One-loop corrections to the Higgs boson invisible decay in the dark doublet phase of the N2HDM

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The **problem**

The **Standard Model**, while very accurate, still cannot explain several experimental observations. One of these observations is the existence of **Dark Matter**.

The **model**

Next-to-Minimal 2 Higgs Doublet Model (**N2HDM**)

- **SM extension** with additional $SU(2)_L$ doublet and singlet.
- Two $\mathbb{Z}_2$ symmetries in the potential
- **Dark Doublet Phase (DDP)**: the singlet and one of the doublets have non zero VEV.

The **new particles**

The N2HDM features several **new scalar particles** including **two DM candidates**

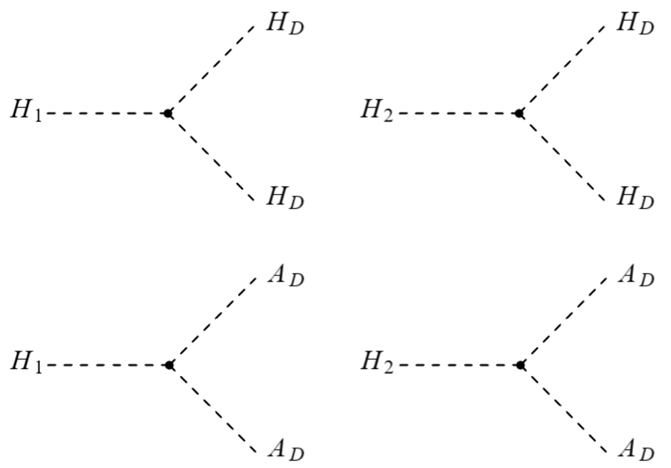
Scalar Higgses	H_1 H_2
Charged Higgses	H^+ H^-
DM Candidates	H_D A_D

The **objective**

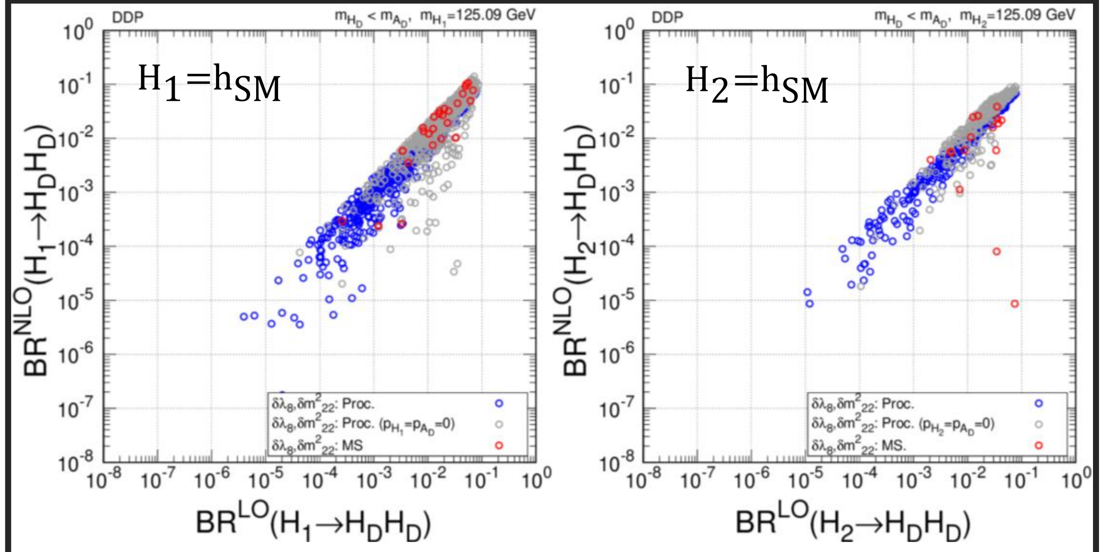
- Calculate the **radiative corrections** to the decay rates of the SM-like scalars to the DM candidates.
- **Constrain the parameter space** of the model by comparing the loop-corrected rates to the current limit on the Higgs-to-invisible decay rate.

The **invisible decays**

The N2HDM allows for four possible decays of the Higgs to dark matter candidates.



The **results**



• MS-bar • OS Proc • ZEM Proc

- Experimental measurements on properties of the Higgs boson set the upper limit for the Higgs-to-invisible branching ratio to 0.10.
- NLO corrections using the **MS-bar scheme** on the dark coupling parameters are very **numerically unstable**.
- Using a **process dependent** renormalization scheme (OS or ZEM), most points of the parameter space have branching ratios **below the limit**.

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BACKUP

N2HDM Scalar Sector

Fields

$$\Phi_1 = \begin{pmatrix} \phi_1^\pm \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^\pm \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

$$\Phi_S = v_S + \rho_S$$

Potential

$$m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^2 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left((\Phi_1^\dagger\Phi_2)^2 + h.c.\right)$$
$$+\frac{m_S^2}{2}\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2$$

Symmetries

$$\mathbb{Z}_2^{(1)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \Phi_S \to \Phi_S$$
$$\mathbb{Z}_2^{(2)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to \Phi_2, \quad \Phi_S \to -\Phi_S$$

