Dirac Fermionic Dark Matter Confronting the Latest Data

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It is well known that the Dirac fermionic dark matter (DM) is seriously constrained by the spin-independent (SI) experiments of DM-nucleus elastic scattering. To evade the vector interaction of DM with the Z boson, we take the quantum numbers of the Dirac DM to be $I \neq 0, I_3 = Y = 0$. The effective couplings from loop contribution should be considered. We find that there is a cancellation in one-loop diagrams, which largely reduces the cross section and makes the Dirac DM viable in the direct search. Besides, for a generic isospin I, we survey the Dirac DM mass constrained by the recent results of PandaX-II, XENON1T and LUX experiments in the direct search, the observed DM relic density, and the H.E.S.S and Fermi-LAT astrophysical observations in the indirect search. With the Sommerfeld enhancement effect, we find that the H.E.S.S. data and the observed DM relic density become serious constraints on the DM mass. The $I = 1$ case is ruled out and Dirac DM masses are forced to be within the ranges of a few to few tens TeV for $2 \leqslant I \leqslant 4$ and few tens to few hundreds TeV for $I \geqslant 5$.

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1. Introduction

One of the most promising DM candidate is so-called the weakly interacting massive particles (WIMPs) which are non-luminous and non-baryonic cold DM (CDM) matter. The DM particles are assumed to be created thermally during the big bang, and froze out of thermal equilibrium escaping the Boltzmann suppression in the early Universe [1] and the recent measured value of DM relic density is $\Omega_{\text{obs}}h^2 = 0.1186 \pm 0.0020$ [2]. So for, there are three complementary searching strategies to detect the DM particles in experiments including the direct detection of DM-nucleus scattering in underground laboratories, the indirect detection of DM annihilation processes in astrophysical observation and the DM direct production at colliders. The null results of finding the DM from direct search of PandaX-II [3], XENON1T [4], LUX [5] experiments, and from the indirect search of H.E.S.S [6] and Fermi-LAT [7] astrophysical observations put the related upper limits on spin-independent (SI), spin-dependent (SD) DM-nucleus scattering cross sections and the velocity averaged DM annihilation cross sections respectively.

In this report, we work on a Dirac fermionic dark matter model by adding a Dirac fermionic multiplet χ with arbitrary I and Y on standard model (SM), and the Lagrangian can be written as [8]

$$
\begin{aligned}
\mathscr{L} &= \mathscr{L}_{SM} + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi \\
&= \mathscr{L}_{SM} + \bar{\chi}^j \gamma^\mu (i\partial_\mu - gW_\mu^a T_{jk}^a + g'B_\mu Y_j \delta_{jk})\chi^k - m_\chi \bar{\chi}^i \chi^i \\
&\supset \frac{g}{\cos\theta_W} T^3 \bar{\chi}^0 \gamma^\mu \chi^0 Z_\mu.
\end{aligned}
\tag{1.1}
$$

where W_μ^a and B_μ are the known electroweak $SU(2)_L$ and $U(1)$ gauge fields, respectively, and θ_w and g is the weak mixing angle and weak coupling, repectively. In this model, the SM is minimally extended so that the DM can only interact with the SM gauge bosons. Besides, there is only one free parameter, the DM mass m_χ that makes the model much simpler. As in most DM models, we may assign DM to be Z_2-odd and SM particles Z_2-even to maintain the stability of DM. In this way, the DM do not interact with SM Higgs and fermions at tree level. From Eq. (1.1), we assign the DM particle with quantum numbers $I \neq 0, I_3 = Y = 0$ to avoid the vector interaction of DM with the Z boson at tree level so that the spin-independent (SI) cross section σ^{SI} of MD-nucleus elastic scattering is vanishing at tree level.
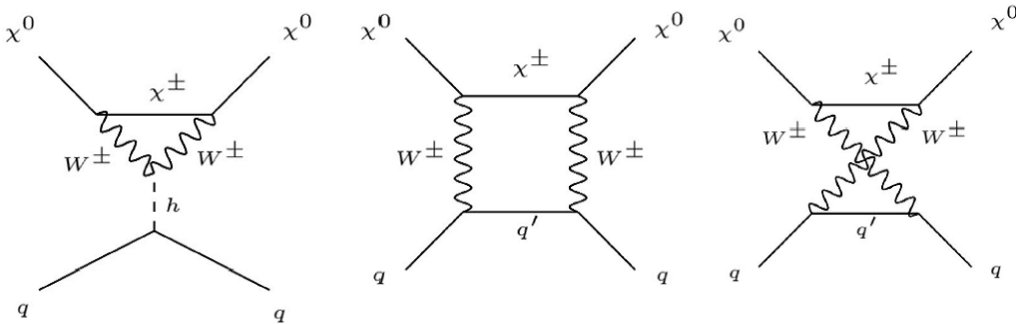

