Scalar extensions: DM and LHC signals

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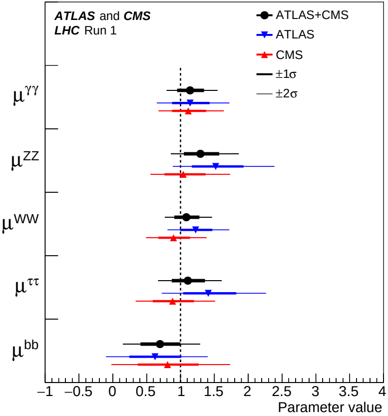
We love our Standard Model, don't we?

Current formulation finalised in the 70's predicted:

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

What's up at the LHC?

- Higgs looks SM-like
- No significant deviation from the SM
- No signs of new physics
- Is that all there is?



[JHEP 08 (2016) 045]

Do we really love the SM though?

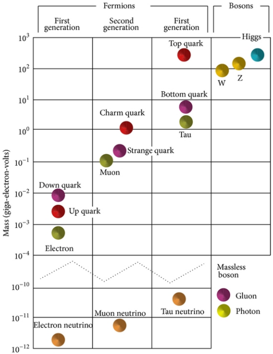
What is missing:

- An explanation for the Femion mass hierarchy
- EW vacuum stability
- Baryon asymmetry in the universe
  - Strongly first order phase transition
  - Sufficient amount of CP-Violation
- No suitable candidate for Dark Matter
- ...

Fermion mass hierarchy

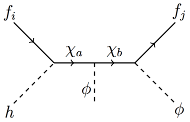
SM: no explanation for

- $m_t/m_e \approx 10^6$
- $m_t/m_\nu \approx 10^{11}$



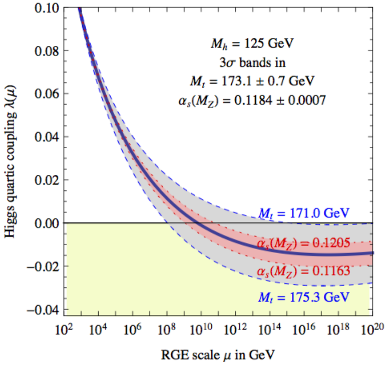
BSM: solutions

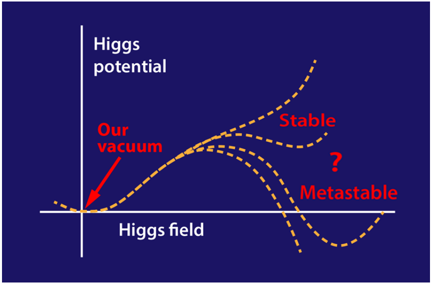
- SM + 2 scalar doublets
  Weinberg's private Higgs model
- SM + singlet scalar +...
  Froggatt-Nielsen mechanism



$\Rightarrow$ Scalar extensions

EW vacuum stability





$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$\Rightarrow$ Scalar extensions

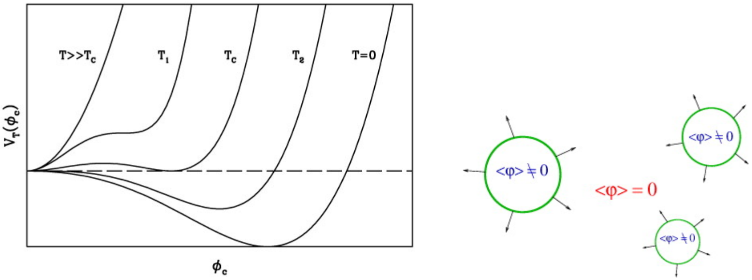
[JHEP 1312, 089 (2013)]

Baryon asymmetry in the Universe

Sakharov's conditions:

- B-violation
- C & CP violation
- Departure from thermal equilibrium

Strongly 1^{st} order phase transition



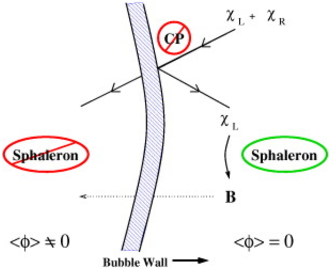
$$V_{eff}(\phi, T) = V_0(\phi) + V_1(\phi) + \Delta V_1^{(T)}(\phi, T)$$

SM scalar potential does not go through a first order phase transition.

$\Rightarrow$ Scalar extensions

[Phys. Rev. Lett. 77 (1996)]

C & CP violation



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ub} \neq V_{ub}^{*} ; V_{td} \neq V_{td}^{*} \Rightarrow \text{CPV}$$

Observation $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \gg 10^{-20}$ provided by SM

New sources of CPV needed.

$\Rightarrow$ Scalar extensions

Dark Matter

How we know it exists:

- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- ...

Fritz Zwicky in 1933 using the Virial theorem

Dark Matter

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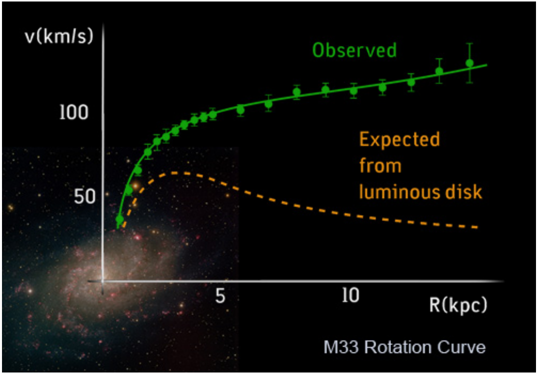
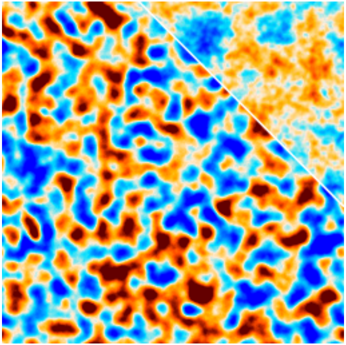


Vera Rubin & Kent Ford in 1960s

Dark Matter

How we know it exists:

- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- ...

