Higgs-portal dark matter models

Ref: Arcadi, Djouadi, Raidal, 1903.03616, Phys. Rept.

Higgs-portal scalar dark matter

Real scalar field χ for DM, SM Higgs field Φ

$$\mathcal{L} \supset -\frac{1}{2}M_\chi^2\chi^2 - \frac{1}{4}\lambda_\chi\chi^4 - \frac{1}{4}\lambda_{H\chi\chi}\Phi^\dagger\Phi\chi^2$$

Unitary gauge $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$, $\Phi^\dagger\Phi = \frac{1}{2}(v+H)^2 = \frac{v^2}{2} + vH + \frac{H^2}{2}$, $\left\langle \Phi^\dagger\Phi \right\rangle = \frac{v^2}{2}$

Mass term $\mathcal{L} \supset -\frac{1}{2}M_\chi^2\chi^2 - \frac{1}{4}\lambda_{H\chi\chi}\left\langle \Phi^\dagger\Phi \right\rangle\chi^2 = -\frac{1}{2}m_\chi^2\chi^2$, $m_\chi^2 = M_\chi^2 + \frac{1}{4}\lambda_{H\chi\chi}v^2$

Higgs-portal coupling $\mathcal{L} \supset -\frac{1}{4}\lambda_{H\chi\chi}vH\chi^2 - \frac{1}{8}\lambda_{H\chi\chi}H^2\chi^2$

H-χ-χ vertex $H - \begin{matrix}\chi \\ \chi\end{matrix} = -\frac{i}{2}\lambda_{H\chi\chi}v$ SM H-f-f vertex $H - \begin{matrix}\nearrow f \\ \nwarrow f\end{matrix} = -i\frac{m_f}{v}$

DM-quark scattering $\chi(p_1) + q(k_1) \to \chi(p_2) + q(k_2)$,

$$\begin{matrix} \chi \diagdown\!\diagup \chi \\ \quad | H \\ q \nearrow\!\searrow q \end{matrix}$$

$q \equiv p_1 - p_2 = k_2 - k_1$, $t \equiv q^2$

$$i\mathcal{M}_{\chi q} = -\frac{i}{2}\lambda_{H\chi\chi}v\frac{i}{t - m_H^2}\left(-i\frac{m_q}{v}\right)\bar{u}(k_2)u(k_1) \xrightarrow{t\to 0} \frac{i\lambda_{H\chi\chi}m_q}{2m_H^2}\bar{u}(k_2)u(k_1)$$

Effective vertex $\begin{matrix}\chi \diagdown\!\diagup \chi \\ q \nearrow\!\searrow q\end{matrix} = iG_{\chi q}$, $G_{\chi q} \equiv \frac{\lambda_{H\chi\chi}m_q}{2m_H^2}$

DM-quark effective interaction $\mathcal{L}_{\chi q} = \sum_q \frac{G_{\chi q}}{2}\chi^2\bar{q}q$

DM-nucleon effective interaction $\mathcal{L}_{\chi N} = \sum_{N=n,p}\frac{G_{\chi N}}{2}\chi^2\bar{N}N$

$G_{\chi N} = m_N\sum_q \frac{G_{\chi q}}{m_q}f_q^N = \frac{\lambda_{H\chi\chi}m_N f_N}{2m_H^2}$, $f_N \equiv \sum_q f_q^N$, $f_c^N = f_b^N = f_t^N \equiv f_Q^N = \frac{2}{27}(1 - f_u^N - f_d^N - f_s^N)$

$f_u^p = 0.0208 \pm 0.0015$, $f_d^p = 0.0411 \pm 0.0028$

$f_u^n = 0.0189 \pm 0.0014$, $f_d^n = 0.0451 \pm 0.0027$ [Hoferichter, *et al*., 1506.04142, PRL]

$f_s^p = f_s^n = 0.043 \pm 0.011$ [Junnarkar, Walker-Loud, 1301.1114, PRD]

$\Rightarrow$ $f_u^p + f_d^p + f_s^p = 0.105$, $f_u^n + f_d^n + f_s^n = 0.107$

$\Rightarrow$ $f_Q^p = 0.0663$, $f_Q^n = 0.0661$

$\Rightarrow$ $f_p = \sum_q f_q^p = 0.304$, $f_n = \sum_q f_q^n = 0.305$, $f_p \simeq f_n$

