Collider signatures of dark CP violation

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The SM and beyond

SM predictions confirmed:

- the W & Z (1983)
- the top quark (1995)
- the tau neutrino (2000)
- "a" Higgs boson (2012)

What is missing:

- Fermion mass hierarchy explanation
- Dark Matter candidate
- Baryon asymmetry

$\Rightarrow$ Non-minimal Higgs frameworks

BSMs to the rescue

Scalar extensions with and 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
  - Types I, II, III, IV: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ CPV, ~~DM~~
  - IDM - 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

CP-violating DM in 3HDMs

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

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

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

The scalar potential with explicit CPV

$$V_{3HDM} = V_0 + V_{Z_2}$$

$$V_0 = \sum_{i}^{3} \Big[-\mu_i^2 (\phi_i^\dagger \phi_i) + \lambda_{ii} (\phi_i^\dagger \phi_i)^2 \Big]$$

$$+ \sum_{i,j}^{3} \Big[\lambda_{ij} (\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij} (\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \Big]$$

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

$$+\lambda_4 (\phi_3^\dagger \phi_1)(\phi_2^\dagger \phi_3) + \lambda_5 (\phi_1^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_6 (\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_1)$$

$$+\lambda_7 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_2) + \lambda_8 (\phi_3^\dagger \phi_1)(\phi_3^\dagger \phi_2) + h.c.$$

The Z_2 symmetry

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

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

Input parameters and constraints

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 θ_2, θ_{12}

Constraints taken into account include:

- Stability of the potential
- Positive-definitness of the Hessian
- Limits from gauge bosons width:
- Limits on charged scalar mass and lifetime:
- Null DM collider searches excluding simultaneously:
- S,T,U parameters

Relevant DM scenarios

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

- Scenario A: no coannihilation

$$m_{S_1} \ll m_{S_2}, m_{S_3}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$$

- Scenario B: coannihilation with S_3

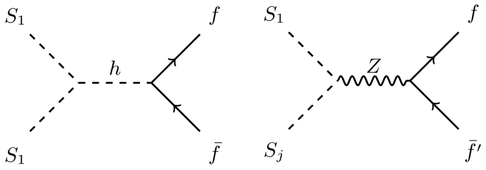
$$m_{S_1} \sim m_{S_3} \ll m_{S_2}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$$

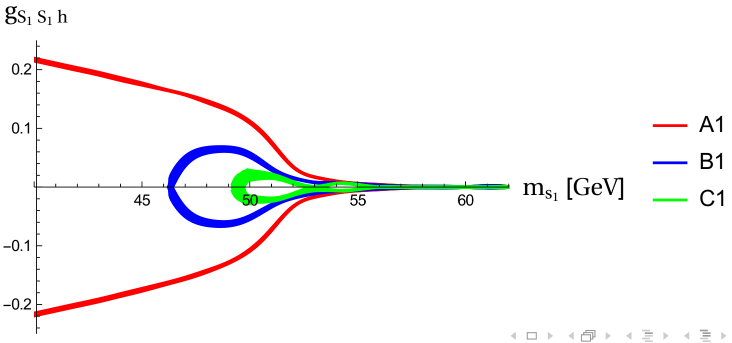
- Scenario C: coannihilation with all neutral particles

$$m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm}, m_{S_2^\pm}$$

Low DM mass region

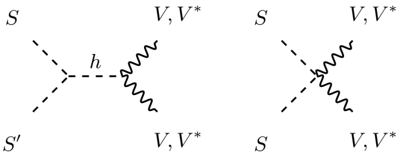
Higgs-mediated and Z-mediated (co)annihilation

