Dark Matter Phenomenology in Z'_2 broken Two Higgs Doublet Model with Complex Singlet Extension

Julia Ziegler with Juhi Dutta, Cheng Li, Gudrid Moortgat-Pick, Tabira Farah Sheikh

Can we explain DM in a 2HDMS?

~~Dark Matter~~ [redacted] ~~Model~~
[redacted] ~~Singlet Extension~~

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What is Dark Matter (DM)?

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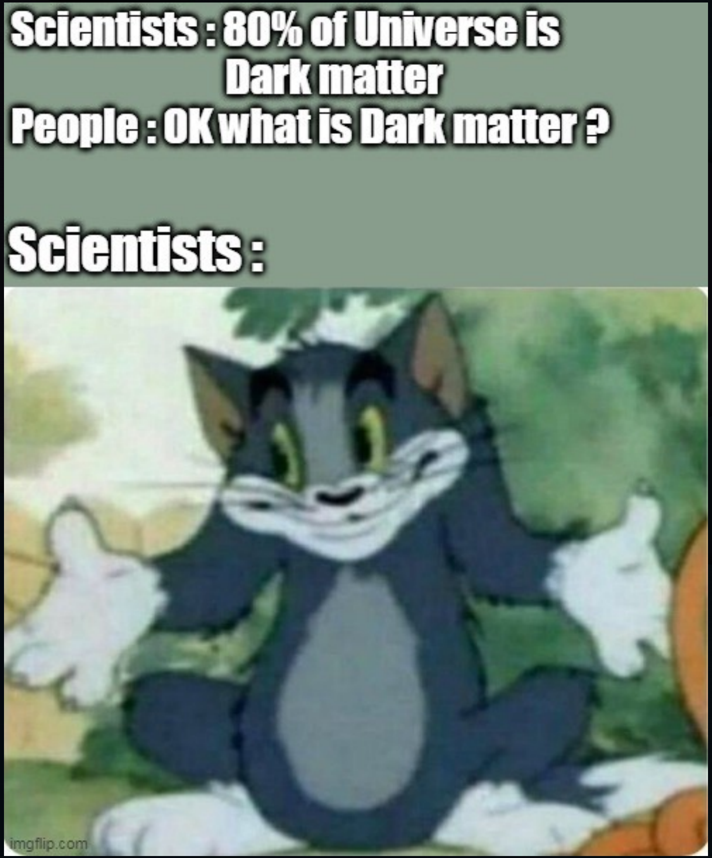

[https://imgflip.com/i/3s0055]

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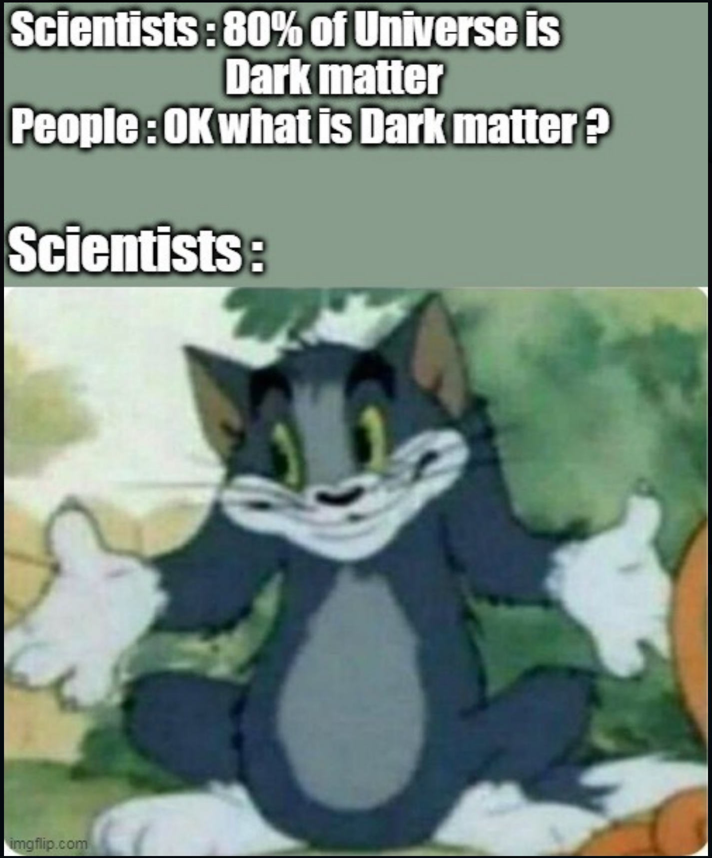


[https://imgflip.com/i/3s0055]

Properties:
- Massive
- Electrically neutral
- Colourless
- Stable
- Barely interacts with ordinary matter (except through gravity)

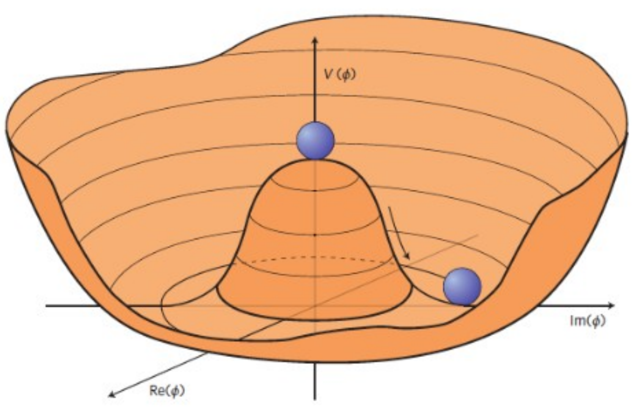
Proofs:
- Rotation curves of galaxies
- Gravitational lensing
- Cosmic microwave background
- Structure of the universe, galaxy formation
- Mass location during galactic collisions

What is a Two Higgs Doublet Model with Complex Singlet Extension (2HDMS)?

What is a 2HDMS?

- **SM Higgs Potential**

$$V_{\rm SM} = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



[Higgs Physics, Ellis, arXiv: 1312.5672]

- **2HDMS Higgs Sector Potential**

[Notation as in: S. Baum and N. R. Shah, 2018]

$$V = V_{2HDM} + V_S$$

$$\begin{aligned} V_{2HDM} = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 \\ & + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \end{aligned}$$

$$\begin{aligned} V_S = {} & m_S^2 S^\dagger S + \left[\frac{m_S'^2}{2}S^2 + h.c.\right] \\ & + \left[\frac{\lambda_1''}{24}S^4 + h.c.\right] + \left[\frac{\lambda_2''}{6}(S^2S^\dagger S) + h.c.\right] + \frac{\lambda_3''}{4}(S^\dagger S)^2 \\ & + S^\dagger S[\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2] + [S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + h.c.] \end{aligned}$$

$=\lambda_1''$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix} \qquad \langle\Phi_i\rangle = \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix}$$

$$S = \frac{1}{\sqrt{2}}(v_S + \rho_S + iA_S) \qquad \langle S\rangle = \frac{v_S}{\sqrt{2}}$$

DM candidate

What is a 2HDMS? - Symmetries

V_{2HDM} symmetric under U(1), all parameters real $\Phi_i \overset{U(1)}{\rightarrow} e^{i\theta}\Phi_i$ $\Phi_i^\dagger \overset{U(1)}{\rightarrow} e^{-i\theta}\Phi_i^\dagger$	➡ V_{2HDM} symmetric under CP
V_{2HDM} symmetric under Z2 (Type II 2HDM) (broken spontaneously) (broken softly to avoid domain walls) $\Phi_1 \overset{Z_2}{\rightarrow} -\Phi_1$ $\Phi_2 \overset{Z_2}{\rightarrow} \Phi_2$	➡ Avoids FCNC (Φ_1 couples only to down-type quarks and leptons, Φ_2 couples only to up-type quarks)
V_{2HDMS} symmetric under Z2' $\Phi_1 \overset{Z_2'}{\rightarrow} \Phi_1$ $\Phi_2 \overset{Z_2'}{\rightarrow} \Phi_2$ $S \overset{Z_2'}{\rightarrow} -S$	➡ Stabilisation of DM

What is a 2HDMS? - Particle Content

Mass squared matrix:

$$[M^2]_{ij} = \frac{\partial^2 V}{\partial \varphi_i^\dagger \partial \varphi_j}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}}$$

Rotation matrices:

$$R^\pm(\beta) = \begin{pmatrix} -s_\beta & c_\beta \\ c_\beta & s_\beta \end{pmatrix}$$

$$R(\alpha_1,\alpha_2,\alpha_3) = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1}c_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ s_{\alpha_1}s_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} & -c_{\alpha_1}s_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}c_{\alpha_3} & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}$$

$$R^A(\beta) = \begin{pmatrix} -s_\beta & c_\beta \\ c_\beta & s_\beta \end{pmatrix}$$

Mass eigenvalues and eigenfields:

$$\mathrm{diag}(m^2_{H^\pm}, m^2_{G^\pm}) = R^\pm M^2_{\text{charged}} R^{\pm T}, \qquad \begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = R^\pm \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$\mathrm{diag}(m^2_{h_1}, m^2_{h_2}, m^2_{h_3}) = R M^2_{\text{scalar}} R^T, \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

=m_{hSM}≈125 GeV

$$\mathrm{diag}(m^2_A, m^2_{G^0}) = R^A M^2_{\text{pseudo}} R^{AT}, \qquad \begin{pmatrix} A \\ G^0 \end{pmatrix} = R^A \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$\mathrm{diag}(m^2_{A_S}) = M^2_{A_S}, \qquad \begin{pmatrix} A_S \end{pmatrix} = \begin{pmatrix} A_S \end{pmatrix}$$

Minimisation conditions:

$$0 = \frac{\partial V}{\partial \Phi_1}\Big|_{\Phi_i=\langle\Phi_i\rangle, S=\langle S\rangle}$$

$$0 = \frac{\partial V}{\partial \Phi_2}\Big|_{\Phi_i=\langle\Phi_i\rangle, S=\langle S\rangle}$$

$$0 = \frac{\partial V}{\partial S}\Big|_{\Phi_i=\langle\Phi_i\rangle, S=\langle S\rangle}$$

⇒ eliminate m_{11}, m_{22}, m_S

What is a 2HDMS? - Basis Change

Interaction Basis Parameters:
$\lambda_{1,\,2,\,3,\,4,\,5}$, $\lambda'_{1,\,2,\,4,\,5}$, $\lambda''_{1,3}$, m^2_{12}, m'^2_S, v_S, $\tan\beta$

$\lambda'_1=\lambda'_4$,
$\lambda'_2=\lambda'_5$

Mass Basis Parameters:
$m_{h1,\,h2,\,h3,\,A,\,AS,\,H\pm}$, c_{h1bb}, c_{h1tt}, m^2_{12}, m'^2_S, v_S, $\tan\beta$, alignm

$$v = \sqrt{v_1^2 + v_2^2}$$
$$\tan(\beta) = \frac{v_2}{v_1}$$

$$c_{h_1bb} = \frac{R_{11}}{\cos\beta}$$
$$c_{h_1tt} = \frac{R_{12}}{\sin\beta}$$

$$alignm = |\sin(\beta - (\alpha_1 + \alpha_3 \cdot \mathsf{sgn}(\alpha_2)))| \in [0.98, 1]$$

