A model for the Higgs inflation and its testability at the ILC

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LCWS12: 23 Oct. 2012

1.Introduction

Why we need an inflation?

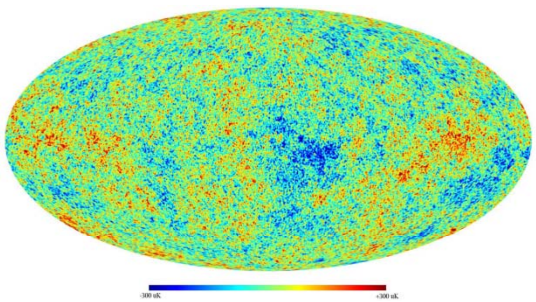
- The flatness problem

$$\Omega_0 = 1.002 \pm 0.011$$

$$|\Omega_P - 1| \lesssim O(10^{-60})$$

The Universe is flat
but the standard cosmology
cannot explain this flatness.

- The horizon problem



The temperature of the CMB
is almost the same value but
light cone cover less than 2°

These problems can be solved by exponential expansion.

1.Introduction

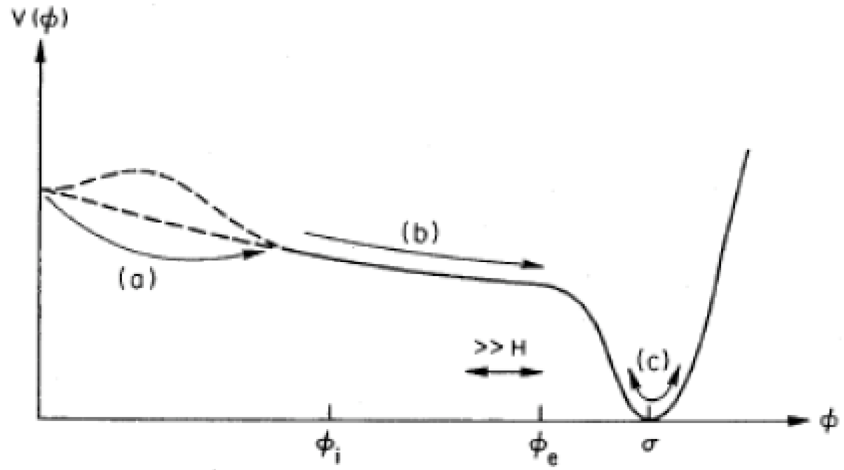
Inflation

We introduce a real scalar ϕ

$$\mathscr{L} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

⇩

$$H^2 = \frac{V}{3M_P^2} \qquad \left(H = \frac{\dot{a}}{a} \right)$$



If H is a constant, The Universe expands by exponential.

⇨ $\varepsilon \equiv \frac{1}{2} M_P{}^2 (V'/V)^2 << 1 \quad \eta \equiv M_P{}^2 V''/V << 1$

If potential satisfies the slow-roll condition,
ϕ can act as an inflaton.

2.Higgs inflation

Inflaton＝Higgs

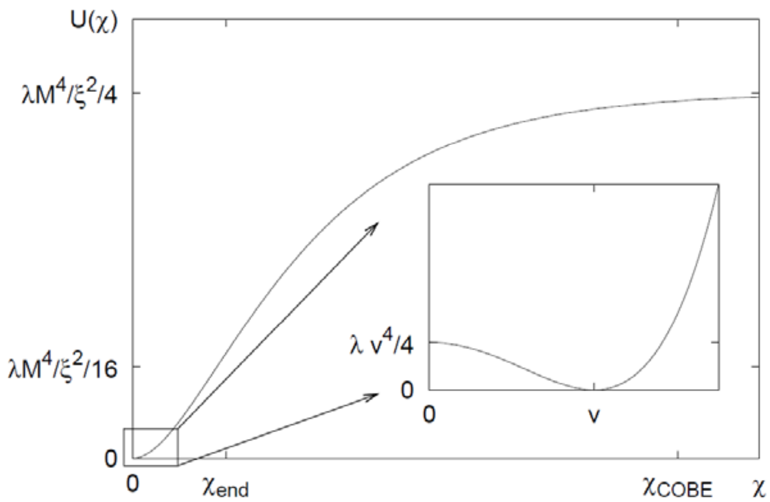
- **Higgs boson mass (m_h=126GeV)**
- **Slow-roll condition(ε, η)**
- **CMB temperature fluctuations (P_R)**

$$\varepsilon \equiv \tfrac{1}{2} M_P{}^2 (V'/V)^2 << 1$$
$$\eta \equiv M_P{}^2 V''/V << 1$$

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R$$

$$V(\chi) = \left(1 + \exp\left(-\frac{2\chi}{\sqrt{6} M_P}\right)\right)^{-2}$$

$$\left(\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}}\right)$$



Bezrukov and Shaposhnikov (2008)

