Coscattering Dark Matter in Inverse Scotogenic Models

Zhi-Long Han

School of Physics and Technology, University of Jinan

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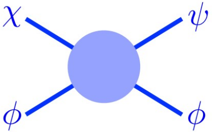
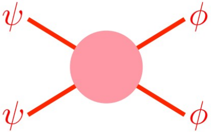
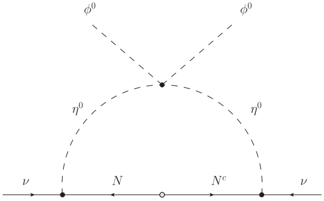
Introduction

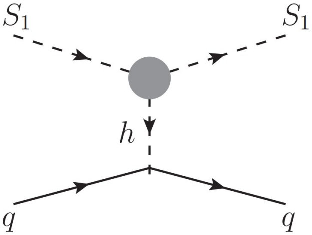
- ⋆ The WIMP dark matter typically requires a thermally averaged annihilation cross section $\langle \sigma v \rangle \sim 2 \times 10^{-26}\text{cm}^3\text{s}^{-1}$.
- ⋆ Well known three exceptions [Phys. Rev. D 43, 3191 (1991)]
  - Coannihilation: mutual annihilation of multiple species
  - Forbidden: annihilation into heaver states
  - Resonance: annihilation near a pole in the cross section
- ⋆ The fourth exception [Phys.Rev.Lett. 119 (2017) 6, 061102]
  - Coscattering: inelastic conversions with its heavier partner
  - χ/ψ interchange : $\chi\phi \to \psi\phi$
  - ψ annihilation: $\psi\psi \to \phi\phi$

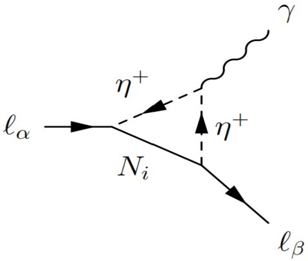




The Scotogenic Model







⋆ Neutrino masses are generated via loop diagrams mediated by the dark particles.

⋆ When dark matter pair annihilates via the Yukawa portal interactions, stringent constraints are from lepton flavor violation.

⋆ When dark matter annihilates via the Higgs/Vector portal interactions, stringent constraints are from direct detection.

⋆ New viable pathway for dark matter: Coscattering mechanism

Theoretical Framework

⋆ Scotogenic inverse model: doublet fermion $\Psi \equiv (\psi^0, \psi^-)^T$, singlet fermion χ and three real singlet scalar $\phi_i (i = 1, 2, 3)$

⋆ Assuming the scalar mass spectrum $m_{\phi_1} \lesssim m_{\phi_2} \ll m_{\phi_3}$ for simplicity

⋆ The most general scalar potential:

$$
\begin{aligned}
-\mathcal{L}_V &= \left(\frac{\lambda_1}{2}\phi_1^2 + \frac{\lambda_2}{2}\phi_2^2 + \lambda_{12}\phi_1\phi_2\right) H^\dagger H + \frac{\lambda_{22}}{4}\phi_1^2\phi_2^2 \\
&\quad + \frac{\lambda_{13}}{6}\phi_1\phi_2^3 + \frac{\lambda_{31}}{6}\phi_1^3\phi_2 + \frac{\lambda_{14}}{12}\phi_1^4 + \frac{\lambda_{24}}{12}\phi_2^4,
\end{aligned}
\tag{1}
$$

⋆ The Yukawa interaction of the dark scalars is

$$
\mathcal{L}_Y = y_{i\alpha}\phi_i \bar{\Psi} \ell_\alpha + \text{H.C.}, \tag{2}
$$

where $\ell_\alpha = (\nu_\alpha, \ell_\alpha^-)^T$ is the SM lepton doublets.

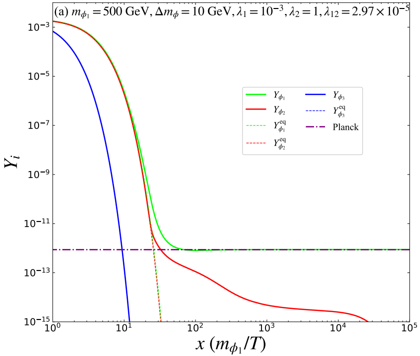
Higgs Portal: Relic Density

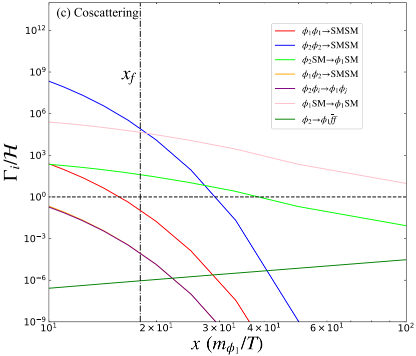
⋆The Boltzmann equation for dark matter ϕ_1 is

