# Collider signatures of extra inert scalars in the I(2+1)HDM

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# The potential with $Z_2$ symmetry

The most general phase invariant part of the 3HDM potential has the following form:

$$
\begin{aligned}
V_0 = & -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \mu_3^2(\phi_3^\dagger\phi_3) \\
& +\lambda_{11}(\phi_1^\dagger\phi_1)^2 + \lambda_{22}(\phi_2^\dagger\phi_2)^2 + \lambda_{33}(\phi_3^\dagger\phi_3)^2 \\
& +\lambda_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_{23}(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_{31}(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1) \\
& +\lambda'_{12}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda'_{23}(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) + \lambda'_{31}(\phi_3^\dagger\phi_1)(\phi_1^\dagger\phi_3).
\end{aligned} \tag{1}
$$

We add $Z_2$ group potential terms

$$
V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c. \tag{2}
$$

charge assignment:

$$
g = \mathrm{diag}\left(-1, -1, +1\right). \tag{3}
$$

# Mass eigenstates

The scalar fields can be parametrised as:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}, \tag{4}$$

with $v^2 = \frac{\mu_3^2}{\lambda_{33}}$.

**The fields from the active doublet**

$$\begin{aligned} m_{G^0}^2 &= m_{G^\pm}^2 = 0 \\ m_h^2 &= 2\mu_3^2 \end{aligned} \tag{5}$$

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with $v^2 = \frac{\mu_3^2}{\lambda_{33}}$.

**The CP-even neutral inert fields**

$$R_{\theta_h} = \begin{pmatrix} \cos\theta_h & \sin\theta_h \\ -\sin\theta_h & \cos\theta_h \end{pmatrix}, \qquad \tan 2\theta_h = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda_{\phi_1} - \mu_2^2 + \Lambda_{\phi_2}}$$

$$m_{H_1}^2 = (-\mu_1^2 + \Lambda_{\phi_1})\cos^2\theta_h + (-\mu_2^2 + \Lambda_{\phi_2})\sin^2\theta_h - 2\mu_{12}^2 \sin\theta_h \cos\theta_h$$
$$m_{H_2}^2 = (-\mu_1^2 + \Lambda_{\phi_1})\sin^2\theta_h + (-\mu_2^2 + \Lambda_{\phi_2})\cos^2\theta_h + 2\mu_{12}^2 \sin\theta_h \cos\theta_h$$

where $\Lambda_{\phi_1} = \frac{1}{2}(\lambda_{31} + \lambda'_{31} + 2\lambda_3)v^2, \quad \Lambda_{\phi_2} = \frac{1}{2}(\lambda_{23} + \lambda'_{23} + 2\lambda_2)v^2$

# Mass eigenstates

The scalar fields can be parametrised as:

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with $v^2 = \frac{\mu_3^2}{\lambda_{33}}$.

**The charged inert fields**

$$R_{\theta_c} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}, \quad \tan 2\theta_c = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda'_{\phi_1} - \mu_2^2 + \Lambda'_{\phi_2}}$$

$$m_{H_1^\pm}^2 = (-\mu_1^2 + \Lambda'_{\phi_1})\cos^2\theta_c + (-\mu_2^2 + \Lambda'_{\phi_2})\sin^2\theta_c - 2\mu_{12}^2 \sin\theta_c \cos\theta_c$$
$$m_{H_2^\pm}^2 = (-\mu_1^2 + \Lambda'_{\phi_1})\sin^2\theta_c + (-\mu_2^2 + \Lambda'_{\phi_2})\cos^2\theta_c + 2\mu_{12}^2 \sin\theta_c \cos\theta_c$$

$$\text{where} \quad \Lambda'_{\phi_1} = \frac{1}{2}(\lambda_{31})v^2, \quad \Lambda'_{\phi_2} = \frac{1}{2}(\lambda_{23})v^2$$

# Mass eigenstates

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with $v^2 = \frac{\mu_3^2}{\lambda_{33}}$.

**The CP-odd neutral inert fields**

$$R_{\theta_a} = \begin{pmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{pmatrix}, \quad \tan 2\theta_a = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda''_{\phi_1} - \mu_2^2 + \Lambda''_{\phi_2}}$$

$$m_{A_1}^2 = (-\mu_1^2 + \Lambda''_{\phi_1}) \cos^2\theta_a + (-\mu_2^2 + \Lambda''_{\phi_2}) \sin^2\theta_a - 2\mu_{12}^2 \sin\theta_a \cos\theta_a$$

$$m_{A_2}^2 = (-\mu_1^2 + \Lambda''_{\phi_1}) \sin^2\theta_a + (-\mu_2^2 + \Lambda''_{\phi_2}) \cos^2\theta_a + 2\mu_{12}^2 \sin\theta_a \cos\theta_a$$

where $\Lambda''_{\phi_1} = \frac{1}{2}(\lambda_{31} + \lambda'_{31} - 2\lambda_3)v^2, \quad \Lambda''_{\phi_2} = \frac{1}{2}(\lambda_{23} + \lambda'_{23} - 2\lambda_2)v^2$

# Mass eigenstates

The scalar fields can be parametrised as:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}, \tag{4}$$

with $v^2 = \frac{\mu_3^2}{\lambda_{33}}$.

