Dark Matter in multi-inert doublet models

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Based on
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and work in progress
with
S. King & S. Moretti & D. Sokolowska
J. Hernandez & A. Cordero & D. Rojas

Cosmo seminar 2/3/16

1. Introduction and motivation
2. I(1+1)HDM: the Inert doublet model
3. I(2+1)HDM: extending the Inert doublet model
4. Conclusions and outlook

Higgs particle discovered

- 2012 – a Higgs boson discovered at the LHC

$$\text{ATLAS: } M_h = 125.36\,\text{GeV}$$
$$\text{CMS: } M_h = 125.03\,\text{GeV}$$

- very SM-like
- yet we do expect some New Physics to exist
  - Dark Matter
  - baryon asymmetry and baryogenesis
  - extra source of CP violation
  - vacuum stability
  - ...

Dark Matter (DM)

around 25 % of the Universe is:

- cold
- non-baryonic
- neutral
- very weakly interacting

$\Rightarrow$ **W**eakly **I**nteracting **M**assive **P**article

- stable due to the discrete symmetry

$$\underbrace{\text{DM DM} \to \text{SM SM}}_{\text{pair annihilation}}, \quad \underbrace{\text{DM} \not\to \text{SM}, \ldots}_{\text{stable}}$$

Higgs-portal DM

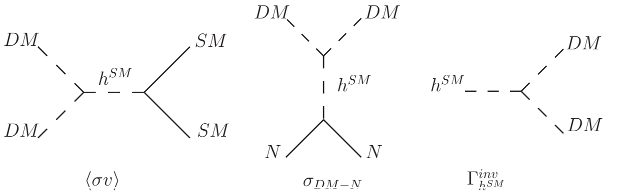
Simplest realisation: the SM with Φ_{SM} + Z_2-odd scalar S:

$$S \to -S, \quad \text{SM fields} \to \text{SM fields}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - \frac{1}{2}m_{DM}^2 S^2 - \lambda_{DM} S^4 - \lambda_{hDM}\Phi_{SM}^2 S^2$$

Higgs-portal interaction:

$$\text{SM sector} \xleftrightarrow{\text{Higgs}} \text{DM sector}$$



given by the same coupling

The Inert Doublet Model
I(1+1)HDM

2HDM with 1 Inert and 1 Higgs doublet

A two Higgs Doublet Model

Two Higgs Doublet Model (2HDM):

- two scalar $SU(2)_W$ doublets Φ_1, Φ_2 with the hypercharge $Y = +1$
- rich phenomenology: different types of vacua, hierarchy in Yukawa couplings, CP violation in the scalar sector, baryogenesis, ...
- a 2HDM with an exact Z_2 symmetry: the Inert Doublet Model

  $\rightarrow$ SM-like Higgs boson

  $\rightarrow$ a Dark Matter candidate

The Inert Doublet Model

Scalar potential V invariant under a Z_2-transformation:

$$Z_2: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \text{SM fields} \to \text{SM fields}$$

$$\begin{aligned} V &= -\frac{1}{2}\left[m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2\right] + \frac{1}{2}\left[\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2\right] \\ &+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\lambda_5 \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right] \end{aligned}$$

- The potential is explicitly Z_2-symmetric
- Only Φ_1 couples to fermions
- All parameters are real – no CP violation

The Inert minimum

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- The whole Lagrangian is explicitly Z_2-symmetric
- Φ_1 – active as in SM (SM-like Higgs boson h)

  Φ_2 "dark" or inert doublet with 4 dark scalars $(H, A, H^{\pm})$, no interaction with fermions
- only Φ_2 has odd Z_2-parity

  → the lightest scalar is **a candidate for the dark matter**

Constraints

(1) **Vacuum stability**: scalar potential V bounded from below

(2) **Existence of the Inert vacuum**: a *global* minimum of V

(3) **Perturbative unitarity**: eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$