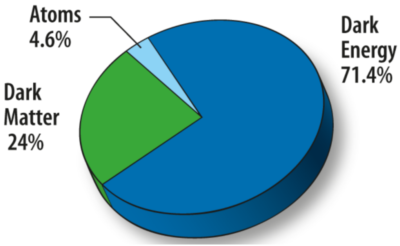


Planck CMB simulator

WIMP Dark Matter

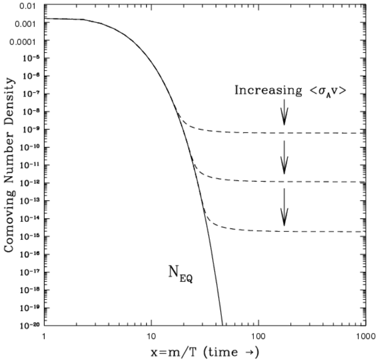
Characteristics:

- Cold (non-relativistic at the onset of galaxy formation)
- Non-baryonic
- Neutral & weakly interacting
- Stable due to a discrete symmetry



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

WIMP Dark Matter freeze-out

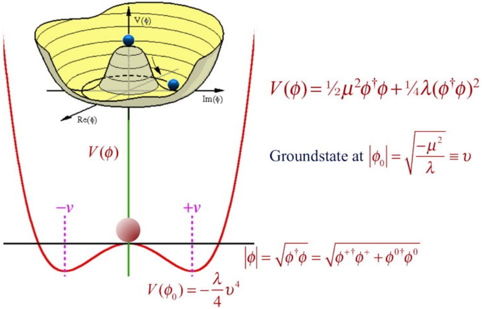


Observed relic density: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$

BSMs to the rescue!

Just fiddling with the scalar sector

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \psi + h.c. \\
& + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$



SM + singlet scalar extensions

ϕ S

real singlet

complex singlet

more than one singlets

SM + inert real singlet DM, ~~CPV~~

DM protected by a Z_2 symmetry $(+,-)$:

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

Z_2 symmetric Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 + \frac{1}{2}\mu_s^2 S^2 - \lambda_s S^4 - \lambda_{hs}\Phi^2 S^2$$

Z_2 symmetry respected by the vacuum $(v, 0)$:

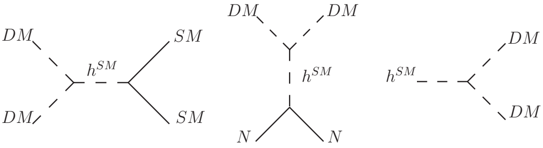
$$\phi = \begin{pmatrix} G^+ \\ \frac{v_h+h+iG^0}{\sqrt{2}} \end{pmatrix}, \quad S = \left(\frac{s}{\sqrt{2}}\right)$$

SM+RS: scalar DM

Higgs-portal interactions:

$$V = -\frac{1}{2}\mu_h^2\phi^2 + \lambda_h\phi^4 - \frac{1}{2}\mu_s^2 S^2 + \lambda_s S^4 + \lambda_{hs}\phi^2 S^2$$

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



$\langle \sigma v \rangle$ σ_{DM-N} $\Gamma^{inv}_{h^{SM}}$

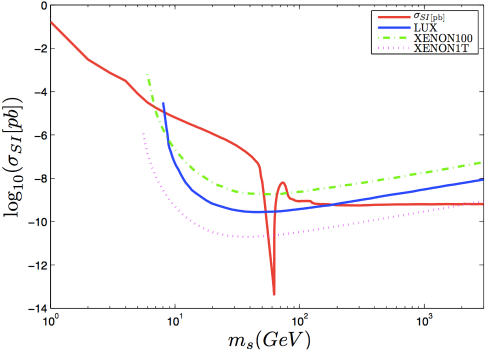
governed by the same coupling

What constrains the parameter space?

- Bounded from below potential: $h, s \to \infty \;\Rightarrow V > 0$
- Vacuum stability: $E_{v_{EW}} < E_{v_i}$ or $\tau_{v_{EW}} >$ age of the universe
- Perturbative unitarity: $|\lambda_i| \leq 4\pi, \; |\Lambda_i| \leq 8\pi$
- Higgs decays: $BR(h \to inv.) < 20\% \;\Rightarrow \lambda_{hs}$ small
- Relic density: λ_{hs} large
- Direct and indirect detection: λ_{hs} small

SM+RS: scalar DM is in trouble

Relic density + direct detection constraints:



+ Higgs decays + SM vacuum stability + purturbativity constraints:

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

[JHEP 12, 044 (2015)]

SM + active real singlet ~~DM~~, ~~CPV~~

Z_2 broken by the vacuum:

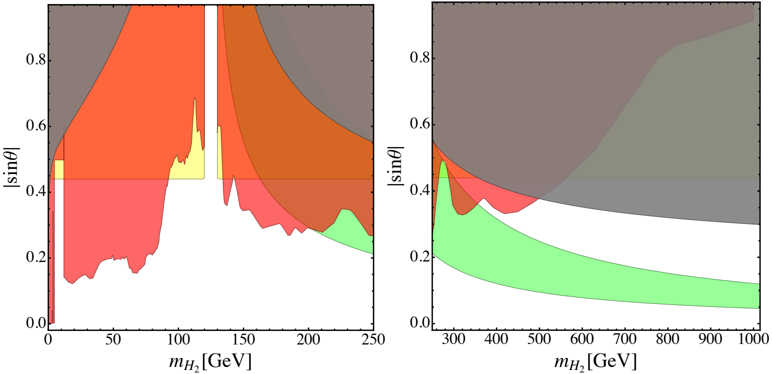
$$\phi = \begin{pmatrix} G^+ \\ \frac{v_h + h + iG^0}{\sqrt{2}} \end{pmatrix}, \quad S = \left(\frac{v_s + s}{\sqrt{2}} \right)$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

$$\tan 2\theta = \lambda_{hs} v_h v_s / (\lambda_h v_h^2 - \lambda_s v_s^2)$$

no DM candidate

What *else* constrains the parameter space?



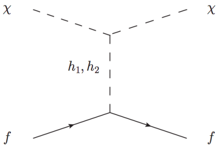
Excluded by direct searches, precision tests, H_1 couplings measurements and preferred by potential stability.

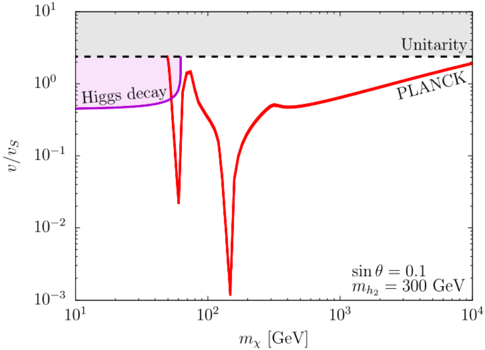
[JHEP 05, 057 (2015)]

SM + complex singlet DM, ~~CPV~~

$S = (v_s + s + i\chi)/\sqrt{2} \to Z_2$-symmetry broken, CP conserves DM

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$





[Phys.Rev.Lett.119 (2017)]

Further singlet extensions DM, CPV

SM+ 2 singlet scalars:

$S_1 \to -S_1, \quad S_2 \to -S_2, \quad \text{SM fields} \to \text{SM fields}$

- DM: the lightest particle from the dark sector s_1, s_2
- Introducing coannihilation channels: $s_1 s_2 \to h \to SM$
- CPV in the dark sector $s_1, \chi_1, s_2, \chi_2 \to d_1, d_2, d_3, d_4$

[Phys.Rev.D. 83 (2011)]

2 Higgs doublet model (2HDM)

ϕ_1, ϕ_2

CPC-2HDM

CPV-2HDM

IDM

The CP-conserving 2HDM (~~CPV~~, ~~DM~~)

The general scalar potential:

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

Dangerous FCNCs appear

$$\mathcal{L}_Y = y^1_{ij}\bar{\psi}_i\psi_j\phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\phi_2$$

$$Z_2 \text{ symmetry } (\phi_1 \to +\phi_1,\ \phi_2 \to -\phi_2) \Rightarrow \lambda_6 = \lambda_7 = 0$$

The CP-conserving 2HDM

Z_2 symmetry: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$

$$-\mathcal{L}_Y = Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R + Y_d \bar{Q}'_L \phi_d d'_R + Y_e \bar{L}'_L \phi_e e'_R + \mathrm{h.c.}$$

	ϕ_1	ϕ_2	u_R	d_R	e_R	$Q_L,\ L_L$	ξ_d	ξ_u	ξ_l
Type-I	$+$	$-$	$-$	$-$	$-$	$+$	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$+$	$-$	$-$	$+$	$+$	$+$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type-X	$+$	$-$	$-$	$-$	$+$	$+$	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$+$	$-$	$-$	$+$	$-$	$+$	$-\tan\beta$	$\cot\beta$	$\cot\beta$

$$\tan\beta = \langle\phi_2\rangle / \langle\phi_1\rangle$$

The CP-conserving 2HDM

The doublets compositions:

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

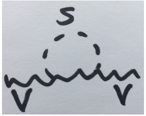
Mass eigenstates:

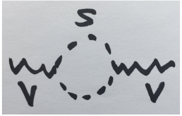
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix}$$

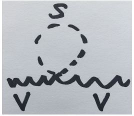
$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} a_1^0 \\ a_2^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Extra doublets lead to extra constraints

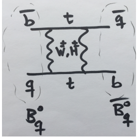
Electroweak precision observables:

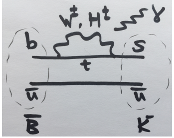


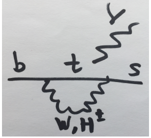


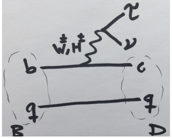


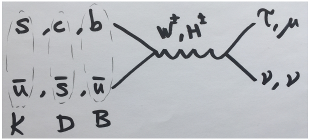
Flavour observables:



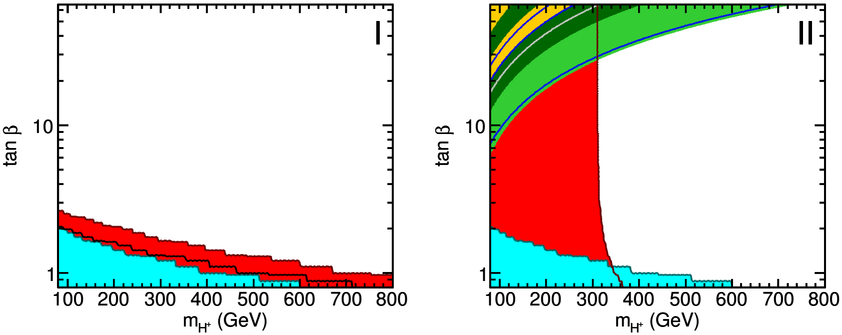








Summary of flavour constraints



Exluded by $BR(B \to X_s\gamma)$, $B^0 - \bar{B}^0$ mixing, $D_s \to \tau\nu_\tau$, $D_s \to \mu\nu_\mu$, $B \to D\tau\nu_\tau$.

