# The triple Higgs self-couplings of the hidden SU(2) vector dark matter model

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# Outline

# INTRODUCTION

- After the Higgs discovery $m_h = 125.09\ GeV$, there are still somme problems : EW scale origin, Dark Matter, Neutrino mass, Dark energy, Inflation .. etc.
- The vector DM model proposed by $SU(2)_{HS}$ based on a hidden gauge symmetry $SU(2)_{HS}$, where the DM interacts with the SM particles only via mixing between the $SU(2)_{HS}$ doublet and the Higgs doublet.
- The DM candidate must be a stable particle, with no direct interaction with the electroweak and strong forces. Its stability can be guaranteed by imposing an appropriate symmetry, which can be discrete or continuous. In addition, it has also to be nonrelativistic particle.
- Triple Higgs coupling and the di-Higgs production turn out to be so important to shed light on new physics and to understand the electroweak symmetry breaking.

# MODEL



- This model based on enlarging the gauge symmetry of the SM to include a non-Abelian gauge symmetry $SU(2)_{HS}$, under which all SM particles are singlets.
- The scalar sector of the model contains a new doublet that is charged under the group $SU(2)_{HS}$ and is singlet under the SM gauge group.
- The extra gauge bosons, associated with $SU(2)_{HS}$, are denoted by $A^{\mu}$ can serve as vector DM candidates they couple to the SM only through the Higgs portal.
- we identify the $m_h \sim$125-GeV eigenstate to be the SM-like Higgs boson and $\eta$ the other eigenstate ; therefore, we have two cases where the SM-like Higgs eigenstate is the (1) light or the (2) heavy eigenstate.

# MODEL

- The Lagrangian in the mass eigenstates basis write as

$$
\begin{aligned}
\mathcal{L} \supset\ & -\frac{1}{2}m_\eta^2\eta^2 - \frac{1}{2}m_h^2h^2 - (h\,c_\beta + \eta\,s_\beta)\left(\sum_f \frac{m_f}{\upsilon} f\bar{f}\right) \\
& + \left[\frac{s_\beta^2}{2\upsilon}\eta^2 + \frac{c_\beta^2}{2\upsilon}h^2 + \frac{s_{2\beta}}{2\upsilon}\eta h + \eta s_\beta + hc_\beta\right]\left(\frac{2m_W^2}{\upsilon}W_\mu^+W^{-\mu}\right. \\
& + \left[\frac{s_\beta^2}{2\upsilon}\eta^2 + \frac{c_\beta^2}{2\upsilon}h^2 + \frac{s_{2\beta}}{2\upsilon}\eta h + \eta s_\beta + hc_\beta\right]\left(\frac{m_Z^2}{\upsilon}Z^\mu Z_\mu\right) \\
& + \left[\frac{c_\beta^2}{2\upsilon_\phi}\eta^2 + \frac{s_\beta^2}{2\upsilon_\phi}h^2 - \frac{s_{2\beta}}{2\upsilon_\phi}\eta h + \eta c_\beta - hs_\beta\right]\left(\frac{m_A^2}{\upsilon_\phi}A_\mu \cdot A^\mu\right) \\
& - \frac{1}{6}\rho_h h^3 - \frac{1}{6}\rho_\eta\eta^3 - \frac{1}{2}\rho_1\eta^2 h - \frac{1}{2}\rho_2 h^2\eta + \frac{1}{2}m_A^2 A_\mu \cdot A^\mu
\end{aligned}
$$

# Thoeretical and Experiemental Constraints

- Unitarity constraints

$$\lambda_m \leq 8\pi, \quad \lambda, \lambda_\phi \leq 4\pi, \quad 3(\lambda + \lambda_\phi) \pm \sqrt{9(\lambda - \lambda_\phi)^2 + 4\lambda_m^2} \leq 8\pi.$$

- Vacuum Stability and Perturbativity

$$4\lambda\lambda_\phi > \lambda_m^2,$$

- Constraints on the Higgs Decays

# Thoeretical and Experiemental Constraints



$$\Gamma_{inv}\left(h \to AA\right) = 3\frac{g_\phi^2\, m_h^3 s_\beta^2}{64\pi\, m_A^2}\sqrt{1-4\frac{m_A^2}{m_h^2}}\left\{1-4\frac{m_A^2}{m_h^2}+12\frac{m_A^4}{m_h^4}\right\}.$$

$$\Gamma_{und}\left(h \to \eta\eta\right) = \frac{\rho_1^2}{32\pi\, m_h}\sqrt{1-4\frac{m_\eta^2}{m_h^2}}.$$

$$\Gamma_h = \Gamma_{BSM} + c_\beta^2\, \Gamma_h^{SM}.$$

$\Gamma_{BSM} = \Gamma_{invisible}$ for case 1 ; and $\Gamma_{BSM} = \Gamma_{invisible} + \Gamma_{undetermined}$ for case 2.

