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Top quark mediated dark matter

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ABSTRACT

We study the top quark portal dominated dark matter interactions, and its implications for the gamma ray line searches. In this picture, the dark matter interactions with photons and gluons are loop induced by the axial anomaly of the top quark current. We show there can be a natural suppression of the tree-level annihilation of dark matter, and the photon channel in turn has a substantial rate when the main annihilation proceeds into gluons. We observe a competition between the indirect detection of gamma ray line and the search with monojet plus missing energy events at LHC, and the 7 TeV data already set an upper bound of $\sim 10^{-28}$ cm^3 s^{-1} on the photonic annihilation cross section. This upper limit is compatible with a thermal WIMP scenario.

1. Introduction

The existence of dark matter (DM) in the universe has been established by various cosmological observations, yet its identity has not been uncovered. Many experiments are now going on in order to directly or indirectly detect its trace. The indirect detection using the monochromatic cosmic gamma ray could serve as a clear evidence for DM being from particle physics origin. Since the DM is electric neutral, its annihilation into two photons must happen at loop level, naively suppressed by a factor of $(\alpha/\pi)^2$ compared with the tree-level annihilation to charged final states. For thermal weakly interacting massive particle (WIMP) picture whose total annihilation cross section is around a picobarn, the induced two photon annihilation rate is far below the current Fermi LAT sensitivity.

Early this year, there were several analysis [1–3] of the 4-year Fermi data showing the positive signatures in the gamma line search from the galactic center, with energy 130 GeV and a cross section 1.3×10^{-27} cm^3 s^{-1} if originating from DM annihilation [4]. This is only one order of magnitude below the thermal cross section. A more recent data reprocessing performed by the Fermi-LAT Collaboration shows a similar line-like feature which slightly shifts to 135 GeV. While the significance of this excess remains at $\sim 3\sigma$, it seems at present one cannot exclude the uncertainties from systematics or the earth limb photon background [5]. On the conservative side, the global analysis of Fermi data offers an upper bound on the DM to two photon annihilation cross section, which is around 10^{-27} cm^3 s^{-1} for photon energy 130 GeV [6].

The above hint has inspired a plethora of theoretical studies [7,8] on DM models that can give an "enhanced" gamma ray feature from annihilation. Questions need to be addressed include: whether this signal can be reconciled with thermal DM paradigm; what are the correlated phenomena and in turn their constraints [9–11]. Possible answers to the former question involve the suppression or elimination of direct annihilation to light charged standard model (SM) fermions. In many cases, additional states other than the DM itself are introduced, playing the role of co-annihilator or intermediate states (real or virtual) in the annihilation.

In this Letter, we investigate a case when DM–χ couples predominantly with the top quark [12,13], and assume the couplings to other SM fermions or bosons are negligibly small throughout the discussion. For the bulk of this work, we consider the case when the DM is lighter than the top quark. In this case, it cannot annihilate into both on-shell top quark and antiquark, and we notice a fact that the three-body annihilation threshold $m_t + m_W + m_b \approx 256$ GeV, is only a few GeV below twice of the suspected gamma line energy in Fermi (~ 130–135 GeV), or twice of the corresponding DM mass. This indicates additional final state phase space suppression for the process $\chi\bar{\chi} \to tW^-\bar{b}$ or $\bar{t}W^+b$. Meanwhile, the DM can also annihilate into two photons via the top quark loop. The ratio between the two cross sections can be estimated as

$$\frac{\sigma v_{\chi\bar{\chi}\to\gamma\gamma}}{\sigma v_{\chi\bar{\chi}\to tWb}} \sim 4\pi\left(\frac{\alpha}{\pi}\right)^2\frac{m_\chi^2}{\delta m^2}, \tag{1}$$

where the factor 4π stands for a generic ratio of two- and three-body final state phase spaces, and $\delta m \approx 2m_\chi - m_t - m_W - m_b$ provides additional suppression when the later is being kinematically squeezed. For $m_\chi \sim 130$ GeV and $\delta m \sim$ few GeV, the ratio

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can be as large as 0.1. It serves as one motivation to study possible enhanced gamma ray line signals with this setup. Another advantage of the top quark portal is that the continuum gamma ray constraint turns out to be less severe [11].

A particular feature of the top quark loop induced annihilations into $\gamma\gamma$ and gg discussed here is that, they always proceed through the axial anomaly of the top quark current. For the mass range $m_\chi \lesssim 130$ GeV, the $\chi\bar{\chi} \to gg$ channel will dominate over the three-body one and lead to the largest ratio of photonic to the total annihilation cross section, which is $\sim 0.4\%$. The DM mass indicated from the Fermi data lies within this window.

The main consequences of the above picture are as follows. Such top quark portal being behind the Fermi gamma ray line implies a sizable effective coupling of DM to gluons. The total annihilation cross section exceeds that required for the thermal relic density. This case is severely constrained by LHC measurement of missing energy plus monojet events and has been excluded using the 7 TeV data. On the other hand, the thermal WIMP case is still allowed by LHC data. The two photon annihilation cross section is about one order of magnitude smaller than that needed to explain Fermi, but large enough to be probed with more data and future experimental sensitivity [14]. We foresee an intimate interplay between DM collider searches and indirect detections.

2. Top quark portal and DM annihilations

In this work, we consider the DM as a Dirac fermion and write down its effective couplings with the top quark. In order to avoid large coupling to the lighter quarks, such as the bottom, and preserve the SM gauge symmetry, we choose only the coupling to the right-handed top quark. The viable operator at lowest dimensions is [15]

$$\mathcal{L}_{\rm portal} = \frac{1}{\Lambda^2}\left[\bar{\chi}\gamma_\mu(a+\gamma_5)\chi\right]\left[\bar{t}\gamma^\mu(1+\gamma_5)t\right], \tag{2}$$

where Λ is the cutoff of the effective interaction and a is a real number.

