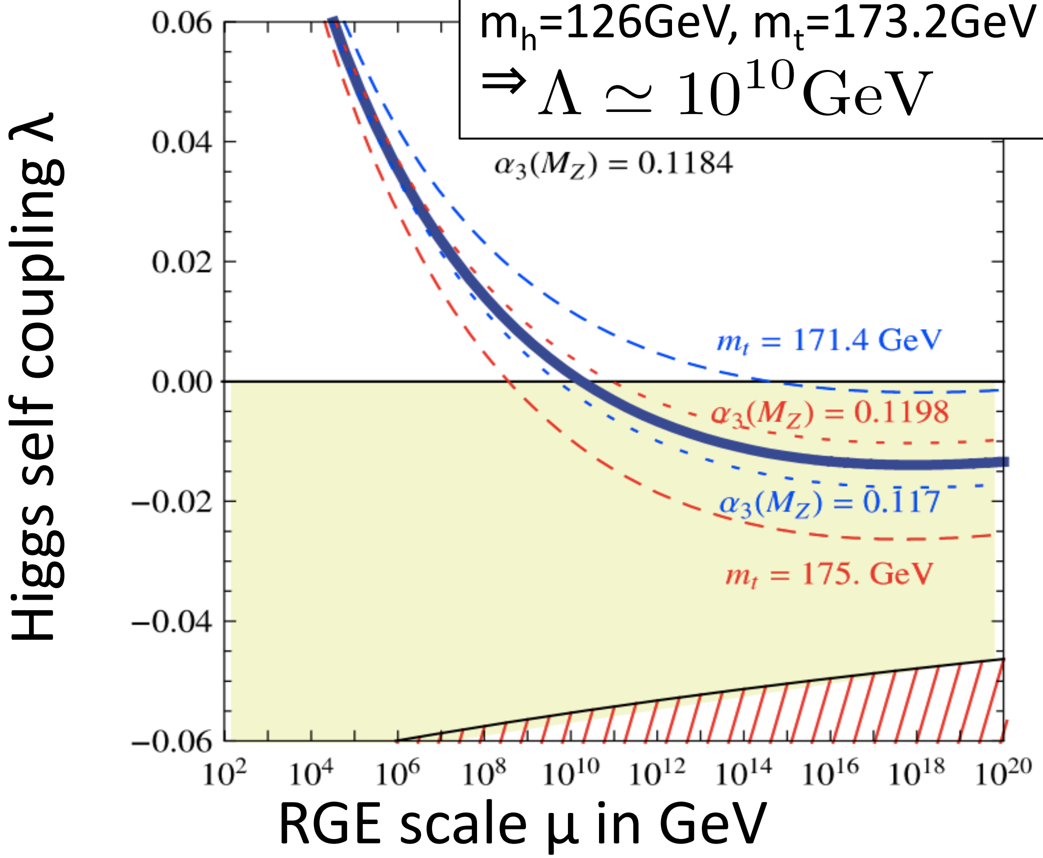
➡ $$\Lambda_{\rm U} = \frac{M_P}{\xi} > \Lambda_{\rm I}(\simeq 10^{17}{\rm GeV})$$

Since the singlet scalar boson does not interact with gauge bosons, we can solve unitarity problem.

(Ⅱ)Problem of vacuum stability

J.Elias-Miro et al, Phys. Lett. B 709, 222 (2012)

m_h=126GeV, m_t=173.2GeV
$\Rightarrow \Lambda \simeq 10^{10}\mathrm{GeV}$



$$\Lambda_{\rm I} = \frac{M_P}{\sqrt{\xi}}$$

The vacuum is difficult to be stable up to the inflation scale.

(Ⅱ)Solution of vacuum stability by second doublet field (Φ_2)

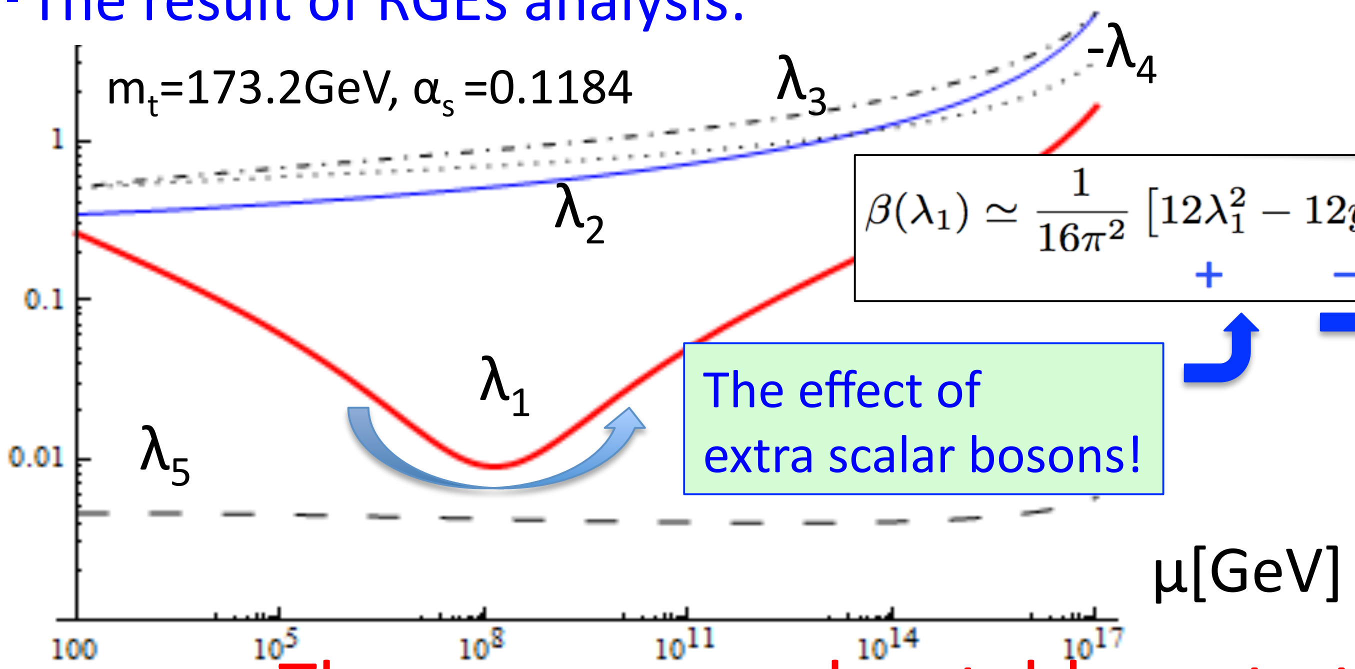
$$V_{2HDM} = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

N. G. Deshpande, E. Ma, Phys. Rev. D **18**, 2574(1978)

- Constraints on vacuum stability:

$$\lambda_1(\mu) > 0,\ \lambda_2(\mu) > 0,\ \lambda_3(\mu) + \lambda_4(\mu) + \lambda_5(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0$$

- The result of RGEs analysis:



$$\beta(\lambda_1) \simeq \frac{1}{16\pi^2}[12\lambda_1^2 - 12y_t^4 + \{2\lambda_3^2 + 2(\lambda_3+\lambda_4)^2 + 2\lambda_5^2\}]$$

+ − +

S.Kanemura, T.Kasai, Y.Okada, arXiv: 9903289 [hep-ph]

The vacuum can be stable up to the inflation scale.