# Thoeretical and Experiemental Constraints



- The invisible and undetermined branching ratio must respect the constraints

$$\mathcal{B}_{inv} < 0.26,\ \mathcal{B}_{und} < 0.22,\ \mathcal{B}_{inv} + \mathcal{B}_{und} \leq 0.47.$$

- In addition, the Higgs total decay width should lie in the range

$$1.0\ \mathrm{MeV} < \Gamma_h < 6.0\ \mathrm{MeV}.$$

# Thoeretical and Experiemental Constraints



- DM Direct Detection Constraints

$$\sigma_{SI}(NA \to NA) = \frac{1}{64\pi} f^2 g_\phi^4 \, s_{2\beta}^2 m_N^2 \, \frac{\upsilon_\phi^2}{\upsilon^2} \frac{(m_h^2 - m_\eta^2)^2}{m_h^4 m_\eta^4} \left(\frac{m_N}{m_N + m_A}\right)^2$$

- Renormalization Group Equation.
- Dark matter relic density.

$$\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001.$$

# Triple Higgs Coupling



- Indirect probe of the triple Higgs coupling can be carried out through investigating the loop effects in some observables such as the single Higgs production, and the electroweak precision observables.
- The direct measurement of the triple Higgs coupling at the LHC is possible and can be achieved through the di-Higgs production. This production is dominated by the gluon-gluon fusion process.
- The triple Higgs coupling $\lambda_{hhh}$ in our model, gets modified due to the mixing with the scalar $\eta$, and in addition, it receives new one-loop contributions by the scalar $\eta$ and the new gauge bosons $A_i$.

# Triple Higgs Coupling



- we can parametrize $\lambda_{hhh}$ as

$$\lambda_{hhh} = \lambda_{hhh}^{SM}(1 + \Delta_{hhh}),$$

where $\Delta_{hhh}$ is the triple Higgs relative enhancement, at one-loop the triple Higgs coupling in the SM is given by

$$\lambda_{hhh}^{SM} \simeq \frac{3m_h^2}{\upsilon}\left[1 - \frac{m_t^4}{\pi^2\upsilon^2 m_h^2}\right].$$

# Triple Higgs Coupling

- We considered the Higgs triple self-coupling $\lambda_{hhh}$ as the third derivative of the Higgs one-loop effective potential

$$\lambda_{hhh} = \frac{\partial^3 V_{eff}}{\partial h^3},$$

where the one-loop effective potential can be given by

$$V_{eff}\left(h', \eta'\right) = V^0 + \frac{1}{64\pi^2} \sum_i n_i m_i^4\left(h', \eta'\right)\left(\log\left(\frac{m_i^2}{\Lambda^2}\right) - \frac{3}{2}\right),$$

Here, $m_i^2\left(h', \eta'\right)$ are the field-dependent squared masses ; and $\Lambda$ is the renormalization scale

# Triple Higgs Coupling





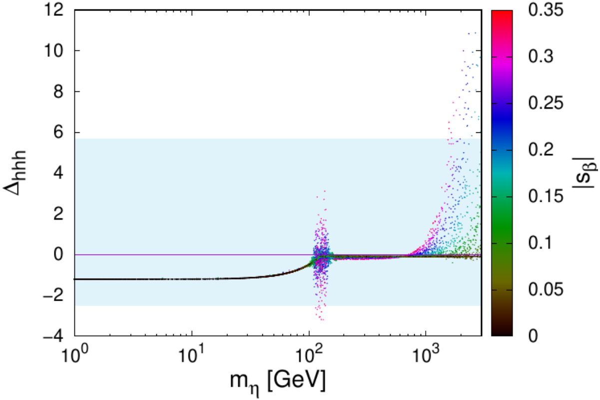
- Therefore, the triple Higgs coupling $\lambda_{hhh}$ writes as

$$\lambda_{hhh} = \left\{ c_\beta^3 \frac{\partial^3 V_{eff}}{\partial h'^3} - 3c_\beta^2 s_\beta \frac{\partial^3 V_{eff}}{\partial \eta' \partial h'^2} + 3c_\beta s_\beta^2 \frac{\partial^3 V_{eff}}{\partial \eta'^2 \partial h'} - s_\beta^3 \frac{\partial^3 V_{eff}}{\partial \eta'^3} \right\} \Big|_{h'=}$$

# Triple Higgs Coupling



- we show the triple Higgs relative enhancement $\Delta_{hhh}$ versus the new scalar mass, where the palette shows the scalar mixing. The sky-blue band represents the allowed values of $\Delta_{hhh}$ by the recent ATLAS measurements.



# CONCLUSION



- The model respect both theoretical and experimental constraints, such as perturbative unitarity, vacuum stability, perturbativity, experimental bound on the DM direct detection, the observed DM relic density, and the constraints from the Higgs decay where the invisible or/and undetermined branching ratio where the Higgs total decay width must respect the existing experimental constraints.
- In the decoupling limit $m_\eta >> m_h$, as in many extensions of the SM, the Higgs mixing effects and the presence of new fields coupled to the Higgs doublet induce significant corrections to the SM prediction of the triple Higgs self-couplings $\lambda_{hhh} = (1 + \Delta_{hhh})\lambda_{hhh}^{SM}$.

- We have found that, up to one-loop level, the effect of the new scalar $\eta$ and the vector DM $A_i$ lead to a relative enhancement $\Delta_{hhh}$ that lies between -250 % and +1200 %.
- Indeed, part of the benchmark points are already excluded by the recent measurements by ATLAS collaboration.
- So, the measurement of triple higgs coupling $\lambda_{hhh}$ is a crucial task in the LHC, although being challenging, in future collider experiments that can be tested our model.

Thank you for your attention.