Detecting light leptophilic gauge boson at BESIII detector

Peng-fei Yin, Jia Liu and Shou-hua Zhu
Institute of Theoretical Physics & State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
(Dated: July 14, 2009)

The $O(GeV)$ extra $U(1)$ gauge boson named U-boson, has been proposed to mediate the interaction among leptons and dark matter (DM), in order to account for the observations by PAMELA and ATIC. In such kind of models, the extra $U(1)$ gauge group can be chosen as $U(1)_{L_i-L_j}$ with $L_i$ the $i$-th generation lepton number. This anomaly-free model provides appropriate dark matter relic density and boost factor required by experiments. In this work the observability of such kind of U-boson at BESIII detector is investigated through the processes $e^+e^-\rightarrow U\gamma$, followed by $U\rightarrow e^+e^-$, $U\rightarrow \mu^+\mu^-$ and $U\rightarrow \nu\tau$. In the invisible channel where U-boson decays into neutrinos, BESIII can measure the coupling of the extra $U(1)$ down to $O(10^{-4}) \sim O(10^{-5})$ because of the low Standard Model backgrounds. In the visible channel where U-boson decays into charged lepton pair, BESIII can only measure the coupling down to $O(10^{-3}) \sim O(10^{-4})$ due to the large irreducible QED backgrounds.

PACS numbers: 12.60.-i, 13.66.Hk, 95.35.+d

I. INTRODUCTION

Over the past several years, the existence of dark matter (DM) has been confirmed by many astronomical observations, but its exact nature is still unknown. The annihilation or decay products of DM like photons, neutrinos and antimatter particles may be observed by DM indirect detecting experiments. Among these methods, detecting positrons or anti-protons from DM is a challenge due to the background induced by cosmic-rays or other astrophysical sources and various uncertainties during anti-matter propagation. Recently PAMELA satellite experiment reported an excess in flux ratio of positrons to the sum of electrons and positrons around 10GeV to 100GeV while the flux ratio of anti-proton to proton has no obvious deviation from the prediction from cosmic-rays [1]. In addition, the ATIC reported the total flux of electrons plus positrons spectrum measurement up to 1TeV in which there is a bump over the background around 300GeV to 800GeV [2]. These results provide a new perspective to DM research which has quite different features compared to "popular" candidates in the literatures.

The ATIC electron/positron excess suggests a heavy dark matter around $O(1)TeV$. To accommodate the PAMELA results, the DM seems to be leptophilic to avoid the anti-proton excess (If the measured anti-matter particles are produced in the nearby DM subhalo [3] or we use some special cosmic-ray propagation models [4], this constraint may be loosen). For the annihilating DM, there is a significant mismatch, namely the expected thermal-DM annihilation cross-section is much smaller than those required by PAMELA and ATIC measurements. There is a class of DM scenarios which can satisfy all past experiments. The extraordinary prediction of this scenario is that there are some new light scalars or gauge bosons to mediate DM sector (eg. [5, 6]). The exchange of light mediator should increase the DM annihilation cross section at low velocity, such as in the Galaxy today, comparing with the velocity in the epoch of freeze-out due to the so-called "Sommerfeld enhancement" [5, 6, 7]. Moreover if such mediators are the only DM products from DM annihilation and they are light enough to forbid the decays into baryons, the DM will produce only charged leptons. In this scenario such mediator may actually interact with all the Standard Model(SM) particles through the mixing with SM $U(1)_Y$ gauge field or Higgs field (eg. [8, 9]). Instead we can impose the new symmetry to make sure that the mediator only interacts with leptons, at least at the tree-level [10, 11].

For example the mediator can be the gauge boson of an extra $U(1)_{L_i-L_j}$ [12, 13], where $L_i$ is the number of i-th generation of lepton. This model is anomaly free due to the cancelation between two generation of leptons with opposite $U(1)$ charge. In this paper we will focus on the search of this kind of light new gauge boson at BESIII detector.