$$
\begin{aligned}
\frac{dY_{\phi_1}}{dx} &= -\frac{s}{\mathcal{H}x}\Bigg[\langle\sigma v\rangle_{\phi_1\phi_1\to\mathrm{SMSM}}\left(Y_{\phi_1}^2-(Y_{\phi_1}^{\mathrm{eq}})^2\right)+\langle\sigma v\rangle_{\phi_1\phi_2\to\mathrm{SMSM}}\left(Y_{\phi_1}Y_{\phi_2}-Y_{\phi_1}^{\mathrm{eq}}Y_{\phi_2}^{\mathrm{eq}}\right)\\
&- \langle\sigma v\rangle_{\phi_2\mathrm{SM}\to\phi_1\mathrm{SM}}\left(Y_{\phi_2}Y_{\mathrm{SM}}^{\mathrm{eq}}-\frac{Y_{\phi_2}^{\mathrm{eq}}}{Y_{\phi_1}^{\mathrm{eq}}}Y_{\phi_1}Y_{\mathrm{SM}}^{\mathrm{eq}}\right)-\langle\sigma v\rangle_{\phi_2\phi_2\to\phi_1\phi_1}\left(Y_{\phi_2}^2-\frac{(Y_{\phi_2}^{\mathrm{eq}})^2}{(Y_{\phi_1}^{\mathrm{eq}})^2}Y_{\phi_1}^2\right)\\
&- \langle\sigma v\rangle_{\phi_1\phi_2\to\phi_1\phi_1}\left(Y_{\phi_1}Y_{\phi_2}-\frac{Y_{\phi_2}^{\mathrm{eq}}}{Y_{\phi_1}^{\mathrm{eq}}}Y_{\phi_1}^2\right)-\langle\sigma v\rangle_{\phi_2\phi_2\to\phi_1\phi_2}\left(Y_{\phi_2}^2-\frac{Y_{\phi_2}^{\mathrm{eq}}}{Y_{\phi_1}^{\mathrm{eq}}}Y_{\phi_1}Y_{\phi_2}\right)\\
&- \frac{\Gamma_{\phi_2\to\phi_1\bar{f}f}}{s}\left(Y_{\phi_2}-\frac{Y_{\phi_2}^{\mathrm{eq}}}{Y_{\phi_1}^{\mathrm{eq}}}Y_{\phi_1}\right)\Bigg],
\end{aligned}
\tag{3}
$$

Pair annihilation : $\phi_1\phi_1 \to \mathrm{SMSM}$, Coannihilation : $\phi_1\phi_2 \to \mathrm{SMSM}$ Coscattering : $\phi_2\mathrm{SM} \to \phi_1\mathrm{SM}$, Conversion : $\phi_2\phi_i \to \phi_1\phi_j$, Decay : $\phi_2 \to \phi_1\bar{f}f$

Coscattering Benchmark

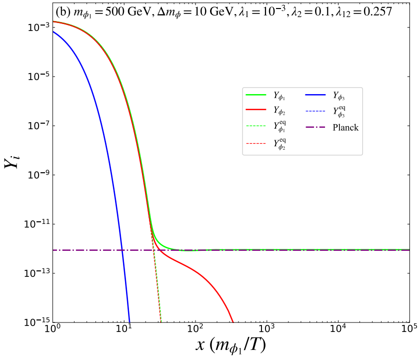


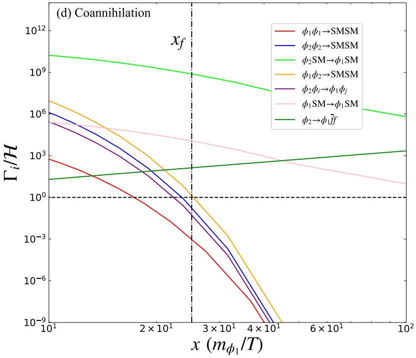


⋆ Large value of λ_2, tiny value of λ_{12}, small value of λ_1.

⋆ The last reaction to decouple which changes the number density of ϕ_1 is the coscattering process $\phi_2\mathrm{SM} \to \phi_1\mathrm{SM}$.

