Probing MeV Dark Matter at Low-Energy e^+e^- Colliders

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It has been suggested that the pair annihilation of dark matter particles χ with mass between 0.5 and 20 MeV into e^+e^- pairs could be responsible for the excess flux (detected by the INTEGRAL satellite) of 511 keV photons coming from the central region of our Galaxy. The simplest way to achieve the required cross section while respecting existing constraints is to introduce a new vector boson U with mass M_U below a few hundred MeV. We point out that over most of the allowed parameter space, the process $e^+e^- \to U\gamma$, followed by the decay of U into either an e^+e^- pair or an invisible ($\nu\bar{\nu}$ or $\chi\bar{\chi}$) channel, should lead to signals detectable by current B-factory experiments. A smaller, but still substantial, region of parameter space can also be probed at the Φ factory DAΦNE.

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Within the context of Einsteinian gravity, evidence for the existence of dark matter (DM) is overwhelming [1]. Analyses of the cosmic microwave background anisotropy, and other data on the large scale structure of the Universe, have determined many cosmological parameters with unprecedented precision [2]. Along with analyses of big bang nucleosynthesis (BBN) [3], this data also show the DM must be largely nonbaryonic. Since neutrinos can contribute only a small fraction [1], this strongly points towards the existence of an exotic, neutral, stable particle χ, with relic density Ω_χ satisfying [2]

$$\Omega_\chi h^2 = 0.113 \pm 0.0085 \quad (\text{at } 1\sigma), \tag{1}$$

where the scaled Hubble constant $h \simeq 0.7$ [2].

Dark matter particles should clump due to gravitational attraction. At the galactic center, their density might be so high that their annihilation into lighter, known particles could lead to visible signals. Final states containing hard photons play a special role in this, since photons travel in straight lines and are easy to detect.

Looking for an excess of hard photons from the center of our Galaxy, the INTEGRAL satellite indeed observed a large flux of photons with energy of 511 keV [4]. This sharp line can only come from the annihilation of nonrelativistic e^+e^- pairs. However, most estimates of positron production by astrophysical sources fall well short of the required flux giving rise to the speculation [5] that the annihilation of light DM particles χ into e^+e^- final states could be responsible for this signal. While the mass m_χ can exceed m_e substantially (since the positrons produced in χ annihilation quickly lose energy through scattering on neutral atoms), it has been pointed out [6] that annihilation into $e^+e^-\gamma$ final states, in spite of being a higher-order process, would overproduce MeV photons if $m_\chi >$ 20 MeV, leading to

$$m_e \leq m_\chi \leq 20 \text{ MeV}. \tag{2}$$

Recently, it has been argued [7] that there exists evidence for a nonastrophysical source of MeV photons, in which case the upper end of the range (2) would be favored.

In order to produce the required flux of positrons, one needs an annihilation cross section $\sigma_{\text{ann}}(\chi\bar{\chi} \to e^+e^-)$

$$10^{-3} \text{ fb} \leq v\sigma_{\text{ann}}(m_\chi/1 \text{ MeV})^{-2}\kappa \leq 1 \text{ fb}. \tag{3}$$

Here v is the relative velocity of the two χ particles in their center-of-mass system (cms) frame, and σ is to be computed at $v \sim 10^{-3}c$. Note that models of the galaxy fix the DM mass density; the number density, which enters quadratically in the calculation of the positron flux, therefore scales as m_χ^{-1}. Finally, $\kappa = 1$ if χ is self-conjugate (i.e., a Majorana particle), whereas $\kappa = 2$ if $\chi \neq \bar{\chi}$, since then only half of all encounters of DM particles can lead to annihilation events. To be on the safe side, in (3) we have expanded the range given in the original publication [5] by an order of magnitude in either direction. This may be overly conservative [8], since one here only needs the DM density averaged over a significant volume, which is thought to be better known than that right at the galactic center.

A cross section in the range (3) implies that $e^+e^- \leftrightarrow \chi\bar{\chi}$ reactions were in equilibrium down to temperatures well below m_χ. Since successful BBN requires a starting temperature $T \geq 0.7$ MeV [9], it is safe to assume that χ particles indeed were in thermal equilibrium. Their relic density then turns out to be [10] inversely proportional to the thermal average of their total annihilation cross section into all final states containing only standard model (SM) particles:

$$\Omega_{\text{DM}} h^2 \propto \langle v\sigma_{\text{tot}}\rangle^{-1}. \tag{4}$$

Given the mass constraint (2), to the leading order, annihilation is possible only into e^+e^- and $\nu\bar{\nu}$ final states; the first channel must exist, since χ particles are supposed to annihilate into e^+e^- pairs even today. Assuming χ forms (nearly) *all* DM, the relic density resulting from Eq. (4) must fall in the range (1). This constraint, interpreted using

Eq. (4) and Eq. (3), is compatible only if the present $\sigma_{\rm ann}$ is strongly suppressed compared to that at decoupling. This is most easily achieved [5,11,12] if $\chi\bar{\chi}$ annihilation proceeds only from a P-wave initial state, in which case $v\sigma_{\rm ann} \propto v^2$; note that $v^2 \sim 0.1$ when χ particles decoupled, while $v^2 \sim 10^{-6}$ today.