It is the well-motivated scientific goal to search for such light boson $X$ at the low-energy $e^+e^-$ colliders due to its possible leptophilic feature. Obviously $X$ should not contradict with the known measurements, such as anomalous magnetic moments of charged leptons $g-2$, $\nu-e$ scattering cross section, etc. [12]. Provided that the $X$ is light, the interactions between $X$ and SM particles should be weak. However the signals of $X$ at colliders may be heavily polluted by large QED backgrounds. On the other hand, the invisible decay of $X$, i.e. $X$ decays into final states which do not interact with detector, is promising because the irreducible SM backgrounds arise from neutrino which is suppressed by $O(Q^2/m_X^2)$ for low energy linear collider [21]. It should be emphasized that missing energy measurements are always challenging from the experimental point of view. Thus the detection of light gauge boson at the low-energy experiments is a great challenge. As a result, large luminosity is required in order to collect enough events and suppress QED back-
In this paper, we extend our previous investigation on light new gauge boson \([20]\) to \(O(GeV)\) at BESIII detector. In the previous work \([20]\), the possibilities of detecting \(O(MeV)\) new gauge boson, usually called U-boson in the literature, has been scrutinized. Such \(O(MeV)\) U-boson is used to explain the excess of 511 keV photon line which was observed by INTEGRAL \([14]\). In fact, research on extra light gauge boson has a long history which was observed by INTEGRAL \([14]\). In this paper, we do not focus on this investigation and allocate it to the further studies.

Generally speaking, the mixing parameters \(\kappa\) and \(\lambda_{SH}\) among the new bosons and SM bosons are not zero, but they tend to be small due to the limits from low energy experiments. If we forbid these mixing parameters at the tree level, they will be induced from the higher order contributions. But the interactions by higher order contributions are usually small \([10]\). In this work, we neglect the mixing effects for simplicity. The scalar potential can be written as \(\mu_s^2|\phi|^2 + \lambda_s|\phi|^4\). After the spontaneous symmetry breaking of \(S\) with the vacuum expectation value \(v_S/\sqrt{2}\), U boson obtains mass to be \(m_U = g_s v_S/2\). In our work we do not work on the possibility of searching light scalar \(S\) which has been discussed in the Ref. \([25]\). There is also an extra heavy particle \(\chi\) as the candidate of DM in the model. The particle \(\chi\) can be a scalar or vector-like fermion (such choice is the simplest way to construct anomaly-free model) with mass around 1TeV which is favored by ATIC experiment. The Lagrangian of DM can be written as \([10]\)

\[
\mathcal{L}_{DM} = \begin{cases} \chi(xD - m_\chi) & \chi \text{ is fermion} \\ |Dx\chi|^2 - m_\chi^2|\chi|^2 & \chi \text{ is scalar} \end{cases}
\]

The parameters \(m_\chi\) and \(g_\chi\) are important in the DM sector, but they have negligible effects on the low-energy experiments. The parameter \(m_U\) is important in both sectors and it mediates the interactions among the DM and the SM particles.Note that the interactions between U-boson and leptons are vector-like and the U-boson couples also with the neutrinos. In addition, the \(U - \ell - \ell\) couplings \(g_\ell\) are universal for two generations of leptons. These couplings have been constrained by many known low energy measurements. From these observations, the constraint on the contributions to the anomalous magnetic moments of the charged leptons \(a_\ell = (g_\ell - 2)/2\) induced by U-boson are very stringent. The additional contributions from U-boson for a vector-like interactions is given by \([13]\)

\[
d\alpha_\ell^V \simeq g_\ell^2 / 4\pi^2 \int_0^1 dx \frac{m_\ell^2 x^2 (1 - x)}{m_U^2 x^2 + m_\ell^2(1 - x)}.
\]

For the \(g_\ell\), following the discussion in Ref. \([13, 28]\), we have the constraint \(\delta a_\ell^V < 1.5 \times 10^{-11}\). For the \(g_\mu\) and \(g_\tau\), we impose conservative constraints as \(\delta a_\mu^V < 2.6 \times 10^{-9}\) and \(\delta a_\tau^V < 1.3 \times 10^{-2}\) by using the results.
from Ref. [29] and Ref. [30] respectively. Another stringent constraint for vector-like coupling arises from low-\(|m_\nu^2|\) neutrino-electron scattering [31] as \(|\langle f_e f_e \rangle / m_T^2 < G_F|^{15}\). The universal leptonic couplings can be written as \(|\langle f_e f_e \rangle / m_T^2 < G_F|^{15}\). Combining all these constraints, the coupling \(g_3\) should be smaller than \(O(10^{-3})\).