What is a 2HDMS? - Important Couplings

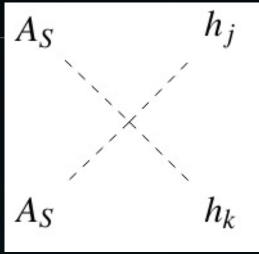
$$\lambda_{h_j h_k A_S A_S} = \frac{\partial^4 V}{\partial h_j \partial h_k \partial A_S \partial A_S}$$

$$= \frac{-i}{v v_S}\Big[-\Big(\frac{1}{3}\sum_{l=1}^{3} m_l^2 R_{l1} R_{l3}\Big)\frac{R_{j1}R_{k1}}{c_\beta} - \Big(\frac{1}{3}\sum_{l=1}^{3} m_l^2 R_{l2} R_{l3}\Big)\frac{R_{j2}R_{k2}}{s_\beta}$$

$$+ \Big[4m_S'^2 + 2m_{A_S}^2 + \frac{4v}{3v_S}\Big(\Big(\sum_{l=1}^{3} m_l^2 R_{l1} R_{l3}\Big)c_\beta + \Big(\sum_{l=1}^{3} m_l^2 R_{l2} R_{l3}\Big)s_\beta\Big)$$

$$+ \Big(\sum_{l=1}^{3} m_l^2 R_{l3}^2\Big)\Big]\frac{R_{j3}R_{k3}v}{v_S}\Big]$$

m_{h1}, m_{h2}, m_{h3}

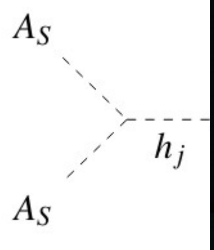


$$\frac{\lambda_{h_j A_S A_S}}{v} = \frac{1}{v}\frac{\partial^3 V}{\partial h_j \partial A_S \partial A_S}$$

$$= \frac{-i}{v v_S}\Big[-\Big(\frac{1}{3}\sum_{l=1}^{3} m_l^2 R_{l1} R_{l3}\Big)R_{j1} - \Big(\frac{1}{3}\sum_{l=1}^{3} m_l^2 R_{l2} R_{l3}\Big)R_{j2}$$

$$+ \Big[4m_S'^2 + 2m_{A_S}^2 + \frac{4v}{3v_S}\Big(\Big(\sum_{l=1}^{3} m_l^2 R_{l1} R_{l3}\Big)c_\beta + \Big(\sum_{l=1}^{3} m_l^2 R_{l2} R_{l3}\Big)s_\beta\Big)$$

$$+ \Big(\sum_{l=1}^{3} m_l^2 R_{l3}^2\Big)\Big]R_{j3}\Big]$$



What now?

- ✔ What is DM?
- ✔ What is a 2HDMS?

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- ✔ What is a 2HDMS?

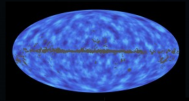
Can we explain DM in a 2HDMS?

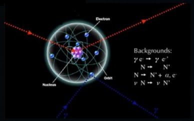
What now?

- What is DM?
- What is a 2HDMS?
- Find a viable benchmark (in accordance with 96 GeV excess at CMS + LEP)

arxiv: 2112.11958 by S. Heinemeyer, C. Li et al

- Calculate DM observables (relic density, direct detection cross section) + vary some parameters





SARAH
SPheno
micrOMEGAs

- Compare results to measurements from experiments

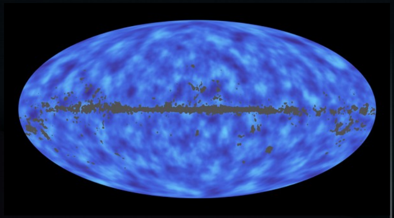
Planck, LUX-ZEPLIN

- (Extra: compare to model with v_S=0)

arxiv: 2203.05509 by J. Dutta et al

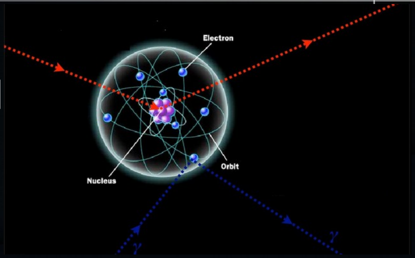
DM Observables

- Relic density (=amount of DM left in universe today)
- Planck constraint: $\Omega h^2 \approx 0.12$



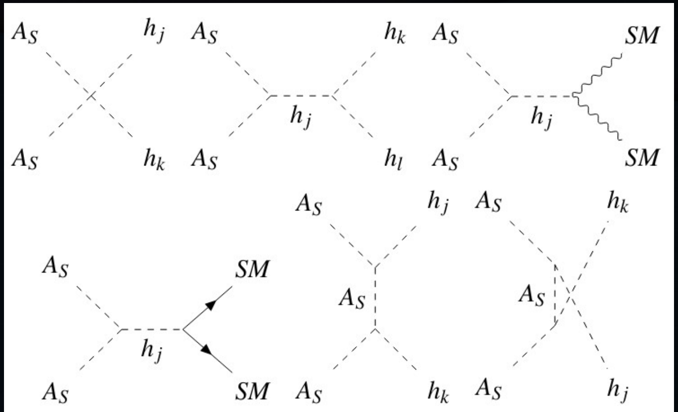
[https://www.nasa.gov]

- Direct detection CS (=elastic scattering of DM on nucleon)
- LUX-ZEPLIN (LZ) constraint depends on DM mass



[arXiv:1605.08788]

Contributing Diagrams:



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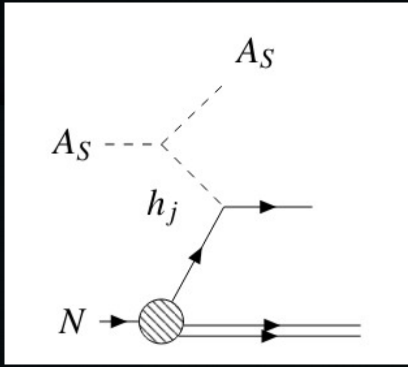
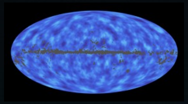


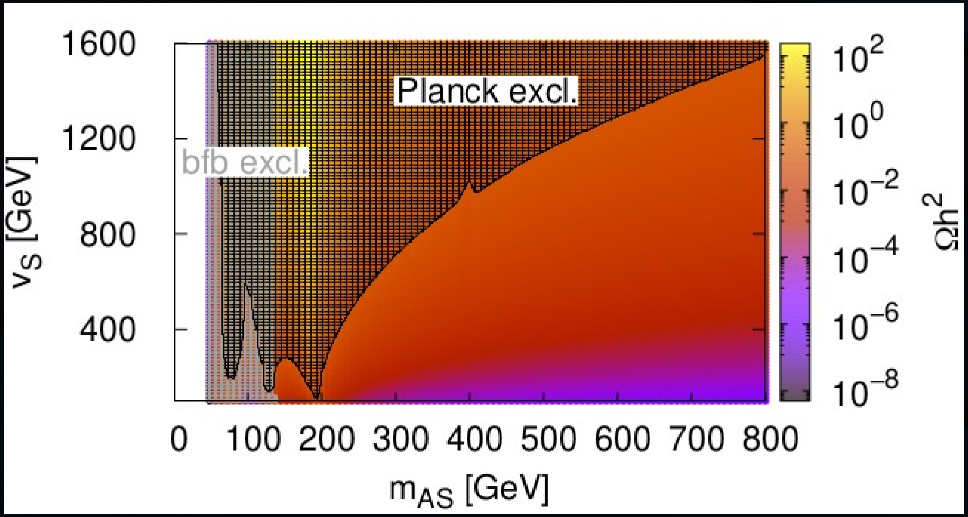
DM Observables

HiggsBounds HiggsSignals approved

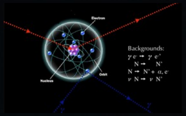
m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}	$m_{H^\pm}$	v_S
96 GeV	125.09 GeV	800 GeV	800 GeV	200 GeV	800 GeV	100 GeV
$\tan(\beta)$	$c_{h_1 bb}$	$c_{h_1 tt}$	m_{12}^2	$m_S'^2$	$alignm$	
10	0.05	0.27	$-1.01 \cdot 10^5\,\mathrm{GeV}^2$	$-1 \cdot 10^4\,\mathrm{GeV}^2$	1	

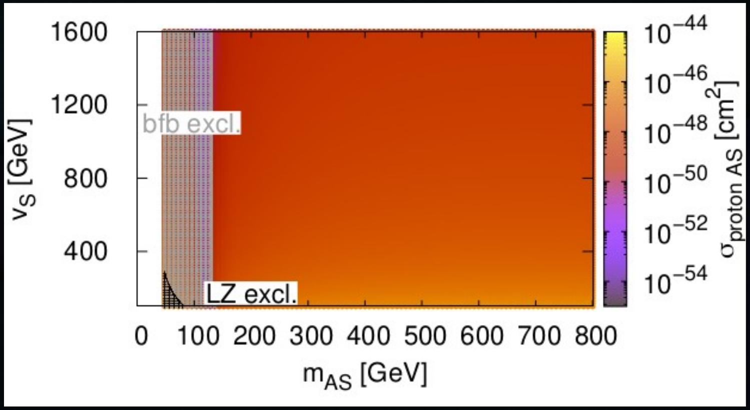
- **Relic density**

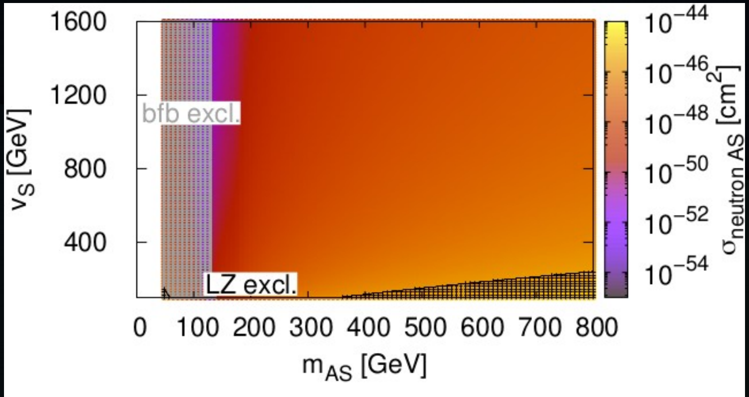




- **Direct detection CS**







DM Observables

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HiggsSignals
approved

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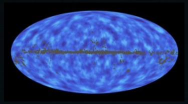
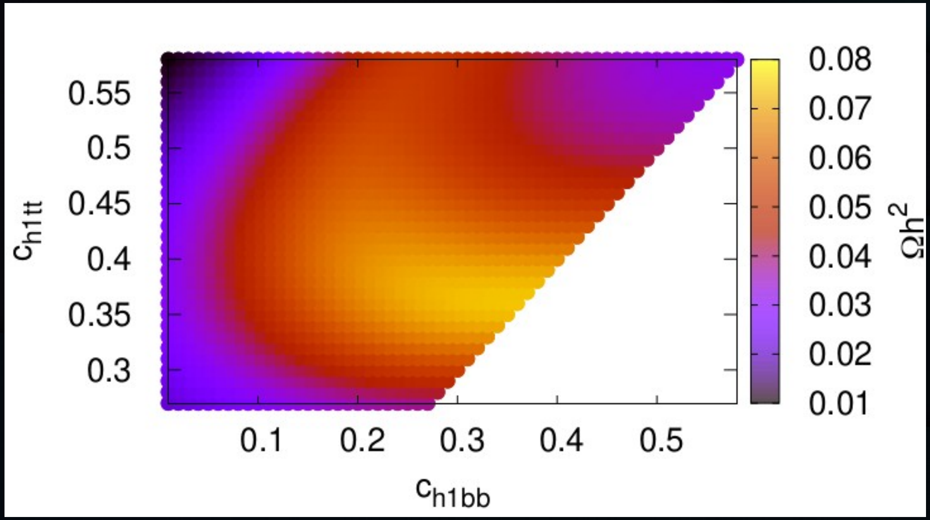
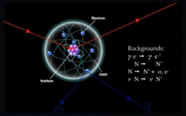
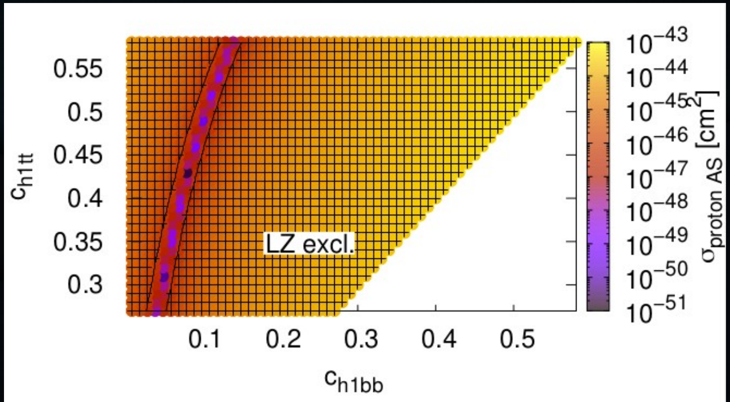


