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More evidence in favor of light dark matter particles?

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In a previous work, it was found that the light dark matter scenario could be a possible explanation to the 511 keV emission line detected at the center of our galaxy. Here, we show that hints of this scenario may also have been discovered in particle physics experiments. This could explain the discrepancy between the measurement of the fine structure constant and the value referenced in the CODATA. Finally, our results indicate that some of the light dark matter features could be tested in accelerators. Their discovery might favor $N = 2$ supersymmetry.

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I. INTRODUCTION

Despite many experimental and theoretical efforts, the origin of almost 95% of the universe remains unknown. About one third of the content of the Universe seems to be made of matter, but only a few percent is to attribute to ordinary matter. The rest, called dark matter (DM), is expected to be made of neutral weakly interacting massive particles. Their mass is generally believed to be above the proton mass. However, recent studies have pointed out that lighter particles are possible, and perhaps even more promising from the astrophysical point of view.

Light dark matter (LDM) particles are supposed to annihilate into pairs of leptons-anti leptons. When they lose their energy and decay (or annihilate, as in the case of electrons and positrons) they produce energetic photons that can be detected by modern gamma-ray telescopes.

The total DM annihilation cross section can be written as $\sigma v_r \equiv a + bv^2$. In this expression, v_r and v are the DM relative and individual velocity, respectively. In the case of the LDM scenario, this cross section must satisfy two constraints in order to be compatible with current observations: First, it must have the correct value to explain why dark matter constitutes precisely 23% of the universe [1]. This value is about $(\sigma v_r)_{|\mathrm{prim}} \sim 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$, and it is valid in the early universe (when $v \sim c/3$). Secondly, it must decrease with time: $(\sigma v_r)_{\mathrm{MW}}$ in the Milky Way must be $\sim 10^{-5}$ times smaller than $(\sigma v_r)_{|\mathrm{prim}}$ to avoid an overproduction of low-energy gamma rays within our galaxy [2].

The combination of these two constraints yields $a \lesssim 10^{-31}(m_{\mathrm{dm}}/\mathrm{MeV})^2\ \mathrm{cm}^3\,\mathrm{s}^{-1}$ and $b \sim 10^{-25}(m_{\mathrm{dm}}/\mathrm{MeV})^2\mathrm{cm}^3\,\mathrm{s}^{-1}$, valid at any time. From the particle physics point of view, the problem is to find a candidate with the appropriate annihilation cross section. A simple solution consists in coupling DM particles to a new neutral gauge boson (Z'). In this case, there is no a term ($a = 0$) and the b term can be set to the correct value by imposing specific values of the Z' couplings [3]. Strictly speaking, DM could also be coupled to new particles F having a mass $m_F > 100$ GeV (to satisfy accelerator limits). The net effect is to introduce an a term in σv_r, which must be smaller than $10^{-31}(m_{\mathrm{dm}}/\mathrm{MeV})^2\mathrm{cm}^3\,\mathrm{s}^{-1}$ to satisfy the gamma-ray constraint [3].

The LDM scenario has been shown to provide an elegant explanation of the 511 keV emission line detected at the center of our galaxy. Many experiments had measured the intensity of this emission over the years, but they lacked the resolution to determine its morphology. Recently, however, INTEGRAL/SPI experiment provided a surface brightness map which unambiguously indicates the presence of an extended source located at the galactic center [4]. The observed flux is in good agreement with previous data [5], and the morphology is well reproduced by a 2D Gaussian with a full width half maximum of ~10°.

This gamma-ray emission line can be interpreted in terms of e^+e^- annihilations, although the origin of low-energy positrons remains a matter of heated debate. Standard explanations (e.g., astrophysical sources) have been proposed, but most of them seem excluded by the value of the bulge-to-disc ratio [6] or rely on rather controversial hypotheses (jet emission [7], positron propagation [8], etc.). In contrast, the LDM scenario seems to be quite an appealing and simple explanation despite the fact that it certainly involves more exotic physics [9]. In this framework, the DM particles (with a mass $m_{dm} < m_\mu$) would annihilate into electron-positron pairs. Assuming a microgauss-scale magnetic field, the latter remain confined in the galactic center, losing all their kinetic energy by collisions with the baryonic material and eventually annihilating into monoenergetic photons of 511 keV.

