Dark Matter Phenomenology in 2HDMS in the light of 95 GeV excess

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based on arXiv: 2308.05653 (*Accepted to EPJ C)* *and ongoing work*

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Motivation

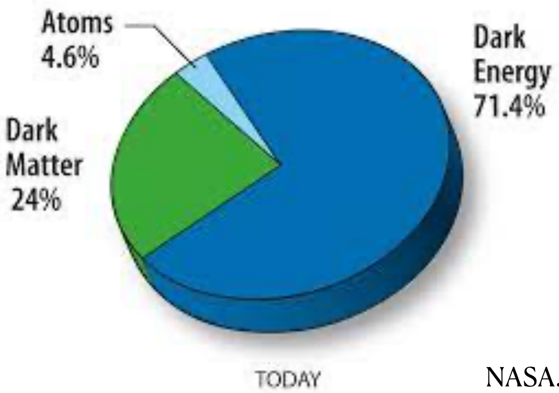
- Dark matter constitutes about 95% of the universe and yet remains unknown.

- Scalar singlets under the SM gauge group $\Longrightarrow$ potential dark matter candidates communicates to the SM via the 125 GeV Higgs as the portal to the dark sector, however stringently constrained from dark matter direct detection data.

- Additional portals to dark matter via extra Higgses as in singlet extended multi-Higgs models relaxes direct detection constraints with potential prospects for collider signals.

- Extended scalar sectors are well motivated models addresses several issues such as dark matter, baryogenesis, inflation and potential sources of gravitational waves.

- Extra degree of freedom provides potential to fit light scalar excesses at 2-3σ, such as 95 GeV excess in the $b\bar{b}$ and $\gamma\gamma$ modes at LEP and CMS.



NASA.

The Model

- Consider a softly broken Z_2 (to avoid FCNC) symmetric Type II 2HDM augmented with a complex scalar singlet S, stabilized under Z_2'.

- SM quantum numbers:

Fields	Z_2	Z_2'
Φ_1	+1	+1
Φ_2	-1	+1
S	+1	-1

$$\Phi_i = \begin{pmatrix} \phi_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + h_i + i a_i) \end{pmatrix}, \quad i = 1, 2,$$

$$S = \frac{1}{\sqrt{2}}(v_S + h_S + i a_S)$$

- The scalar potential is: $V_{2HDMS} = V_{2HDM} + V_S,$

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

$$V_S = m_S^2 (S^\dagger S) + \frac{m_S^{2'}}{2}(S^2 + h.c) + \lambda_3''(S^\dagger S)^4 + \lambda_1'' S^2 (S^\dagger S) + h.c + \lambda_1'' S^2 (S^\dagger S) + h.c$$

$$+\lambda_1' S^\dagger S \Phi_1^\dagger \Phi_1 + \lambda_2' S^\dagger S \Phi_2^\dagger \Phi_2 + S^2(\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2) + h.c.$$

Baum, et.al, *JHEP*12(2018)044

- After electroweak symmetry breaking, particle content: $h_1, h_2, h_3, A, H^{\pm}, A_S$.