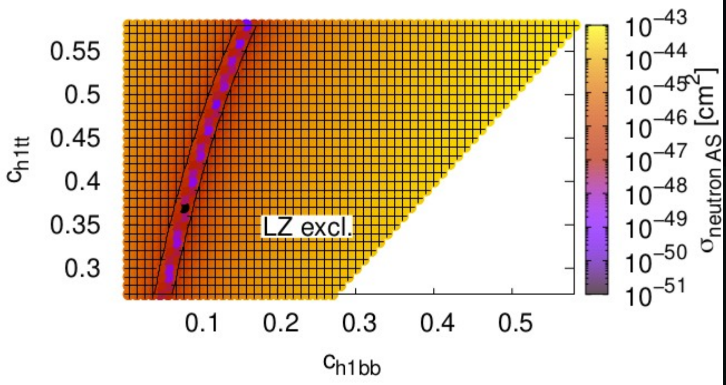


$$c_{h_1bb} = \frac{R_{11}}{\cos\beta} \qquad c_{h_1tt} = \frac{R_{12}}{\sin\beta} \qquad c_{h_iff} = \frac{g_{h_iff}}{g_{H_{\rm SM}ff}}$$

- **Direct detection CS**







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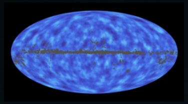

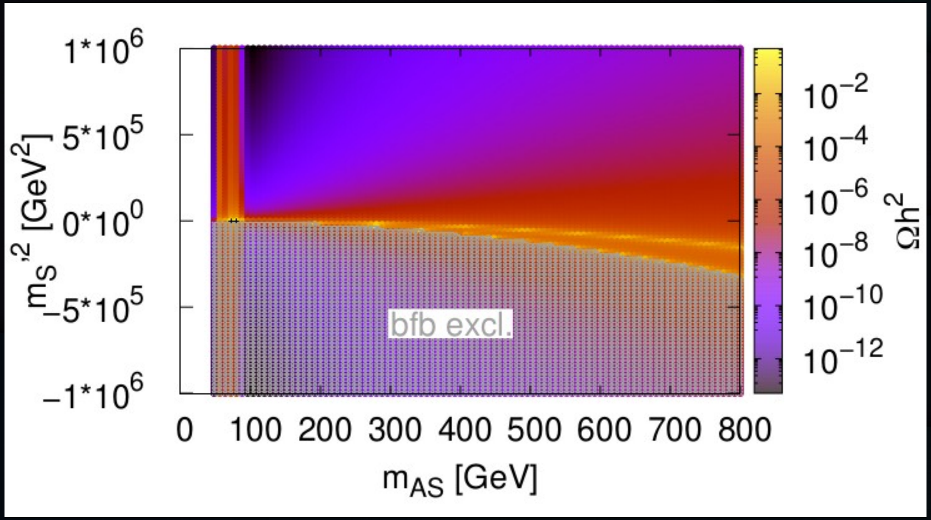

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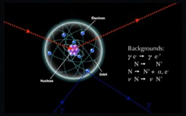

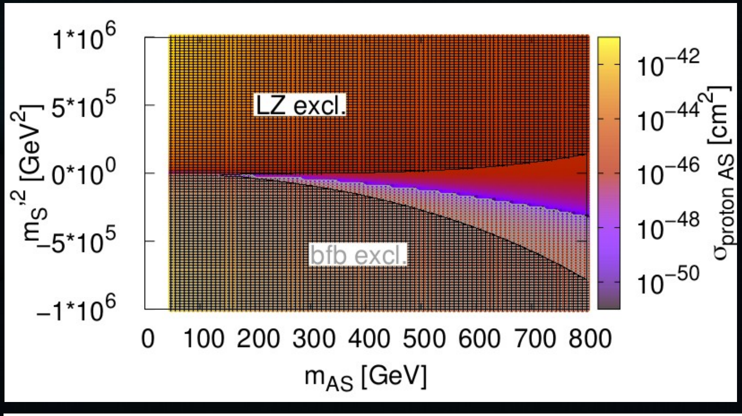

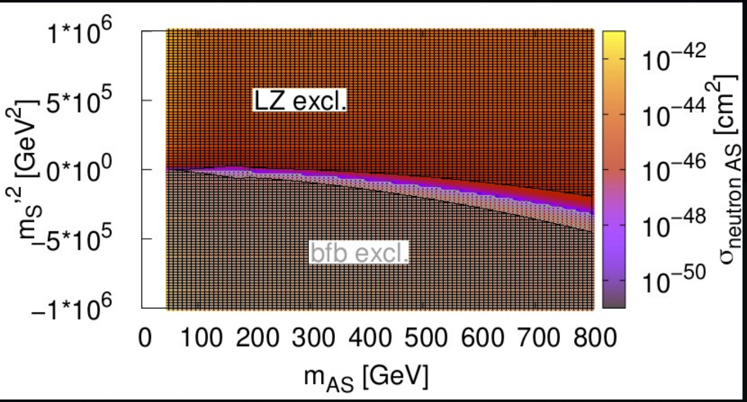

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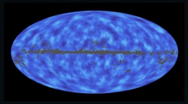

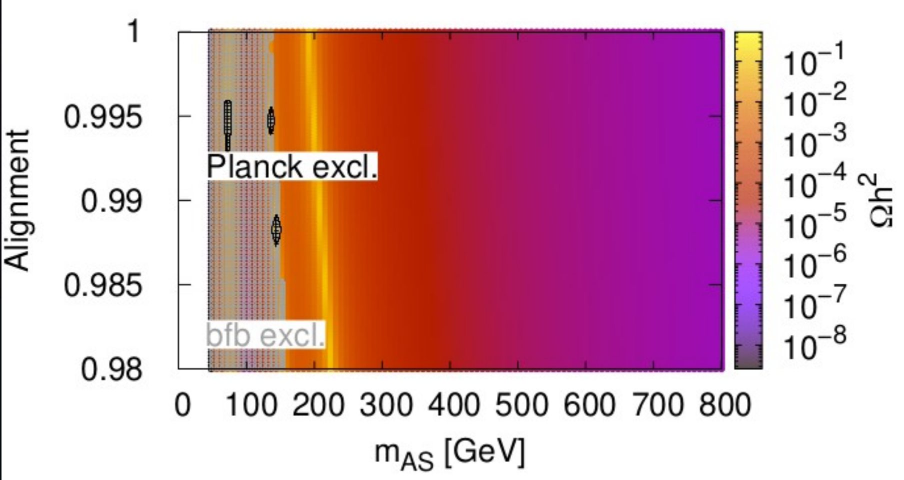

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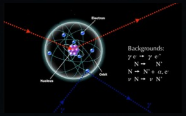
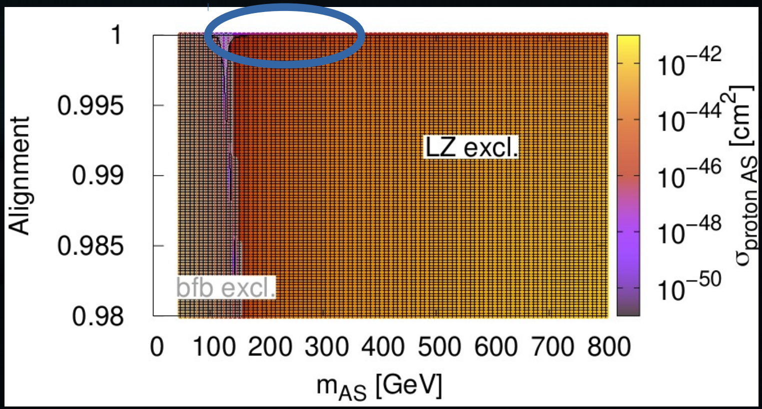
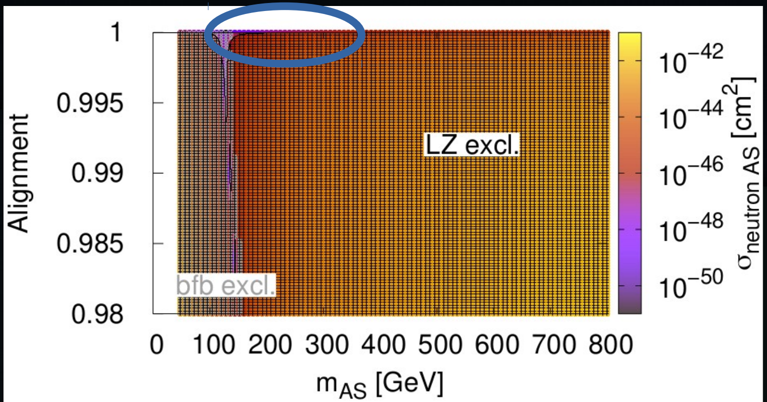
- **Direct detection CS**







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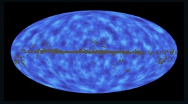

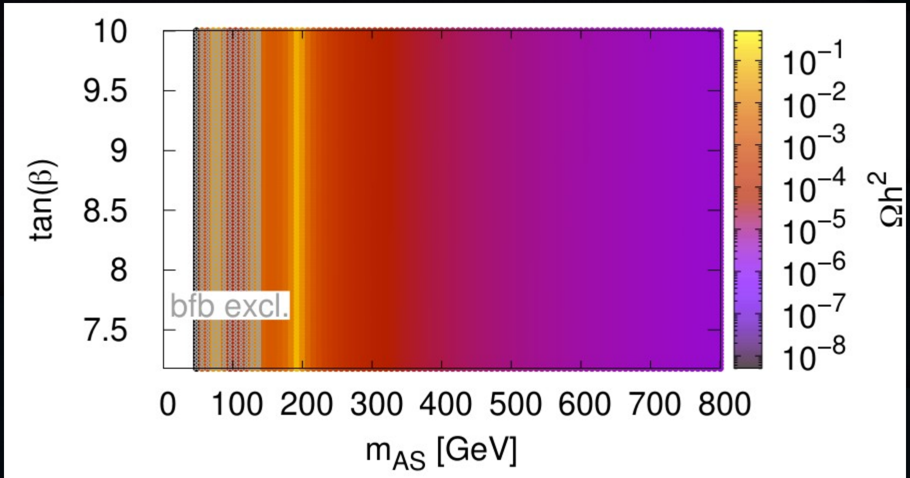

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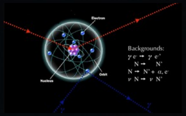

