Dipole DM: Model Definitions

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1 Dipole Dark Matter Model (DipoleDM_full_UFO)

The Dipole DM model extends the SM by adding two Dirac Fermions (χ_1 and χ_0) and a real scalar (ϕ), all singlets under the SM gauge group. The Lagrangian of the model is given by:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\phi + \mathcal{L}_\chi + \mathcal{L}_{\rm dipole} + \mathcal{L}_{H\chi}, \tag{1.1}$$

where $\mathcal{L}_{\rm SM}$ represents the SM Lagrangian and

$$\mathcal{L}_\phi = (\partial^\mu \phi)^2 - \mu_2^2|\phi|^2 - \lambda_2\phi^4 - \lambda_3\phi^2|H|^2\,, \tag{1.2}$$

$$\mathcal{L}_\chi = i\overline{\chi}_i \not{\partial}\chi_i - \tilde{M}_{ij}\overline{\chi}_i\chi_j - (y_\chi)_{ij}\,\overline{\chi}_i\chi_j\phi\,, \tag{1.3}$$

$$\mathcal{L}_{\rm dipole} = \frac{(C_{\gamma\chi\chi})_{ij}}{\Lambda}\overline{\chi}_i\sigma^{\mu\nu}\chi_j F_{\mu\nu}\,, \tag{1.4}$$

$$\mathcal{L}_{H\chi} = \frac{(C_{H\chi\chi})_{ij}}{\Lambda}\overline{\chi}_i\chi_j|H|^2\,. \tag{1.5}$$

In the equations above, $\sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$ and H represents the Higgs doublet.

The model Lagrangian given in Eq. (1.1) contains the scalar potential:

$$V_{H,\phi} = \mu_1^2|H|^2 + \lambda_1|H|^4 + \mu_2^2\phi^2 + \lambda_2\phi^4 + \lambda_3\phi^2|H|^2\,. \tag{1.6}$$

Assuming that both H and ϕ develop vevs, $\langle\phi\rangle = v_D/\sqrt{2}$ and $\langle H\rangle = v/\sqrt{2}$, we obtain the mass eigenstates h and S:

$$\begin{aligned} h &= (\sqrt{2}H^0 - v)\cos\alpha - (\sqrt{2}\phi - v_D)\sin\alpha\,, \\ S &= (\sqrt{2}\phi - v_D)\cos\alpha + (\sqrt{2}H^0 - v)\sin\alpha\,. \end{aligned} \tag{1.7}$$

Where the mixing angle (α) is given by

$$\tan(2\alpha) \equiv \frac{\lambda_3 v v_D}{\lambda_1 v^2 - \lambda_2 v_D^2}\,. \tag{1.8}$$

and with masses:

$$m_{S,h}^2 = \lambda_1 v^2 + \lambda_2 v_D^2 \mp \left(\lambda_1 v^2 - \lambda_2 v_D^2\right)\sqrt{1 + \tan^2(2\alpha)}\,, \tag{1.9}$$

Using the above equations, we can express the quartic couplings (λ_i) and the mass parameters (μ_i) in terms of the physical masses, mixing angle and vevs:

$$\lambda_1 = \frac{1}{2v^2}\left(\cos^2\alpha\, m_h^2 + m_S^2 \sin^2\alpha\right), \tag{1.10}$$

$$\lambda_2 = \frac{1}{2v_D^2}\left(\cos^2\alpha\, m_S^2 + m_h^2 \sin^2\alpha\right), \tag{1.11}$$

$$\lambda_3 = \frac{1}{v_D v}\left(m_S^2 - m_h^2\right)\sin\alpha\cos\alpha\,, \tag{1.12}$$

$$\mu_1^2 = -\left(\lambda_1 v^2 + \lambda_3 \frac{v_D^2}{2}\right), \tag{1.13}$$

$$\mu_2^2 = -\left(\lambda_2 v_D^2 + \lambda_3 \frac{v^2}{2}\right) \tag{1.14}$$

Therefore, the parameters of the scalar potential ($\mu_{1,2}$ and $\lambda_{1,2,3}$) can be replaced by m_h, m_S, v, v_D and $\sin\alpha$.

Finally, the dark fermion mass matrix $\tilde{M}_{ij}$ is defined in the mass eigenstate basis:

$$\tilde{M}_{ij} = M_i\delta_{ij} - \frac{v_D}{\sqrt{2}}(y_\chi)_{ij} - \frac{v^2}{2\Lambda}(C_{H\chi\chi})_{ij}$$

where M_i are the physical masses.

In addition to the Lagrangian in Eq. (1.1), the effective $h - G - G$ and $S - G - G$ couplings induced by a top quark loop were also included as effective operators:

$$\mathcal{L}_{GG\phi} = -\frac{1}{4}\cos\alpha F(m_h^2/m_t^2)G^{\mu\nu}G_{\mu\nu}h - \frac{1}{4}\sin\alpha F(m_S^2/m_t^2)G^{\mu\nu}G_{\mu\nu}S$$

where $F(x)$ is the effective loop function.