In a renormalizable theory, some particle must mediate $\chi\bar{\chi} \to e^+e^-$ annihilation. The simplest possibility [5,12] is to introduce a light spin-1 boson U coupling to both e^+e^- and $\chi\bar{\chi}$ states. If χ is a Majorana spin-1/2 fermion or complex scalar, $\sigma_{\rm ann}(\chi\bar{\chi} \to f\bar{f})$ is given by [12]

$$v\sigma_{\rm ann} = \frac{\beta_f g_\chi^2}{12\pi s}\left\{\frac{(s-4m_\chi^2)[s\Sigma_f + m_f^2(6\Pi_f - \Sigma_f)]}{(s-M_U^2)^2 + \Gamma_U^2 M_U^2} + \xi\left(\frac{m_f m_\chi}{M_U^2}\right)(3\Sigma_f - 6\Pi_f)\right\}, \quad (5)$$

where $\xi = 1(0)$ for spinor (scalar), $\beta_f = \sqrt{1 - 4m_f^2/s}$, $\Pi_f = g_{f_L} g_{f_R}$, and $\Sigma_f = g_{f_L}^2 + g_{f_R}^2$, with g_{f_L} and g_{f_R} being the left- and right-handed $Uf\bar{f}$ couplings. The $U\chi\bar{\chi}$ coupling g_χ is purely axial vector for a Majorana χ. The first line in Eq. (5) is a pure P-wave contribution. We discount, henceforth, a Dirac χ as it would, in general, have a large S-wave contribution to σ thereby making it difficult to reconcile the constraints (1) and (3).

Since $\Gamma_U \ll M_U$ for realistic couplings, the usual [10] nonrelativistic expansion of the cross section in powers of v breaks down if $2m_\chi \simeq M_U$ and the thermal averaging has to be done numerically [13]. The strong velocity dependence of the cross section ($s - 4m_\chi^2 \simeq v^2 m_\chi^2$ if $v^2 \ll 1$) in Eq. (3) also has to be treated properly. For simplicity, we assume a thermal velocity distribution, with a rather high temperature $T = 10^{-6} m_\chi$; smaller temperatures, which are probably more realistic, would require larger couplings, which would be easier to test at e^+e^- colliders.

Figures 1 and 2 show the parameter space spanned by M_U and the product of couplings $g_\chi g_{e_R}$ for the case that χ is a Majorana fermion (complex scalar). The regions allowed by the constraints (2)–(4) are enclosed by the solid curves, with distinct allowed regions for $2m_\chi < M_U$ ($2m_\chi > M_U$). We consider only $g_{e_L} = 0$ since this implies $g_{\nu_L} = 0$ if U is a gauge boson of a gauge group G_U that simply multiplies the gauge group of the SM. Note that νe scattering data impose the very strong constraint [12], $g_{\nu_L}\sqrt{g_{e_L}^2 + g_{e_R}^2} < M_U^2 G_F$. For $g_{e_L} = g_{\nu_L}$ and $g_{e_R} = 0$, this would exclude the entire DM-allowed range (which is invariant under $g_{e_R} \leftrightarrow g_{e_L}$) of Fig. 1, and most of Fig. 2. Finally, for $g_{e_L} = 0$, DM constraints apply essentially to the product $g_\chi g_{e_R}$. The individual values matter only if $2m_\chi \sim M_U$, in which case the value of the decay width Γ_U is relevant.