(4) **Higgs mass**: $M_h = 125$ GeV

$$(1)-(4) \Rightarrow m_{22}^2 \lesssim 9 \cdot 10^4\,\text{GeV}^2,\ \lambda_1 = 0.258,\ \lambda_2 < 8.38,\ \lambda_3, \lambda_{345} > -1.47,$$

(5) **EWPT & LEP**: bounds on masses of the scalars

$$M_{H^\pm} \gtrsim 70 - 90\ \text{GeV}$$

$$\delta_A = M_A - M_H < 8\,\text{GeV} \Rightarrow M_H + M_A > M_Z$$

$$\text{excluded}: M_H < 80\ \text{GeV}, M_A < 100\ \text{GeV and } \delta_A > 8\ \text{GeV}$$

Relic density constraints

(6) ***H* as DM candidate**: $M_H < M_A, M_{H^\pm}$ with proper $\Omega_{DM} h^2$

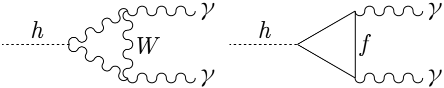
$$0.1118 < \Omega_{DM} h^2 < 0.128$$

$$\lambda_{345} \sim g_{HHh} \text{ and } M_i$$

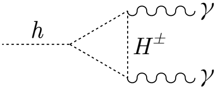
- Strongly constrained by LHC and DD:
    - **low DM mass** $M_H \lesssim 10$ GeV, $\lambda_{345} \sim \mathcal{O}(0.5)$
    - **medium DM mass** $M_H \approx (40 - 160)$ GeV, $\lambda_{345} \sim \mathcal{O}(0.05)$
- DD sensitivity very low:
    - **high DM mass** $M_H \gtrsim 500$ GeV, $\lambda_{345} \sim \mathcal{O}(0.1)$

LHC constraints from $h \to \gamma\gamma$

- $h\gamma\gamma$ not present at tree level
- At loop level in the SM



- In the IDM – additional $H^\pm$



- Experiment: signal strength $R_{\gamma\gamma} \simeq 1$

Summary of the I(1+1)HDM

$Br(h \to inv) + R_{\gamma\gamma} + \Omega_{DM} h^2 \quad \Rightarrow \quad$ strong limits on IDM

- Low DM mass excluded
- $M_H < M_h/2 \Rightarrow R_{\gamma\gamma} > 1$
- $M_h/2 < M_H < M_W$ & H constitutes 100% of DM $\Rightarrow R_{\gamma\gamma} < 1$
- Heavy DM $\Rightarrow R_{\gamma\gamma} \approx 1$

Extending the Inert doublet model

I(2+1)HDM

3HDM with 2 Inert and 1 Higgs doublet

Three-Higgs Doublet Models (3HDMs)

Three-Higgs Doublet Models:

- three $SU(2)$ doublets, ϕ_1, ϕ_2, ϕ_3
  one Higgs doublet per family
  with the SM-Higgs doublet quantum numbers
- richer symmetry groups than the 2HDMs
  discrete, continuous, CP, Generalised CP
- richer particle spectrum
  3 scalars, 2 pseudo-scalars, 2 charged

I(2+1)HDM

Z_2-symmetry in I(2+1)HDM:

$$\phi_1 \to -\phi_1,\ \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3,\ \text{SM fields} \to \text{SM fields}$$

Z_2-invariant potential:

$$\begin{aligned} V &= \sum_i^3 \left[-|\mu_i^2|(\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 \right] \\ &+ \sum_{ij}^3 \left[\lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right] \\ &+ \left(-\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c. \right) \end{aligned}$$

- All parameters real
- Only ϕ_3 couples to fermions
- Explicit Z_2-symmetry

DM in I(2+1)HDM

Z_2-invariant vacuum state:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

- ϕ_3 – SM-like doublet with SM-like Higgs h
- Z_2-odd doublets ϕ_1 and ϕ_2 mix:

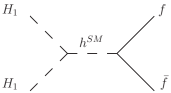
$$H_1 = \cos\alpha_H H_1^0 + \sin\alpha_H H_2^0, \quad H_2 = \cos\alpha_H H_2^0 - \sin\alpha_H H_1^0$$

(similar for A_i and $H_i^\pm$)

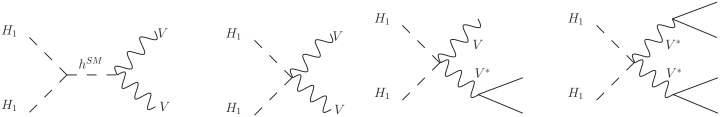
- 4 neutral and 2 charged Z_2-odd particles (double the IDM)
- H_1 – **DM candidate**, other dark particles heavier

Dark Matter Annihilation

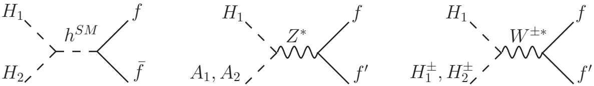
- annihilation through Higgs into fermions; dominant channel for $M_{DM} < M_h/2$



- annihilation to gauge bosons; crucial for heavier masses



- coannihilation; when particles have similar masses



DM Annihilation Scenarios

Low mass region:

(A) **no coannihilation effects**:

$$M_{H_1} < M_{H_2,A_1,A_2,H_1^\pm,H_2^\pm}$$

(D) **coannihilation** with $H_2, A_{1,2}$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} < M_{H_1^\pm,H_2^\pm}$$

Heavy mass region:

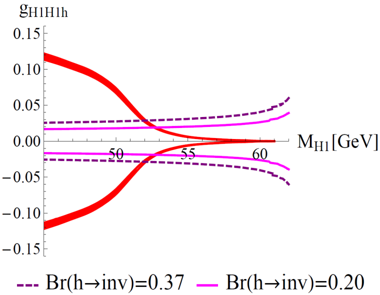
(G) **coannihilation** with $H_2, A_{1,2}, H^\pm_{1,2}$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} \approx M_{H_1^\pm,H_2^\pm}$$

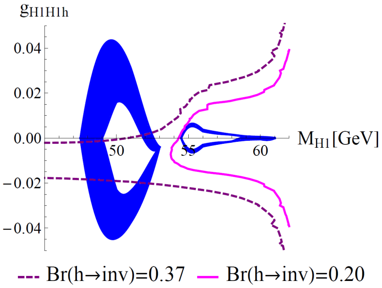
(H) **coannihilation** with $A_1, H_1^\pm$:

$$M_{H_1} \approx M_{A_1} \approx, M_{H_1^\pm} < M_{H_2,A_2,H_2^\pm}$$

LHC vs Planck $M_{DM} < M_h/2$



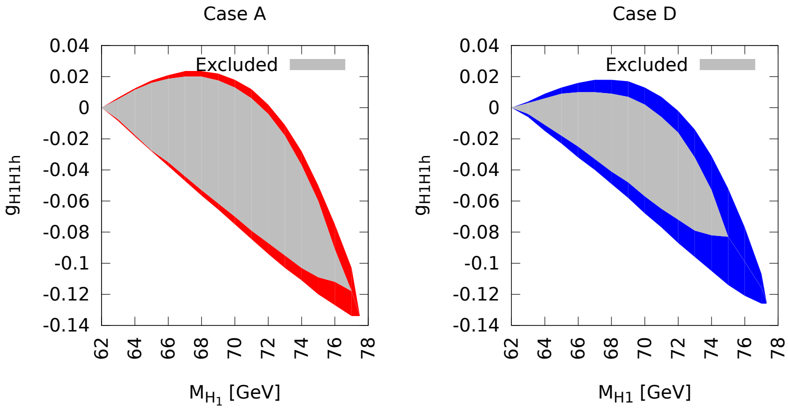
case A



case D

- $Br(h \to inv) < 37\%$ & $\Omega_{DM} h^2 \Rightarrow$
  - Case A: $M_{DM} \gtrsim 53\,\mathrm{GeV}$
  - Case D: most masses are OK