III. LIGHT GAUGE BOSON INTERACTING WITH DM

From section II, we can see that the couplings among U-boson and SM particles are small. However the couplings among U-boson and DM can be large. It is quite natural to assume the main products of DM annihilations are light U-bosons. In this section we will investigate the couplings among U-boson and SM particles are small. However the coupling cross section at freeze-out epoch is

\[ \sigma v \sim \frac{\left(1 - \frac{m_U^2}{m_X^2}\right)^2}{16 \pi m_X^2 (1 - \frac{m_U^2}{m_X^2})^2}. \]  

It is obvious that the cross section only depends on \(g_X\) and \(m_X\) when \(m_U/m_X\) approaches 0 for light U-boson here. For the scalar DM case, the results can be written as

\[ \sigma v \sim g_X^4 \frac{1 - \frac{m_U^2}{m_X^2}}{8 \pi m_X^2}. \]

If the DM also carries extra \(U(1)\) charge, the cross section requires an extra factor \(1/2\) for averaging initial DM charge [31]. If the DM mass is \(O(\text{TeV})\), the correct relic density requires \(g_X \sim O(10^{-1})\). Comparing with \(g_l \leq 0.7 \times 10^{-3}\) depicted in last section, we can conclude that DM should have much larger \(U(1)\) charge than those of the SM leptons (some possibilities to explain this feature have been discussed in the Ref. [10]).

In the Fig. we show the possible parameter region which satisfies the relic density \(0.085 < \Omega h^2 < 0.119\). From the figure we can see that the \(g_X\) is indeed \(O(10^{-1})\) for DM with mass of \(O(\text{TeV})\).

![Fig. 1: The ellipses indicate the region of the \(m_X, g_X\) plane which satisfied the relic density \(0.085 < \Omega h^2 < 0.119\), with \(m_U = 0.5\text{GeV}\). Solid lines denote for fermion DM and dash lines denote for scalar DM.](image)

The light U-boson may enhance the DM annihilation cross section at low velocity in the Galaxy today due to the non-perturbative effect named "Sommerfeld enhancement" (a complete analysis can be found in the Ref. [34]). This non-relativistic quantum effect arises because the two particle wave functions are distorted away from plane wave by the presence of a potential if their kinetic energy are low enough. In the language of quantum field theory, it corresponds to the contribution of ladder diagrams due to the exchange of some light scalars or gauge bosons during two incoming DM particles undergoing some annihilation reaction. In the non-relativistic limit, the exchange of a scalar boson or a vector boson would give the same result [32]. This enhancement can be described by a factor \(S\) which is defined as a factor to multiply with the tree level DM annihilation cross section, \(\sigma = \sigma_0 S\). This factor is essential to interpret the difference between the DM cross section required by the correct thermal relic density and the PAMELA/ATIC positron anomaly.

In order to calculate \(S\), we use the simplified quantum mechanical method in literatures by solving the \(l = 0\) Schrödinger equation with an attractive Yukawa potential \(V(r) = -\frac{\alpha m_U}{r} e^{-m_U r} [34].\)
$1/m_{\chi}\psi''(r) + \frac{\alpha}{r}e^{-m_{\chi}r}\psi(r) = -m_{\chi}\beta^2\psi(r), \quad (8)$

where $\psi(r)$ is the reduced two-body wave function, $m_{\chi}$ and $m_U$ are the masses of DM and the light gauge boson respectively, $\beta = v/c$ is the velocity of DM in the center-of-mass frame and $\alpha = g_\chi^2/(4\pi)$. The boundary condition can be chosen as $\psi'(\infty)/\psi(\infty) = im_{\chi}\beta$. Then the Sommerfeld factor $S$ is given by $S = |\psi(\infty)/\psi(0)|^2$. The behavior of $S$ depends on four parameters $m_U$, $m_{\chi}$, $\alpha$ and the velocity of DM $\beta$.

Since the DM particles do not have monochromatic relative velocity, a more realistic result needs to consider the speed distribution of DM in the Galaxy. Here we assume the DM velocity distribution in the halo as a single truncated Maxwell-Boltzmann distribution $f(v) \propto v^2 \exp(-v^2/2\sigma_v^2)$ with velocity dispersion $\sigma_v$. [32]. The average of the Sommerfeld enhancement over the distribution of relative velocities in the halo is,

$$\bar{S} = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_v^3} \int_{\nu_{esc}}^{\infty} dv \ v^2 \exp(-v^2/2\sigma_v^2) S(v). \quad (9)$$

The numerical results of $S$ and $\bar{S}$ are given in the Fig.2, Fig.3 and Fig.4. We can see that the velocity distribution function $f(v)$ has large possibility to have velocity around $O(\sigma_v)$, with the most probable velocity at $\sqrt{2}\sigma_v$. If the $\sigma_v$ is very small, then $f(v)$ behaves like some delta function around $O(\sigma_v)$. In this case, the $S$ has the same behavior with $S$. If the $\sigma_v$ is quite large, the $f(v)$ is a broad distribution around $O(\sigma_v)$. In this case, the $\bar{S}$ is the composition of different $S(v)$. In Fig.2 and Fig.3 the behavior of $S$ and $\bar{S}$ agree with the above discussion.

