[arXiv:2104.03184]
under submission to JHEP

Impact of NLO corrections to the Higgs boson invisible decay in N2HDM

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LHC Higgs Working Group WG3 (BSM), online, July 7

Introduction

- After the discovery of the Higgs boson at the LHC, its properties have been measured in detail.

  → Current data shows that discovered Higgs behaves SM-like.

  → Much parameter space is constrained for extended Higgs sectors.

- Still we do not know much about the structure of the Higgs sector.
  - Numbers of Higgs fields, symmetries
  - Hierarchy problem
  - Relation with BSM phenomena
  - etc.

  → We pursue a relation between Higgs sector and dark matter.

Dark matter searches

- Direct searches of dark matter (XENON1T, LUX, Panda X, DARWIN, etc.)
  - Scalar DM is searched by the spin independent cross section of DM-nuclei scattering.
  - Sensitive DM mass range: $\mathcal{O}(10)\mathrm{GeV} \sim \mathcal{O}(1)\mathrm{TeV}$
- Higgs boson invisible decay (LHC, HL-LHC, ILC, FCC, etc.) This work
  - In the SM, H—> inv. happens through H—>ZZ*, but the BR is very small.
  - H—> DM DM contributes to this process, thus DM can be tested.
  - Sensitive DM mass range: $< m_h/2$

Higgs boson invisible decay

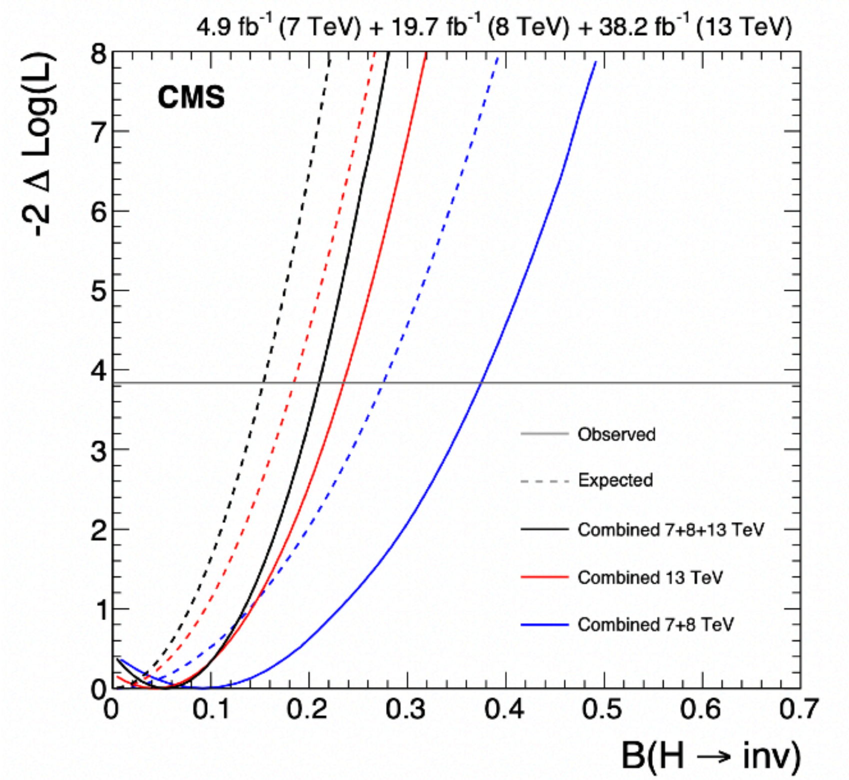
Recent results

Combined results of Run I and Run II at 95% CL.

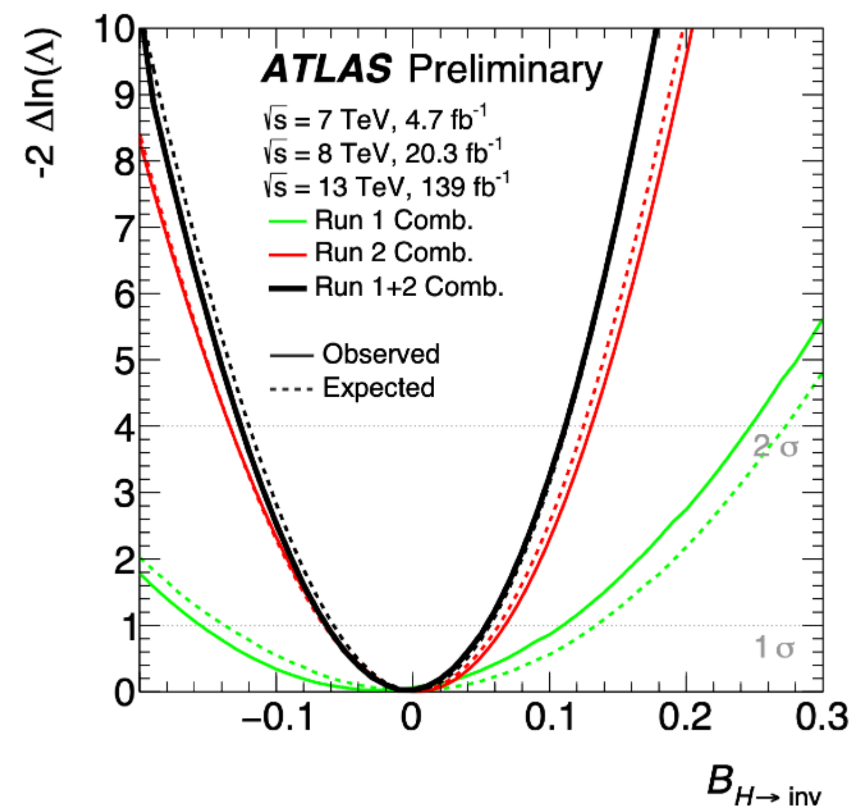
CMS: $\mathrm{BR}_{\mathrm{inv.}} <$ 0.19

