DM in 3HDMs

Stefano Moretti

University of Southampton

In collaboration with

S. F. King & V. Keus & D. Sokolowska & J. Hernandez & D. Rojas & A. Cordero

JHEP 1411 (2014) 016 & JHEP 1511 (2015) 003 & JHEP 1612 (2016) 014

Scalars 2017

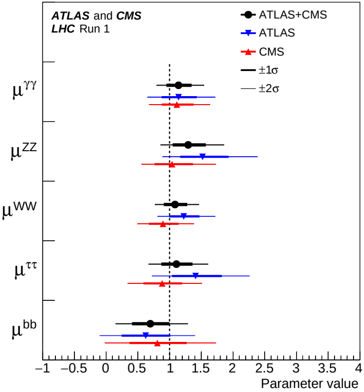
1. Introduction and motivation
2. DM in CP-Conserving (CPC) 3HDM
3. DM in CP-Violating (CPV) 3HDM
4. Summary

The Standard Model and its shortcomings

- A Higgs boson discovered
- No significant deviation from the SM
- No signs of new physics

But no explanation for

- DM
- Fermion mass hierarchy
- Extra sources of CPV
- Vacuum stability



JHEP 08 (2016) 045

DM

- Cold (non-relativistic at the onset of galaxy formation)
- Non-baryonic
- Neutral and weakly interacting

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

- Stable due to a discrete symmetry

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

- Freeze-out (drop out of thermal equilibrium)
- Agree with the observed relic density

$$\Omega_{DM} h^2 = 0.1199 \pm 0.0027$$

3HDMs

- Somebody actually ordered the muon (I.I. Rabi, "Who ordered that?" (a quip in 1957, verbal)). $\rightarrow$ see Howie Haber's talk!
- *Numquam ponenda est pluralitas sine necessitate* ('Plurality must never be posited without necessity', Wikipedia), i.e., "Among competing hypotheses, the one with the fewest assumptions should be selected", Ockham's razor argument (from *Quaestiones et decisiones in quattuor libros Sententiarum Petri Lombardi*).
- "Everything should be made as simple as possible, but not simpler", Einstein's razor argument (from "On The Method of Theoretical Physics", The Herbert Spencer Lecture, delivered in Oxford (10 June 1933), published in Philosophy of Science, Vol. 1, No. 2 (April 1934), p. 165).
- Are Higgs portal models and 2HDMs too simple?

3HDMs

Scalar extensions with or without a Z_2 symmetry:

- Higgs portal models: SM + scalar singlet
  - $\phi_{SM},\ S \quad \Rightarrow \quad$ CPV, ~~DM~~
  - $\phi_{SM},\ S \quad \Rightarrow \quad$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ CPV, ~~DM~~
  - IDM $\equiv$ I(1+1)HDM: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: $\phi_1,\ \phi_2,\ \phi_3 \quad \Rightarrow \quad$ CPV, ~~DM~~
  - I(1+2)HDM: $\phi_1,\ \phi_2,\ \phi_3 \quad \Rightarrow \quad$ DM, CPV
  - I(2+1)HDM: $\phi_1,\ \phi_2,\ \phi_3 \quad \Rightarrow \quad$ CPV, DM

DM in CPC 3HDM

$$\phi_1, \phi_2, \phi_3$$

$$g_{Z_2} = diag(-1, -1, +1)$$

$$VEV = (0, 0, v)$$

The scalar potential with real parameters

$$
\begin{aligned}
V_{3HDM} &= V_0 + V_{Z_2} \\
V_0 &= \sum_{i}^{3}\Big[-\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2\Big] \\
&\quad + \sum_{i,j}^{3}\Big[\lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)\Big] \\
V_{Z_2} &= -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c. \\
&\quad + \lambda_4(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_3) + \lambda_5(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_6(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1) \\
&\quad + \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2) + \lambda_8(\phi_3^\dagger\phi_1)(\phi_3^\dagger\phi_2) + h.c.
\end{aligned}
$$

The Z_2 symmetry

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

DM in CPC 3HDM

Z_2-invariant vacuum state:

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

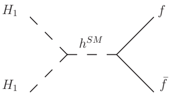
- ϕ_3 – SM-like doublet with SM-like Higgs h
- Z_2-odd doublets ϕ_1 and ϕ_2 mix:

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

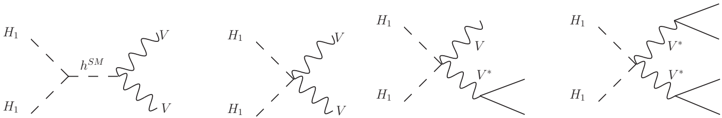
  (similar for A_i and $H_i^{\pm}$)
- 4 neutral and 4 charged Z_2-odd particles (double the IDM)
- H_1 – **DM candidate**, other dark particles heavier

DM annihilation

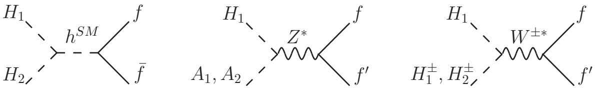
- annihilation through Higgs into fermions; dominant channel for $M_{DM} < M_h/2$



