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

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Motivation

- The Standard Model (SM), although one of the most successful theories in Physics, is incomplete. It does not explain very important experimental observations:
  - Baryon asymmetry
  - Neutrino masses
  - **Dark matter**
- To address these issues, we turn to Beyond the Standard Model (BSM) models. Some of these models are extensions of the SM;
- The discovery of the Higgs boson and the increasingly precise experimental measurements of its properties allow us to probe BSM models with extended Higgs sectors.

Goal: study a SM extension that features a dark sector and use the experimental measurements of the Higgs boson to constrain the model's parameter space at NLO.

[D. Azevedo, **P. Gabriel**, M. Mühlleitner, K. Sakurai and R. Santos, One-loop Corrections to the Higgs Boson Invisible Decay in the Dark Doublet Phase of the N2HDM, [arXiv:2104.03184]] (accepted for publication on JHEP)

The Dark Doublet Phase (DDP) of the N2HDM

- The scalar potential of the N2HDM contains two Higgs doublets and a singlet

$$V_{scalar} = m_{11}^2\Phi_1^\dagger\Phi_1 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left((\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right)$$
$$+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\Phi_1^\dagger\Phi_1\Phi_S^2 + \frac{\lambda_8}{2}\Phi_2^\dagger\Phi_2\Phi_S^2$$

- CP conservation and two $\mathbb{Z}_2$ symmetries are imposed on the potential

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

Spontaneosly broken in the DDP ($v_S \neq 0$)

- Dark Doublet Phase (DDP): $\langle\Phi_1\rangle \neq 0, \langle\Phi_2\rangle = 0, \langle\Phi_S\rangle \neq 0$

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \rho_1 + iG^0) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H_D^+ \\ \frac{1}{\sqrt{2}}(H_D + iA_D) \end{pmatrix}$$

$$\Phi_S = v_S + \rho_S$$

Visible Sector → Higgs bosons: $\boxed{H_1, H_2}$ → $\boxed{\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix} \rho_1 \\ \rho_S \end{pmatrix}}$

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

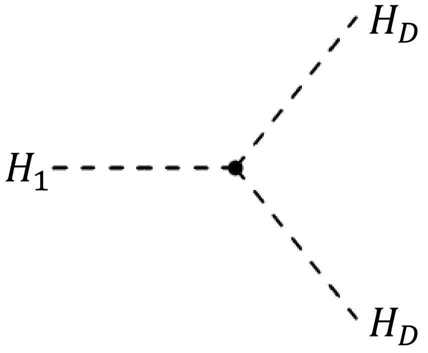
Dark Sector
- Charged Higgs: H_D^+, H_D^-
- Dark neutral scalars: $\boxed{\boldsymbol{H_D}, A_D}$ → DM candidates

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

[I. Engeln, P. Ferreira, M.M. Mühlleitner, R. Santos and J. Wittbrodt, JHEP 08 (2020) 085]

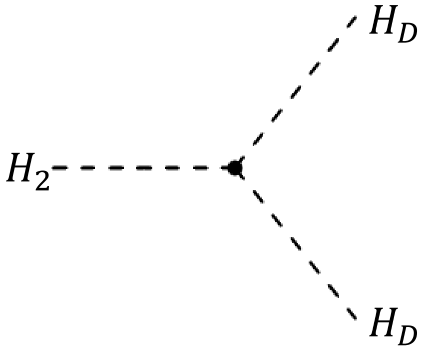
Higgs decays to dark matter

Light Higgs ($h_{125} = H_1$)