ATLAS: $\mathrm{BR}_{\mathrm{inv.}} <$ 0.11

[CMS,PLB793, 520 (2019)]



[ATLAS-CONF-2020-052]



Future sensitivity

[J. de Blas et al., JHEP 01, 139 (2020)]

HL-LHC: $\mathrm{BR}_{\mathrm{inv.}} <$ 0.019 ILC: $\mathrm{BR}_{\mathrm{inv.}} <$ 0.0026 FCC: $\mathrm{BR}_{\mathrm{inv.}} <$ 0.00024

Next-to two Higgs doublet model (N2HDM)

The Higgs potential is composed of scalar doublets Φ_1, Φ_2 and singlet Φ_S as

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

$$
\begin{aligned}
V = \; & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\
+ \; & \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \mathrm{h.c.}\right] \\
+ \; & \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\Phi_1^\dagger \Phi_1 \Phi_S^2 + \frac{\lambda_8}{2}\Phi_2^\dagger \Phi_2 \Phi_S^2 \,,
\end{aligned}
$$

where Z2 symmetries $\mathbb{Z}_2^{(1)} \times \mathbb{Z}_2^{(2)}$ are imposed:

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

There are four different minima that triggers $\mathrm{SU}(2)_{\mathrm{I}} \times \mathrm{U}(1)_{\mathrm{Y}} \to U(1)_{\mathrm{EM}}$.

broken phase (BP): $\langle \Phi_1 \rangle \neq 0 \,, \langle \Phi_2 \rangle \neq 0 \,, \langle \Phi_S \rangle \neq 0 \,,$	2HDM+ HS	HS: Higgs singlet
dark doublet phase (DDP): $\langle \Phi_1 \rangle \neq 0 \,, \langle \Phi_2 \rangle = 0 \,, \langle \Phi_S \rangle \neq 0 \,,$	IDM+ HS	DS: Dark singlet
dark singlet phase (DSP): $\langle \Phi_1 \rangle \neq 0 \,, \langle \Phi_2 \rangle \neq 0 \,, \langle \Phi_S \rangle = 0 \,,$	2HDM+ DS	
full dark phase (FDP): $\langle \Phi_1 \rangle \neq 0 \,, \langle \Phi_2 \rangle = 0 \,, \langle \Phi_S \rangle = 0 \,.$	IDM+ DS	

Dark doublet phase (DDP)

In DDP, component fields can be defined by

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \rho_1 + i\, G^0\right) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H_D^+ \\ \frac{1}{\sqrt{2}}\left(H_D + i\, A_D\right) \end{pmatrix}, \quad \Phi_S = v_s + \rho_s \,,$$

There are 6 physical states:

Dark scalars: $H_D, \; A_D \;, H_D^{\pm}$ CP- even Higgs bosons : $\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_S \end{pmatrix}$

→ H_D (or A_D) can be DM candidate.

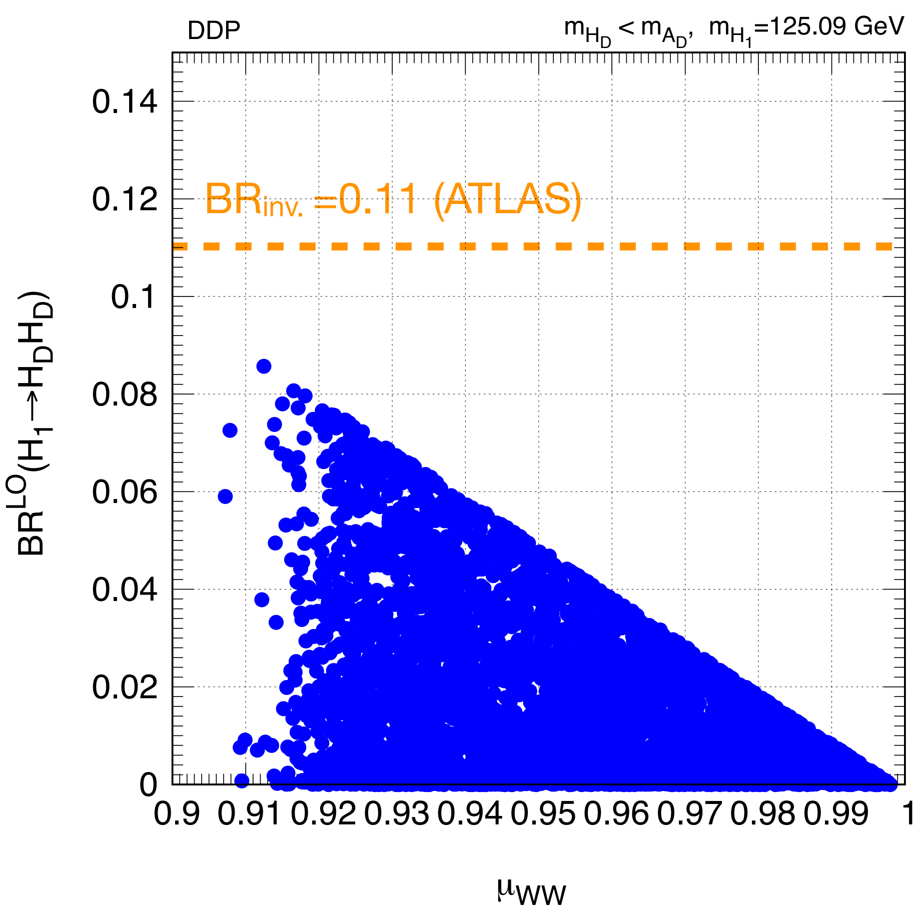
The following 11 parameters are chosen as input parameters:

$$v \,, \quad v_s \,, \quad m_X\,(X = H_D, A_D, H_D^{\pm}, H_1, H_2)\,, \quad \alpha \,, \quad m_{22}^2 \,, \quad \lambda_2 \,, \quad \lambda_8$$

$$V \ni m_{22}^2 |\Phi_2|^2 \; + \lambda_2 |\Phi_2|^4 \; + \lambda_8 |\Phi_2|^2 \Phi_S^2$$

$\mathrm{BR_{inv.}}$ vs Higgs signal strength

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



$$BR^{\rm LO}(H_1 \to H_D H_D) = \frac{\Gamma^{\rm LO}(H_1 \to H_D H_D)}{\Gamma_{H_1}}$$

$$= \frac{\lambda^2_{H_1 H_D H_D}}{32\pi^2 m_{H_1} \Gamma_{H_1}} \sqrt{1 - \frac{4m^2_{H_D}}{m^2_{H_1}}}$$

$$\mu_{WW} = \frac{\sigma(pp \to h_{125} \to WW)}{\sigma_{\rm SM}(pp \to h_{125} \to WW)}$$

- The constraint from the Higgs signal strength → $BR_{\rm inv.} \lesssim 0.09$
- This is stronger than the current bound of $\mathrm{BR_{inv.}}$ by ATLAS.

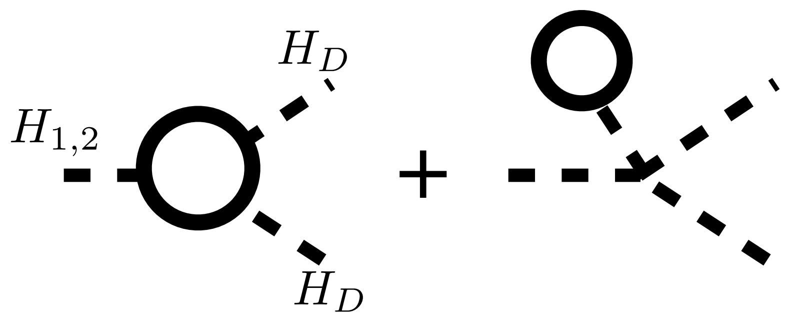
Radiative corrections change the picture ?

Calculations of NLO corrections to $H_{1,2} \rightarrow H_D H_D$

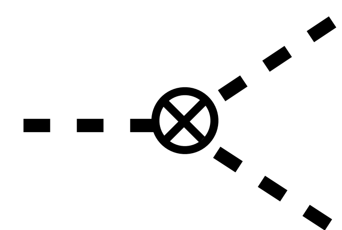
- Decay rate at NLO

$$\Gamma^{\rm NLO}(H_{1,2} \to H_D H_D) = \Gamma^{\rm LO}\left[1 + \frac{2}{\lambda_{H_{1,2}H_D H_D}} {\rm Re}(\mathcal{M}^{\rm 1PI} + \mathcal{M}^{\rm CT})\right]$$

$\mathcal{M}^{\rm 1PI}$:



$\mathcal{M}^{\rm CT}$:



$\ni \delta m_{22}^2 + \delta\lambda_8$

- Renormalization

  - Masses, mixing angles : OS scheme
  - $\delta m_{22}^2, \quad \delta\lambda_8$: We use three different schemes.

OS process-dependent scheme : $\Gamma^{\rm LO}_{H_i \to A_D A_D} \stackrel{!}{=} \Gamma^{\rm NLO}_{H_i \to A_D A_D} \quad (i = 1, 2)$

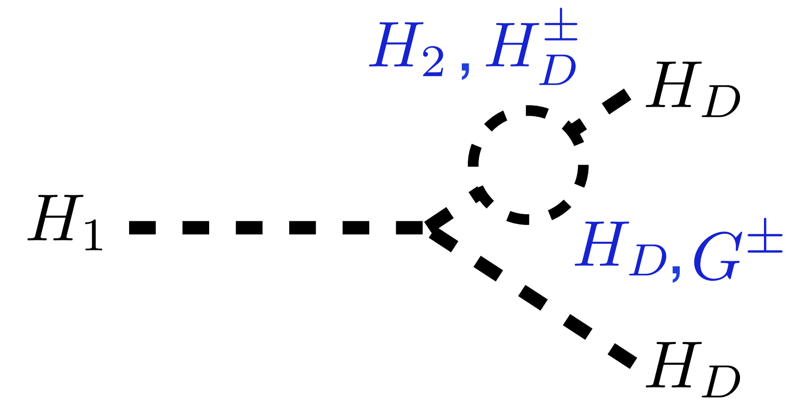
ZEM process-dependent scheme : $(\mathcal{M}_i^{\text{1-loop}})\Big|_{p_i^2 = \, p_{A_D}^2 = 0} = 0$