[Phys.Rev. D81 (2010)]

LEP and LHC constraints

LEP bounds:

$$m_{H^\pm} + m_{H,A} > m_{W^\pm}, \qquad m_H + m_A > m_Z, \qquad 2m_{H^\pm} > m_Z$$

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

$$\text{if } M_H < 80 \text{ GeV and } M_A < 100 \text{ GeV} \Rightarrow M_A - M_H < 8 \text{ GeV}$$

LHC bounds for long lived $m_{S_i} < m_h/2$:

$$\mathrm{BR}(h \to \mathrm{inv}) = \frac{\sum_{i,j} \Gamma(h \to S_i S_j)}{\Gamma_h^{\mathrm{SM}} + \sum_i \Gamma(h \to S_i S_j)} < 0.23 - 0.36$$

LHC bound on the total decay signal strength:

$$\mu_{tot} = \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h_{\mathrm{SM}} \to XX)} = \frac{\Gamma_{tot}^{SM}(h)}{\Gamma_{tot}^{SM}(h) + \Gamma^{inert}(h)} = 1.17 \pm 0.17 \quad \text{at } 3\sigma$$

Even more LHC constraints

LHC bound on $h \to \gamma\gamma$ signal strength:

$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\rm 2HDM}\,\Gamma(h)^{\rm SM}}{\Gamma(h \to \gamma\gamma)^{\rm SM}\,\Gamma(h)^{\rm 2HDM}} = 1.16^{+0.20}_{-0.18}$$

Modified by

- charged scalars contribution to $\Gamma(h \to \gamma\gamma)^{\rm 2HDM}$
- light neutral scalars contribution to $\Gamma(h)^{\rm 2HDM}$

Exotic decay channels in 2HDM

Channels	Possible final states
$H \to AA,\ hh$	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)$
$H \to AZ, A \to HZ,\ hZ$	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)\,(\ell\ell/qq/\nu\nu)$
$H \to H^+H^-$	$(tb/\tau\nu/cs)$
$H/A \to H^\pm W^\mp$	$(tb/\tau\nu/cs)\,(\ell\nu/qq')$
$H^\pm \to hW^\pm, HW^\pm, AW^\pm$	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)\,(\ell\nu/qq')$

[JHEP 09 (2016) 093]

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

The scalar potential with softly broken Z_2 symmetry:

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

The only source of CPV-violation:

$$\mathrm{Im}\mu_3^2 = \frac{v^2}{2}\mathrm{Im}\lambda_5 \sin\beta\cos\beta$$

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

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+h_1^0+ia_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+h_2^0+ia_2^0}{\sqrt{2}} \end{pmatrix}$$

The Higgs basis and mass eigenstates

Rotating the doublets to the "Higgs Baiss":

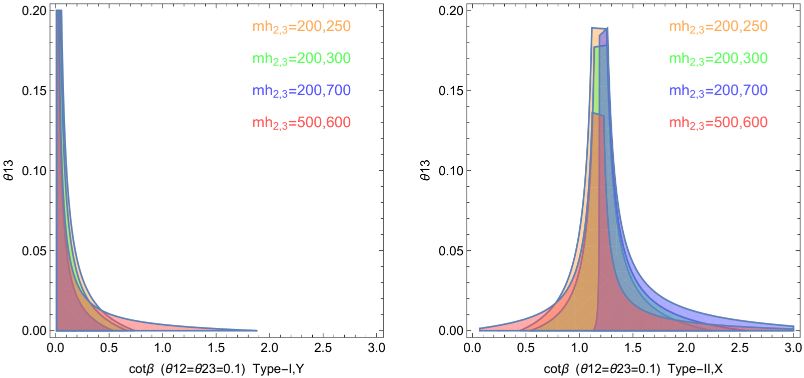
$$\begin{pmatrix} \widehat{\phi}_1 \\ \widehat{\phi}_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

Now diagonalising the 3×3 neutral mass matrix

$$\begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ \phi_3^0 \end{pmatrix} = \begin{pmatrix} 1 & \theta_{12} & \theta_{13} \\ -\theta_{12} & 1 & \theta_{23} \\ -\theta_{13} & -\theta_{23} & 1 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

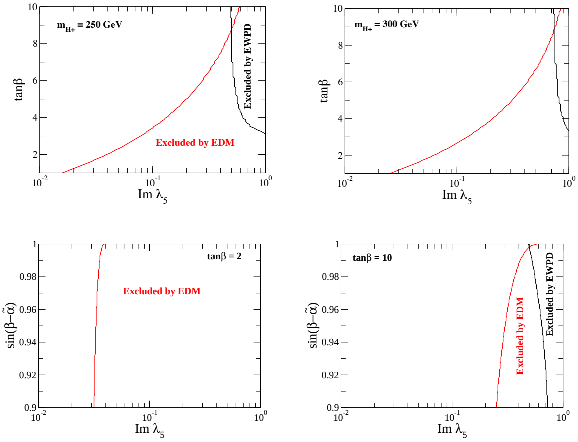
The CPV angles, θ_{13} and θ_{23}, are constrained by EDM data.