Model Parameters

The model parameters are given in Table 1 as well as their naming convention in the UFO model and their default values. The $C_{\gamma\chi\chi}$ and $C_{H\chi\chi}$ matrices are assumed to be real and symmetric.

Feynman rules

The relevant Feynman rules for the BSM particles are given in Table 2 below. Here, f represents any of the SM fermions and q any SM quark.

Table 1. Model parameters, their respective names in the UFO model and default values.

Parameter	UFO name	Default Value
Λ	LambdaUV	5 TeV
$(C_{\gamma\chi\chi})_{11}$	Caxx1	0
$(C_{\gamma\chi\chi})_{00}$	Caxx0	0
$(C_{\gamma\chi\chi})_{10}$	Caxx10	0.1
$(C_{H\chi\chi})_{11}$	Chxx1	0
$(C_{H\chi\chi})_{00}$	Chxx0	0
$(C_{H\chi\chi})_{10}$	Chxx10	0.1
$(y_\chi)_{11}$	ychi1	1.0
$(y_\chi)_{00}$	ychi0	0
$(y_\chi)_{10}$	ychi10	0
$\sin\alpha$	sina	0.2
v_D	vevD	1 TeV
m_S	MSd	1.5 TeV
M_0	M0	425 GeV
M_1	M1	500 GeV

Table 2. Feynman rules for the relevant interactions in the full model.

Interaction	Vertex term
$\chi_i\,\chi_j\,h$	$\frac{i}{\sqrt{2}}(y_\chi)_{ij}\sin\alpha - i\frac{v}{\Lambda}(C_{H\chi\chi})_{ij}\cos\alpha$
$\chi_i\,\chi_j\,A^\mu$	$-i\frac{1}{\Lambda}(C_{\gamma\chi\chi})_{ij}(\gamma^\mu \not{p} - \not{p}\gamma^\mu)$
$S\,\chi_i\,\chi_j$	$-\frac{i}{\sqrt{2}}(y_\chi)_{ij}\cos\alpha - i\frac{v}{\Lambda}(C_{H\chi\chi})_{ij}\sin\alpha$
$S\,h\,h$	$-i\frac{m_S^2}{2v}\left(1+2\frac{m_h^2}{m_S^2}\right)\left(\cos\alpha + 2\frac{v}{v_D}\sin\alpha\right)\sin(2\alpha)$
$S\,f\,\bar{f}$	$-i\frac{m_f}{v}\sin\alpha$
$S\,W_\mu^-\,W_\nu^+$	$2ig^{\mu\nu}\frac{m_W^2}{v}\sin\alpha$
$S\,Z_\mu\,Z_\nu$	$2ig^{\mu\nu}\frac{m_Z^2}{v}\sin\alpha$

2 Minimal Dipole Model (DipoleDM_minimal_UFO)

The minimal scenario assumes that χ_0 only couples through the effective operators and these have zero entries in the diagonal:

$$(C_{\gamma\chi\chi})_{ij} = (C_{H\chi\chi})_{ij} = 0 \text{ , if } i = j \tag{2.1}$$

$$(y_\chi)_{ij} = 0 \text{ , if } i = 0 \text{ or } j = 0 \tag{2.2}$$

With the above assumptions the Lagrangian simplifies to:

$$\mathcal{L}_\chi = i\overline{\chi}_i \not{\partial} \chi_i - \tilde{M}_{ij}\overline{\chi}_i \chi_j - (y_\chi)_{11}\,\overline{\chi}_1 \chi_1 \phi\,, \tag{2.3}$$

$$\mathcal{L}_{\text{dipole}} = \frac{(C_{\gamma\chi\chi})_{01}}{\Lambda}\overline{\chi}_0 \sigma^{\mu\nu} \chi_1 F_{\mu\nu} + h.c.\,, \tag{2.4}$$

$$\mathcal{L}_{H\chi} = \frac{(C_{H\chi\chi})_{01}}{\Lambda}\overline{\chi}_0 \chi_1 |H|^2 + h.c.\,. \tag{2.5}$$

resulting in the vertices given in Table 3.

Table 3. Feynman rules for the relevant interactions in the **minimal** model.

Interaction	**Vertex term (Minimal)**
$\chi_1\,\chi_1\,h$	$\frac{i}{\sqrt{2}}(y_\chi)_{11}\sin\alpha$
$S\,\chi_1\,\chi_1$	$-\frac{i}{\sqrt{2}}(y_\chi)_{11}\cos\alpha$
$\chi_1\,\chi_0\,h$	$-i\frac{v}{\Lambda}(C_{H\chi\chi})_{01}\cos\alpha$
$S\,\chi_1\,\chi_0$	$-i\frac{v}{\Lambda}(C_{H\chi\chi})_{01}\sin\alpha$
$\chi_1\,\chi_0\,A^\mu$	$-i\frac{1}{\Lambda}(C_{\gamma\chi\chi})_{01}(\gamma^\mu \not{p} - \not{p}\gamma^\mu)$