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

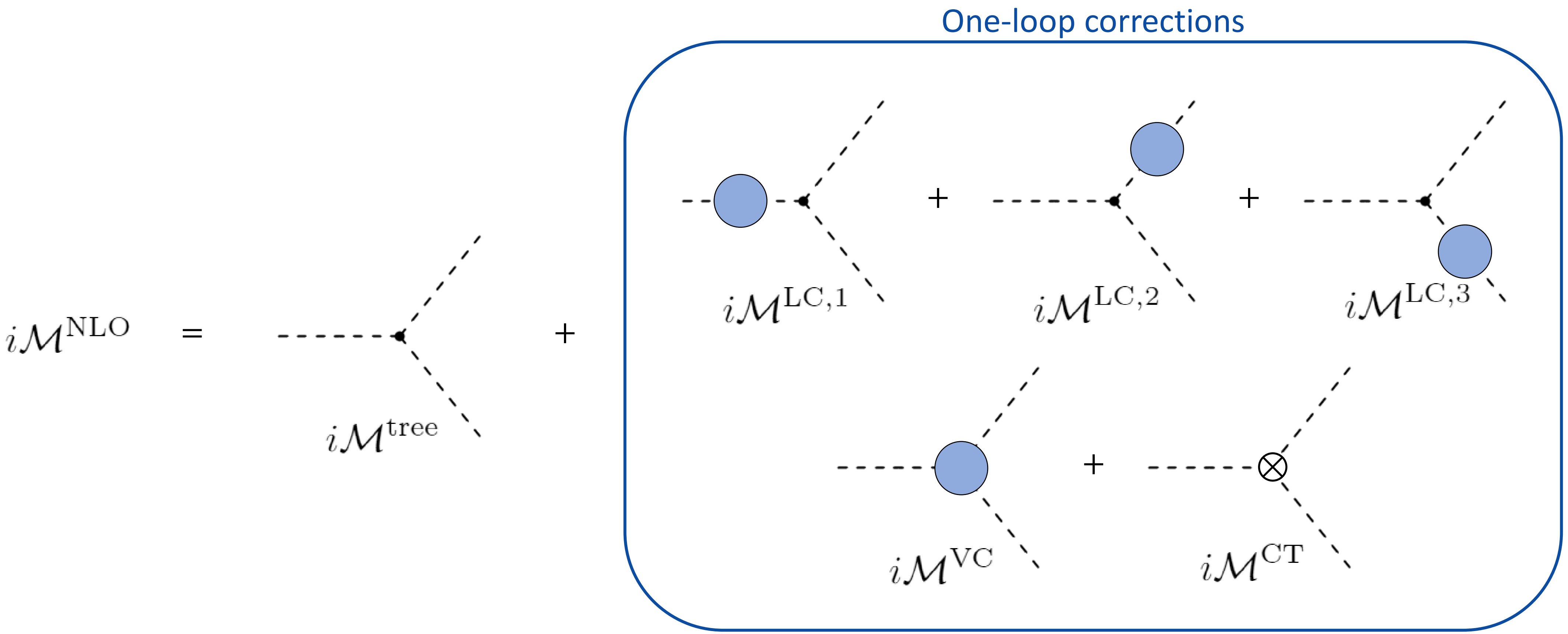
Heavy Higgs ($h_{125} = H_2$)



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

- In the Heavy Higgs scenario, the parameter space is more constrained due to the upper bound on the mass of the non-SM Higgs boson H_1.
- Also in the Heavy Higgs scenario, the SM Higgs has an additional decay channel due to the kinematically allowed process $H_2 \to H_1 H_1$. This affects the values of the branching ratios.

One-loop corrections



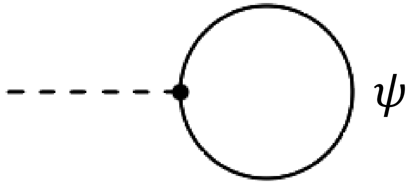
$$\Gamma^{\mathrm{NLO}}_{H_i \to H_D H_D} = \Gamma^{\mathrm{LO}}_{H_i \to H_D H_D} + \frac{\sqrt{m^2_{H_i} - 4m^2_{H_D}}}{16\pi m^2_{H_i}} \mathrm{Re}\left[(\mathcal{M}^{\mathrm{tree}}_{H_i \to H_D H_D})^* \mathcal{M}^{\mathrm{1loop}}_{H_i \to H_D H_D} \right]$$

$$BR^{\mathrm{NLO}}(H_i \to H_D H_D) = \frac{\Gamma^{\mathrm{NLO}}_{H_i \to H_D H_D}}{\Gamma^{\mathrm{NLO}}_{H_i}}$$

Renormalization

- Calculation of the amplitudes of loop diagrams often leads to divergent integrals

$$\int_0^\infty \frac{\mathrm{d}^4 \mathrm{p}_\psi}{(2\pi)^4} \frac{1}{p_\psi^2 - m_\psi^2} \xrightarrow{\quad p_\psi \to \infty \quad} \text{UV divergence}$$



- Divergent parts are isolated through dimensional regularization;
- We assume that parameters and field wave-functions can be decomposed into a renormalized quantity (finite) and a counter-term (infinite)

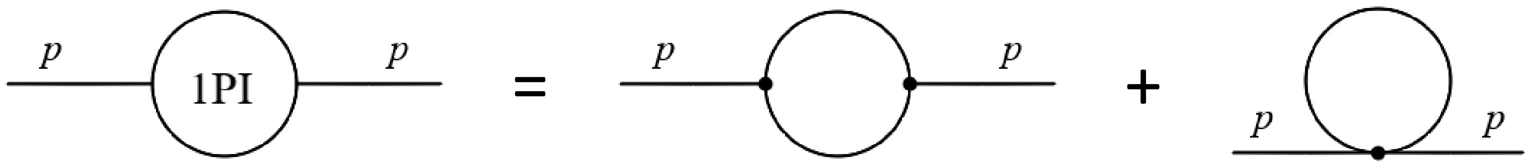
$$\rho_0 = \rho + \delta\rho \qquad\qquad \phi_0 = \sqrt{Z}\phi \approx \left(1 + \frac{\delta Z}{2}\right)\phi$$

- All counter-terms must be fixed in such way that they cancel out all the divergent terms, leaving the renormalized amplitudes finite.