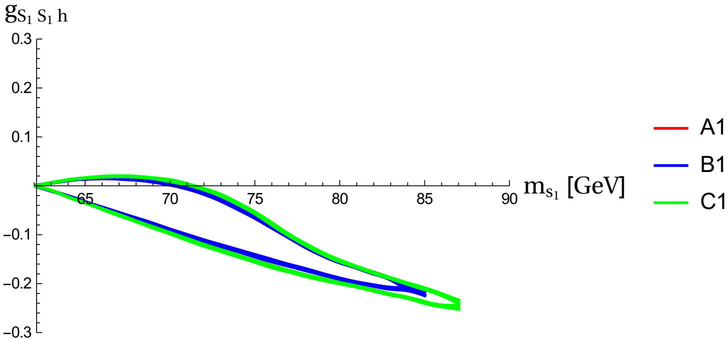




Medium DM mass region

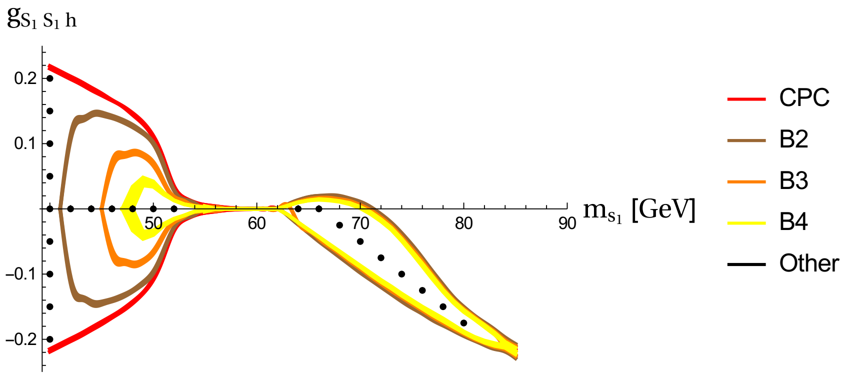
Higgs-mediated and quartic (co)annihilation





Filling the plot

C-type scenarios are the winners!



Relevant DM scenarios

In the heavy mass region ($m_{S_1} > 400$ GeV):

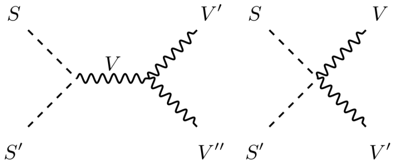
- Scenario G: coannihilation within the "family"

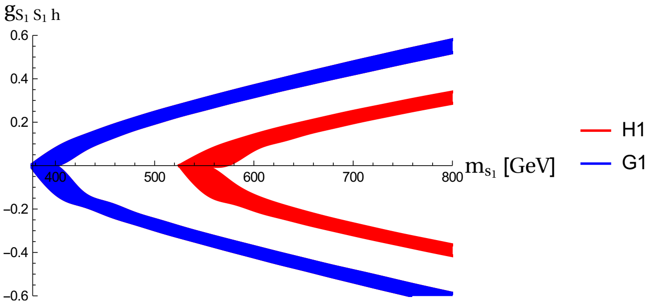
$$m_{S_1} \sim m_{S_3} \sim m_{S_1^\pm} \ll m_{S_2} \sim m_{S_4} \sim m_{S_2^\pm}$$

- Scenario H: coannihilation with all inert particles

$$m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$$

Heavy DM mass region

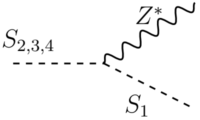




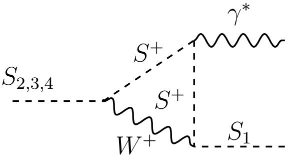
Collider signatures of CPV DM

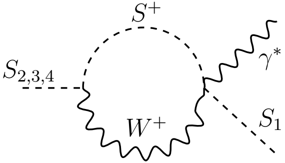
Inert cascade decays at the LHC

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):



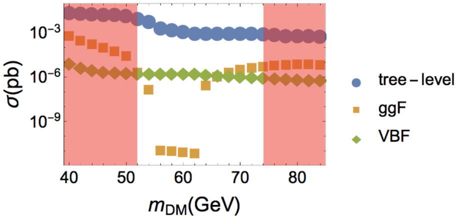


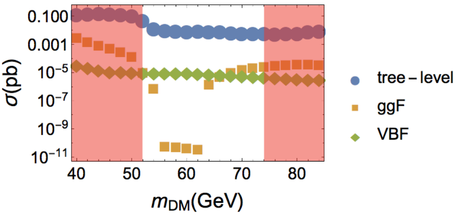
$E^T_{miss} + e^+e^-$ signals at the LHC

