Probing Large Dark Matter Masses While Conserving Relic Density

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Abstract

This paper examines possible parameters for a dark matter model that is based on a dark photon, Z', as a mediator between dark matter and Standard Model particles. Relatively large dark matter masses (in the GeV to TeV range) are probed to see if it is possible to generate the observed relic density of dark matter with such large masses. In order to achieve this, it is crucial that this calculation is performed at resonance. With an observed relic density of about 0.12, we found it possible for dark matter to have a mass of about 100 TeV with couplings $\delta_l \approx 0.5$ and $g_\chi \approx 2.25$, which predicts that it is possible to achieve large dark matter masses with perturbative couplings at resonance.

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1 Introduction

In the search for dark matter (DM), it has become increasingly popular to study models that include dark mediators which allow DM to communicate with the Standard Model (SM). Until now, DM has only been observed through gravitational interactions, motivating large scale models, including halo and cluster structures. However, there is more to DM than what can be understood through gravitational interactions. Through the existence of a dark mediator, arises the possibility of indirect detection of DM at particle colliders such as the Large Hadron Collider (LHC) [1] and telescopes such as Fermi-LAT [2]. Although such experiments haven't detected DM particles yet, they have placed useful bounds on the parameters for particle models, such as a lower mass bound [3, 4, 5]. The most important parameters discussed in this paper are the masses of the DM particle (M_{DM}) and dark mediator ($M_{Z'}$) as well as the kinetic mixing (δ_l), and coupling constant (g_χ).

Bounds on such parameters have resulted not only from indirect detection searches, but also from understanding DM through it's gravitational interactions. For example, one of the most studied qualities of DM is the density that exists today, called the relic density, which is an observable feature. With a few assumptions, the relic density can also be calculated using the freeze-out of the annihilation process of DM to SM. Thermal freeze-out occurs when the interaction rate of DM annihilation is about equal to the Hubble expansion rate [6], as discussed further in section 2.2.

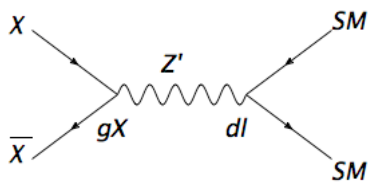
This paper examines possible parameters for a DM model that includes a dark photon, Z', as a mediator. The two simplest DM annihilation processes for this model are shown in Figure 1 where χ and $\bar{\chi}$ represent a DM particle-antiparticle pair. Figure 1a shows the desired annihilation process that is discussed in this report. The lack of detection at experiments has highly constrained the possible masses of light DM [5], so this report focuses on massive DM, ranging from about 2×10^4 GeV up to about 10^5 GeV. The goal of this report is to find the largest possible mass of the DM particle, M_{DM}, with which reasonable values of g_χ and δ_l give the correct relic density.

To achieve this goal, first the theory behind the calculation of relic density is described in Section 2. Section 3 discusses the programs used for the actual calculation of relic density, and Section 4 shows how the maximum mass was found, first finding resonance in Section 4.1, then calculating the relic density in Section 4.2, and finally finding the largest M_{DM} in Section 4.3.

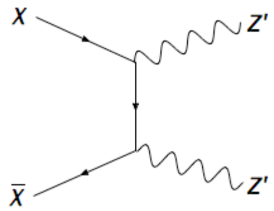
2 Theory

2.1 Model

As mentioned in the introduction, the DM model being considered is based on a massive dark photon that allows DM to couple to SM fermions and bosons. Figure 1a shows the desired annihilation. Here g_χ is the coupling constant responsible for the DM to Z' coupling and δ_l is the kinetic mixing between the dark photon and the SM photon,



(a) Feynman diagram of DM to SM annihilation via the dark photon, Z'.



(b) Feynman diagram of DM to Z' annihilation.

Figure 1

effectively determining the coupling of the Z' to SM particles. Together, these two parameters determine the total coupling constant of the annihilation. The SM particles that can take part in this interaction are the up, down, strange, charm, bottom and top quarks, the electron, tauon, muon, and their neutrinos, and the W^+, W^-, and the Z boson.