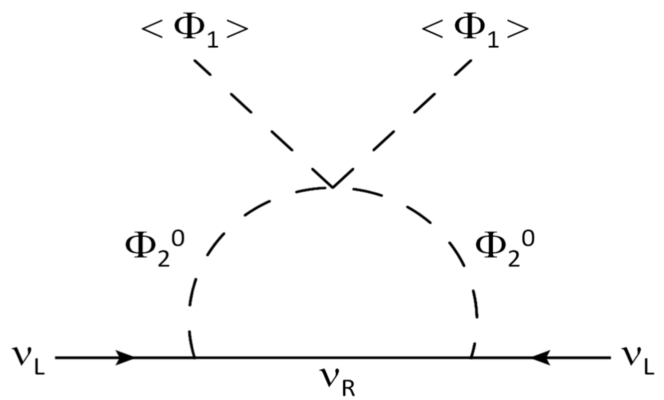
Extension to a radiative seesaw scenario ($\Phi_1+\Phi_2+\nu_R+\sigma$)

- In a radiative seesaw model, we introduce second scalar doublet (Φ_2) and right-handed neutrinos (ν_R) imposing unbroken Z_2 symmetry.
- The extra lightest neutral particle can be DM candidate by Z_2 symmetry and we can explain m_ν at the loop diagram.

Particle contents (A is DM in our model)

h, H, A, $H^\pm$, ν_R, (σ)

Z_2-even: h; Z_2-odd: H, A, $H^\pm$, ν_R



E.Ma, PRD**73**, 077301(2006)

- We can explain DM & m_ν in addition to inflation.
- We found the parameter regions satisfying perturbative unitarity (σ) & vacuum stability (Φ_2).

The result of RGEs analysis decide mass spectrum!

- DM direct detection (XENON100) & relic density (WMAP)
- To avoid Higgs invisible decay

$\Rightarrow$ $63\mathrm{GeV} \lesssim m_A \lesssim 66\mathrm{GeV}$

- Condition of the stable potential for scalar bosons as inflatons
- Vacuum stability & Triviality bound
- LEP bound

$\Rightarrow$ $m_H \lesssim 100\mathrm{GeV}$

$\Rightarrow$ $142\mathrm{GeV} \lesssim m_{H^\pm} \lesssim 146\mathrm{GeV}$

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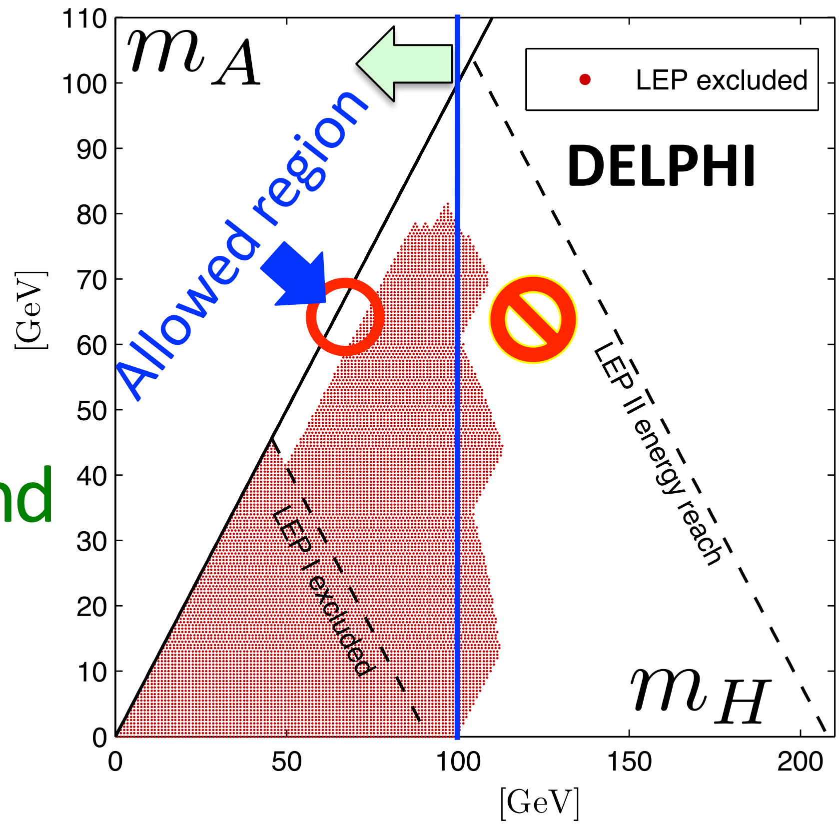
- DM direct detection (XENON100) & relic density (WMAP)
- To avoid Higgs invisible decay

$\Rightarrow 63\mathrm{GeV} \lesssim m_A \lesssim 66\mathrm{GeV}$

- Condition of the stable potential for scalar bosons as inflatons
- Vacuum stability & Triviality bound
- LEP bound

$\Rightarrow m_H - m_A \lesssim 8\mathrm{GeV}$

$\Rightarrow 142\mathrm{GeV} \lesssim m_{H^\pm} \lesssim 146\mathrm{GeV}$

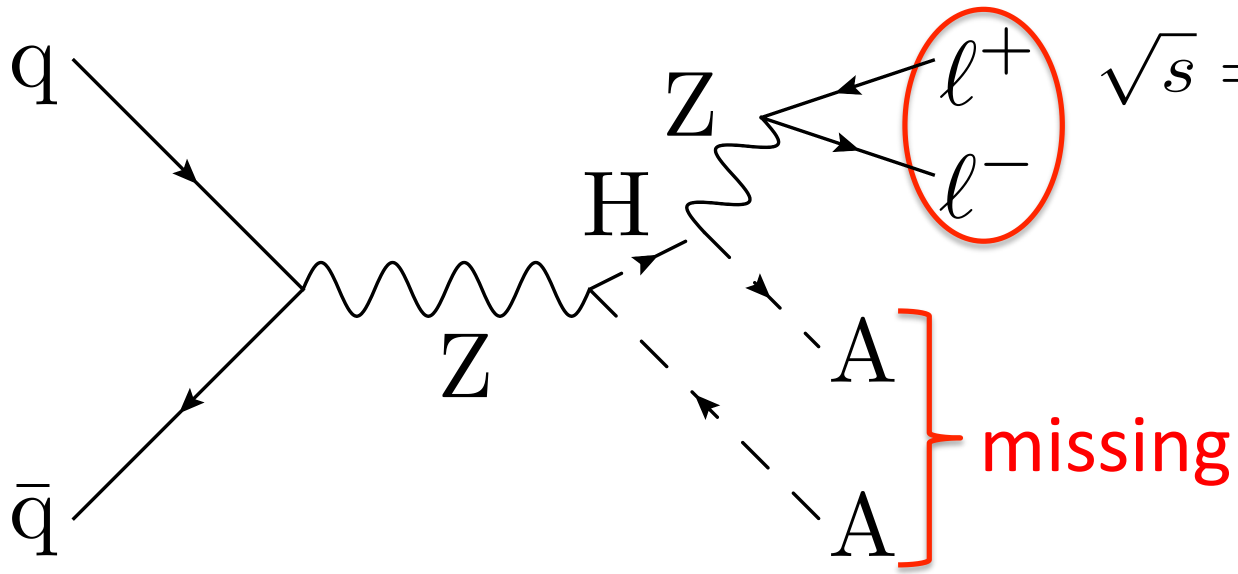


E.Lundstrom, M.Gustafsson, J.Edsjo, Phys. Rev. D **79**, 035013 (2009)↑

It is difficult to test our model at LHC!