(ZEM: Zero External Momentum)

$\overline{\rm MS}$ scheme

Extra Higgs loop contributions

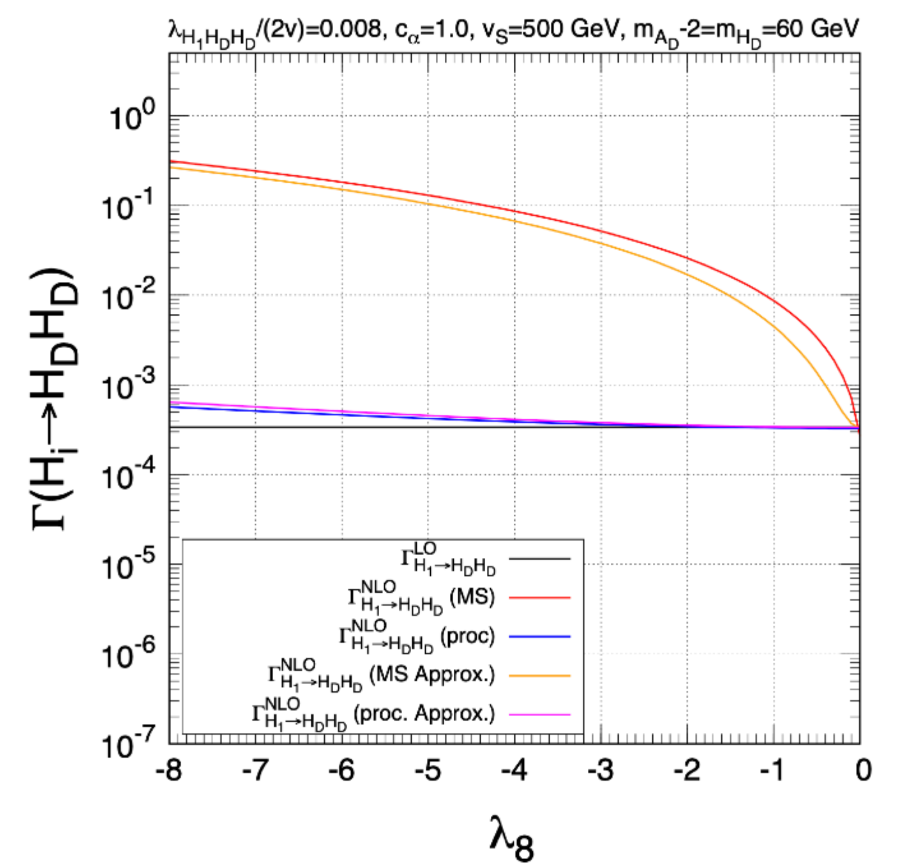
- Approximate formula ($\overline{\text{MS}}$ scheme)



We take $\cos\alpha \to 1,\ \lambda_{H_1 H_D H_D} \ll 1$

$$\Gamma_{H_1\to H_D H_D} \simeq \Gamma^{\rm LO}\left(1 - \frac{4}{v}\frac{1}{16\pi^2}\Big[\underbrace{\lambda^2_{H_2 H_D H_D}}_{\overset{\alpha\to 0}{=}(-\lambda_8 v_S)^2} B_0(m^2_{H_D}, m_{H_2}, m_{H_D}) + 2\lambda^2_{H_D H_D^+ G^-} B_0(m^2_{H_D}, m_{H_D^\pm}, m_{G^\pm})\Big]\right)$$

[D. Azevedo P. Gabriel,M. Mühlleitner, KS, R. Santos]