WMAP:

$$P_R = 2.430 \pm 0.091 \times 10^{-9}$$

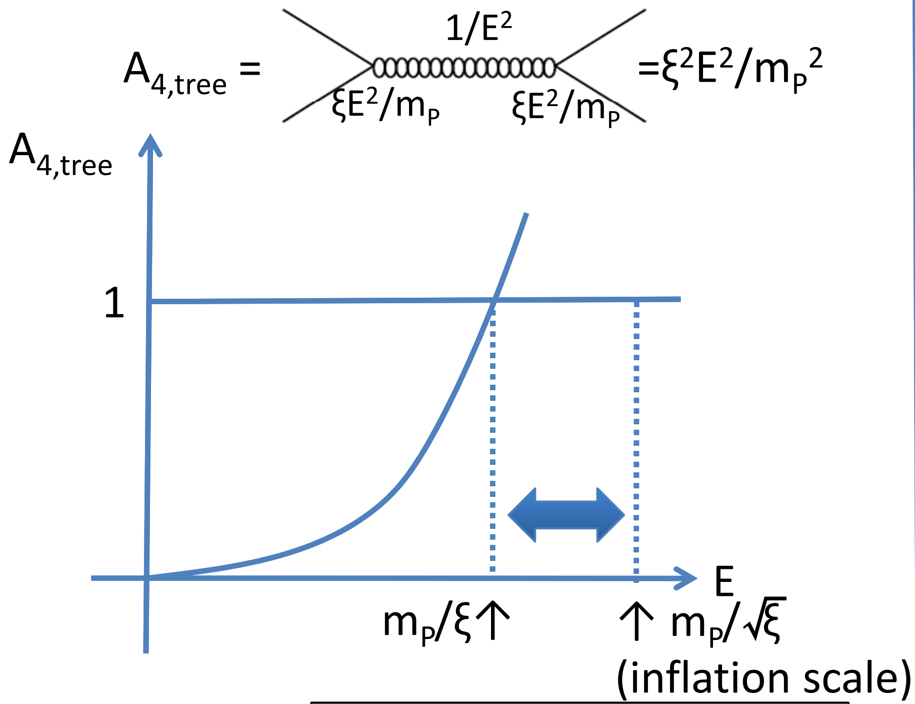
⇨ $$\xi = 5 \times 10^4 \sqrt{\lambda}$$

SM-Higgs satisfies ε, η and P_R !

But! Problems in the simplest case

(Ⅰ)Unitarity

T. Han and S. Willenbtock, Phys. Lett. B 616, 215 (2005)

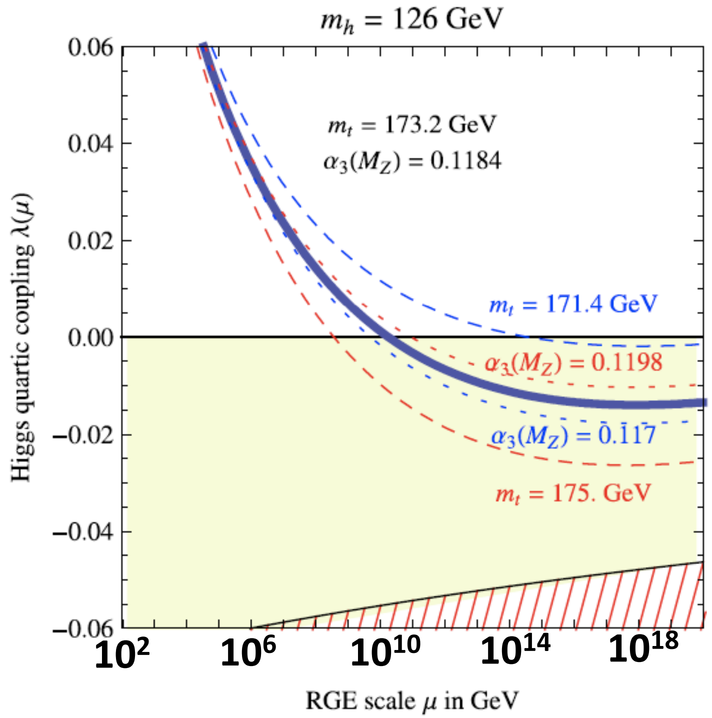


$\xi = O(10^4) \Rightarrow \Lambda \sim m_P/\xi$

Unitarity is broken at $O(10^{15})$ GeV

(Ⅱ)Vacuum stability

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



$m_h = 126\,\text{GeV} \Rightarrow \Lambda \sim 10^{10}\,\text{GeV}$

Vacuum cannot be stabilized at $O(10^{10})$ GeV

⇒Simplest Higgs inflation cannot reach to the inflation scale

Solutions for the problems

(Ⅰ) Unitarity G.F.Giudice, H.M.Lee, PLB694, 294(2011)

We add a heavy scalar particle saving unitarity.

(Ⅱ) Vacuum stability⇒ Extended Higgs sector.