E.Dolle, X.Miao, S.Su, B.Thomas, PRD81, 035003(2010)

- AH production is dominant.



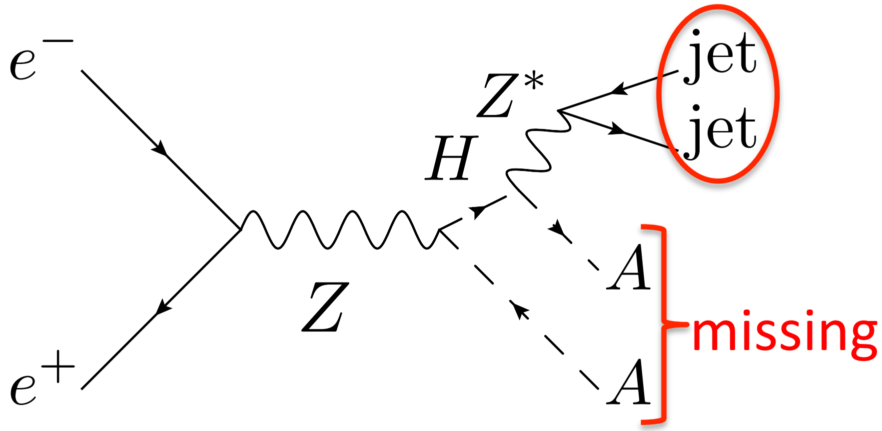
$\sqrt{s} = 14\text{TeV}$

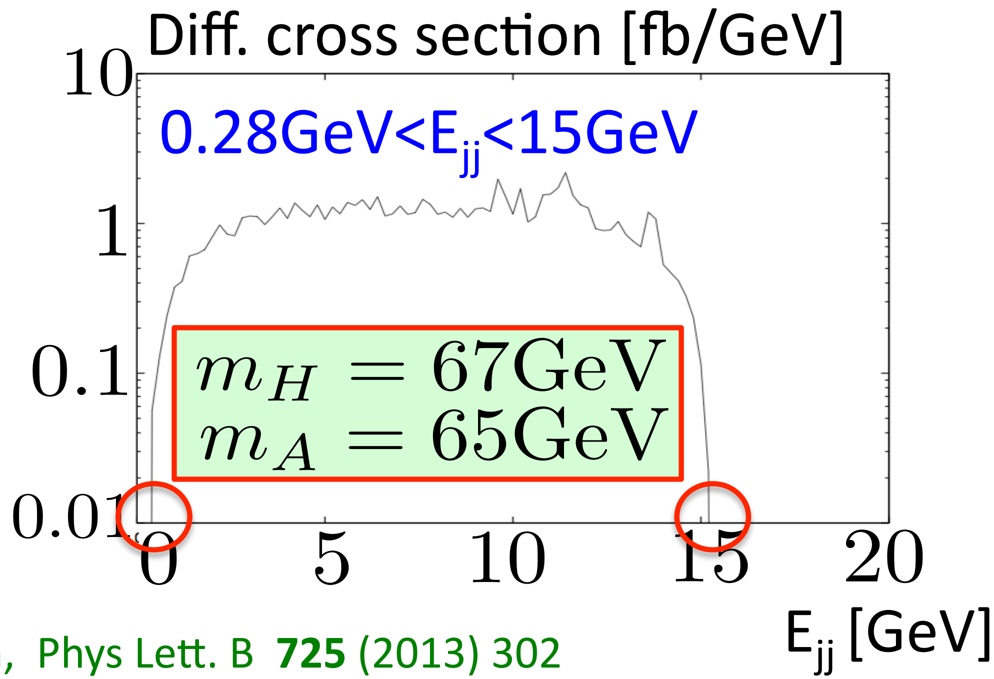
Benchmark: $m_H - m_A$ =[70, 50, 10]GeV (m_A =65GeV).

Not satisfy inflation constraints.

Even considering some cuts, $S/\sqrt{B}$=0.02 (too small!).

Testability at the ILC $\sqrt{s} = 500\text{GeV}$





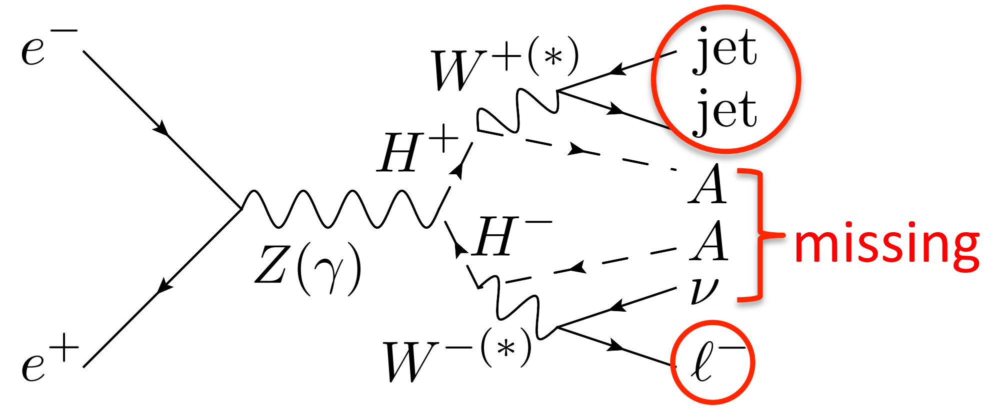
↓The relation between inert scalar masses and energy distribution.

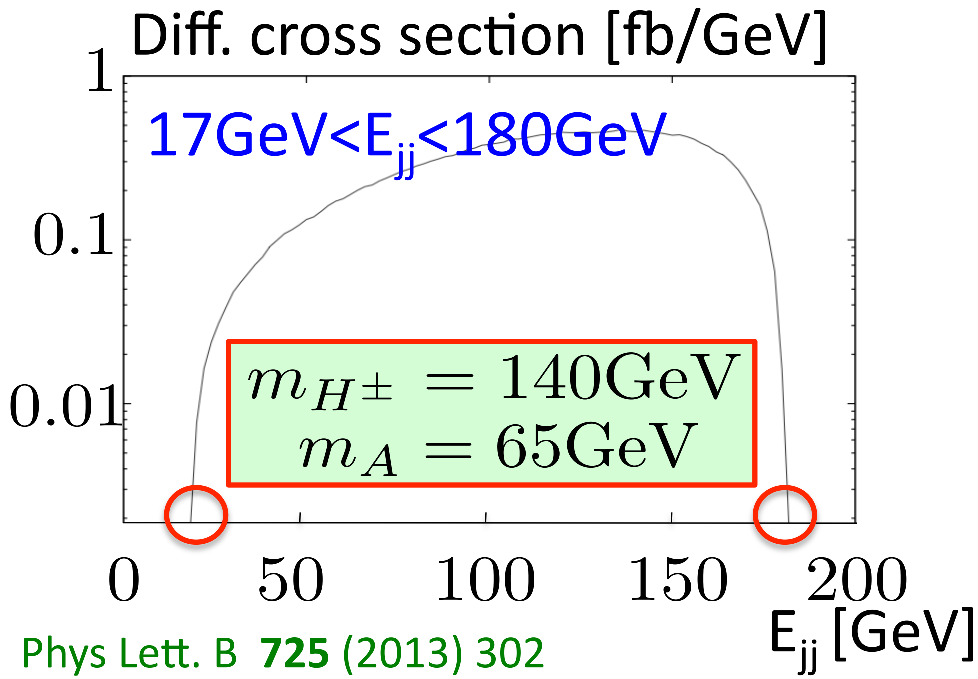
M.Aoki, S.Kanemura, H.Yokoya, Phys Lett. B **725** (2013) 302

$$\frac{m_H^2 - m_A^2}{4m_H^2}\left(\sqrt{s} - \sqrt{s - 4m_H^2}\right) < E_{jj} < \frac{m_H^2 - m_A^2}{4m_H^2}\left(\sqrt{s} + \sqrt{s - 4m_H^2}\right)$$

We can measure (m_H , m_A) by looking at the endpoint of energy distribution.