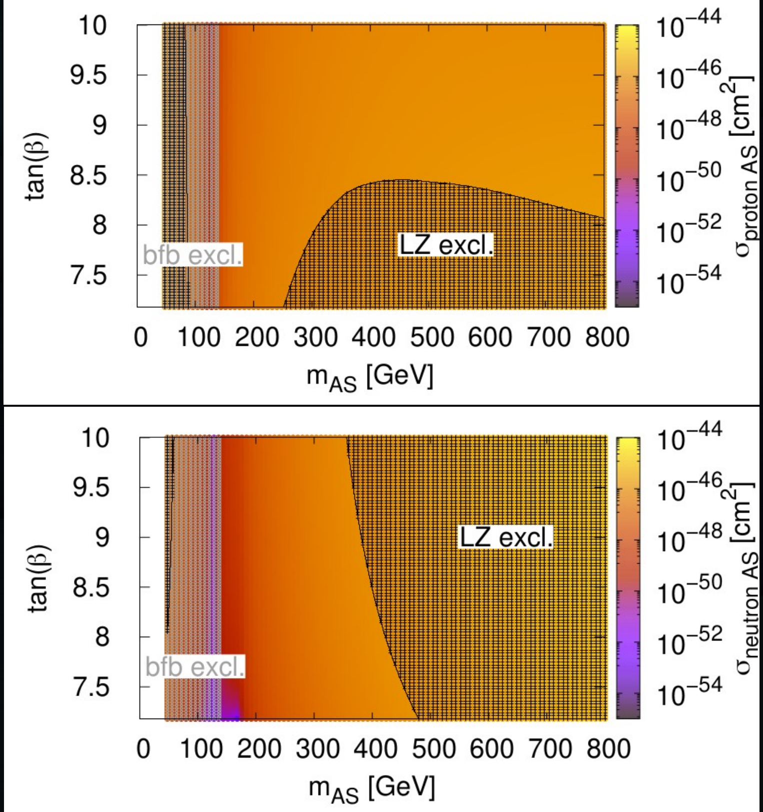

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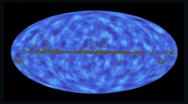
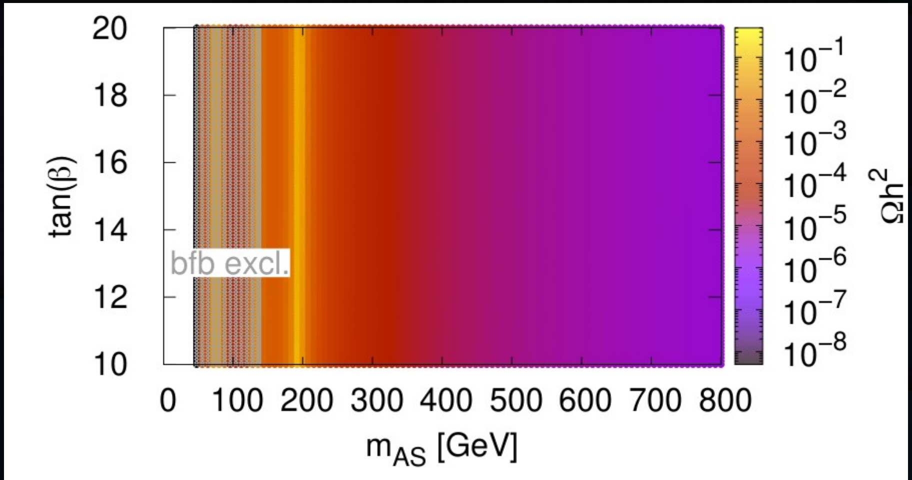
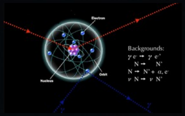
10	0.05	0.27	$-1.01 \cdot 10^5\ \mathrm{GeV}^2$	$-1 \cdot 10^4\ \mathrm{GeV}^2$	1	

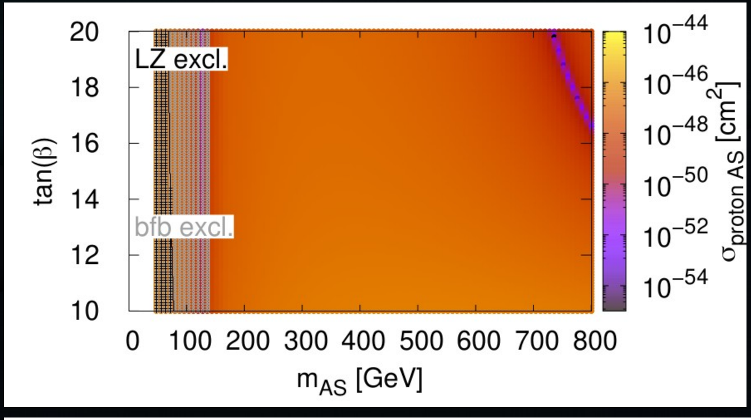
- **Relic density**

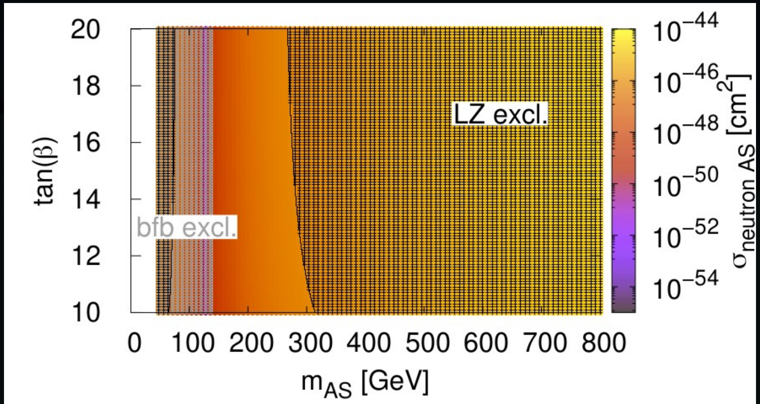




- **Direct detection CS**







What is a 2HDMS? - Wrap Up

DM candidate:	A_S (pseudo-scalar component of singlet S)
Number of free parameters:	13
Symmetries:	U(1) + all parameters real (not broken), Z_2 (spontaneously + softly broken), Z'_2 (spontaneously broken)
Higgs sector particles:	1 charged: $H^\pm$, 1 charged GB: $G^\pm$, 3 scalars: h_1, h_2, h_3, 1 pseudo-scalar: A, 1 pseudo-scalar GB: G^0, 1 pseudo-scalar DM: A_S
DM to scalar Higgs couplings parameters:	V_S, $\tan\beta$, m'^2_S, m^2_{AS}, c_{h1bb}, c_{h1tt}, alignm, $m^2_{h1,\,h2,\,h3}$

DM Observables – Wrap Up

m_{AS}:	Low and high values (130 GeV – 800 GeV) allowed
v_S:	Low and high values (100 GeV – 1500 GeV) allowed
c_{h1bb} - c_{h1tt}:	Strongly constrained
m'^2_S:	Strongly constrained
alignm:	Strongly constrained
tanβ:	High values (7 – 20) allowed (for m_{AS} between 130 GeV – 250 GeV)

Comparison with v_s=0

Comparison with v_S=0

	$v_S \neq 0$	$v_S = 0$
DM candidate:	A_S (pseudo-scalar component of singlet S) $m^2_{AS} = -(2m'^2_S + (2/3)\lambda''_1 v^2_S + 2(\lambda'_4 v^2_1 + \lambda'_5 v^2_2)$	$S=(1/\sqrt{2})(\rho_S+iA_S)$ $m^2_\chi = m^2_S + (1/2)(\lambda'_1 v^2_1 + \lambda'_2 v^2_2)$
Number of free parameters:	15	15
Symmetries:	U(1) + all parameters real (not broken), Z_2 (spontaneously + softly broken), Z'_2 (spontaneously broken)	U(1) + all parameters real (not broken), Z_2 (spontaneously + softly broken), Z'_2 (not broken)
Higgs sector particles:	1 charged: $H^\pm$, 1 charged GB: $G^\pm$, 3 scalars: h_1, h_2, h_3, 1 pseudo-scalar: A, 1 pseudo-scalar GB: G^0, 1 pseudo-scalar DM: A_S	1 charged: $H^\pm$, 1 charged GB: $G^\pm$, 2 scalars: h, H, 1 pseudo-scalar: A, 1 pseudo-scalar GB: G^0, 1 DM: S
DM to scalar Higgs couplings parameters:	$\lambda'_1, \lambda'_2, \lambda'_4, \lambda'_5, \lambda''_1, \lambda''_3$	$\lambda'_1, \lambda'_2, \lambda'_4, \lambda'_5$

Comparison with v_s=0, in Interaction Basis

m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}	$m_{H^\pm}$	v_S
86.1 GeV	125 GeV	724 GeV	724 GeV	470 GeV	728 GeV	10^{-4} GeV
$\tan(\beta)$	α_1	α_2	α_3	m_{12}^2	$m_S'^2$	
5	0.198	$\frac{\pi}{2}+10^{-9}$	10^{-9}	$1.01\cdot10^5$ GeV^2	$-1.18\cdot10^5$ GeV^2	

λ_1	λ_2	λ_3	λ_4	λ_5	$\tan\beta$	m_{12}^2	v_S
-0.902	0.259	17.2	-0.144	0.0460	5	$1.01\cdot10^5$ GeV^2	10^{-4} GeV
λ_1'	λ_2'	λ_3''	λ_4'	λ_5'	λ_1''	$m_S'^2$	
0.042	0.042	$5.56\cdot10^{11}$	0.1	0.1	$5.56\cdot10^{11}$	$-1.18\cdot10^5$ GeV^2	

m_h	m_H	m_A	m_χ	$m_{H^\pm}$	m_S
125 GeV	724 GeV	724 GeV	339 GeV	728 GeV	$1.13\cdot10^5$ GeV^2
$\tan(\beta)$	α	m_{12}^2	$m_S'^2$		
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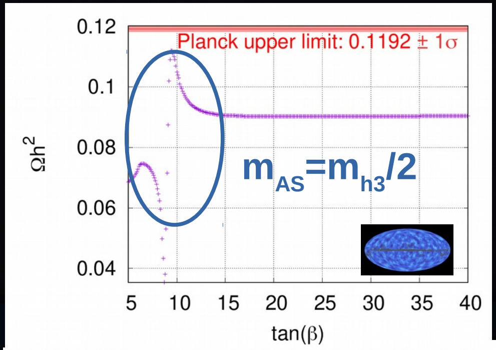
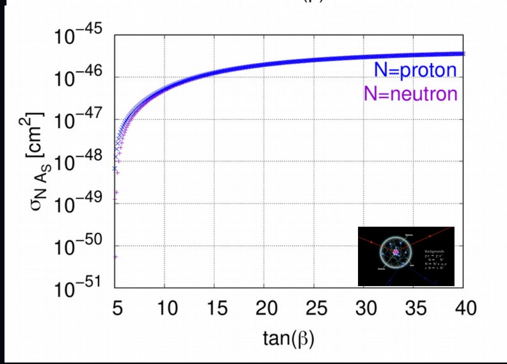
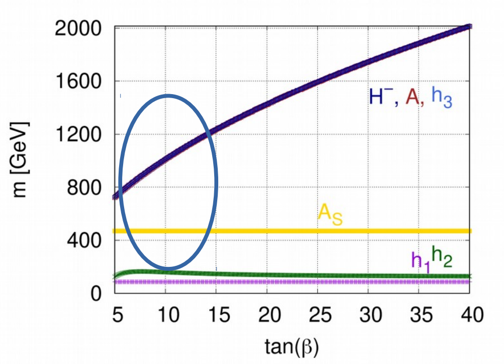
λ_1	λ_2	λ_3	λ_4	λ_5	$\tan\beta$	m_{12}^2	m_S
0.233	0.249	0.390	-0.167	0.001	5	$-1.01\cdot10^5$ GeV^2	$1.13\cdot10^5$ GeV^2
λ_1'	λ_2'	λ_3''	λ_4'	λ_5'	λ_1''	$m_S'^2$	
0.042	0.042	0.1	0.1	0.1	0.1	$1.13\cdot10^5$ GeV^2	