・Renormalization group equations

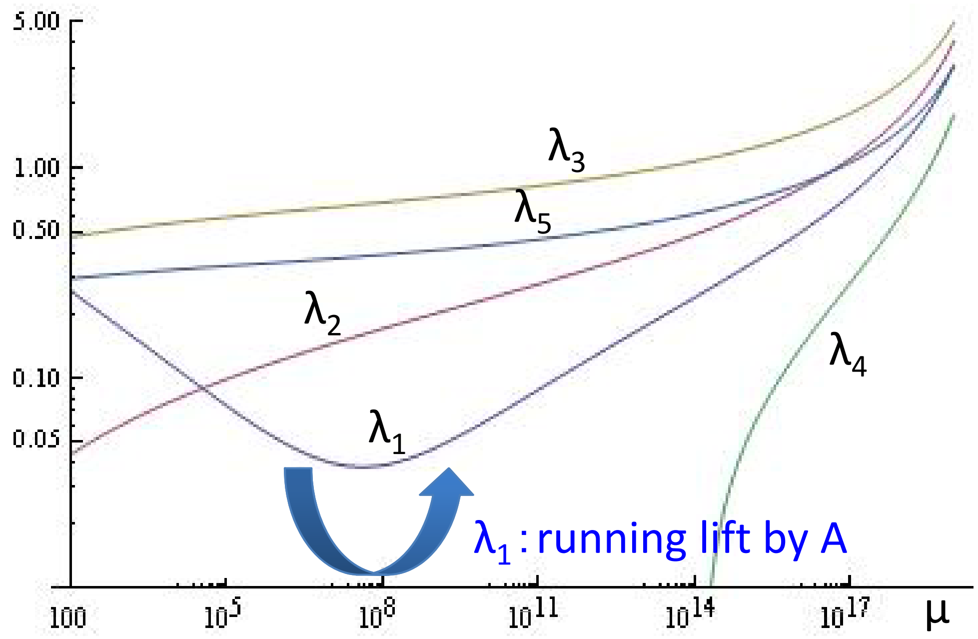
$$16\pi^2\mu\frac{d\lambda_1}{d\mu} \sim 12\lambda_1^2 - 12y_t^4 \underline{+A}$$

The new bosonic loop cancel the y_t effect!

2HDM

$$A = 2\lambda_3^2 + 2(\lambda_3+\lambda_4)^2 + 2\lambda_5^2 > 0$$

S.Kanemura, T.Kasai, Y.Okada, Phys.Lett. B471 (1999)



m_h=126GeV, m_t=173.5GeV

Previous work

The inert doublet model

Gong, Lee and Kang (2012)

$$V = \frac{M_P R}{2} + (\xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2)R$$
$$+\mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2]$$

$$\Phi_1 = (\phi^+, \phi^0)$$
$$\Phi_2 = [H^+, (H^0 + iA^0)/\sqrt{2}]$$

$$m_h^2 = \lambda_1 v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$
$$m_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2$$
$$m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2$$

Vacuum stability:

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

Inflaton condition:

$$\lambda_2\xi_1 - (\lambda_3 + \lambda_4)\xi_2 > 0$$
$$\lambda_1\xi_2 - (\lambda_3 + \lambda_4)\xi_1 > 0$$
$$\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2 > 0$$

CMB temperature fluctuations: $a \equiv \xi_1/\xi_2$

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

Inflation can be explained

⇕

Dark matter and neutrino masses cannot be explained.

3.Our Model

Inert + ν_R

Our model can explain:

Inflation (inert doublet model)

Neutrino masses (radiative seesaw)

Dark matter (CP-odd higgs A)

The mass spectrum is almost determined from the current data.

Our model can be tested by measuring model parameters at collider experiments

3.Our Model

Inflation

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

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

CMB temperature fluctuations:

$$a \equiv \xi_1/\xi_2$$

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3.Our Model

Inflation

$$V = \frac{M_P R}{2} + (\xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2)R$$
$$+\mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2]$$

Vacuum stability:

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CMB temperature fluctuations:

$$a \equiv \xi_1/\xi_2$$
$$\xi_2\sqrt{\frac{2(\lambda_1 + a^2\lambda_2 - 2a(\lambda_3+\lambda_4))}{\lambda_1\lambda_2 - (\lambda_3+\lambda_4)^2}} \simeq 5\times 10^4$$
$$\frac{\lambda_5}{\xi_2}\frac{a\lambda_2 - (\lambda_3+\lambda_4)}{\lambda_1 + a^2\lambda_2 - a(\lambda_3+\lambda_4)} \leq 4\times 10^{-12}$$

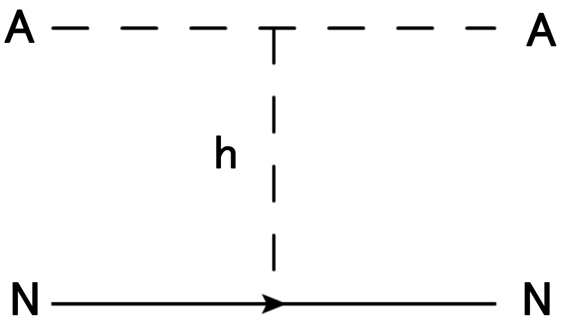
$a\lambda_2 - (\lambda_3+\lambda_4) \approx 0$
at the inflation scale

⇩

λ_5 becomes a large value

3.Our Model

Dark matter



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

$$\lambda_{hAA} \equiv \lambda_3 + \lambda_4 - \lambda_5$$

$$f_N \equiv \sum_{q=u,d,s} m_N f_{Tq} + \frac{2}{9} m_N f_{Tg}$$

For vacuum stability bound $\lambda_1 > 0 \to \lambda_{3,4,5} \gtrsim O(0.1)$

$\lambda_{hAA} = 0.1 \;\to\; \sigma(AN \to AN) \sim 1.5 \times 10^{-44}\ \mathrm{cm}^2$

(XENON100: $\sigma(AN \to AN) < 2 \times 10^{-45}\mathrm{cm}^2$)

XENON collaboration (2012)

$\lambda_3+\lambda_4-\lambda_5 \approx O(0.01)$ at $O(10^2)$ GeV

3.Our Model

Mass spectrum

	10^2GeV	10^{17}GeV
λ_1	0.262	1.75
λ_2	0.367	9.00
λ_3	0.495	7.11
λ_4	-0.447	-3.16
λ_5	0.0700	0.116

← m_H=126GeV (LHC)

← Inflation

← Dark matter(WMAP+XENON100)

m_h=126GeV

m_H=92.0GeV
$m_{H\pm}$=141GeV
m_A=65.0GeV

a=0.4,
$\xi_2=5\times 10^5$,
$\mu_2^2 \sim 4230\text{GeV}^2$

$m_A < m_H\ (\approx 90\text{GeV}) < m_h < m_{H\pm}\ (\approx 140\text{GeV})$

Our model predicts
the mass spectrum of inert scalar bosons !