$(H_1, A_1, H_1^{\pm})$ first generation
$(H_2, A_2, H_2^{\pm})$ second generation.

We assume:

$$m_{H_1} < m_{H_2}, m_{A_{1,2}}, m_{H^{\pm}_{1,2}}. \tag{5}$$

$H_1$ **dark matter candidate**

# Simplified couplings

We focus on a simplified case where

$$\mu_1^2 = n\mu_2^2, \quad \lambda_3 = n\lambda_2, \quad \lambda_{31} = n\lambda_{23}, \quad \lambda'_{31} = n\lambda'_{23}, \qquad (6)$$

resulting in

$$\Lambda_{\phi_1} = n\Lambda_{\phi_2}, \quad \Lambda'_{\phi_1} = n\Lambda'_{\phi_2}, \quad \Lambda''_{\phi_1} = n\Lambda''_{\phi_2}, \qquad (7)$$

Note that when $n \to 0$ we recover the I(1+1)HDM.

In this study we choose the set $(m_{H_1}, m_{H_2}, g_{H_1 H_1 h}, \theta_a, \theta_c, n)$, where $g_{H_1 H_1 h}$ is the Higgs-DM coupling.

# Parameters of the model

$$\Lambda_{\phi_2} = \frac{v^2 g_{H_1 H_1 h}}{4(\sin^2\theta_h + n\cos^2\theta_h)},$$

$$\mu_2^2 = \Lambda_{\phi_2} - \frac{m_{H_1}^2 + m_{H_2}^2}{1+n},$$

$$\mu_{12}^2 = \frac{1}{2}\sqrt{(m_{H_1}^2 - m_{H_2}^2)^2 - (-1+n)^2(\Lambda_{\phi_2} - \mu_2^2)^2},$$

$$\Lambda''_{\phi_2} = \frac{2\mu_{12}^2}{(1-n)\tan 2\theta_a},$$

$$\Lambda'_{\phi_2} = \frac{2\mu_{12}^2}{(1-n)\tan 2\theta_c},$$

$$\lambda_2 = \frac{1}{2v^2}(\Lambda_{\phi_2} - \Lambda''_{\phi_2}),$$

$$\lambda_{23} = \frac{2}{v^2}\Lambda'_{\phi_2},$$

$$\lambda'_{23} = \frac{1}{v^2}(\Lambda_{\phi_2} + \Lambda''_{\phi_2} - 2\Lambda'_{\phi_2}),$$

$$\tan^2\theta_h = \frac{m_{H_1}^2 - n m_{H_2}^2}{n m_{H_1}^2 - m_{H_2}^2}.$$

# Cascade decays

- $H_1$ is absolutely stable
- All other inerts are unstable
- Inert sector is accessed by the the Higgs particle
- We study

$$gg \to \text{pair of inerts} \to \cdots \to nH_1(\gamma/Z)$$

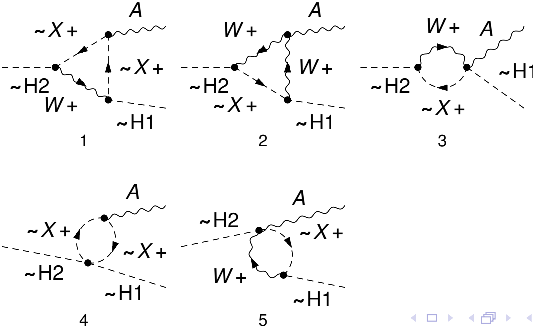
resulting in highly energetic EM showers, alongside $E_T^{\text{miss}}$

# Radiative decays of heavy inerts

We focus on a specific signature that arise in the model, namely the $E_T^{\text{miss}}$ and 2 charged leptons. This kind of process do not exist in the I(1+1)HDM.