Coannihilation Benchmark

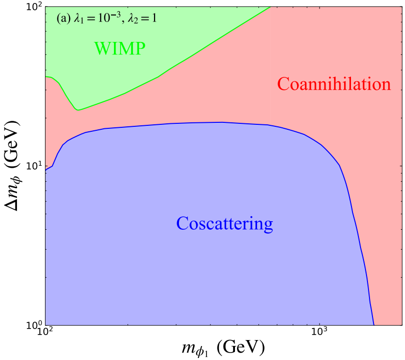


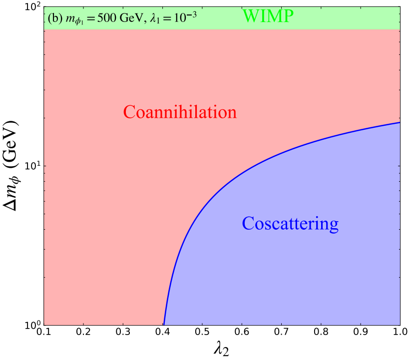


⋆ Relatively large value of λ_2 and λ_{12}, small value of λ_1.

⋆ The last reaction to decouple which changes the number density of ϕ_1 is the coannihilation process $\phi_1\phi_2 \to \mathrm{SMSM}$.

Freeze-out phases





- ⋆ Coscattering favors $\Delta m_\phi \lesssim 20$ GeV, light dark matter $m_{\phi_1} \lesssim 1$ TeV, and large $\lambda_2 \gtrsim 0.4$.
- ⋆ Traditional WIMP favors large mass splitting.
- ⋆ Coannihilation is dominant in the transition region.

Phenomenology of Dark Matter ϕ_1

⋆ Four benchmark scenario:

[a] $\lambda_2 = 1, \Delta m_\phi = 1$ GeV [b] $\lambda_2 = 1, \Delta m_\phi = 10$ GeV

[c] $\lambda_2 = 0.1, \Delta m_\phi = 1$ GeV [d] $\lambda_2 = 0.1, \Delta m_\phi = 10$ GeV

⋆ Perform a scan in the following parameter ranges:

$$m_{\phi_1} \in [10, 2000]\ \mathrm{GeV}, \lambda_1 \in [10^{-4}, 1], \lambda_{12} \in [10^{-5}, 1]. \tag{4}$$

The DM relic density is required within the 3σ range of the Planck result

⋆ The spin-independent scattering cross section is calculated as

$$\sigma_{\rm SI} = \frac{\lambda_1^2 C^2 m_n^4}{4\pi (m_{\phi_1} + m_n)^2 m_h^4}, \tag{5}$$

where $C \simeq 0.3$ is a nucleon matrix element dependent constant, and m_n is the nucleon mass.

Higgs Decay

Light scalars induce new decay modes of the SM Higgs as $h \to \phi_i \phi_j$. The decay widths are calculated as

$$\Gamma_{h\to\phi_1\phi_1} = \frac{\lambda_1^2 v_H^2}{32\pi m_h}\sqrt{1-\frac{4m_{\phi_1}^2}{m_h^2}}, \tag{6}$$

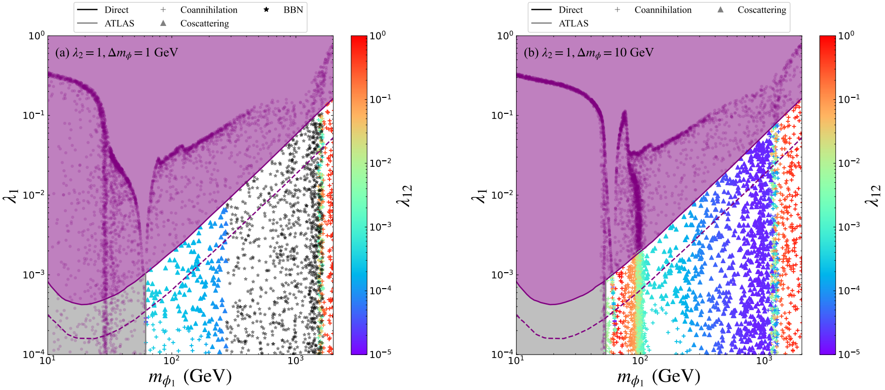
$$\Gamma_{h\to\phi_1\phi_2} = \frac{\lambda_{12}^2 v_H^2}{16\pi m_h^3}\sqrt{(m_h^2-\Delta m_\phi{}^2)(m_h^2-(\Delta m_\phi+2m_{\phi_1})^2)}, \tag{7}$$

$$\Gamma_{h\to\phi_2\phi_2} = \frac{\lambda_2^2 v_H^2}{32\pi m_h}\sqrt{1-\frac{4(m_{\phi_1}+\Delta m_\phi)^2}{m_h^2}}, \tag{8}$$

⋆ The ATLAS upper limits of invisible and undetected non-SM Higgs boson decays are $\mathrm{BR}_{\mathrm{inv.}} < 0.11$ and $\mathrm{BR}_{\mathrm{u.}} < 0.12$.

⋆ For $\lambda_2 \geq 0.1$, the region with $m_{\phi_2} < m_h/2$ is totally excluded.

