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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

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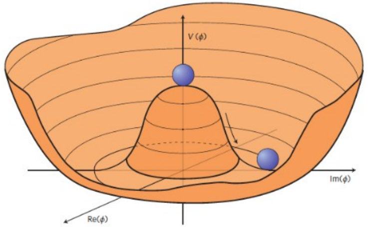
Dark Matter Phenomenology in Z'_2 broken Two Higgs Doublet Model with Complex Singlet Extension

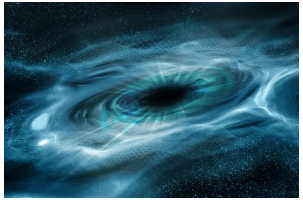
The Standard Model (SM)



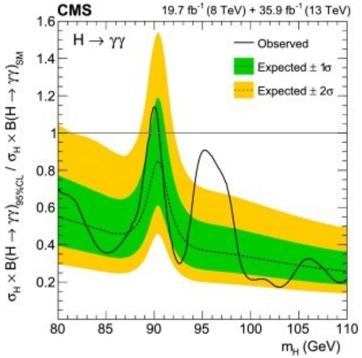
$$V_{SM} = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

?

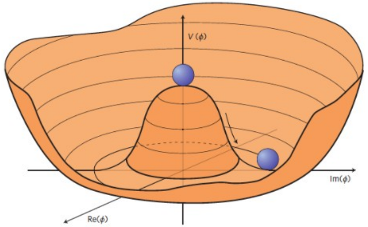
Explain cold dark matter (DM)



Explain new physics via extended Higgs sector, e.g. 95 GeV excess



Extend SM → Two Higgs Doublet Model with Complex Singlet (2HDMS)



Constraints:
Theoretical
(bfb, unitarity, vacuum stability (EVADE))
Experimental
(HiggsBounds, Planck, LUX-ZEPLIN/XENON-1T, Fermi-LAT)

Dark Matter (DM) Phenomenology
(Relic Density, Indirect Detection, Direct Detection)

SARAH
SPheno
micrOMEGAs

Collider Phenomenology
(HL-LHC, Future Lepton Colliders)

Pythia
Delphes
MadAnalysis
WHIZARD
Madgraph

2HDMS Higgs Sector Potential

[Notation as in: Baum and Shah, arXiv: 1808.02667]

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

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

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

for this study:
$\lambda_2'' = \lambda_1''$

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

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

DM Candidate

DM Candidate Properties:

- **massive**
- **electrically neutral**
- **colourless**
- **stable**

2HDMS Higgs Sector Potential

[Notation as in: Baum and Shah, arXiv: 1808.02667]

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

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

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

for this study:
$\lambda_2'' = \lambda_1''$

V_{2HDMS} Symmetric Under	
$\Phi_j \overset{U(1)}{\rightarrow} e^{i\theta}\Phi_j$ $\Phi_j^\dagger \overset{U(1)}{\rightarrow} e^{-i\theta}\Phi_j^\dagger$	**avoids charge-parity violation**
$\Phi_1 \overset{Z_2}{\rightarrow} -\Phi_1$ $\Phi_2 \overset{Z_2}{\rightarrow} \Phi_2$ **(softly broken by m_{12}^2)**	**avoids flavour changing neutral currents**
$\Phi_j \overset{Z_2'}{\rightarrow} \Phi_j$ $S \overset{Z_2'}{\rightarrow} -S$	**stabilization of DM**

2HDMS Higgs Sector Potential

[Notation as in: Baum and Shah, arXiv: 1808.02667]

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

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

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

for this study:
$\lambda_2'' = \lambda_1''$

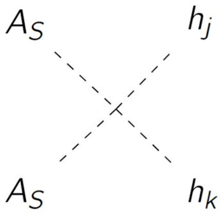
Other Properties	
number of free parameters:	15
DM mass:	$m_{A_S}^2 = \frac{\partial^2 V}{\partial A_S^\dagger \partial A_S}\Big\vert_{\Phi_1=\langle\Phi_1\rangle\ \Phi_2=\langle\Phi_2\rangle,\ S=\langle S\rangle} = -(2m_S'^2 + v_S^2(\frac{\lambda_1''}{3} + \frac{\lambda_1''}{3}) + 2(\lambda_4' v_1^2 + \lambda_5' v_2^2))$
Higgs sector particles:	1 charged: $H_\pm$, 1 charged GB: $G_\pm$, 3 scalars: h_1, h_2, h_3, SM-like 1 pseudo scalar: A, 1 pseudo scalar GB: G_0, 1 pseudo scalar DM: A_S
portal couplings:	λ_1', λ_2', λ_4', λ_5', $\lambda_1''=\lambda_2''$, λ_3''

2HDMS Couplings: DM to Scalar

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_{1,2,3}) \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

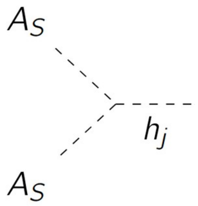
$$v = \sqrt{v_1^2 + v_2^2}$$

$$\tan(\beta) = \frac{v_2}{v_1}$$



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

$$= -i[(\lambda_1' - 2\lambda_4')R_{j1}R_{k1} + (\lambda_2' - 2\lambda_5')R_{j2}R_{k2} - \frac{1}{2}(\lambda_1'' - \lambda_3'')R_{j3}R_{k3}]$$



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

$$= -i[(\lambda_1' - 2\lambda_4')c_\beta R_{j1} + (\lambda_2' - 2\lambda_5')s_\beta R_{j2} - \frac{v_S}{2v}(\lambda_1'' - \lambda_3'')R_{j3}]$$

2HDMS Basis Change

Interaction Basis Parameters:

$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \tan\beta, v_S, m_S^{2\prime},$
$\lambda_1', \lambda_2', \lambda_4', \lambda_5', \lambda_1'' = \lambda_2'', \lambda_3''$

$\Downarrow$

Mass Basis Parameters:

$m_{h_1}, m_{h_2}, m_{h_3}, m_A, m_{A_S}, m_{H^\pm}, \delta_{14}', \delta_{25}',$
$\tan\beta, v_S, c_{h_1 bb}, c_{h_1 tt}, \tilde{\mu}^2, m_S'^2, alignm$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_{1,2,3}) \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

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

$$c_{h_1 bb} = \frac{R_{11}}{\cos\beta}$$
$$c_{h_1 tt} = \frac{R_{12}}{\sin\beta}$$

$$\tilde{\mu}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

$$\delta_{14}' = \lambda_4' - \lambda_1'$$
$$\delta_{25}' = \lambda_5' - \lambda_2'$$

$$alignm = |\sin(\beta - \alpha_1 - \alpha_3 \cdot sgn(\alpha_2))|$$
$$\approx 1$$
$= 1$ in alignment limit (couplings of h_2 will be SM-like)

2HDMS Benchmark Point (BP)

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_{1,2,3}) \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}	$m_{H^\pm}$	δ'_{14}	δ'_{25}
95 GeV	125.09 GeV	900 GeV	900 GeV	325.86 GeV	900 GeV	−9.6958	0.2475
$\tan(\beta)$	v_S	$c_{h_1 bb}$	$c_{h_1 tt}$	$\tilde{\mu}^2$	$m_S'^2$	*alignm*	★
10	239.86 GeV	0.2096	0.4192	8.128×10^5 GeV^2	-4.809×10^4 GeV^2	0.9998	