4.Phenomenology

LHC

Q.H.Cao, E.Ma, G.Rajasekaran(2007)

$$pp \to Z^* \to AH \to HHZ^* \to HH\ell^+\ell^-$$

$$15 \text{ GeV} \leq P_T^\ell \leq 40 \text{ GeV} \quad |\eta^\ell \leq 3.0|$$

$$\cos\theta_{\ell\ell} \geq 0.9 \quad \cos\phi_{\ell\ell} \geq 0.9$$

$$E_{T miss} \leq 60 \text{ GeV} \quad m_{\ell\ell} \leq 10 \text{ GeV}$$

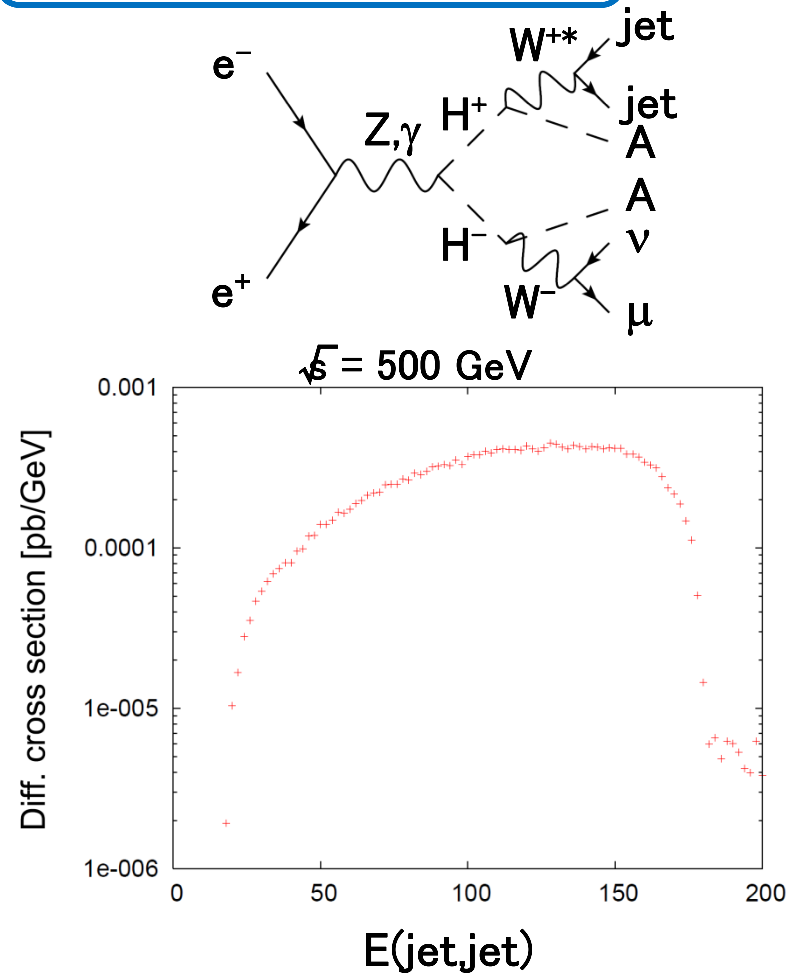
BKGD	basic	optimal	$m_{\ell\ell} < 10\,\text{GeV}$
WW	1.1×10^5	110	62
ZZ	2.1×10^4	3	0
total	1.3×10^5	113	62

