More Stringent Constraints on the Unitarised Fermionic Dark Matter Higgs Portal

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June 4, 2019

Overview

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Introduction to the Fermionic Higgs Portal Model

- We revisit the simplest model of Higgs portal fermionic dark matter (DM)
- The DM in this scenario is thermally produced via interactions with the Higgs boson
- The model-independent treatment of DM within the effective field theory (EFT) suffers from unitarity violation at high energy
- Unitarisation represents a tool for theoretically reliable calculations of observables without the requirement for a particular UV completion
- In this work we demonstrate the usefulness of the K-matrix unitarisation prescription among the most well-studied fermionic Higgs portal dark matter models [4, 5]

The EFT description

- We hypothesise a DM Dirac fermion, χ, of mass m_χ. It carries no Standard Model (SM) gauged charges and, thus, the lowest order dimension-5 effective operator that describes cold thermal relic dark matter interactions with the SM particles is

$$\begin{aligned}\mathcal{L} &= \frac{1}{\Lambda} H^\dagger H \bar{\chi}(\cos\xi + i\gamma_5 sin\xi)\chi \\ &= \frac{1}{\Lambda}\left(vh + \frac{1}{2}h^2\right)\bar{\chi}(\cos\xi + i\gamma_5 \sin\xi)\chi \ ,\end{aligned} \tag{1}$$

where Λ is the EFT cut-off scale parameter and ξ is the CP-violating phase.

- In the second line, we expanded the EW Higgs doublet H around its expectation value $v \approx 246$ GeV in the unitary gauge, $H = \frac{1}{\sqrt{2}}(0, v+h)^{\mathrm{T}}$

Unitarity Considerations

- At low energy $E << \Lambda$, the Higgs-dark matter portal Eq. (1) is dominated by the dimension-4 $h\bar{\chi}\chi$ operators. These operators are renormalisable and also perturbative, provided $v \lesssim \Lambda$
- However, at high energy, the Higgs-DM interactions are dominated by non-renormalisable dimension-5 $h^2\bar{\chi}\chi$ interactions. In fact, for $E \gtrsim \Lambda$ the scattering amplitudes described by $h^2\bar{\chi}\chi$ operators grow as E/Λ, signalling violation of perturbative unitarity.
- This violation of unitarity is actually fictitious and reflects inapplicability of perturbative treatment to the EFT
- Solution, use a unitarisation prescription or introduce a UV completion

K-matrix Unitarisation of the Fermion Dark Matter Higgs Portal

- Here we use the K-matrix unitarisation prescription to extract model independent constraints
- It is useful to recall the K-matrix unitarisation formalism in a general context first. The unitarity of scattering operator S

$$S = 1 + 2iT \ , \tag{2}$$

implies that the transition operator T satisfies the following constraint (the well known optical theorem)

$$T - T^{\dagger} = 2iT^{\dagger}T \ . \tag{3}$$

We now define the K operator as the solution of the equation

$$K = T - iTK \ . \tag{4}$$

K-Matrix Unitarisation Details Continued...

- If one regards K as known with T solved from Eq. (4), then T will satisfy the unitarity constraint Eq. (3) if and only if K is Hermitian i.e. $K^\dagger = K$. Within perturbation theory, the expansion $T = T_0 + T_1 + \ldots$, implies that one can approximate K by the tree-level contribution T_0 to the full T-operator i.e. $K = T_0$, providing T_0 is Hermitian[1]. If so, the unitarised tree-level T^U operator can simply be written as

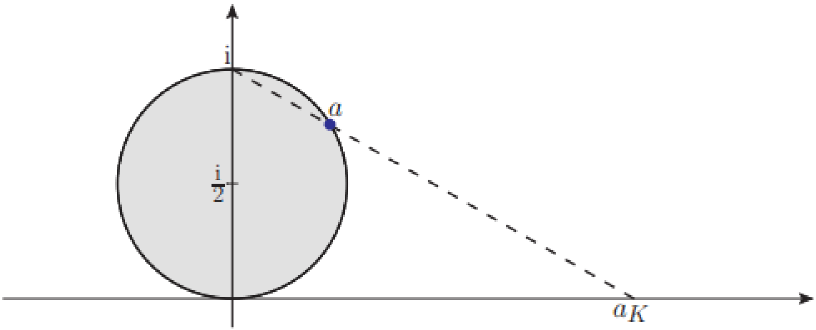
$$T^U = \frac{T_0}{1 - iT_0^\dagger} \,, \tag{5}$$

- For small T_0, $T^U \simeq T_0$, while for large T_0, the unitarised operator becomes $T^U = i$. Such a stereographic projection of T_0 to T^U on the unit circle centred at $(0, i/2)$ is well defined as long as the eigenvalues of T_0 do not lie above $(0, i)$ on the Argand plane.