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

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$$c_{h_1 tt} = \frac{R_{12}}{\sin\beta}$$

$$\tilde{\mu}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

$$\delta'_{14} = \lambda'_4 - \lambda'_1$$
$$\delta'_{25} = \lambda'_5 - \lambda'_2$$

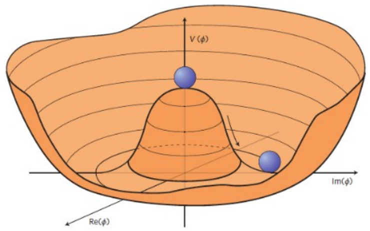
$alignm = |\sin(\beta - \alpha_1 - \alpha_3 \cdot sgn(\alpha_2))|$
≈ 1
$= 1$ in alignment limit (couplings of h_2 will be SM-like)

Constraints Checked:
Higgs Bounds,
bounded from below (bfb),
unitarity, vacuum stability (EVADE),
Planck, LUX-ZEPLIN (LZ), Fermi-LAT,
including 95 GeV excess*

BP allowed by these constraints!

***γγ channel at CMS (~2.9 σ), bb channel at LEP (~2 σ), investigated in S. Heinemeyer, C. Li, et al, 2021, arxiv:2112.11958**

Extend SM → Two Higgs Doublet Model with Complex Singlet (2HDMS)



Constraints:
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Dark Matter (DM) Phenomenology
(Relic Density, Indirect Detection, Direct Detection)

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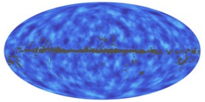
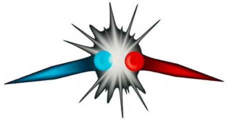
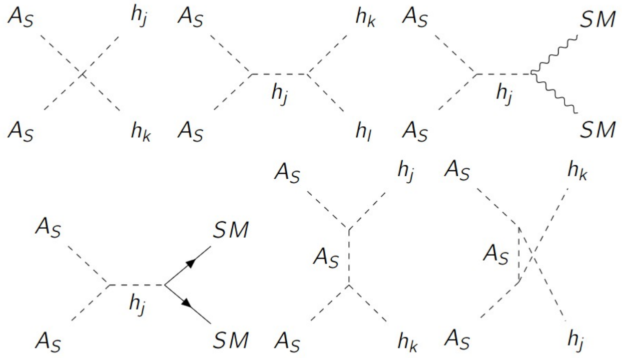
DM Phenomenology

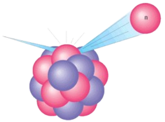


Relic Density
(=amount of DM left in universe today),
constraints from Planck : $\Omega h^2 \approx 0.12$

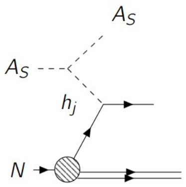


Indirect Detection Annihilation CS
(=annihilation of two DM particles),
constraints from Fermi-LAT (depends on DM mass an annihilation channel)





Direct Detection CS
(=elastic scattering of DM on nucleon),
constraints from LUX-ZEPLIN (LZ)
depends on DM mass



DM Phenomenology

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$\tan(\beta)$	v_S	$c_{h_1 bb}$	$c_{h_1 tt}$	$\tilde{\mu}^2$	$m_S'^2$	$alignm$	★
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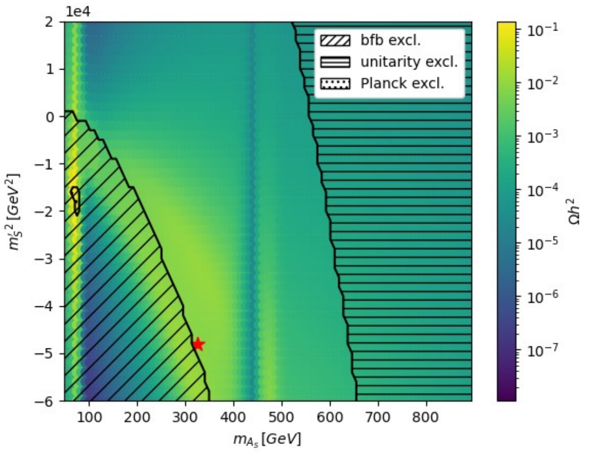
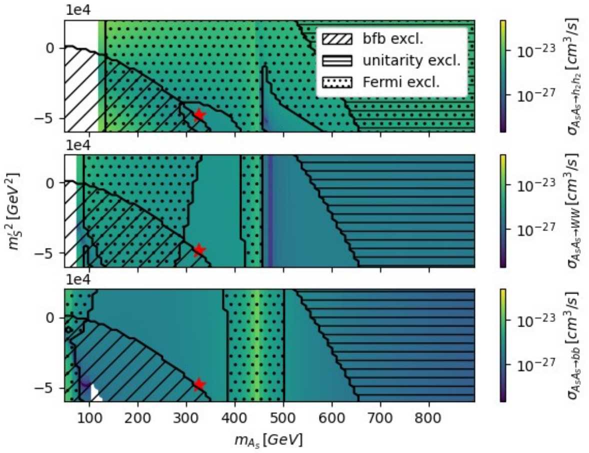
Relic Density



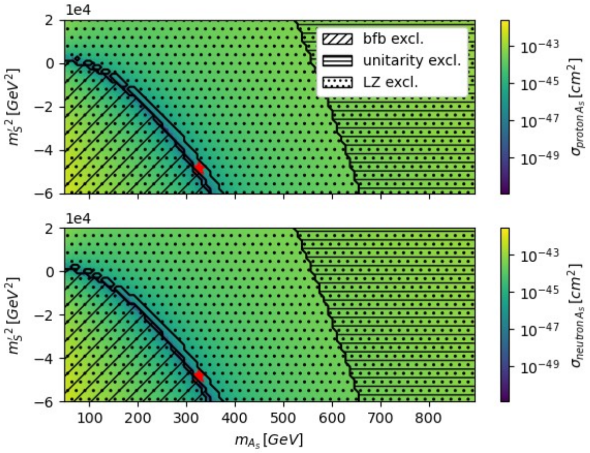
- dip at: $m_{AS} \approx 62.5$ GeV = $m_{h2}/2$
- drops for: $m_{AS} > 95$ GeV = m_{h1}
- dip at: $m_{AS} \approx 450$ GeV = $m_{h3}/2$

Indirect Detection



- peak at: $m_{AS} \approx 450$ GeV = $m_{h3}/2$
- some white areas: CS is too low

Direct Detection



- minimum along arched line
- very strong constraints from LUX-ZEPLIN (LZ)