HiggsPortal_01.eps

Spin-independent DM-nucleon scattering cross section [Eq. (16) in Yu *et al*., 1112.6052, NPB]

$$\sigma_{\chi N}^{\rm SI} = \frac{m_N^2 G_{\chi N}^2}{4\pi (m_\chi + m_N)^2} = \frac{\lambda_{H\chi\chi}^2 m_N^4 f_N^2}{16\pi m_H^4 (m_\chi + m_N)^2}$$

$$m_p \simeq m_n, \quad f_p \simeq f_n \quad \Rightarrow \quad \sigma_{\chi p}^{\rm SI} \simeq \sigma_{\chi n}^{\rm SI}$$

Invisible Higgs decay $H \to \chi\chi$

$$i\mathcal{M} = -\frac{i}{2}\lambda_{H\chi\chi} v, \quad |\mathcal{M}|^2 = \frac{1}{4}\lambda_{H\chi\chi}^2 v^2$$

Invisible Higgs decay width $\Gamma_{\rm inv} = \frac{1}{2}\frac{|\mathcal{M}|^2}{16\pi m_H}\sqrt{1-\frac{4m_\chi^2}{m_H^2}} = \frac{\lambda_{H\chi\chi}^2 v^2 \beta_\chi}{128\pi m_H}, \quad \beta_\chi \equiv \sqrt{1-\frac{4m_\chi^2}{m_H^2}}$

Higgs-portal Majorana fermionic dark matter

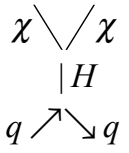
Majorana spinor field χ for DM, SM Higgs field Φ

$$\mathcal{L} \supset -\frac{1}{2}M_\chi \bar{\chi}\chi - \frac{\lambda_{H\chi\chi}}{4\Lambda}\Phi^\dagger \Phi \bar{\chi}\chi$$

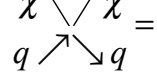
Mass term $\mathcal{L} \supset -\frac{1}{2}M_\chi \bar{\chi}\chi - \frac{\lambda_{H\chi\chi}}{4\Lambda}\frac{v^2}{2}\bar{\chi}\chi = -\frac{1}{2}m_\chi \bar{\chi}\chi, \quad m_\chi = M_\chi + \frac{\lambda_{H\chi\chi}v^2}{4\Lambda}$

Higgs-portal coupling $\mathcal{L} \supset -\frac{\lambda_{H\chi\chi}v}{4\Lambda}H\bar{\chi}\chi$, H-χ-χ vertex $H - \begin{matrix}\chi \\ \chi\end{matrix} = -\frac{i\lambda_{H\chi\chi}v}{2\Lambda}$

DM-quark scattering $\chi(p_1) + q(k_1) \to \chi(p_2) + q(k_2)$,



$$i\mathcal{M}_{\chi q} = -\frac{i\lambda_{H\chi\chi}v}{2\Lambda}\frac{i}{t-m_H^2}\left(-i\frac{m_q}{v}\right)\bar{u}(k_2)u(k_1) \xrightarrow{t\to 0} \frac{i\lambda_{H\chi\chi}m_q}{2\Lambda m_H^2}\bar{u}(k_2)u(k_1)$$

Effective vertex  $= iG_{\chi q}, \qquad G_{\chi q} \equiv \frac{\lambda_{H\chi\chi}m_q}{2\Lambda m_H^2}$

DM-quark effective interaction $\mathcal{L}_{\chi q} = \sum_q \frac{G_{\chi q}}{2}\bar{\chi}\chi\bar{q}q$

DM-nucleon effective interaction $\mathcal{L}_{\chi N} = \sum_{N=n,p}\frac{G_{\chi N}}{2}\bar{\chi}\chi\bar{N}N$

$$G_{\chi N} = m_N \sum_q \frac{G_{\chi q}}{m_q} f_q^N = \frac{\lambda_{H\chi\chi}m_N f_N}{2\Lambda m_H^2}$$

Spin-independent DM-nucleon scattering cross section [Eq. (44) in Zheng *et al*., 1012.2022, NPB]

$$\sigma_{\chi N}^{\rm SI} = \frac{m_N^2 m_\chi^2 G_{\chi N}^2}{\pi (m_\chi + m_N)^2} = \frac{\lambda_{H\chi\chi}^2 m_N^4 m_\chi^2 f_N^2}{4\pi\Lambda^2 m_H^4 (m_\chi + m_N)^2}$$