To better understand the dependence of $S$ on its four free parameters, we discuss the behavior of $S$ by simplifying the equation under reasonable approximation. Since the light gauge boson is much lighter than the DM, we can expand the Yukawa potential. The Eq.8 can then be written as,

$$1/m_{\chi}\psi''(r) + \frac{\alpha}{r}\psi(r) = (-m_{\chi}\beta^2 + \alpha m_U)\psi(r). \quad (10)$$

If $\sqrt{\alpha m_U/m_{\chi}} \ll \beta$, the behavior of DM annihilation by exchange U-boson is similar with Coulomb scattering. If $\alpha \ll \beta$ (and automatically $\sqrt{\alpha m_U/m_{\chi}} \ll \beta$, because $m_U \ll m_{\chi}$ in our case), the enhancement can be negligible with $S \approx 1$. This is the non-enhancement case. If $\sqrt{\alpha m_U/m_{\chi}} \lsim \beta \lsim \alpha$, the $S$ is enhanced by $1/\beta$ with $S \approx \pi a/\beta$. This is the moderate enhancement case. In the Fig.4 the lines with $\beta = 10^{-2}, 10^{-3}$ correspond to the moderate enhancement. Before the saturation, we can see $\bar{S}$ grows with $1/\sigma_v$ linearly. However, $\bar{S}$ does not go to infinity because it saturates at some small velocity dispersion. We can see if the mass $m_{\chi}$ is small, the value of $\sigma_v$ to reach the saturation platform is also small.

If $\sqrt{\alpha m_U/m_{\chi}} \ll \beta$, the Eq.10 has the similar form as the equation describing hydrogen atom. The positiveness of the right hand side of the equation points to the existence of bound states which can significantly enhance the $S$ [34, 36]. The enhancement is finite due to the saturation in the low velocity regime or finite width of the bound state. Close to the resonance, $S \approx \frac{\alpha m_U}{m_{\chi} \beta^2}$, which is the resonance enhancement case. Recalling the energy level of hydrogen atom $E_n$, the equation meets different resonances when we vary the value of $m_{\chi}$. Therefore the resonances appear periodically in the Fig.2 and Fig.4.
In addition for $\sqrt{\alpha m_U/m_\chi} \gg \beta$, the equation can neglect the term which contains $\beta$. That is the reason why the resonances locate at the same $m_\chi$ for different values of $\beta$ or $\sigma_\nu$ in the Fig. 2 and Fig. 3. In the Fig. 4 the line with $m_U = 1GeV$ shows that it is close to a resonance when $\sigma_\nu$ is low enough which makes it different from other four moderate enhancement cases.

![FIG. 4: The averaged Sommerfeld enhancement factor $⟨S⟩$ as a function of DM velocity dispersions $\sigma_\nu$. Here we choose $m_\chi = 17eV$ and $g_\chi = 0.55$ ($\alpha = 2.41 \times 10^{-2}$). Five curves denote different U-boson mass as $10GeV$, $5GeV$, $0.5GeV$, $1GeV$, $0.1GeV$, from bottom to top.](image)

From Fig. 2 Fig. 3 and Fig. 4 we can see that the Sommerfeld enhancement is around $O(10^2)$ for a typical DM velocity dispersion of $10^{-3}$ in the halo today. For the lower velocity, the enhancement will increase significantly. Such large enhancement is required to explain PAMELA/ATIC results.

**IV. SEARCHING FOR U-BOSON VIA $e^+e^- \rightarrow U\gamma$ PROCESS**

At the BESIII detector, the luminosity of $e^+e^-$ collision is $10^{33}cm^{-2}s^{-1}$ at $\sqrt{s} = 3.097GeV$. In our numerical simulations we choose $e^+e^-$ integrated luminosity as $20fb^{-1}$ which corresponds to data samples collected within four years. Throughout the paper, we utilize the package CalcHEP [37] to simulate signal and corresponding background processes after appropriate modifications of the model file.

In the model we adopted here, the U-boson does not directly couple with quarks, so the signals and backgrounds are mainly leptons and photons. Since the $\sqrt{s}$ which we adopted in this paper is lower than $2m_\tau$, the U-boson at BESIII can not decay into two tau leptons. Thus, we do not take into account the tau signals. In the visible decay channel, the U-boson decays to electrons and muons. In the invisible decay channel, the U-boson decays to corresponding neutrinos.