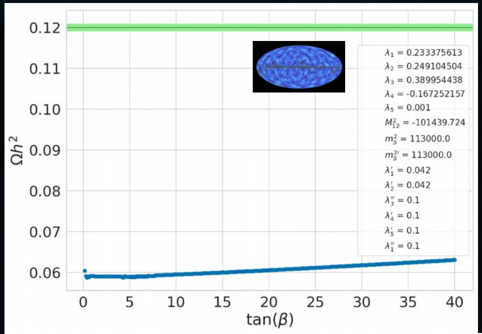
$v_s \neq 0$

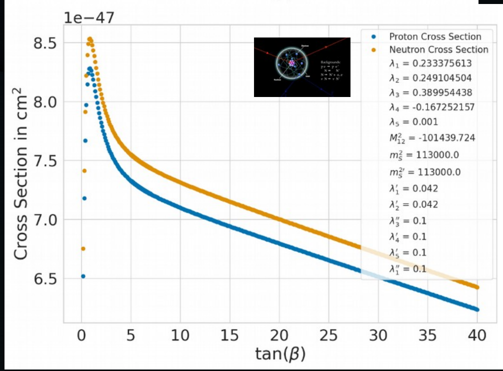
$v_s = 0$

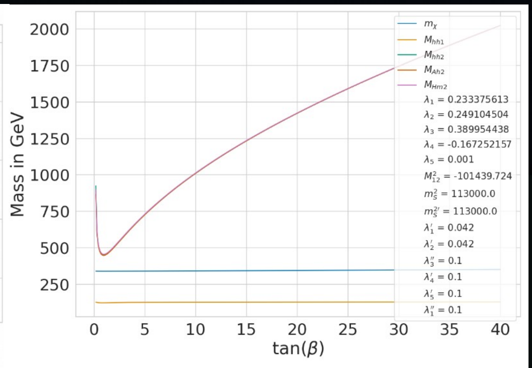












[Merle Schreiber, Master Thesis: Dark Matter Phenomenology in a Two Higgs Doublet Model with an Additional Complex Singlet]

Comparison with v_s=0, in Interaction Basis

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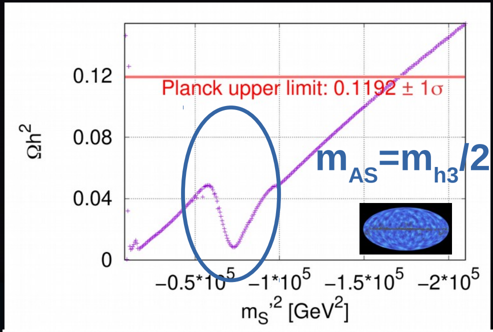
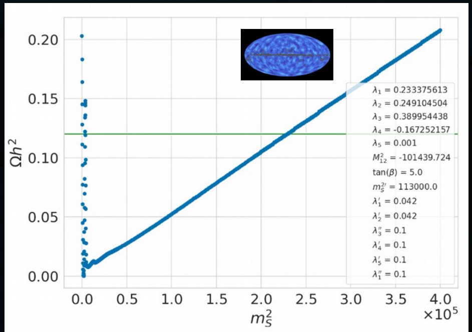
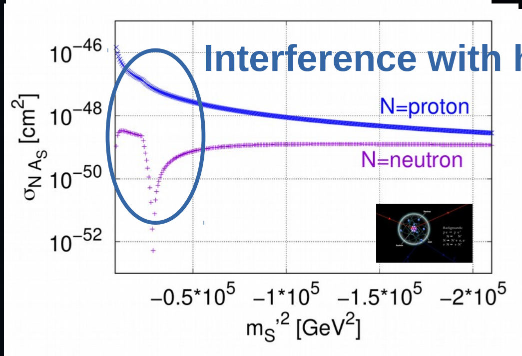
λ_1'	λ_2'	λ_3''	λ_4'	λ_5'	λ_1''	$m_S'^2$	
0.042	0.042	0.1	0.1	0.1	0.1	$1.13\cdot10^5$ GeV^2	

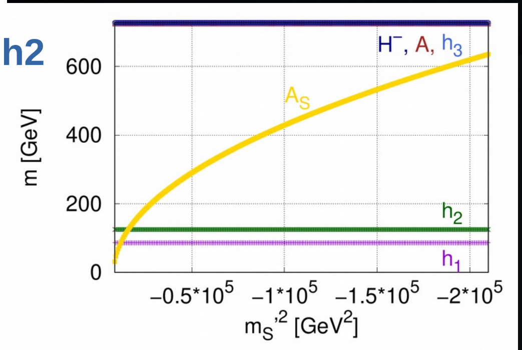


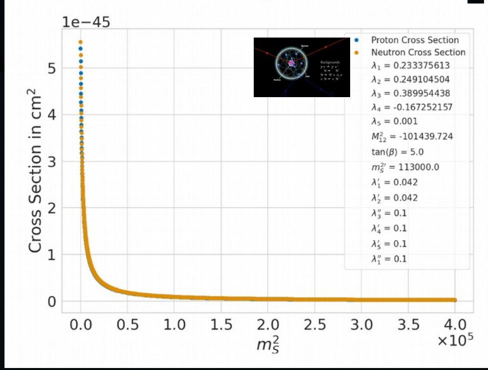
$v_s\neq0$

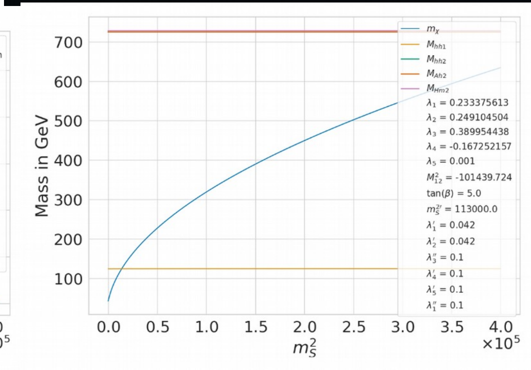
$v_s=0$











[Merle Schreiber, Master Thesis: Dark Matter Phenomenology in a Two Higgs Doublet Model with an Additional Complex Singlet]

SUMMARY

Done:

- **Pseudo-scalar A_S from 2HDMS as DM candidate**
- **Derived masses and DM couplings from potential**
- **Found viable benchmark + scanned some parameter regions + calculated relic density and direct detection CS**
- **Compared to experiments + included bfb constraints**
- **Compared to model with v_S=0**

To Do:

- **Find ‘better’ benchmark (do full scan)**
- **Include constraints from tree-level perturbative unitarity**
- **Include future collider prospects + collider signals**

SUMMARY

Done:

- **Pseudo-scalar A_S from 2HDMS as DM candidate**
- **Derived masses and DM couplings from potential**
- **Found viable b** [redacted]

[redacted] **ompared to experiments + included bfb constraints**

- **Compared to model with v_S=0**

To Do:

- **Find 'better' benchmark (do full scan)**
- **Include constrain** [redacted] **ee-** [redacted] **ects** [redacted]

Can we explain DM in a 2HDMS?

SUMMARY

Done:

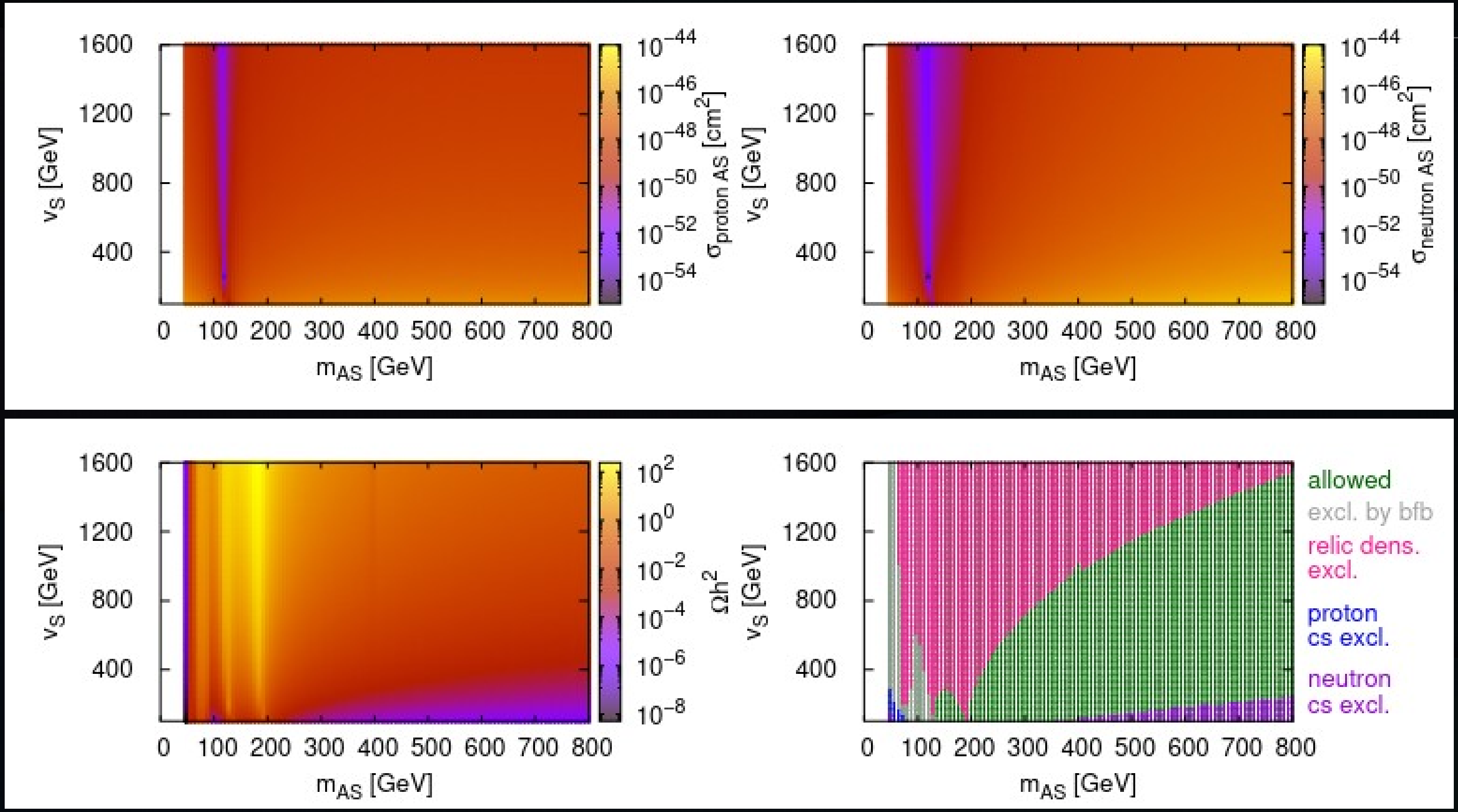
- **Pseudo-scalar A_S from 2HDMS as DM candidate**
- **Derived masses and DM couplings from potential**
- **Found viab** [redacted]
- [redacted] **ompared to experiments + included bfb constraints**
- **Compared to model with v_S=0**

To Do:

- **Find 'better' benchmark (do full scan)**
- **Include constrai** [redacted] **e-** [redacted] **ects** [redacted]

Can we explain DM in a 2HDMS?