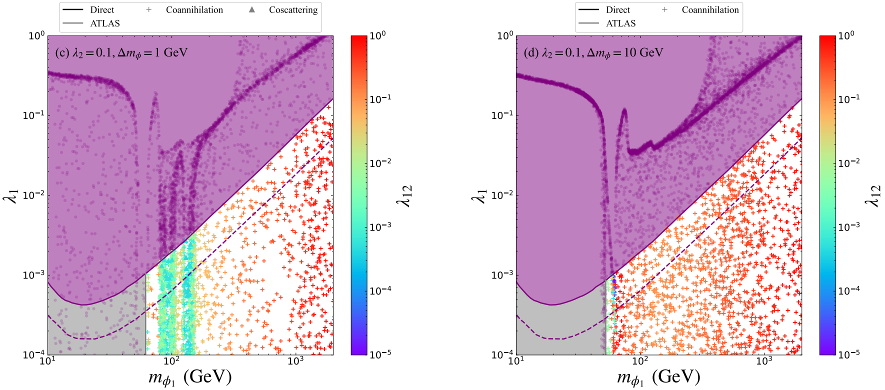
Direct Detection and Higgs Decay



Scenario [a] Samples distributed within $m_{\phi_1} \lesssim 270$ GeV and $3 \times 10^{-4} \lesssim \lambda_1 \lesssim 7.6 \times 10^{-3}$ are dominated by coscattering.

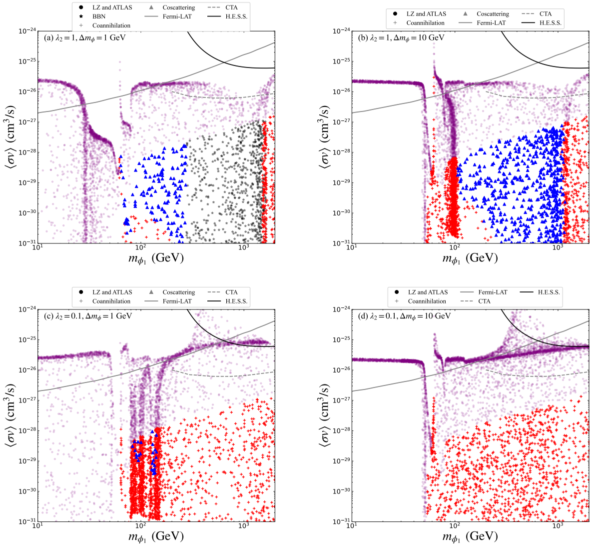
Scenario [b] Increasing Δm_ϕ to 10 GeV can satisfy the BBN constraint for coscattering within 100 GeV $\lesssim m_{\phi_1} \lesssim 1150$ GeV

Direct Detection and Higgs Decay



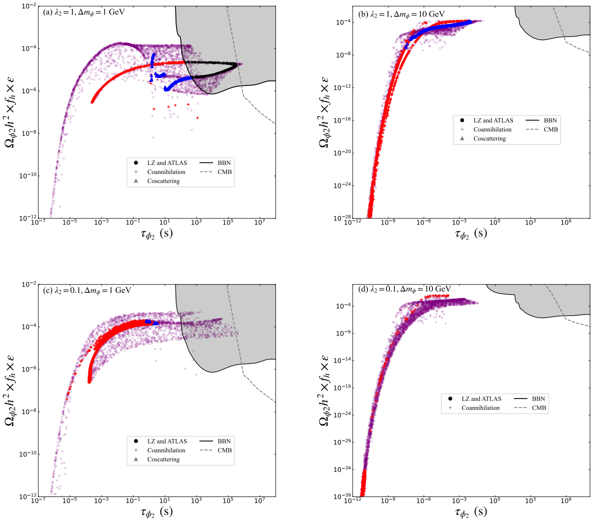
Scenario [c] Coscattering appears around $m_{\phi_1} \sim 100$ GeV.
Scenario [d] No coscattering samples.

Indirect Detection



Under the tight constraints from direct detection, indirect detection is not promising even for the future experiments.

Cosmological constraints on long-lived ϕ_2



The decay width $\Gamma_{\phi_2} \propto \lambda_{12}^2 (\Delta m_\phi)^5$. BBN imposes limits on $\tau_{\phi_2} \gtrsim 50$ s, which exclude certain samples with $\Delta m_\phi = 1$ GeV.