On-Shell scheme

$$G(p^2) = \frac{i}{p^2 - m_\phi^2 + \hat{\Sigma}_\phi(p^2)} \qquad \hat{\Sigma}_\phi(p^2) = \Sigma_\phi(p^2) - \delta m_\phi^2 + \frac{\delta Z_\phi^*}{2}(p^2 - m_\phi^2) + (p^2 - m_\phi^2)\frac{\delta Z_\phi}{2}$$

$i\Sigma_\phi(p^2) =$



Renormalization conditions:

1. Pole of the propagator must be at the mass ($p^2 = m_\phi^2$)

$$\hat{\Sigma}_\phi(m_\phi^2) = 0$$

2. Residue of the propagator must be fixed at i

$$\left.\frac{\partial \hat{\Sigma}_\phi(p^2)}{\partial p^2}\right|_{p^2 = m_\phi^2} = 0$$

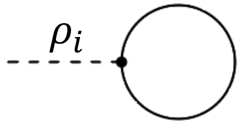
3. No mixing at the propagator pole (only for mixing fields)

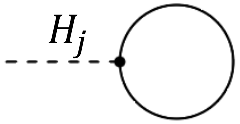
$$\hat{\Sigma}_{\phi_i \phi_j}\left(m_{\phi_j}^2\right) = 0, \qquad (i \neq j)$$

$$\boxed{\begin{gathered} \delta m_\phi^2 = \Sigma_\phi^{Tad}(m_\phi^2) \\ \delta Z_\phi = -Re\left[\left.\frac{\partial \Sigma_\phi^{Tad}(p^2)}{\partial p^2}\right|_{p^2 = m_\phi^2}\right] \\ \delta Z_{\phi_i \phi_j} = \frac{2}{m_i^2 - m_j^2} Re\left[\Sigma_{\phi_i \phi_j}^{Tad}\left(m_{\phi_j}^2\right)\right], (i \neq j) \end{gathered}}$$

Tadpole renormalization

$$T_i = \left\langle \frac{\partial V}{\partial \rho_i} \right\rangle \qquad T_{H_j} = \sum_i R_{ji} T_i \qquad i \in \{1, S\} \quad j \in \{1, 2\}$$

$iT_i =$ 

$iT_{H_j} =$ 

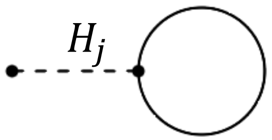
- The N2HDM scalar potential contains terms linear in the CP-even fields of the visible sector.
- These linear terms can be represented by tadpole Feynman diagrams.
- The vacuum is fixed at the proper value by requiring that the tadpole terms vanish at the vacuum state (minimum conditions)

Renormalization condition: $T_i + \delta T_i = 0$

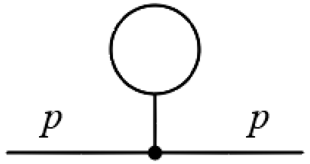
$$\underbrace{v_0 = v + \delta v \qquad v_{S_0} = v_S + \delta v_S}_{\text{Alternative tadpole scheme}}$$

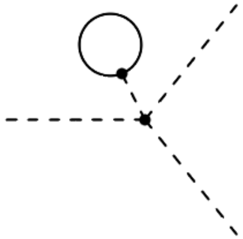
$$\delta v = c_\alpha \frac{i}{m_{H_1}^2} iT_{H_1} + s_\alpha \boxed{\frac{i}{m_{H_2}^2} iT_{H_2}}$$

$$\delta v_S = -s_\alpha \frac{i}{m_{H_1}^2} iT_{H_1} + c_\alpha \frac{i}{m_{H_2}^2} iT_{H_2}$$

$\frac{i}{m_{H_j}^2} iT_{H_j} =$ 

$$i\Sigma_\phi^{Tad}(p^2) = i\Sigma_\phi(p^2) +$$





[J. Fleischer and F. Jegerlehner, Phys. Rev. D 23 (1981) 2001]

[M. Krause, D. Lopez-Val, M. Mühlleitner and R. Santos, JHEP 12 (2017) 077]