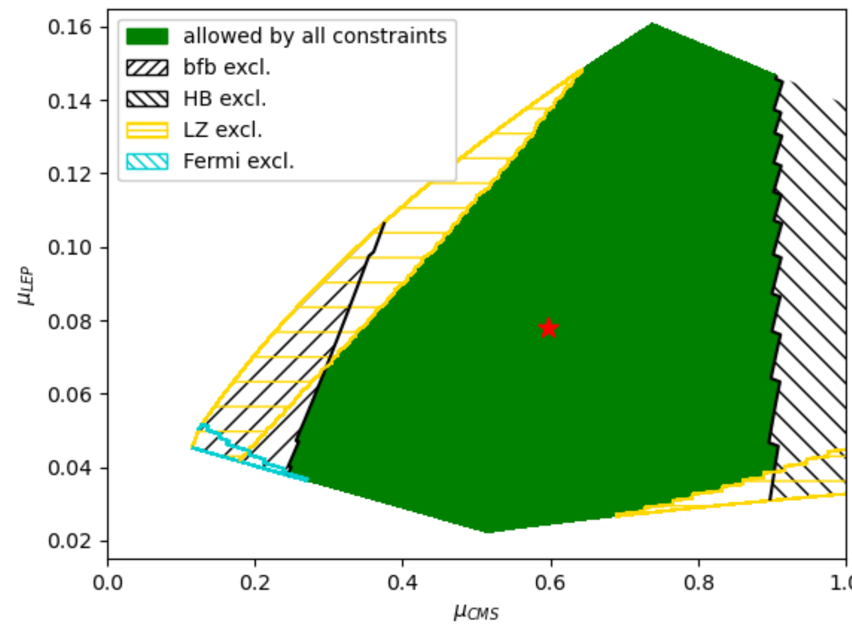
Interplay of DM and 95 GeV Higgs

m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}
95 GeV	125.09 GeV	900 GeV	900 GeV	325.86 GeV
$m_{H^\pm}$	$m_S'^2$	δ'_{14}	δ'_{25}	$\tan(\beta)$
900 GeV	$-4.809 \times 10^4\,\mathrm{GeV}^2$	-9.6958	0.2475	10
v_S	c_{h_1bb}	c_{h_1tt}	$alignm$	$\tilde{\mu}^2$
239.86 GeV	0.2096	0.4192	0.9998	$8.128 \times 10^5\,\mathrm{GeV}^2$

Benchmark point **BP1**

Parameters	Range
c_{h_1bb}	$[0.0996, 0.320]$
c_{h_1tt}	$[0.309, 0.529]$

$$\mu_{b\bar{b}}^{2HDMS} \propto |c_{h_1VV}|^2,$$



Allowed region consistent with 95 GeV excess, theoretical and experimental constraints from Higgs and dark matter searches.

$$\mu_{\gamma\gamma}^{2HDMS} \propto \frac{(|c_{h_1t\bar{t}}|)^2}{(|c_{h_1b\bar{b}}|)^2} \propto (\frac{\tan\alpha_1}{\tan\beta})^2$$

$$\mu_{\mathrm{LEP}}^{b\bar{b}} = 0.117^{+0.057}_{-0.057},$$

S.Heinemeyer et.al,
Phys. Rev. D 106 (2022), no. 7 075003

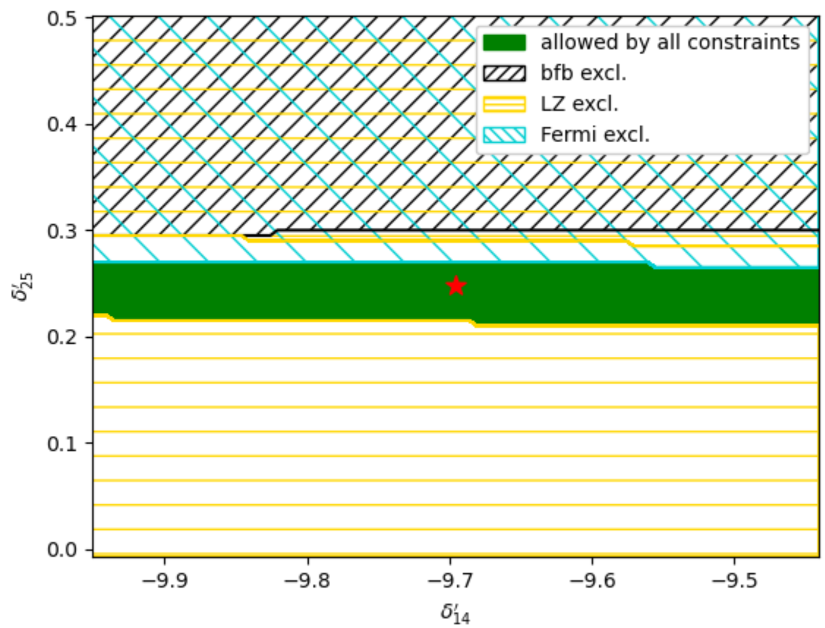
$$\mu_{\gamma\gamma}^{\mathrm{CMS}} = \frac{\sigma^{\exp}(pp \to \phi \to \gamma\gamma)}{\sigma^{\mathrm{SM}}(pp \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