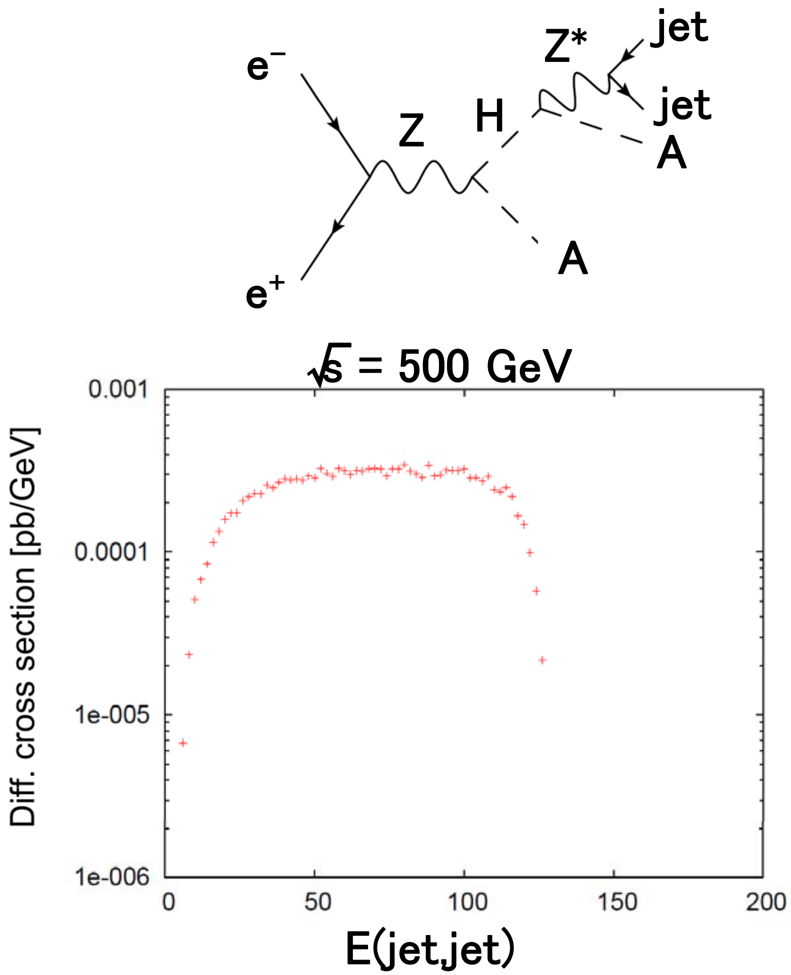
Signal (m_{H^0}, m_{A^0})	basic	optimal	$m_{\ell\ell} < 10\,\text{GeV}$
(50, 60)	117	37	37
S/B	9×10^{-4}	0.33	0.60
$S/\sqrt{B}$	0.32	3.48	4.70
(50, 70)	433	56	50
S/B	3.3×10^{-3}	0.50	0.81
$S/\sqrt{B}$	1.20	5.27	6.35
(50, 80)	680	38	26
S/B	5.2×10^{-3}	0.34	0.42
$S/\sqrt{B}$	1.89	3.57	3.3