Electric charge renormalization

- The physical value of the electric charge is defined as the $ee\gamma$ coupling for on-shell external particles in the Thomson limit;
- The renormalization of the electrical charge is done assuming the condition that all corrections to the $ee\gamma$ vertex must vanish when the external particles are on their mass-shell ($p_\gamma^2 = 0,\ p_e^2 = m_e^2$);
- Due to a Ward identity, the charge counter-term can be expressed simply as a function of the photon and Z boson self-energies.

$$e_0 = (1 + \delta Z_e)e \qquad \alpha = \frac{e^2}{4\pi} \qquad \delta Z_e^{\alpha(0)} = \underbrace{\boxed{\frac{1}{2}\frac{\partial \Sigma_{\gamma\gamma}^T(p^2)}{\partial p^2}\bigg|_{p^2=0}}}_{\text{large log corrections}} + \frac{s_W}{c_W}\frac{\Sigma_{\gamma Z}^T(0)}{m_Z^2}$$

- To minimize the effect of the log contributions, we use the G_μ scheme in which the fine-structure constant is written as a function of the very well measured Fermi constant G_μ;
- A large part of the corrections is included at LO and must be subtracted from the explicit corrections to avoid double counting.

$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu m_W^2}{\pi}\left(1 - \frac{m_W^2}{m_Z^2}\right) \qquad \boxed{\delta Z_e\Big|_{G_\mu} = \delta Z_e^{\alpha(0)} - \underbrace{\boxed{\frac{1}{2}(\Delta r)_{1\mathrm{L}}}}_{\substack{\text{Corrections to muon decay} \\ f(\Sigma_{\gamma\gamma}^T, \Sigma_{ZZ}^{Tad,T}, \Sigma_{\gamma Z}^T, \Sigma_W^{Tad,T})}}}$$

[A. Denner, Fortsch. Phys. 41 (1993) 307]
[A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, Phys. Rev. D 74 (2006) 013004]

Mixing angle renormalization

- The renormalization of the mixing angle is done using the KOSY scheme

$$\alpha_0 = \alpha + \delta\alpha \qquad R(\alpha+\delta\alpha) = \begin{pmatrix} \cos(\alpha+\delta\alpha) & \sin(\alpha+\delta\alpha) \\ -\sin(\alpha+\delta\alpha) & \cos(\alpha+\delta\alpha) \end{pmatrix} = R(\alpha)R(\delta\alpha)$$

- Using the rotation matrix to perform the rotation between the bare gauge and mass eigenstates, we get a relation between the mixing angle counter-term and the off-diagonal WFRCs.

$$\begin{pmatrix} H_{1,0} \\ H_{2,0} \end{pmatrix} = R(\alpha_0)^T \begin{pmatrix} \rho_{1,0} \\ \rho_{S,0} \end{pmatrix} = R(\delta\alpha)^T R(\alpha)^T \sqrt{Z_\rho} \begin{pmatrix} \rho_1 \\ \rho_S \end{pmatrix} = \underbrace{\boxed{R(\delta\alpha)^T R(\alpha)^T \sqrt{Z_\rho} R(\alpha)}}_{\sqrt{Z_H}} \underbrace{\boxed{R(\alpha)^T \begin{pmatrix} \rho_1 \\ \rho_S \end{pmatrix}}}_{\begin{pmatrix} H_1 \\ H_2 \end{pmatrix}}$$

Must be consistent with the OS scheme

$$\sqrt{Z_H} \approx \begin{pmatrix} 1 + \frac{\delta Z_{H_1H_1}}{2} & \delta C + \delta\alpha \\ \delta C - \delta\alpha & 1 + \frac{\delta Z_{H_2H_2}}{2} \end{pmatrix}$$

$$\sqrt{Z_H}^{OS} \approx \begin{pmatrix} 1 + \frac{\delta Z_{H_1H_1}}{2} & \frac{\delta Z_{H_1H_2}}{2} \\ \frac{\delta Z_{H_2H_1}}{2} & 1 + \frac{\delta Z_{H_2H_2}}{2} \end{pmatrix}$$

$$\sqrt{Z_H} = \sqrt{Z_H}^{OS} \Rightarrow \begin{cases} \frac{\delta Z^{OS}_{H_1H_2}}{2} = \delta C + \delta\alpha \\ \frac{\delta Z^{OS}_{H_2H_1}}{2} = \delta C - \delta\alpha \end{cases} \qquad \boxed{\delta\alpha = \frac{\delta Z_{H_1H_2} - \delta Z_{H_2H_1}}{4}}$$