![FIG. 5: Photon energy distribution of SM background for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ with $|\cos \theta_\gamma| < 0.9$.](image)

A. Invisible decay mode $U \rightarrow \nu\bar{\nu}$

The signal process is

$$e^+e^- \rightarrow U\gamma \rightarrow \nu\bar{\nu}\gamma.$$  \hspace{1cm} (11)

The main SM backgrounds for the signal process are

$$e^+e^- \rightarrow \nu\bar{\nu}\gamma.$$  \hspace{1cm} (12)

In Fig. 5 we show the photon energy distribution for backgrounds with $|\cos \theta_\gamma| < 0.9$. Here $\theta_\gamma$ corresponds to the angle among electron beam line and photon. The background has the continuous photon comparing with the mono-energetic photon from signal which has energy $E = (s - m_\gamma^2)/(2\sqrt{s})$. Note that the background is from higher-order contributions, i.e. $O(\alpha G_F^2/s)$, compared to the signal. At the BESIII, the energy resolution for electrons or photons is about $2.3%/\sqrt{E(GeV)} \pm 1\%$ with the energy measurement range from $20MeV$ to $2GeV$ [38]. Therefore we impose the cuts as following,

$$E_\gamma > (s - m_\gamma^2)/(2\sqrt{s}) - 0.2GeV$$  \hspace{1cm} (13)

$$|\cos \theta_\gamma| < 0.9.$$  \hspace{1cm} (14)

In Fig. 6 we show the lower limit of $q_\eta$ for detecting U-boson as a function of $m_U$ with $S/\sqrt{S+B} > 5$, in which $S$ and $B$ represent the number of events for signal and background respectively$^1$. We also give the possible constraints from the $g-2$ and low energy $\nu - e$ cross section.

---

$^1$ In Ref. [20], there is a typo for the definition of significance in invisible channel which should be $S/\sqrt{S+B}$. Our numerical results agree with the result in Ref. [20]. The reason for choosing $S/\sqrt{S+B}$ other than $S/\sqrt{B}$ in the invisible channel is that the background is extremely low. The number of background $B$ is usually below 1. However, in the visible channel, we choose $S/\sqrt{B}$ because both signal and background have enough statistics.
can be detected by BESIII with 20 fb$^{-1}$ $e^+e^-$ luminosity as a function of $m_U$ for invisible channel. The dash lines indicate the upper bounds from low-energy experiments. The lower dash line shows the constraints from low energy $\nu - e$ cross section; the upper one comes from the measurement of $g_\mu - 2$. We do not show the looser upper bound from $g_\mu - 2$ and $g_\pi - 2$, since they are larger than $O(10^{-2})$ here.

B. Visible decay mode $U \to l\bar{l}$

The U boson can decay into charged lepton pairs which has the signal $e^+e^- \to U\gamma \to l\bar{l}\gamma$. In the signal process the $m_{l\bar{l}}$ peaks around $m_U$, and the SM background has the smooth $m_{l\bar{l}}$ except around $\sqrt{S}$ and low energy region due to $t$-channel contributions with soft photon and $s$-channel contributions, respectively [20].

In Fig. 7 and Fig. 8 we show the $m_{e\bar{e}}$ and $m_{\mu\bar{\mu}}$ distribution of the SM backgrounds. Since the signal peaks around $m_U$, the resolution of $m_{l\bar{l}}$ is important to suppress the backgrounds. To clearly separate the electron and photon, the BESIII requires directions of two particle has an open angle larger than $20^\circ$ [30]. Thus we have the following cut conditions,

$$|m_{l\bar{l}} - m_U| < 1, 3 \text{ or } 5 \text{MeV},$$

$$\cos(\theta_i) < 0.9,$$

$$\cos(\theta_{l\gamma}) < 0.94,$$

where $\theta_i$ ($i = l, \bar{l}, \gamma$) corresponds to the angles among initial electron beam line and final state particles respectively. The $\theta_{l\gamma}$ means the angle between the lepton and photon in the final states. Many photons with energy lower than $O(10)\text{MeV}$ come from the final state radiation of $e^+e^- \to l^+l^-$. The direction of radiated $\gamma$ is close to the direction of outgoing charge leptons. So it is obvious to see that the Eq. (17) excludes most $l^+l^-\gamma$ events with low $m_{l\bar{l}}$ in the Fig. 7 and Fig. 8. We give three kinds of ideal $m_{l\bar{l}}$ resolution cuts which are 1MeV, 3MeV and 5MeV. The huge background has been suppressed at least two orders of magnitude via cuts in Eqs. (15-17).

