One, Two, Three Higgs Doublets (DM in 3HDM)

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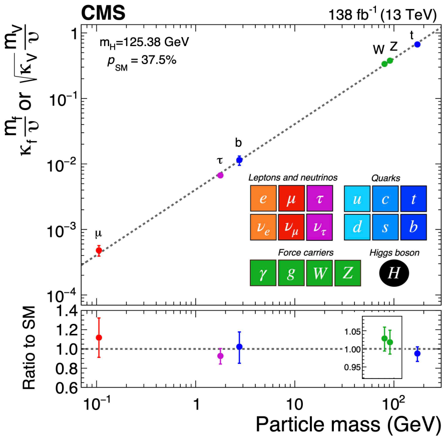
The Standard Model and its shortcomings

- 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



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: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$
- *And, of course, spin-0, scalar or pseudoscalar (eg, here scalar case)*

3HDMs

- Somebody actually ordered the muon (I.I. Rabi, "Who ordered that?" (a quip in 1957, verbal)).
- *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 (ie, active or inert):

- 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

(3HDMs also used in flavour problem: 3 VEVs for 3 generations)

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

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

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

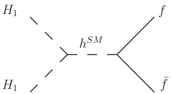
Constraints

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

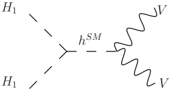
- Contraints from void Higgs searches and Higgs discovery data
- Limits from gauge bosons width:
  $m_{S_i} + m_{S_j^\pm} \geq m_W, \;\; m_{S_i} + m_{S_j} \geq m_Z, \;\; 2\, m_{S_{1,2}^\pm} \geq m_Z$
- Limits on charged scalar mass and lifetime:
  $m_{S_i^\pm} \geq 70 \;\; \mathrm{GeV}, \quad \tau \leq 10^{-7} \; \mathrm{s} \rightarrow \Gamma_{\mathrm{tot}} \geq 10^{-18} \;\; \mathrm{GeV}$
- 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, g-2, EDMs (for CPV)

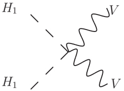
DM annihilation

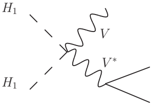
- annihilation through Higgs into fermions: dominant channel for $M_{DM} < M_h/2$

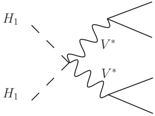


- annihilation to gauge bosons: crucial for heavy masses

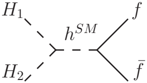


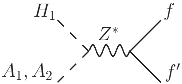


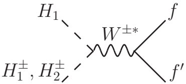




- coannihilation: when particles have similar masses







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 $H_2, A_{1,2}, H_{1,2}^\pm$:

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

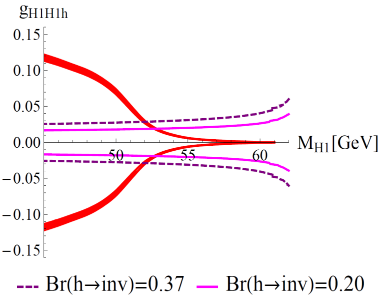
(H1) **coannihilation** with $A_1, H_1^\pm$:

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

(Use micrOMEGAs for DM constraints)

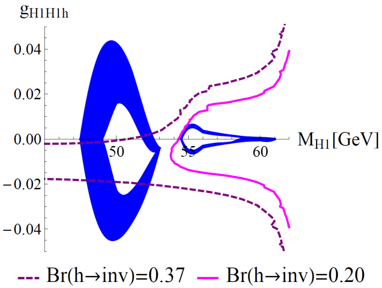
LHC vs Planck $M_{DM} < M_h/2$

Small m(H1)-m(H2)