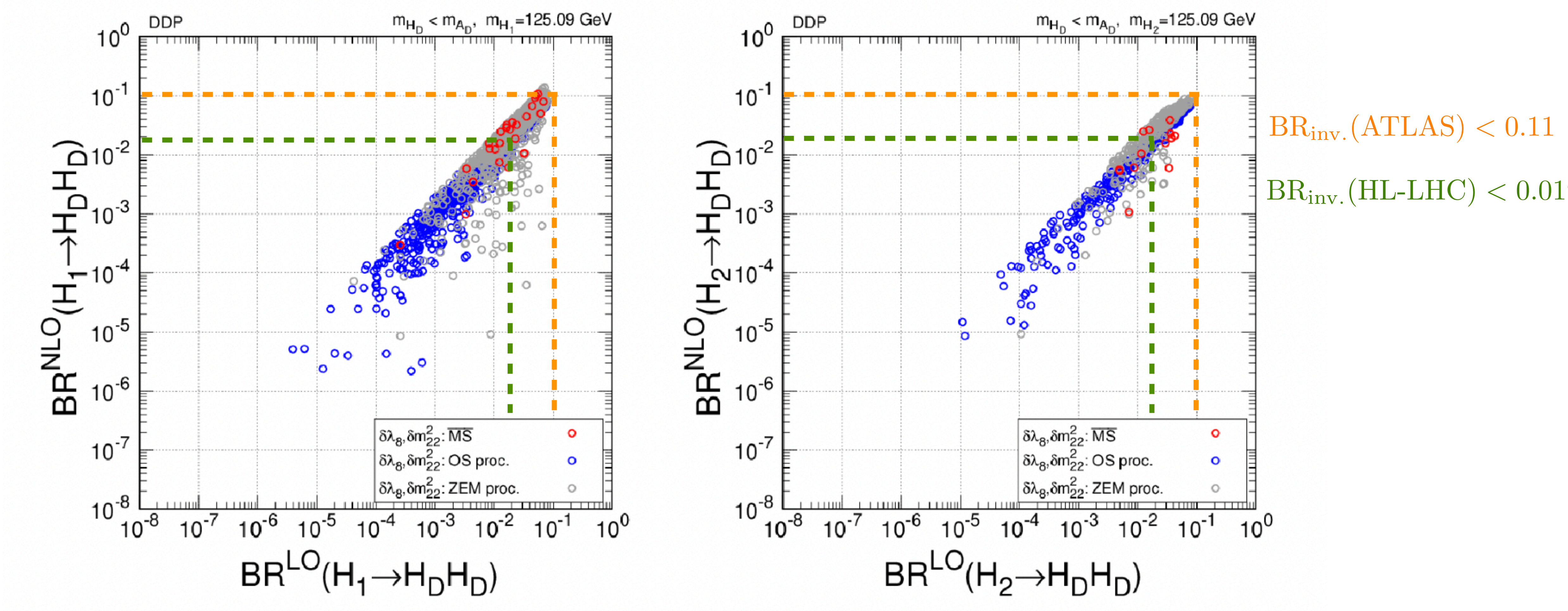


- Many terms suppressed by $\lambda_{H_1 H_D H_D}$.
- The H_2 loop can enhance the corrections.
- For OS proc. scheme, the corrections can be reasonable.

A cancellation between $\mathcal{M}^{\rm loop}_{H_1\to H_D H_D}$ and $\mathcal{M}^{\rm loop}_{H_1\to A_D A_D}$ occurs.

Correlation between BR^{LO} and BR^{NLO}

[D. Azevedo P. Gabriel,M. Mühlleitner, KS, R. Santos]



- We generates parameter points with ScannerS. [M. Muhlleitner, M. O. Sampaio, R. Santos, J. Wittbrodt, arXiv:2007.02985]
  - Theoretical constraints: perturbative unitarity, Higgs potential bounded from below
  - Experimental constraints: DM constraints, extra Higgs searches, Higgs presicion, electroweak precision
- Furthermore, we picked up points with the NLO corrections below 100%.

  → For ZEM scheme, some parameter space would be excluded by $BR_{inv.}$(ATLAS).

  → At HL-LHC era, effect of the NLO corrections become more important.

Summary

- We calculated NLO corrections to $H_{1,2}$ —> H_D H_D , in dark doublet phase (DDP) in N2HDM. This process contributes to the Higgs boson invisible decay.

- At LO analysis, constraints from Higgs signal strength severe than those from Higgs invisible decay.

- When we include the NLO corrections to the Higgs invisible decay, the situation can be changed.

  → In some parameter regions, BR(H_1 –> $H_D H_D$)^{NLO} for ZEM scheme can reach sensitivity of the recent result by ATLAS.

- As a future work, we also study this process in other phases of the N2HDM.

Buck up

Parameter range for scan analysis

We scan input parameters in the following range:

$$
\begin{aligned}
&1\ \text{GeV} < m_{H_D} < 62\ \text{GeV}\,, \quad 1\ \text{GeV} < m_{A_D} < 1500\ \text{GeV} \quad (m_{A_D} > m_{H_D}) \\
&65\ \text{GeV} < m_{H_D^\pm} < 1500\ \text{GeV}\,, \quad 10^{-3}\ \text{GeV}^2 < m_{22}^2 < 5\cdot 10^5\ \text{GeV}^2\,, \\
&1\ \text{GeV} < v_S < 5000\ \text{GeV}\,, \quad -\pi/2 < \alpha < \pi/2\,, \\
&0 < \lambda_2 < 4\pi\,, \quad -4\pi < \lambda_8 < 4\pi\,.
\end{aligned}
$$