Constraints on portal couplings $\delta'_{14} - \delta'_{25}$

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

- Stringent constraints from LZ and Fermi-LAT data as well from boundedness-from-below constraints.

$$\frac{\lambda_{h_j A_S A_S}}{v} = [\frac{\sum_{i=1}^{3} m_{h_i}^2 R_{i1} R_{i3}}{3 v v_S \cos(\beta)} + \frac{4\delta'_{14}}{3}] c_\beta R_{j1}$$
$$+ [\frac{\sum_{i=1}^{3} m_{h_i}^2 R_{i2} R_{i3}}{3 v v_S \sin(\beta)} + \frac{4\delta'_{25}}{3}] s_\beta R_{j2}$$
$$- [\frac{2}{v v_S}(2m_S'^2 + m_{A_S}^2 + (\frac{\sum_{i=1}^{3} m_{h_i}^2 R_{i1} R_{i3}}{3 v v_S \cos(\beta)} + \frac{\delta'_{14}}{3}) 2v^2 c_\beta^2$$
$$+ (\frac{\sum_{i=1}^{3} m_{h_i}^2 R_{i2} R_{i3}}{3 v v_S \sin(\beta)} + \frac{\delta'_{25}}{3}) 2v^2 s_\beta^2) + \frac{\sum_{i=1}^{3} m_i^2 R_{i3}^2}{v v_S}] R_{j3},$$



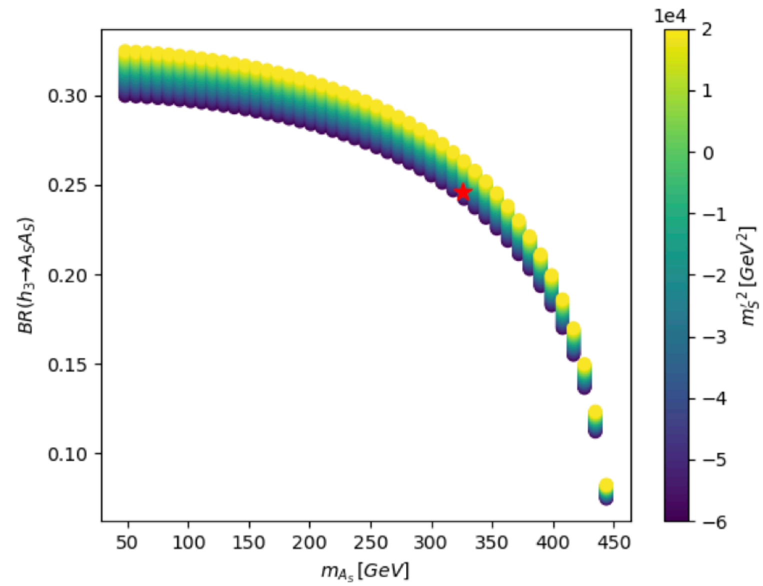
Effect of δ'_{25} dominant δ'_{14} over due to multiplicative factor of $\sin\beta$.

Collider Phenomenology

- The presence of a dark matter candidate allows new decay modes for the heavy Higgs h_3 to open up $\Longrightarrow$ Missing energy signals at colliders!

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

Decay modes for h_3 in BP1.