case A

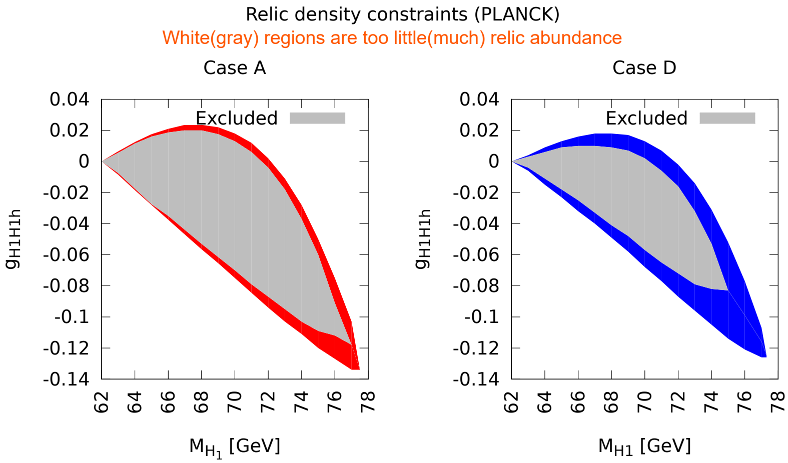
Large m(H1)-m(H2)



case D

- $Br(h \to inv) < 20\%$ & $\Omega_{DM} h^2$
  - Case A: $M_{DM} \gtrsim 53$ GeV
  - Case D: most masses are OK

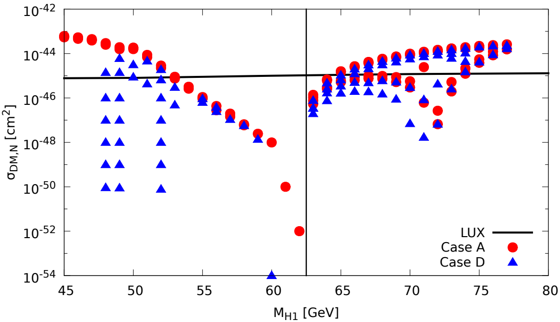
Planck constraints: $M_{DM} > M_h/2$



Relic density values are dominated by three couplings:

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

Direct detection limits



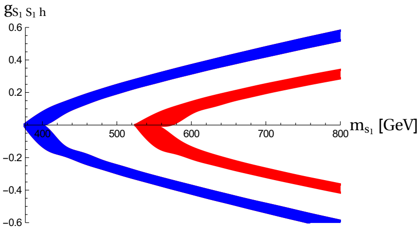
Case D: new region in agreement with LUX with respect to Case A

Can be lighter than in I(1+1)HDM

- Same parameter space survives indirect detection constraints

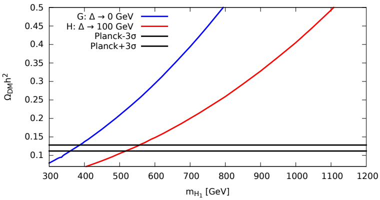
Heavy DM mass region

Planck measurements



Gauge limit for the I(2+1)HDM

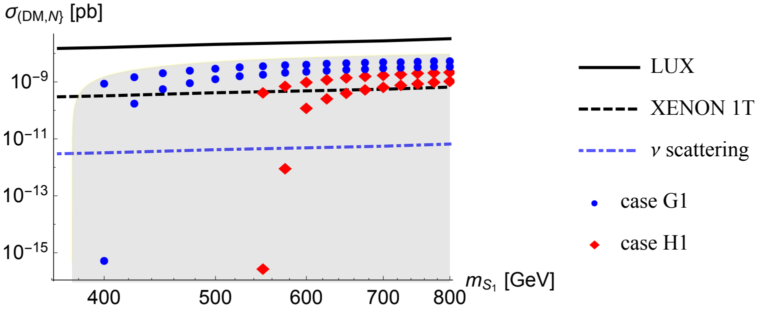
All quartic couplings λi are set to zero



- Enabled by coannihilation, *more substantial* than in I(1+1)HDM
- Beware of Higgs-DM coupling role: $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

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

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

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

The Z_2 symmetry

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

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 $g_{S_1 S_1 h}$, 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

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

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

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

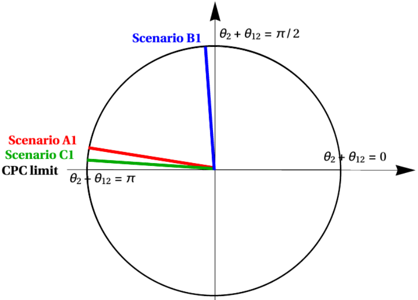
S_1 is assumed to be the DM candidate

(No contributions to EDMs: only active Higgs can couple to fermions.)