Testability at the ILC $\sqrt{s} = 500\text{GeV}$





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We can measure ($m_{H\pm}$, m_A) by looking at the endpoint of energy distribution.

Conclusions

- In Higgs inflation scenario, it would be difficult to satisfy perturbative unitarity and vacuum stability.
- These problems can be solved by multi-Higgs models.
- In the framework of a radiative seesaw scenario with multi-Higgs structure, we can explain not only DM, neutrino masses but also inflation.
- We can test this scenario at the ILC by measuring the energy distribution of the inert scalar pair productions.

Back Up

Original Higgs inflation

F. L. Bezrukov, M. Shaposhnikov, Phys. Lett. B **659**, 703(2008)

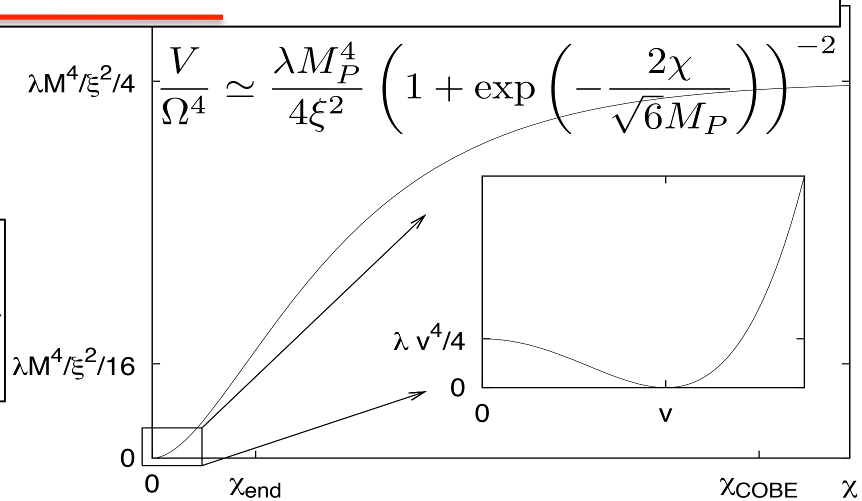
$$\frac{\mathcal{L}_J}{\sqrt{-g^J}} = |D_\mu H|^2 - V - \frac{1}{2}(M_P^2 + 2\xi H^\dagger H)\mathcal{R}$$

$$\mathcal{R} = \Omega^{-2}\hat{\mathcal{R}} + 6\Omega^{-3}\Omega_{;\mu\nu}g^{E\mu\nu} \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

$$\frac{\mathcal{L}_E}{\sqrt{-g^E}} = \frac{1}{2\Omega^2}\left[1 + \frac{6\xi h^2}{M_P^2\Omega^2}\right](\partial_\mu h)^2 - \frac{V}{\Omega^4} - \frac{1}{2}M_P^2\hat{\mathcal{R}}$$

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + \frac{6\xi^2 h^2}{M_P^2}}{\Omega^4}}$$

$$\frac{\mathcal{L}_E}{\sqrt{-g^E}} = \frac{1}{2}(\partial_\mu \chi)^2 - \frac{V}{\Omega^4} - \frac{1}{2}M_P^2\hat{\mathcal{R}}$$



Unitarity problem

C.P.Burgess, H.M.Lee, M.Trott, JHEP **1007**, 007(2010)

$$h \ll \frac{M_P}{\xi}$$

$$v + h \to (\langle\chi\rangle + \chi)[1 - (\langle\chi\rangle + \chi)^2/\Lambda^2] + \ldots$$

$$\langle\chi\rangle = v(1 + v^2/\Lambda^2) + \ldots \qquad \Lambda \equiv \frac{M_P}{\xi}$$

Higgs self interaction

$$U(\chi) \equiv \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}(v + h(\chi))^4$$
$$\simeq \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}[(\langle\chi\rangle + \chi)^4 - 4(\langle\chi\rangle + \chi)^6/\Lambda^2]$$

$$\boxed{\lambda v h^3 \to \lambda v(1 - 19\frac{v^2}{\Lambda^2})\chi^3}$$

Higgs-Gauge interaction

$$\frac{1}{8\Omega^2}[2g^2(v+h)^2 W_\mu^+ W^{-\mu} + (g^2 + g'^2)(v+h)^2 Z_\mu Z^\mu]$$

$$-\left(M_W^2 W_\mu^+ W^{-\mu} + \frac{M_Z^2}{2} Z_\mu Z^\mu\right)\left(\frac{2\bar{h}}{v_h} + \frac{\bar{h}^2}{v_h^2}\right) =$$

$$-\frac{M_W^2}{v_h^2} W_\mu^+ W^{-\mu} \bar{\chi}^2 \left(1 - 12\frac{\xi^2 v_h^2}{M_P^2}\right) - \frac{2M_W^2}{v_h} W_\mu^+ W^{-\mu} \bar{\chi} \left(1 - 3\frac{\xi^2 v_h^2}{M_P^2}\right)$$
$$-\frac{M_Z^2}{2v_h^2} Z_\mu Z^\mu \bar{\chi}^2 \left(1 - 12\frac{\xi^2 v_h^2}{M_P^2}\right) - \frac{2M_Z^2}{v_h} Z_\mu Z^\mu \bar{\chi} \left(1 - 3\frac{\xi^2 v_h^2}{M_P^2}\right)$$

Introduce singlet scalar field

G.F.Giudice, H.M.Lee, Phys.Lett.B **694**, 294(2011)

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = |D_\mu H| + \frac{1}{2}(\partial_\mu \sigma)^2 - V - \frac{1}{2}(M_P^2 + 2\xi H^\dagger H + \zeta\sigma^2)\mathcal{R}$$

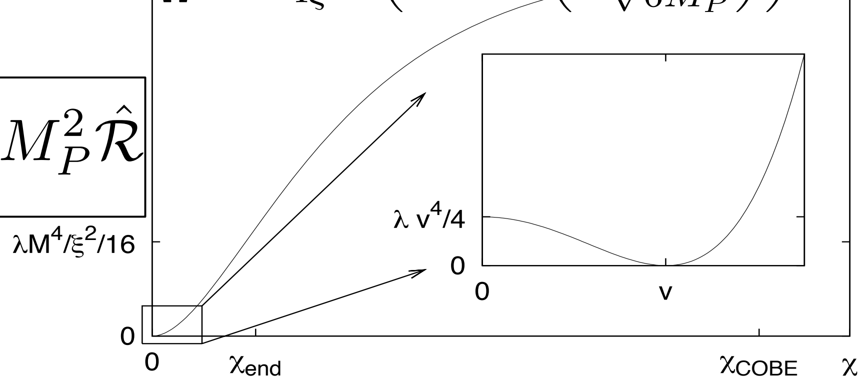
$$\mathcal{R} = \Omega^{-2}\hat{\mathcal{R}} + 6\Omega^{-3}\Omega_{;\mu\nu}g^{E\mu\nu} \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2} + \frac{\zeta\sigma^2}{M_P^2}$$