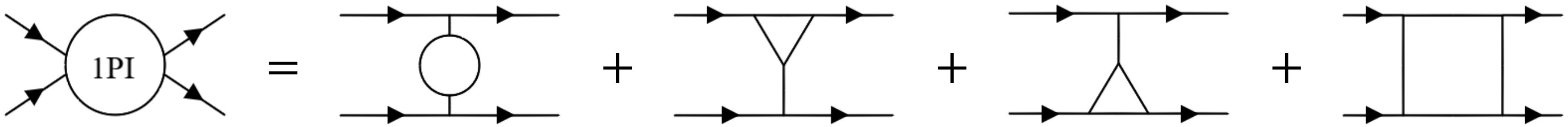
Gauge-dependent terms do not vanish in the final amplitude

$$\delta Z_{\phi_i\phi_j} = \frac{2}{m_i^2 - m_j^2} Re\left[\Sigma^{Tad}_{\phi_i\phi_j}\left(m^2_{\phi_j}\right)\right], (i \neq j)$$

[S. Kanemura, Y. Okada, E. Senaha and C.-P. Yuan, Physical Review D 70 (2004)]

Mixing angle renormalization – pinch technique

- Based on the fact that any physical process must be gauge-independent;
- We use a toy scattering process in order to obtain gauge-independent self-energies;
- In a scattering process the gauge-dependences cancel-out at the self-energy level



$$\mathcal{M}(s,t,m_i) = \mathcal{M}_{\text{self}}(t,\xi) + \mathcal{M}_{\text{tri}}(t,m_i,\xi) + \mathcal{M}_{\text{box}}(t,s,m_i,\xi)$$

$$\frac{\partial^2 \mathcal{M}_{\text{box}}}{\partial\xi\partial s} = 0 \longrightarrow \mathcal{M}_{\text{box}} = \hat{\mathcal{M}}_{\text{box}}(t,s,m_i) + h(t,m_i,\xi) \longrightarrow \tilde{\mathcal{M}}_{\text{tri}}(t,m_i,\xi) = \mathcal{M}_{\text{tri}}(t,m_i,\xi) + h(t,m_i,\xi)$$

$$\frac{\partial^2 \tilde{\mathcal{M}}_{\text{tri}}}{\partial\xi\partial m_i} = 0 \longrightarrow \tilde{\mathcal{M}}_{\text{tri}} = \hat{\mathcal{M}}_{\text{tri}}(t,m_i) + f(t,\xi) \longrightarrow \hat{\mathcal{M}}_{\text{self}}(t,\xi) = \underbrace{\mathcal{M}_{\text{self}}(t,\xi) + f(t,\xi)}$$

Gauge-dependence must cancel

$$\Sigma^{\text{PT}}(\text{p}^2) = \Sigma^{Tad}(p^2)\Big|_{\xi=1} + \Sigma^{Add}(p^2)$$

$$\boxed{\delta\alpha = \frac{1}{2\left(m_{H_1}^2 - m_{H_2}^2\right)} Re\left(\left[\Sigma_{H_1H_2}^{Tad}\left(m_{H_1}^2\right) + \Sigma_{H_1H_2}^{Tad}\left(m_{H_2}^2\right)\right]_{\xi=1} + \Sigma_{H_1H_2}^{Add}\left(m_{H_1}^2\right) + \Sigma_{H_1H_2}^{Add}\left(m_{H_2}^2\right)\right)}$$

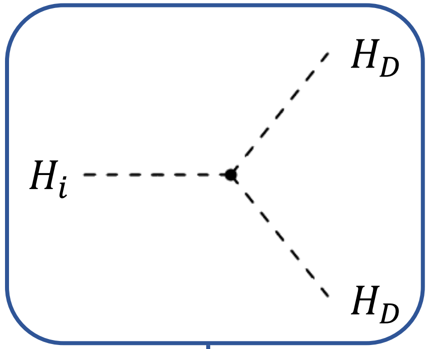
[J. M. Cornwall and J. Papavassiliou, Phys.Rev.D 40 (1989) 3474]

Renormalization of the dark parameters

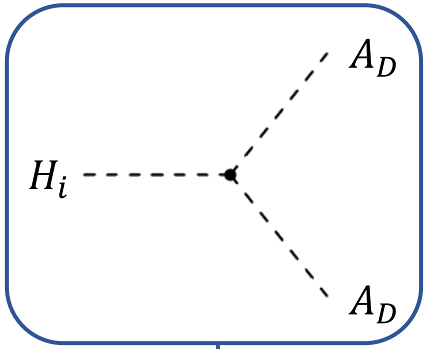
- Counter-terms for m_{22}^2 and λ_8 fixed using three different renormalization schemes separately
  - $\overline{\text{MS}}$ scheme: the counter-terms are fixed in such way that they exactly cancel the remaining divergent terms
  - Process-dependent scheme: consists in using a set of auxiliary processes that have couplings that depend on the parameters we wish to renormalize and requiring that they respect the renormalization condition:

$$\Gamma_{\text{Aux}}^{\text{NLO}} = \Gamma_{\text{Aux}}^{\text{LO}} \Rightarrow Re\left(\mathcal{M}_{Aux}^{1loop}\right) = 0$$