2.2 Relic Density

If DM interacts with the SM through some dark mediator, the surviving density of DM that exists today is be governed by the thermal freeze-out of the DM to SM annihilation. If, in the early universe, DM was in thermal equilibrium with the plasma and the SM in equilibrium with the photon bath, the relic abundance is given by [7]:

$$\Omega_\chi h^2 \approx \Omega_{DM} h^2 \frac{\langle \sigma_{th} v \rangle}{\langle \sigma_{\chi\chi} v \rangle} \tag{1}$$

where Ω_χ represents the abundance of the DM particle, χ, relative to the current critical density of the universe, h is the Hubble constant, and $\langle \sigma_{\chi\chi} v \rangle$ represents the total annihilation cross section of χ times velocity, averaged over the thermal distribution in the early Universe. $\Omega_{DM} h^2$ and $\langle \sigma_{th} v \rangle$ are measurable quantities: $\langle \sigma_{th} v \rangle$ the annihilation cross section required to obtain the DM abundance, $\Omega_{DM} h^2$, which can be found through cosmological observations. In the simplest case of tree level, s-channel processes, this equation simplifies to [1]:

$$\Omega_{DM} h^2 \approx \frac{2 \times 2.4 \times 10^{-10} GeV^{-2}}{\langle \sigma_{\chi\chi} v \rangle}. \tag{2}$$

This value of relic density must agree with the observed value given by the Planck Collaboration as $0.1199 \pm 0.0027 \approx 0.12$ [8].

As shown in equation 2, relic density depends inversely on the cross section of DM annihilation. The cross section, σ, is effectively a sum of the scattering amplitudes of the possible interactions. Using the model described in section 2.1, this was calculated and simplified with Mathematica, resulting in[1]:

$$\sigma = (x)\frac{\delta_l^2 gp^2 g_X^2\sqrt{M_{DM}^2 + p^2}(3M_{DM}^2 + 2p^2)}{12p\Gamma^2 M_{Z'}^2 + (M_{Z'}^2 - 4M_{DM}^2 - p^2)^2\pi} \tag{3}$$

$$x = \begin{cases} \frac{5}{12} & down, strange, bottom \\ \frac{17}{12} & up, charm, top \\ \frac{5}{4} & e, \tau, \mu \\ \frac{1}{4} & \nu_e, \nu_\tau, \nu_\mu \\ \frac{1}{8} & W^+, W^-, Z \end{cases} \tag{4}$$

Equation 4 shows the different factors for the possible interactions with SM particles. In this equation, p represents the momentum and $gp = \frac{91.1876}{80.385}\sqrt{\frac{4\pi}{127.9}}$. Equation 3 also introduces the width, Γ, which, for this model, is given by the equation:

$$\Gamma = \begin{cases} \frac{m_{Z'}}{24\pi}(\frac{41dl^2gp^2}{4} + 2gX^2\sqrt{1 - \frac{4m_{DM}^2}{m_{Z'}^2}}\frac{(1+2m_{DM}^2)}{m_{Z'}^2}) & 2m_{DM} < m_{Z'} \\ \frac{41dl^2gp^2m_{Z'}}{96\pi} & 2m_{DM} \geq m_{Z'} \end{cases} \tag{5}$$

2.3 Resonance

For DM masses at the scale that is probed in this report, the relic density is usually higher than what is measured. However, when the mass of the dark photon happens to be about twice the mass of the DM particle, the annihilation is at resonance. At resonance, the probability that DM annihilates with itself increases, thus giving a lower relic density [9]. This allows for the DM mass to be increased and still give the measured relic density. To find exactly where this resonance is, the relic density was calculated around $M_{Z'} = 2M_{DM}$, as shown in figure 2.

