Dark Matter and Extended Higgs Physics: A Muon Collider Perspective on the Singlet-Enhanced Two Higgs Doublet Model

Sheikh Farah Tabira

with Juhi Dutta, Jayita Lahiri, Cheng Li, Gudrid Moortgat-Pick, Julia Ziegler

Institut für Theoretische Physik
Universität Hamburg

January 23, 2025

2HDMS

- We consider a CP conserving type II Two Higgs Doublet Model extended by complex scalar singlet (2HDMS)
- Φ_1 couples to down-type quarks and Φ_2 couples to up-type quarks
- The scalar potential is,

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

2HDMS

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

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

2HDMS

The singlet and doublet fields can be written as,

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

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

Particle content

$$h_1, h_2, h_3, A, H^\pm, A_S$$

2HDMS

The minimisation conditions are,

$$0 = \frac{\partial V}{\partial \Phi_1}\bigg|_{\substack{\Phi_1=\langle\Phi_1\rangle \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}} = \frac{1}{\sqrt{2}}\left[m_{11}^2 v_1 - m_{12}^2 v_2 + \frac{\lambda_1}{2} v_1^3 + \frac{\lambda_{345}}{2} v_1 v_2^2 + \left(\frac{\lambda_1'}{2} v_1 + \lambda_4' v_1\right) v_S^2\right]$$

$$0 = \frac{\partial V}{\partial \Phi_2}\bigg|_{\substack{\Phi_1=\langle\Phi_1\rangle \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}} = \frac{1}{\sqrt{2}}\left[m_{22}^2 v_2 - m_{12}^2 v_1 + \frac{\lambda_2}{2} v_2^3 + \frac{\lambda_{345}}{2} v_1^2 v_2 + \left(\frac{\lambda_2'}{2} v_2 + \lambda_5' v_2\right) v_S^2\right]$$

$$0 = \frac{\partial V}{\partial S}\bigg|_{\substack{\Phi_1=\langle\Phi_1\rangle \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}} = \frac{1}{\sqrt{2}}\left[m_S^2 v_S + m_S'^2 v_S + \frac{\lambda_1''}{12} v_S^3 + \frac{\lambda_2''}{3} v_S^3 + \frac{\lambda_3''}{4} v_S^3\right.$$

$$\left. + \frac{v_S}{2}\left(\lambda_1' v_1^2 + \lambda_2' v_2^2\right) + v_S\left(\lambda_4' v_1^2 + \lambda_5' v_2^2\right)\right]$$

2HDMS

- Eliminate the free parameters $m_{11}^2, m_{22}^2, m_S^2$
- Set $\lambda_1'' = \lambda_2''$

Interaction basis

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

- where $\tan\beta = \frac{v_2}{v_1}$ and $m_S'^2$ is the coefficient of the DM mass term
- Using the rotation matrix R in terms of the mixing angles $\alpha_1, \alpha_2, \alpha_3$, we go to the mass basis

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

2HDMS

Mass basis

$$m_{h_1}, m_{h_2}, m_{h_3}, m_A, m_{A_S}, m_{H^\pm}, \lambda'_1 - 2\lambda'_4, \lambda'_2 - 2\lambda'_5,$$

$$\tan\beta, v_S, c_{h_1 bb}, c_{h_1 tt}, \tilde{\mu}^2, \lambda''_1 - \lambda''_3, \mathrm{alignm}, \ldots$$

$$c_{h_1 tt} = \frac{\sin(\alpha_1)\cos(\alpha_2)}{\sin(\beta)} \qquad \Rightarrow \alpha_1 = \arctan\left(\frac{c_{h_1 tt}}{c_{h_1 bb}}\tan(\beta)\right),$$

$$c_{h_1 bb} = \frac{\cos(\alpha_1)\cos(\alpha_2)}{\cos(\beta)} \qquad \Rightarrow \alpha_2 = \arccos\left(\cos(\beta)\cdot\sqrt{\tan(\beta)^2 c_{h_1 tt}^2 + c_{h_1 bb}^2}\right)$$

$$\mathrm{alignm} = \left|\sin\left(\beta - (\alpha_1 + \alpha_3\cdot\mathrm{sgn}(\alpha_2))\right)\right| \qquad \Rightarrow \alpha_3 = \frac{\beta - \alpha_1 - \arcsin(\mathrm{alignm})}{\mathrm{sgn}(\alpha_2)}$$