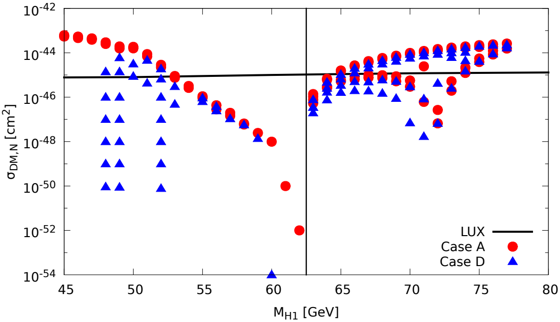
Planck constraints: $M_{DM} > M_h/2$



Relic density values are dominated by three couplings:

$g_{DMVV}, \quad g_{hVV}, \quad g_{H_1H_1h}$

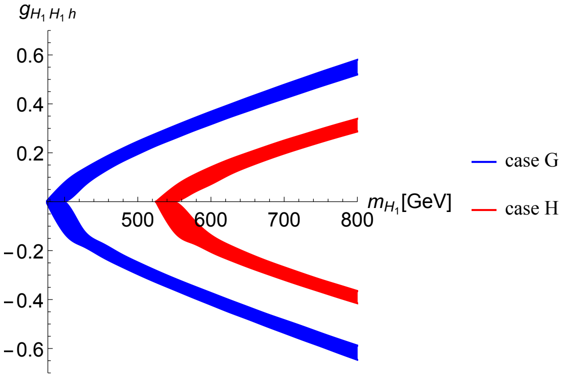
Direct detection limits



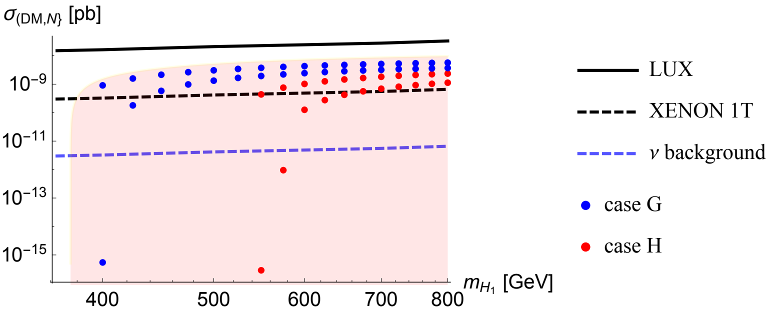
Case D: new region in agreement with LUX with respect to Case A

Heavy mass regime $M_{DM} > M_W$

- case H – like the I(1+1)DM: $M_{H_1} \gtrsim 525$ GeV
- case G – new region: $M_{H_1} \gtrsim 360$ GeV