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = \frac{1}{2\Omega^2}\left[1 + \frac{6\xi h^2}{M_P^2\Omega^2}\right](\partial_\mu h)^2 + \frac{1}{2\Omega^2}\left[1 + \frac{6\zeta\sigma^2}{M_P^2\Omega^2}\right](\partial_\mu \sigma)^2 - \frac{V}{\Omega^4} - \frac{1}{2}M_P^2\hat{\mathcal{R}}$$

$$\frac{d\chi_h}{dh} = \sqrt{\frac{\Omega^2 + \frac{6\xi^2 h^2}{M_P^2}}{\Omega^4}} \qquad \frac{d\chi_\sigma}{dh} = \sqrt{\frac{\Omega^2 + \frac{6\zeta^2 \sigma^2}{M_P^2}}{\Omega^4}}$$

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = \frac{1}{2}(\partial_\mu \chi_h)^2 + \frac{1}{2}(\partial_\mu \chi_\sigma)^2 - \frac{V}{\Omega^4} - \frac{1}{2}M_P^2\hat{\mathcal{R}}$$

$$\frac{V}{\Omega^4} \simeq \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$



Our model

$$V = \frac{1}{2}M_P^2\left(1+\frac{2\xi_1|\Phi_1|^2+2\xi_2|\Phi_2|^2+\zeta\sigma^2}{M_P^2}\right)R$$
$$+\mu_1^2|\Phi_1|^2+\mu_2^2|\Phi_2|^2+\mu_\sigma^2\sigma^2$$
$$+\frac{1}{2}\lambda_1|\Phi_1|^4+\frac{1}{2}\lambda_2|\Phi_2|^4+\frac{1}{8}\lambda_\sigma\sigma^4$$
$$+\lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+\frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2+h.c.)$$

Two Higgs doublet model

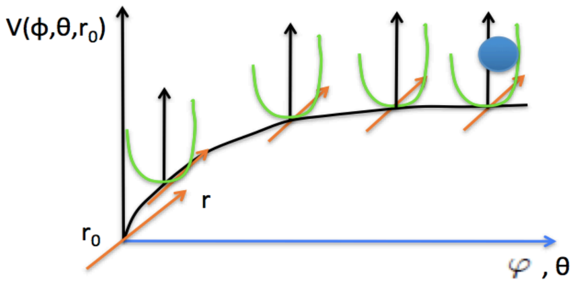
The relation of coupling constants

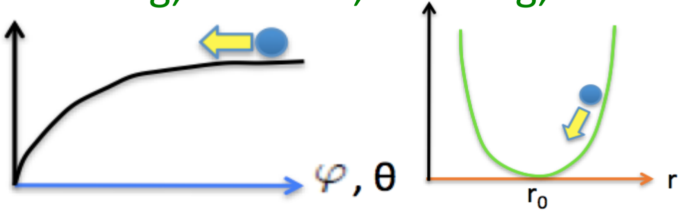
$$\frac{[\lambda_1\lambda_2-(\lambda_3+\lambda_4)^2]\lambda_\sigma/2}{[\lambda_1\lambda_2-(\lambda_3+\lambda_4)^2]\zeta^2+[\lambda_2\xi_1^2+\lambda_1\xi_2^2-(\lambda_3+\lambda_4)\xi_1\xi_2]\lambda_\sigma}\equiv\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2}\simeq(10^4)^{-2}$$

The behavior of the Higgs fields as inflatons

$$V = V_{2HDM} + \frac{M_P^2}{2}\mathscr{R} + (\xi_1 \Phi_1^2 + \xi_2 \Phi_2^2)\mathscr{R}$$

J.-O.Gong, H.M.Lee, S.K.Kang, JHEP **1204**, 128(2012)





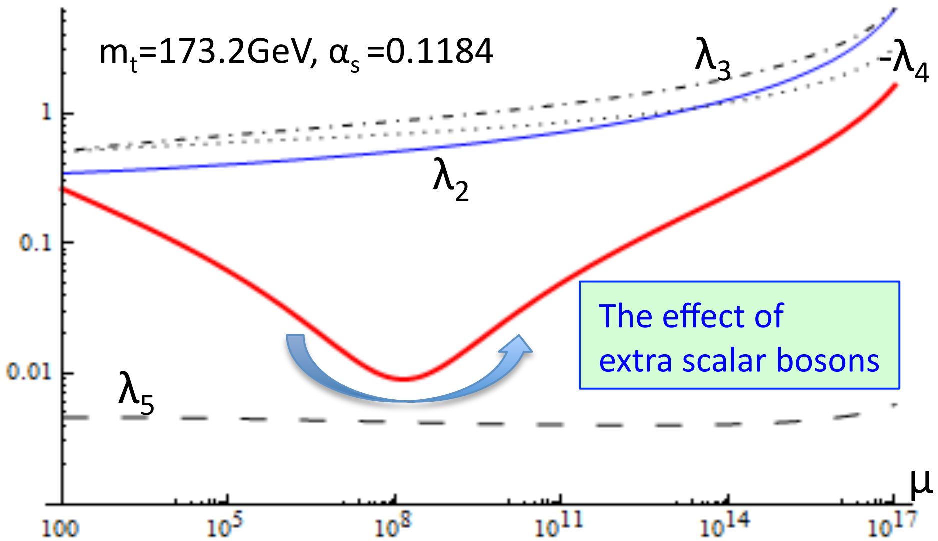
Two Higgs fields (Φ_1 , Φ_2) play a role of inflatons.

⇒In the previous study, they discussed the specific case that only one Higgs field plays a role of inflaton.

Condition of the stable potential for scalar bosons as inflatons

$$\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2 > 0$$

Renormalization Group Equations



- Higgs self coupling:

$$\beta(\lambda_1) = \frac{1}{16\pi^2}\Big[12\lambda_1^2 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 4\lambda_3\lambda_4 - 12y_t^4 + 12y_t^2\lambda_1 + \frac{9}{4}g^4 + \frac{3}{2}g^2g'^2 + \frac{3}{4}g'^4 - 3\lambda_1(3g^2+g'^2)\Big],$$

SM-like Higgs — Boson ⟺ Top quark

$$\beta(\lambda_2) = \frac{1}{16\pi^2}\Big[12\lambda_2^2 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 4\lambda_3\lambda_4 + \frac{9}{4}g^4 + \frac{3}{2}g^2g'^2 + \frac{3}{4}g'^4 - 3\lambda_2(3g^2+g'^2)\Big]$$

$$\beta(\lambda_3) = \frac{1}{16\pi^2}\Big[6\lambda_1\lambda_3 + 2\lambda_1\lambda_4 + 6\lambda_2\lambda_3 + 2\lambda_2\lambda_4 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + \frac{9}{4}g^4 + \frac{3}{4}g'^4 - \frac{3}{2}g^2g'^2 - 3\lambda_3(3g^2+g'^2) + 6\lambda_3 y_t^2\Big],$$

$$\beta(\lambda_4) = \frac{1}{16\pi^2}\Big[2\lambda_4(\lambda_1+\lambda_2+4\lambda_3+2\lambda_4) + 8\lambda_5^2 + 3g^2g'^2 - 3\lambda_4(3g^2+g'^2) + 6\lambda_4 y_t^2\Big]$$

$$\beta(\lambda_5) = \frac{1}{16\pi^2}\Big[2\lambda_5(\lambda_1+\lambda_2+4\lambda_3+6\lambda_4) - 3\lambda_5(3g^2+g'^2) + 6\lambda_5 y_t^2\Big].$$