A short calculation of the largest mass that gives the observed relic density calculated away from the resonance allows a meaningful comparison to the results found in this paper, calculated at resonance. Away from resonance, the general approximation for cross section is [2]:

$$\langle\sigma v\rangle \simeq \frac{\alpha^2}{M_{DM}^2} \quad , \quad \alpha = \frac{g^2}{4\pi} \tag{6}$$

for some coupling g. Using equation 2 with $\Omega_{DM}h^2 = 0.12$ to solve for the cross section, M_{DM} becomes a function of g. The lower and upper bounds for g are usually around 0.1 and $\sqrt{4\pi}$, respectively. When these two values are plugged in, the resulting DM masses are $M_{DM,g=0.1} \approx 13$ GeV and $M_{DM,g=\sqrt{4\pi}} \approx 1.6 \times 10^4$ GeV. These masses are much smaller than those pursued in this report.

[1]Note that since $M_{DM} >> M_{SM}$, M_{SM} is approximated to have zero mass, allowing for a simpler equation.

[2]This equation is correct up to a factor, which is DM model dependent.

3 Programs

While it is possible to calculate the relic density of DM manually, the code micrOMEGAs was used to make the calculations more efficient. MicrOMEGAs can calculate relic density when given a DM model and parameters, such as δ_l, g_χ, M_{DM}, and $M_{Z'}$. The different decay channels and their relative contribution into the calculation of relic density were also made available. To read more about the specific calculations that produce relic density, refer to [10]. Since it was important that the calculations were done at resonance, to guarantee that relic density was being calculated correctly, the width and cross section of a given annihilation process were calculated manually using equations 3 and 5 and fed to micrOMEGAs.

4 Results

4.1 Finding Resonance

Equations 3 and 5 show that the parameters that can be varied that influence the outcome of relic density are δ_l, g_χ, M_{DM}, and $M_{Z'}$. In order to find the greatest DM mass that gives the measured relic density, it is important to be at resonance. As suggested in section 2.3, resonance depends on the mass of the dark photon with respect to the mass of the DM particle. To find this relationship, the relic density was calculated with fixed δ_l, g_χ, and M_{DM} and varying $M_{Z'}$. This was done for multiple values of M_{DM}, one of which is shown in Figure 2. As seen in this figure, the resonance occurs when $M_{Z'} \approx 2 \times M_{DM}$. When the data was examined more precisely, it was found that $M_{Z'}$ and M_{DM} differed by a factor of 2.002 at resonance. This factor was independent of δ_l, g_χ, and M_{DM}. Throughout the rest of this paper, $M_{Z'}$ is set to $2.002 \times M_{DM}$.

To check the validity of Figure 2, notice that above resonance relic density increases with $M_{Z'}$, which would be expected since away from resonance $\langle \sigma v \rangle \sim \frac{g^4}{m^2}$ and $\Omega \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{g^4}$. The dip of relic density below resonance is also an indicator that the data is physically plausible, because at $M_{Z'} \leq M_{DM}$ the annihilation of DM to two Z', pictured in Figure 1b, becomes possible. This extra decay channel increases the total cross section and thus decreases the relic density.

4.2 Calculating Relic Density, Ω_{DM}

With the relationship between $M_{Z'}$ and M_{DM} fixed, another parameter was varied to find the maximum M_{DM} that gives the correct relic density. To do this efficiently, M_{DM} and δ_l were varied while the relic density was calculated. Figure 3 shows an example for which $g_\chi = 2.5$. The upper limit of δ_l is bounded by the perturbative unitarity limit. From this plot, it can be anticipated that the largest value for M_{DM} with reasonable values of g_χ and δ_l is around 10^5 GeV.

The process of calculating relic density with varying M_{DM} and δ_l was repeated for g_χ values ranging from 0.5 to 4. To conserve perturbative unitarity, $g_\chi < \sqrt{4\pi} \approx 4$ [11]. The