Displaced vertex signature of ϕ_2

⋆ Higgs portal channels at LHC

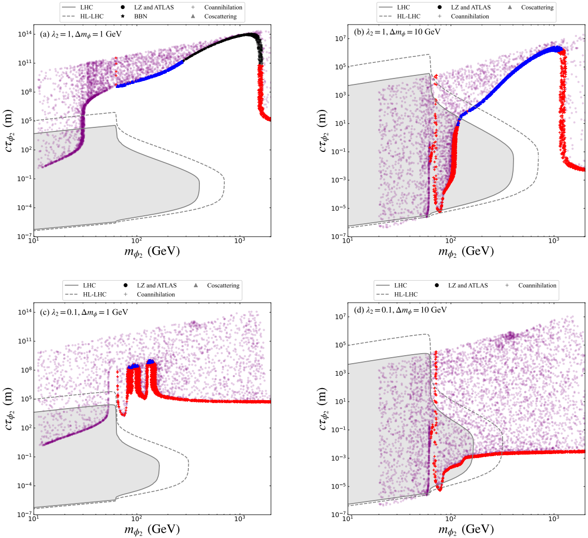
$$pp \to h^{(\star)} \to \phi_1\phi_2 \to \phi_1\phi_1 \bar{f} f, \tag{9}$$
$$pp \to h^{(\star)} \to \phi_2\phi_2 \to \phi_1\phi_1 \bar{f} f \bar{f} f, \tag{10}$$

⋆ The number of events for the one displaced vertex $N_{\rm DV}$ is

$$\begin{aligned} N_{\rm DV} &= L_{\rm int} \times \sigma(pp \to \phi_1\phi_2) \times P_{\rm dec} \times \text{BR}_{\rm vis} \times \kappa_1 \\ &+ 2L_{\rm int} \times \sigma(pp \to \phi_2\phi_2) \times P_{\rm dec} \times \text{BR}_{\rm vis} \times \kappa_2, \end{aligned} \tag{11}$$

$L_{\rm int} = 139$ fb^{-1} for LHC and $L_{\rm int} = 3000$ fb^{-1} for HL-LHC
$P_{\rm dec}$ is the decay probability within detector, BR$_{\rm vis} \simeq 1$,
optimistic estimation with the detection efficiency $\kappa_{1,2} = 1$
vanishing background, the sensitive region is derived with $N_{\rm DV} = 3$

Sensitive region of the one DV



$\Delta m_\phi = 1$ GeV is beyond the reach of LHC.

$\Delta m_\phi = 10$ GeV, LHC covers coannihilation or coscattering samples with $m_{\phi_2} \lesssim 200$ GeV.

Yukawa Portal: Relic Density

⋆The Boltzmann equation for dark matter ϕ_1 is

$$\begin{aligned}\frac{dY_{\phi_1}}{dx} &= -\frac{s}{\mathcal{H}x}\Bigg[\langle\sigma v\rangle_{\phi_1\phi_1\to\bar{\ell}\ell}\left(Y_{\phi_1}^2-(Y_{\phi_1}^{\rm eq})^2\right)+\langle\sigma v\rangle_{\phi_1\phi_2\to\bar{\ell}\ell}\left(Y_{\phi_1}Y_{\phi_2}-Y_{\phi_1}^{\rm eq}Y_{\phi_2}^{\rm eq}\right)\\ &-\langle\sigma v\rangle_{\phi_2\ell\to\phi_1\ell}\left(Y_{\phi_2}Y_\ell^{\rm eq}-\frac{Y_{\phi_2}^{\rm eq}}{Y_{\phi_1}^{\rm eq}}Y_{\phi_1}Y_\ell^{\rm eq}\right)-\frac{\Gamma_{\phi_2\to\phi_1\bar{\ell}\ell}}{s}\left(Y_{\phi_2}-\frac{Y_{\phi_2}^{\rm eq}}{Y_{\phi_1}^{\rm eq}}Y_{\phi_1}\right)\Bigg],\end{aligned} \tag{12}$$

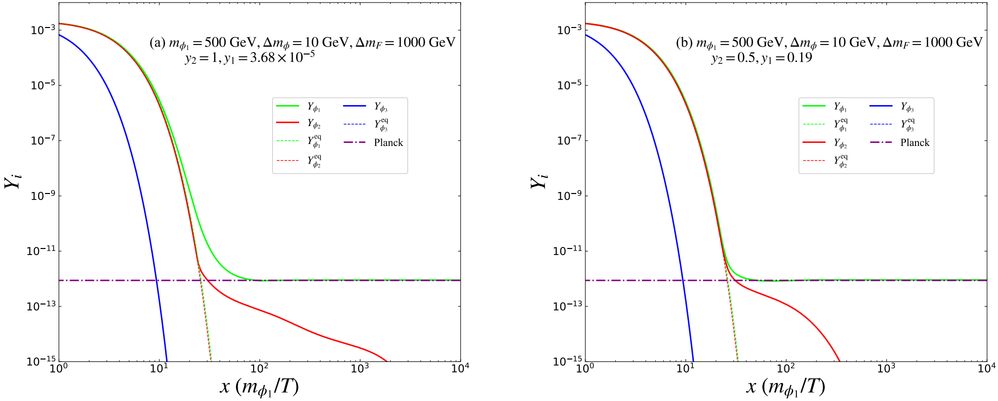
Pair annihilation : $\phi_1\phi_1\to\bar{\ell}\ell$, Coannihilation : $\phi_1\phi_2\to\bar{\ell}\ell$
Coscattering : $\phi_2\mathrm{SM}\to\phi_1\mathrm{SM}$, Decay : $\phi_2\to\phi_1\bar{\ell}\ell$