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

2HDMS

Portal Couplings

$$\lambda_1' - 2\lambda_4',$$

$$\lambda_2' - 2\lambda_5'$$

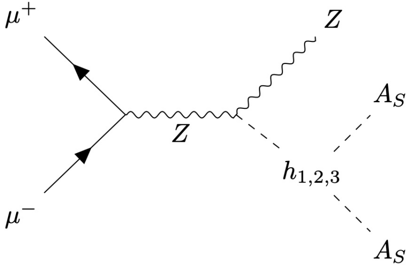
- Couples A_S to h_i
- Influence on DM observables

Benchmarks

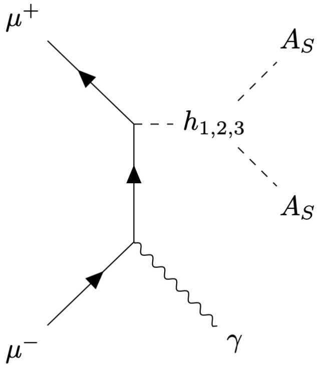
	m_{h_3} (GeV)	m_χ (GeV)	Ωh^2	$BR(h_3 \to \chi\chi)$	$BR(h_2 \to \chi\chi)$
BP3	700	156.0	1.61×10^{-4}	0.69	-
BP55	650	55.6	0.11	3.81×10^{-9}	0.0199
BP2900	2900	1000	0.111	0.04	-

Table: Benchmarks **BP3, BP55, BP2900** with $m_{h_1} = 95.4$ GeV, $m_{h_2} = 125.09$ GeV consistent with theoretical as well as experimental constraints

DM Production Processes



(a) $\mu^- \mu^+ \to Z A_s A_s$

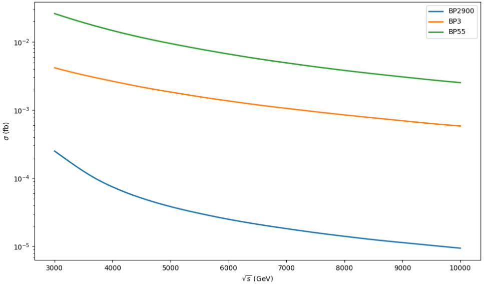


(b) $\mu^- \mu^+ \to A_s A_s \gamma$

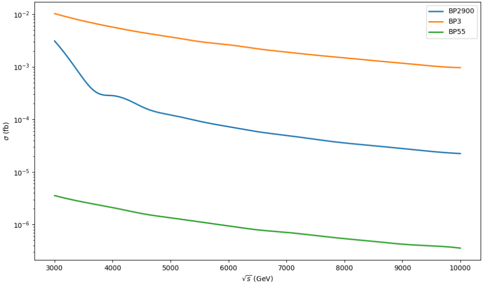
Analysis

- Unpolarised cross sections σ against $\sqrt{s}$
- Polarised cross sections against $\sqrt{s}$ for different P_{eff} [-100%, +100%]
- Angular distribution for ZA_sA_s
- All analysis done using WHIZARD