- annihilation to gauge bosons; crucial for heavy masses



- coannihilation; when particles have similar masses



Constraints

1. Theoretical constraints (unitarity, vacuum stability, positive-definitness of the Hessian, etc.)
2. Experimental constraints

- Contraints from void Higgs searches and Higgs discovery data
- Limits from gauge bosons width:
  $m_{S_i} + m_{S_j^\pm} \geq m_W, \;\; m_{S_i} + m_{S_j} \geq m_Z, \;\; 2\, m_{S_{1,2}^\pm} \geq m_Z$
- Limits on charged scalar mass and lifetime:
  $m_{S_i^\pm} \geq 70 \;\mathrm{GeV}, \quad \tau \leq 10^{-7}\;\mathrm{s} \rightarrow \Gamma_{\mathrm{tot}} \geq 10^{-18}\;\mathrm{GeV}$
- Null DM collider searches excluding simultaneously:
  $m_{S_i} \leq 100 \;\mathrm{GeV},\; m_{S_1} \leq 80 \;\mathrm{GeV},\; \Delta m(S_1, S_i) \geq 8 \;\mathrm{GeV}$
- S,T,U parameters

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:

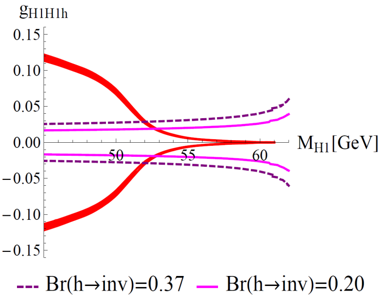
(G1) **coannihilation** with $H_2, A_{1,2}, H_{1,2}^\pm$:

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

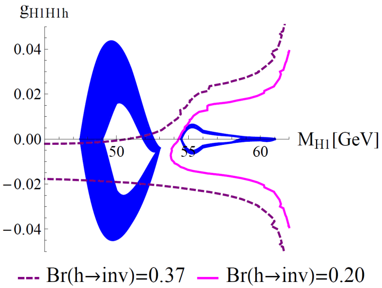
(H1) **coannihilation** with $A_1, H_1^\pm$:

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

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



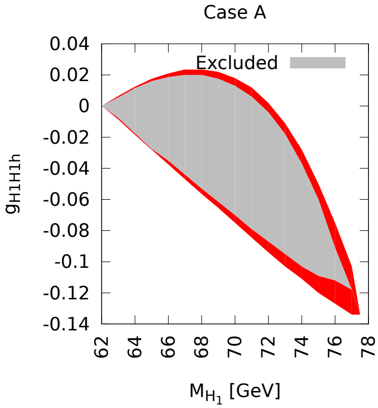
case A

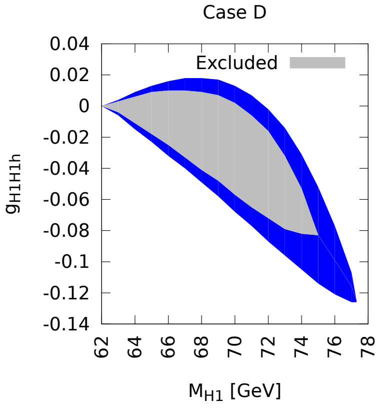


case D

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

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

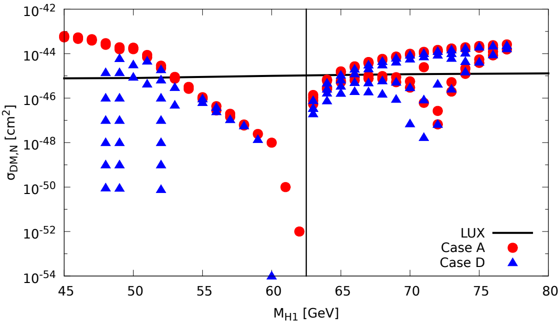




Relic density values are dominated by three couplings:

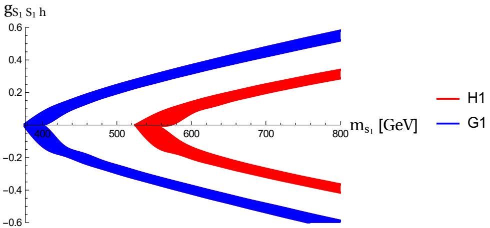
g_{hVV}, $g_{H_1H_1VV}$, $g_{H_1H_1h}$

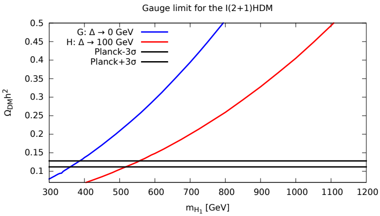
Direct detection limits



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

Heavy DM mass region

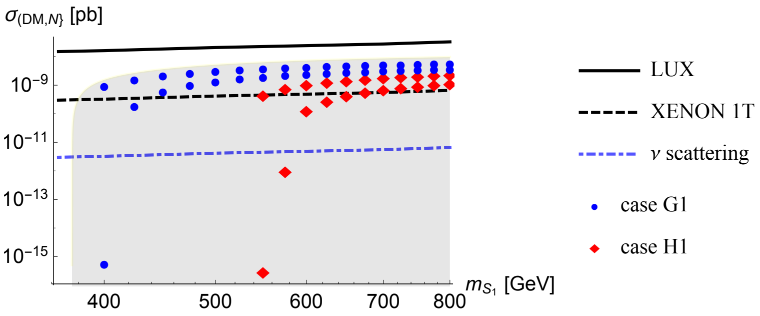




- Enabled by coannihilation, more numerous than in IDM
- Beware of $(\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5)$