[1] In fact, for CP-conserving scalar channel scattering processes, T_0 is symmetric and real. For the CP-violating pseudoscalar channel scattering processes, T_0 is Hermitian.

Stereographic Projection

- This procedure is the matrix analogue of a stereographic projection in the complex plane



Partial Wave Expansion

- We may use the partial wave expansion to compute the relevant T-matrix elements
- The generic partial wave expansion of the T-matrix in the helicity basis for $2 \to 2$ scattering can be written

$$T^J_{\lambda'\lambda} = \langle J\lambda_c\lambda_d | T | J\lambda_a\lambda_b \rangle = \int d\Omega \langle \Omega\lambda_c\lambda_d | T | 0\lambda_a\lambda_b \rangle D^J_{\lambda\lambda'}(\phi, \theta, 0) \ , \tag{6}$$

  where λ_a , λ_b and λ_c , λ_d are the initial and final state particle helicities respectively and $\lambda = \lambda_a - \lambda_b$, $\lambda' = \lambda_c - \lambda_d$. The Wigner D-functions are denoted $D^J_{\lambda\lambda'}(\phi, \theta, 0)$.
- The partial wave expansion here is dominated by the terms with total angular momentum $J = 0$.

Matrix Elements and Cross-sections

- The T-matrix is related to the familiar Lorentz invariant amplitude $\mathcal{M}_{fi}$ by

$$\langle \Omega \lambda_c \lambda_d | T | 0 \lambda_a \lambda_b \rangle = \frac{1}{32\pi^2} \sqrt{\frac{4 p_f p_i}{s}} \mathcal{M}_{fi} \ , \tag{7}$$

where p_f and p_i are the initial and final state particle momenta for $2 \to 2$ scattering in the CoM frame. The total non-averaged scattering cross section can then be written as

$$\sigma_{fi} = \frac{4\pi}{s - 4m_\chi^2} \sum_{hel} \sum_J (2J+1) | T^J_{\lambda' \lambda} |^2 \ . \tag{8}$$

- The thermally averaged cross-section used to compute the dark matter relic abundance is given as usual by

$$\langle \sigma v \rangle = \frac{1}{8 m_\chi^4 T K_2^2(m_\chi / T)} \int_{4m_\chi^2}^{\infty} \sigma(s)(s - 4m_\chi^2) \sqrt{s} K_1(\sqrt{s}/T) ds \ , \tag{9}$$

Unitarity Violating T-matrix Elements

$$T_{0\ \chi_{L,R}\bar{\chi}_{L,R}\to hh} = \pm\frac{((s-4m_h^2)(s-4m_\chi^2))^{\frac{1}{4}}(\sqrt{s-4m_\chi^2}\cos\xi \mp i\sqrt{s}\sin\xi)}{8\pi\sqrt{s}\Lambda} \longrightarrow \propto \frac{\sqrt{s}}{8\pi\Lambda}\ , \qquad (10)$$

- can compute for the time-reversed processes. Similarly, for the longitudinal EW gauge bosons ($V \equiv W^\pm, Z^0$)

$$T_{0\ \chi_{L,R}\bar{\chi}_{L,R}\to VV} = \mp\frac{(2m_V^2-s)((s-4m_V^2)(s-4m_\chi^2))^{\frac{1}{4}}\left(\sqrt{s-4m_\chi^2}\cos\xi \mp i\sqrt{s}\sin\xi\right)}{8\pi\sqrt{s}\Lambda(s-m_h^2+im_h\Gamma_h)} \longrightarrow \propto \frac{\sqrt{s}}{8\pi\Lambda}\ , \qquad (11)$$

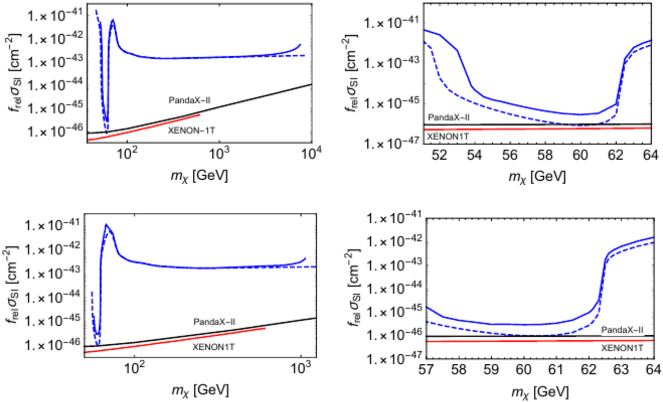
- Therefore, the total cross section $\sigma(s)$ computed within EFT is not reliable at large values of s.
- Although the integrand in Eq. (9) is Boltzmann suppressed, the resulting thermal averaged cross section is still overestimated, requiring larger values of Λ to compensate to account for the observed dark matter relic abundance.