Cross Sections at the Muon Collider

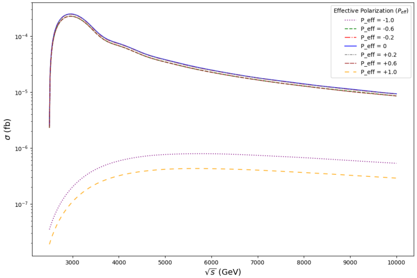


(a) Unpolarised cross sections for $\mu^-\mu^+ \to ZA_sA_s$

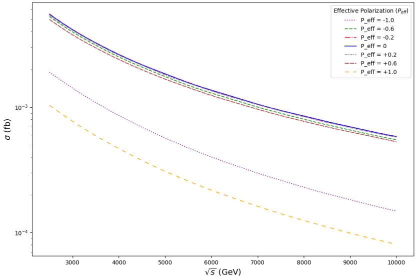


(b) Unpolarised cross sections for $\mu^-\mu^+ \to A_sA_s\gamma$

Polarised Cross Sections: $\mu^-\mu^+ \rightarrow ZA_sA_s$



(a) σ against $\sqrt{s}$ for **BP2900**



(b) σ against $\sqrt{s}$ for **BP3**

Polarised Cross Sections: $\mu^-\mu^+ \to ZA_sA_s$

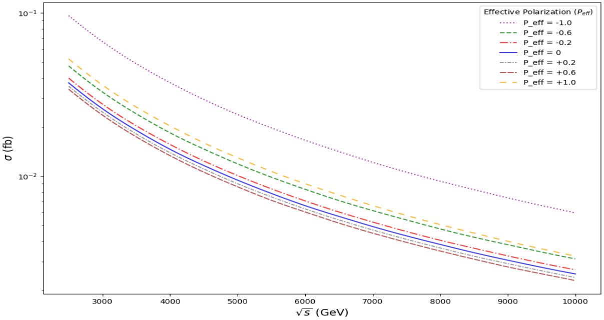


Figure: σ against $\sqrt{s}$ for **BP55**

Angular Distribution for Outgoing Z: $\mu^-\mu^+ \to ZA_sA_s$

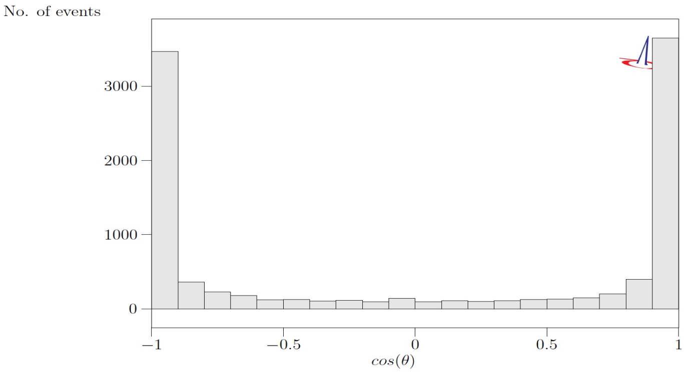
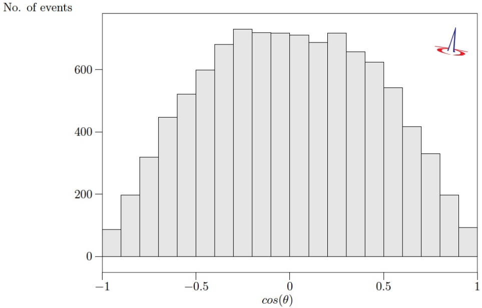
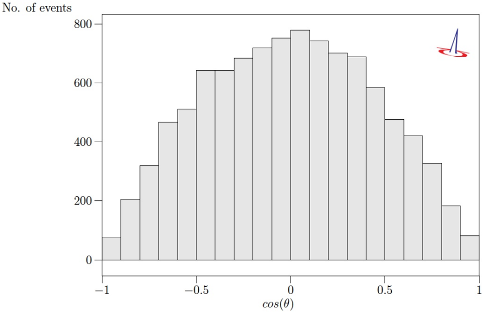


Figure: Unpolarised angular distribution for **BP3** at $\sqrt{s} = 3$ TeV

Angular Distribution of Outgoing Z: $\mu^-\mu^+ \to ZA_sA_s$



(a) Angular distribution for **BP3** at $\sqrt{s} = 3$ TeV for $P_{\text{eff}} = +100\%$



(b) Angular distribution for **BP3** at $\sqrt{s} = 3$ TeV for $P_{\text{eff}} =$ -100%

