PROCEEDINGS OF SCIENCE

Effect of thermal fluctuations on dark matter annihilation cross section

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We are interested in thermal corrections to dark matter (DM) annihilation cross sections in a MSSM-inspired BSM theory, having bino-like Majorana DM (χ), annihilating to SM fermions through Yukawa interactions via a charged scalar channel in freeze-out scenario. We apply real-time formalism of thermal field theory (TFT) to investigate corrections due to thermal fluctuations of DM annihilation cross section at NLO. We utilize generalized Grammer and Yennie approach in TFT to assure IR divergence cancellation between K-photon of virtual and $\widetilde{K}$-photon of real corrections at NLO to DM annihilation processes ($\chi\bar{\chi} \to f\bar{f}$). We calculate the thermal correction to the finite remainder in TFT. Our calculations shows quadratic thermal dependence of annihilation cross section of DM ($\sigma_T \sim \mathcal{O}(T^2)$) considering scalar to be heavy compared to DM and SM fermions.

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1. Introduction

Relic abundance of dark matter (DM) in our universe is increasingly accurately measured ($\Omega_c h^2 = 0.1200 \pm 0.0012$) by the successive generation of experiments. Boltzmann equation determines the yield using the DM annihilation cross section (ACS) as one of the input; contributions due to thermal fluctuations thus assume importance alongside with the contribution from quantum fluctuations. We calculate NLO correction to ACS of DM in a MSSM inspired model (Eq:1), due to pure thermal fluctuations [1]. We utilized generalized Grammer and Yennie technique [3–5] in order to separate IR safe part from the IR divergent, in ACS. This technique ensures cancellation of soft IR divergences order by order, provided real emission and absorption processes are taken into account. We calculate contributions to ACS due to the finite G-photon contribution for virtual corrections [1].

2. Model and approximations

In the model of interest, the dark matter candidate is an $SU(2)\times U(1)$ singlet Majorana fermion, χ, which interacts with SM doublet fermions, $f = (f^0, f^-)^T$, via scalar partners $\phi = (\phi^+, \phi^0)^T$ through a Yukawa interaction [2],

$$
\begin{aligned}
\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{f}\left(i\not{D} - m_f\right) f + \frac{1}{2}\overline{\chi}\left(i\not{\partial} - m_\chi\right)\chi \\
+ \left(D^\mu\phi\right)^\dagger\left(D_\mu\phi\right) - m_\phi^2\phi^\dagger\phi + \left(\lambda\overline{\chi}P_L f^-\phi^+ + \text{h.c.}\right) \ . \qquad (1)
\end{aligned}
$$

Feynman diagrams for t-channel and u-channel process for annihilation of DM are shown in Fig.1.

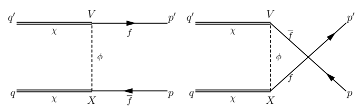

Figure 1: t- and u-channel tree level feynman diagram for DM annihilation process $\chi\chi \to f\overline{f}$

The NLO corrections are shown in Fig.2. Both t-channel and u-channel counterparts (not shown) contribute to ACS .

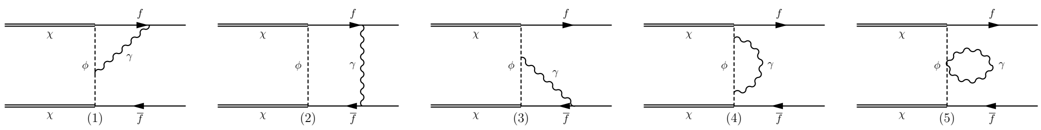

Figure 2: t-channel NLO virtual process for $\chi\chi \to f\overline{f}$

In our calculations, approximation on the propagator for the mediator scalar is taken as follows [1],

$$
\frac{-i}{(l+k)^2 - m_\phi^2} = \frac{-i}{(l^2 - m_\phi^2) + 2l.k + k^2} \approx \frac{i}{l^2 - m_\phi^2}\left(1 - \frac{2l.k + k^2}{l^2 - m_\phi^2}\right) \qquad (2)
$$

3. Results

In non-relativistic limit, i.e., s-wave contribution in dynamical scalar approximation (Eq:2), pure thermal correction to ACS can be seen from the Table:1. It shows helicity suppressed thermal correction up to quadratic, $O(T^2)$ and quartic, $O(T^4)$ terms [1].

Table 1: The NLO cross section, $\sigma v_{rel} \sim Int^a + Int^b v_{rel}^2$, in the non-relativistic limit, with $D = (m_\chi^2 - m_f^2 + m_\phi^2)$, in units of $\alpha T^2 \lambda^4 P'/(24Ps)$.

Diagram	γ/f	Int^a_{NLO} (T^2 contribution)	Int^a_{NLO} (T^4 contribution)
1	γ	$-8m_\chi^2 m_f^2(m_f^2 - m_\phi^2)/D^4$	0
	f	$4m_\chi^2 m_f^2(5m_\chi^2 - 5m_f^2 + m_\phi^2)/D^4$	0
	$\text{Total}_{\gamma+f}$	$2m_\chi^2 m_f^2(5m_\chi^2 - 9m_f^2 + 5m_\phi^2)/D^4$	0
2	γ	$-8m_\chi^2 m_f^2/D^3$	0
	f	$-6m_f^2(2m_\chi^2 - m_f^2)/D^3$	$-\frac{21\pi^2T^2}{10m_\chi^2 D^3} m_f^2(2m_\chi^2 - m_f^2)$
	$\text{Total}_{\gamma+f}$	$-m_f^2(14m_\chi^2 - 3m_f^2)/D^3$	$-\frac{21\pi^2T^2}{10m_\chi^2 D^3} m_f^2(2m_\chi^2 - m_f^2)$
3	γ	$-8m_\chi^2 m_f^2(m_f^2 - m_\phi^2)/D^4$	0
	f	$4m_\chi^2 m_f^2(3m_\chi^2 - 2m_f^2 + m_\phi^2)/D^4$	0
	$\text{Total}_{\gamma+f}$	$2m_\chi^2 m_f^2(3m_\chi^2 - 6m_f^2 + 5m_\phi^2)/D^4$	0
4	γ	$32m_\chi^4 m_f^2/D^4$	$-\frac{56\pi^2T^2}{15D^5} m_\chi^2 m_f^2(m_\chi^2 - m_f^2)$
5	γ	$-16m_\chi^2 m_f^2/D^3$	0
All	$\text{Total}_{\gamma+f}$	$\frac{1}{D^3} m_f^2(2m_\chi^2 + 3m_f^2)+$ $\frac{2}{D^4} m_f^2 m_\chi^2(10m_\phi^2 + 24m_\chi^2 - 15m_f^2)$	$-\frac{21\pi^2T^2}{10m_\chi^2 D^3} m_f^2(2m_\chi^2 - m_f^2)$ $-\frac{56\pi^2T^2}{15D^5} m_\chi^2 m_f^2(m_\chi^2 - m_f^2)$

For s-wave, relative size of the NLO contribution *for each* flavour of fermion pair is given by

$$\begin{aligned} \frac{\sigma^a_{NLO}}{\sigma^a_{LO}} &= \frac{\pi\alpha T^2}{6m_\phi^2} \frac{m_f^2(22m_\chi^2 + 3m_f^2)}{m_f^2 m_\chi^2} , \\ &\approx \frac{11\pi\alpha}{3} \frac{T^2}{m_\phi^2} , \end{aligned} \tag{3}$$

Details are available in Ref.[1].

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