As sketched in the introduction, the annihilation of DM has the following channels (see also Figs. 1 and 3)

$$\chi\bar{\chi} \to \begin{cases} tW^-\bar{b}, & \bar{t}W^+b, \\ \gamma\gamma, & \gamma Z, \\ gg. \end{cases} \tag{3}$$

The annihilation to $\gamma\gamma$, γZ and gg all happen via virtual top quark loop, which we calculate in details below.

2.1. Annihilation $\chi\bar{\chi} \to tWb$

For the three-body annihilation, we obtain the amplitude square

$$\begin{aligned}
&\overline{|\mathcal{A}_{\chi\bar{\chi}\to tWb}|^2} \\
&\quad = 2\times\frac{8g^2}{\Lambda^4 M_W^2}\frac{m_t^2}{(s-2\sqrt{s}\,p_3^0)^2} \\
&\qquad \times\left\{(a+1)^2(p_2\cdot p_3)\left[M_W^2(p_1\cdot p_5)+2(p_1\cdot p_4)(p_4\cdot p_5)\right]\right. \\
&\qquad + (a-1)^2(p_1\cdot p_3)\left[M_W^2(p_2\cdot p_5)+2(p_2\cdot p_4)(p_4\cdot p_5)\right] \\
&\qquad \left. + (a^2-1)m_\chi^2\left[M_W^2(p_3\cdot p_5)+2(p_3\cdot p_4)(p_4\cdot p_5)\right]\right\},
\end{aligned} \tag{4}$$

where t, W b are labeled as 3, 4, 5 respectively, the pre-factor 2 takes into account of the charge-conjugation process. Here $s \approx 4(m_\chi + T_f)^2$ or $4m_\chi^2$ during the DM freeze out and today, respectively. In the numerical calculation, we set the freeze out temperature $T_f \approx m_\chi/25$, in order to approximate the thermal average.

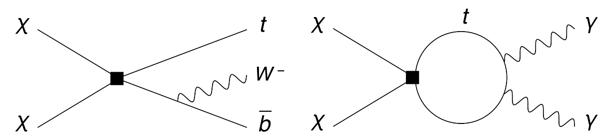

Fig. 1. DM annihilation channels. Left: tree-level three-body process, kinematically suppressed in the phase space. Right: top quark loop induced annihilation into two photons.

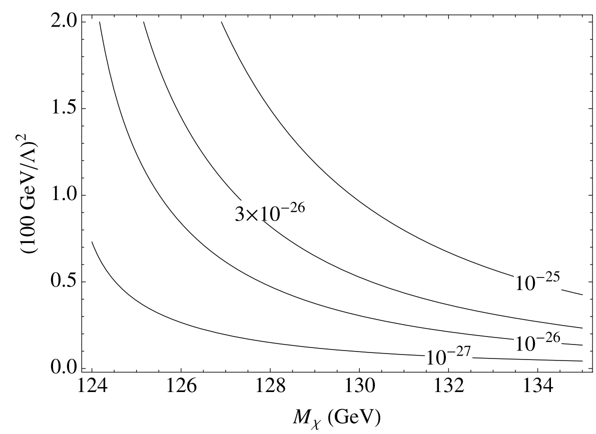

Fig. 2. Cross section for the three-body annihilation $\chi\bar{\chi} \to tWb$ during freeze-out ($T_f \approx m_\chi/25$, which corresponds to velocity $v_f \approx 0.3$), in units of cm^3/s. Here we set $a = 0$. Notice such annihilation will not happen today if $m_\chi \lesssim 128$ GeV.

We integrate over the general three-body final state phase space as given in Appendix A [16]. The resulting cross section during the freeze out is shown in Fig. 2. As one can see, the three-body annihilation can be highly suppressed by kinematics in the final state phase space, when the DM mass approaches the threshold for the t, W, b final states from above. The annihilation of DM today is more suppressed or even forbidden due to much lower velocity.

In view of this suppression, it is meaningful to examine the other loop-level processes.

2.2. Annihilation $\chi\bar{\chi} \to \gamma\gamma$

We first examine the DM annihilation into a pair of photons, which leads to a spectacular line on top of the gamma ray spectrum. The DM annihilation into photons can take place when the top quark lines are closed into a loop (see Fig. 1). When the tree-level annihilation is suppressed as shown above, the loop-level annihilation into photons could be more notable.

Using the interaction Eq. (2), the annihilation of DM into two photons arises from the axial current $\bar{t}\gamma^\mu\gamma_5 t$, evaluated inside the triangle loop in Fig. 1. The corresponding contribution from a vector current vanishes due to the charge-conjugation invariance. Following the generic calculation of axial anomaly [17,18], the finite amplitude is

$$\mathcal{A}_{\chi\bar{\chi}\to\gamma\gamma} = \frac{3\alpha Q_t^2 m_\chi}{2\pi^3\Lambda^2}A_3(k_1,k_2)\bar{v}_\chi(p_2)\gamma_5 u_\chi(p_1)\varepsilon^{k_1k_2e_1e_2}, \tag{5}$$

where on-shell photon conditions have been implemented, $k_{1,2}$ are the photon momenta, and the factor 3 stands for the color factor. If the top quark is integrated out, the effective operator for the annihilation becomes $m_\chi\bar{\chi}\gamma_5\chi F\tilde{F}$. The annihilation of DM to photons happens only through the axial current anomaly, and only the axial part of the dark matter current contributes. This also agrees with the argument [19] that, the process $\nu\bar{\nu} \to \gamma\gamma$ vanishes if the initial neutrinos are massless.