If m_A = 65 GeV and m_H is large,
it would be difficult to test
at the LHC

4.Phenomenology

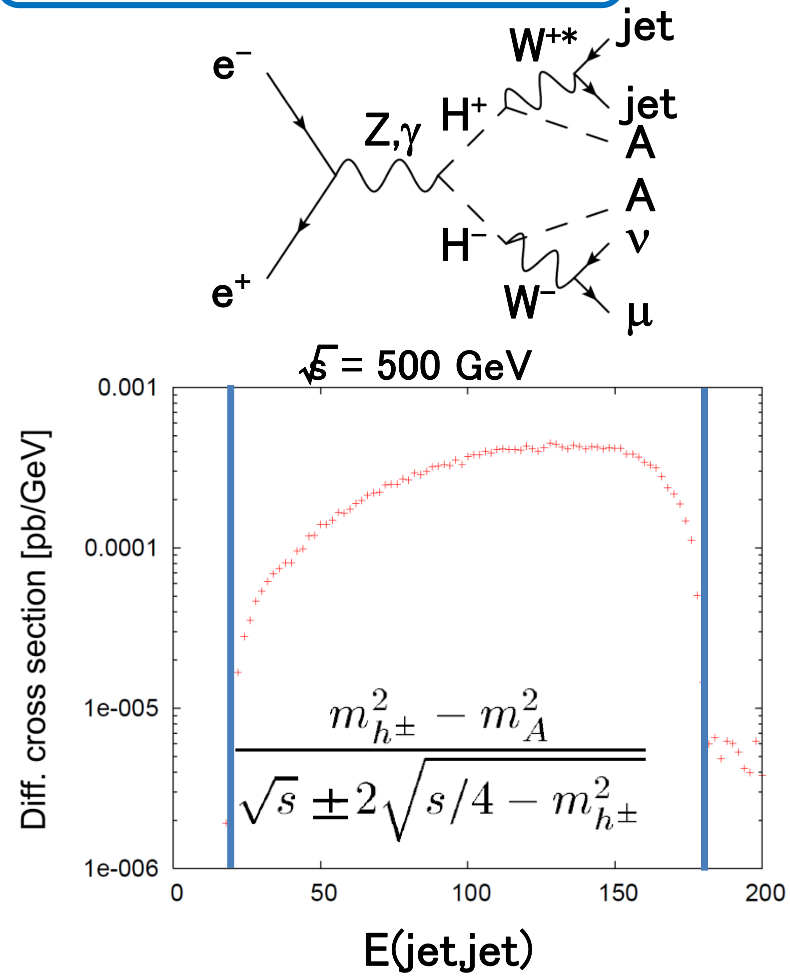
ILC

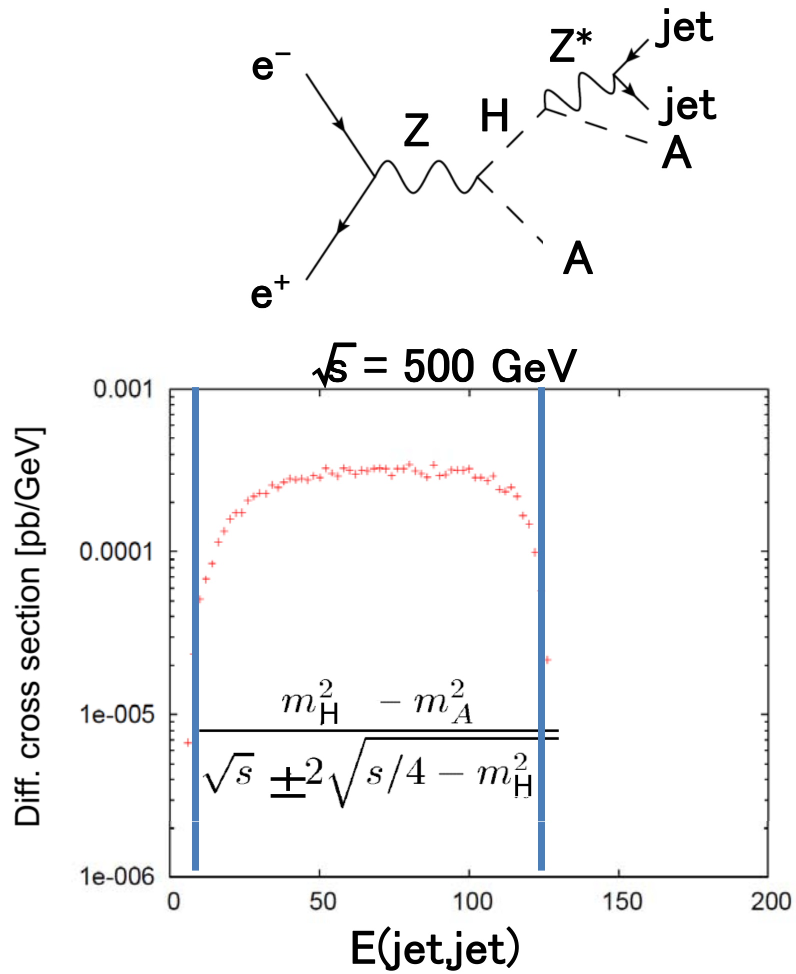




4.Phenomenology

ILC

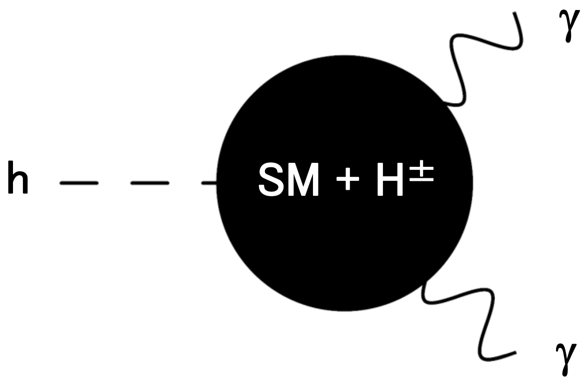




The mass spectrum of inert scalar bosons could be measured at the ILC

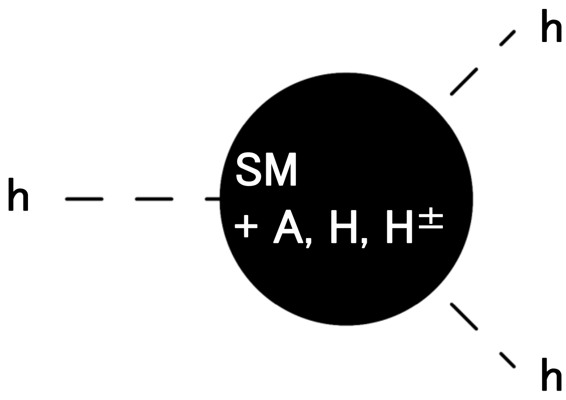
4.Phenomenology

h to γγ



$$\frac{BR[h_1 \to \gamma\gamma]}{BR[h_{SM} \to \gamma\gamma]} \approx 0.982$$

λ_{hhh}



$$\frac{\lambda_{hhh} - \lambda^{SM}_{hhh}}{\lambda^{SM}_{hhh}} \approx 0.0118$$

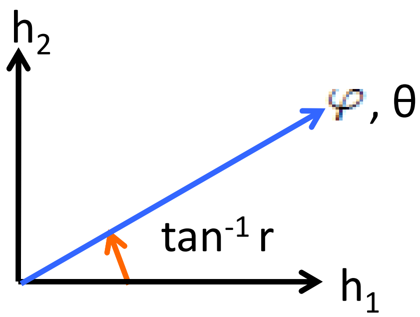
5.Conclusion

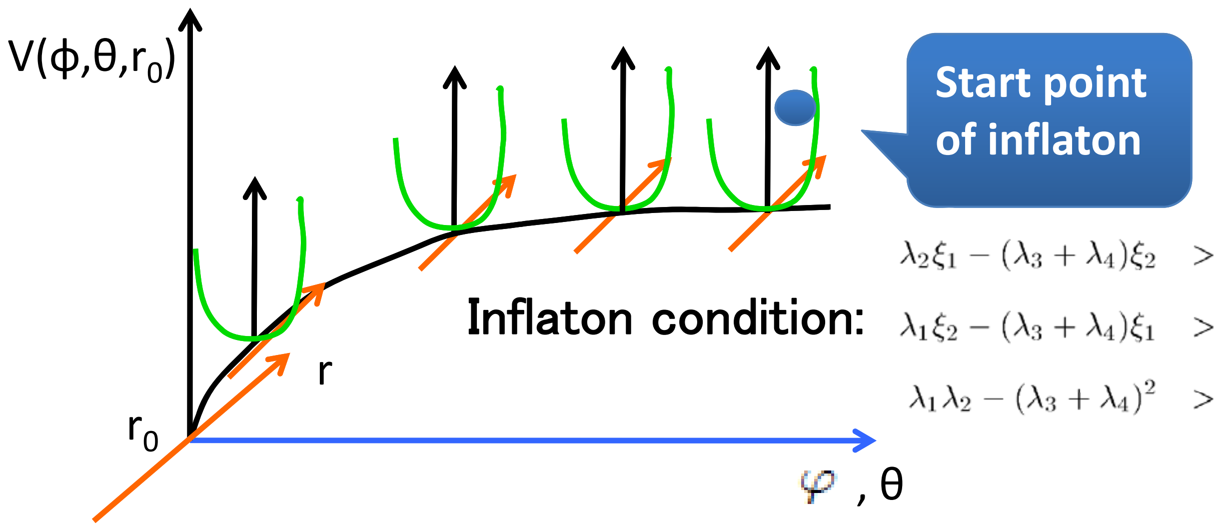
① We consider the case of the Higgs inflation.
② It is difficult that SM act as the inflation
③ We show that inflation, dark matter and neutrino masses can be explained simultaneously by the inert doublet with right handed neutrinos.
④ **Our model predicts mass spectrum of inert scalar boson.**
⑤ **Mass spectrum of inert scalar boson could be tested at the ILC.**
⑥ **If Higgs and inert doublet components act as an inflaton, this case could be tested at the ILC.**