How much CPV is allowed?



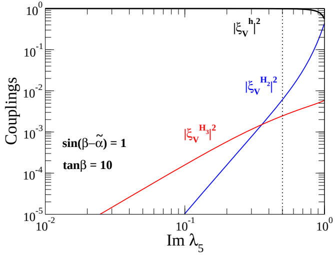
[arXiv:1712.09613]

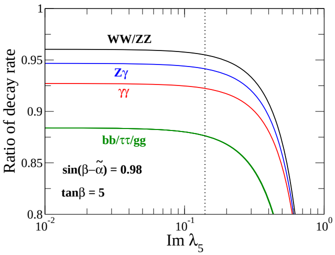
CPV 2HDM-I: bounds on the parameter space

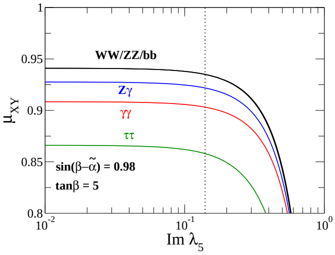


[JHEP 1604 (2016) 048]

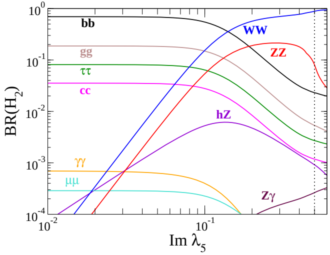
CPV 2HDM-I: LHC signatures

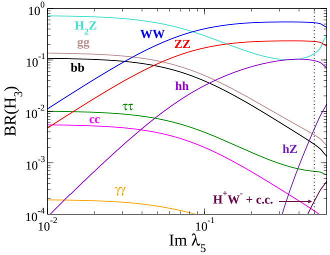


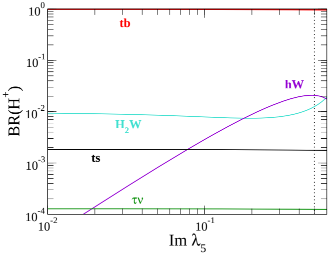




CPV 2HDM-I: LHC signatures







2HDM with DM: the Inert Doublet Model ($\cancel{CPV}$)

Scalar potential with an exact Z_2 symmetry:

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

$$\begin{aligned} V &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 \end{aligned}$$

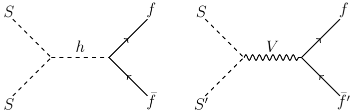
The vacuum respects the Z_2 symmetry:

$$\langle\phi_1\rangle = v, \quad \langle\phi_2\rangle = 0$$

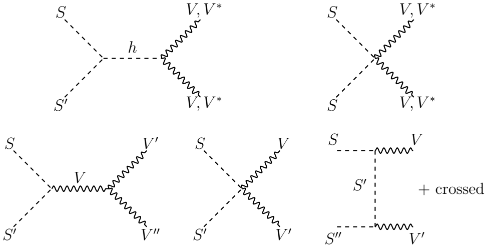
DM is the lightest neutral particle from the inert doublet: H, A

(Co)annihilation channels, $S = H, A, H^{\pm}$

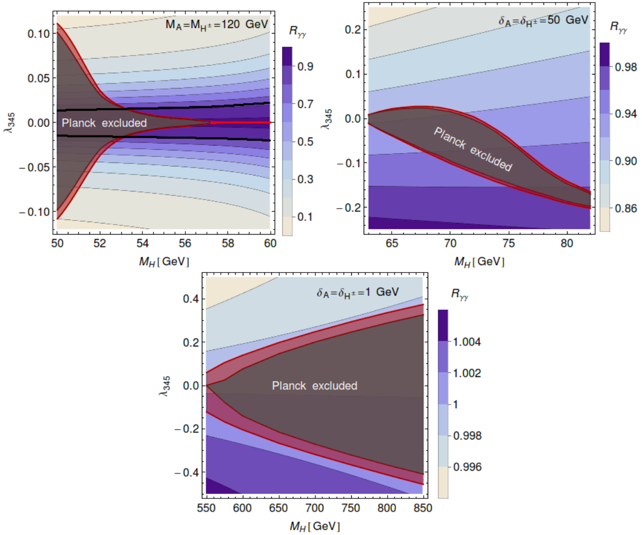
In the low mass region, $m_{DM} < m_Z$:



In the medium/heavy mass region, $m_{DM} \gtrsim m_Z$:



IDM with all constraint taken into account



[JHEP 09, 055 (2013)]

3-Higgs doublet models

I(1+2)HDM

$(0, v, v)$

I(2+1)HDM

$(0, 0, v)$

The scalar potential with explicit CPV

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

The Z_2 symmetry

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

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

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

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

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

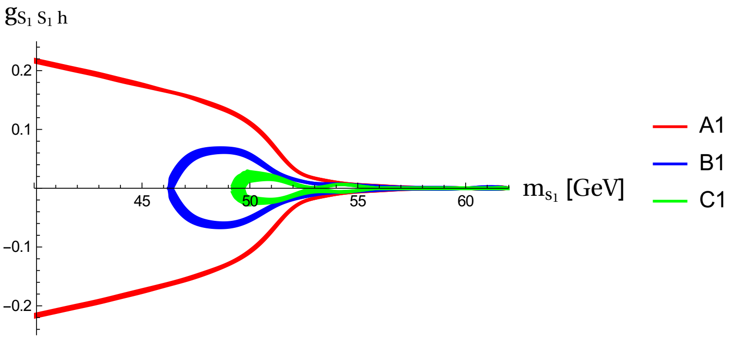
S_1 is assumed to be the DM candidate

Low DM mass region

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

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

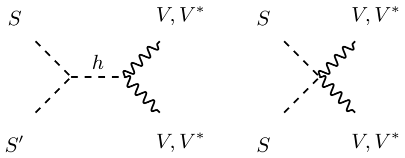
Scenario C: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm}, m_{S_2^\pm}$

