Phenomenology of inflation inspired two Higgs doublet model with singlet (2HDMS)

Master Thesis Project - Work in Progress

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Outline

Motivation

- Flatness Problem
- Horizon Problem
  $\Rightarrow$ Inflation
- expansion by a factor of 10^{30} within 10^{-32} s

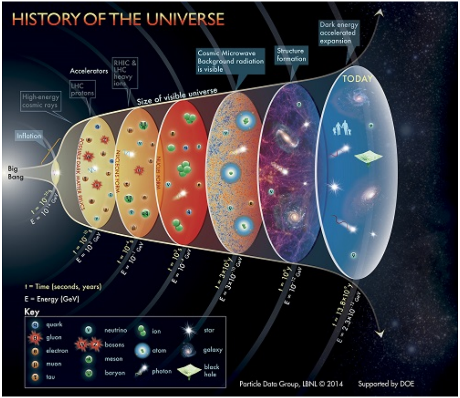


Figure: history of the universe, from [3]

This Work: add inflation term to 2HDMS and look at the Higgs sector

2HDMS Overview

- $SU(2)_L$ fields:

$$\phi_1 = \begin{pmatrix} \chi_1^+ \\ \nu_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix} \quad \phi_2 = \begin{pmatrix} \chi_2^+ \\ \nu_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}$$

- Singlet

$$S = \nu_S + \frac{\rho_S + i\eta_S}{\sqrt{2}}$$

impose $\mathbb{Z}_2$ symmetry to avoid flavour changing neutral currents

$$\phi_2 \Rightarrow -\phi_2$$

impose $\mathbb{Z}_3$ symmetry

$$\begin{pmatrix} \phi_2 \\ S \end{pmatrix} = \begin{pmatrix} \exp\left(i\frac{2\pi}{3}\right) & 0 \\ 0 & \exp\left(-i\frac{2\pi}{3}\right) \end{pmatrix} \begin{pmatrix} \phi_2 \\ S \end{pmatrix}$$

Potential

Add $\mathbb{Z}_3$ breaking inflation term.

$$V = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \frac{\lambda_3}{2}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)$$
$$+ \frac{\lambda_4}{2}(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_2) + m_S^2(S^\dagger S) + \lambda_1'(\phi_1^\dagger\phi_1)(S^\dagger S) + \lambda_2'(\phi_2^\dagger\phi_2)(S^\dagger S)$$
$$+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + (-m_{12}^2(\phi_1^\dagger\phi_2) + mu_{12}S(\phi_1^\dagger\phi_2) + \mu_{S1}S^3$$
$$+ \mu_{inf}S(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2) + h.c.)$$

Define

$$\nu = \sqrt{\nu_1^2 + \nu_2^2} \quad \tan\beta = \frac{\nu_2}{\nu_1}$$

Tadpole equations

Minimization conditions:

$$\left.\frac{\partial V}{\partial \phi_1}\right|_{\substack{\phi_1=\nu_1\\ \phi_2=\nu_2\\ S=\nu_S}} = 0, \quad \left.\frac{\partial V}{\partial \phi_2}\right|_{\substack{\phi_1=\nu_1\\ \phi_2=\nu_2\\ S=\nu_S}} = 0, \quad \text{and} \quad \left.\frac{\partial V}{\partial \phi_S}\right|_{\substack{\phi_1=\nu_1\\ \phi_2=\nu_2\\ S=\nu_S}} = 0.$$

Thus we can replace m_{11}, m_{22} and m_S with

$$m_{11}^2 = -\lambda_1 v_1^2 - \Big(\lambda_3 + \lambda_4\Big)\nu_2^2 - 2\mu_{inf}\nu_1^2 + \Big(m_{12} - \mu_{12}\nu_S\Big)\frac{\nu_2}{\nu_1}$$

$$m_{22}^2 = -\lambda_2 v_2^2 - \Big(\lambda_3 + \lambda_4\Big)\nu_1^2 - 2\mu_{inf}\nu_1^2 + \Big(m_{12} - \mu_{12}\nu_S\Big)\frac{\nu_1}{\nu_2}$$