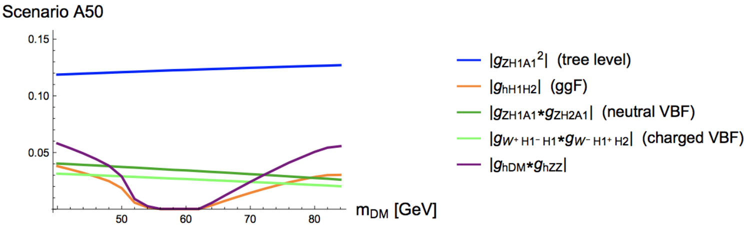
- Higgs-strahlung at tree level:
  $q\bar{q} \to Z \to S_1 S_{2,3,4} \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$
- Higgs-strahlung at loop level:
  $q\bar{q} \to Z \to S_1 S_{2,3,4} \to S_1 S_1 \gamma^* \to S_1 S_1 e^+ e^-$
- Gluon-fusion at tree level:
  $pp \to h \to S_1 S_{2,3,4} \to S_1 S_1 Z^* \to S_1 S_1 e^+ e^-$
- Vector boson fusion at loop level:
  $q_i q_j \to q_k q_l S_1 S_{2,3,4} \to q_k q_l S_1 S_1 \gamma^* \to q_k q_l S_1 S_1 e^+ e^-$

Benchmark	$m_{H_2} - m_{H_1}$	$m_{A_1} - m_{H_1}$	$m_{A_2} - m_{H_1}$	$m_{H_1^\pm} - m_{H_1}$	$m_{H_2^\pm} - m_{H_1}$
A50	50	75	125	75	125
I5	5	10	15	90	95
I10	10	20	30	90	100

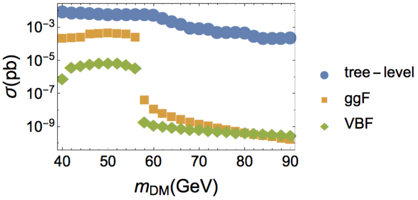
Scenario A50

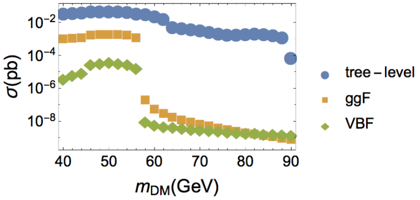


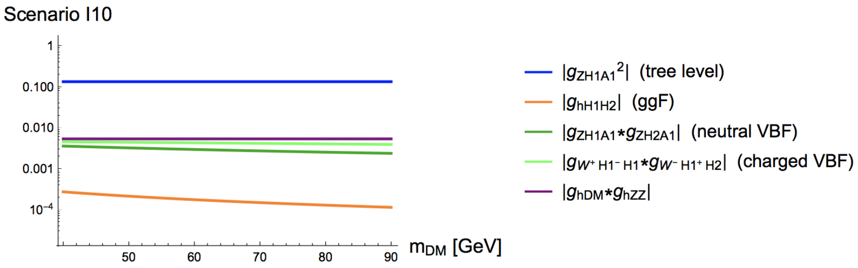




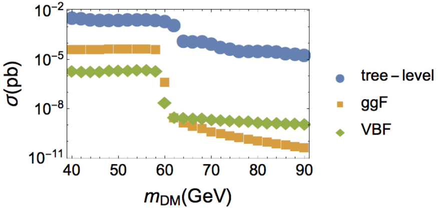
Scenario I10

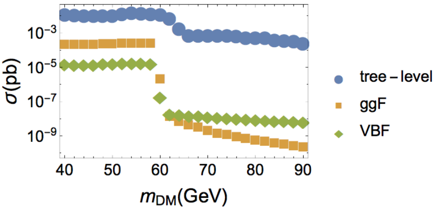


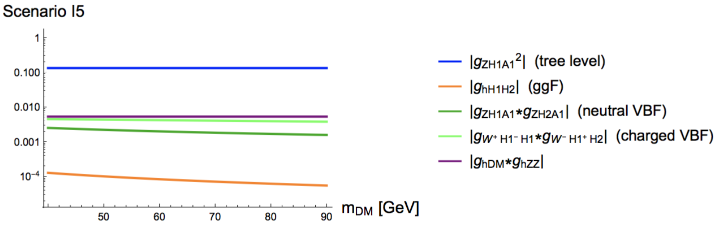




Scenario I5


10^{-2}
10^{-5}
10^{-8}
10^{-11}
σ(pb)
40 50 60 70 80 90
m_{DM}(GeV)
tree – level
ggF
VBF