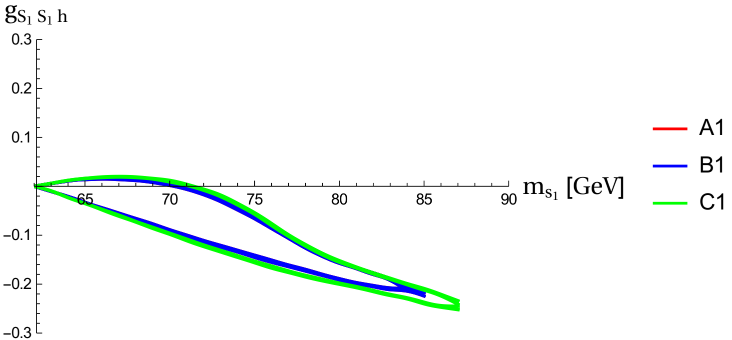


[JHEP 1612 (2016) 014]

Medium DM mass region

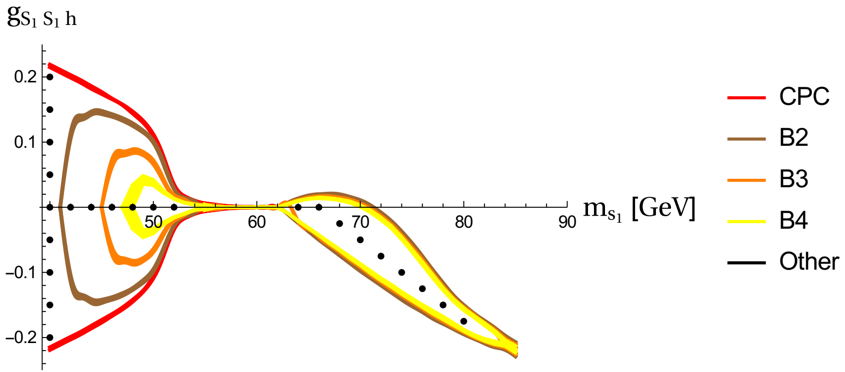
Cancellation between diagrams leas to an asymmetric plot:





Filling the plot

With CP-violation one can cover the entire plot:

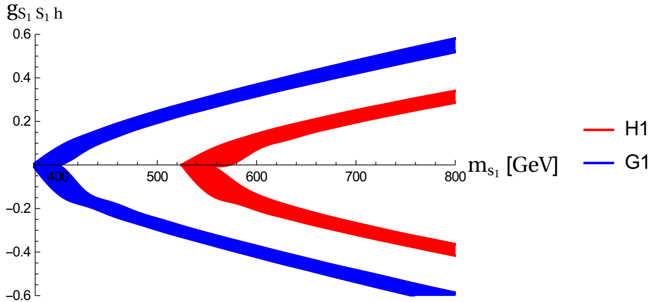


[JHEP 1612 (2016) 014]

Heavy DM mass region

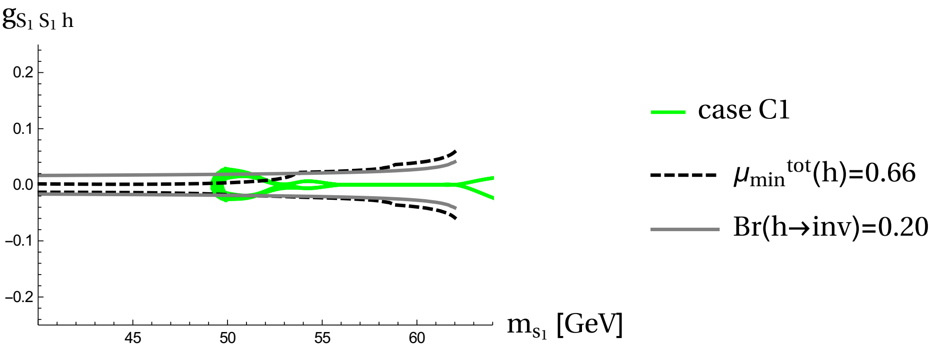
Scenario G: $m_{S_1} \sim m_{S_3} \sim m_{S_1^\pm} \ll m_{S_2} \sim m_{S_4} \sim m_{S_2^\pm}$

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



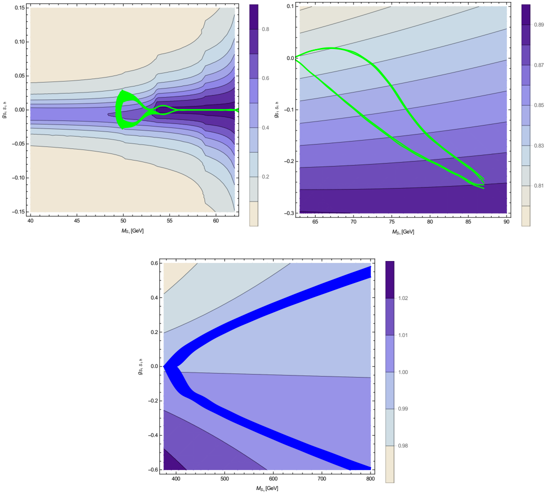
[JHEP 1612 (2016) 014]