$$g_{H_1 H_1 Z_L Z_L} = \lambda_{345} + 2(M_{H_2}^2 - M_{H_1}^2)/v^2$$

Direct detection (notation, $S \equiv H$ here)



DM in CPV 3HDM

$$\phi_1, \phi_2, \phi_3$$

$$g_{Z_2} = diag(-1, -1, +1)$$

$$VEV = (0, 0, v)$$

The scalar potential with explicit CPV

$$
\begin{aligned}
V_{3HDM} &= V_0 + V_{Z_2} \\
V_0 &= \sum_i^3 \left[-\mu_i^2 (\phi_i^\dagger \phi_i) + \lambda_{ii} (\phi_i^\dagger \phi_i)^2 \right] \\
&+ \sum_{i,j}^3 \left[\lambda_{ij} (\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij} (\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right] \\
V_{Z_2} &= -\mu_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_1 (\phi_1^\dagger \phi_2)^2 + \lambda_2 (\phi_2^\dagger \phi_3)^2 + \lambda_3 (\phi_3^\dagger \phi_1)^2 + h.c. \\
&+ \lambda_4 (\phi_3^\dagger \phi_1)(\phi_2^\dagger \phi_3) + \lambda_5 (\phi_1^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_6 (\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_1) \\
&+ \lambda_7 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_2) + \lambda_8 (\phi_3^\dagger \phi_1)(\phi_3^\dagger \phi_2) + h.c.
\end{aligned}
$$

The Z_2 symmetry

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

Parameters of the model

- no new phenomenology from $\lambda_4, \cdots, \lambda_8$ terms $\rightarrow \lambda_{4-8} = 0$
- "dark" parameters $\lambda_1, \lambda_{11}, \lambda_{22}, \lambda_{12}, \lambda'_{12}$
- "dark democracy" limit
  $\mu_1^2 = \mu_2^2, \quad \lambda_3 = \lambda_2, \quad \lambda_{31} = \lambda_{23}, \quad \lambda'_{31} = \lambda'_{23}$
- fixed by the Higgs mass $\mu_3^2 = v^2\lambda_{33} = m_h^2/2$

7 important parameters

- CPV and mass splittings $\mu_{12}^2 = |\mu_{12}^2|e^{i\theta_{12}}, \ \lambda_2 = |\lambda_2|e^{i\theta_2}$
- Higgs-DM coupling $\lambda_2, \lambda_{23}, \lambda'_{23}$
- Mass scale of inert particles μ_2^2

Can remap in

- DM mass m_{S_1}, mass splittings $\delta_{S_2-S_1}, \ \delta_{S_1^\pm - S_1}, \ \delta_{S_2^\pm - S_1^\pm}$, Higgs-DM coupling $g_{S_1S_1h}$, CPV phases $\theta_2, \ \theta_{12}$ ($\theta_2 + \theta_{12}$ in observables)

The CP-mixed mass eigenstates

The doublet compositions

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

The mass eigenstates

$$S_1 = \frac{\alpha H_1^0 + \alpha H_2^0 - A_1^0 + A_2^0}{\sqrt{2\alpha^2 + 2}}, \quad S_2 = \frac{-H_1^0 - H_2^0 - \alpha A_1^0 + \alpha A_2^0}{\sqrt{2\alpha^2 + 2}}$$

$$S_3 = \frac{\beta H_1^0 - \beta H_2^0 + A_1^0 + A_2^0}{\sqrt{2\beta^2 + 2}}, \quad S_4 = \frac{-H_1^0 + H_2^0 + \beta A_1^0 + \beta A_2^0}{\sqrt{2\beta^2 + 2}}$$

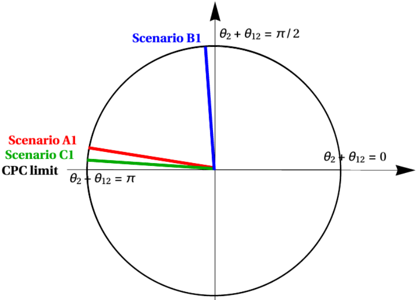
$$S_1^\pm = \frac{e^{\mp i\theta_{12}/2}}{\sqrt{2}}(H_2^\pm + H_1^\pm), \quad S_2^\pm = \frac{e^{\mp i\theta_{12}/2}}{\sqrt{2}}(H_2^\pm - H_1^\pm)$$