In the CPC case there is only one possibility. The 1-loop process

$$h \to H_2^* H_1 \to \gamma^* H_1 H_1 \to l^+ l^- H_1 H_1 \tag{8}$$



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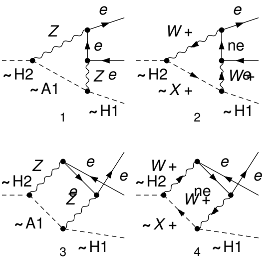


Figure : This amplitude is proportional to $g^4$, while the others diagrams are proportional to $eg^2$. Hence, the contribution from the box diagrams is very small, of the order of 5 %, and the results are negligible

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Feynman rule for effective vertex

$$-2ig_e K(p_{H_1} - p_{H_2})^\mu$$

$K$ was obtained with LoopTools

$$K^2 = \frac{4\pi^3 m_{S_2}^3}{3} \frac{\Gamma(H_2 \to H_1 e^+ e^-)}{I_2} \quad (9)$$

where

$$I_2 = \int_{(m_{23}^2)_{min}}^{(m_{23}^2)_{max}} dm_{23}^2 \lambda(m_{H_2}, m_{H_1}, m_{23}) \quad (10)$$

and $m_{23}^2 = 2k_2 \cdot p_2 + m_{H_1^2}$.

# Other signatures

- $E_T^{\text{miss}} + 6$charged leptons

$$h \to A_1^* A_2^* \to Z^* H_1 Z^* H_2 \to Z^* H_1 Z^* \gamma^* H_1 \to l^+ l^- l^+ l^- l^+ l^- H_1 H_1$$

- $E_T^{\text{miss}} + 8$charged leptons

$$h \to A_2^* A_2^* \to Z^* H_2 Z^* H_2 \to Z^* Z^* \gamma^* H_1 \gamma^* H_1 \to l^+ l^- l^+ l^- l^+ l^- l^+ l^- H_1 H_1$$

However, this last process cannot be calculated with CalcHEP.

# Coannihilation scenarios relevant for DM studies

- $\Delta = m_{H_2} - m_{H_1}$
- $\delta_A = m_{A_1} - m_{H_1}$, $\delta_C = m_{H_1^\pm} - m_{H_1}$
- $\delta'_A = m_{A_2} - m_{H_1}$, $\delta'_C = m_{H_2^\pm} - m_{H_1}$

A Large $\Delta$, $\delta_A$, $\delta_C \Rightarrow$ large $\delta'_A$, $\delta'_C$.

D Small $\Delta$, $\delta_A$, large $\delta_C \Rightarrow$ large $\delta'_C$ while $\delta'_A$ can be small.

These scenarios are the only phenomenologically relevant for $m_{\mathrm{DM}} < m_h/2$ region due to LEP limits[1].

For $m_{\mathrm{DM}} > m_W$:

- **Case G.** Small $\delta_A$, $\delta_C$, $\Delta$ where all inert particles are close in mass and coannihilate with each other.
- **Case H.** Small $\delta_A$, $\delta_C$ and large $\Delta$. 2nd generation decoupled from 1st. Only diagrams with fields from 1st generation.

[1] V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP **1411**, 016 (2014) doi:10.1007/JHEP11(2014)016 [arXiv:1407.7859 [hep-ph]].

**scenA50**

$\Delta = 50\text{GeV}$

$\delta_A = 70\text{GeV}$

$\delta_C = 70\text{GeV}$

$n = 0.5$

**scenA100**

$\Delta = 100\text{GeV}$

$\delta_A = 115\text{GeV}$

$\delta_C = 115\text{GeV}$

$n = 0.5$

**scenG**

$\Delta = 1\text{GeV}$

$\delta_A = 1.5\text{GeV}$

$\delta_C = 1.5\text{GeV}$

$n = 0.998$

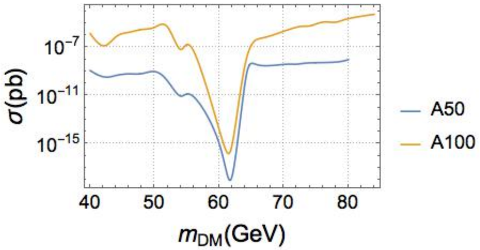
**scenH**

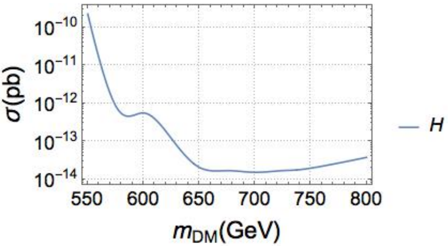
$\Delta = 100\text{GeV}$

$\delta_A = 2\text{GeV}$

$\delta_C = 2\text{GeV}$

$n = 0.8$

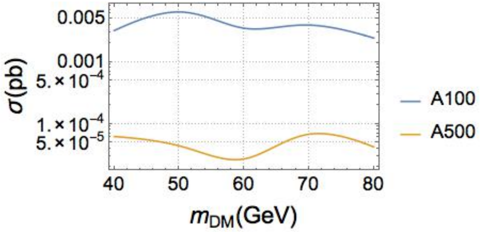


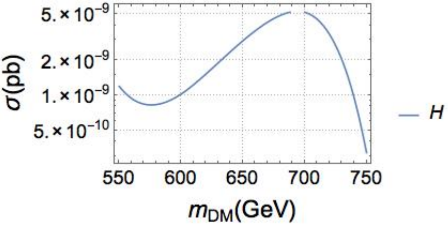




$\Delta = m_{H_2} - m_{H_1}$, $\delta_A = m_{A_1} - m_{H_1}$, $\delta_C = m_{H_1^\pm} - m_{H_1}$