Only a narrow range of couplings is allowed in Fig. 1 on account of an S-wave contribution surviving for our choice of $g_{e_L} = 0$. Even though proportional to m_e^2, for small m_χ it would lead to a present annihilation cross section above the range (3), unless $2m_\chi$ is quite close to M_U. In the latter case, the kinetic energy of the DM particles in the early Universe was sufficient to allow efficient annihilation through the exchange of on-shell U-bosons, whereas those at the galactic center are so slow that they can only annihilate through the exchange of off-shell Us. This also gives the required large enhancement of the cross section at decoupling relative to that at the galactic center, even for a nonvanishing S-wave contribution. However, if $2m_\chi$ is too close to (but still below) M_U, the relic density constraint (1) will require very small couplings, too small to satisfy the constraint (3). For small M_U, the allowed range of m_χ values is, therefore, very narrow, e.g., $0.72\,\text{MeV} \leq m_\chi \leq 0.76\,\text{MeV}$ for $M_U = 2\,\text{MeV}$. For larger M_U, and cor-

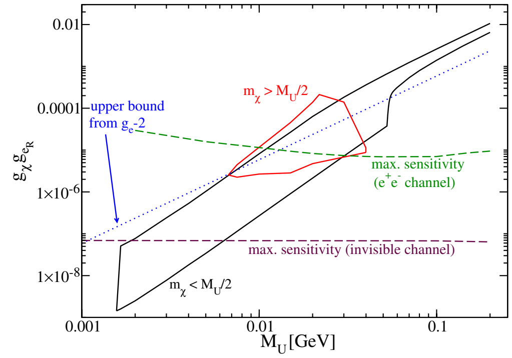

FIG. 1 (color online). Parameter space for a Majorana χ with $g_{e_L} = g_\nu = 0$ and $g_\chi = 10 g_{e_R}$. In between the solid curves, χ has the correct relic density, and the correct cross section to explain the flux of 511 keV photons emerging from the galactic center; the red (black) curves correspond to $2m_\chi < (>) M_U$. The dotted (blue) line indicates the upper bound on g_{e_R} from $(g_e - 2)$ measurements. The dashed curves show the maximal sensitivity of DAΦNE to $e^+e^- \to U\gamma$ production, for $U \to e^+e^-$ (upper, dark green, curve) and U decaying invisibly (lower, magenta curve). The DM constraints are essentially independent of the ratio g_χ/g_{e_R}, whereas the $g_e - 2$ constraint as well as the sensitivity limits are independent of g_χ. Results for $g_{e_R} = g_{e_L}$ are similar to those for scalar χ (Fig. 2).

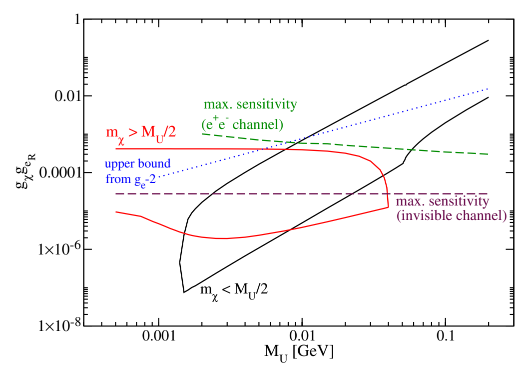

FIG. 2 (color online). Parameter space of the model with a complex scalar as MeV dark matter χ annihilating through the exchange of spin-1 U bosons, for $g_{e_L} = g_\nu = 0$ and $g_\chi = 1$. Notation is as in Fig. 1, except that the indicated sensitivities are now those that can be achieved at the B factories.

respondingly larger m_χ, the S-wave contribution $\propto m_e^2$ becomes less important, and a wider range of values of m_χ is allowed, e.g., $m_\chi > 11$ MeV for $M_U = 60$ MeV; this lower bound on m_χ increases only slowly for even larger values of M_U. Recall that values of m_χ close to the upper bound of 20 MeV are preferred [7] since they allow to describe an excess of MeV photons from the galactic center.

With the S-wave contribution vanishing for a scalar χ, the allowed parameter space is much wider (Fig. 2). The DM constraints are now compatible with the entire range of m_χ except for values very close to $M_U/2$ where today's $\sigma_{\rm ann}$ comes out too small (for $2m_\chi$ just below M_U) or too large (for $2m_\chi$ just above M_U) [14] if the couplings are chosen to satisfy the constraint (1). For example, for $M_U = 2$ MeV, the range 0.91 MeV $\le m_\chi \le$ 1.04 MeV is excluded. Note that in both figures, smaller couplings correspond to larger (smaller) m_χ if $2m_\chi < (>) M_U$.