DM Phenomenology

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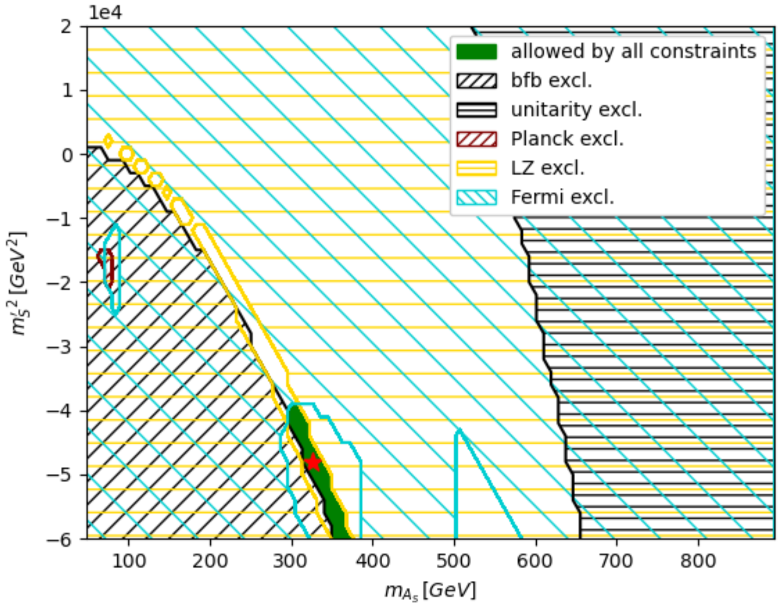
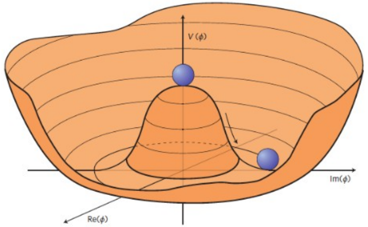
Allowed Parameter Space



→ strongest constraints from:
- **bounded from below (bfb)**
- **unitarity**
- **LUX-ZEPLIN (LZ)**
- **Fermi-LAT**

→ narrow allowed band around BP

Extend SM → Two Higgs Doublet Model with Complex Singlet (2HDMS)



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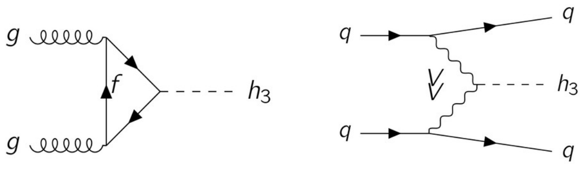
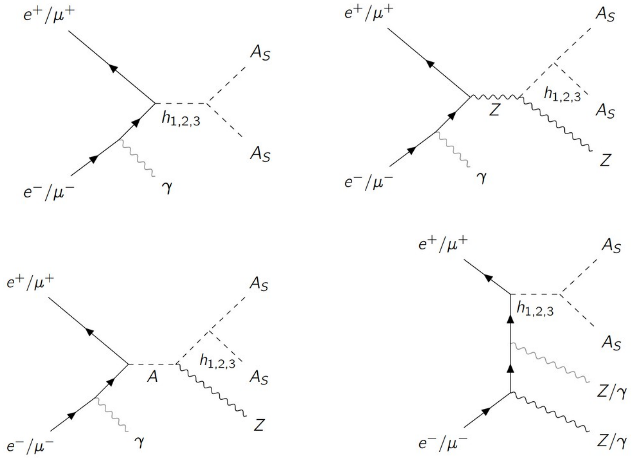
Collider Phenomenology

HL-LHC



Future Lepton Colliders ($e^+e^-/\mu^+\mu^-$)



Collider Phenomenology HL-LHC

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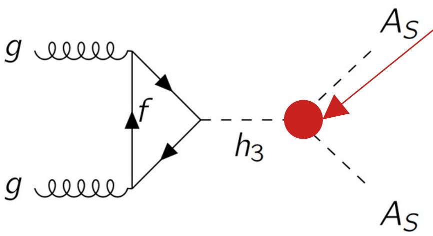
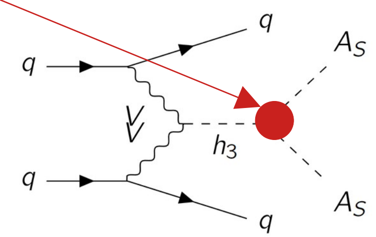
$\tan(\beta)$	v_S	c_{h_1bb}	c_{h_1tt}	$\tilde{\mu}^2$	m'^2_S	*alignm*	
10	239.86 GeV	0.2096	0.4192	8.128×10^5 GeV^2	-4.809×10^4 GeV^2	0.9998	

BR($h_3 \to A_SA_S$) ≈ 0.247





significance S of signal s over background b:

$$\mathcal{S} = \sqrt{2\times\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]}$$

→ very low significance for BP

Process	**C1**	**C2**	**C3**	**C4**	**C5**
GGF	696	137	114	114	114
$\mathcal{S}$	1.356 σ				

Process	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**
VBF	0.98	0.39	0.28	0.23	0.23	0.23
$\mathcal{S}$	0.007 σ					

m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}	$m_{H^\pm}$	δ'_{14}	δ'_{25}
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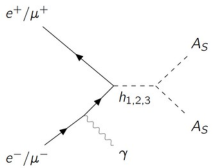
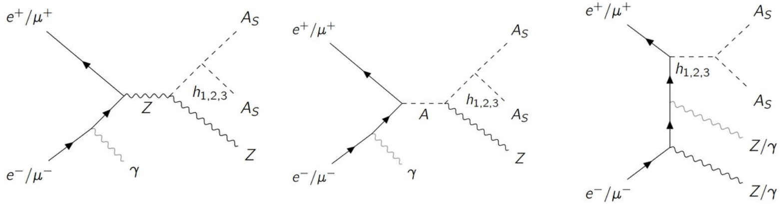
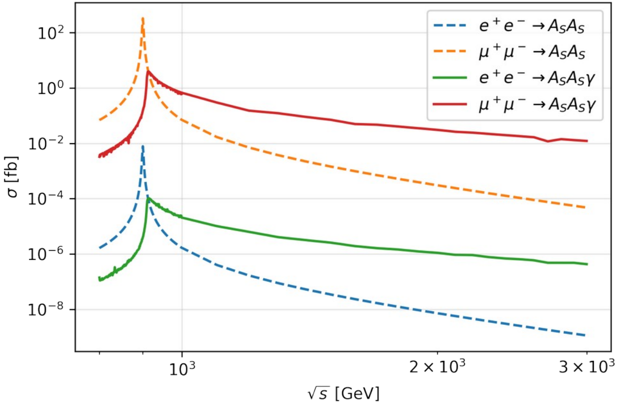
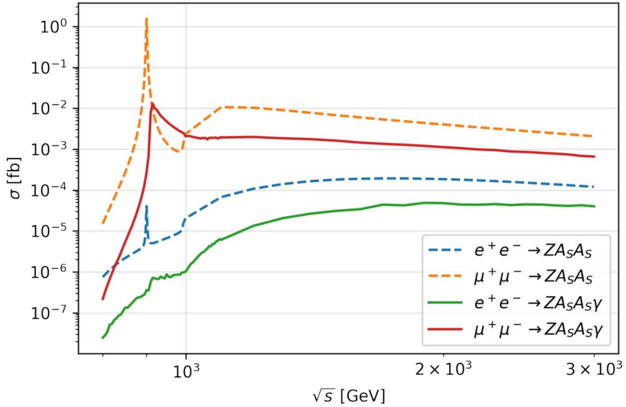
Collider Phenomenology
Future Lepton Colliders ($e^+e^-/\mu^+\mu^-$)



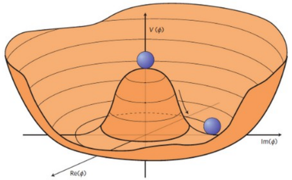






→ higher cross section for muon collider (larger Yukawa coupling)
→ resonant peak at $\sqrt{s}$ = 900 GeV = m_{h3}