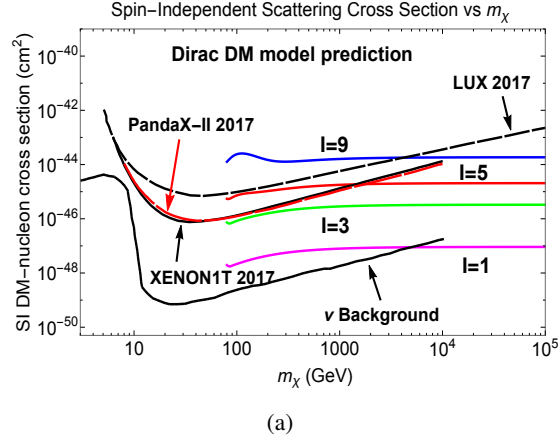Figure 1: Non-vanishing one-loop diagrams for the effective interaction of Dirac DM with quarks

(a)

Figure 2: Dirac DM model prediction for SI cross section of DM scattering off the nuclei ^{129,131}Xe in the direct search.

2. Dirac fermionic dark matter in the direct search

In spite of $\sigma^{SI} = 0$ at tree level, we need to consider the non-vanishing one-loop diagrams for the effective interaction of Dirac DM with quarks shown in Fig. 1. We find that there exists a cancellation so that the large component ($\sim 1/M_W^2$) of the effective vector-vector (VV) coupling is vanishing for all quark flavors (see [9]).

In Fig. 2, we show the plot of σ^{SI} versus m_χ. The prediction values sitting simultaneously below the upper limits of PandaX-II and XENON1T SI-experiments [3, 4] are allowed. We also show the upper limit of LUX SI-experiment, especially for DM mass greater than 10 TeV. We survey the DM mass from the W-boson mass to 100 TeV. For $1 \le I \le 3$, all DM mass in this region are allowed in principle. However, for $I = 1$ we can not distinguish the DM event from neutrino event when $m_\chi > 5.2$ TeV below the curve of the neutrino background. For $I > 3$, we find that PandaX-II provides a lower mass bound with $m_\chi = 0.67, 1.93, 3.51, 6.75$ and 10.00 GeV for $I = 4, 5, 6, 7$ and 8, respectively. Hence the cancellation in the large component ($\sim 1/M_W^2$) of VV interaction, largely reduces the cross section of DM-nucleus elastic scattering and makes the Dirac DM model viable in the direct search.

3. Dirac Fermionic Dark Matter in the Indirect Search

Let us now consider the DM annihilation processes. The DM particles became non-relativistic when they froze out of thermal equilibrium in the early universe. Hence we need to take into account the Sommerfeld enhancement effect [10]. Analytic formulas of the Sommerfeld enhancement factors for arbitrary I are obtained using the SU(2) symmetric limit and the Hulthén approximation [9].

Figs. 3(a) and 3(b) show the plots of $\langle \sigma(\chi^0 \bar{\chi}^0 \to W^+ W^-) v \rangle$ versus m_χ without and with considering the Sommerfeld enhancement effect for $I = 1, 3, 5, 7$ and 9. In each plot, we see that the low mass region with $m_\chi \lesssim 0.55$ TeV are ruled out by the Fermi-LAT constraint and the H.E.S.S data is use to constrain the mass region with $0.55 < m_\chi \lesssim 70$ TeV. The Sommerfeld enhancement

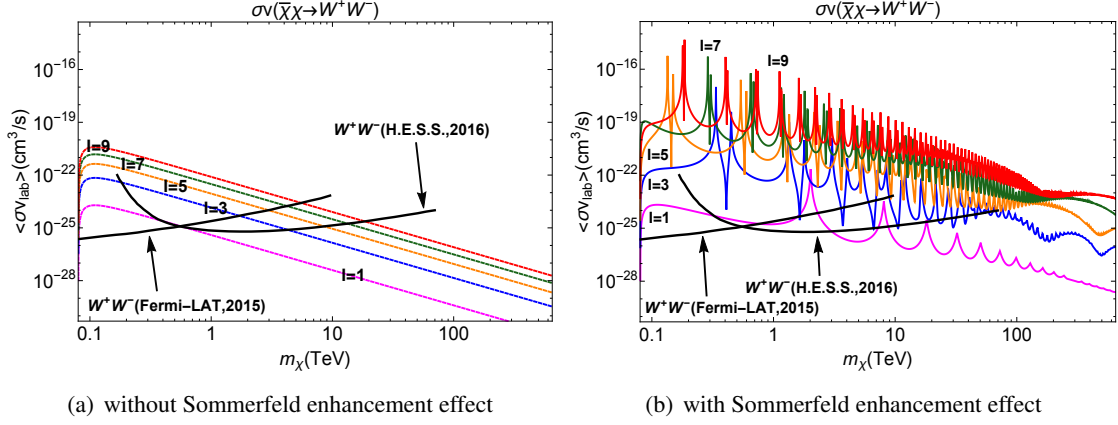(a) without Sommerfeld enhancement effect   (b) with Sommerfeld enhancement effect