$$m_S^2 = -\lambda_1' v_1^2 - \lambda_2' v_2^2 - \frac{\lambda_3''}{2} - \frac{\mu_{S1}}{2}\nu_S - \mu_{12}\frac{\nu_1\nu_2}{\nu_S} - \mu_{inf}\left(\frac{\nu_1^2}{\nu_S} + \frac{\nu_2^2}{\nu_S}\right)$$

free Parameter

Interaction basis

$$\tan\beta, \lambda_{1,2,3,4}, \lambda'_{1,2}, \lambda''_{3}, m^2_{12}, \mu_{12}, \mu_{S1}, \nu_S, \mu_{inf}$$

Mass matrices

$$M^2_{S,ij} = \frac{\partial^2 V}{\partial\rho_i\rho_j}\Big|_{\substack{\phi_1=\nu_1\\ \phi_2=\nu_2\\ S=\nu_S}} \quad M^2_{P,ij} = \frac{\partial^2 V}{\partial\eta_i\eta_j}\Big|_{\substack{\phi_1=\nu_1\\ \phi_2=\nu_2\\ S=\nu_S}} \quad M^2_{C,ij} = \frac{\partial^2 V}{\partial\chi_i\chi_j}\Big|_{\substack{\phi_1=\nu_1\\ \phi_2=\nu_2\\ S=\nu_S}}$$

Rotate into mass basis

$$RM^2_S R^\dagger = M^{dia}_h \quad R_A M^2_P R^\dagger_A = M^{dia}_a$$

$$\tan\beta, \alpha_{1,2,3,4}, m_{h1,2,3}, m_{a1,2}, m_\pm, \nu_S, \mu_{inf}$$

Constraints

Experimental:
Measurement of Standard Model Higgs (HiggsSignals)
Constraints for BSM searches (HiggsBounds)

(not implemented yet:)
Theoretical:
Tree level pertubative unitary
Boundness from below
Vacuum stability

95 GeV Excess

Excess at $\sim 95.4 GeV$ in

- $gg \rightarrow h \rightarrow \gamma\gamma$
  CMS: 2.9 σ local significance
  ATLAS: 1.7 σ local significance
- $gg \rightarrow h \rightarrow \tau^+\tau^-$
  CMS: 2.6 σ local significance
- $e^+e^- \rightarrow Z\phi \rightarrow Zbb$
  LEP: 2.1 σ local significance

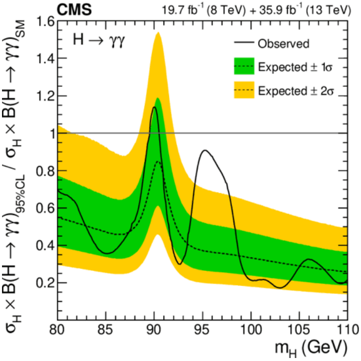


Figure: Expected and observed exclusion limits of the production cross section/branching fraction H $->\gamma\gamma$, from [1]

Results: Working Point

$\mu_{inf} \rightarrow$ impact on trilinear couplings expected
choose point at alignment limit

m_{h1}	m_{h2}	m_{h3}	m_{A2}	m_{A2}	m_{Hm}
600	125.09	95.4	450	500	800
a_1	a_2	a_3	a_4	v	$\tan(\beta)$
-0.694738	0	0	0	174.104234	1.2

Table: Parameters at alignment limit

Results: Trilinear Couplings

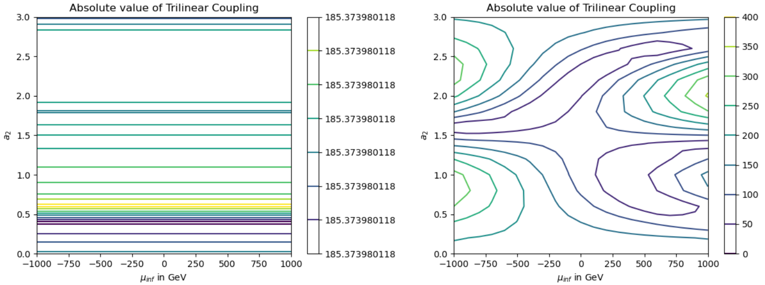


Figure: Absolute value of trilinear couplings in dependance of a_2/a_3 and μ_{inf}