Conclusions



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

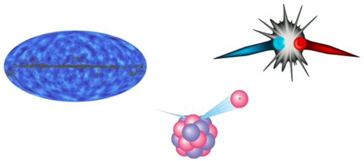
$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix}$$

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

arXiv: 2308.05653

Dark Matter (DM) Phenomenology

(Relic Density, Indirect Detection, Direct Detection)



- can fit 95 GeV excess in 2HDMS
- strong constraints from: bfb, unitarity, LZ, Fermi-LAT

Collider Phenomenology

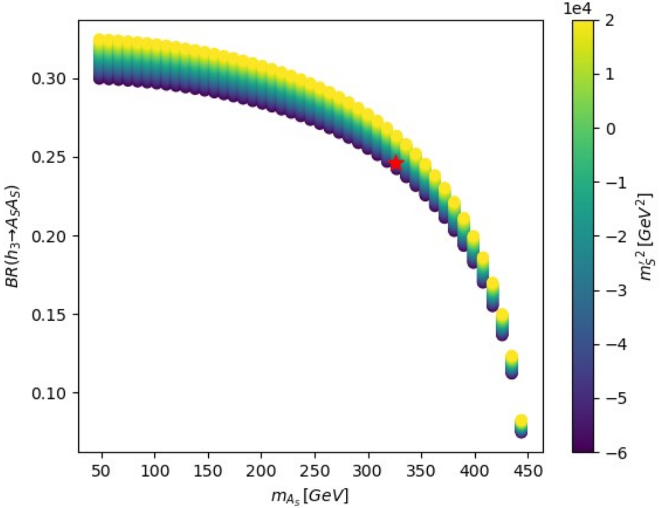
(HL-LHC, Future Lepton Colliders)

- significance at HL-LHC rather low
  → can be improved with machine learning
  → comprehensive parameter scans planned
- potentially promising prospects at Future Lepton Colliders
  → further improvement with polarized beams
  → further parameter scans planned
- muon collider shows best prospects of production cross section

Backup

m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}	$m_{H^\pm}$	δ'_{14}	δ'_{25}
95 GeV	125.09 GeV	900 GeV	900 GeV	325.86 GeV	900 GeV	−9.6958	0.2475
$\tan(\beta)$	v_S	$c_{h_1 bb}$	$c_{h_1 tt}$	$\tilde{\mu}^2$	m'^2_S	$alignm$	★
10	239.86 GeV	0.2096	0.4192	8.128×10^5 GeV^2	-4.809×10^4 GeV^2	0.9998	

Decay Modes	Branching Ratio (BR)
$h_3 \to b\bar{b}$	0.412
$h_3 \to A_S A_S$	0.247
$h_3 \to t\bar{t}$	0.106
$h_3 \to \tau\tau$	0.064
$h_3 \to h_2 h_2$	0.061
$h_3 \to h_1 h_2$	0.035
$h_3 \to h_1 h_1$	0.022



Backup

Signal Region A: Mono-jet + $\not{E}_T$

We generated the gluon gluon fusion process with h_3 successively decaying into a pair of DM candidates in `Madgraph_aMC_v3.4.1`. For **BP1**, $\sigma_{GGF} \times BR(h_3 \times A_S A_S) = 0.232$ fb. We perform the signal analyses using the following cuts successively from Ref. [58] on the benchmark **BP1**,

- **C1**: The final state consists of up to four jets with $p_T > 30$ GeV and $|\eta| < 2.8$.
- **C2**: We demand a large $\not{E}_T > 250$ GeV.
- **C3**: The hardest leading jet has $p_T > 250$ GeV with $|\eta| < 2.4$.
- **C4**: We demand $\Delta\Phi(j, \not{E}_T) > 0.4$ for all jets and $\Delta\Phi(j, \not{E}_T) > 0.6$ for the leading jet.
- **C5**: A lepton-veto is imposed for electrons with $p_T > 20$ GeV and $|\eta| < 2.47$ and muons with $p_T > 10$ GeV and $|\eta| < 2.5$.

The SM background is obtained from the ATLAS mono-jet + $\not{E}_T$ search studied in Ref. [58]. We present the signal cut-flow table in Table. 9. The statistical significance

Process	C1	C2	C3	C4	C5
GF	696	137	114	114	114
$\mathcal{S}$	1.356 σ				

Table 9. The cut flow table for the number of signal events for **BP1** at leading order (LO) and signal significance $\mathcal{S}$ at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000\ \text{fb}^{-1}$. The SM background is obtained from Ref. [58].

Signal Region B: 2 j + $\not{E}_T$

Generating the VBF process at LO analogously as described for the fusion process, we obtain, $\sigma_{VBF} \times BR(h_3 \to A_S A_S) = 0.011$ fb. We perform the signal analyses for the 2 j + $\not{E}_T$ final state, using the following cuts from [58] for the benchmark **BP1**,

- **D1**: The final state consists of at least two jets with $p_T(j_1) > 80$ and $p_T(j_2) > 40$ GeV and $\Delta\Phi(j_i, \not{E}_T) > 0.5$.
- **D2**: We demand $\eta j_1 j_2 < 0$ and $\Delta\Phi j_1 j_2 < 1.5$.
- **D3**: We demand $|\Delta\eta|_{jj} > 3.0$.
- **D4**: The invariant mass of the two forward jets is required to be large, i.e, $M_{jj} > 600$ GeV.
- **D5**: We demand $\not{E}_T > 200$ GeV.
- **D6**: Furthermore, a lepton veto is imposed for electrons with $p_T > 20$ GeV or muons with $p_T > 10$ GeV.

Process	D1	D2	D3	D4	D5	D6
VBF	0.98	0.39	0.28	0.23	0.23	0.23
$\mathcal{S}$	0.007 σ					

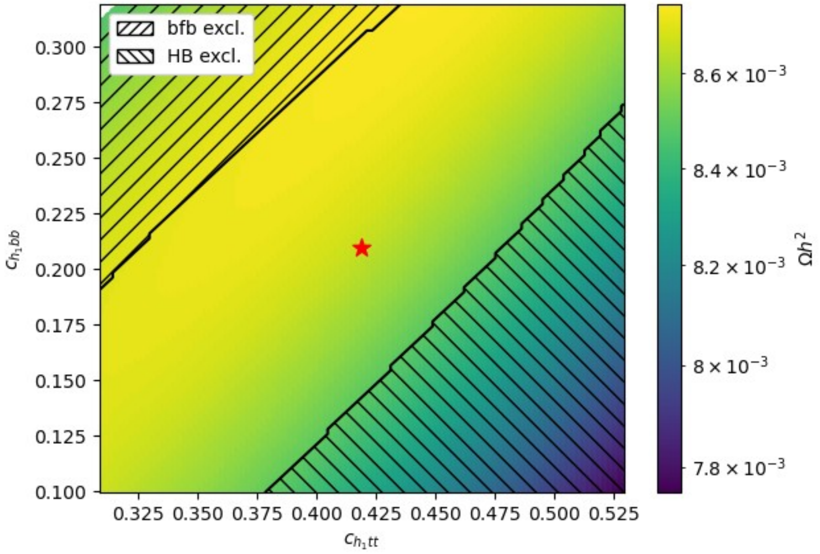
Table 10. The cut flow table for the signal cross-sections for **BP1** at LO and signal significance $\mathcal{S}$ at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000\ \text{fb}^{-1}$. The SM background is obtained from Ref. [58].