S_1 is assumed to be the DM candidate

Relevant DM scenarios

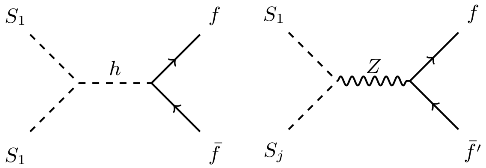
In the low mass region ($m_{S_1} < m_Z$):

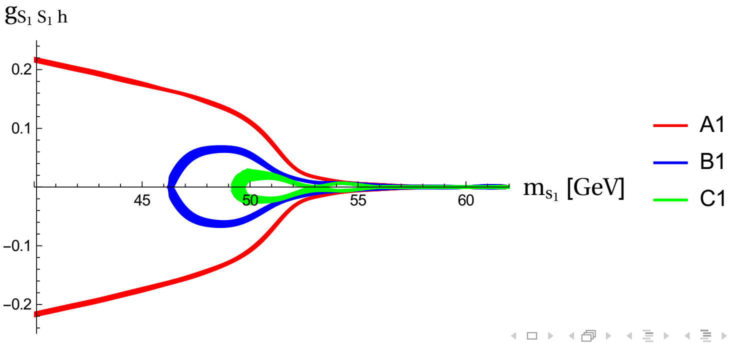
- Scenario A1: no coannihilation, $m_{S_1} \ll m_{S_2}, m_{S_3}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$
- Scenario B1: coannihilation with S_3, $m_{S_1} \sim m_{S_3} \ll m_{S_2}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$
- Scenario C1: coannihilation with all neutral particles, $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm}, m_{S_2^\pm}$



Low DM mass region

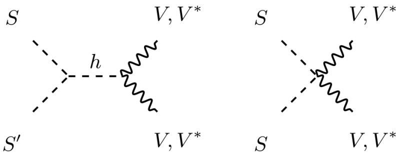
Higgs-mediated and Z-mediated (co)annihilation

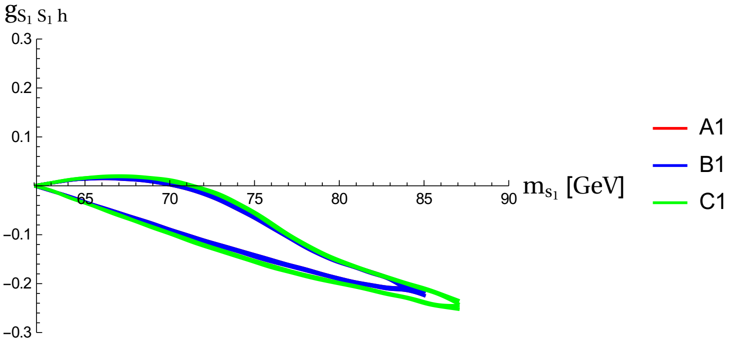




Medium DM mass region

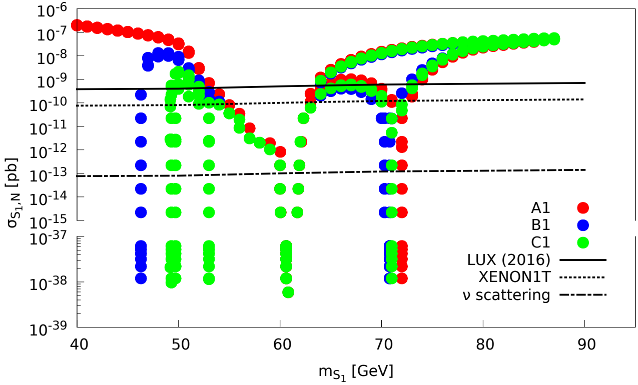
Higgs-mediated and quartic (co)annihilation



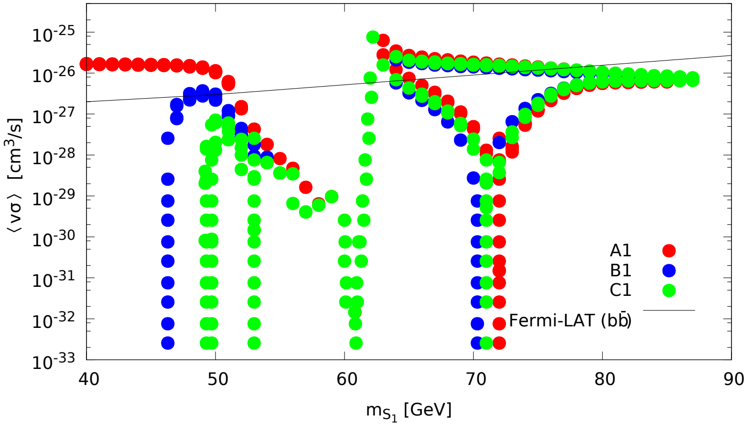


Direct detection

$$\sigma_{DM,N} \propto g_{hDM}^2/(m_{DM}+m_N)^2$$

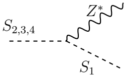


Indirect detection

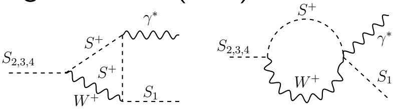


Summary

- Both DM and CPV from scalar sector $\rightarrow$ beyond 2HDM
- CPC case in I(2+1): observable heavy DM (absent in I(1+1)HDM)
- CPV in I(1+2)HDM (not studied here)
    - IDM-like inert sector: CPC DM
    - CPV in the active sector: $\tilde{H}_1, \tilde{H}_2, \tilde{H}_3$
    - Interesting LHC phenomenology, but mimics CPV 2HDM
- CPV 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: 4 more $S_i S_j Z/\gamma$ vertices, inert cascades
- Both CPC & CPV new LHC signatures in I(2+1)HDM:



Large mass splitting

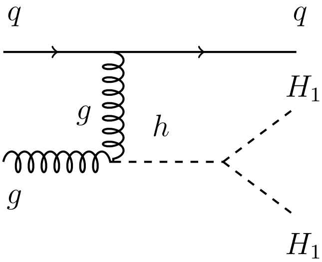


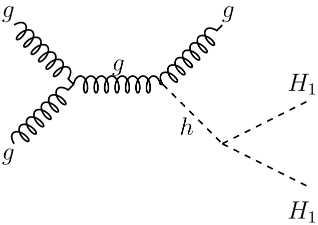
Small mass splitting

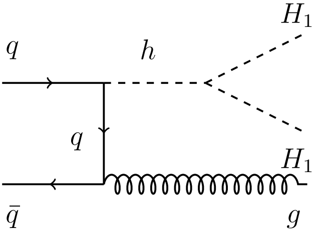
$\rightarrow$ see Dorota Sokolowska's talk!

BACKUP SLIDES

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

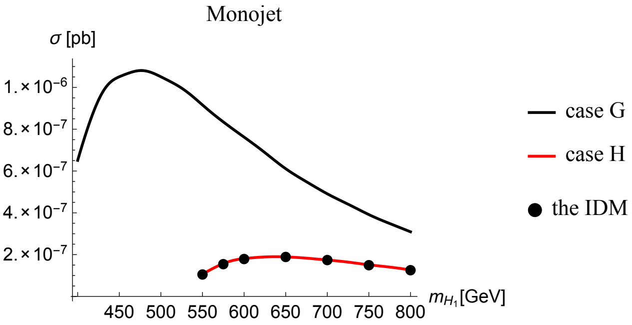




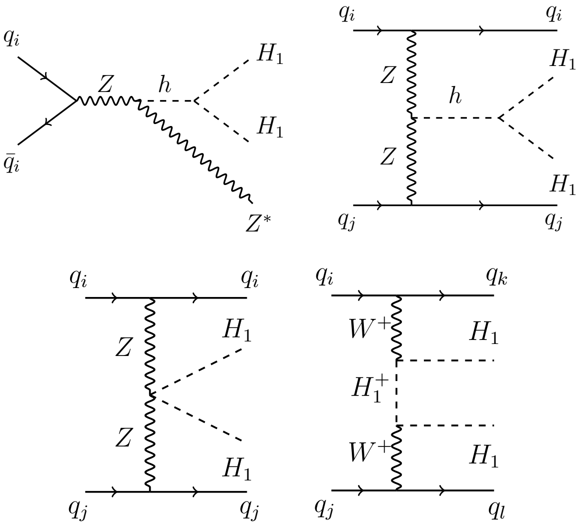


LHC signals: monojet channels

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

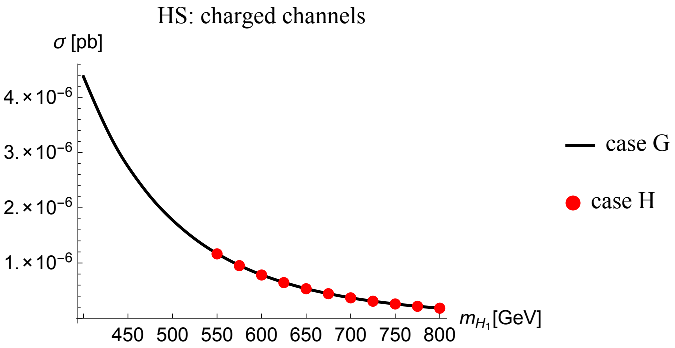


LHC signals: dijet channels $pp \to H_1 H_1 + 2$ jets



LHC signals: dijet channels

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



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 bounds on CPV DM

Higgs invisible branching ratio and total decay

From ATLAS and CMS

$$\mathrm{Br}(h \to \mathrm{inv}) < 0.23 - 0.36$$

for $m_{i,j} < m_h/2$ if long lived

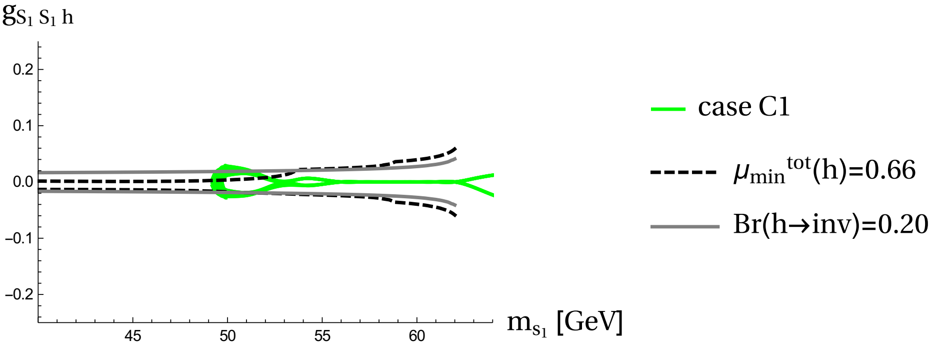
$$\mathrm{BR}(h \to \mathrm{inv}) = \frac{\sum_{i,j} \Gamma(h \to S_i S_j)}{\Gamma_h^{\mathrm{SM}} + \sum_i \Gamma(h \to S_i S_j)}$$

The total decay signal strength

$$\mu_{tot} = \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h_{\mathrm{SM}} \to XX)} = \frac{\Gamma_{tot}^{SM}(h)}{\Gamma_{tot}^{SM}(h) + \Gamma^{inert}(h)}$$