$\Rightarrow a_3 \neq 0$ leads to non constant trilinear coupling in dependance of μ_{inf}

Results: Cross section

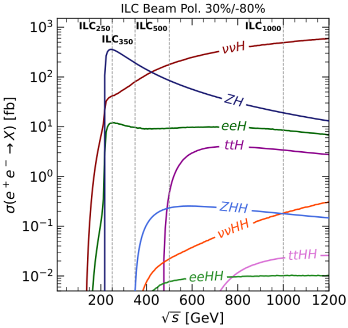


Figure: Dependance of CME of Crossection from e^+e^- channels, from [2]

$\Rightarrow$ expect change in cross section with 3 Higgs vertices
look at $e^+e^- \to zh_2h_2$,
$CME = 500$
and $e^+e^- \to \nu\nu h_2h_2$,
$CME = 1000$
set $a_3 = 0.3$
Beam Pol. $30\%/-80\%$

Results: Cross section

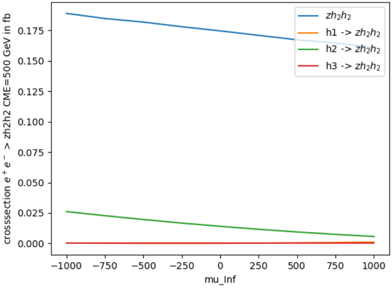
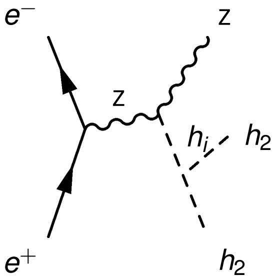


Figure: Crossection $e^+e^- -> Zh_2h_2$

with $h_i -> zh_2h_2$:



Results: Cross section

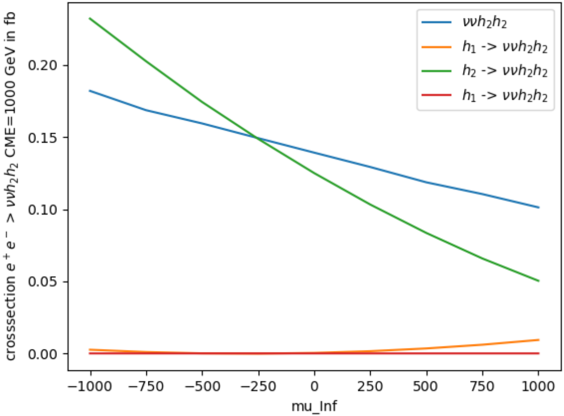


Figure: Crossection $e^+e^- -> \nu\nu h_2 h_2$

with $h_i -> \nu\nu h_2 h_2$ all diagrams with $h_i h_2 h_2$-vertex

Outlook

- include higher loops (AnyH3)
- include other channels
- systematic analysis of the parameter space
- precision required to measure the μ_{inf}
- apply other symmetries to the 2HDMS

Sources

Cms Collaboration.
Search for a standard model-like higgs boson in the mass range between 70 and 110 gev in the diphoton final state in proton-proton collisions at $\sqrt{\{s\}} = 8$ and 13 tev.
2018.

Daniel Schieber, 2024.

John Smart.
The riddle of development and the challenge to cosmology.
EVO DEVO BIOLOGY, EVO DEVO COSMOLOGY, 2017.