Backup

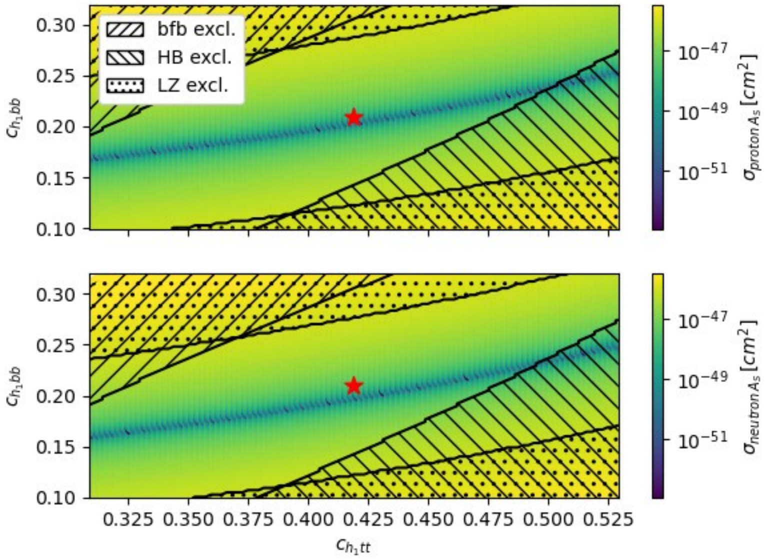
Future Lepton Colliders:
Event generation with WHIZARD,
cuts:

- **Photon cuts: $E_\gamma > 10$ GeV, $\Theta > 7^\circ$**

Backup

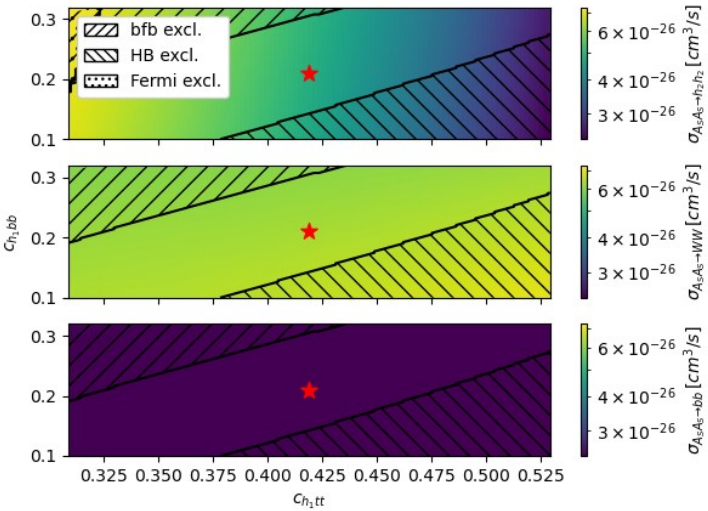


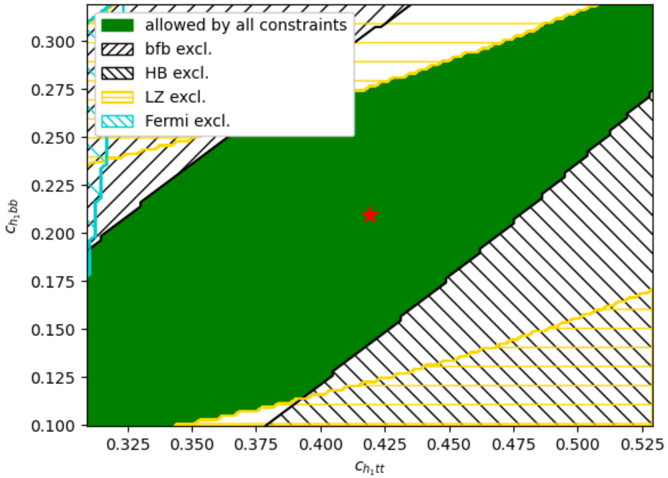
bfb excl.
HB excl.
0.300
0.275
0.250
0.225
0.200
0.175
0.150
0.125
0.100
$c_{h_1 bb}$
0.325 0.350 0.375 0.400 0.425 0.450 0.475 0.500 0.525
$c_{h_1 tt}$
8.6×10^{-3}
8.4×10^{-3}
8.2×10^{-3}
8×10^{-3}
7.8×10^{-3}
Ωh^2



bfb excl.
HB excl.
LZ excl.
0.30
0.25
0.20
0.15
0.10
$c_{h_1 bb}$
10^{-47}
10^{-49}
10^{-51}
$\sigma_{proton\, A_s}\, [cm^2]$
$\sigma_{neutron\, A_s}\, [cm^2]$
0.325 0.350 0.375 0.400 0.425 0.450 0.475 0.500 0.525
$c_{h_1 tt}$

Backup


bfb excl.
HB excl.
Fermi excl.
c_{h_1bb}
c_{h_1tt}
$\sigma_{A_sA_s\to h_2h_2}\,[cm^3/s]$
$\sigma_{A_sA_s\to WW}\,[cm^3/s]$
$\sigma_{A_sA_s\to bb}\,[cm^3/s]$
6×10^{-26}
4×10^{-26}
3×10^{-26}
0.325 0.350 0.375 0.400 0.425 0.450 0.475 0.500 0.525
0.1
0.2
0.3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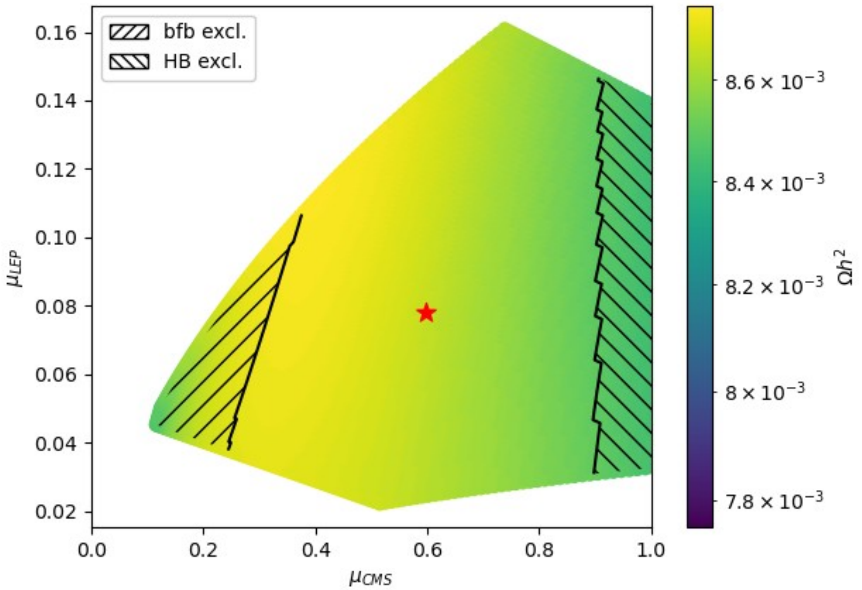
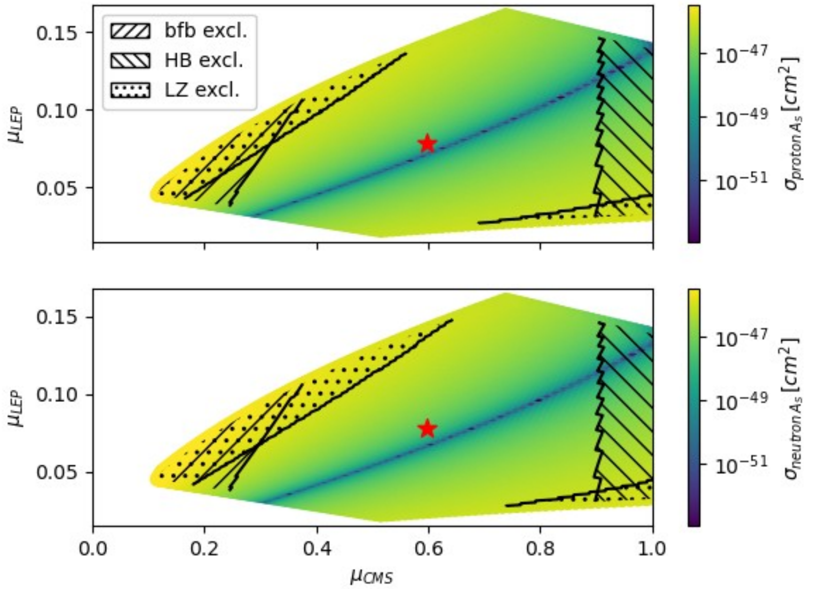
bfb excl.
HB excl.
LZ excl.
Fermi excl.
c_{h_1bb}
c_{h_1tt}
0.100 0.125 0.150 0.175 0.200 0.225 0.250 0.275 0.300
0.325 0.350 0.375 0.400 0.425 0.450 0.475 0.500 0.525