HiggsPortal_02.eps

Invisible Higgs decay $H(p) \to \chi(k_1) + \chi(k_2)$

$$i\mathcal{M} = -\frac{i\lambda_{H\chi\chi} v}{2\Lambda}\bar{u}(k_1)v(k_2), \quad (i\mathcal{M})^* = \frac{i\lambda_{H\chi\chi} v}{2\Lambda}\bar{v}(k_2)u(k_1)$$

$$\overline{|\mathcal{M}|^2} = \sum_{\text{spins}} |\mathcal{M}|^2 = \frac{\lambda_{H\chi\chi}^2 v^2}{4\Lambda^2}\sum_{\text{spins}} \text{tr}[u(k_1)\bar{u}(k_1)v(k_2)\bar{v}(k_2)] = \frac{\lambda_{H\chi\chi}^2 v^2}{4\Lambda^2}\text{tr}[(\not{k}_1 + m_\chi)(\not{k}_2 - m_\chi)]$$

$$= \frac{\lambda_{H\chi\chi}^2 v^2}{4\Lambda^2}[\text{tr}(\not{k}_1\not{k}_2) - 4m_\chi^2\text{tr}(\mathbf{1})] = \frac{\lambda_{H\chi\chi}^2 v^2}{\Lambda^2}(k_1 \cdot k_2 - m_\chi^2)$$

$$m_H^2 = (k_1 + k_2)^2 = 2m_\chi^2 + 2k_1 \cdot k_2, \quad k_1 \cdot k_2 = \frac{m_H^2}{2} - m_\chi^2$$

$$k_1 \cdot k_2 - m_\chi^2 = \frac{m_H^2}{2} - 2m_\chi^2 = \frac{m_H^2}{2}\left(1 - \frac{4m_\chi^2}{m_H^2}\right) = \frac{m_H^2\beta_\chi^2}{2}$$

Invisible Higgs decay width $\Gamma_{\text{inv}} = \frac{1}{2}\frac{\overline{|\mathcal{M}|^2}}{16\pi m_H}\sqrt{1 - \frac{4m_\chi^2}{m_H^2}} = \frac{\lambda_{H\chi\chi}^2 v^2 m_H \beta_\chi^3}{64\pi\Lambda^2}$

Higgs-portal vector dark matter

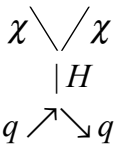
Real vector field χ^μ for DM, SM Higgs field Φ

$$\mathcal{L} \supset \frac{1}{2}M_\chi^2\chi_\mu\chi^\mu + \frac{1}{4}\lambda_\chi(\chi_\mu\chi^\mu)^2 + \frac{1}{4}\lambda_{H\chi\chi}\Phi^\dagger\Phi\chi_\mu\chi^\mu$$

Mass term $\mathcal{L} \supset \frac{1}{2}M_\chi^2\chi_\mu\chi^\mu + \frac{1}{4}\lambda_{H\chi\chi}\frac{v^2}{2}\chi_\mu\chi^\mu = \frac{1}{2}m_\chi^2\chi_\mu\chi^\mu, \quad m_\chi^2 = M_\chi^2 + \frac{1}{4}\lambda_{H\chi\chi}v^2$

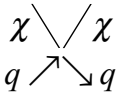
Higgs-portal coupling $\mathcal{L} \supset \frac{1}{4}\lambda_{H\chi\chi}vH\chi_\mu\chi^\mu$, H-χ-χ vertex $H -\!\!<\!\!\begin{matrix}\chi_\mu \\ \chi_\nu\end{matrix} = \frac{i}{2}\lambda_{H\chi\chi}vg^{\mu\nu}$

χq scattering $\chi(p_1) + q(k_1) \to \chi(p_2) + q(k_2)$,



$$q \equiv p_1 - p_2 = k_2 - k_1, \quad t \equiv q^2$$

$$i\mathcal{M}_{\chi q} = \varepsilon_\mu(p_1)\varepsilon_\nu^*(p_2)\frac{i}{2}\lambda_{H\chi\chi}v\frac{i}{t - m_H^2}\left(-i\frac{m_q}{v}\right)\bar{u}(k_2)u(k_1) \xrightarrow{t\to 0} -\frac{i\lambda_{H\chi\chi}m_q}{2m_H^2}\varepsilon_\mu(p_1)\varepsilon_\nu^*(p_2)\bar{u}(k_2)u(k_1)$$