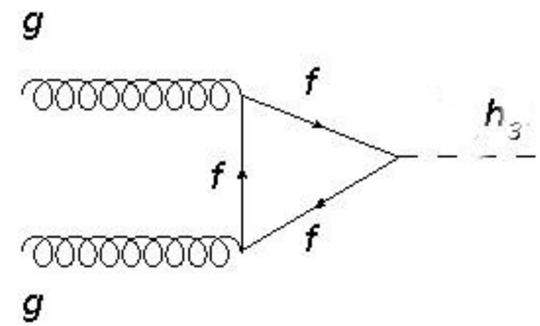


Variation of BR($h_3 \to A_S A_S$) vs. DM mass for BP1 and Higgs constraints.

Signals at HL-LHC

- Signal: Mono-jet + MET
  $\sigma_{GGF} \times BR(h_3 \times A_S A_S) = 0.232$ fb for m_{h_3}=900 GeV.

Using cuts: $N_j <= 4, p_T(j) > 30, \eta < 2.8, \not{E}_T > 250 GeV,$
$\Delta\Phi(j, \not{E}_T) > 0.4, \Delta\Phi(j_1, \not{E}_T) > 0.6, N_\ell = 0,$ signal significance = 1.36(LO) and 2.6σ (NNLO+NNLL).

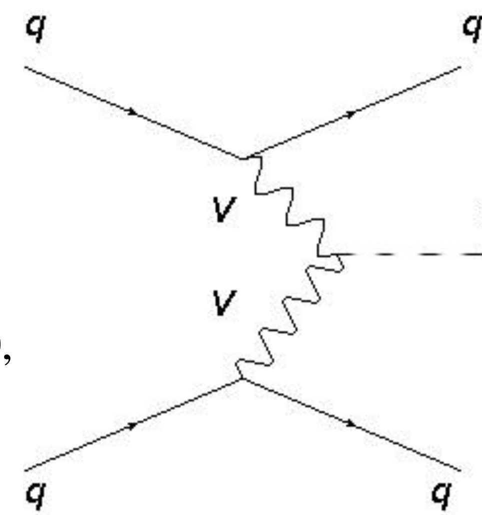


Gluon Fusion production.

- Signal: 2 forward jets + MET
  $\sigma_{VBF} \times BR(h_3 \rightarrow A_S A_S)$= 0.011 fb.

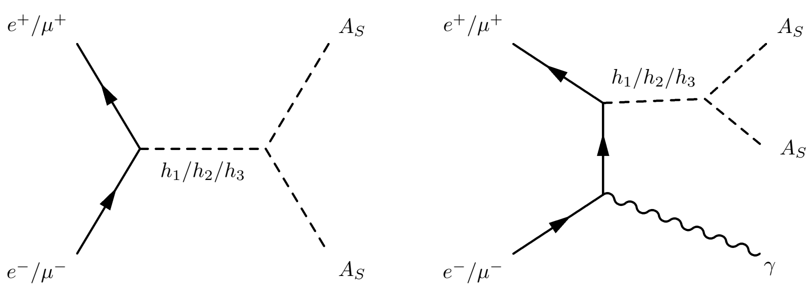
- Using cuts: $p_T(j_1) > 80 GeV, p_T(j_2) > 40 GeV, \Delta\Phi(j, \not{E})_T > 0.5,$
  $\eta_{j_1 j_2} < 0, \Delta\Phi_{j_1 j_2} < 1.5, \Delta\eta_{j_1, j_2} > 3.0, M_{j_1 j_2} > 600 GeV, \not{E}_T > 200 GeV, N_\ell = 0,$
  signal significance = 0.00032σ (LO) and 0.0055 σ (NNLO) .