Relevant DM scenarios

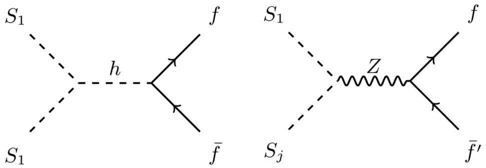
In the low mass region ($m_{S_1} < m_Z$):

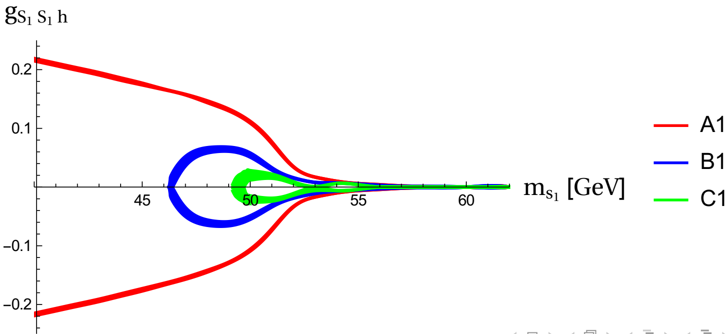
- Scenario A1: no coannihilation, $m_{S_1} \ll m_{S_2}, m_{S_3}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$
- Scenario B1: coannihilation with S_3,
  $m_{S_1} \sim m_{S_3} \ll m_{S_2}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$
- Scenario C1: coannihilation with all neutral particles,
  $m_{S_1} \sim m_{S_3} \sim m_{S_2}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



Low DM mass region

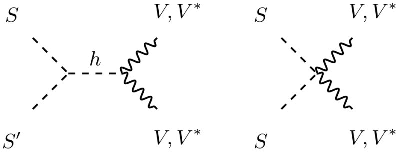
Higgs-mediated and Z-mediated (co)annihilation

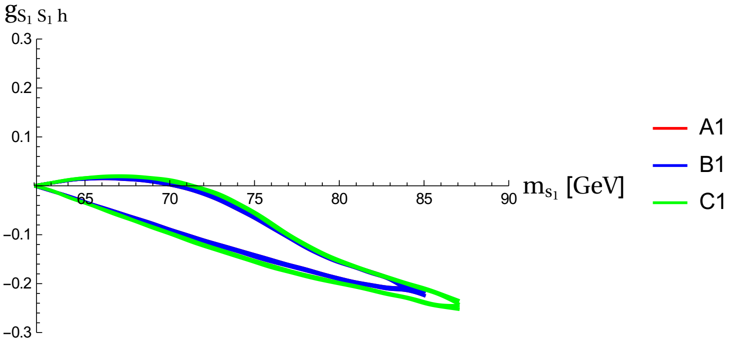




Medium DM mass region

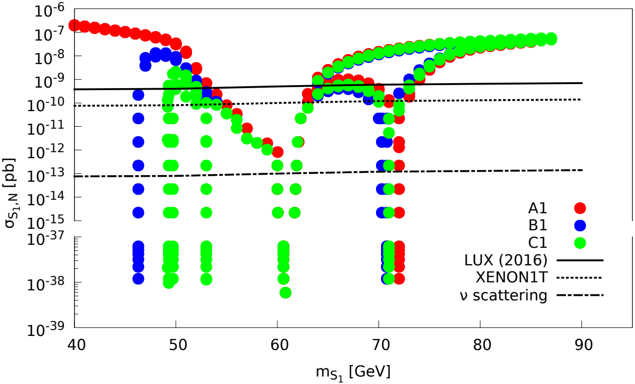
Higgs-mediated and quartic (co)annihilation