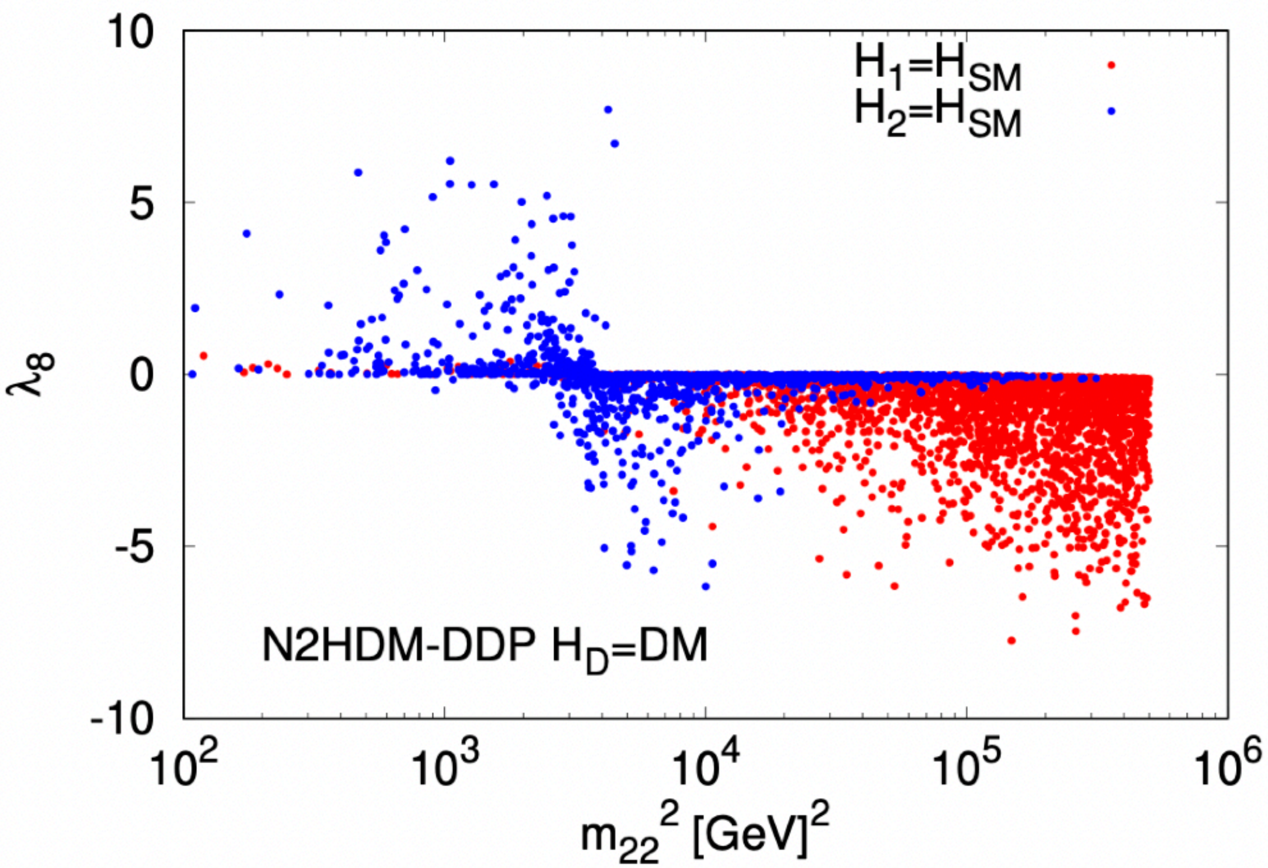
In scenario 1 we take the remaining parameters as

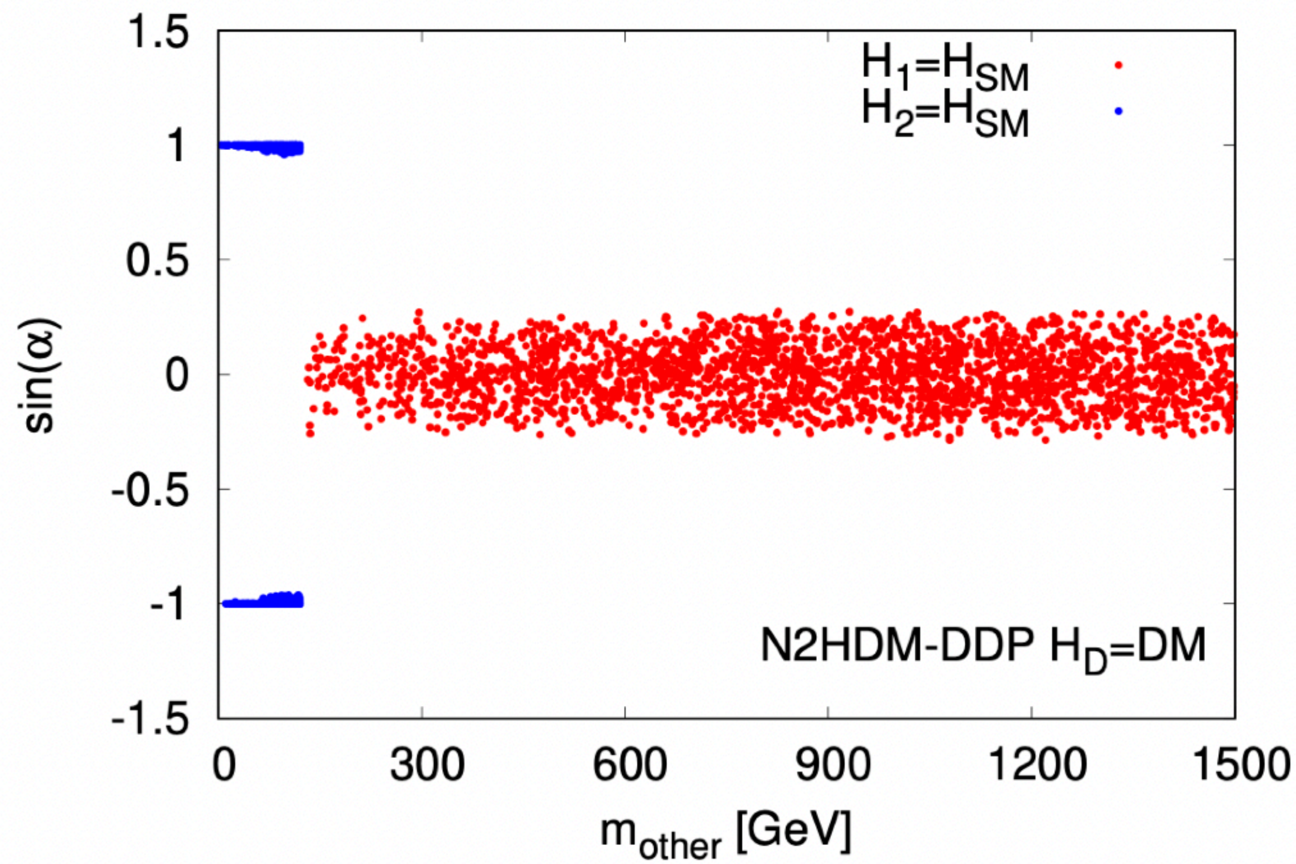
$$m_{H_1} = 125.09\ \text{GeV}, \quad 130\ \text{GeV} < m_{H_2} < 1500\ \text{GeV}$$