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Here, we shall see that the LDM scenario must have two important ingredients. Both should be of experimental/theoretical interest.

II. CAN THE MORPHOLOGY OF THE EMISSION BE WELL REPRODUCED BY LDM ANNIHILATIONS?

The answer is given in Fig. 1 where we plotted the predictions of the LDM model compared to the INTEGRAL/SPI results. We used a Navarro Frenk White profile to describe the dark matter halo of the Milky Way and a Gaussian source with FWHM between 6° and 18° (reported 2-σ confidence limits) to fit the observational data. Assuming any reasonable mass distribution for our galaxy (i.e., $\rho \sim r^{-3}$ at large radii) and using a realistic description of its velocity dispersion profile, we obtain that LDM annihilations produce a significant amount of positrons, even far away from the galactic center. However, the 511 keV emission is expected to be mostly from the bulge, since the baryon density in the outer parts of the halo is simply too small for the positrons to lose their kinetic energy. For a fixed total flux, one obtains less photons from the outer regions when a cuspy density profile is assumed, in better agreement with INTEGRAL/SPI. On the other hand, the dark matter profile cannot be too cuspy, because the possibility of a pointlike source is excluded by the data with a high confidence level. A thorough analysis of which halo models might be compatible with the observed morphology of the 511 keV line emission will be presented elsewhere.

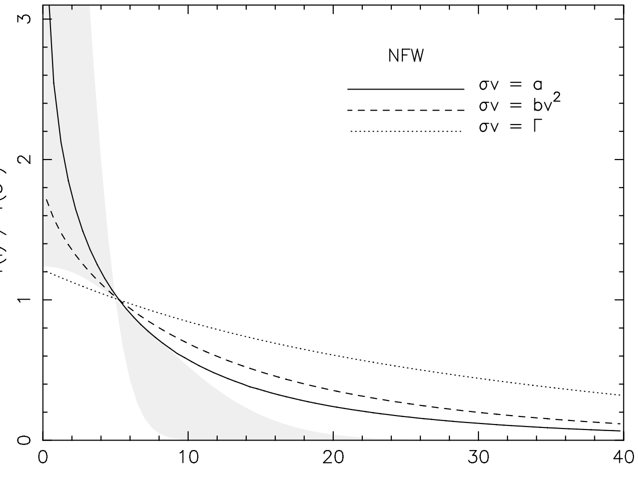

FIG. 1. Galactic 511 keV emission integrated over ±15° in latitude and normalized to the flux at $l = 5°$. Shaded area encloses approximate 2-σ limits from INTEGRAL/SPI. Solid and dashed lines show the predictions for LDM with $b = 0$ and $a = 0$, respectively. Dotted line represents the emission profile expected for decaying dark matter. A NFW model has been used for the Milky Way halo.

For a NFW profile [10] with $\rho_s = 0.183$ GeV cm^{-3} and $r_s = 25$ kpc, the total flux at the Earth ($r_\odot = 8.5$ kpc) is

$$\Phi_{\rm tot} = m_{\rm MeV}^{-2}(130 a_{26} + 1.37 \times 10^{-4} b_{26})\ {\rm cm}^{-2}\,{\rm s}^{-1}, \quad (1)$$

that we expressed in terms of the dimensionless parameters $m_{\rm MeV} \equiv m_{\rm dm}/(1\ {\rm MeV})$, $a_{26} \equiv a/(10^{-26}\ {\rm cm}^{-3}\,{\rm s}^{-1})$, and $b_{26} \equiv b/(10^{-26}\ {\rm cm}^{-3}\,{\rm s}^{-1})$. Because of our naive prescription for positron propagation (each e^+ is assumed to instantly yield two 511 keV photons), most of the emission comes from large angular distances from the galactic center. A fairer comparison with SPI data can be obtained by restricting ourselves to the inner 16°. This roughly corresponds to the instrument's field of view and encloses most of the detected emission. Using the NFW density profile, we now obtain

$$\Phi_{16} = m_{\rm MeV}^{-2}(46.3 a_{26} + 2.98 \times 10^{-5} b_{26})\ {\rm cm}^{-2}\,{\rm s}^{-1}. \quad (2)$$