Fig. 8 and Fig. 9 show the lower limit of $g_l$ as a function of $m_U$ with $S/\sqrt{B} > 5$ for signal channel $e^+e^- \to U\gamma \to e\bar{e}\gamma$ and $e^+e^- \to U\gamma \to \mu\bar{\mu}\gamma$ respectively. The conventions are the same with Fig. 6. We can see that the $g_l$ can reach around $10^{-3} \sim 10^{-4}$ which is similar for the two visible channels. Note that the invisible channel can reach the $10^{-4} \sim 10^{-5}$ region because of the lower SM background.

V. CONCLUSIONS AND DISCUSSIONS

In this paper we investigated one unified DM picture which can account for the recent PAMELA/ATIC observations while still consistent with other measurements, in a model with an extra $U(1)_{L_i-L_j}$ gauge group with $L_i$ the $i$-th generation lepton number. In order to obtain the boost factor (BF) via the so-called Sommerfeld
FIG. 9: Same with Fig.8 but for signal channel $e^+e^- \rightarrow U\gamma \rightarrow e\gamma$. The solid lines from bottom to top denote different cuts with 1MeV, 3MeV and 5MeV in Eq.(13) respectively.

Recently, Fermi [48] and H.E.S.S. [49] give their results on the electron and positron flux. The sharp ATIC "bump" at 300 ~ 800 GeV are not reported. For annihilating DM, the $e^+e^-$ channel is not eagerly needed since there is no peak. The $\mu^+\mu^-$ and $\tau^+\tau^-$ channels are needed to fit the Fermi data. In annihilation scenario, the light new mediating particle is usually needed to provide the Sommerfeld enhancement. If it is an extra U(1) gauge boson, it is difficult to avoid the decay to $e^+e^-$ in the scenarios where the new gauge boson couples to leptons via kinetic mixing to photon. But it can avoid $e^+e^-$ if this extra U(1) assigns charge directly on leptons, like $U(1)_{\mu-\tau}$, discussed in this paper (unfortunately, such new gauge boson in the model with extra $U(1)_{\mu-\tau}$ would not easily be produced in the low-energy $e^+e^-$ colliders). Interestingly, if it is a scalar boson which has mixing with Higgs, it naturally avoids $e^+e^-$ since the couplings with leptons are proportional to lepton mass [50, 51]. It should be mentioned that $\mu^+\mu^-$ and $\tau^+\tau^-$ channels in annihilation scenario usually receive stringent limits from gamma and neutrino observations, while decay scenario can cleanly compatible with these observations [53, 54]. For decaying DM, the $\mu$ and $\tau$ leptons are also needed to interpret Fermi. This usually relies on some special requirements on the Yukawa coupling coefficients [52].

FIG. 10: Same with Fig.9 but for signal channel $e^+e^- \rightarrow U\gamma \rightarrow \mu\bar{\nu}\gamma$. 

In annihilation experiments, the light new gauge boson $O(GeV)$ is required, though the DM is around $O(TeV)$. After showing that the required BF can be easily realized, we simulated the signal and background of U-boson at BESIII detector. Our studies showed that it is possible to detect such light leptophilic U-boson at the BESIII via the process of $e^+e^- \rightarrow U\gamma$, followed by $U \rightarrow e^+e^-$, $U \rightarrow \mu^+\mu^-$ and $U \rightarrow \nu\tau$. All the U-boson decay modes can be utilized to search for U-boson. For the U-boson invisible decay mode $U \rightarrow \nu\tau$, the BESIII can measure the coupling of the extra $U(1)$ down to $O(10^{-4}) \sim O(10^{-5})$ with 5$\sigma$ significance. For the charged lepton decay modes, the 5$\sigma$ detecting limit can reach $10^{-4} \sim 10^{-3}$ for U-boson mass $m_U = 0.5 GeV \sim 3 GeV$. In fact, the U-boson search at BESIII can also be carried out at $\sqrt{s} = 2 \sim 5 GeV$. By the scanning of $\sqrt{s}$, it is even possible to detect the U-boson by the $e^+e^-$ and/or $\mu^+\mu^-$ resonances.