We use $\mu_{tot} = 1.17 \pm 0.17$ at 3σ level.

Relic density vs. Higgs decay bounds



$h \to \gamma\gamma$ signal strength bounds

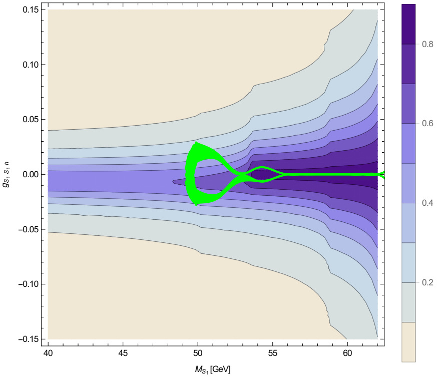
From ATLAS and CMS: $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$

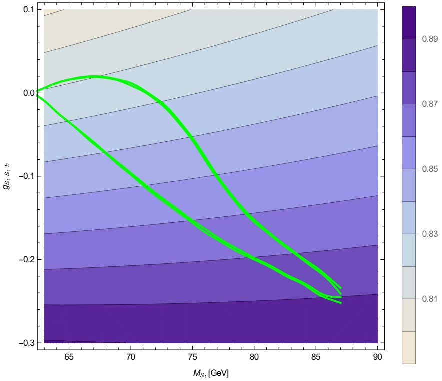
$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\mathrm{3HDM}}\,\Gamma(h)^{\mathrm{SM}}}{\Gamma(h \to \gamma\gamma)^{\mathrm{SM}}\,\Gamma(h)^{\mathrm{3HDM}}}$$

Modified by

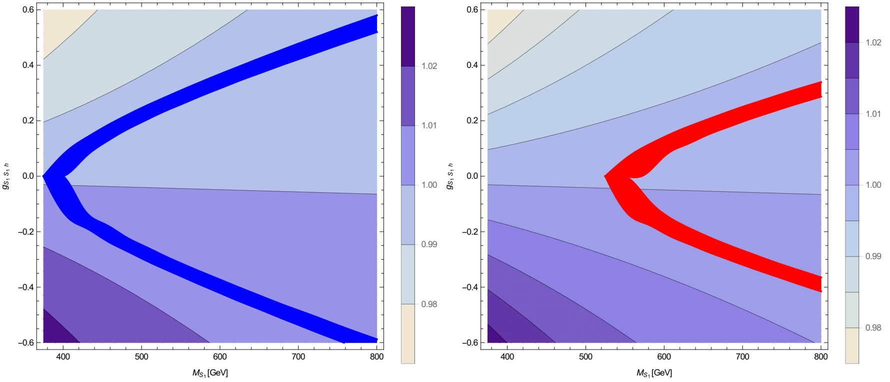
- charged scalars contribution to $\Gamma(h \to \gamma\gamma)^{\mathrm{3HDM}}$
- light neutral scalars contribution to $\Gamma(h)^{\mathrm{3HDM}}$

Relic density vs. $\mu_{\gamma\gamma}$ - scenario C





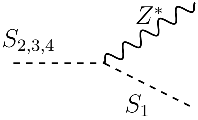
Relic density vs. $\mu_{\gamma\gamma}$ - scenarios G & H



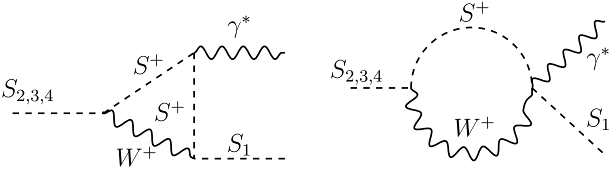
LHC signatures of CPV DM

Inert cascade decays at the LHC

When there is a large mass splitting between DM and other inert particles:



When there is a small mass splitting between DM and other inert particles (winning scenarios):