The surface brightness beyond 16° is expected to be below $m_{\rm MeV}^{-2}(70 a_{26} + 7 \times 10^{-5} b_{26})\ {\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$ or even smaller because of the low baryon density outside the galactic center. This is likely to be too faint to be detected by SPI, so a NFW profile is able to fit the observed 511 keV emission if the total flux is equated to expression (2). A more precise assessment of the best-fit values of the coefficients a_{26}, b_{26}, and $m_{\rm MeV}$ requires a realistic treatment of the SPI instrumental response matrix.

A preliminary analysis hinted that a "pure" velocity-dependent cross section (i.e., Z' exchange only) could be entirely responsible for the 511 keV signal. Here, we show that the emission profile arising from this term is shallower than the one due to the a term. This is a generic conclusion, regardless of the particular model assumed for the Milky Way mass. Therefore, our present conclusion is that, unlike stated in previous studies, the a term should be included indeed. Moreover, accounting for the observed flux (with a b term only) would require $m_{\rm dm} <$ 1 MeV, which would have a tremendous impact on primordial nucleosynthesis. Setting $\Phi_{16} = 10^{-3}\ {\rm cm}^{-2}\,{\rm s}^{-1}$ (the INTEGRAL's result), we conclude that a_{26} must be of the order of

$$\begin{aligned} a_{26} &\sim 2.1610^{-5} m_{\rm MeV}^2 \quad \text{or} \\ (\sigma v_r)_{\rm MW} &\sim 2.16\ 10^{-31} m_{\rm MeV}^2\ {\rm cm}^3\,{\rm s}^{-1}, \end{aligned} \quad (3)$$

in order to explain the 511 keV line, assuming that LDM annihilations constitute the main source of low-energy positrons.

Finally, we note that (i) fermionic LDM candidates cannot account for the observed flux because $a_{26} \ll 10^{-7} m_{\rm MeV}^2$ for these particles (except perhaps in the marginal case where they would exchange a light gauge boson with axial couplings to ordinary matter [11]; in this case m_{dm} should be ~10 MeV), (ii) LDM annihilations should proceed through both F and Z' exchanges. The extra gauge boson is necessary to obtain the correct relic density, while the F exchange is needed to explain the the 511 keV signal. We confirm that decaying DM cannot fit the emission in a NFW profile [12].

The need for (fermionic) F particles is of interest for both atomic and particle physics experiments. Their contribution to the muon and electron anomalous magnetic moment $(g-2)_{\mu,e}$ is given by $\delta a_{\mu,e} \sim \frac{f_l f_r}{16\pi^2} \frac{m_{\mu,e}}{m_{F_{\mu,e}}}$. Noting that the quantity $\frac{f_l f_r}{m_{F_e}}$ also enters the expression of σv_r, we obtain $(\sigma v_r)_{\mathrm{MW}} \simeq (0.864, 3.456) 10^{-31} (\frac{\delta a_e}{10^{-12}})^2$ cm^3 s^{-1} (depending on whether DM is made of self-conjugate particles or not). $(\sigma v_r)_{\mathrm{MW}}$ is dominated by its a term. The above expression matches Eq. (3) when $\delta a_e = (a_e^{\mathrm{exp}} - a_e^{\mathrm{th}}) \simeq (1.58, 0.79) 10^{-12} m_{\mathrm{MeV}}$, respectively. Yet, we expect the experimental value a_e^{exp} to be somewhat larger than the theoretical estimate a_e^{th}.