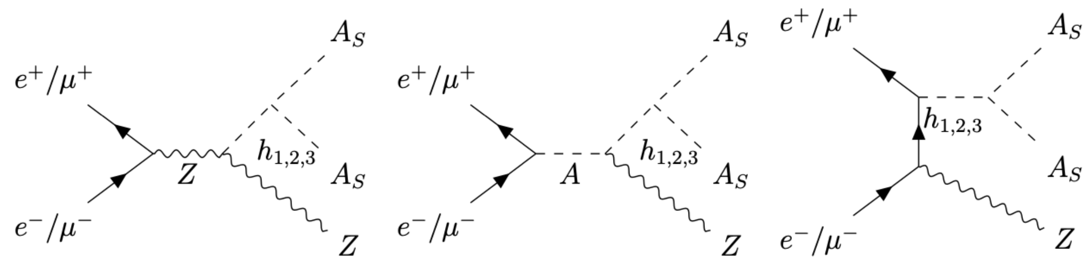
Lighter masses for m_{h_3} could potentially improve the sensitivity along with machine learning techniques as seen in Dey, et.al JHEP 09 (2019) 004 .

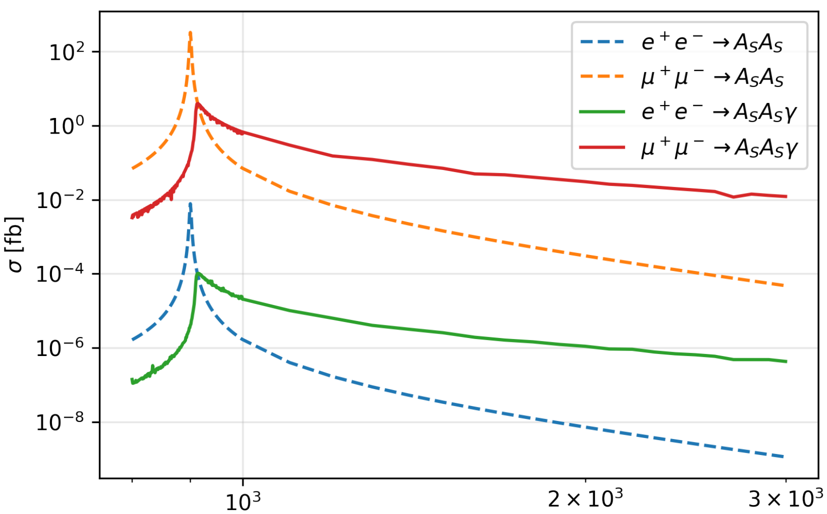


Vector boson production.

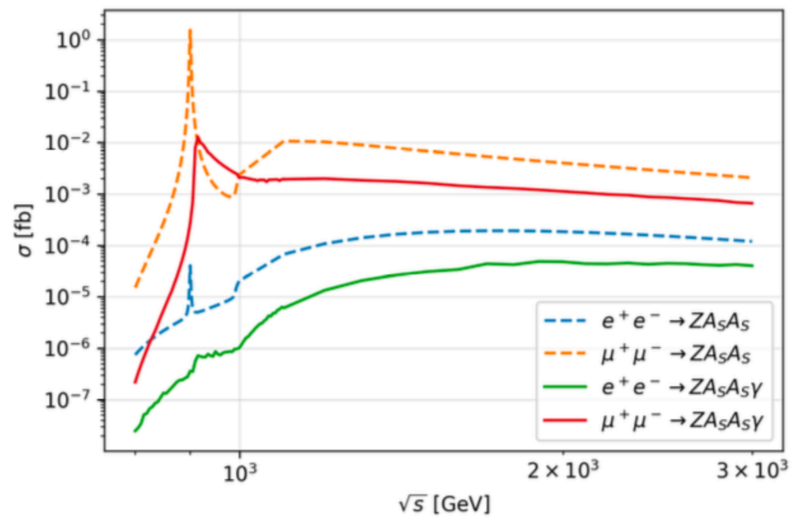
Signals at lepton colliders







Mono-photon + Missing Energy



Mono-Z + Missing Energy

Significant enhancements near the higgs resonance region observed in muon colliders due to the muon Yukawa coupling $\Longrightarrow$ complementary searches to LHC.

Preliminary results.