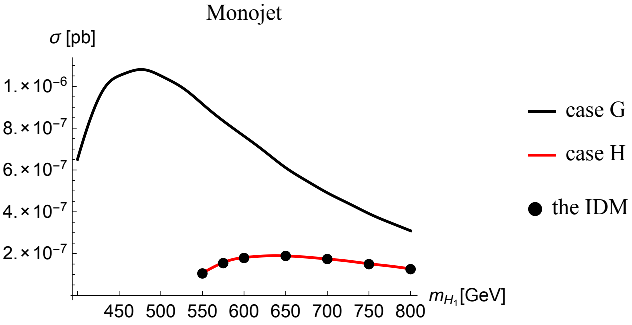
Direct detection limits



Case G: new region in agreement with LUX with respect to Case H

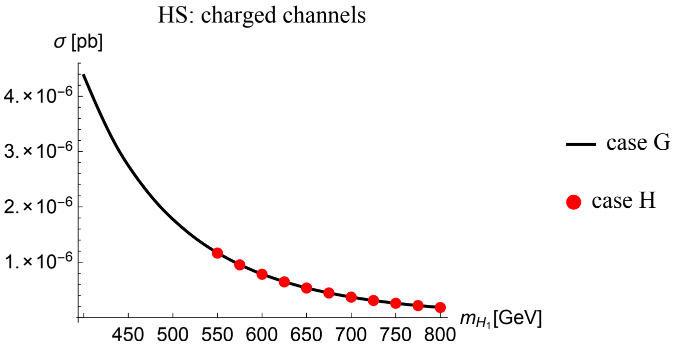
LHC signals: monojet channels

Monojet channels $gg \to gH_1H_1, \;\; q\bar{q} \to gH_1H_1, \;\; qg \to qH_1H_1$



LHC signals: dijet channels

- Vector Boson Fusion: $q_i q_j \to H_1 H_1 q_k q_l$
- Higgs-Strahlung: $q_i \bar{q}_j \to V^* H_1 H_1$



Summary

- I(1+1)DM
  - a good DM model with rich phenomenology, however, very constrained.
- I(2+1)HDM
  - viable DM candidate
  - large dark sector

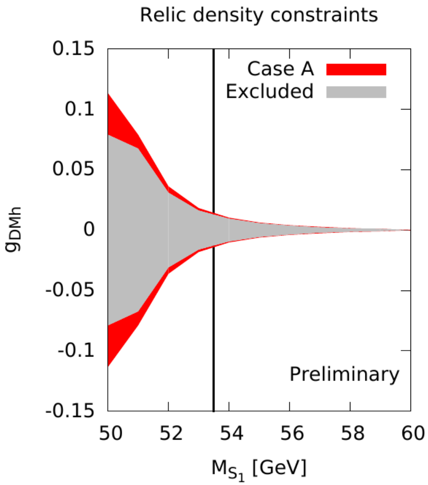
    → In the light mass region: $46\text{ GeV} \lesssim m_{DM} \lesssim 62\text{ GeV}$

    → In the heavy mass region: $360\text{ GeV} \lesssim m_{DM} \lesssim 525\text{ GeV}$
  - Observable at the LHC

Outlook

- CP-Violation in I(2+1)HDM
  - SM-like active sector: $H_3 \equiv h^{SM}$
  - CPV in the inert sector: $H_{1,2}, A_{1,2} \rightarrow S_{1,2,3,4}$ CPV DM
  - New observables at the LHC: $S_i S_j Z$ vertices
- CP-Violation in I(1+2)HDM
  - IDM-like inert sector: CPC DM
  - CPV in the active sector: $\tilde{H}_1, \tilde{H}_2, \tilde{H}_3$
  - Interesting LHC phenomenology

CP-mixed DM


Relic density constraints
Case A
Excluded
Preliminary
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
g_{DMh}
50
52
54
56
58
60
M_{S_1} [GeV]

BACKUP SLIDES

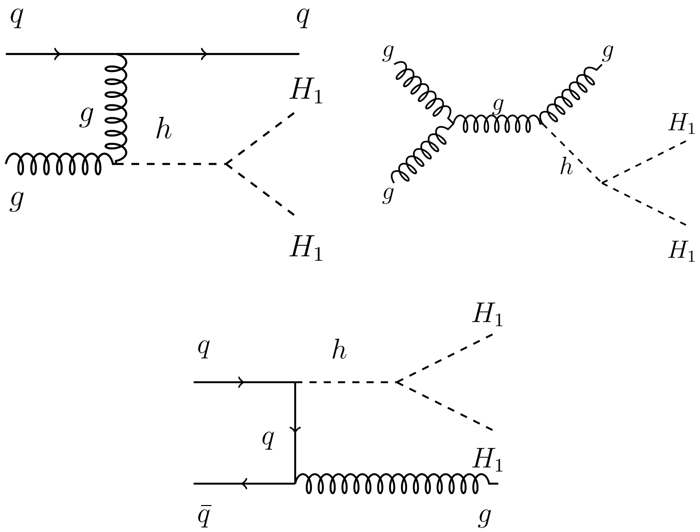
Indirect searches

- I(1+1)HDM:
  indirect detection signatures: internal bremsstrahlung in the processes of $H_1 H_1 \to W^+ W^- \gamma$ mediated by a charged scalar in the t-channel.