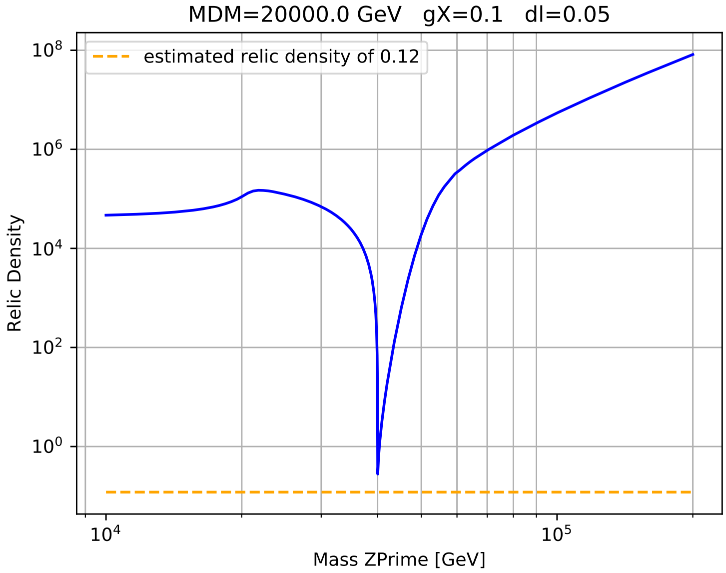


Figure 2: A plot of relic density vs $M_{Z'}$ with $M_{DM} = 20,000$ GeV, $g_\chi = 0.1$, and $\delta_l = 0.05$. The measured relic density is shown for reference (dotted yellow line).

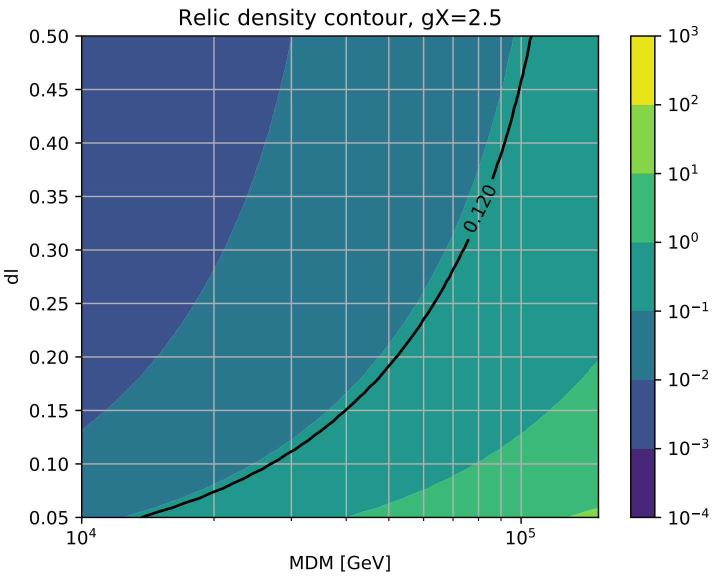


Figure 3: Shown are values of relic density with varying M_{DM} and δ_l. $M_{Z'} = 2.002 \times M_{DM}$ and $g_\chi = 2.5$. $\Omega_{DM} = 0.12$ is shown by the black line.

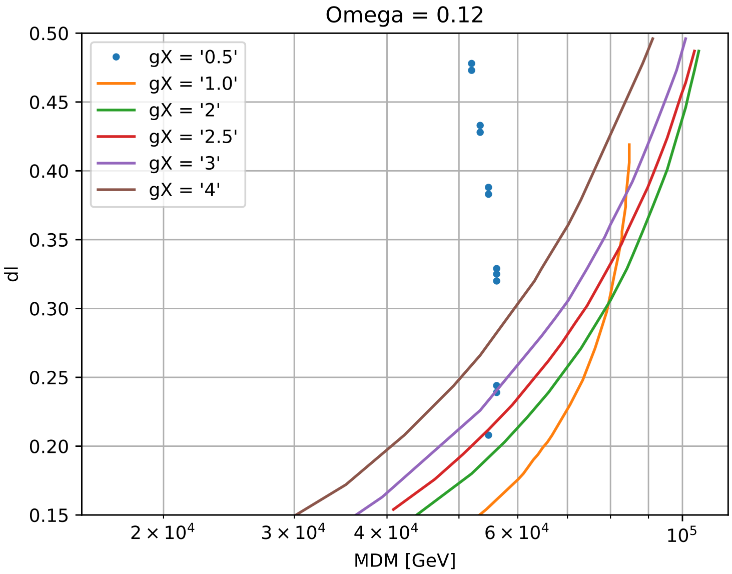


Figure 4: Contour lines for $\Omega_{DM} = 0.12$ with different g_χ. Note that at $M_{DM} = 10^5$, the correct relic density is reached with δ_l between 0.45 and 0.5 and g_χ ranging between 2 and 3.