Effective vertex  $= iG_{\chi q}, \qquad G_{\chi q} \equiv -\frac{\lambda_{H\chi\chi}m_q}{2m_H^2}$

DM-quark effective interaction $\mathcal{L}_{\chi q} = \sum_q \frac{G_{\chi q}}{2}\chi_\mu\chi^\mu\bar{q}q$

DM-nucleon effective interaction $\mathcal{L}_{\chi N} = \sum_{N=n,p}\frac{G_{\chi N}}{2}\chi_\mu\chi^\mu\bar{N}N$

$$G_{\chi N} = m_N\sum_q \frac{G_{\chi q}}{m_q}f_q^N = -\frac{\lambda_{H\chi\chi}m_N f_N}{2m_H^2}$$

HiggsPortal_03.eps

Spin-independent DM-nucleon scattering cross section [Eq. (50) in Yu *et al*., 1112.6052, NPB]

$$\sigma_{\chi N}^{\rm SI} = \frac{m_N^2 G_{\chi N}^2}{4\pi (m_\chi + m_N)^2} = \frac{\lambda_{H\chi\chi}^2 m_N^4 f_N^2}{16\pi m_H^4 (m_\chi + m_N)^2}$$

Invisible Higgs decay $H(p) \to \chi(k_1) + \chi(k_2)$

$$i\mathcal{M} = \frac{i}{2}\lambda_{H\chi\chi} v g^{\mu\nu} \varepsilon_\mu^*(k_1)\varepsilon_\nu^*(k_2), \quad (i\mathcal{M})^* = -\frac{i}{2}\lambda_{H\chi\chi} v g^{\rho\sigma} \varepsilon_\rho(k_1)\varepsilon_\sigma(k_2)$$

$$k_1^2 = k_2^2 = m_\chi^2, \quad \frac{k_1 \cdot k_2}{m_\chi^2} = \frac{m_H^2}{2m_\chi^2} - 1$$

$$\overline{|\mathcal{M}|^2} = \sum_{\rm spins} |\mathcal{M}|^2 = \frac{\lambda_{H\chi\chi}^2 v^2}{4} \sum_{\rm spins} g^{\mu\nu} g^{\rho\sigma} \varepsilon_\mu^*(k_1)\varepsilon_\rho(k_1)\varepsilon_\nu^*(k_2)\varepsilon_\sigma(k_2)$$

$$= \frac{\lambda_{H\chi\chi}^2 v^2}{4} g^{\mu\nu} g^{\rho\sigma} \left(-g_{\mu\rho} + \frac{k_{1\mu}k_{1\rho}}{m_\chi^2}\right)\left(-g_{\nu\sigma} + \frac{k_{2\nu}k_{2\sigma}}{m_\chi^2}\right) = \frac{\lambda_{H\chi\chi}^2 v^2}{4}\left(\delta^\nu{}_\rho - \frac{k_1^\nu k_{1\rho}}{m_\chi^2}\right)\left(\delta^\rho{}_\nu - \frac{k_{2\nu}k_2^\rho}{m_\chi^2}\right)$$

$$= \frac{\lambda_{H\chi\chi}^2 v^2}{4}\left[4 - \frac{k_1^2}{m_\chi^2} - \frac{k_2^2}{m_\chi^2} + \frac{(k_1\cdot k_2)^2}{m_\chi^4}\right] = \frac{\lambda_{H\chi\chi}^2 v^2}{4}\left[2 + \left(\frac{m_H^2}{2m_\chi^2} - 1\right)^2\right]$$

$$= \frac{\lambda_{H\chi\chi}^2 v^2}{4}\left(3 + \frac{m_H^4}{4m_\chi^4} - \frac{m_H^2}{m_\chi^2}\right) = \frac{\lambda_{H\chi\chi}^2 v^2 m_H^4}{16 m_\chi^4}\left(1 - \frac{4m_\chi^2}{m_H^2} + \frac{12m_\chi^4}{m_H^4}\right)$$

Invisible Higgs decay width $\Gamma_{\rm inv} = \frac{1}{2}\frac{\overline{|\mathcal{M}|^2}}{16\pi m_H}\sqrt{1 - \frac{4m_\chi^2}{m_H^2}} = \frac{\lambda_{H\chi\chi}^2 v^2 m_H^3 \beta_\chi}{512\pi m_\chi^4}\left(1 - \frac{4m_\chi^2}{m_H^2} + \frac{12m_\chi^4}{m_H^4}\right)$

HiggsPortal_04.eps