Back up

Inflation of inert doublet model

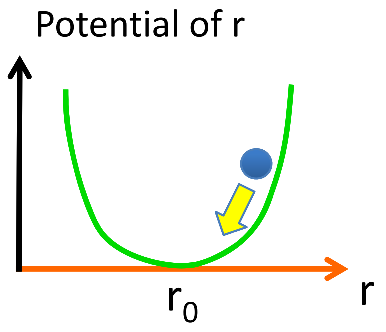
$$\begin{cases} \Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_1 \end{pmatrix} \\ \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_2 e^{i\theta} \end{pmatrix} \end{cases} \Rightarrow \begin{cases} r = \frac{h_2}{h_1} \\ \varphi = \sqrt{\frac{3}{2}} \log(1 + \xi_1 h_1^2 + \xi_2 h_2^2) \end{cases}$$

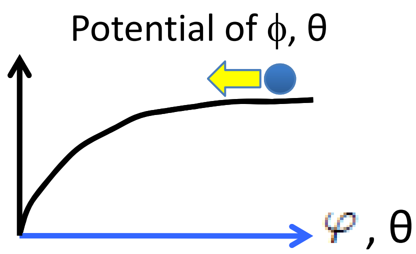




Inflaton condition:

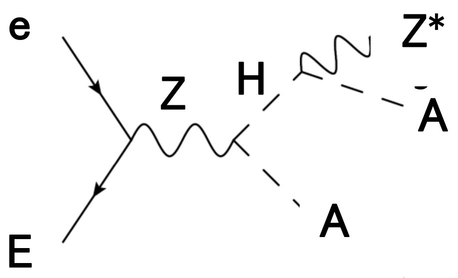
$$\begin{aligned} \lambda_2\xi_1 - (\lambda_3 + \lambda_4)\xi_2 &> 0 \\ \lambda_1\xi_2 - (\lambda_3 + \lambda_4)\xi_1 &> 0 \\ \lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2 &> 0 \end{aligned}$$