Since it is natural to assume $g_{\nu_L} = 0$ for our choice of $g_{e_L} = 0$, the only relevant model-independent laboratory constraints come from processes involving only electrons, the most sensitive being the anomalous magnetic moment of the electron [12]. Using the analytical results of [15] and comparing with the most recent results for SM prediction and measurement [16], we find [11]

$$-6 \times 10^{-9} \le \left(\frac{1\ \text{MeV}}{M_U}\right)^2 (3 g_{e_L} g_{e_R} - g_{e_L}^2 - g_{e_R}^2) \le 3 \times 10^{-8}$$

at 95% C.L. The resulting upper limit on the product $g_{e_R} g_\chi$ is shown as dotted (blue) line in Figs. 1 and 2. While the data weakly favor a small positive contribution [17], U-boson loops can account for it only if $g_{e_L} \simeq g_{e_R}$. This would either imply a sizable $U\nu\bar{\nu}$ coupling, or a model where the U gauge group is embedded nontrivially into the electroweak gauge group, rendering the construction of a complete, renormalizable model more complicated. As long as g_{e_L} is zero, $(g_e - 2)$ imposes a rather severe constraint (Figs. 1 and 2) entirely independent of g_χ. With DM constraints operating essentially on the product $g_\chi g_{e_R}$, the parameter space that also satisfies the $(g_e - 2)$ constraint becomes larger for larger g_χ. Together, the constraints exclude scenarios with $g_\chi \ll g_{e_R}$. In the opposite limit, namely $g_\chi = 1 (\gg g_{e_R})$, they together exclude scenarios with M_U much above 200 MeV, as shown in Fig. 2. Other constraints on the U boson have been discussed in the literature [17,18]; however, they are more model dependent in that they involve couplings that are not required from DM phenomenology. Hence we ignore these constraints here, and instead turn to a discussion how this model can be tested at e^+e^- colliders. Scenarios with $g_\nu = 0$ but $g_e \neq 0$ may also be favored by BBN [19].

As noted above, the U boson must couple to e^+e^- pairs in order to explain the excess flux of 511 keV photons. The process $e^+e^- \to U\gamma$ [11] will therefore have a nonvanishing cross section if the cms energy $\sqrt{s} > M_U$:

$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha(g_{e_L}^2 + g_{e_R}^2)}{2s^2(s - M_U^2)} \left[\frac{s^2 + M_U^4}{\sin^2\theta} - \frac{(s - M_U^2)^2}{2}\right], \quad (6)$$

where α is the fine structure constant and $\theta \equiv \theta_\gamma$ is the emerging angle of the photon. Since existing constraints imply $M_U \le 0.2$ GeV, the produced U bosons can decay only into e^+e^- pairs, pairs of DM particles χ, or perhaps neutrinos. This gives rise to two possible collider signatures, with $e^+e^-\gamma$ and $\gamma +$ "nothing" final states and we explore the detectability of both. We focus on low-energy colliders, since the signal cross section will drop $\propto 1/s$ for $s \gg M_U^2$. Specifically, we analyze the two signatures at the Φ factory DAΦNE, which operates at $\sqrt{s} = m_\phi = 1.02$ GeV, and at the B factories, which operate at $\sqrt{s} = 10.6$ GeV; the reduced cross section at the latter is overcompensated by the higher accumulated luminosity ($\sim$500 fb^{-1} for both B factories combined, as compared to $\sim$500 pb^{-1} at the Φ factory).

The $e^+e^-\gamma$ final state receives a large contribution from $\mathcal{O}(\alpha^3)$ QED processes. But whereas the signal events have invariant mass of the outgoing e^+e^- pair M_{ee} very close to M_U, the background distribution has peaks at $M_{ee} \simeq \sqrt{s}$ (from t-channel diagrams with soft γ emission) and at a few m_e (from s-channel diagrams). We therefore require that (i) the produced particles must not be too close to the beam pipe, $|\cos\theta_i| < 0.9$ for $i = e^\pm, \gamma$; (ii) $M_{ee} \in [M_U - 1\ \text{MeV}, M_U + 1\ \text{MeV}]$, where the spread is given by the mass resolution of the KLOE detector [20]; we assumed that the BABAR and BELLE detectors at the B factories have similar resolution. The second cut implies that the photon is quite energetic, since $E_\gamma = (s - M_{ee}^2)/(2\sqrt{s})$. The signal is considered detectable if $N_{\rm signal} > 5\sqrt{N_{\rm bckgd}}$.

The resulting sensitivity limits are indicated by the (upper) dashed (dark green) curves in Figs. 1 and 2. Signal and background have been calculated with the COMPHEP package [21], augmented to include U bosons. Note that these are *maximal* sensitivities in that we assume a branching ratio $B(U \to e^+e^-) = 1$. This may well be realistic for $2m_\chi > M_U$, but for the assumptions made in the figures, is not realistic otherwise; since we assumed $g_\chi \gg g_{e_R}, g_{e_L}$ in these plots, the invisible $U \to \chi\bar{\chi}$ decay mode will dominate if it is open. However, since the $e^+e^-\gamma$ final state is background dominated, the sensitivity limit on g_{e_R} only scales like $B(U \to e^+e^-)^{-0.25}$.