It turns out that there exists a small discrepancy between the theoretical prediction and the experimental measurement. The latter is about $\delta a_e \sim (3.44 - 3.49) 10^{-11}$ (the first number is obtained from the positron $g-2$, while the second one is from the electrons) [13]. This discrepancy is generally "disregarded" because the new physics processes that are generally considered are supposed to yield a much smaller contribution. Here, we see that DM particles with a mass of $m_{\mathrm{dm}} \sim (21.8, 43.6)$ MeV (depending on whether DM is made of self-conjugate particles or not) could surprisingly explain the discrepancy. On the other hand, greater masses would yield a too large value of δa_e.

The discrepancy between a_e^{exp} and a_e^{th} thus appears for the first time related to a new physics process. To determine a_e^{th}, we used the fine structure constant obtained from the Quantum Hall effect α_{QH}. The latter is seen to be the most accurate experimental determination of α. However, it is never used by particle physicists, since it leads to an unexplained discrepancy. To obtain a perfect agreement between theory and observations, one instead "forces" a_e^{th} to match a_e^{exp}. The value of α thus obtained (denoted α_{st}) is quoted in the international reference CODATA [14], and it is used to get theoretical estimates of other processes. But this procedure yields wrong results if the discrepancy between a_e^{exp} and a_e^{th} is due to new physics. If it is so, then one should use the experimental value of α (for example α_{QH}) instead of α_{st} to make theoretical predictions.

The difference between α_{st} and α_{QH} is about $4 10^{-6}$. One may think that this is totally negligible. However, this is enough to change a_e^{th}. A modification in α does not affect the value of a_μ^{th} (the muon $g-2$). But F particles might do. The latter was found to be smaller than the experimental value by a few 10^{-9} units [15]. This discrepancy is widely considered as a possible case for new physics and its precise value is of crucial interest.

We based our previous estimate of $\delta a_e = a_e^{\mathrm{exp}} - a_e^{\mathrm{th}}$ on α_{QH}. Other experimental values of α can be found in the literature (obtained notably from the measurement of the Rydberg constant, Josephson effect, and muonium). The most precise values are thought to come from the Quantum Hall effect and the Rydberg constant, and they both give $a_e^{\mathrm{exp}} - a_e^{\mathrm{th}} > 0$. Nevertheless, if we use the other two values we obtain a negative discrepancy, which cannot be explained by the presence of F particles—at least not in the simple form considered here (although they are not excluded either).

Assuming universality and F exchange, we obtain a relationship between the electron and muon $g-2$:

$$\left(\frac{\delta a_\mu}{10^{-9}}\right) = 2.1 (m_{Fe}/m_{F\mu}) \left(\frac{\delta a_e}{10^{-11}}\right). \tag{4}$$

Plugging the measured discrepancy for δa_e into the above expression and assuming $m_{Fe} = m_{F\mu}$, we find $\delta a_\mu \sim 7\ 10^{-9}$. The E821 experiment measured $\delta a_\mu \sim (2.7 \pm 1.04) 10^{-9}$ (using e^+e^- data). One can therefore explain both the anomalous values of the muon and electron $g-2$ by introducing a set of F particles satisfying $m_{Fe} \sim m_{F\mu}/x$, with presumably $x \gtrsim 2$. The correct approach to determine x more precisely would be to estimate a_μ^{th} by using α_{QH}. But as mentioned earlier, this has not been done yet. Note that, to our knowledge, it is the first time that a possible connection between δa_e and δa_μ is established. One could make a prediction for the tau $g-2$. However present experiments still lack the sensitivity to challenge the standard model (SM) predictions.

Unambiguous signatures of F particles could be detected in the Large Hadron Collider, unless they turn out to be heavier than a few TeV. They could be produced through e^+e^- collisions and detected through their two-body decay (i.e., F going into electrons and DM particles). F particles have been introduced to explain the 511 keV line. If the LDM scenario is not the explanation to this emission, then the spin-1 boson becomes the only ingredient that is really needed for LDM to be viable.