$\Omega_{DM} = 0.12$ contour lines for each value of g_χ were then plotted on one graph, shown in Figure 4. From this figure, it is clear that the correct relic density can be reached for M_{DM} as high as about 10^5 GeV with multiple values of g_χ and δ_l. The largest M_{DM} is found with $g_\chi \approx 2$ and $\delta_l \approx 0.5$.

4.3 Finding the largest M_{DM}

Finally, to show the largest M_{DM} that gives the correct relic density with plausible values of g_χ and δ_l, the mass corresponding to $\Omega_{DM} \approx 0.12$ was calculated for varying g_χ and δ_l. This was done for multiple points, as shown in figure 5. The black dots show the data points and the color gradient shows the values of M_{DM}, interpolating between points. While this is a fairly rough approximation, it is clear that the largest M_{DM} value that gives $\Omega_{DM} = 0.12$, is $M_{DM} = 105.2$ TeV, which is possible with $\delta_l = 0.491$ and $g_\chi = 2.25$. When compared to the DM mass calculated in section 4.1, it is clear that using the resonance allows for a much larger M_{DM}.

5 Conclusion

In this paper, a simple model of DM has been used to examine the possibility of relatively massive DM. The model is based on a dark photon which allows DM to interact with the SM. The parameters of this model are varied to match the observed relic density, $\Omega_{DM} \approx 0.12$ and manipulated to find the largest M_{DM}. We found the greatest possible

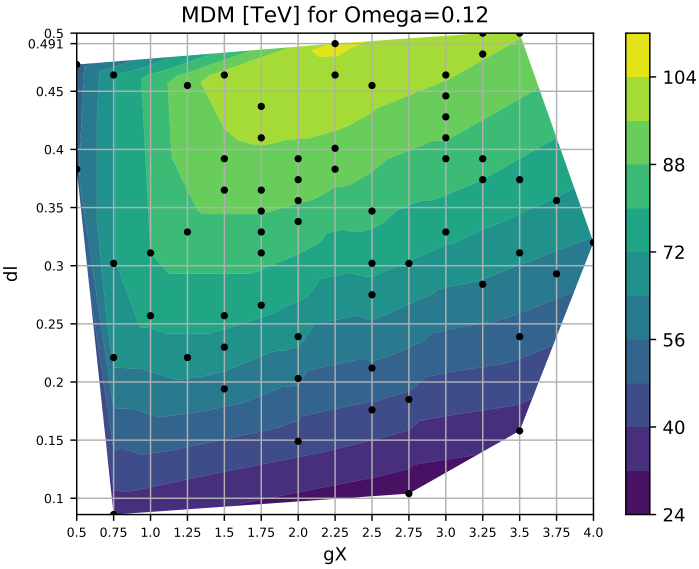


Figure 5: A contour plot of M_{DM} with varying g_χ and δ_l for $\Omega_{DM} \approx 0.12$. Data points shown as black dots with their M_{DM} values shown by the color gradient. The highest value, $M_{DM} = 105.2$ TeV corresponds to $\delta_l = 0.491$ and $g_\chi = 2.25$.

DM mass to be 105.2 TeV, which gives the observed relic density with the parameters $\delta_l = 0.491$ and $g_\chi = 2.25$. These calculations assume that DM was in thermal equilibrium with the plasma in the early universe, that the SM was in thermal equilibrium with the photon bath, and that $M_{DM} >> M_{SM}$ so that we can effectively set $M_{SM} = 0$. We are only considering tree level, s-channel annihilations, as pictured in Figure 1a. The calculations were done at resonance, showing that larger DM masses are possible with perturbative couplings. MicrOMEGAs is used in the calculation for relic density, and since the code only takes perturbative effects into account, it is important that we stay within the perturbative unitarity limit. We have made some effort to do so, but we acknowledge that this could be done in more detail in the future.

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