Backup, Plots w/o Constraints



CS:

- Grows with m_{AS}
- Falls with v_s

Peaks and dips:

- Dip at $m_{AS}=m_{h2}$: interference effect

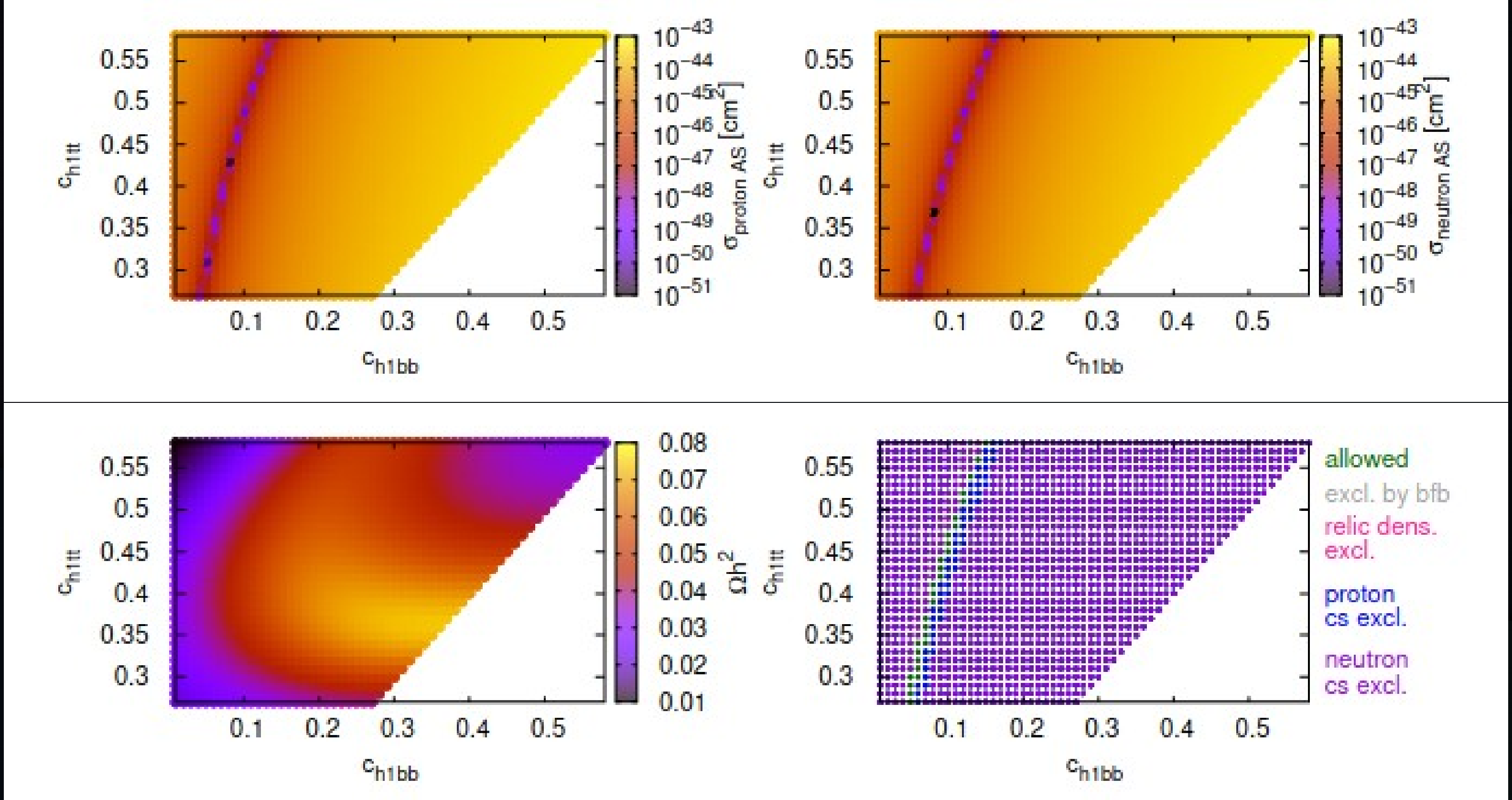
Relic:

- Falls with m_{AS}
- Grows with v_s

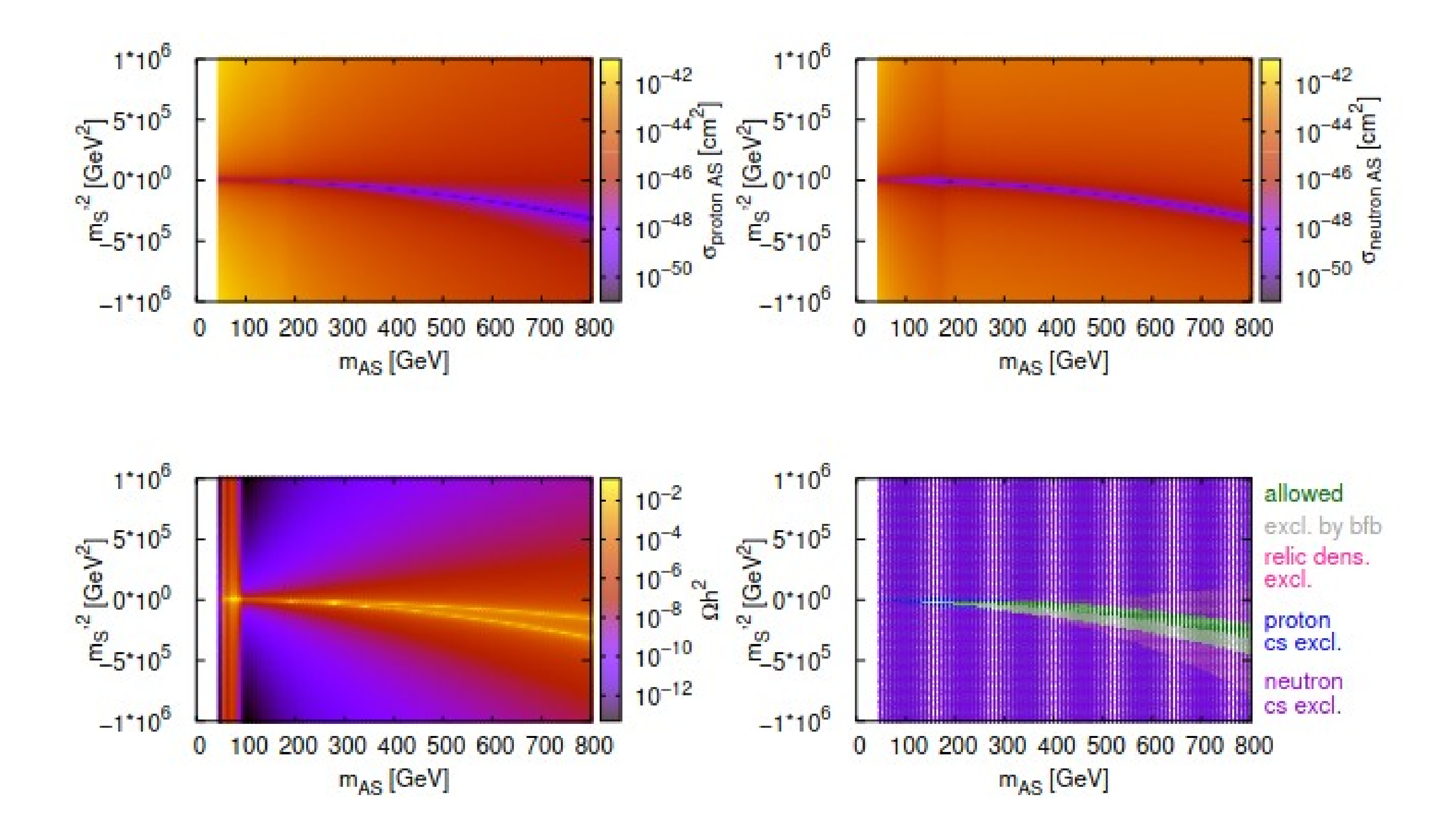
Peaks and Dips:

- Dip at $m_{AS}=m_{h2}/2$: resonant annihilation AS AS → h2
- Dip at $m_{AS}=m_{h1}$: AS AS → h1 h1 opens up
- Peak at m_{AS}=131 GeV: minimum in couplings
- Peak at m_{AS}=194 GeV: interference with scalars
- Dip at $m_{AS}=m_{h3}/2$: resonant annihilation AS AS → h3