- Gauge coupling / Top Yukawa coupling

$$\beta(g_s) = \frac{-7g_s^3}{16\pi^2},\quad \beta(g) = \frac{-3g^3}{16\pi^2},\quad \beta(g') = \frac{7g'^3}{16\pi^2},$$

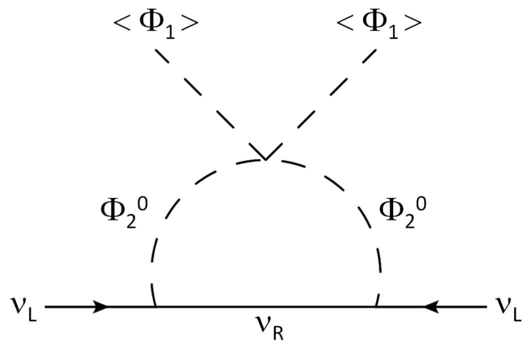
$$\beta(y_t) = \frac{y_t}{16\pi^2}\Big[\frac{9}{2}y_t^2 - 8g_s^2 - \frac{9}{4}g^2 - \frac{17}{12}g'^2\Big],$$

$$\beta(\lambda_i) = \mu\frac{\partial\lambda_i}{\partial\mu}$$

K.Inoue et al., Prog. Theor. Phys. **63**, 234(1980)

DM & m_ν on radiative seesaw scenario

E.Ma, PRD**73**, 077301(2006)



$$\mathcal{L}_{\text{Yukawa}} = Y_\ell \overline{L_L} \Phi_1 \ell_R + Y_\nu \overline{L_L} \Phi_2^c \nu_R + h.c.$$

$$\mathcal{L}_{\text{scalar}} = -V(\Phi_1, \Phi_2)$$:Φ_2 & ν_R are Z_2-odd fields.

Neutrino masses:

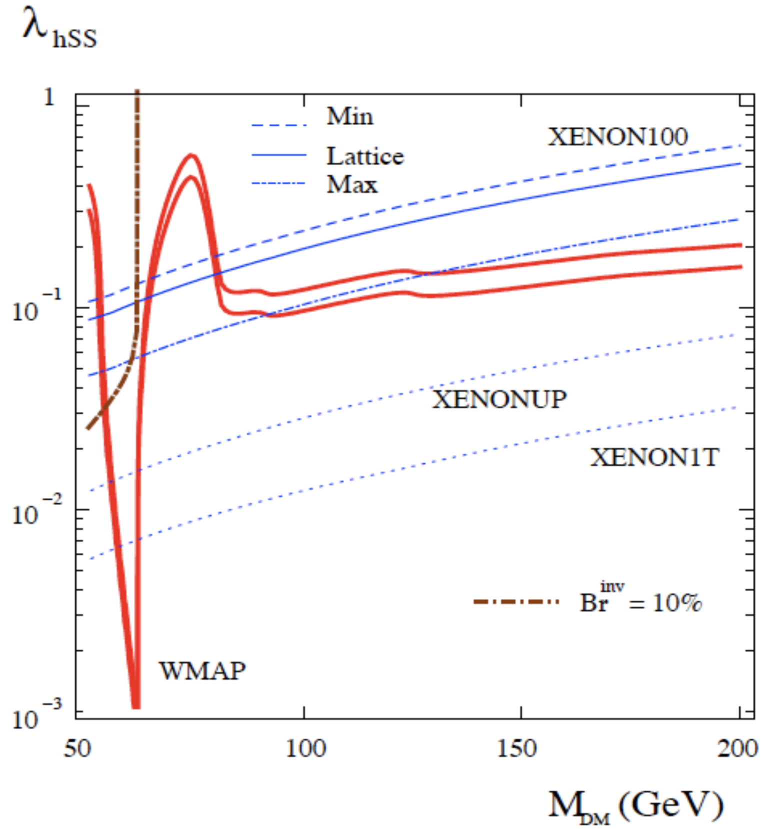
$$(m_\nu)_{ij} = \sum_k \frac{(Y_\nu)_i^k (Y_\nu)_j^k M_R^k}{16\pi^2} \left[\frac{m_H^2}{m_H^2 - (M_R^k)^2} \ln \frac{m_H^2}{(M_R^k)^2} - \frac{m_A^2}{m_A^2 - (M_R^k)^2} \ln \frac{m_A^2}{(M_R^k)^2} \right]$$

$$\simeq \sum_k \frac{(Y_\nu)_i^k (Y_\nu)_j^k M_R^k}{16\pi^2} \frac{\lambda_5 v^2}{(M_R^k)^2}$$

$$\frac{(Y_\nu)_i^k (Y_\nu)_j^k}{M_R^k} \simeq \mathcal{O}(10^{-11})\text{GeV}^{-1}$$

$$M_R^k \simeq \mathcal{O}(10^7)\text{GeV} \Rightarrow (Y_\nu)_i^k \simeq \mathcal{O}(10^{-2})$$

Constraints on dark matter mass (m_A)



$$\sigma(AN \to AN) \simeq \frac{\lambda_{hAA}^2}{4m_h^4} \frac{m_N^2}{\pi(m_A + m_N)^2} f_N^2$$

$$f_N = \sum_q m_N f_{Tq} + \frac{2}{9} m_N f_{TG}$$

$$\boxed{\lambda_{hAA} = \lambda_3 + \lambda_4 - \lambda_5 \lesssim 0.036}$$

$\Rightarrow m_A < 66\text{GeV}$

A.Djouadi et al. arXiv:1112.3299[hep-ph]

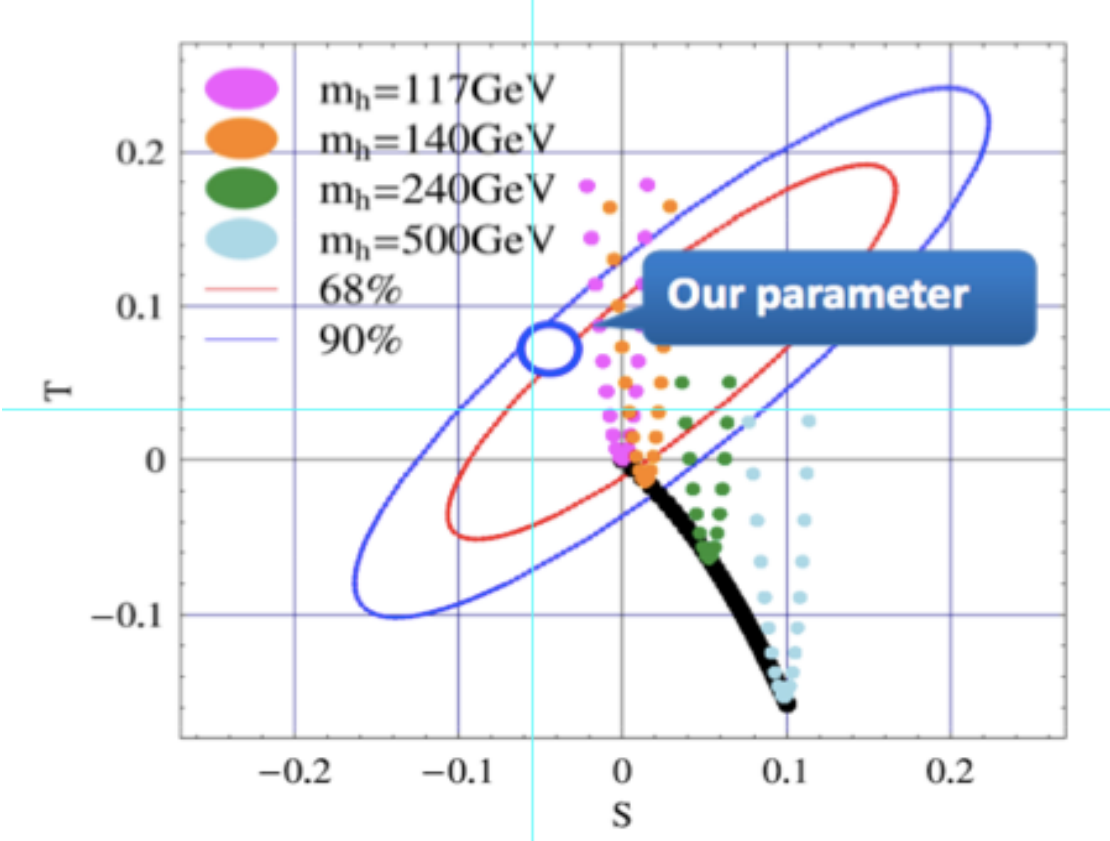
Constraint on Higgs invisible decay from LHC J.R.Espinosa, arXiv:1207.1717[hep-ph]

