Search for light dark matter at the accelerators. NA64 experiment
Поиск легкой темной материи на ускорителях. NA64 эксперимент

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Мы даем обзор по поиску легкой темной материи на ускорителях, включая NA64 эксперимент. Обсуждается феноменология, связанная с поиском легкой темной материи и темного фотона на ускорителях. Представлены основные экспериментальные ускорительные ограничения на модели легкой темной материи.

We review the search for light dark matter and dark photon at the accelerators including the NA64 experiment. The phenomenology related with the search for light dark matter and dark photon at the accelerators is discussed. The main experimental accelerator bounds on light dark matter models are presented.

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1. Introduction

At present the most striking evidence in favour of new physics beyond the Standard model (SM) is the observation of dark matter (DM) (as a review see for example [1, 2]). There are a lot of candidates for the role of DM. In particular, there are LDM (light dark matter) models [3] (as a review see for example [4, 5]) with the mass of LDM particles $O(1)\ MeV \leq m_{LDM} \leq O(1)\ GeV$. The LDM models are renormalizable models with the spin 1 or spin 0 messenger connecting our world and the dark matter world. The standard assumption is that in the hot early Universe the DM particles were in the equilibrium with the observed particles is often used. During the Universe expansion the temperature decreases and at some point the thermal decoupling of the DM starts. Namely, at some temperature the annihilation cross-section of DM particles

$$DMparticles \to SMparticles$$

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becomes too small to perform the equilibrium of DM particles with the SM particles and the DM particles decouple. The experimental data are in favour of the scenario with cold relic for which the freeze-out temperature is much lower the DM particle mass, i.e. the nonrelativistic DM particles decouple. The value of the DM annihilation cross-section at the decoupling epoch determines the value of the current DM density. The observed value of the DM density fraction $\frac{\rho_{DM}}{\rho_c} \approx 0.23$ allows to estimate the DM annihilation cross-section and hence to estimate the DM discovery potential both in direct underground and accelerator experiments. The annihilation cross-section is estimated at the level $\sigma_{an} = O(1)\ pb$ and the value of the cross-section depends rather weakly on the mass of the LDM particle. Models with the LDM can be classified by the spin of the LDM particles and the mediator spin. Models with additional light vector bosons (vector portal) are rather popular now. In these models light vector boson A' mediates between the SM world and dark sector. Among the models with vector boson messenger the model with dark photon [6, 7] is probably the most simple and elegant. However other light vector boson models , in particular, the models with $B - L$ and $L_\mu - L_\tau$ interactions are also used as alternative LDM models.

The aim of this paper is the review of the search for dark photon and LDM at the NA64 fixed target experiment [8–11] at CERN and related accelerator experiments. The paper is organized as follows. In the next section we discuss the LDM phenomenology related with the search for dark photon and LDM at the accelerators. In the section 3 we describe the NA64 experiment. In section 4 we review the main results obtained at the NA64 and other accelerator experiments. Section 5 contains final remarks.

2. The LDM phenomenology with dark photon messenger

In this section we give mini review of existing phenomenology related with LDM models. In dark photon model [6] the additional light vector boson A' interacts with the gauge $SU_c(3) \otimes SU_L(2) \otimes U(1)$ fields of the SM due to nonzero mixing with the $U(1)$ SM gauge field. The Lagrangian of the model is represented in the form

$$L = L_{SM} + L_{SM,dark} + L_{dark}\,, \tag{1}$$

where L_{SM} is the SM Lagrangian and

$$L_{SM,dark} = -\frac{\epsilon}{2\cos\theta_w} B^{\mu\nu} F'_{\mu\nu}\,. \tag{2}$$

Here $B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\nu$, $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, ϵ is the mixing parameter, and L_{dark} is the LDM - Lagrangian [1]. At present scalar, Dirac, pseudo-Dirac and Majorana LDM models are often considered. For the scalar LDM the

[1]The field B_μ is the $U(1)$ gauge field of the SM.