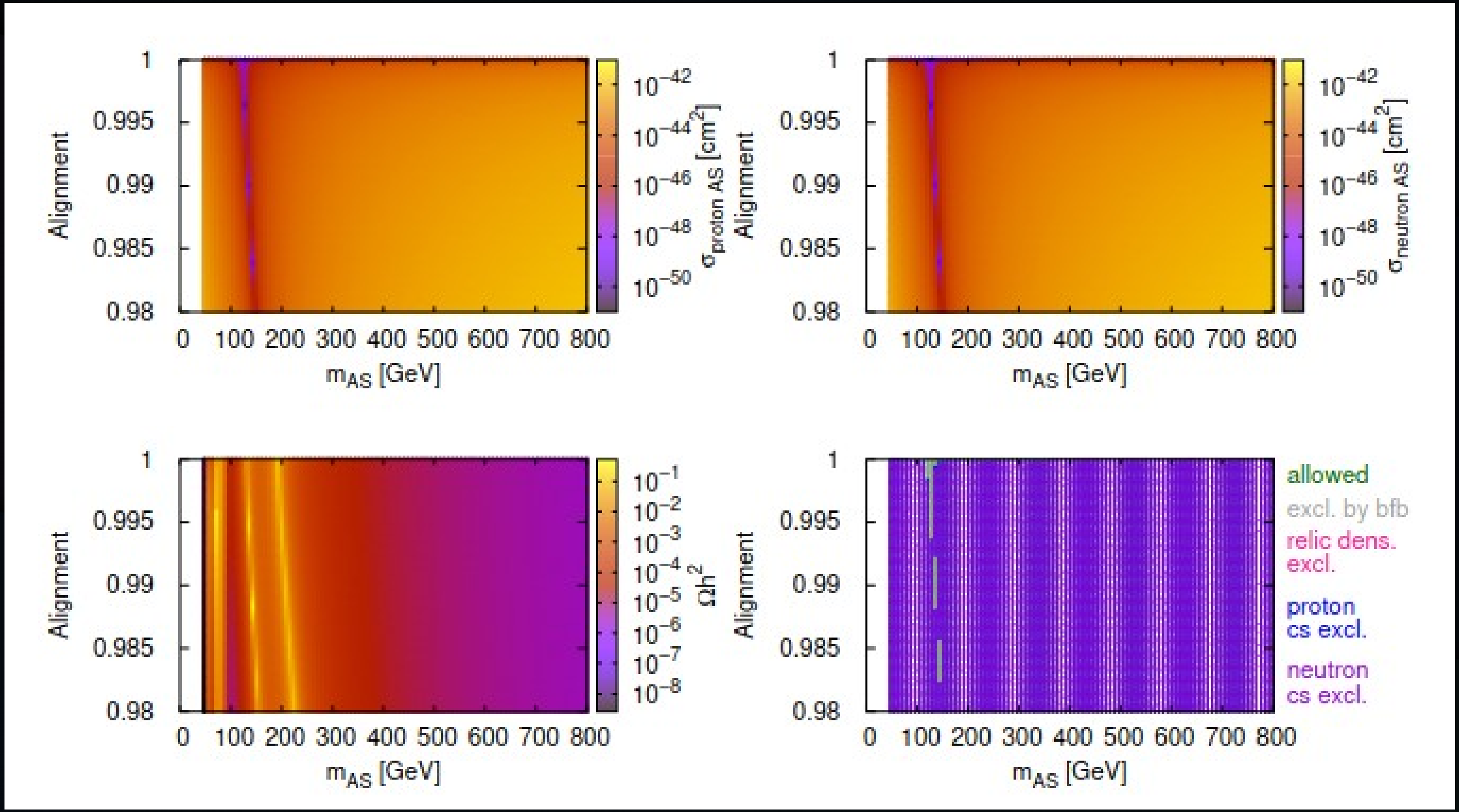
Backup, Plots w/o Constraints



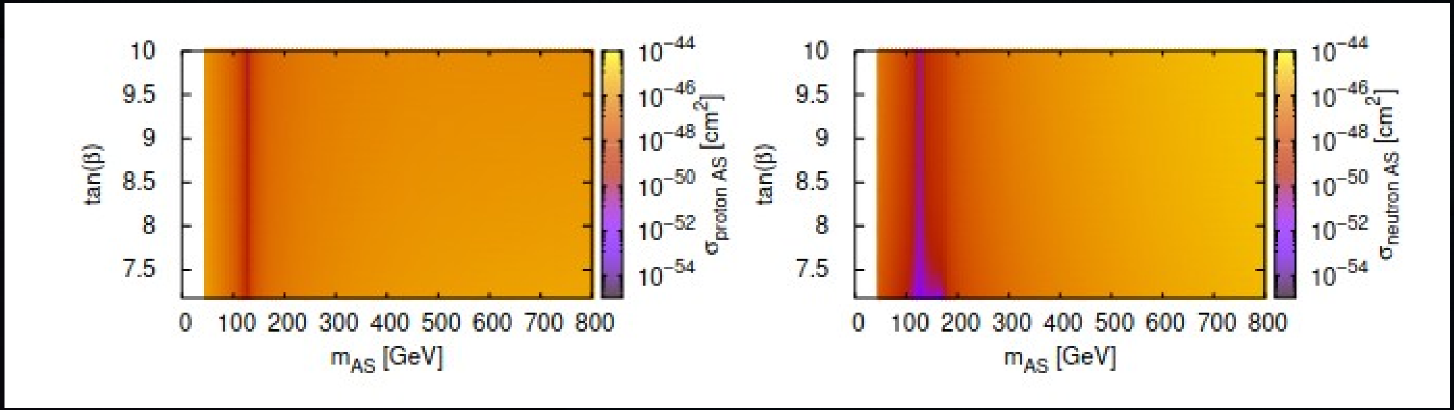
Backup, Plots w/o Constraints

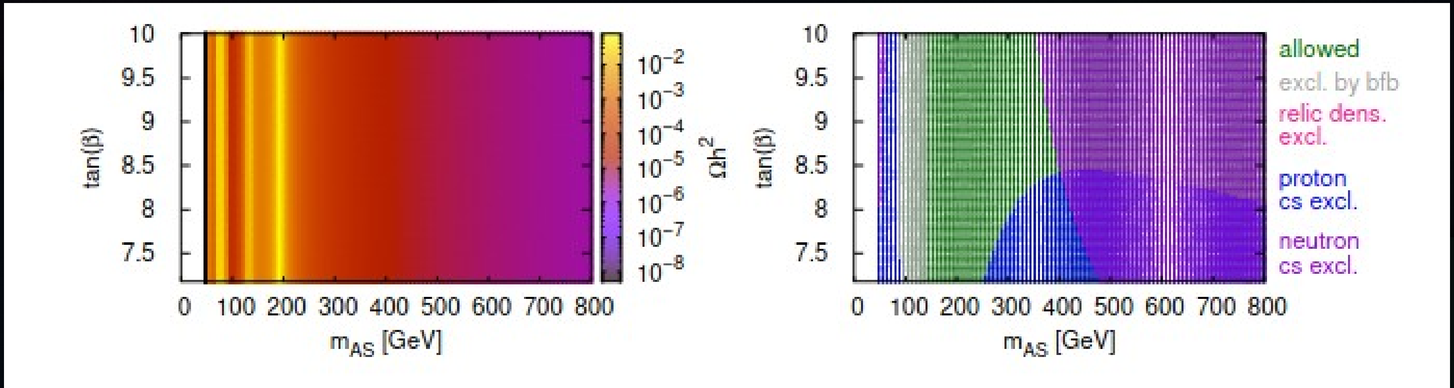


Backup, Plots w/o Constraints

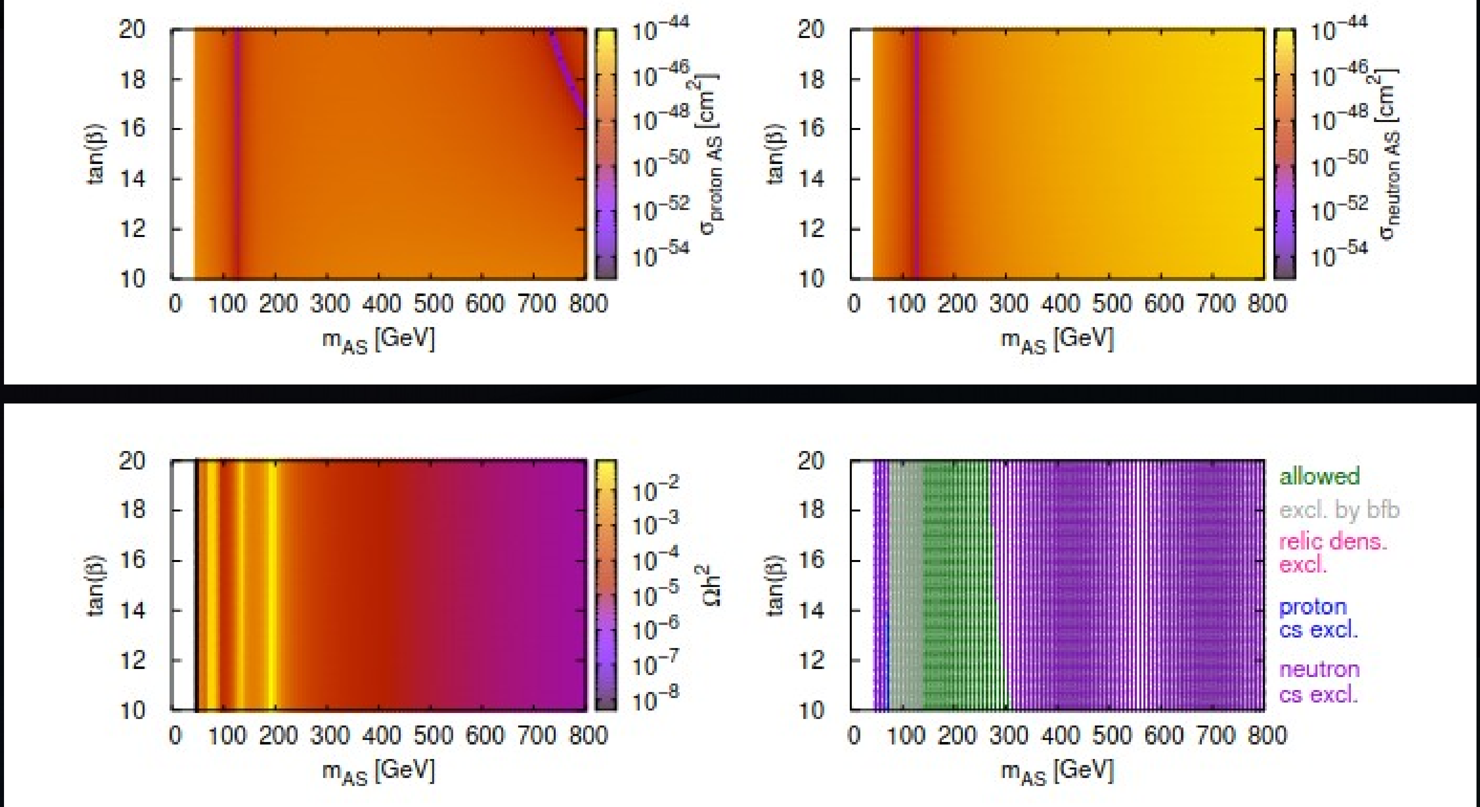


Backup, Plots w/o Constraints





Backup, Plots w/o Constraints



Backup, DM Couplings in Interaction Basis

$$\lambda_{h_j h_k A_S A_S} = \frac{\partial^4 V}{\partial h_j \partial h_k \partial A_S \partial A_S}$$
$$= -i[(\lambda_1' - 2\lambda_4')R_{j1}R_{k1} + (\lambda_2' - 2\lambda_5')R_{j2}R_{k2} - \frac{1}{2}(\lambda_1'' - \lambda_3'')R_{j3}R_{k3}]$$
$$\frac{\lambda_{h_j A_S A_S}}{v} = \frac{1}{v}\frac{\partial^3 V}{\partial h_j \partial A_S \partial A_S}$$
$$= -i[(\lambda_1' - 2\lambda_4')c_\beta R_{j1} + (\lambda_2' - 2\lambda_5')s_\beta R_{j2} - \frac{v_S}{2v}(\lambda_1'' - \lambda_3'')R_{j3}],$$

Backup, Mass Eigenvalues

Charged Block:

$$[M^2_{\text{charged}}]_{ij} = \frac{\partial^2 V}{\partial \phi_i^+ \partial \phi_j^-}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle, \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}} \quad i,i = 1,2$$

$$[M^2_{\text{charged}}] = [\frac{m_{12}^2}{v_1 v_2} - \frac{1}{2}(\lambda_4 + \lambda_5)] \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix}$$

Mass eigenvalues after diagonalisation:

$$m^2_{H^\pm} = [\frac{m_{12}^2}{v_1 v_2} - \frac{1}{2}(\lambda_4 + \lambda_5)](v_1^2 + v_2^2)$$

$$m^2_{G^\pm} = 0$$

Pseudo-Scalar Block:

$$[M^2_{\text{pseudo}}]_{ij} = \frac{\partial^2 V}{\partial \eta_i^\dagger \partial \eta_j}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle, \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}} \quad i,j = 1,2$$

$$[M^2_{\text{pseudo}}] = [\frac{m_{12}^2}{v_1 v_2} - \lambda_5] \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix}$$

Mass eigenvalues after diagonalisation:

$$m^2_A = [\frac{m_{12}^2}{v_1 v_2} - \lambda_5](v_1^2 + v_2^2)$$

$$m^2_{G^0} = 0$$

Backup, Mass Eigenvalues

Scalar Block:

$$[M^2_{\text{scalar}}]_{ij} = \frac{\partial^2 V}{\partial \rho_i^\dagger \partial \rho_j}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle,\\ \Phi_2=\langle\Phi_2\rangle\\ S=\langle S\rangle}} \qquad i,j = 1,2,S$$

$$[M^2_{\text{scalar}}] = \begin{pmatrix} m_{12}^2\frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 & (\lambda_1' + 2\lambda_4')v_1 v_S \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2\frac{v_1}{v_2} + \lambda_2 v_2^2 & (\lambda_2' + 2\lambda_5')v_2 v_S \\ (\lambda_1' + 2\lambda_4')v_1 v_S & (\lambda_2' + 2\lambda_5')v_2 v_S & (\frac{\lambda_1''}{6} + \frac{2\lambda_1''}{3} + \frac{\lambda_3''}{2})v_S^2 \end{pmatrix}$$

Where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$.