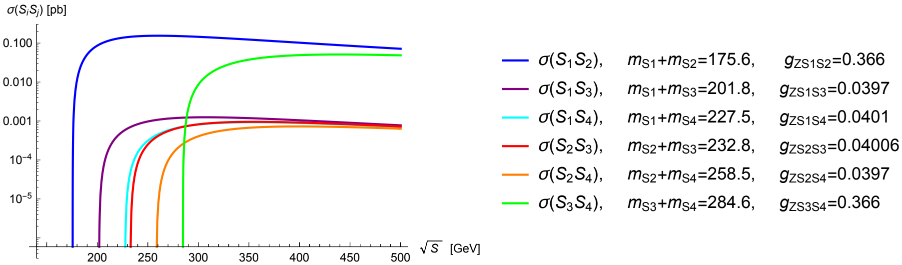

10^{-3}
10^{-5}
10^{-7}
10^{-9}
σ(pb)
40 50 60 70 80 90
m_{DM}(GeV)
tree – level
ggF
VBF


Scenario I5
1
0.100
0.010
0.001
10^{-4}
50 60 70 80 90
m_{DM} [GeV]
$|g_{ZH1A1}{}^2|$ (tree level)
$|g_{hH1H2}|$ (ggF)
$|g_{ZH1A1}*g_{ZH2A1}|$ (neutral VBF)
$|g_{W^+H1^-H1}*g_{W^-H1^+H2}|$ (charged VBF)
$|g_{hDM}*g_{hZZ}|$

Production thresholds of the Z boson

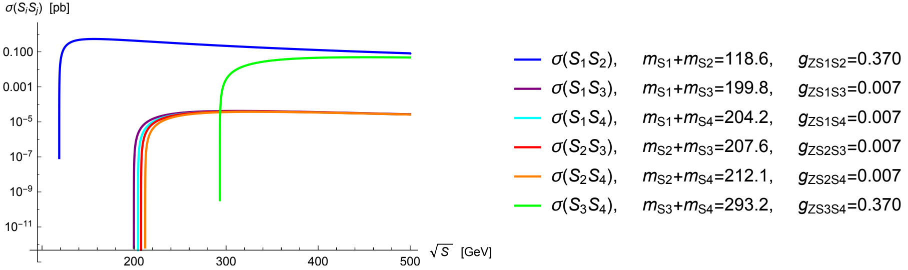
- The process $e^+e^- \to Z^* \to S_i S_j$ $(i, j = 1, ...4)$
- A simple collider energy scan combined with a trivial counting experiment in the detectors
- Three benchmark points with the cross section as large as a few picobarns at $\sqrt{s}$ values accessible by future e^+e^- colliders
- The proximity (or otherwise) of these thresholds would serve as characteristic signatures of different BPs with different DM properties.

Type A



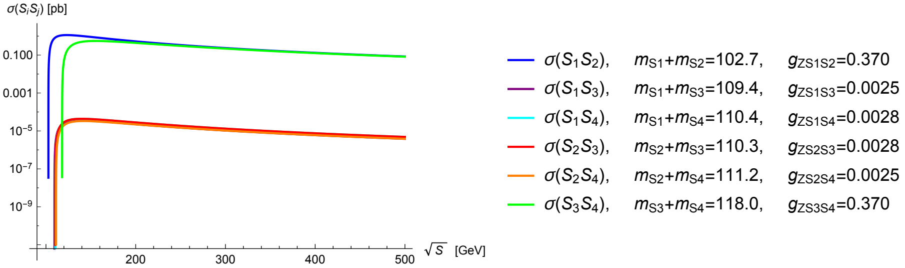
$$m_{S_1} = 72.331 \text{ GeV}, \quad m_{S_2} = 103.313 \text{ GeV}, \quad m_{S_1^\pm} = 106.235 \text{ GeV},$$
$$m_{S_3} = 129.467 \text{ GeV}, \quad m_{S_4} = 155.178 \text{ GeV}, \quad m_{S_2^\pm} = 157.588 \text{ GeV}.$$