Relic density vs. Higgs decay bounds



[JHEP 1612 (2016) 014]

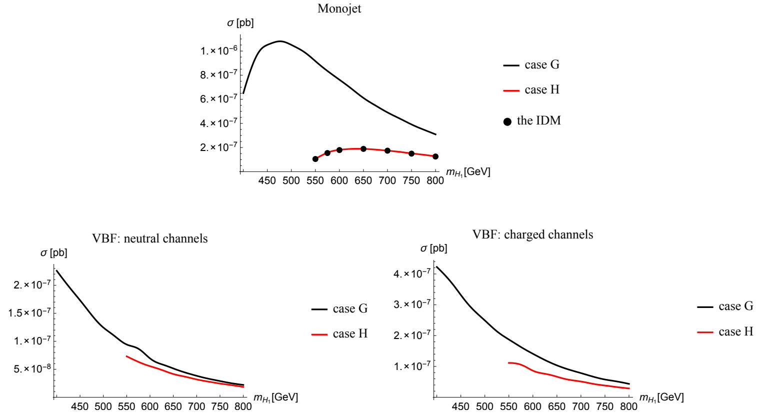
Relic density vs. $\mu_{\gamma\gamma}$



[JHEP 1612 (2016) 014]

I(2+1)HDM at the LHC

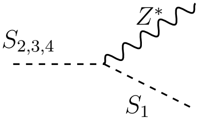
Monojet and dijet channels in the heavy mass region:



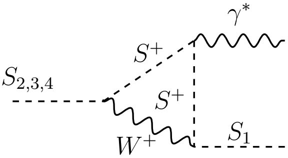
[JHEP 1511 (2015) 003]

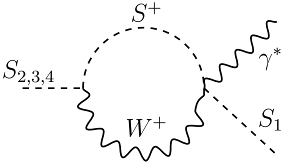
Inert cascade decays at the LHC

Large mass splitting present in 2HDM:



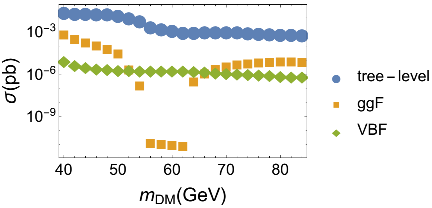
Small mass splitting smoking gun of 3HDM:

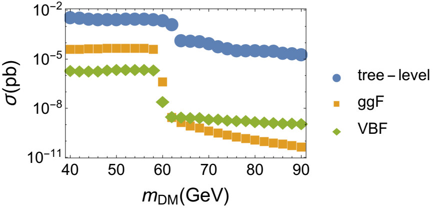




$E^T_{miss} + f\bar{f}$ at the LHC

- Tree level process: $q\bar{q} \to Z^* \to H_1 A_{1,2} \to H_1 H_1 Z^* \to H_1 H_1 f\bar{f}$
- ggF process: $gg \to h \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$
- VBF process: $q_i q_j \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$



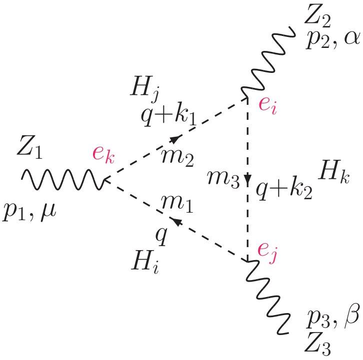


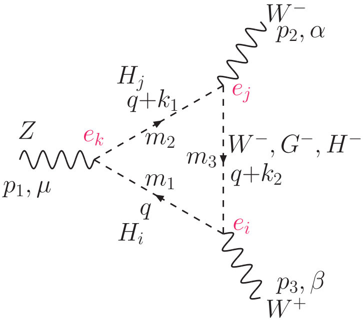
$m_{S_i} - m_{DM} \simeq 50$ GeV, $m_{S_i} - m_{DM} \simeq 5$ GeV

[arXiv:1712.09598]

Other CPV observables

ZZZ and ZWW vertices with non-identical scalars in the loop





[JHEP 1605 (2016) 025]

Summary

Scalar extensions with or without a Z_2 symmetry:

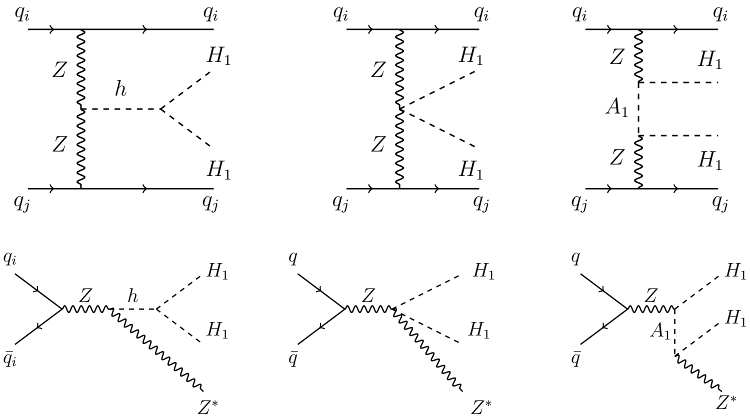
- SM + scalar singlet(s)
  - $\phi_{SM},\ S \quad \Rightarrow \quad$ DM, ~~CPV~~
  - $\phi_{SM},\ S_1,\ S_2 \quad \Rightarrow \quad$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ CPV, ~~DM~~
  - IDM - I(1+1)HDM: $\phi_1,\ \phi_2 \quad \Rightarrow \quad$ 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