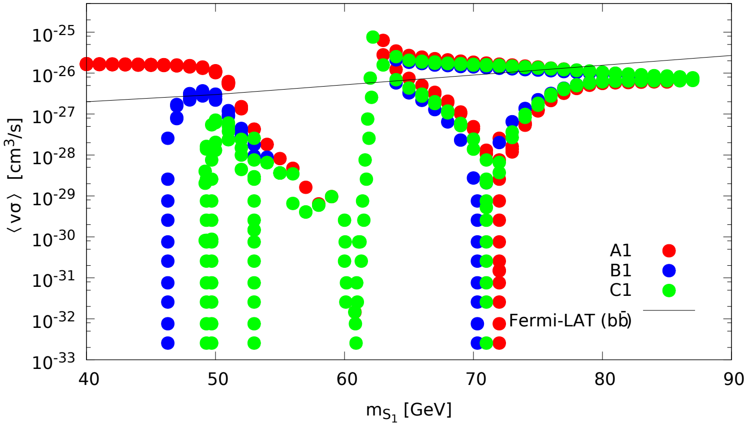


Direct detection

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

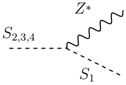


Indirect detection

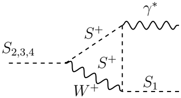


Summary

- 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(2+1)HDM:
  - SM-like active sector: $H_3 \equiv h^{SM}$ (with possible inert loops, eg, in $\gamma\gamma$ decays)
  - CPV in the inert sector: $H_{1,2}, A_{1,2} \rightarrow S_{1,2,3,4}$ CPV DM (dark CPV)
  - Light DM viable like in I(1+1)HDM, add accessible heavy one
- *Adding second discrete symmetry, two-component DM:*
  - *Parameter space exists compliant with all constraints*
  - *DD can access light component & iDD can access heavy one*
  - *Simultaneous collider signals, two-kink MET, etc. distributions (LHC, FCCee)*
- Still mono-*X*, *etc.*, plus new *viable* collider signatures in I(2+1)HDM:



Large mass splitting



Small mass splitting

(ie, inert cascades)

$\rightarrow$ see Hernandez-Sanchez' talk!

$Z_2 \times Z_2'$-symmetric 3HDM

2 scalar doublets + the SM Higgs doublet

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

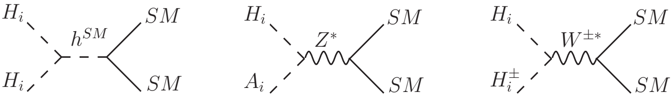
$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1 + iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2 + iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h + iG^0}{\sqrt{2}} \end{pmatrix}$$

J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

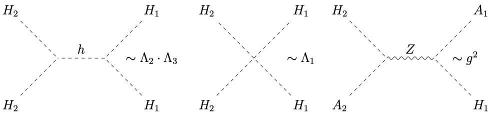
Two-component Dark Matter: H_1, H_2

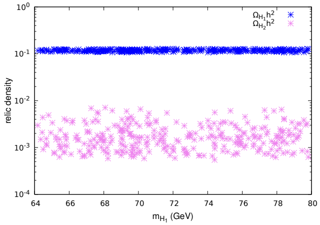
The lightest neutral field from each doublet is a viable DM candidate:

$m_{H_1} < m_{A_1} < m_{H_1^\pm}$ $\qquad$ $m_{H_2} < m_{A_2} < m_{H_2^\pm}$



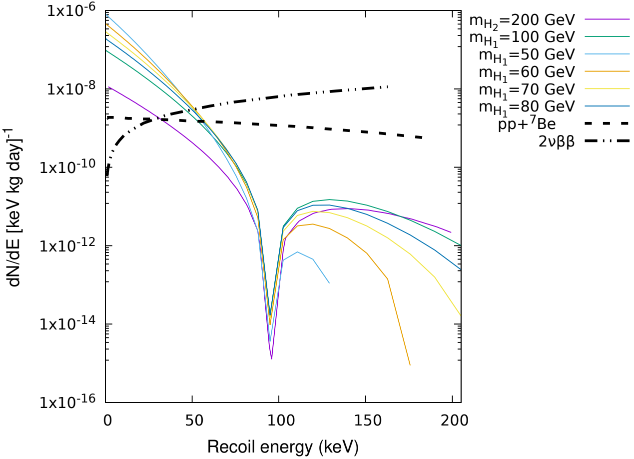
The conversion processes play an important role in DM production.