Backup

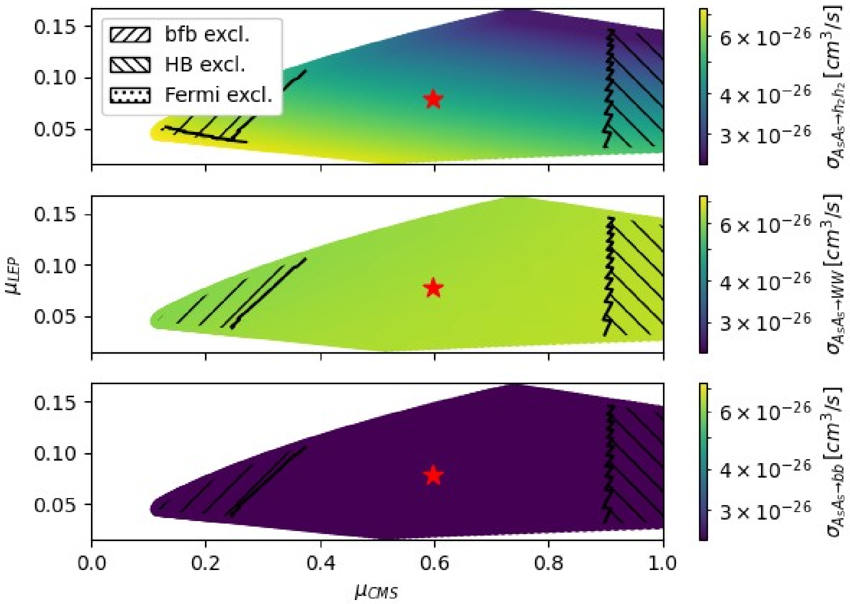


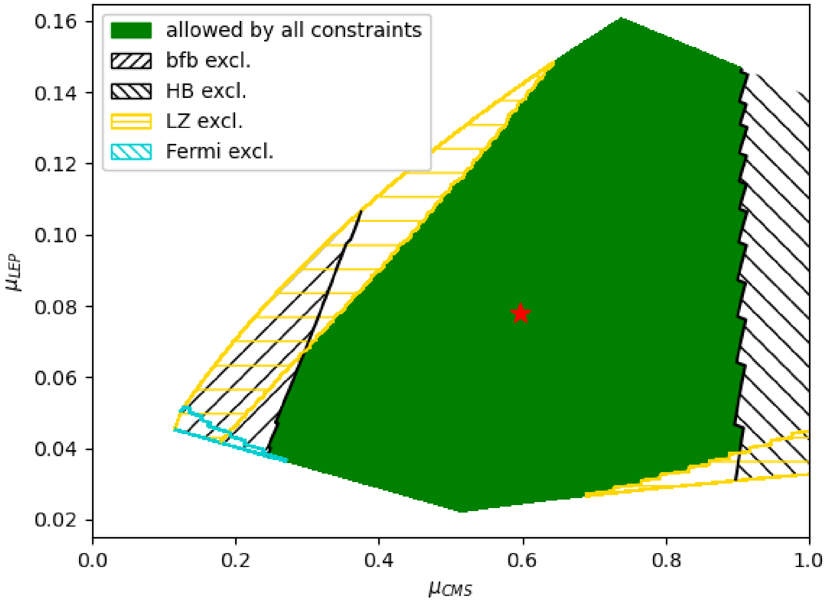
bfb excl.
HB excl.
μ_{LEP}
μ_{CMS}
Ωh^2
8.6×10^{-3}
8.4×10^{-3}
8.2×10^{-3}
8×10^{-3}
7.8×10^{-3}



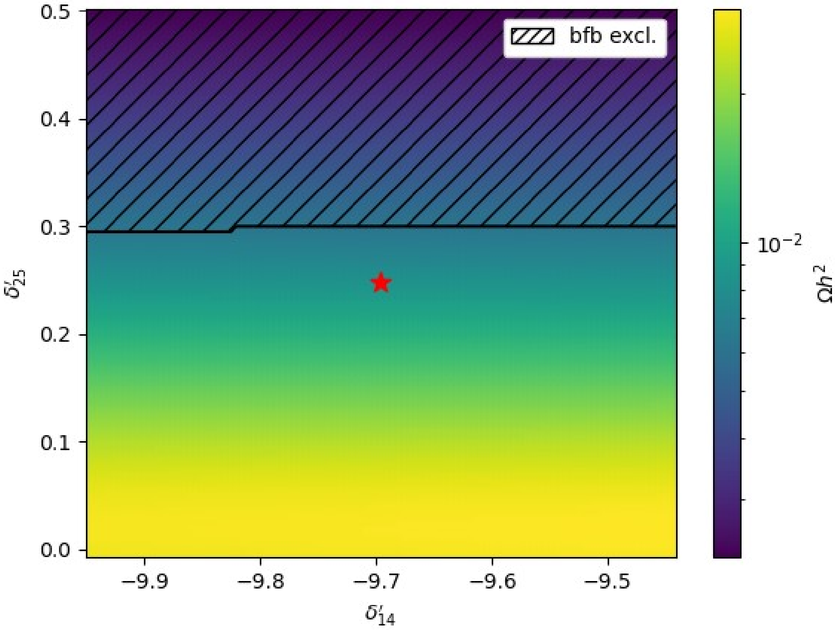
bfb excl.
HB excl.
LZ excl.
μ_{LEP}
μ_{CMS}
$\sigma_{proton\,A_S}\,[cm^2]$
$\sigma_{neutron\,A_S}\,[cm^2]$
10^{-47}
10^{-49}
10^{-51}