Main process



Auxiliary process



Same dependence on δm_{22}^2 and $\delta\lambda_8$

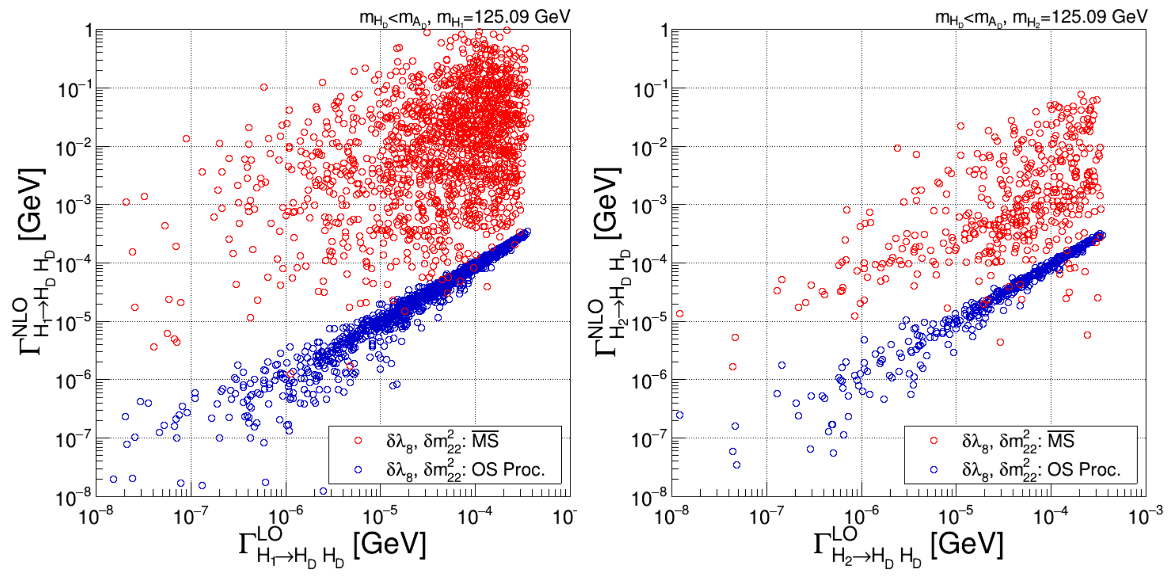
$$\mathcal{M}_{H_i\to A_D A_D}^{1loop} = \mathcal{M}_{H_i\to A_D A_D}^{VC} + \mathcal{M}_{H_i\to A_D A_D}^{CT}\Big|_{\delta m_{22}^2,\delta\lambda_8=0} + \boxed{\mathcal{M}_{H_i\to A_D A_D}^{\delta m_{22}^2,\delta\lambda_8}}$$

$$\mathcal{M}_{H_i\to A_D A_D}^{\delta m_{22}^2,\delta\lambda_8} = \mathcal{M}_{H_i\to H_D H_D}^{\delta m_{22}^2,\delta\lambda_8}$$

$$\boxed{\begin{aligned}\mathcal{M}_{H_i\to H_D H_D}^{1loop} &= \mathcal{M}_{H_i\to H_D H_D}^{VC} + \mathcal{M}_{H_i\to H_D H_D}^{CT}\Big|_{\delta m_{22}^2,\delta\lambda_8=0} \\ &\quad -\mathcal{M}_{H_i\to A_D A_D}^{VC} - \mathcal{M}_{H_i\to A_D A_D}^{CT}\Big|_{\delta m_{22}^2,\delta\lambda_8=0}\end{aligned}}$$