Besides the low energy collider search for light leptophilic U-boson, we would like to mention the interesting features in the DM indirect and direct detection experiments. First, If the $U(1)$ group is gauged under $U(1)_{\mu-\tau}$, the final positron spectrum from DM annihilation does not fit ATIC results very well. It requires heavier DM than $U(1)_{\mu-\tau}$ and $U(1)_{\mu-\tau}$, cases, because the initial energy spectrum of positron from $\mu$ or $\tau$ are quite soft. Second, because $U - \nu$ couplings equal to $U - l^\pm$, DM annihilations will produce high energy neutrinos with energy of $m_\chi/2$. It is possible to detect such neutrino flux in the next generation of neutrino telescopes such as IceCube, Antares, etc [40](Moreover, the $U(1)_{\mu-\tau}$ will induce the interaction between the high-energy neutrinos and the background neutrinos. Measuring high-energy cosmic neutrino flux spectrum at neutrino telescopes may find an absorption feature due to the new $U(1)$ interaction [41]). On the other hand, the Super-Kamiokande(Super-K) data of neutrinos from the Galaxy Center(GC) [42] can be used to constrain the model. If the U-boson have decay channel to electron/positron, we only need a boost factor of a few hundreds to explain PAMELA/ATIC results, since the positron spectrum from such decay channel is quite hard [43]. Fortunately, such boost factor does not violate the Super-K limit, especially for DM profile which is smooth in the GC [41, 44, 45]. Third, the $\chi - e$ interaction may induce visible leptonic recoils far larger than nuclear recoils at the DM direct detection experiments, because the DM only directly couples to leptophilic U-boson. This feature may be used to explain the DAMA modulation signal [10, 46], but it still faces some problems [47].
VI. ACKNOWLEDGEMENTS

This work was supported in part by the Natural Sciences Foundation of China (Nos. 10775001, 10635030).