Backup

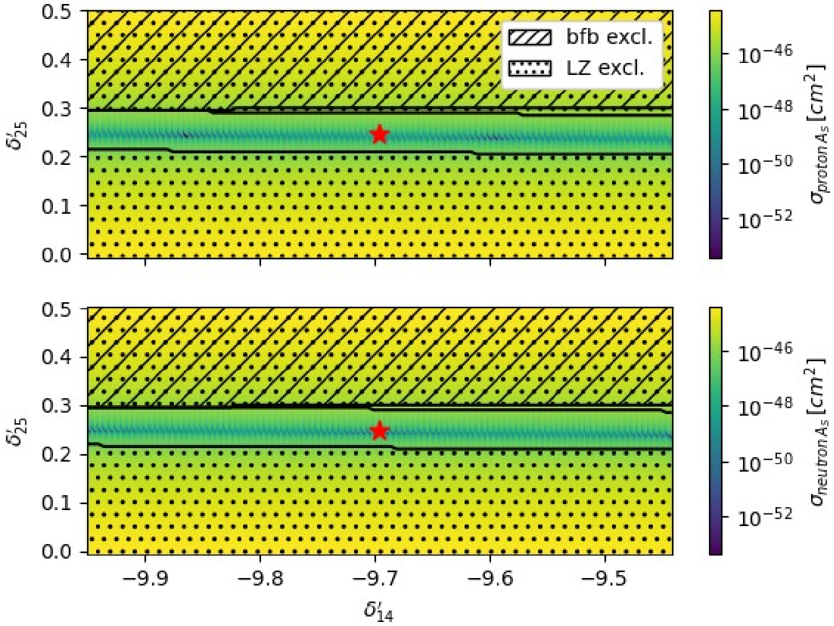

bfb excl.
HB excl.
Fermi excl.
0.15
0.10
0.05
μ_{LEP}
0.0
0.2
0.4
0.6
0.8
1.0
μ_{CMS}
6×10^{-26}
4×10^{-26}
3×10^{-26}
$\sigma_{A_sA_s \to h_2h_2}\,[cm^3/s]$
$\sigma_{A_sA_s \to WW}\,[cm^3/s]$
$\sigma_{A_sA_s \to bb}\,[cm^3/s]$


allowed by all constraints
bfb excl.
HB excl.
LZ excl.
Fermi excl.
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
μ_{LEP}
0.0
0.2
0.4
0.6
0.8
1.0
μ_{CMS}

Backup

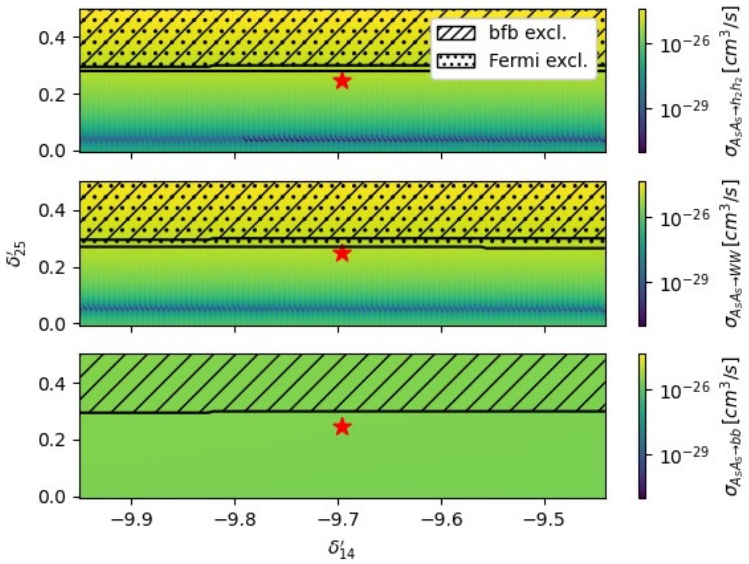


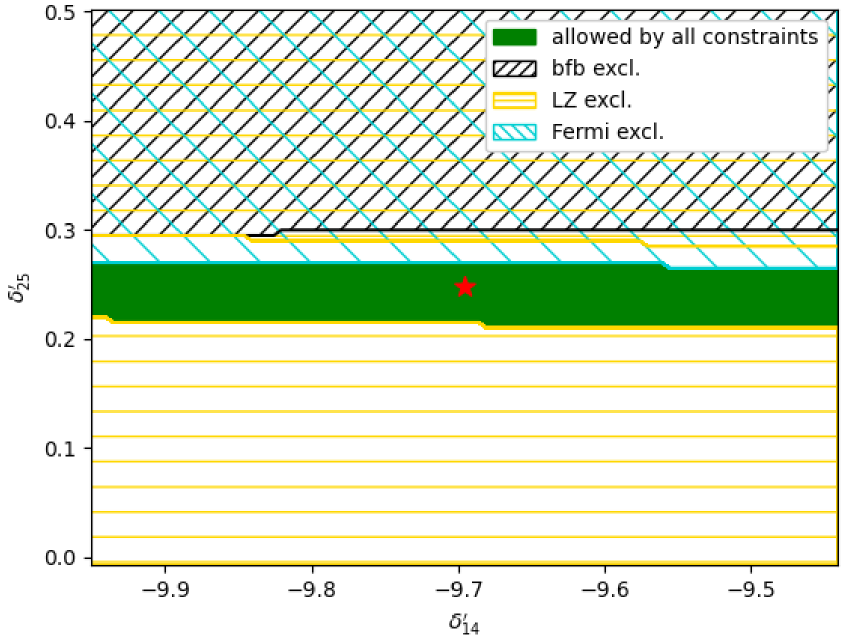
bfb excl.
0.5
0.4
0.3
0.2
0.1
0.0
−9.9
−9.8
−9.7
−9.6
−9.5
δ'_{25}
δ'_{14}
10^{-2}
Ωh^2



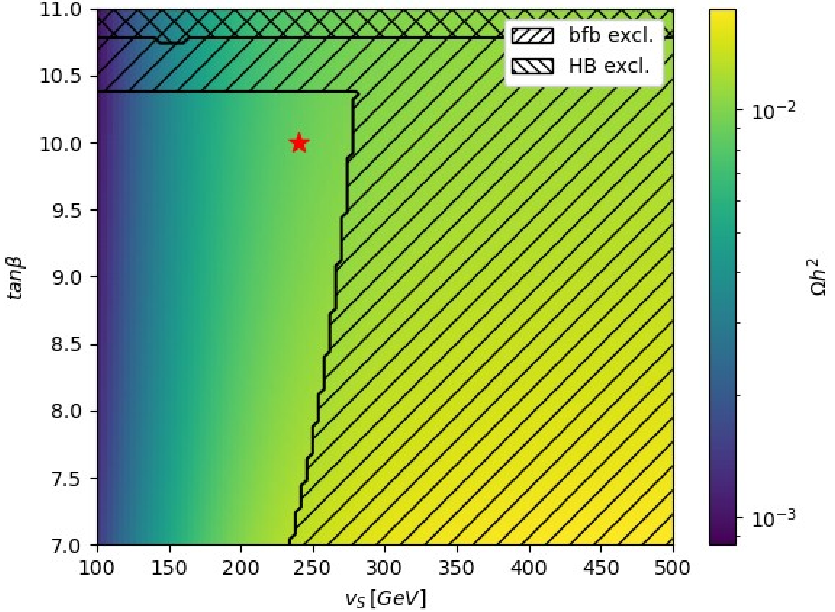
bfb excl.
LZ excl.
δ'_{25}
δ'_{14}
−9.9
−9.8
−9.7
−9.6
−9.5
10^{-46}
10^{-48}
10^{-50}
10^{-52}
$\sigma_{proton\,A_s}\,[cm^2]$
$\sigma_{neutron\,A_s}\,[cm^2]$