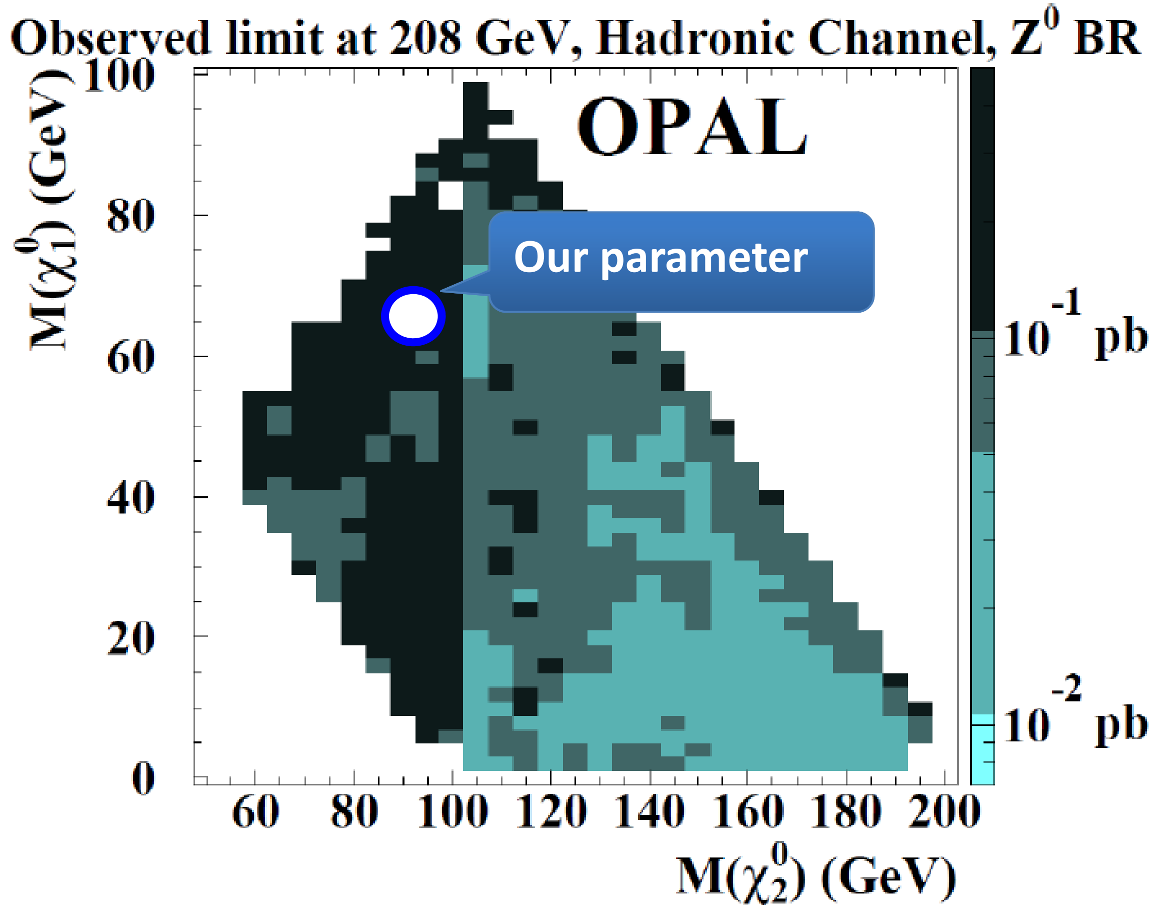


Inflation is happened on minimum value of r

LEP bound

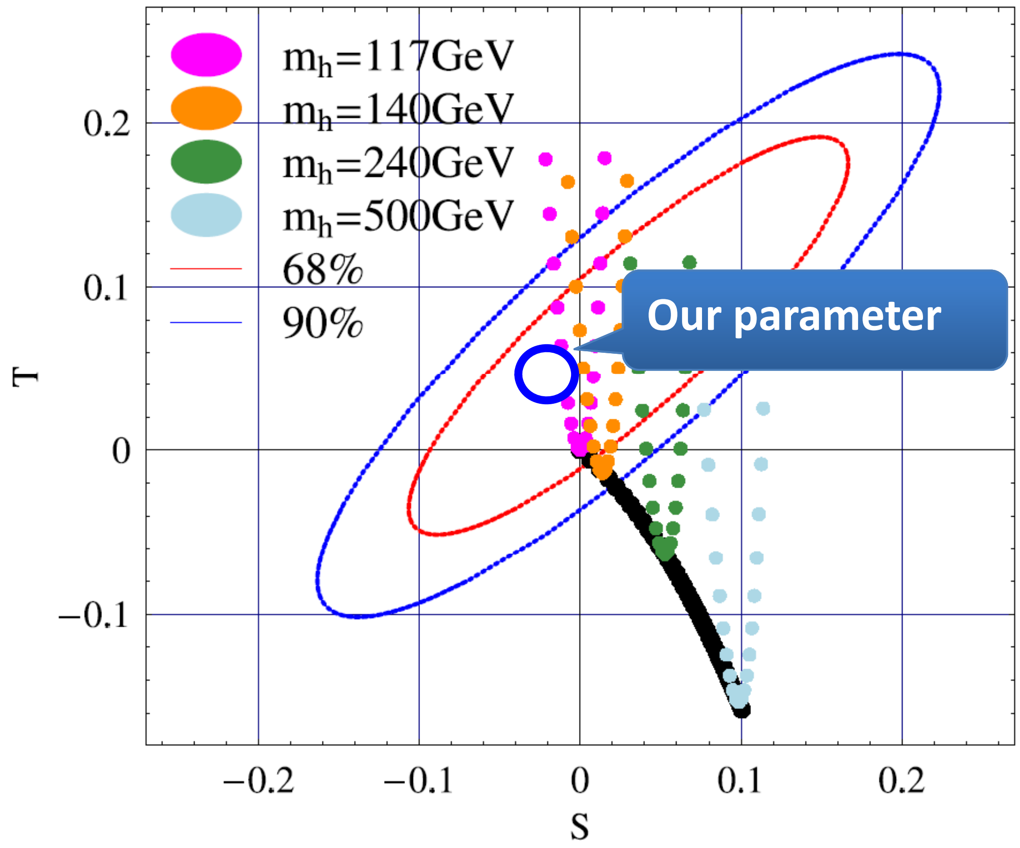


XS ≈ 1 × 10^{-1} pb



Our parameter consistent with LEP bound

LEP bound



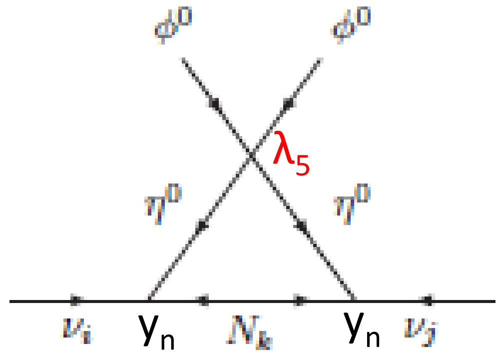
Our parameter consistent with LEP bound

3.Our model

Inert + ν_R

- Inflation
- Dark matter
- neutrino masses

Ma model



$$m_\nu = \frac{\lambda_5 v^2}{8\pi^2}\frac{y_n^2}{M}\left(\ln\frac{M^2}{m_0^2} - 1\right)$$

M:majorana mass of N_k,
m_0:mass of inert higgs (η^0)

E. Ma, Phys. Rev. D **73**, 077301 (2006)

Our model can explain these problem and would be tested at collider experiments