[1] O. Adriani et al., arXiv:0810.4994 [astro-ph]; O. Adriani et al., arXiv:0810.4995 [astro-ph].
[2] J. Chang et al., Nature 456, 362 (2008).
[3] D. Hooper, A. Stebbins and K. M. Zurek, arXiv:0812.3202 [hep-ph].
[4] P. Grajek, G. Kane, D. J. Phalen, A. Pierce and S. Watson, arXiv:0807.1508 [hep-ph].
[5] N. Arkani-Hamed, D. P. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713 [hep-ph].
[6] M. Pospelov and A. Ritz, arXiv:0810.1502 [hep-ph].
[7] H. Baer, K. m. Cheung and J. F. Gunion, Phys. Rev. D 59, 075002 (1999) arXiv:hep-ph/9806361; J. Hisano, S. Matsumoto, M. M. Nojiri and O. Saito, Phys. Rev. D 71, 063528 (2005) arXiv:hep-ph/0412003; J. Hisano, S. Matsumoto, M. Nagai, O. Saito and M. Senami, Phys. Lett. B 646, 34 (2007) arXiv:hep-ph/0610249; M. Cirelli, A. Strumia and M. Tamburini, Nucl. Phys. B 787, 152 (2007) arXiv:0706.4071 [hep-ph]; J. March-Russell, S. M. West, D. Cumberbatch and D. Hooper, JHEP 0807, 058 (2008) arXiv:0801.3440 [hep-ph]; M. Cirelli, M. Kadastik, M. Raidal and A. Strumia, arXiv:0809.2409 [hep-ph].
[8] E. J. Chun and J. C. Park, JCAP 0902, 026 (2009) arXiv:0812.0308 [hep-ph].
[9] M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin, JHEP 0904, 014 (2009) arXiv:0901.0283 [hep-ph].
[10] P. J. Fox and E. Poppitz, arXiv:0811.3393 [hep-ph].
[11] S. Baek and P. Ko, arXiv:0811.1646 [hep-ph].
[12] X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D 43 (1991) 22; X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D 44 (1991) 2118; R. Foot, X. G. He, H. Lew and R. R. Volkas, Phys. Rev. D 50 (1994) 4571 arXiv:hep-ph/9404205; S. Baek, N. G. Deshpande, X. G. He and P. Ko, Phys. Rev. D 64 (2001) 055006 arXiv:hep-ph/0104144.
[13] X. J. Bi, X. G. He and Q. Yuan, arXiv:0903.0122 [hep-ph].
[14] C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, Phys. Rev. Lett. 92, 101301 (2004) arXiv:astro-ph/0309686.
[15] P. Fayet, Phys. Rev. D 75, 115017 (2007) arXiv:hep-ph/0702176.
[16] P. Fayet, Phys. Lett. B 95, 285 (1980); P. Fayet, Nucl. Phys. B 187, 184 (1981).
[17] S. N. Gninenko and N. V. Krasnikov, Phys. Lett. B 427, 307 (1998) arXiv:hep-ph/9802375; S. N. Gninenko and N. V. Krasnikov, Phys. Lett. B 513, 119 (2001) arXiv:hep-ph/0102222.
[18] C. Bouchiat and P. Fayet, Phys. Lett. B 608, 87 (2005) arXiv:hep-ph/0410260; P. Fayet, arXiv:hep-ph/0607094; P. Fayet, Phys. Rev. D 74, 054034 (2006) arXiv:hep-ph/0607318.
[19] N. Borodatchenkova, D. Choudhury and M. Drees, Phys. Rev. Lett. 96, 141802 (2006) arXiv:hep-ph/0510147.
[20] S. h. Zhu, Phys. Rev. D 75, 115004 (2007) arXiv:hep-ph/0701001.
[21] C. H. Chen, C. Q. Geng and C. W. Kao, Phys. Lett. B 683, 400 (2008) arXiv:0708.0937 [hep-ph].
[22] C. Boehm and P. Fayet, Nucl. Phys. B 683, 219 (2004) arXiv:hep-ph/0305261.
[23] N. Arkani-Hamed and N. Weiner, JHEP 0812, 104 (2008) arXiv:0810.0714 [hep-ph].
[24] M. Pospelov, arXiv:0811.1030 [hep-ph].
[25] B. Batell, M. Pospelov and A. Ritz, arXiv:0903.0363 [hep-ph].
[26] R. Essig, P. Schuster and N. Toro, arXiv:0903.3941 [hep-ph].
[27] M. Reece and L. T. Wang, arXiv:0904.1743 [hep-ph].
[28] D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. 100, 120801 (2008) arXiv:0808.1154 [physics.atom-ph].
[29] G. W. Bennett et al. [Muon G-2 Collaboration], Phys. Rev. D 73, 072003 (2006) arXiv:hep-ex/0602035.
[30] J. Abdallah et al. [DELPHI Collaboration], Eur. Phys. J. C 35, 159 (2004) arXiv:hep-ex/0406010.
[31] R. C. Allen et al., Phys. Rev. D 47, 11 (1993) L. B. Auerbach et al. [SLND Collaboration], Phys. Rev. D 63, 112001 (2001) arXiv:hep-ex/0101039.
[32] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996), arXiv:hep-ph/9506380.
[33] R. Lengo, JHEP 0905, 024 (2009) arXiv:0902.0688 [hep-ph].
[34] L. Pieri, M. Lattanzi and J. Silk, arXiv:0902.4330 [astro-ph.HE].
[35] J. Boyo, arXiv:0903.0413 [astro-ph.HE].
[36] J. D. March-Russell and S. M. West, arXiv:0812.0559 [astro-ph].
[37] A. Pukhov, arXiv:hep-ph/0412191.
[38] D. M. Asner et al., arXiv:0809.1869 [hep-ex].
[39] Private communication with Yu-jun Mao.
[40] J. Liu, P. f. Yin and S. h. Zhu, arXiv:0812.0964 [astro-ph].
[41] D. Hooper, Phys. Rev. D 75, 123001 (2007) arXiv:hep-ph/0701194.
[42] S. Desai et al. [Super-Kamiokande Collaboration], Phys. Rev. D 70, 083523 (2004) [Erratum-ibid. D 70, 109901 (2004)] arXiv:hep-ex/0404025.
[43] I. Cholis, G. Dobler, D. P. Finkbeiner, L. Goodenough and N. Weiner, arXiv:0811.3641 [astro-ph].
[44] H. Yuksel, S. Horiuchi, J. F. Beacom and S. Ando, Phys. Rev. D 76, 123506 (2007) arXiv:0707.0196 [astro-ph].
[45] J. Hisano, M. Kawasaki, K. Kohri and K. Nakayama, arXiv:0812.0219 [hep-ph].
[46] R. Bernabei et al., Phys. Rev. D 77, 023506 (2008) arXiv:0712.0562 [astro-ph].
[47] Y. Cui, D. E. Morrissey, D. Poland and L. Randall, arXiv:0901.0557 [hep-ph].
[48] A. A. Abdo et al. [The Fermi LAT Collaboration], arXiv:0905.0025 [astro-ph.HE].
[49] H. E. S. Aharonian, arXiv:0905.0105 [astro-ph.HE].
[50] L. Bergstrom, J. Edsjo and G. Zaharijas, arXiv:0905.0333 [astro-ph.HE].
[51] K. Kohri, J. McDonald and N. Sahu, arXiv:0905.1312 [hep-ph].
[52] P. Meade, M. Papucci, A. Strumia and T. Volansky, arXiv:0905.0480 [hep-ph].
[53] S. Shirai, F. Takahashi and T. T. Yanagida, arXiv:0905.0388 [hep-ph].