Backup

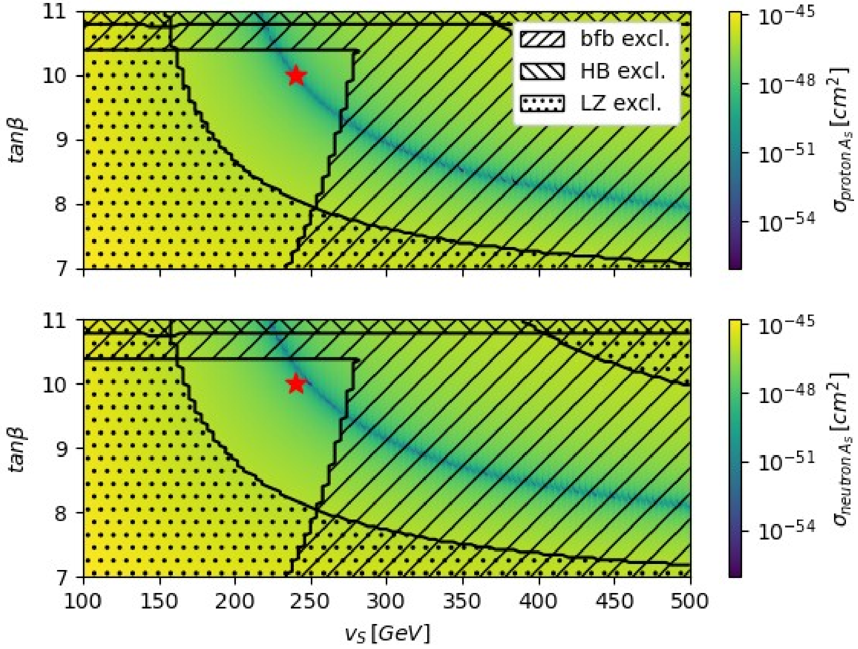

bfb excl.
Fermi excl.
δ'_{25}
δ'_{14}
$\sigma_{A_SA_S \to h_2h_2}\,[cm^3/s]$
$\sigma_{A_SA_S \to WW}\,[cm^3/s]$
$\sigma_{A_SA_S \to bb}\,[cm^3/s]$
10^{-26}
10^{-29}
−9.9
−9.8
−9.7
−9.6
−9.5
0.0
0.2
0.4


allowed by all constraints
bfb excl.
LZ excl.
Fermi excl.
δ'_{25}
δ'_{14}
0.0
0.1
0.2
0.3
0.4
0.5
−9.9
−9.8
−9.7
−9.6
−9.5

Backup

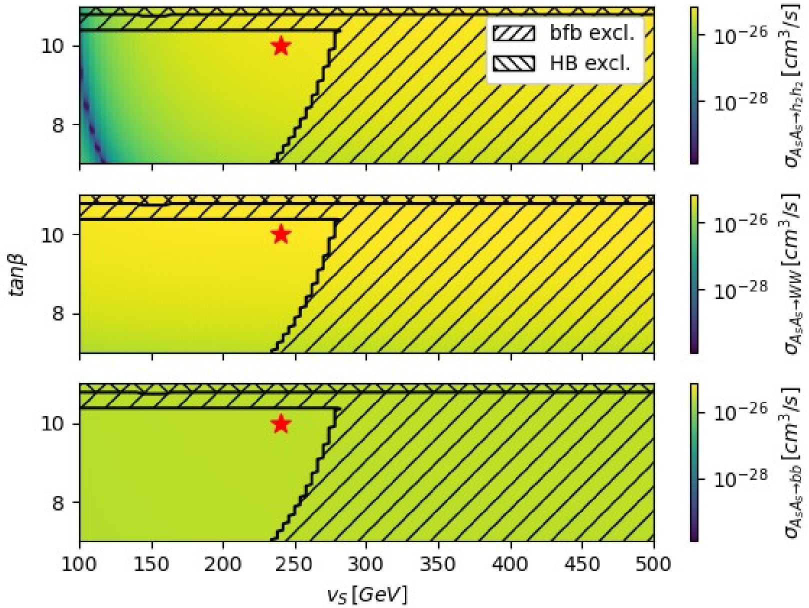


bfb excl.
HB excl.
$\tan\beta$
$v_S\,[GeV]$
Ωh^2
10^{-2}
10^{-3}

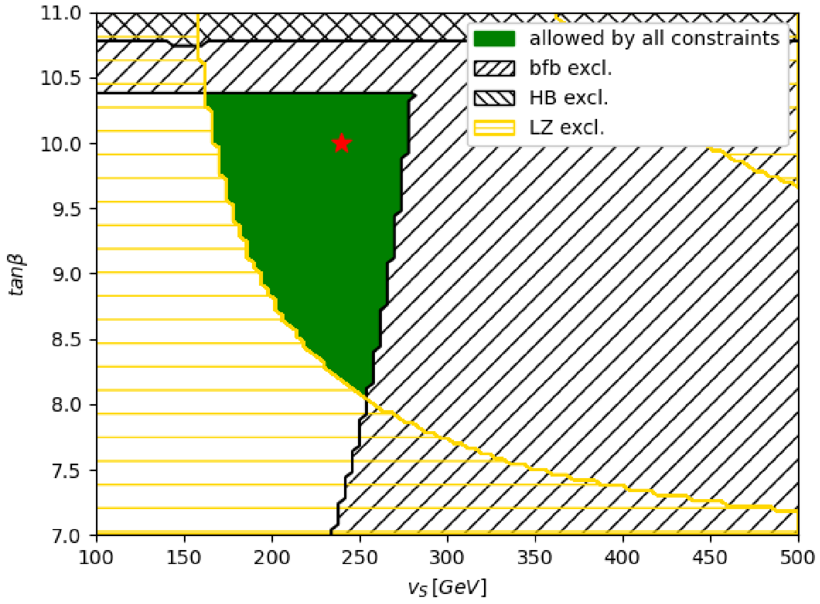


bfb excl.
HB excl.
LZ excl.
$\tan\beta$
$v_S\,[GeV]$
$\sigma_{proton\,A_s}\,[cm^2]$
$\sigma_{neutron\,A_s}\,[cm^2]$
10^{-45}
10^{-48}
10^{-51}
10^{-54}

Backup



bfb excl.
HB excl.
10
8
10
8
10
8
tanβ
100
150
200
250
300
350
400
450
500
$v_S\,[GeV]$
10^{-26}
10^{-28}
$\sigma_{A_sA_s\to h_2h_2}\,[cm^3/s]$
$\sigma_{A_sA_s\to WW}\,[cm^3/s]$
$\sigma_{A_sA_s\to bb}\,[cm^3/s]$



allowed by all constraints
bfb excl.
HB excl.
LZ excl.
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
tanβ
100
150
200
250
300
350
400
450
500
$v_S\,[GeV]$