Hints of the presence of a light gauge boson also may have been detected [16]. Assuming universal couplings, it was found that, albeit small, the Z' couplings could be "large" enough to modify the neutrino-quark elastic scattering cross sections when the Z' mass is about a few GeV. NuTeV collaboration measured these cross sections and found small deviations [17]. QCD corrections (isospin violations, strange sea asymmetry) could well be the explanation of this anomaly [18]. However, QCD uncertainties are still very large and, in some cases, even increase the anomaly. Therefore, it is worthwhile to consider the existence of a light gauge boson seriously. Figure 2 illustrates how a light Z' can solve the NuTeV anomaly. (Note that a QCD explanation does not exclude the existence of a Z', but it certainly sets an upper limit on its mass.)

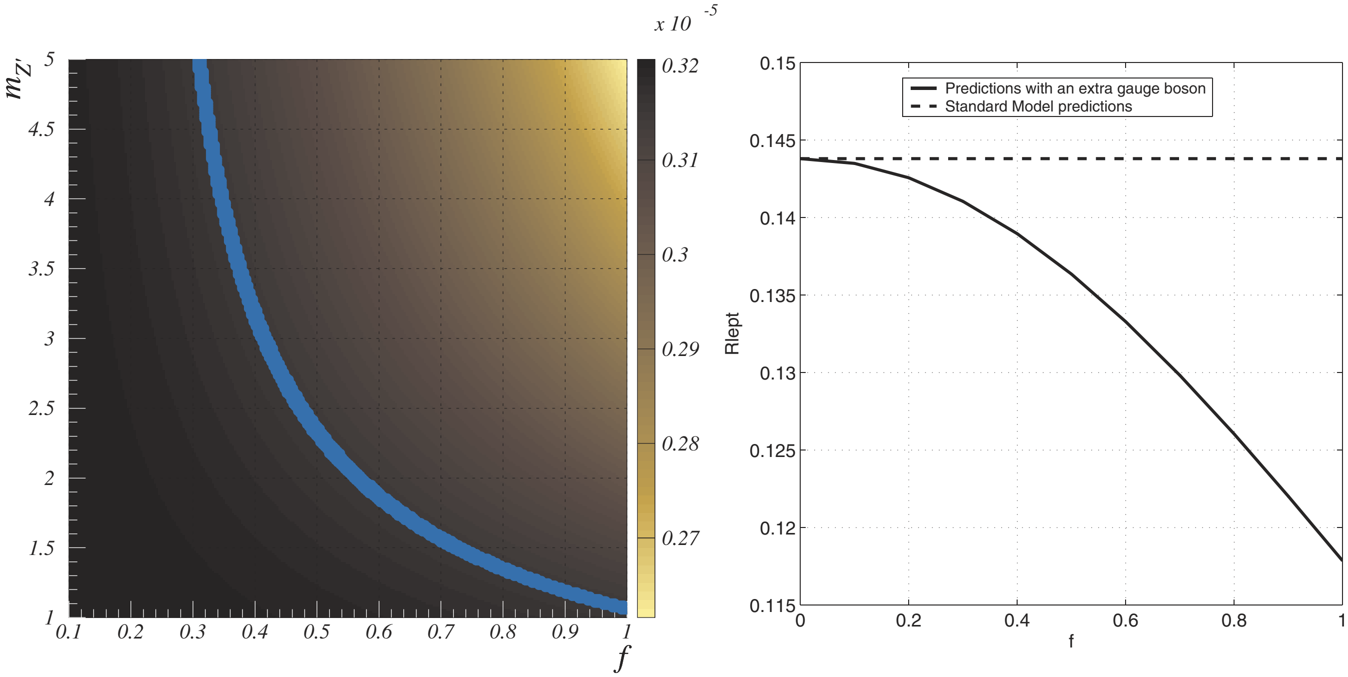

FIG. 2 (color online). The left panel represents how NuTeV's observable R_{num} is affected by a Z'. R_{num} values in presence of a Z' are symbolized by the shaded regions ranging from dark to light (colors ranging from black to yellow). The standard model predicts $R_{\text{num}} = \sum_{u,d}[G_F c_\nu^q c_a^q] = 3.2072\ 10^{-6}$ [dark (black) region] while NuTeV finds $3.1507\ 10^{-6}$. The parameters of the gauge boson that impressively fit the NuTeV anomaly (without error bars) are represented by the center (blue) curve with $f_q f_\nu = f^2 10^{-6}(m_{Z'}/\text{GeV})^2$. On the right panel, we show our predictions for R_{lept}, using $f_e f_\nu = f^2 10^{-6}(m_{Z'}/\text{GeV})^2$.