In scenario 2, we set as

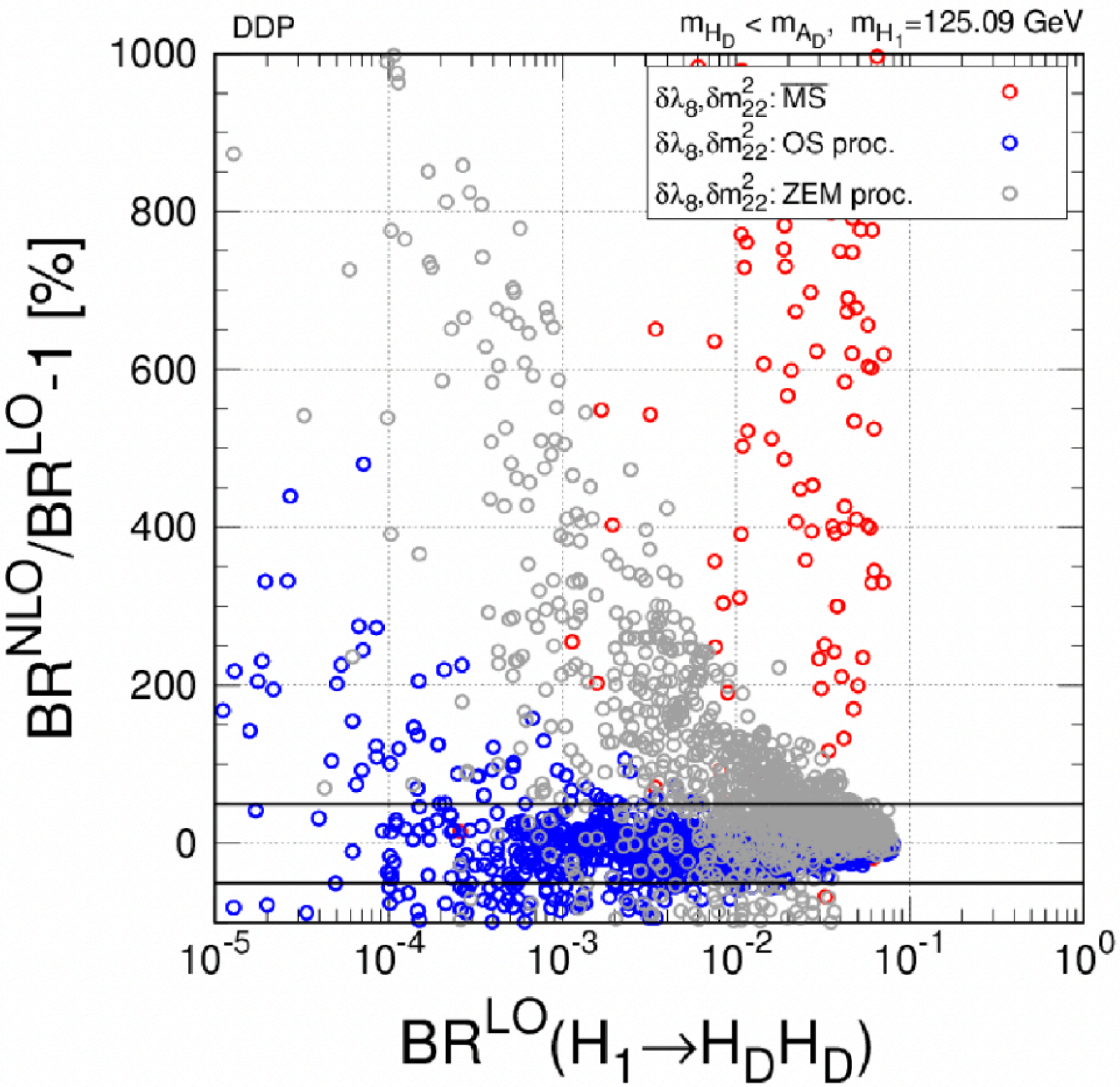
$$1\ \text{GeV} < m_{H_1} < 120\ \text{GeV}, \quad m_{H_2} = 125.09\ \text{GeV}.$$