⋆ Differences from the Higgs portal:

1. No conversion terms $\phi_2\phi_i\to\phi_1\phi_j$ between the scalars
2. Only involve SM leptons via Yukawa interaction $y_{i\alpha}\phi_i\bar{\Psi}\ell_\alpha$

⋆ The effective Yukawa coupling $y_i=\sqrt{|y_{ie}|^2+|y_{i\mu}|^2+|y_{i\tau}|^2}$

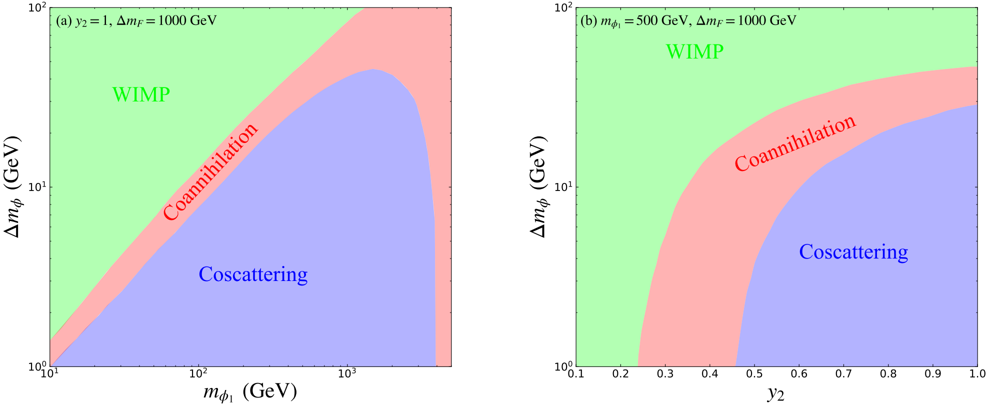
Coscattering and Coannihilation Benchmark



(a): Large value of y_2, tiny value of y_1, Coscattering $\phi_2\ell \to \phi_1\ell$

(b): Relatively large value of y_2, y_1, Coannihilation $\phi_1\phi_2 \to \bar{\ell}\ell$

Freeze-out phase



- ⋆ Coscattering favors $\Delta m_\phi / m_{\phi_1} \lesssim 0.1$, $m_{\phi_1} \lesssim 2$ TeV and $y_2 \gtrsim 0.5$.
- ⋆ Coannihilation favors $\Delta m_\phi / m_{\phi_1} \sim 0.1$, $y_2 \gtrsim 0.25$.

Constraints from LFV

⋆ The branching ratio of $\mu \to e\gamma$ can be expressed as

$$\mathrm{BR}_{\mu\to e\gamma} = \frac{3\alpha_{\rm em}}{64\pi G_f^2 m_F^4}\left|\sum_i y_{ie}^* y_{i\mu} G(m_{\phi_i}^2/m_F^2)\right|^2, \tag{13}$$

where Fermi constant $G_f = 1.17\times 10^{-5}~\mathrm{GeV}^{-2}$ and fine structure constant $\alpha_{\rm em} = 1/137$. And

$$G(a) = \frac{2-3a-6a^2+a^3+6a\log a}{6(1-a)^4}. \tag{14}$$

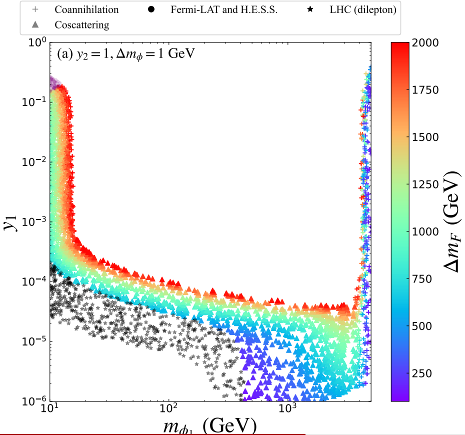
⋆ MEG experiment is $\mathrm{BR}_{\mu\to e\gamma} < 1.5\times 10^{-13}$, which roughly requires the condition $|\sum y_{ie}y_{i\mu}| \lesssim 10^{-3}$ for TeV scale m_F.
⋆ Hierarchical Yukawa couplings as $|y_{ie}| \ll |y_{i\mu}| \lesssim |y_{i\tau}| \sim \mathcal{O}(1)$