Type B



$$m_{S_1} = 55.441 \text{ GeV}, \quad m_{S_2} = 63.219 \text{ GeV}, \quad m_{S_1^\pm} = 79.184 \text{ GeV},$$
$$m_{S_3} = 144.377 \text{ GeV}, \quad m_{S_4} = 148.842 \text{ GeV}, \quad m_{S_2^\pm} = 159.203 \text{ GeV}.$$

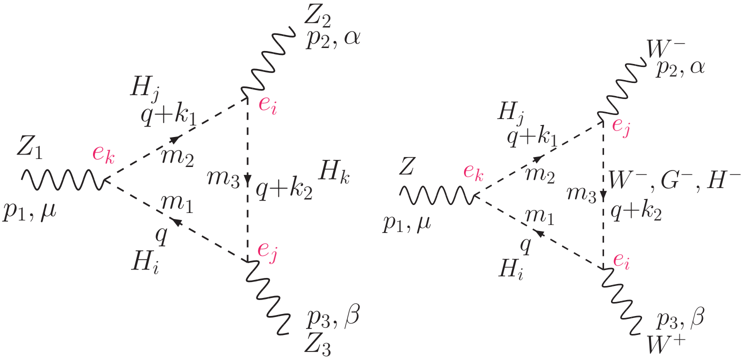
Type C



$$m_{S_1} = 50.925 \text{ GeV}, \quad m_{S_2} = 51.793 \text{ GeV}, \quad m_{S_1^\pm} = 99.176 \text{ GeV},$$
$$m_{S_3} = 58.555 \text{ GeV}, \quad m_{S_4} = 59.459 \text{ GeV}, \quad m_{S_2^\pm} = 111.136 \text{ GeV}.$$

Other CPV observables

ZZZ and ZWW vertices



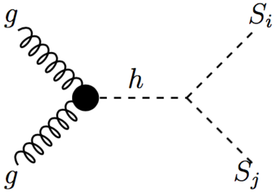
JHEP1605,025(2016)

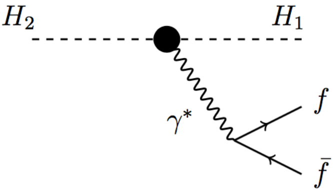
Summary

- 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, however, very limited CPV
- CP-Violation in I(2+1)HDM
  - SM-like active sector: $H_3 \equiv h^{SM}$
  - Unbounded CPV in the inert sector: $H_{1,2}, A_{1,2} \to S_{1,2,3,4}$ CPV DM
  - opens up new regions of parameter space
  - New observables at the LHC: $S_i S_j Z$ vertices