# Results $q\bar{q} \to Z \to A_1^* H_1 \to Z^* H_1 H_1 \to H_1 H_1 e^+ e^-$

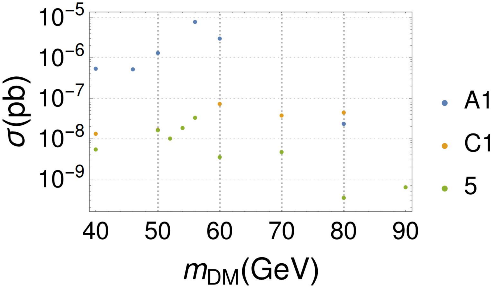
**scenA50**
$\Delta = 50\text{GeV}$
$\delta_A = 70\text{GeV}$
$\delta_C = 70\text{GeV}$
$n = 0.5$
**scenA100**
$\Delta = 100\text{GeV}$
$\delta_A = 115\text{GeV}$
$\delta_C = 115\text{GeV}$
$n = 0.5$
**scenG**
$\Delta = 1\text{GeV}$
$\delta_A = 1.5\text{GeV}$
$\delta_C = 1.5\text{GeV}$
$n = 0.998$
**scenH**
$\Delta = 100\text{GeV}$
$\delta_A = 2\text{GeV}$
$\delta_C = 2\text{GeV}$
$n = 0.8$




$\Delta = m_{H_2} - m_{H_1}$, $\delta_A = m_{A_1} - m_{H_1}$, $\delta_C = m_{H_1^\pm} - m_{H_1}$

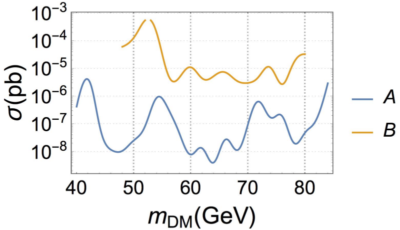
# Exploring other scenarios

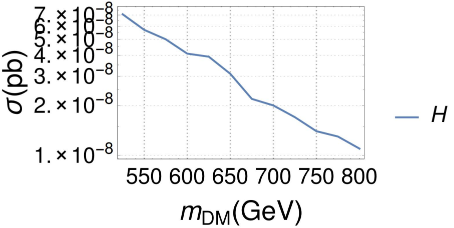



**A1**: $\Delta = 100\text{GeV}$, $\theta_a = \theta_c = 0.3$, $n = 1/3$.
**C1**: $\Delta = 50\text{GeV}$, $\theta_a = 0.38$, $\theta_c = 0.1$, $n = 0.4$.
**5**: $\Delta = 50\text{GeV}$, $\theta_a = \theta_c = 0.3$, $n = 1/2$.

# CPV cross section

**scenA1-CPV**
$\Delta = 125\text{GeV}$
$\delta_A = 50\text{GeV}$
$\delta_C = 50\text{GeV}$
$\theta_2 + \theta_{12} = 3$
**scenA100**
$\Delta = 125\text{GeV}$
$\delta_A = 50\text{GeV}$
$\delta_C = 50\text{GeV}$
$\theta_2 + \theta_{12} = 1.64$
**scenG**
$\Delta = 2\text{GeV}$
$\delta_A = 1\text{GeV}$
$\delta_C = 1\text{GeV}$
$\theta_2 + \theta_{12} = 1.64$
**scenH**
$\Delta = 51\text{GeV}$
$\delta_A = 1\text{GeV}$
$\delta_C = 50\text{GeV}$
$\theta_2 + \theta_{12} = 1.64$



# Summary

- The phenomenology of I(2+1)HDM is interesting. There are many cascade events from 2 to 6 leptons in the final state. This are not possible in the I(1+1)HDM and signal is clean.
- For case CPC, scenario A100 is the one giving the best results, which shows that there could be up to 5 events in Run 3 of LHC.
- For the strahlung-like process the possibilities are better, there could be around 10 events in Run 2.
- For CPV case the best point is $\sigma \sim 5 \times 10^{-4}$, giving a significant enhancement to the process. Around 20 to 80 events for the loop process in Run2 and 80 to 160 in Run 3. The strahlung-like process for CPV is also greater (but still need to check it).
- If many events like this are found that would be an evidence for CP-violation in inert sector.