Angular Distribution of Outgoing Z: $\mu^-\mu^+ \to ZA_sA_s$

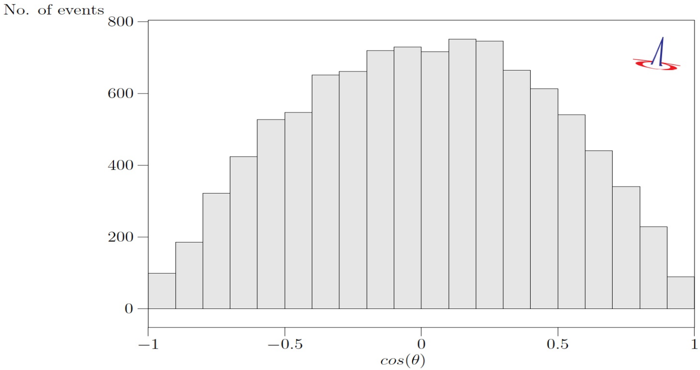
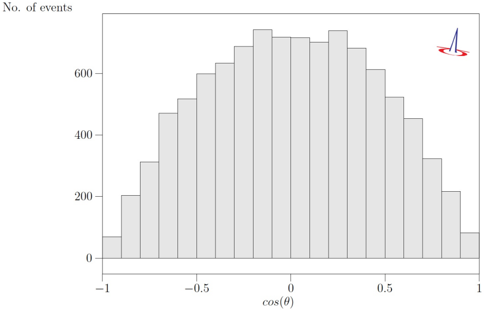
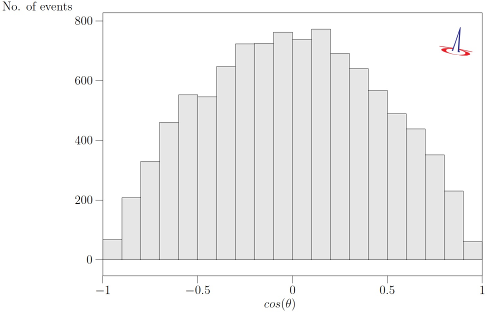


Figure: Unpolarised angular distribution for **BP55** at $\sqrt{s} = 3$ TeV

Angular Distribution for Outgoing Z: $\mu^-\mu^+ \to ZA_sA_s$

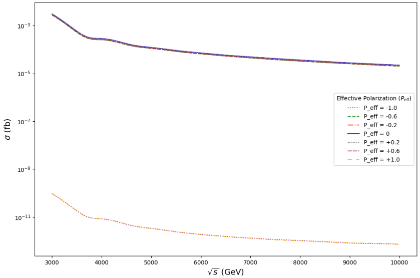


(a) Angular distribution for **BP55** at $\sqrt{s} = 3$ TeV for $P_{\text{eff}} = +100\%$

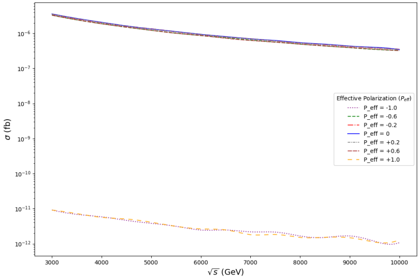


(b) Angular distribution for **BP55** at $\sqrt{s} = 3$ TeV for P_{eff} = -100%

Polarised Cross Sections: $\mu^-\mu^+ \to A_s A_s \gamma$



(a) σ against $\sqrt{s}$ for **BP2900**



(b) σ against $\sqrt{s}$ for **BP55**

Polarised Cross Sections: $\mu^- \mu^+ \to A_s A_s \gamma$

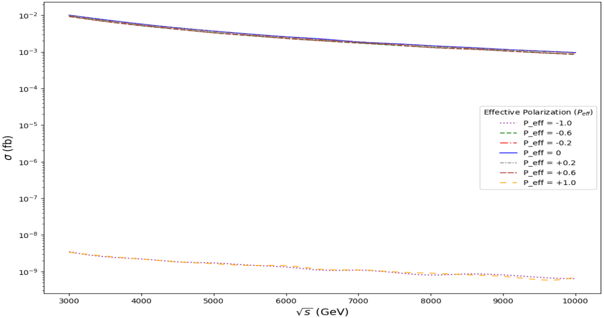


Figure: σ against $\sqrt{s}$ for **BP3**

Takeaways

For $\mu^-\mu^+ \to ZA_sA_s$,

- BP3 gives the best unpolarised cross sections
- Cross sections heavily suppressed at extreme polarisations for BP3 and BP2900 but amplified for BP55

For $\mu^-\mu^+ \to A_sA_s\gamma$

- BP3 gives the best unpolarised cross sections
- Cross sections heavily suppressed at extreme polarisations for all three benchmarks