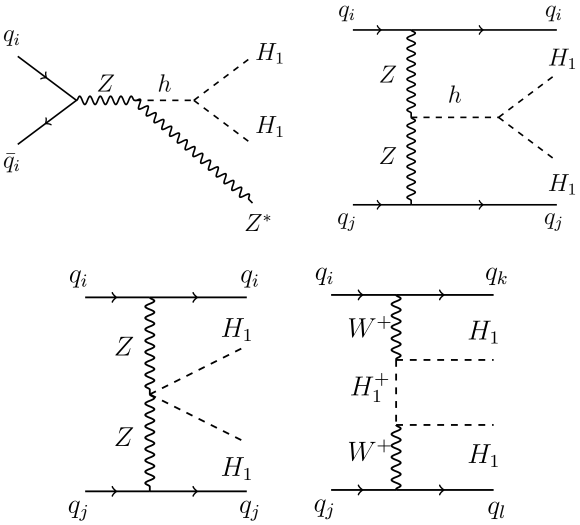
- I(2+1)HDM
  same signature generated through the exchange of any of the two charged scalars $H^{\pm}_{1,2}$.

  The signal could even be stronger for scenario G with larger scalar couplings.

LHC signals: monojet channels $pp \to H_1 H_1 +$ jet



LHC signals: dijet channels $pp \to H_1 H_1 + 2$ jets

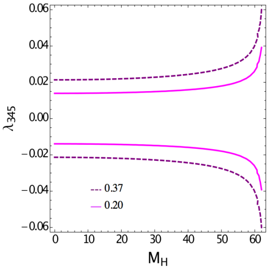


Low DM mass

$$M_H \lesssim 10\,\text{GeV}, \quad M_A \approx M_{H^\pm} \approx 100\,\text{GeV}$$

$h \to AA$ channel closed, $h \to HH$ channel open

main annihilation channel: $HH \to h \to b\bar{b}$



- Correct relic density

  $0.1118 < \Omega_{DM}h^2 < 0.128 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$

- CDMS-II reported event:

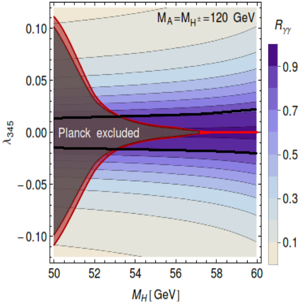
  $M_H = 8.6\text{ GeV} \Rightarrow |\lambda_{345}| \approx (0.3 - 0.4)$

- $Br(h \to inv) \lesssim 0.4 \Rightarrow |\lambda_{345}| \lesssim 0.02$

Low DM mass excluded

Medium DM mass – HH channel open

$$50\,\text{GeV} < M_H < M_h/2\,\text{GeV}, \quad M_A = M_{H^\pm} = 120\,\text{GeV}$$

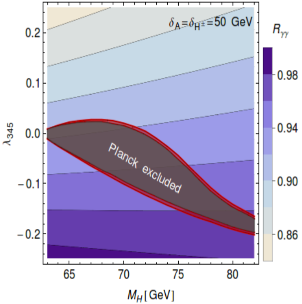


Red bound: $\Omega_{DM}h^2$ in agreement with Planck

Black line: $Br(h \to inv) \approx 0.4$

Medium DM mass – HH channel closed

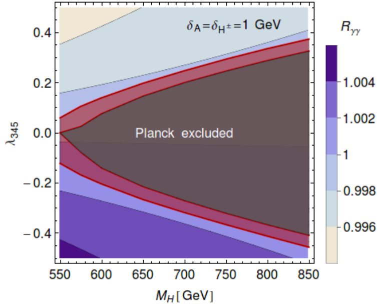
$$M_h/2 < M_H < 83\,\text{GeV}, \quad M_A = M_{H^\pm} = M_H + 50\,\text{GeV}$$