Thus, DAΦNE can probe couplings g_{e_R} down to about 10^{-3}, whereas the B factories would be sensitive to couplings as small as 3×10^{-4}. In both cases the sensitivity gets somewhat worse at small M_U as the background peaks at small M_{ee}. Note that these sensitivity limits are completely independent of g_χ, and of the nature of the DM particle (scalar or Majorana fermion). In particular, for the scenario of Fig. 1, the B factories should be able to probe the entire parameter space with $2m_\chi > M_U$ in this channel. The scenario in Fig. 2 is the worst case scenario for collider experiments. With the DM constraints essentially fixing the product of couplings $g_{e_R} g_\chi$ (for $g_{e_L} = 0$), a large g_χ, as in Fig. 2, therefore leads to small g_{e_R}, and hence small production cross sections.

As already noted, for $g_\chi \gg g_{e_R}$ we expect a large invisible branching ratio for the U boson if $2m_\chi < M_U$. The signal, then, consists of a single monochromatic photon with $E_\gamma = (s - M_U^2)/(2\sqrt{s})$. Unfortunately, the experimental resolution on E_γ is considerably worse than that for M_{ee} [20]. On the other hand, the physics (SM) background now comes from $\nu\bar{\nu}\gamma$ final states, and is thus $\mathcal{O}(\alpha G_F^2 s)$. After simple acceptance cuts, $E_\gamma > 100$ MeV, $|\cos\theta| < 0.9$, the background is already completely negligible at the Φ factory. Even at the B factories we expect $\ll 1$ background event once we require $|\cos\theta| < 0.9$, $E_\gamma > 0.5\sqrt{s} - 200$ MeV [22]. In other words, the photon plus nothing signal is rate, rather than background, limited. We neglect instrumental backgrounds here as these are very specific to the experiment.

The corresponding sensitivity limits are shown by the (lower) dashed (maroon) lines in Figs. 1 and 2. We again show the maximal sensitivity; i.e., here we assumed 100% branching ratio for invisible U decays. We see that DAΦNE can probe a coupling $g_{e_R} \gtrsim 8 \times 10^{-5}$ in this channel, while the B factories would be sensitive to $g_{e_R} \gtrsim 3 \times 10^{-5}$, independent of g_χ. In particular, the B factories would probe the entire parameter space of Fig. 1 with $M_U \geq 4$ MeV in this channel. Even in the worst case scenario of Fig. 2, much of the DM-allowed parameter space would lead to a detectable signal.

A dominant invisible decay mode for the U is not realistic if $2m_\chi > M_U$, unless U also has significant couplings to neutrinos, which, however, is disfavored. We therefore also investigated $\chi\bar{\chi}\gamma$ production through off-shell U exchange. The signal cross section is now proportional to the product $g_{e_R} g_\chi$ (for $g_{e_L} = 0$), just like the DM annihilation cross section (5). Using a modified COMPHEP, we find a detectable signal at the B factories ($\geq$10 events with $|\cos\theta_\gamma| < 0,9$, $E_\gamma > 0.5\sqrt{s} - 200$ MeV in 500 fb^{-1}) if $g_{e_R} g_\chi \geq 2.4 \times 10^{-4}$. This limit depends only weakly on M_U and m_χ, so long as m_χ is not very close to $M_U/2$. This would be sufficient to probe at least the upper end of the DM-allowed region with $2m_\chi > M_U$ in Fig. 2.

In summary, we carefully delineated the allowed parameter space of models with MeV dark matter whose annihilation is mediated by the exchange of a spin-1 U boson. Model parameters must be chosen such that the correct thermal relic density and the correct present annihilation cross section are reproduced; the latter is motivated by the signal of 511 keV photons from the center of our Galaxy. The parameter space is further constrained by the anomalous magnetic moment of the electron. We found that these models can be tested decisively at existing low-energy e^+e^- colliders if the U boson has similar (or greater) coupling strength to electrons as to DM particles (Fig. 1). Such models would be relatively easy to construct by introducing an additional gauge group with small coupling constant. Models where the coupling of the U boson to DM particle is much stronger than that to electrons are much more difficult to probe at colliders (Fig. 2); such a pattern could emerge if U couples to electrons only through mixing with SM gauge bosons, but has direct coupling to DM particles. The single photon plus nothing channel allows to probe much of the parameter space compatible with the DM constraints even in this unfavorable situation. We therefore come to the rather surprising conclusion that the solution of the dark matter puzzle might be found at the existing Φ and B factories.

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