Potential V_{NMSSM}

$$
\begin{aligned}
V_{\text{NMSSM}} = & \left[m^2 H_d + (\mu + \lambda S)^2\right] |H_d|^2 + \left[m^2 H_u + (\mu + \lambda S)^2\right] |H_u|^2 + (m_S^2 \\
& + 2C_\xi \xi S + \frac{2}{3}\kappa A_\kappa S^3 + \left[\xi + \nu S + \kappa S^2 + \lambda H_u \cdot H_d\right]^2 + 2(B_\mu \mu + \\
& + \frac{1}{8}(g_1^2 + g_2^2)(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2} g_2^2 |H_d^\dagger H_u|^2
\end{aligned}
$$

Rotation matrix

$$R = \begin{pmatrix} c(\alpha_1)c(\alpha_2) & s(\alpha_1)c(\alpha_2) & s(\alpha_2) \\ -s(\alpha_1)c(\alpha_3)-c(\alpha_1)s(\alpha_2)s(\alpha_3) & c(\alpha_1)c(\alpha_3)-s(\alpha_1)s(\alpha_2)s(\alpha_3) & c(\alpha_2)s(\alpha_3) \\ s(\alpha_1)s(\alpha_3)-c(\alpha_1)s(\alpha_2)c(\alpha_3) & -c(\alpha_1)s(\alpha_3)-s(\alpha_1)s(\alpha_2)c(\alpha_3) & c(\alpha_2)c(\alpha_3) \end{pmatrix}$$

Trilinear Couplings

$$-\frac{i}{2}\frac{1}{\sqrt{2}}\Big(Z^H_{i1}\Big(Z^H_{j3}\Big(2\Big(2\lambda_1' v_S+\mu_{Inf}+\mu^*_{Inf}\Big)Z^H_{k1}+4\lambda_1' v_1 Z^H_{k3}+\Big(\mu_{12}+\mu^*_{12}\Big)Z^H_{k2}\Big)$$
$$+Z^H_{j2}\Big(4\Big(\lambda_3+\lambda_4\Big)v_1 Z^H_{k2}+4\Big(\lambda_3+\lambda_4\Big)v_2 Z^H_{k1}+\Big(\mu_{12}+\mu^*_{12}\Big)Z^H_{k3}\Big)$$
$$+2Z^H_{j1}\Big(2\Big(\lambda_3+\lambda_4\Big)v_2 Z^H_{k2}+\Big(2\lambda_1' v_S+\mu_{Inf}+\mu^*_{Inf}\Big)Z^H_{k3}+6\lambda_1 v_1 Z^H_{k1}\Big)\Big)$$
$$+Z^H_{i2}\Big(Z^H_{j3}\Big(2\Big(2\lambda_2' v_S+\mu_{Inf}+\mu^*_{Inf}\Big)Z^H_{k2}+4\lambda_2' v_2 Z^H_{k3}+\Big(\mu_{12}+\mu^*_{12}\Big)Z^H_{k1}\Big)$$
$$+Z^H_{j1}\Big(4\Big(\lambda_3+\lambda_4\Big)v_1 Z^H_{k2}+4\Big(\lambda_3+\lambda_4\Big)v_2 Z^H_{k1}+\Big(\mu_{12}+\mu^*_{12}\Big)Z^H_{k3}\Big)$$
$$+2Z^H_{j2}\Big(2\Big(\lambda_3+\lambda_4\Big)v_1 Z^H_{k1}+\Big(2\lambda_2' v_S+\mu_{Inf}+\mu^*_{Inf}\Big)Z^H_{k3}+6\lambda_2 v_2 Z^H_{k2}\Big)\Big)$$
$$+Z^H_{i3}\Big(Z^H_{j1}\Big(2\Big(2\lambda_1' v_S+\mu_{Inf}+\mu^*_{Inf}\Big)Z^H_{k1}+4\lambda_1' v_1 Z^H_{k3}+\Big(\mu_{12}+\mu^*_{12}\Big)Z^H_{k2}\Big)$$
$$+Z^H_{j2}\Big(2\Big(2\lambda_2' v_S+\mu_{Inf}+\mu^*_{Inf}\Big)Z^H_{k2}+4\lambda_2' v_2 Z^H_{k3}+\Big(\mu_{12}+\mu^*_{12}\Big)Z^H_{k1}\Big)$$
$$+Z^H_{j3}\Big(4\lambda_1' v_1 Z^H_{k1}+4\lambda_2' v_2 Z^H_{k2}+\Big(6\lambda_3'' v_S+\mu_{S1}+\mu^*_{S1}\Big)Z^H_{k3}\Big)\Big)\Big)$$