Dark Doublet Phase

Vacuum configuration

$$v_1 = v_{SM} \quad v_2 = 0 \quad v_S \neq 0$$

Minimum conditions

$$m_{11}^2 = -\frac{1}{2}(v_{SM}\lambda_1 + v_S\lambda_7)$$

$$m_S^2 = -\frac{1}{2}(v_{SM}\lambda_7 + v_S\lambda_6)$$

$$m_{12}^2 = 0$$

Mass eigenstates

$$H_1 = \cos\alpha\,\rho_1 - \sin\alpha\,\rho_S$$

$$H_2 = \sin\alpha\,\rho_1 + \cos\alpha\,\rho_S$$

$$H_D = \rho_2$$

$$A_D = \eta_2$$

$$H^\pm = \phi_2^\pm$$

$$m_{H_1} \leq m_{H_2}$$

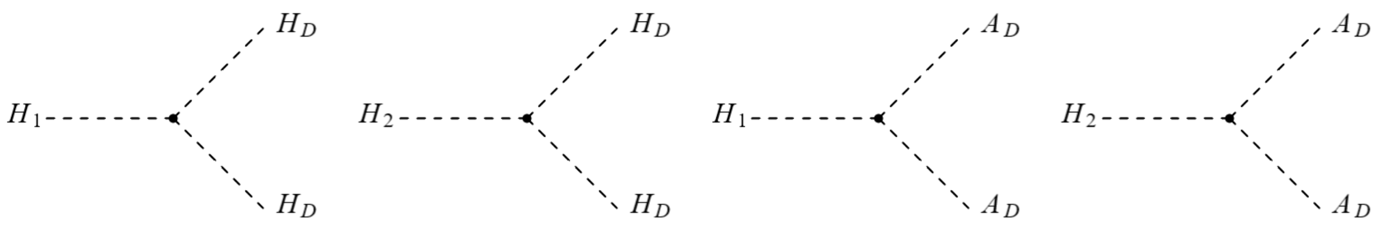
Goldstone bosons

$$G^0 = \eta_1 \quad G^\pm = \phi_1^\pm$$

Mass basis reparameterization

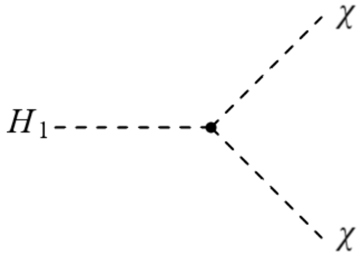
$$\{m_{H_1}^2, m_{H_2}^2, m_{H_D}^2, m_{A_D}^2, m_{H^\pm}^2, v_{SM}, v_S, \alpha, m_{22}^2, \lambda_2, \lambda_8\}$$

SM Higgs-like decays to DM candidates

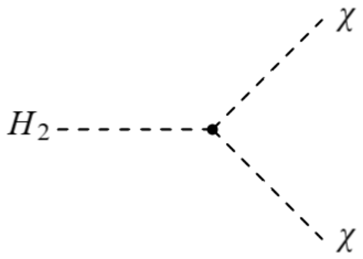


BACKUP

Process renormalization



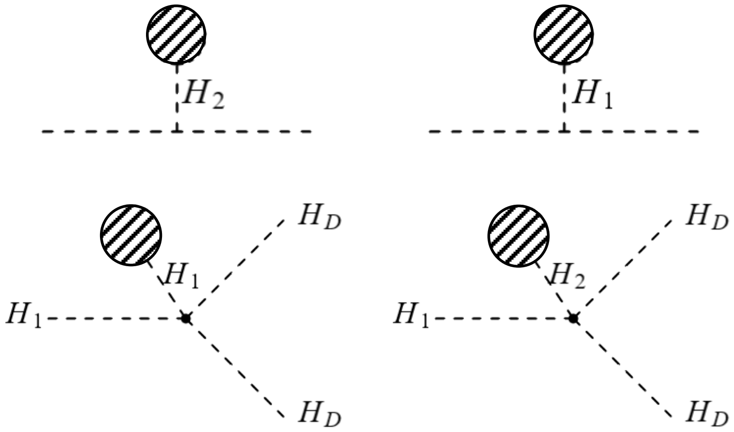
$$\lambda_{H_1\chi\chi} = \frac{\cos\alpha}{v}\left(\lambda_8 v_S^2 + 2m_{22}^2 - 2m_\chi^2\right) - \sin\alpha\,\lambda_8 v_S$$



$$\lambda_{H_2\chi\chi} = -\frac{\sin\alpha}{v}\left(\lambda_8 v_S^2 + 2m_{22}^2 - 2m_\chi^2\right) - \cos\alpha\,\lambda_8 v_S$$

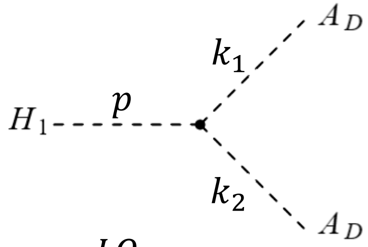
Parameters	Renormalization scheme
$m_{H_1}^2, m_{H_2}^2, m_{H_D}^2, m_{A_D}^2$	On-Shell
H_1, H_2, H_D, A_D	On-Shell
v_{SM}, v_S	Alternative tadpole
α	On-Shell + pinch technique
m_{22}^2, λ_8	MS-bar
	On-Shell Process dependent (OS Proc)
	Zero External Momenta Process dependent (ZEM Proc)

Alternative tadpole scheme



Process dependent scheme

Auxiliary process:



$$\Gamma^{NLO}_{H_1 A_D A_D} = \Gamma^{LO}_{H_1 A_D A_D}$$

Momentum	OS Proc	ZEM Proc
p^2	$m_{H_1}^2$	0
k_1^2, k_2^2	$m_{A_D}^2$	0