The case without universality seems even more interesting as one could perhaps find evidence for a light Z' in high energy colliders! The measurement of the electron $g-2$ restricts the coupling f_e to be less than $f_e \lesssim 5.7\ 10^{-1}(\frac{\delta a_e}{10^{-11}})^{1/2}(\frac{m_{Z'}}{\text{GeV}})$. Also, the product of the Z' couplings to neutrinos and electrons must not exceed $[f_e f_\nu]^{\max} \sim 5.388\ 10^{-7}(\frac{m_{Z'}}{\text{GeV}})^2$, according to the very precise measurement of the elastic scattering of muon neutrinos on electrons by the CHARM-II experiment [19]. CHARM-II's results are in good agreement with the SM predictions. However, the mean experimental value seems to be slightly different from the SM expectations. It is quite surprising but very interesting to see that the introduction of a new gauge boson with couplings $f_e f_\nu \simeq [f_e f_\nu]^{\max}$ allows one to reduce this discrepancy!

Let us assume $f_e \sim f_q$ (although it may be quite challenging to build a theory that predicts $f_\nu < f_e \sim f_q$). On one hand, the NuTeV anomaly can be explained by taking $m_{Z'} <$ GeV. On the other hand, predictions for $e^+e^- \to e^+e^-$ and $e^+e^- \to q\bar{q}$ cross sections will now differ from the SM expectations by a few percent. These two cross sections have been well measured at LEP II. The intriguing point is that small deviations have been found in a preliminary analysis [20]. It is probably too soon to conclude that these deviations are (i) significant, and (ii) indeed due to new physics. However, if they turn out to be confirmed, the effect of a light gauge boson on these cross sections would become of crucial interest for the astro/particle/astroparticle physics communities.

However, since a QCD explanation is possible, one can do a test that does not involve quarks but only leptons (so as to get rid of the QCD corrections). It is based on an already proposed experiment which aims to measure the ratio $R_{\text{lept}} = \sigma_{\nu_\mu e}/(\sigma_{\nu_e e} + \sigma_{\bar{\nu}_\mu e})$, where $\sigma_{\nu_\mu e}$, $\sigma_{\nu_e e}$, and $\sigma_{\bar{\nu}_\mu e}$ are the muon neutrino-, electron neutrino-, and muon anti neutrino-electron elastic scattering cross sections, respectively [21]. If a deviation is measured (as shown in Figure 2 right panel) then it is likely to be due to the presence of a light Z'. If not, this may exclude it or, alternatively, impose even stricter limits on the Z' couplings. This test is independent on $m_{Z'}$ or universality assumptions; it probes the maximal value for $[f_e f_\nu]^{\max}$. If a deviation is found, one has to refer to the NuTeV findings (and evaluate the size of the QCD corrections) to get an estimate of $m_{Z'}$.

III. CONCLUSION

Our study indicates that the LDM scenario could have already shown up in astrophysical and particle physics processes. Direct evidences are needed, but the presence of heavy fermionic particles F may have been already detected through the anomalous value of the electron $g-2$. As a major consequence, the value of the fine structure constant quoted in the CODATA and used for theoretical estimates of various particle physics processes could be wrong. Instead α could be close to its "direct" experimental value! Quantities like the theoretical estimate of the muon $g-2$ (subject of great debate since a few years) may have to be computed again. The existence of both F and Z' (if one relaxes the universality assumptions) could be challenged in high energy colliders. Their discovery would hint in the direction of $N=2$ supersymmetry [22].

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