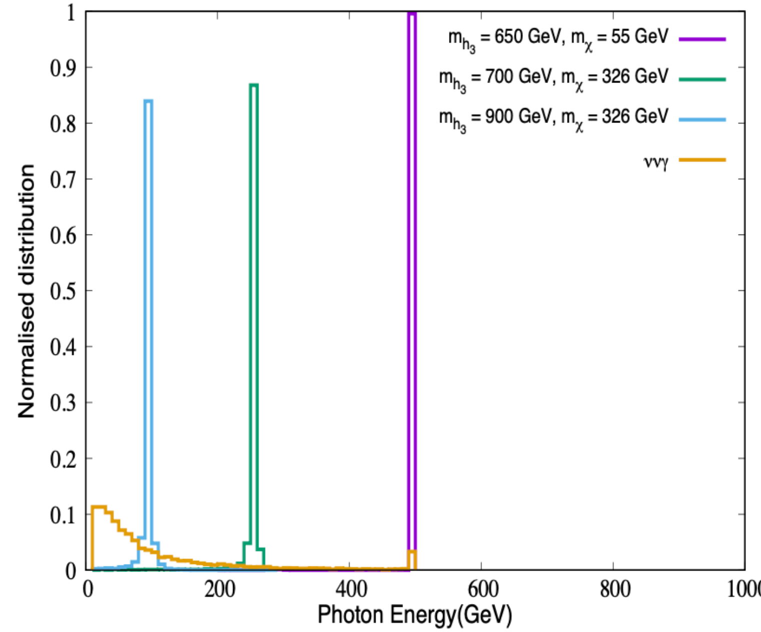
Mono-γ+ missing energy:

- For BP1, with $m_{h_3} = 900$ GeV, significance ~ 2.4 σ at 10 ab^{-1}at 1 TeV muon collider.

- For a lighter Higgs, $m_{h_3} = 700$ GeV, and higher invisible branching to DM ~ 69%, significance ~ 5.3 σ at 10 ab^{-1} for a 1 TeV muon collider.

Mono-Z + missing energy:

- For a lighter Higgs, $m_{h_3} = 600$ sGeV, and light DM~55 GeV and thermal relic, significance ~ 5.3 σ at 10 ab^{-1} for 1 TeV muon collider for leptonic final state.



Benchmarks with heavier Higgs and DM masses and sensitive to higher $\sqrt{s}$ along with potential for other possible signal modes underway!

Summary and Outlook

- We consider the type II 2HDM extended with a complex singlet scalar. For the case where the real part of the complex scalar obtains a vacuum expectation value enabling a mixing between its scalar component and the 2HDM higgs sector. The pseudo scalar component stabilized under a Z_2' symmetry and constitutes DM candidate A_S. The higgs sector consists of $h_1, h_2, h_3, A, H^{\pm}$. The lightest Higgs set to 95 GeV while second-lightest Higgs set to 125 GeV SM-like Higgs.

- Stringent constraints on $\tan\beta, \alpha_1, \alpha_2$ from constraints to fit 95 GeV in bb, $\gamma\gamma$ mode.

- Stringent constraint from boundedness-from-below, direct detection data, indirect detection data from FERMI-LAT $\Longrightarrow$ constrains the DM portal couplings parameter space while being consistent with the 95 GeV excess.

- Potential signals at LHC: Mono-jet + $\not{E}_T$ upto 2.6 σ (NNLO+NNLL) for $m_{h_3} = 900 GeV$ and BR($h_3 \to A_S A_S$) ~ 0.25. Conservative limits placed on m_{h_3}, further improvements for Di-jet + $\not{E}_T$ signals expected for lower m_{h_3}.

- Potentially exciting signals at lepton colliders: e^+e^- and $\mu^+\mu^-$ with enhancements for mono-γ and mono-Z + missing energy signals for the latter. A full collider simulation is underway to span interesting regions of the parameter space - Stay tuned!

Thank You