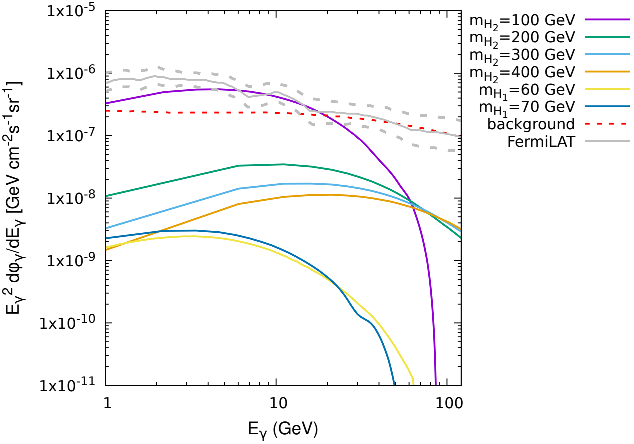
Astrophysical probes: Direct detection XENONnT/LZ

Light DM H_1: probed in the nuclear recoil energy event rate



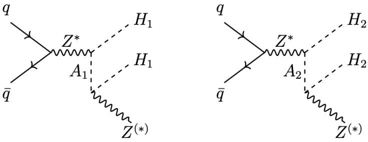
Astrophysical probes: Indirect detection Fermi-LAT

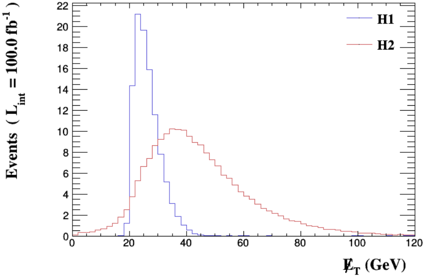
Heavy DM H_2: contributes to the photon flux from the galactic center

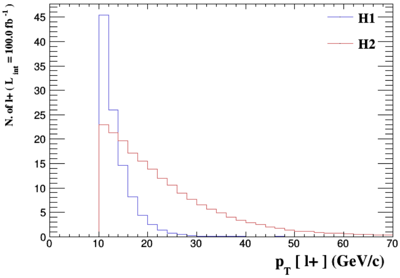


Collider probes: distributions of observables

$m_{H_2} - m_{H_1} > \not{E}_T$ resolution $\Rightarrow$ visible effect in different distributions



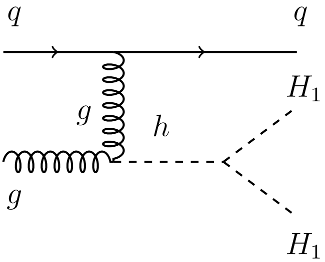


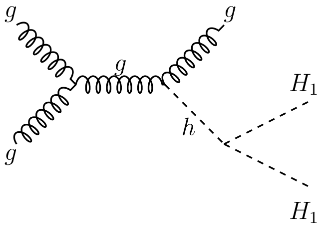


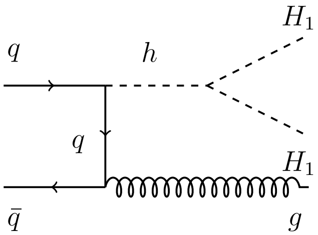
Missing transverse energy and transverse momentum of either lepton $\rightarrow$ see Hernandez-Sanchez' talk!