Results

- We compute the unitarised and non-unitarised thermally averaged dark matter cross section including the relevant $2 \to 2$ annihilation channels, $\chi\bar{\chi} \leftrightarrow \chi\bar{\chi}, VV, hh, f\bar{f}$, where the fermion species f include $f = t, b, c, \tau$
- Next, we fix the dark matter relic abundance to $f_{rel}\Omega_h^2$ where $\Omega_h^2 = 0.1186$ and numerically compute the allowed Λ for a given m_χ
- Consequently, we obtain more stringent constraints for the unitarised theory
- Will show results for CP-even and odd cases
- No direct detection constraint for CP-odd case due to momentum suppression of the spin-independent nucleon cross-section

Direct Detection and Relic Density Results

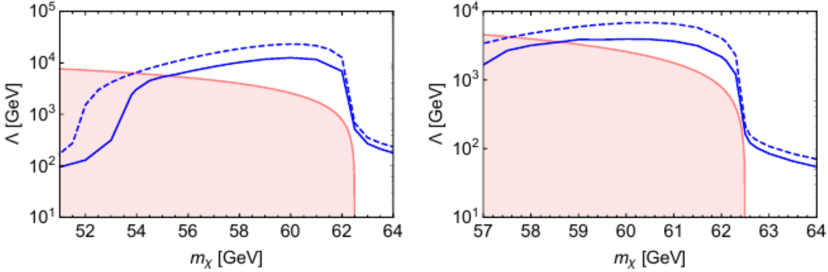
- For the *CP*-even case where $\xi = 0$



- Top panels are for 100% dark matter and bottom panels are for 10% dark matter, unitarised theory (solid blue), original theory (dashed blue)

Collider Constraint Results

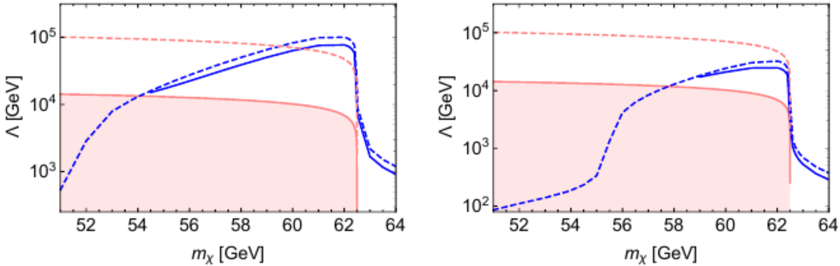
- For the *CP*-even case where $\xi = 0$



- Left panel for 100% dark matter and right panels for 10% dark matter, unitarised theory (solid blue), original theory (dashed blue). Pink solid region is from LHC Higgs to invisible width constraint $\mathcal{B}(h \to \chi\bar{\chi}) < 0.19$

Collider Constraint Results

- For the *CP*-odd case where $\xi = \frac{\pi}{2}$



- Left panel for 100% dark matter and right panels for 10% dark matter, unitarised theory (solid blue), original theory (dashed blue). Pink solid region is from LHC Higgs to invisible width constraint $\mathcal{B}(h \to \chi\bar{\chi}) < 0.19$ and dashed is the projected ILC constraint $\mathcal{B}(h \to \chi\bar{\chi}) < 0.004$

Results

- We observe that the original CP-even theory is compatible within 2σ bounds of XENON1T 2018 data [8] and the central valued limits in PandaX-II [9] in the "resonant Higgs portal", $m_\chi \approx 59 - 61$ GeV (see also [6]).
- Within the unitarised theory, the pure scalar channel is now fully excluded
- Additionally, the non-unitarised theory is not applicable for large dark matter masses where $m_\chi > 2\pi\Lambda$, due to pertubative unitarity violation
- This range is accessible via unitarisation and is now strongly excluded within the current direct detection limits.
- The limits for the CP-odd case can be strengthened relative to LHC constraints and potentially excluded completely by the ILC

Conclusion

- We have revisited the fermionic dark matter Higgs portal EFT by applying the K-matrix unitarisation formalism
- Within the unitarised EFT the relevant scattering processes can be computed reliably in the entire energy range
- By fixing the desired dark matter relic abundance, we computed the corresponding EFT cut-off scale Λ, which is appreciably lower than in the non-unitarised theory.
- Furthermore, unlike the non-unitarised theory, the unitarised EFT is applicable for heavy dark matter masses, $m_\chi \geq 2\pi\Lambda$
- We have found that the fermionic dark matter in the pure scalar CP-even channel is now fully excluded by recent direct dark matter search experiments
- We found more stringent (albeit marginally) constraints in the unitarised CP-odd theory.