Mass eigenvalues after diagonalisation:

$$m^2_{h_1} = \dots$$
$$m^2_{h_2} = \dots$$
$$m^2_{h_3} = \dots$$

Dark Matter Block:

$$[M^2_{\text{DM}}] = \frac{\partial^2 V}{\partial A_S^\dagger \partial A_S}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle\\ \Phi_2=\langle\Phi_2\rangle\\ S=\langle S\rangle}}$$
$$= -(2m_S'^2 + v_S^2(\frac{\lambda_1''}{3} + \frac{\lambda_1''}{3}) + 2(\lambda_4' v_1^2 + \lambda_5' v_2^2))$$

Mass eigenvalue:

$$m^2_{A_S} = -(2m_S'^2 + v_S^2(\frac{\lambda_1''}{3} + \frac{\lambda_1''}{3}) + 2(\lambda_4' v_1^2 + \lambda_5' v_2^2))$$

Backup, Bounded from Below

$$
\begin{aligned}
V_4 = {} & \frac{\lambda_1}{2}(|\Phi_1|^2)^2 + \frac{\lambda_2}{2}(|\Phi_2|^2)^2 + \lambda_3(|\Phi_1|^2)(|\Phi_2|^2) + \lambda_4\rho^2(|\Phi_1|^2)(|\Phi_2|^2) \\
& + \frac{|\lambda_5|}{2}\rho^2(|\Phi_1|^2)(|\Phi_2|^2)\underbrace{[e^{i\varphi_{\lambda_5}}e^{2i\varphi} + e^{-i\varphi_{\lambda_5}}e^{-2i\varphi}]}_{2\cos(\varphi_{\lambda_5}+2\varphi)} \\
& + \frac{|\lambda_1''|}{24}(|S|^2)^2(\underbrace{[e^{i\varphi_{\lambda_1''}}e^{4i\varphi_S} + e^{-i\varphi_{\lambda_1''}}e^{-4i\varphi_S}]}_{2\cos(\varphi_{\lambda_1''}+4\varphi_S)} + 4\underbrace{[e^{i\varphi_{\lambda_1''}}e^{2i\varphi_S} + e^{-i\varphi_{\lambda_1''}}e^{-2i\varphi_S}]}_{2\cos(\varphi_{\lambda_1''}+2\varphi_S)}) \\
& + \frac{\lambda_3''}{4}(|S|^2)^2 + [\lambda_1'(|\Phi_1|^2) + \lambda_2'(|\Phi_2|^2)](|S|^2) \\
& + |\lambda_4'|(|S|^2)(|\Phi_1|^2)\underbrace{[e^{i\varphi_{\lambda_4'}}e^{2i\varphi_S} + e^{-i\varphi_{\lambda_4'}}e^{-2i\varphi_S}]}_{2\cos(\varphi_{\lambda_4'}+2\varphi_S)} \\
& + |\lambda_5'|(|S|^2)(|\Phi_2|^2)\underbrace{[e^{i\varphi_{\lambda_5'}}e^{2i\varphi_S} + e^{-i\varphi_{\lambda_5'}}e^{-2i\varphi_S}]}_{2\cos(\varphi_{\lambda_5'}+2\varphi_S)}.
\end{aligned}
\tag{A.28}
$$

Using that $\min[\cos(\alpha)] = -1$[21], we can find the minimum of the potential and write it in the basis $B = \begin{pmatrix} |\Phi_1|^2 & |\Phi_2|^2 & |S|^2 \end{pmatrix}^T$:

$$
\min[V_4] = B^T \frac{1}{2} \cdot \begin{pmatrix} \lambda_1 & \lambda_3 + \rho^2(\lambda_4 - |\lambda_5|) & \lambda_1' - 2|\lambda_4'| \\ \lambda_3 + \rho^2(\lambda_4 - |\lambda_5|) & \lambda_2 & \lambda_2' - 2|\lambda_5'| \\ \lambda_1' - 2|\lambda_4'| & \lambda_2' - 2|\lambda_5'| & \frac{\lambda_3''}{2} - \frac{5|\lambda_1''|}{6} \end{pmatrix} B. \tag{A.29}
$$

The potential V (Equation 2.1a) is bounded from below, if the matrix in Equation A.29 is copositive: A matrix M is strictly copositive, if the form $x^T M x > 0 \quad \forall x > 0$. In our case $x = B > 0$, which is positive since it contains only squares of absolute values of fields.

Backup, Bounded from Below

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \frac{\lambda_3''}{2} - \frac{5|\lambda_1''|}{6} > 0$$

$$\bar{\lambda}_{12} = \lambda_3 + \rho^2(\lambda_4 - |\lambda_5|) + \sqrt{\lambda_1 \cdot \lambda_2} > 0$$

$$\bar{\lambda}_{13} = \lambda_1' - 2|\lambda_4'| + \sqrt{\lambda_1 \cdot (\frac{\lambda_3''}{2} - \frac{5|\lambda_1''|}{6})} > 0$$

$$\bar{\lambda}_{23} = \lambda_2' - 2|\lambda_5'| + \sqrt{\lambda_2 \cdot (\frac{\lambda_3''}{2} - \frac{5|\lambda_1''|}{6})} > 0$$

$$\sqrt{\lambda_1 \cdot \lambda_2 \cdot (\frac{\lambda_3''}{2} - \frac{5|\lambda_1''|}{6})} + [\lambda_3 + \rho^2(\lambda_4 - |\lambda_5|)] \cdot \sqrt{\frac{\lambda_3''}{2} - \frac{5|\lambda_1''|}{6}}$$

$$+ [\lambda_1' - 2|\lambda_4'|] \cdot \sqrt{\lambda_2} + [\lambda_2' - 2|\lambda_5'|]\sqrt{\lambda_1} + \sqrt{2\bar{\lambda}_{12}\bar{\lambda}_{13}\bar{\lambda}_{23}} > 0.$$

Where we distinguish two cases:

$$\text{Case 1:} \; (\lambda_4 - |\lambda_5|) \geq 0 \quad \Rightarrow \quad \min[V_4] = V_4|_{\rho=0}$$

$$\text{Case 2:} \; (\lambda_4 - |\lambda_5|) < 0 \quad \Rightarrow \quad \min[V_4] = V_4|_{\rho=1}$$

Backup, Scan Range Constraints

Alignment limit

arxiv: 2112.11958
by S. Heinemeyer,
C. Li et al

$$m_{h_1} \in \{95,\ 98\}\ \text{GeV}, \qquad m_{h_2} = 125.09\ \text{GeV}, \qquad m_{a_1} \in \{200,\ 500\}\ \text{GeV},$$
$$|\sin(\beta - (\alpha_1 + \text{sgn}(\alpha_2)\alpha_3))| \in \{0.98, 1\} \qquad \alpha_4 \in \{\frac{\pi}{4},\ \frac{\pi}{2}\}, \qquad v_S \in \{100,\ 2000\}\ \text{GeV},$$
$$\frac{\tan\beta}{\tan\alpha_1} \in \{0, 1\}, \qquad \alpha_2 \in \pm\{0.95,\ 1.3\}\ . \tag{49}$$

Make signal at CMS and LEP not too suppressed

What is a 2HDMS? - Symmetries

- **2HDM potential symmetric under U(1)**
- **All parameters real**

$$\Phi_i \xrightarrow{U(1)} e^{i\theta}\Phi_i$$
$$\Phi_i^\dagger \xrightarrow{U(1)} e^{-i\theta}\Phi_i^\dagger$$

- **Potential symmetric under CP**

$$\Phi_i(t,x) \xrightarrow{P} \eta_P \Phi_i(t,-x)$$
$$\Phi_i(t,x) \xrightarrow{C} \eta_C \Phi_i^\dagger(t,x)$$
$$\Phi_i(t,x) \xrightarrow{CP} \eta_C \eta_P \Phi_i^\dagger(t,-x)$$

What is a 2HDMS? - Symmetries

- Potential symmetric under Z_2
- Spontaneously broken by doublet vevs
- (softly broken by m_{12}-term → to avoid domain walls)

$$\Phi_1 \xrightarrow{Z_2} -\Phi_1$$
$$\Phi_2 \xrightarrow{Z_2} \Phi_2$$
$$S \xrightarrow{Z_2} S$$

$$d_{jR} \xrightarrow{Z_2} -d_{jR}$$
$$e_{jR} \xrightarrow{Z_2} -e_{jR}$$
$$u_{jR} \xrightarrow{Z_2} u_{jR}$$

- Each doublet couples only to one type of fermions → FCNC are avoided
- In Type II:
- Φ_1 couples to down-type, leptons
- Φ_2 couples to up-type

$$V_{\text{Yukawa}} = -(y^1_{ij}\bar{Q}_{iL}\Phi_1 d_{jR} + y^2_{ij}\bar{Q}_{iL}\bar{\Phi}_2 u_{jR} + y^5_{ij}\bar{L}_{iL}\Phi_1 e_{jR})$$

What is a 2HDMS? - Symmetries

- **Potential symmetric under Z'_2**
- **Spontaneously broken by singlet vev**

$$\Phi_1 \xrightarrow{Z'_2} \Phi_1$$

$$\Phi_2 \xrightarrow{Z'_2} \Phi_2$$

$$S \xrightarrow{Z'_2} -S$$

- **S only appears in even powers in the potential → no decaying of DM → DM is stable**

What is a 2HDMS? - Particle Content

Mass squared matrix:

$$[M^2]_{ij} = \frac{\partial^2 V}{\partial \varphi_i^\dagger \partial \varphi_j}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}}$$

$$\varphi_i = \phi_i^+, \rho_i, \eta_i, \rho_S, A_S$$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix}$$

$$S = \frac{1}{\sqrt{2}}(v_S + \rho_S + iA_S)$$

$$[M^2] = \begin{pmatrix} [M^2_{\text{charged}}] & 0 & 0 & 0 \\ 0 & [M^2_{\text{scalar}}] & 0 & 0 \\ 0 & 0 & [M^2_{\text{pseudo}}] & 0 \\ 0 & 0 & 0 & [M^2_{A_S}] \end{pmatrix}$$

$$\text{diag}(m^2_{H^\pm}, m^2_{G^\pm}) = R^\pm M^2_{\text{charged}} R^{\pm T}, \qquad \begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = R^\pm \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$\text{diag}(m^2_{h_1}, m^2_{h_2}, m^2_{h_3}) = R M^2_{\text{scalar}} R^T, \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

$$\text{diag}(m^2_A, m^2_{G^0}) = R^A M^2_{\text{pseudo}} R^{AT}, \qquad \begin{pmatrix} A \\ G^0 \end{pmatrix} = R^A \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$\text{diag}(m^2_{A_S}) = M^2_{A_S}, \qquad \begin{pmatrix} A_S \end{pmatrix} = \begin{pmatrix} A_S \end{pmatrix}$$

What is a 2HDMS? - Particle Content

Rotation matrices:

$$R^{\pm}(\beta) = \begin{pmatrix} -s_\beta & c_\beta \\ c_\beta & s_\beta \end{pmatrix}$$

$$R(\alpha_1,\alpha_2,\alpha_3) = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1}c_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ s_{\alpha_1}s_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} & -c_{\alpha_1}s_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}c_{\alpha_3} & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}$$

$$R^{A}(\beta) = \begin{pmatrix} -s_\beta & c_\beta \\ c_\beta & s_\beta \end{pmatrix}$$

$$\mathrm{diag}(m^2_{H^\pm}, m^2_{G^\pm}) = R^{\pm} M^2_{\mathrm{charged}} R^{\pm T}, \qquad \begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = R^{\pm} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$\mathrm{diag}(m^2_{h_1}, m^2_{h_2}, m^2_{h_3}) = R M^2_{\mathrm{scalar}} R^{T}, \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

$$\mathrm{diag}(m^2_{A}, m^2_{G^0}) = R^{A} M^2_{\mathrm{pseudo}} R^{AT}, \qquad \begin{pmatrix} A \\ G^0 \end{pmatrix} = R^{A} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$\mathrm{diag}(m^2_{A_S}) = M^2_{A_S}, \qquad \begin{pmatrix} A_S \end{pmatrix} = \begin{pmatrix} A_S \end{pmatrix}$$

Minimisation conditions:

$$0 = \frac{\partial V}{\partial \Phi_1}\Big|_{\Phi_i=\langle\Phi_i\rangle, S=\langle S\rangle}$$

$$0 = \frac{\partial V}{\partial \Phi_2}\Big|_{\Phi_i=\langle\Phi_i\rangle, S=\langle S\rangle}$$

$$0 = \frac{\partial V}{\partial S}\Big|_{\Phi_i=\langle\Phi_i\rangle, S=\langle S\rangle}$$

⇒ eliminate m_{11}, m_{22}, m_S