$Br(h \to inv) = 0.05 \pm 0.32$

To avoid kinematically $\Rightarrow m_A > 63\text{GeV}$

Constraint on the electroweak parameters

S.Kanemura, Y.Okada, H.Taniguchi, K.Tsumura, arXiv: 1108.3297[hep-ph]



m_A~65GeV, m_H~67GeV

↓

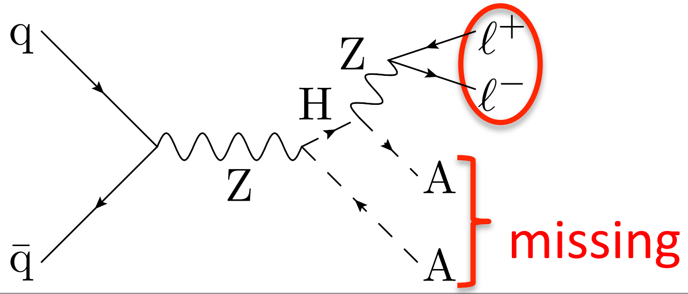
S~ -0.040, T~ 0.095

⇒Our parameter satisfy constraint on S, T parameters

Testability at the LHC

$\sqrt{s} = 14\text{TeV}$

Benchmark	m_h (GeV)	m_A(GeV)	δ_1 (GeV)	δ_2 (GeV)	λ_L
LH1	150	40	100	100	-0.275
LH2	120	40	70	70	-0.15
LH3	120	82	50	50	-0.20
LH4	120	73	10	50	0.0
LH5	120	79	50	10	-0.18



$\delta_1 \equiv m_{H^\pm} - m_A$
$\delta_2 \equiv m_H - m_A$
$\lambda_L \equiv \lambda_3 + \lambda_4 + \lambda_5$

Benchmark	Level I Cuts			Level I+II Cuts		
	σ_{AH} (fb)	$\sigma_{H^+H^-}$ (fb)	σ_{hZ} (fb)	σ_{AH} (fb)	$\sigma_{H^+H^-}$ (fb)	σ_{hZ} (fb)
LH1	9.61	0.82	2.90	6.03	0.46	1.79
LH2	10.28	1.06	5.75	6.53	0.51	3.47
LH3	2.32	0.34	0.01	1.47	0.13	0.01
LH4	3.84	0.19	0	2.07	0.02	0
LH5	0.38	~ 0	0.01	~ 0	0.14	0.01

SM Backgrounds	Level I Cuts σ_{BG} (fb)	Level I+II Cuts σ_{BG} (fb)
WW	621.44	316.97
ZZ/γ^*	132.09	76.46
$t\bar{t}$	4531.51	58.87
WZ/γ^*	113.97	51.85
Wt	709.14	52.11
Total SM Background	6108.15	556.26

<u>Level I Cuts</u>

- Exactly two electrons or muons with opposite charge.
- $p_T^\ell \geq 15$ GeV and $|\eta_\ell| \leq 2.5$ for each of these charged leptons.
- For lepton isolation, we require $\Delta R_{\ell\ell} \geq 0.4$ for the charged-lepton pair, and $\Delta R_{\ell j} \geq$ 0.4 for each combination of one jet and one charged lepton.

<u>Level II Cuts</u>

- No jets with $p_T^j > 20$ GeV and pseudorapidity within the range $|\eta_j| < 3.0$.
- $\not{E}_T > 30$ GeV.

E.Dolle, X.Miao, S.Su, B.Thomas, PRD81, 035003(2010)

Testability at the LHC

$\sqrt{s} = 14\text{TeV}$
$L = 100\text{fb}^{-1}$

E.Dolle, X.Miao, S.Su, B.Thomas, PRD81, 035003(2010)

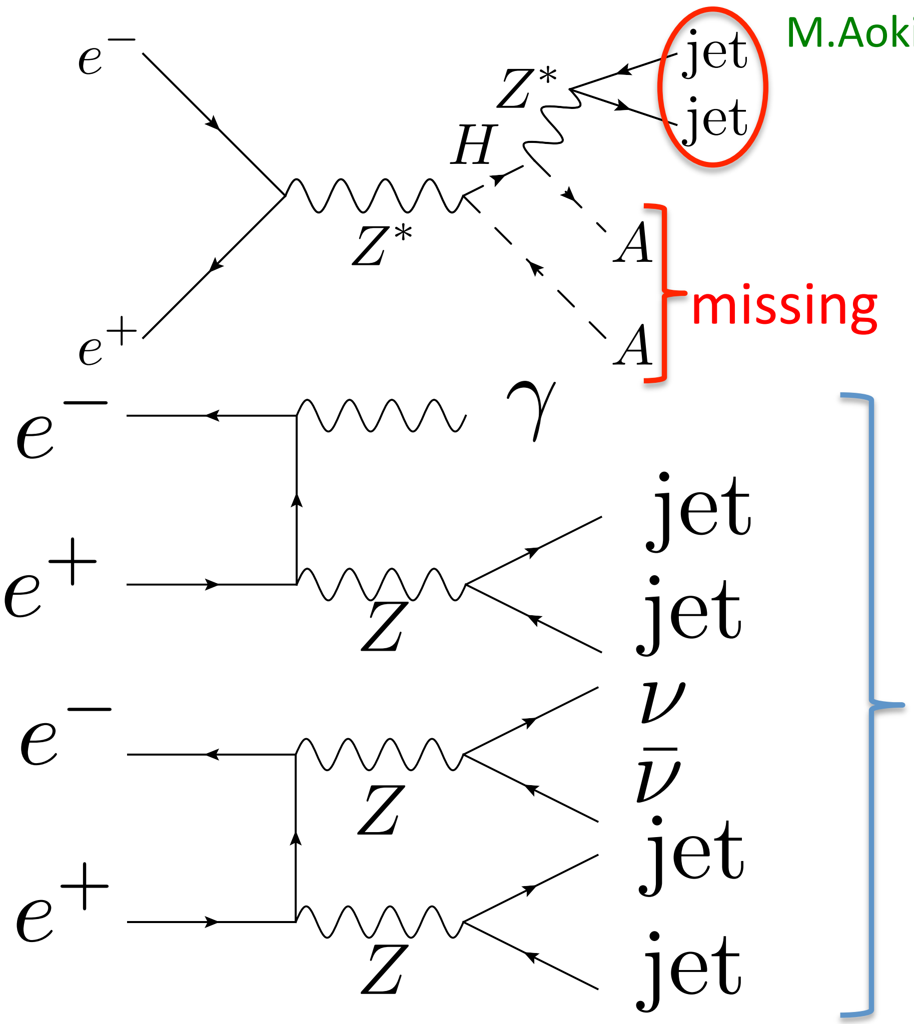
Benchmark	Level III Cuts										
	σ_{AH} (fb)	$\sigma_{H^+H^-}$ (fb)	σ_{hZ} (fb)	σ_{WW} (fb)	σ_{ZZ/γ^*} (fb)	$\sigma_{t\bar{t}}$ (fb)	σ_{WZ/γ^*} (fb)	σ_{Wt} (fb)	$\sigma_{\rm BG}^{\rm comb}$ (fb)	S/B	$S/\sqrt{B}$
LH1	3.42	0.04	1.28	11.59	36.99	4.55	19.52	3.82	77.79	0.04	3.87
LH2	0.89	~ 0	0.01	0.07	0.24	0.11	0.08	0.07	0.58	1.53	11.66
LH3	0.18	~ 0	~ 0	0.03	0.15	0.05	0.04	0.06	0.34	0.52	3.04
LH4	0.19	~ 0	0	0.03	0.15	0.05	0.04	0.06	0.34	0.57	3.29
LH5	0.004	~ 0	~ 0	0.13	0.04	~ 0	0.04	0.01	0.23	0.02	0.02