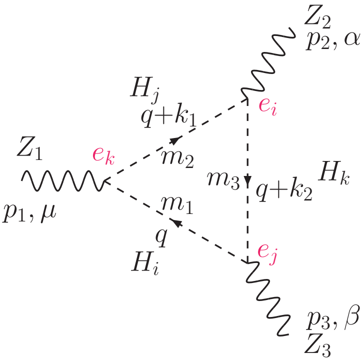


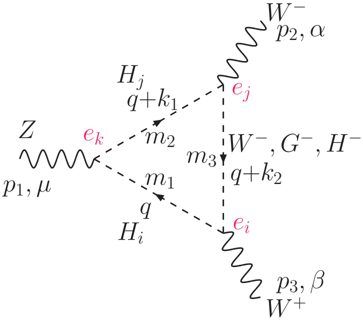
$E^T_{miss} + e^+e^-$ cross section at the LHC

- Higgs-strahlung at tree level:
  $q\bar{q} \to Z \to S_1 S_{2,3,4} \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$ with $\sigma \sim 10^{-2}$ pb
- Higgs-strahlung at loop level:
  $q\bar{q} \to Z \to S_1 S_{2,3,4} \to S_1 S_1 \gamma^* \to S_1 S_1 e^+ e^-$ with $\sigma \sim 10^{-3}$ pb
- Gluon-fusion at tree level:
  $pp \to h \to S_1 S_{2,3,4} \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$ with $\sigma \sim 10^{-5}$ pb

Other CPV observables (JHEP1605,025(2016))

ZZZ and ZWW vertices





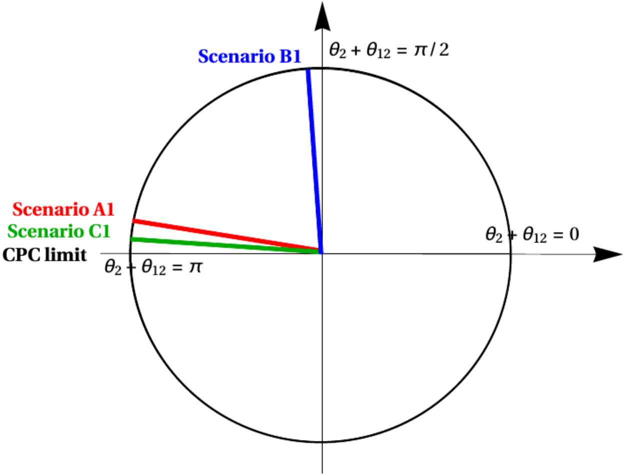
In the CPC limit

$$
\begin{aligned}
\alpha &= \frac{-|\mu_{12}^2|\cos\theta_{12} + v^2|\lambda_2|\cos\theta_2 - \Lambda}{|\mu_{12}^2|\sin\theta_{12} + v^2|\lambda_2|\sin\theta_2} \quad \to \infty \\
\beta &= \frac{|\mu_{12}^2|\cos\theta_{12} + v^2|\lambda_2|\cos\theta_2 - \Lambda'}{|\mu_{12}^2|\sin\theta_{12} - v^2|\lambda_2|\sin\theta_2} \quad \to \infty
\end{aligned}
$$

where

$$
\begin{aligned}
\Lambda &= \sqrt{v^4|\lambda_2|^2 + |\mu_{12}^2|^2 - 2v^2|\lambda_2||\mu_{12}^2|\cos(\theta_{12}+\theta_2)}, \\
\Lambda' &= \sqrt{v^4|\lambda_2|^2 + |\mu_{12}^2|^2 + 2v^2|\lambda_2||\mu_{12}^2|\cos(\theta_{12}+\theta_2)}.
\end{aligned}
$$

Relevant DM scenarios and sum of the CPV phases

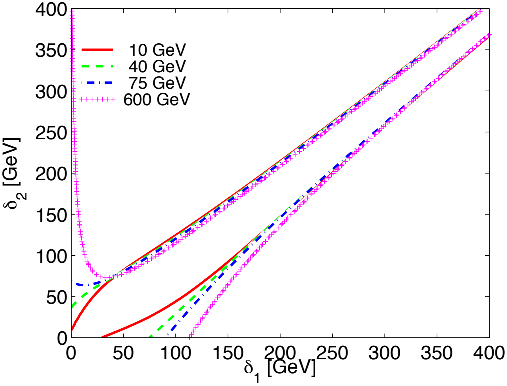


Benchmark scenarios

$$A1: \ \delta_{12} = 125 \text{ GeV}, \delta_{1c} = 50 \text{ GeV}, \delta_c = 50 \text{ GeV}, \theta_2 = \theta_{12} = 1.5$$
$$B1: \ \delta_{12} = 125 \text{ GeV}, \delta_{1c} = 50 \text{ GeV}, \delta_c = 50 \text{ GeV}, \theta_2 = \theta_{12} = 0.82$$
$$C1: \ \delta_{12} = 12 \text{ GeV}, \delta_{1c} = 100 \text{ GeV}, \delta_c = 1 \text{ GeV}, \theta_2 = \theta_{12} = 1.57$$

$$G1: \ \delta_{12} = 2 \text{ GeV}, \delta_{1c} = 1 \text{ GeV}, \delta_c = 1 \text{ GeV}, \theta_2 = \theta_{12} = 0.82$$
$$H1: \ \delta_{12} = 50 \text{ GeV}, \delta_{1c} = 1 \text{ GeV}, \delta_c = 50 \text{ GeV}, \theta_2 = \theta_{12} = 0.82$$