Appendix A Matrix Elements

$$\mathcal{M}_{\chi_L\bar{\chi}_L\to\chi_L\bar{\chi}_L} = \frac{v^2}{\Lambda^2}\left(-\frac{4m_\chi^2\cos^2\xi(1+\cos\theta)}{2m_h^2+(s-4m_\chi^2)(\cos\theta-1)-2im_h\Gamma_h}+\frac{2m_\chi^2-s+2m_\chi^2\cos 2\xi}{s-m_h^2+im_h\Gamma_h}\right)\,, \tag{12}$$

$$\mathcal{M}_{\chi_L\bar{\chi}_L\to\chi_R\bar{\chi}_R} = \frac{1}{\Lambda^2}\left(\frac{\left(\sqrt{s-4m_\chi^2}\,v\cos\xi-i\sqrt{s}\,v\sin\xi\right)^2}{s-m_h^2+im_h\Gamma_h}+\frac{2v^2\sin^2\frac{\theta}{2}\left(i\sqrt{s}\cos\xi+\sqrt{s-4m_\chi^2}\sin\xi\right)^2}{2m_h^2+(s-4m_\chi^2)(1-\cos\theta)-2im_h\Gamma_h}\right)\,, \tag{13}$$

$$\mathcal{M}_{\chi_R\bar{\chi}_R\to\chi_L\bar{\chi}_L} = \frac{1}{\Lambda^2}\left(\frac{\left(\sqrt{s-4m_\chi^2}\,v\cos\xi+i\sqrt{s}\,v\sin\xi\right)^2}{s-m_h^2+im_h\Gamma_h}-\frac{2v^2\sin^2\frac{\theta}{2}\left(\sqrt{s}\cos\xi+i\sqrt{s-4m_\chi^2}\sin\xi\right)^2}{2m_h^2+(s-4m_\chi^2)(1-\cos\theta)-2im_h\Gamma_h}\right)\,, \tag{14}$$

with $\mathcal{M}_{\chi_R\bar{\chi}_R\to\chi_R\bar{\chi}_R} = \mathcal{M}_{\chi_L\bar{\chi}_L\to\chi_L\bar{\chi}_L}$.

- The leading order tree-level scattering processes to generic final state SM fermions f occur via the s-channel exchange of a Higgs boson and are given by

$$\mathcal{M}_{\chi_L\bar{\chi}_L\to f_L\bar{f}_L} = \frac{m_f\sqrt{s-4m_f^2}\left(-\sqrt{s-4m_f^2}\cos\xi + i\sqrt{s}\sin\xi\right)}{\Lambda(s-m_h^2+im_h\Gamma_h)}, \quad (15)$$

$$\mathcal{M}_{\chi_R\bar{\chi}_R\to f_L\bar{f}_L} = \frac{m_f\sqrt{s-4m_f^2}\left(\sqrt{s-4m_f^2}\cos\xi + i\sqrt{s}\sin\xi\right)}{\Lambda(s-m_h^2+im_h\Gamma_h)}, \quad (16)$$

where $\mathcal{M}_{\chi_L\bar{\chi}_L\to f_R\bar{f}_R} = -\mathcal{M}_{\chi_L\bar{\chi}_L\to f_L\bar{f}_L}$ and $\mathcal{M}_{\chi_R\bar{\chi}_R\to f_R\bar{f}_R} = -\mathcal{M}_{\chi_R\bar{\chi}_R\to f_L\bar{f}_L}$.

Appendix B Dark matter-nucleon cross section and Higgs invisible decay width

- The t-channel Higgs mediated elastic scattering of fermionic WIMP on nucleons spin-independent cross section is given by

$$\sigma_{SI}^{\chi N} = 4.7 \times 10^{-38} cm^2 \left(\frac{m_\chi}{\Lambda}\right)^2 \left(\frac{1 GeV}{0.94 GeV + m_\chi}\right)^2 \left[\cos^2\xi + \frac{1}{2}\left(\frac{\mu_{\chi N}}{m_\chi}\right)^2 \nu_\chi^2\right]. \quad (17)$$

  Where $\nu_\chi \sim 220 km/s$ is the DM speed in the nucleon's rest frame and $\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$ is the reduced mass of the WIMP-nucleon system and m_N is the nucleon mass.

- The tree-level Higgs to invisible partial decay width is given by

$$\Gamma_{h\to\bar{\chi}\chi} = \frac{m_h}{8\pi}\frac{v^2}{\Lambda^2}\sqrt{1 - \frac{4m_\chi^2}{m_h^2}}\left(1 - \frac{4m_\chi^2}{m_h^2}\cos^2\xi\right). \quad (18)$$

  Where the total Higgs width is given by $\Gamma_h = \Gamma_{SM} + \Gamma_{h\to\bar{\chi}\chi}$ where $\Gamma_{SM} = 4.21\text{MeV}$.

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