LevelⅢ Cuts

Benchmark	$M_{\ell\ell}^{\rm min}$	$M_{\ell\ell}^{\rm max}$	$\Delta R_{\ell\ell}^{\rm max}$	$\cos\phi_{\ell\ell}^{\rm min}$	$H_T^{\rm min}$	$\not{E}_T^{\rm min}$	$p_{T\ell}^{\rm max}$
LH1	80 GeV	100 GeV	–	–	150 GeV	50 GeV	–
LH2	–	70 GeV	1.2	0.7	200 GeV	100 GeV	–
LH3	20 GeV	50 GeV	0.8	0.7	200 GeV	90 GeV	–
LH4	20 GeV	50 GeV	0.8	0.7	200 GeV	90 GeV	–
LH5	–	10 GeV	0.6	0.9	–	30 GeV	25 GeV

HA pair production

M.Aoki, S.Kanemura, H.Yokoya, Phys Lett. B **725** (2013) 302



Back Ground

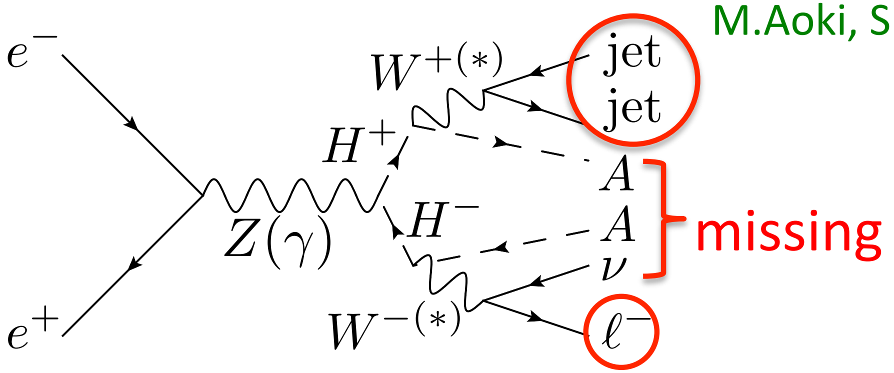
$$\sqrt{s} = 500\text{GeV}$$

$$L = 500\text{fb}^{-1}$$

$$\sigma_{e^-e^+\to HA} \simeq 50\text{fb}^{-1}$$

H^+H^- pair production

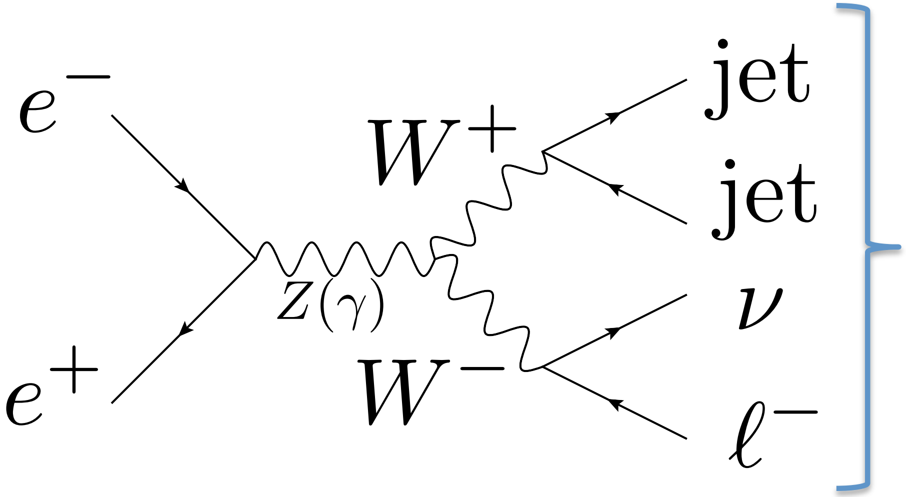
M.Aoki, S.Kanemura, H.Yokoya, Phys Lett. B **725** (2013) 302



$$\sqrt{s} = 500\text{GeV}$$

$$L = 500\text{fb}^{-1}$$

$$\sigma_{e^-e^+\to H^+A^-} \simeq 80\text{fb}^{-1}$$



Back Ground

Branching ratio h→γγ

$$\frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}(h_{\mathrm{SM}} \to \gamma\gamma)} = \frac{|F_1(\tau_W) + 3(\frac{2}{3})^2 F_{1/2}(\tau_t)|^2 + \frac{\lambda_3 v^2}{2m_{H^\pm}} F_0(\tau_{H^\pm})}{|F_1(\tau_W) + 3(\frac{2}{3})^2 F_{1/2}(\tau_t)|^2}$$

$$\simeq 0.9$$

m_W=80.2GeV, m_t=173GeV, m_h~126GeV, $m_{H\pm}$~140GeV

$$F_1 = \frac{2\tau_i^2 + 3\tau_i + 3(2\tau_i - 1)f(\tau_i)}{\tau_i^2} \quad F_{1/2} = -\frac{2[\tau_i + (\tau_i - 1)f(\tau_i)]}{\tau_i^2} \quad F_0 = \frac{\tau_i - f(\tau_i)}{\tau_i^2}$$

$$f(\tau_i) = \begin{cases} arcsin^2 \sqrt{\tau_i} & \tau_i \leq 1 \\ -\frac{1}{4}[log \frac{1+\sqrt{1-\tau_i^{-1}}}{1-\sqrt{1-\tau_i^{-1}}} - i\pi]^2 & \tau_i > 1 \end{cases} \quad \tau_i = (\frac{m_h}{2m_i})^2$$

$$i = W, t, H^\pm$$

P.Posch, Phys. Lett. B **558**, 157(2003)