BACKUP SLIDES

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

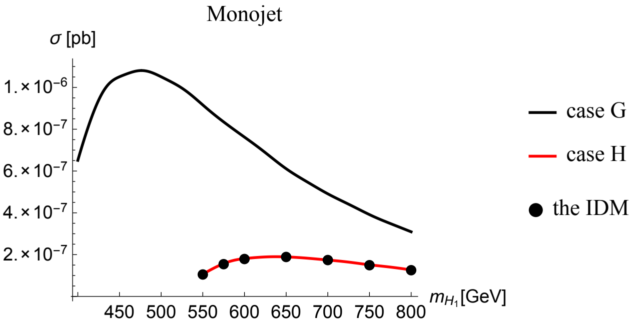




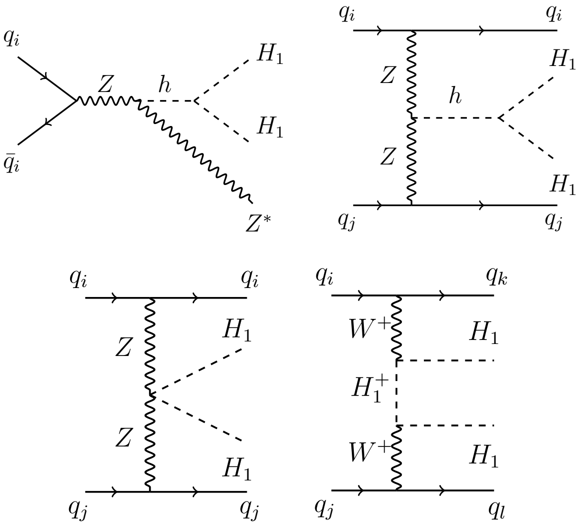


LHC signals: monojet channels

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

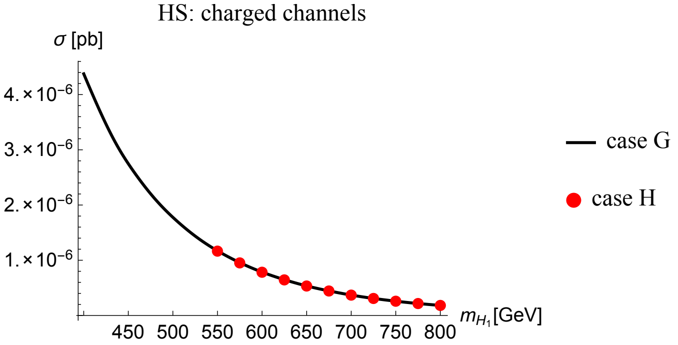


LHC signals: dijet channels $pp \to H_1 H_1 + 2$ jets



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

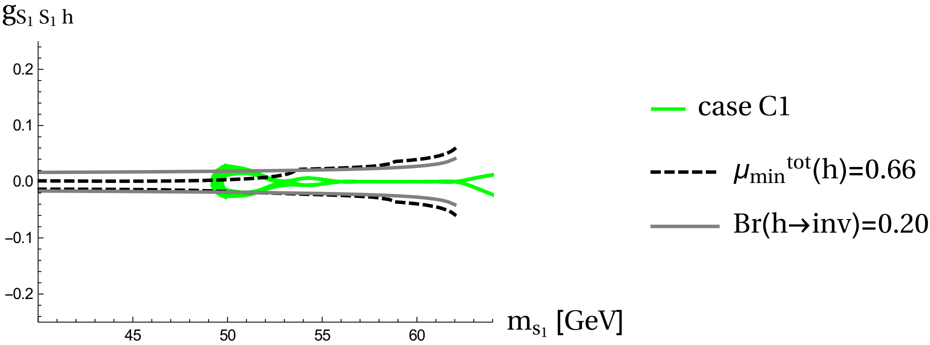
$$\mathrm{BR}(h \to \mathrm{inv}) = \frac{\sum_{i,j} \Gamma(h \to S_i S_j)}{\Gamma_h^{\mathrm{SM}} + \sum_i \Gamma(h \to S_i S_j)}$$

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

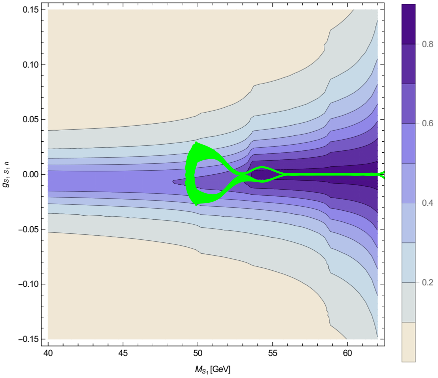
From ATLAS and CMS: $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$

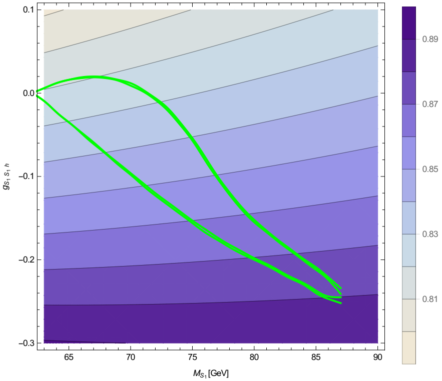
$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\mathrm{3HDM}}\,\Gamma(h)^{\mathrm{SM}}}{\Gamma(h \to \gamma\gamma)^{\mathrm{SM}}\,\Gamma(h)^{\mathrm{3HDM}}}$$

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