Figure 3: Predicted velocity averaged cross sections of galactic DM annihilation to W^+W^- processe for $I = 1, 3, 5, 7$ and 9 cases.

increases the cross sections by 1 to 4 order of magnitude and, hence, the lower limits on the Dirac DM masses are in principle shifted to larger values.

Fig. 4 shows the predicted relic density using $x_f = 24$ for different $I = 1, 2, 4, 5, 7$. The solid (dashed) lines denote the results with (without) the Sommerfeld enhancement effect. The shadow area shows the observed relic density $\Omega_{\rm obs}h^2 = 0.1186 \pm 0.0020$ [2]. This observed relic density provides us the upper mass bounds for DM particles with different isospin I.

4. Conclusion

We summarize our results for $I = 1 \sim 7$ in Table 1. The XENON1T constraint does not provide lower limits on DM masses for $I \leqslant 3$. For the larger I case, the lower mass limit constrained from
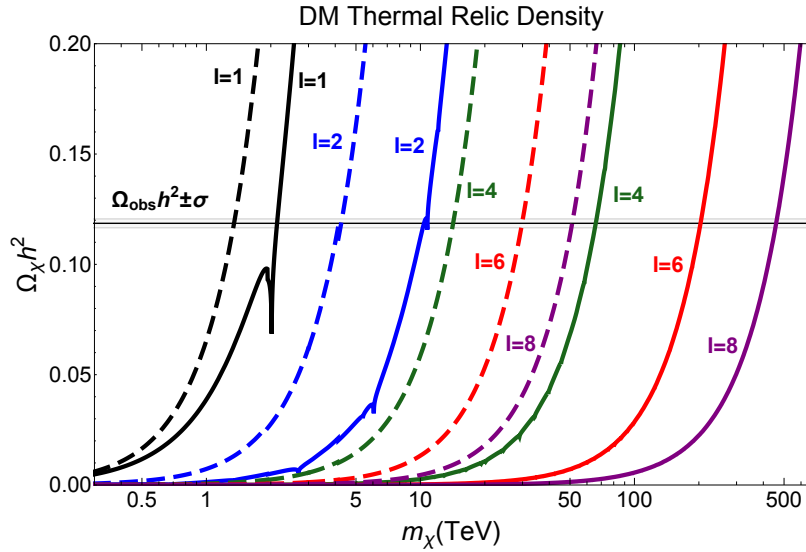

Figure 4: Predicted thermal relic density for $I = 1, 2, 4, 5, 7$.

Table 1: The lower limits m_χ^{LL} obtained from direc and indirect search, the upper limits m_χ^{UL} obtained from the observed relic density are shown. The upper values (lower values within the parentheses) for indirect m_χ^{LL} and relic m_χ^{UL} denote the results with (without) considering the Sommerfeld effect. Dirac DM mass are given in the unit of TeV.

I	1	2	3	4	5	6	7
Direct m_χ^{LL}	—	—	—	0.67	1.93	3.51	6.75
Indirect m_χ^{LL}	3.00 (0.60)	1.09 (2.38)	39.12 (4.29)	41.16 (6.38)	67.33 (8.55)	> 70 (10.86)	> 70 (13.34)
Relic m_χ^{UL}	2.15 (1.36)	10.58 (4.30)	30.30 (8.60)	66.54 (14.34)	123.20 (21.51)	205.23 (30.11)	316.94 (41.14)

the indirect search is more stringent than that from the direct search. The Fermi-LAT and H.E.S.S. upper limits provide lower bounds on m_χ, while the relic density provides upper bounds. Without considering the Sommerfeld effect, all cases (with different isospin I) are allowed, while after turning on the Sommerfeld effect, the $I = 1$ case is ruled out and the Dirac mass is forced to be within the ranges of a few to few tens TeV for $2 \leqslant I \leqslant 4$ and few tens to few hundreds TeV for $I \geqslant 5$.

Acknowledgments

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