S, T, U parameters (Phys.Rev. D80 (2009) 055012)



$\delta_1 = m_{H^\pm} - m_{DM}$ and $\delta_2 = m_A - m_{DM}$

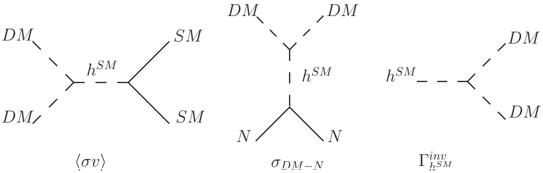
Higgs-portal DM (~~CPV~~)

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

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

Higgs-portal interaction:

$$\text{SM sector} \overset{\text{Higgs}}{\longleftrightarrow} \text{DM sector}$$

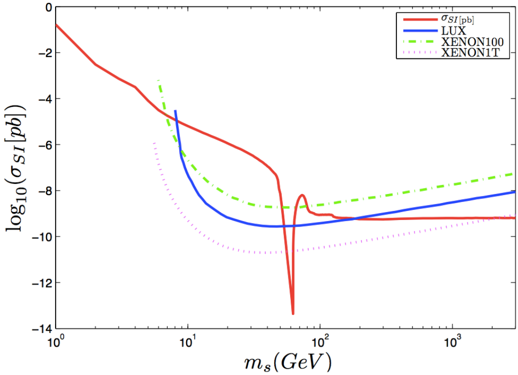


given by the same coupling

Higgs-portal DM

(arXiv:1509.01765)

Relic density + direct detection constraints:



+ Higgs decays + SM vacuum stability + purturbativity constraints:

$$1.1\ \text{TeV} \leq m_{DM} \leq 2.0\ \text{TeV}$$

2HDM with CP-violation (~~DM~~)

The general scalar potential

$$\begin{aligned} V &= \mu_1^2(\phi_1^\dagger\phi_1) + \mu_2^2(\phi_2^\dagger\phi_2) - \left[\mu_3^2(\phi_1^\dagger\phi_2) + h.c.\right] \\ &+ \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ &+ \left[\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + h.c.\right]. \end{aligned}$$

$$Z_2 \text{ symmetry} \Rightarrow \lambda_6 = \lambda_7 = 0$$

The doublets composition with $\tan\beta = v_2/v_1$

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix}$$

CP-mixed mass eigenstates

- 2×2 charged mass-squared matrix

$$\begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix} \Rightarrow \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

- 4×4 neutral mass-squared matrix

$$\begin{pmatrix} a_1^0 \\ h_1^0 \\ a_2^0 \\ h_2^0 \end{pmatrix} \Rightarrow \begin{pmatrix} G^0 \\ H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

CPV severely constrained from SM data

The Inert Doublet Model $(\not{CPV})$

Scalar potential invariant under a Z_2-transformation:

$$Z_2: \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}$$

$$\begin{aligned} V &= -\frac{1}{2}\left[m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2\right] + \frac{1}{2}\left[\lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \lambda_2\left(\phi_2^\dagger\phi_2\right)^2\right] \\ &+ \lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \frac{1}{2}\lambda_5\left[\left(\phi_1^\dagger\phi_2\right)^2 + \left(\phi_2^\dagger\phi_1\right)^2\right] \end{aligned}$$

- All parameters are real $\to$ no CP violation
- Only ϕ_1 couples to fermions
- The whole Lagrangian is explicitly Z_2-symmetric

DM in the IDM

The Inert minimum

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Z_2-symmetry survives the EWSB

$$g_{Z_2} = diag(+1, -1)$$
$$VEV = (v, 0)$$

- ϕ_1 is active (plays the role of the SM-Higgs)
- ϕ_2 is "dark" or inert (with 4 dark scalars $H, A, H^{\pm}$)

$\rightarrow$ the lightest scalar is **a candidate for the DM**

Constraints

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

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

(3) **Perturbative unitarity**

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

(5) **EWPD & LEP & null searches**: bounds on masses of the scalars

$$m_H \lesssim 10\,\text{GeV}, \quad 40\,\text{GeV} < m_H < 150\,\text{GeV}, \quad m_H \gtrsim 500\,\text{GeV}$$

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

$$\delta_A = m_A - m_H < 8\,\text{GeV} \Rightarrow m_H + m_A > m_Z$$

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

Constraints

(6) ***H* as DM candidate**:

$m_H < m_A, m_{H^\pm}$ with proper $\Omega_{DM} h^2$

$\lambda_{345} \sim g_{hDM}$ and m_i

(7) **BR($h \to inv.$) and Direct Detection:**

- medium DM mass: $53\,\text{GeV} \leq m_{DM} \leq 70\,\text{GeV}$
- high DM mass: $525\,\text{GeV} \leq m_{DM}$

$h \to \gamma\gamma$ signal strength (JHEP 09 (2013) 055)