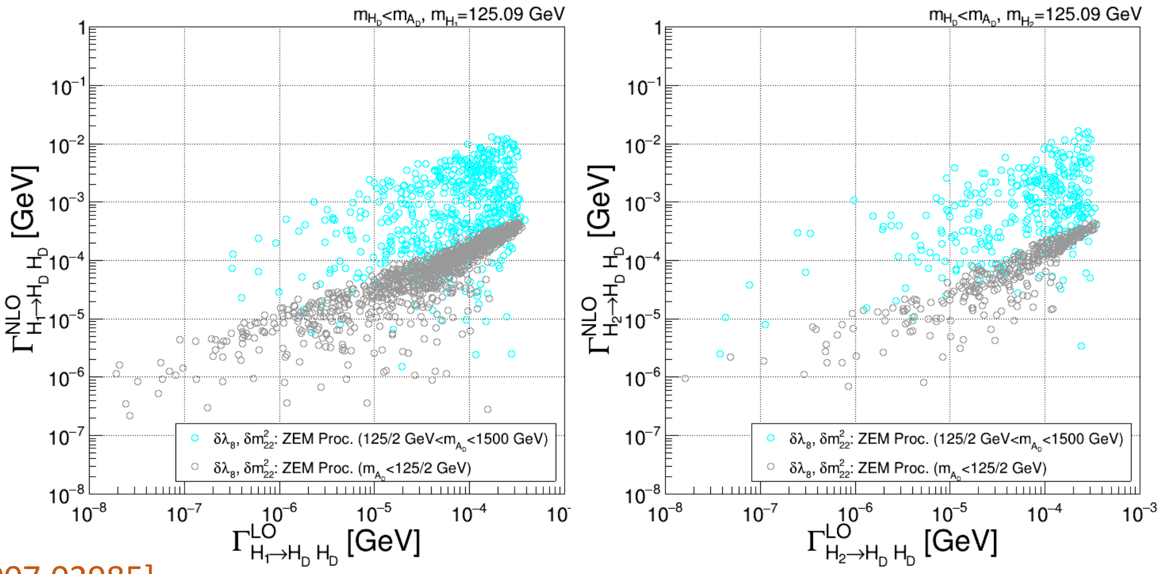
On-Shell (OS)	$p_{H_i}^2 = m_{H_i}^2,\ p_{A_D}^2 = m_{A_D}^2$	$m_{A_D} \leq \dfrac{m_{H_i}}{2}$
Zero External Momentum (ZEM)	$p_{H_i}^2 = p_{A_D}^2 = 0$	No constraints on the masses

Parameter space scan analysis



- LO decay width limited by experimental constraints on the Higgs couplings to SM particles;
- In the $\overline{\text{MS}}$ scheme, the NLO decay widths of most points are several orders of magnitude higher than at LO (very large corrections);
- In the OS process-dependent scheme, the decay widths are more "well-behaved" due to small Δm ($|\Delta m| \lesssim 6$ GeV).

- In the ZEM process-dependent scheme, the points with $m_{A_D} \leq 125/2$ GeV have one-loop corrections similar to the OS process-dependent scheme.
- For points with $m_{A_D} > 125/2$ GeV, the corrections in the ZEM process-dependent scheme become very large due to high Δm.

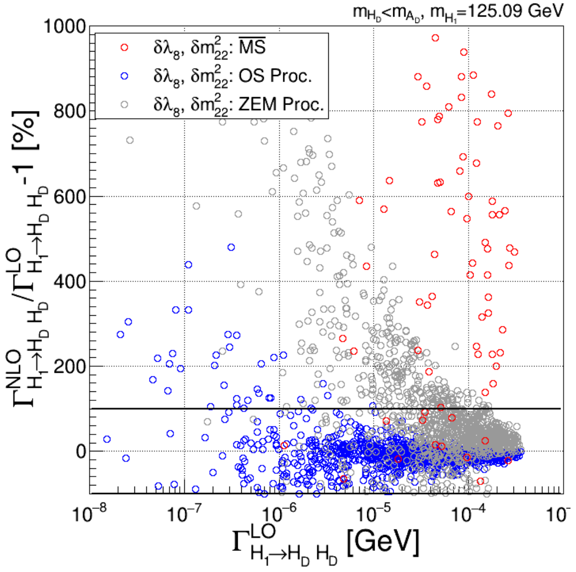


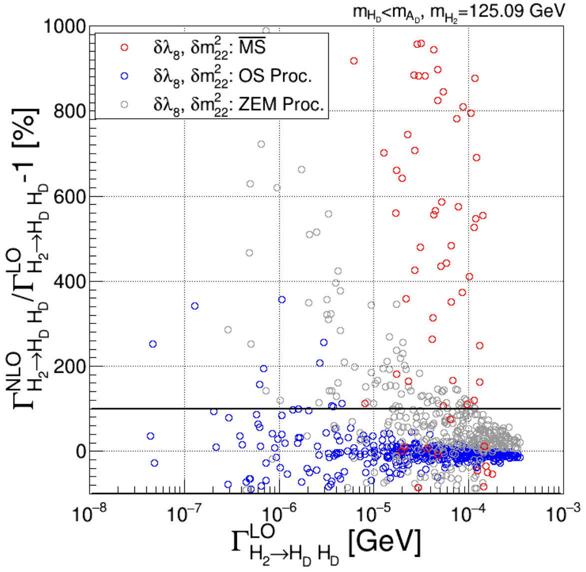
[points generated with ScannerS, containing the most relevant theoretical and experimental constraints]

[R. Coimbra, M.O.P. Sampaio and R. Santos, Eur. Phys. J. C 73 (2013) 2428]