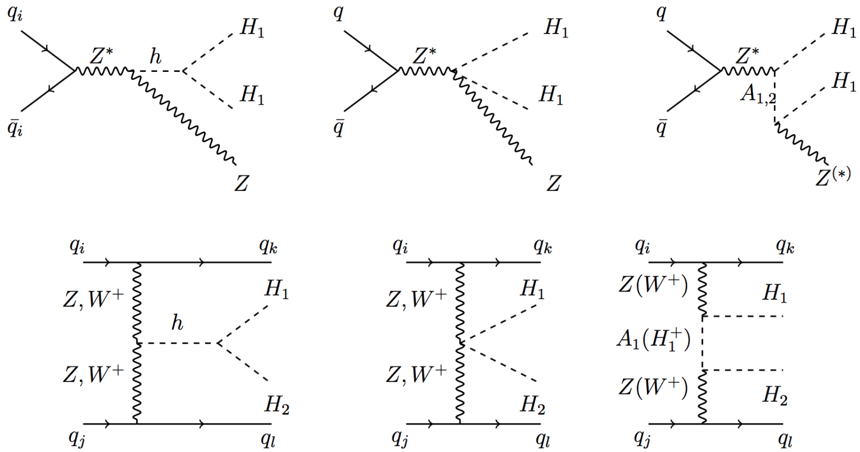
BACKUP SLIDES

ggF processes and the effective vertex





HS and VBF processes



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

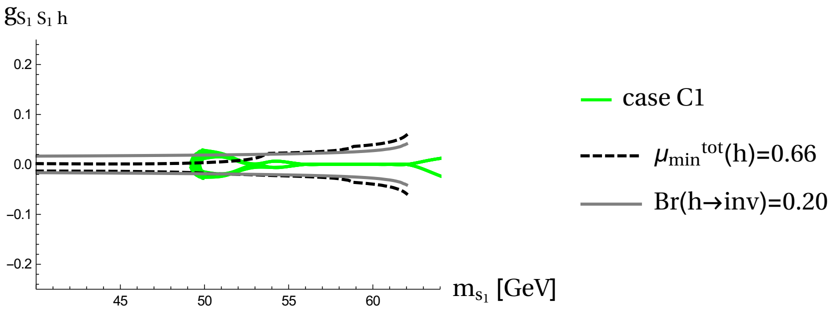
$$\mathrm{BR}(h \to \mathrm{inv}) = \frac{\sum_{i,j} \Gamma(h \to S_i S_j)}{\Gamma_h^{\mathrm{SM}} + \sum_i \Gamma(h \to S_i S_j)}$$

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

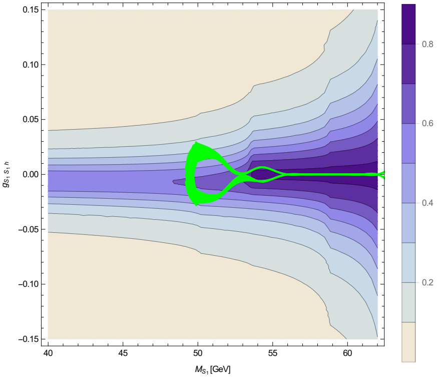
From ATLAS and CMS: $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$

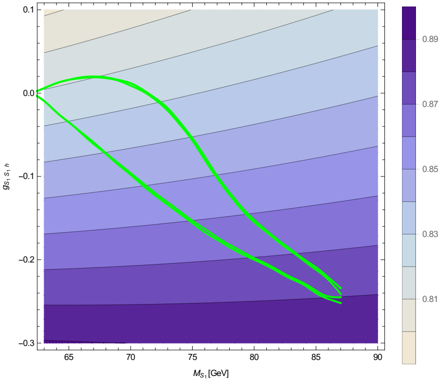
$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\rm 3HDM}\, \Gamma(h)^{\rm SM}}{\Gamma(h \to \gamma\gamma)^{\rm SM}\, \Gamma(h)^{\rm 3HDM}}$$

Modified by

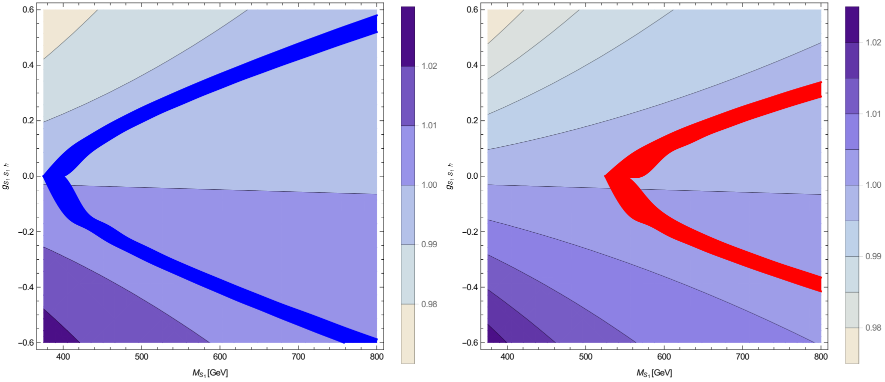
- charged scalars contribution to $\Gamma(h \to \gamma\gamma)^{\rm 3HDM}$
- light neutral scalars contribution to $\Gamma(h)^{\rm 3HDM}$

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





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



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

In the CPC limit

$$\alpha = \frac{-|\mu_{12}^2|\cos\theta_{12} + v^2|\lambda_2|\cos\theta_2 - \Lambda}{|\mu_{12}^2|\sin\theta_{12} + v^2|\lambda_2|\sin\theta_2} \to \infty$$

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

where

$$\Lambda = \sqrt{v^4|\lambda_2|^2 + |\mu_{12}^2|^2 - 2v^2|\lambda_2||\mu_{12}^2|\cos(\theta_{12}+\theta_2)},$$

$$\Lambda' = \sqrt{v^4|\lambda_2|^2 + |\mu_{12}^2|^2 + 2v^2|\lambda_2||\mu_{12}^2|\cos(\theta_{12}+\theta_2)}.$$

Benchmark scenarios

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

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