BACKUP SLIDES

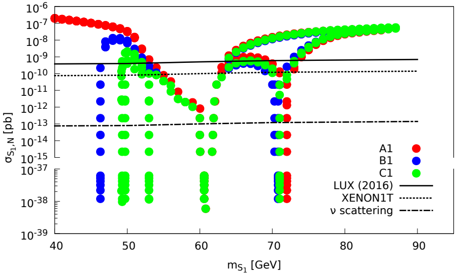
Detailed summary

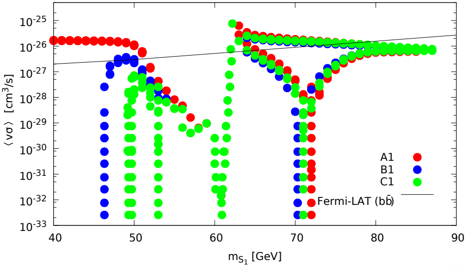
- Both DM and CPV from scalar sector $\to$ beyond one singlet/doublet
- CP-Violation in I(1+2)HDM
  - IDM-like inert sector: CPC DM
  - CPV in the active sector: $\tilde{H}_1, \tilde{H}_2, \tilde{H}_3$
  - EWBG possible
- CP-Violation in I(2+1)HDM
  - SM-like active sector: $H_3 \equiv h^{SM}$
  - CPV in the inert sector: $H_{1,2}, A_{1,2} \to S_{1,2,3,4}$ CPV DM
  - EWBG possible

VBF and HS diagrams

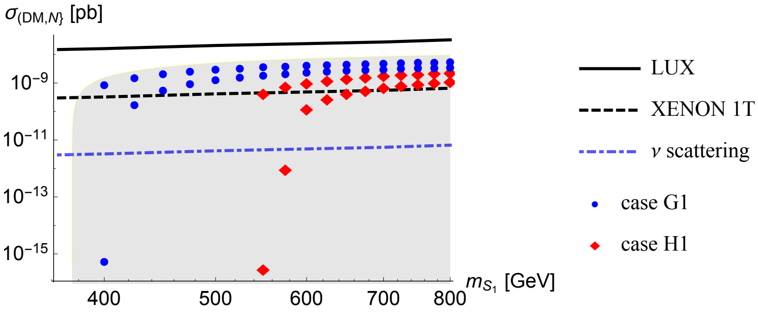


Direct and indirect detection bounds in the low mass region

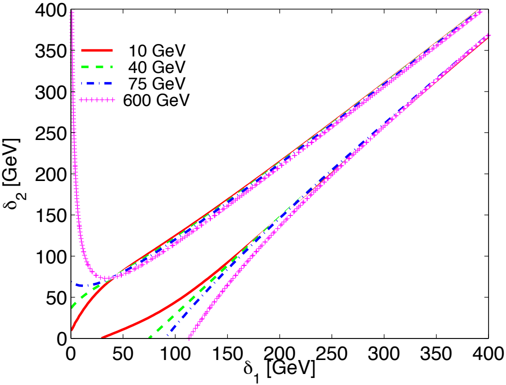




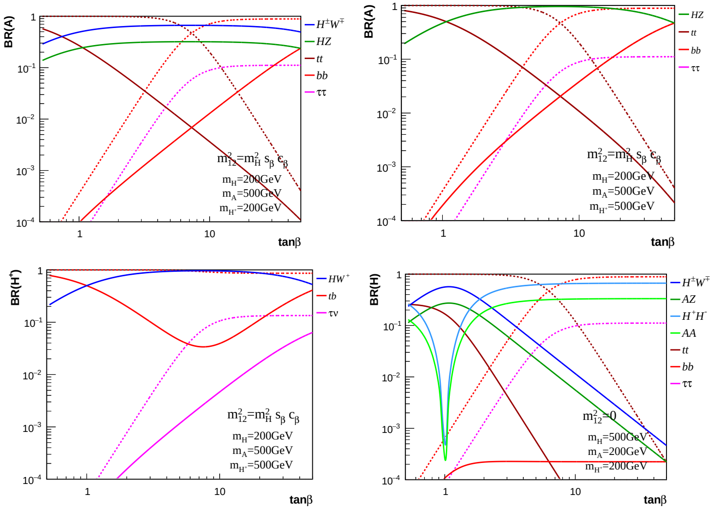
Direct detection bounds in the heavy mass region



S, T, U parameters



$\delta_1 = m_{H^\pm} - m_{DM}$ and $\delta_2 = m_A - m_{DM}$ [Phys.Rev. D80 (2009) 055012]

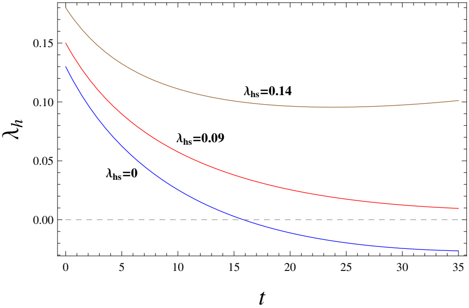


[JHEP 09 (2016) 093]

Electroweak vacuum stability

SM + real singlet scalar

$$V = -\frac{\mu_h^2}{2}\phi^\dagger\phi - \frac{\mu_s^2}{2}S^2 + \frac{\lambda_h}{4}(\phi^\dagger\phi)^2 + \frac{\lambda_s}{4}S^4 + \frac{\lambda_{hs}}{4}(\phi^\dagger\phi)(S^2)$$



[Eur.Phys.J. C72 (2012) 2058]