Red bound: $\Omega_{DM} h^2$ in agreement with Planck

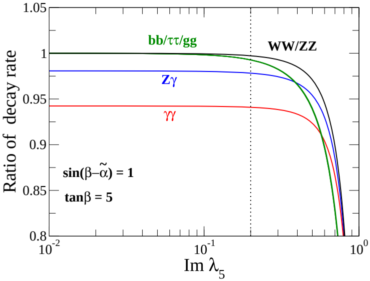
High DM mass

$$M_H \gtrsim 550\,\text{GeV}, \quad M_A = M_{H^\pm} = M_H + 1\,\text{GeV}$$



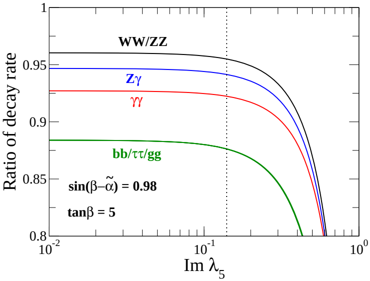
Red bound: $\Omega_{DM}h^2$ in agreement with Planck

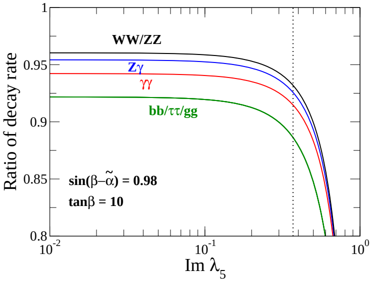
CPV in I(1+2)HDM



The ratio of decay rates of $\tilde{H}_1$ to those of the SM Higgs boson $h_{\rm SM}$ as a function of λ_5^i.

CPV in I(1+2)HDM





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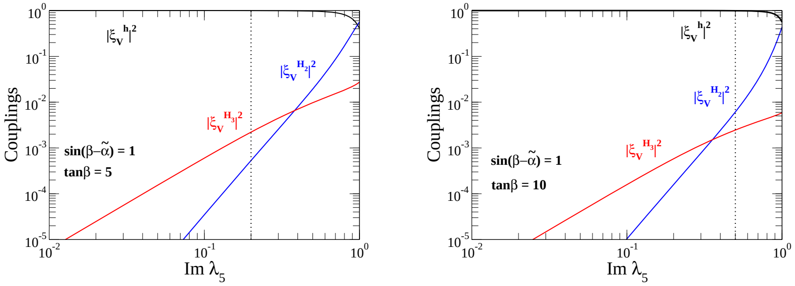
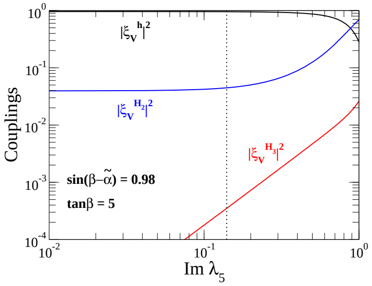
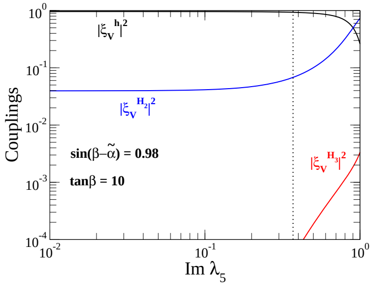
CPV in I(1+2)HDM



The coefficient of the gauge-gauge-scalar type couplings as a function of λ_5^i.

CPV in I(1+2)HDM





The coefficient of the gauge-gauge-scalar type couplings as a function of λ_5^i.