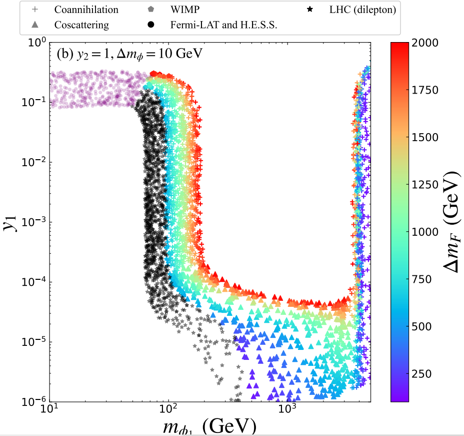
Scan Result

⋆ Four benchmark scenario:

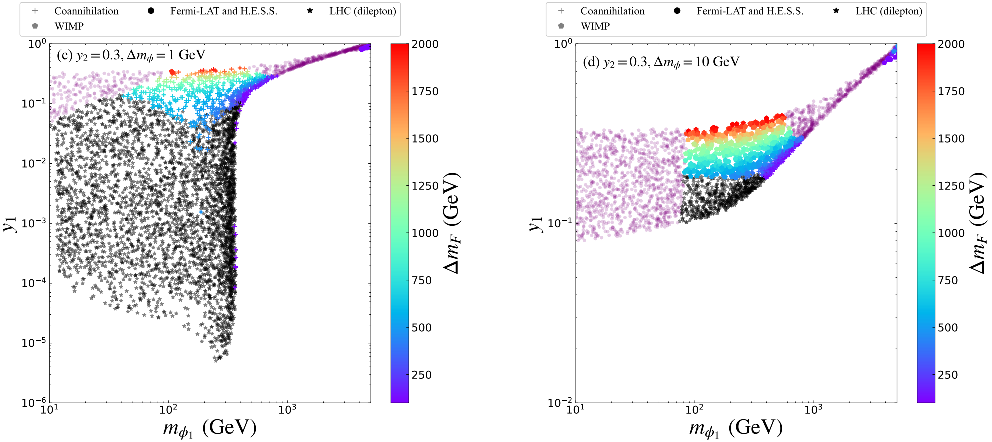
[a] $y_2 = 1, \Delta m_\phi = 1$ GeV [b] $y_2 = 1, \Delta m_\phi = 10$ GeV

[c] $y_2 = 0.1, \Delta m_\phi = 1$ GeV [d] $y_2 = 0.1, \Delta m_\phi = 10$ GeV



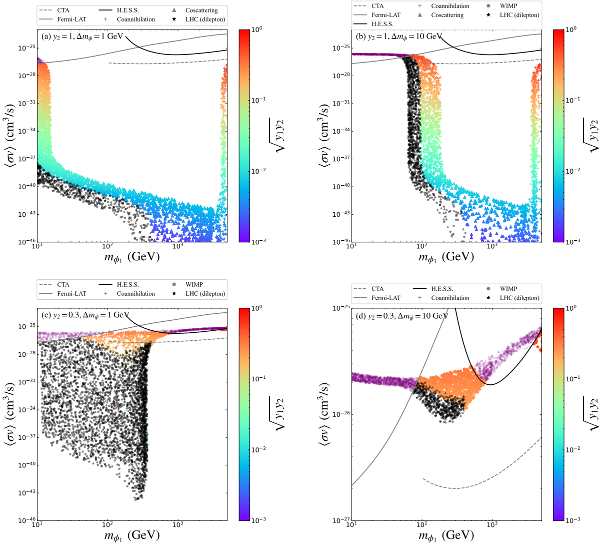


Scan Result



- ⋆ The upper/lower bounds of the samples correspond to the maximum/minimum of Δm_F
- ⋆ Dilepton signature $pp \to \psi^+\psi^- \to \ell^+\ell^- + \not{E}_T$ exclude certain parameter region.

Indirect Detection



- ⋆ WIMP is typically disfavored by indirect detection.
- ⋆ Coannihilation might be tested in the future.
- ⋆ Coscattering is beyond the scope.