[M. Mühlleitner, M. O. P. Sampaio, R. Santos, J. Wittbrodt, (Jul 6, 2020) e-Print: 2007.02985]

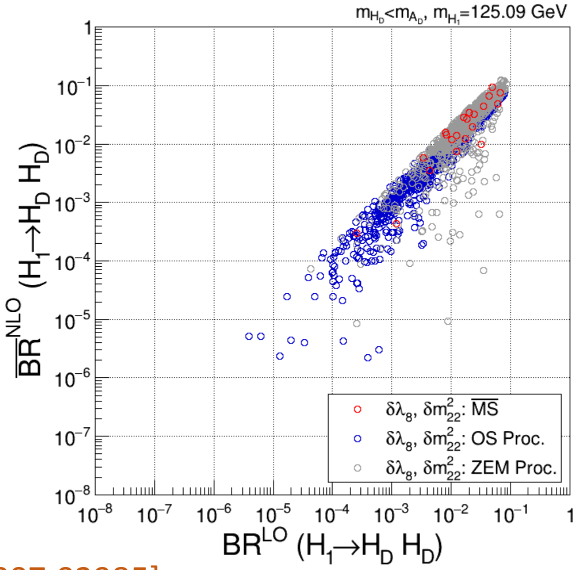
Parameter space scan analysis

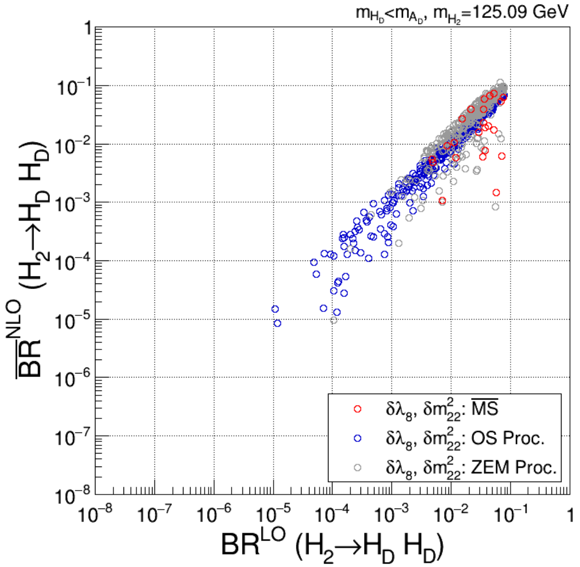




$$m_{A_D} \leq \frac{125}{2}\ \text{GeV}$$

- Corrections in the OS process-dependent scheme mostly between ±100% (most stable);
- Considerable number of points with corrections larger than 100% in the ZEM process-dependent scheme (less stable than OS);
- $\overline{\text{MS}}$ scheme contains very large corrections with very few points having corrections between ±100% (least stable).





- Considering only corrections between ±100% (rough perturbative limit), all surviving points have NLO branching ratios at or bellow the experimental limit ($BR(h_{125} \to inv.) = 0.11$)
- No constraints can be extracted for the parameter space yet.

[points generated with ScannerS, containing the most relevant theoretical and experimental constraints]

[R. Coimbra, M.O.P. Sampaio and R. Santos, Eur. Phys. J. C 73 (2013) 2428]

[M. Mühlleitner, M. O. P. Sampaio, R. Santos, J. Wittbrodt, (Jul 6, 2020) e-Print: 2007.02985]

Summary

- Two possible scenarios for the decay of the SM Higgs boson into a pair of dark matter particles, within the dark doublet phase (DDP) of the N2HDM: the Light Higgs and the Heavy Higgs scenarios.
- Three different schemes were used to renormalize the dark parameters m_{22}^2 and λ_8: the $\overline{\text{MS}}$ scheme and two process-dependent schemes (OS and ZEM). It was shown that with regards to the size of the NLO corrections the $\overline{\text{MS}}$ scheme is too unstable to be trusted in comparison with the process-dependent schemes.
- We scanned over the parameter space and calculated the one-loop corrected partial decay widths of the possible Higgs decays to dark matter, concluding that if we require that the corrections are not unphysically large ($< 100\%$), all the points remain at or below the experimental limit for the Higgs-to-invisible branching ratio ($BR(h_{125} \to inv.) = 0.11$).
- No constraints on the parameter space could be obtained from our results. However, our results are very close to the experimental limit and as the measurements on the couplings and invisible decays of the Higgs boson improve, we are certain that these results will lead to constraints on the parameters space of the DDP in the future.
- In future work, we want to include in these calculations the one-loop corrections to all possible Higgs decays within the DDP. This is needed if we want our results to be reliable as this would reduce the error of the calculated branching ratios to the choice of renormalization scheme.