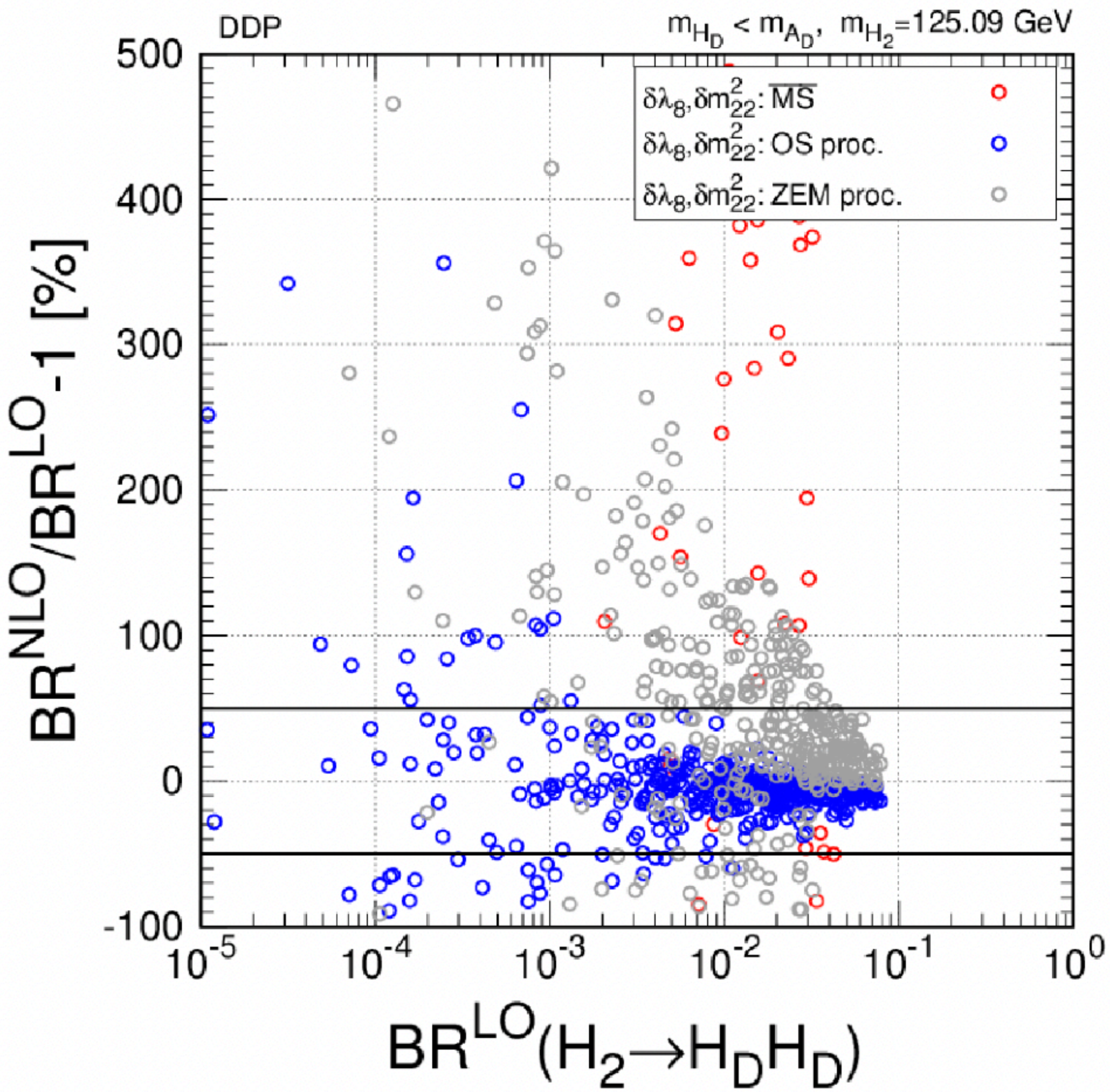
Allowed parameter regions





Size of NLO corrections for the BR





Approximate formula for OS proc. scheme

We take $\cos\alpha \to 1,\ \lambda_{H_1 H_D H_D} \ll 1$.

$$
\begin{aligned}
2\mathrm{Re}\left(\mathcal{M}^{\mathrm{NLO}}_{H_1\to H_D H_D}\right)\mathcal{M}^{\mathrm{LO}}_{H_1\to H_D H_D} \simeq & \frac{-4}{v}\lambda_{H_1 H_D H_D}\left(\Sigma_{H_D H_D}(m^2_{H_D}) - \Sigma_{A_D A_D}(m^2_{A_D})\right) \\
& - \frac{2}{16\pi^2}\lambda^2_{H_1 H_D H_D}\lambda^2_{H_2 H_D H_D} C_0(m^2_{H_D}, m^2_{H_D}, m^2_{H_1}; m_{H_D}, m_{H_2}, m_{H_D}) \\
& + \frac{2}{16\pi^2}\lambda^2_{H_1 A_D A_D}\lambda^2_{H_2 A_D A_D} C_0(m^2_{A_D}, m^2_{A_D}, m^2_{H_1}; m_{A_D}, m_{H_2}, m_{A_D}),
\end{aligned}
$$

$$
\lambda_{H_1 H_D H_D} \overset{\alpha\to 0}{=} -\frac{1}{v}\left(2(m^2_{H_D} - m^2_{22}) - \lambda_8 v_S^2\right)
$$

$$
\lambda_{H_2 H_D H_D} \overset{\alpha\to 0}{=} -\lambda_8 v_S.
$$

$$
\lambda_{H_1 A_D A_D} \overset{\alpha\to 0}{=} \lambda_{H_1 H_D H_D}|_{m_{H_D}\to m_{A_D}}; \quad \lambda_{H_2 A_D A_D} \overset{\alpha\to 0}{=} \lambda_{H_2 H_D H_D}.
$$