Collider Signature through Yukawa Portal

⋆ The dominant processes as

$$pp \to \psi^+\psi^- \to \ell^+\phi_2 + \ell^-\phi_2 \to \ell^+\phi_1\ell^+\ell^- + \ell^-\phi_1\ell^+\ell^-, \tag{15}$$

$$pp \to \bar{\psi}^0\psi^0 \to \bar{\nu}\phi_2 + \nu\phi_2 \to \bar{\nu}\phi_1\ell^+\ell^- + \nu\phi_1\ell^+\ell^-, \tag{16}$$

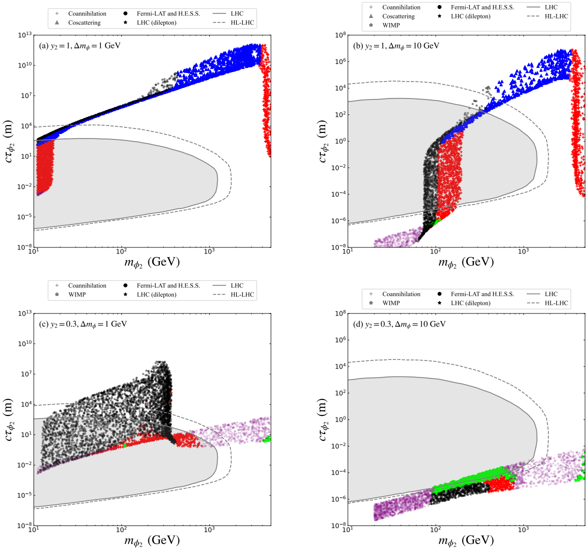
$$pp \to \psi^\pm\psi^0 \to \ell^\pm\phi_2 + \nu\phi_2 \to \ell^\pm\phi_1\ell^+\ell^- + \nu\phi_1\ell^+\ell^-. \tag{17}$$

⋆ The number of events for the one displaced vertex $N_{\rm DV}$ is

$$\begin{aligned} N_{\rm DV} &= 2L_{\rm int} \times \sigma(pp \to \psi^+\psi^-, \bar{\psi}^0\psi^0) \times {\rm BR}^2_{\Psi\to\phi_2\ell} \times P_{\rm dec} \times {\rm BR}_{\rm vis} \times \kappa_1' \\ &+ 2L_{\rm int} \times \sigma(pp \to \psi^\pm\psi^0) \times {\rm BR}^2_{\Psi\to\phi_2\ell} \times P_{\rm dec} \times {\rm BR}_{\rm vis} \times \kappa_2'. \end{aligned}$$

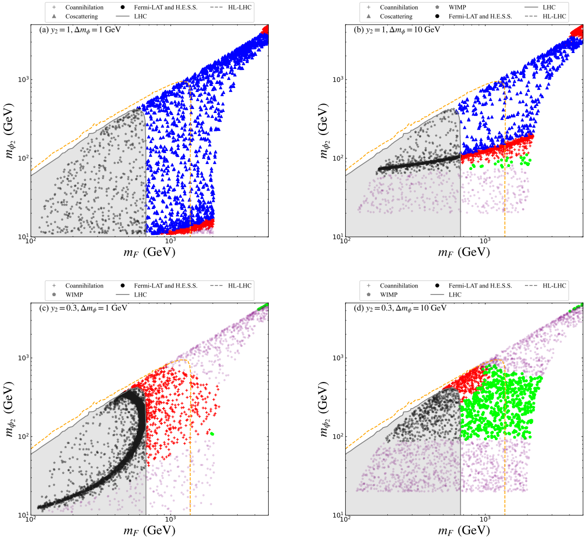
⋆ The decay mode $\phi_2 \to \phi_1\bar{\nu}\nu$, which is invisible at colliders.
The dilepton signature $pp \to \psi^+\psi^- \to \ell^+\ell^- + \not{E}_T$

Displaced Vertex Signature of ϕ_2



LHC could probe coannihilation and coscattering samples with $y_2 = 1$ and m_ϕ below TeV.

Dilepton Signature



- ⋆ LHC has excluded $m_F \lesssim 660$ GeV and $m_{\phi_2} \lesssim 400$ GeV.
- ⋆ HL-LHC probe $m_F \lesssim 1400$ GeV and $m_{\phi_2} \lesssim 900$ GeV.

Conclusion

⋆ Coscattering Dark Matter via the process $\chi_2\mathrm{SM} \to \chi_1\mathrm{SM}$ is viable in the Scotogenic model.

⋆ Higgs portal scenario

1. Coscattering favors small mass splitting Δm_ϕ and large λ_2.
2. Positive direct detection signal, negative indirect detection one.
3. Coannihilation leads to observable displaced vertex signature.

⋆ Yukawa portal scenario

1. Coscattering favors small mass splitting Δm_ϕ and large y_2.
2. Negative direct detection signal, positive indirect detection one.
3. Coannihilation and coscattering both leads to observable displaced vertex and dilepton signature.