Lagrangian has the form

$$L_{dark} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + (\partial_\mu\chi - ie_DA'_\mu\chi)(\partial^\mu\chi - ie_DA'^\mu\chi)^* - m_\chi^2\chi^*\chi + \frac{m_{A'}^2}{2}A'_\mu A'^\mu\,, \quad (3)$$

where χ is the charged scalar LDM field. Here the gauge symmetry

$$A'_\mu \to A'_\mu + \partial_\mu\alpha\,, \quad (4)$$

$$\chi \to exp(ie_D\alpha)\chi \quad (5)$$

is explicitly broken due to nonzero mass term $\frac{m_{A'}^2}{2}A'_\mu A'^\mu$ in the Lagrangian (3). It is possible to use the Higgs mechanism with the Lagrangian

$$L_\phi = (\partial_\mu\phi - ie_DA'_\mu\phi)(\partial^\mu\phi - ie_DA'^\mu\phi)^* - \lambda(\phi^*\phi - c^2)^2 \quad (6)$$

for the obtaining of nonzero dark photon mass. For $m_{A'} \ll m_Z$ the interaction of the dark photon A' with the SM fermions is described by the effective Lagrangian

$$L_{A',SM} = \epsilon e A'_\mu J^\mu_{em}\,, \quad (7)$$

where J^μ_{em} is the electromagnetic current of the SM.

For Dirac LDM χ the Lagrangian has the form

$$L_{dark} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi + e_D\bar{\chi}\gamma^\mu\chi A'_\mu + \frac{m_{A'}^2}{2}A'_\mu A'^\mu\,. \quad (8)$$

For the Majorana LDM[1] with χ_M the main difference from the Dirac LDM consists in the replacement $e_D\bar{\chi}\gamma^\mu\chi A'_\mu \to \frac{e_D}{2}\bar{\chi}_M\gamma^\mu\gamma_5\chi_M A'_\mu$ in the Lagrangian (8). In the model with pseudo-Dirac fermion [12] the introduction of the scalar field ϕ_{PD} with nonzero vacuum average $< \phi_{PD} > \neq 0$ leads to the violation of fermion number due to the repacement of the standard mass term $-m_\chi\bar{\chi}\chi \to -m_\chi\bar{\chi}\chi - (h_{PD}\phi_{PD}\bar{\chi}^c_L\chi_L + h_{PD}\phi_{PD}\bar{\chi}^c_R\chi_R + h.c.)$ in the Lagrangian (8). So the Dirac fermion χ with a mass m_χ "decouples" into two Majorana fermions $\chi_{1,2}$ with masses $m_{\chi_{1,2}} = m_\chi \mp 2h_{PD} < \phi_{PD} >$. In the model with pseudo-Dirac fermion the interaction of dark photon A' with the fields of pseudo-Dirac fermion can be obtained by the replacement $e_D\bar{\chi}\gamma^\mu\chi A'_\mu \to e_D J^\mu_{PD}A'_\mu$, $J^\mu_{PD} = i\bar{\chi}_2\gamma^\mu\chi_1 + h.c.$ in the Lagrangian (8). In the limit $h_{PD} \to 0$ we reproduce the model with Dirac fermion.

In the model with dark photon for the estimation of the interaction of the LDM particles with the SM particles we have to know the values of ϵ and $\alpha_D = \frac{e_D^2}{4\pi}$. At present we can't calculate ϵ and α_D from "the first principles". However it is possible to obtain upper bound on α_D from the condition of the absence of Landau pole singularity for the effective coupling constant $\bar{\alpha}_D(\mu)$ up to some scale Λ [13]. One loop β-function for the effective coupling constant $\bar{\alpha}_D(\mu)$ is

$$\beta(\bar{\alpha}_D) = \frac{\bar{\alpha}_D^2}{2\pi}[\frac{4}{3}Q_F^2 n_F + Q_S^2\frac{n_S}{3}]\,. \quad (9)$$

[1] Here $\chi_{L,R} = \frac{1\mp\gamma_5}{2}\chi$, $\chi^c = C\bar{\chi}$, $\chi_M = \chi_L + \chi^c_L, \chi^c_M = \chi_M, \chi^c_M = C\bar{\chi}_M$ and $C = i\gamma^0\gamma^2$ is the charge conjugation operator.

Here $\beta(\bar{\alpha}_D) \equiv \mu\frac{d\bar{\alpha}_D}{d\mu}$ and n_F (n_s) is the number of fermions(scalars) with $U^{'}(1)$ charges $Q_F(Q_S)$. For the model with pseudo-Dirac fermion we have to introduce additional scalar field ϕ_{PD} with the charge $Q_{PD} = 2$, therefore one-loop β-function in this model is equal to $\beta(\bar{\alpha}_D) = \frac{4\bar{\alpha}_D^2}{3\pi}$. For the model with Majorana fermion we also have to introduce additional scalar field with the charge $Q_S = 2$ and additional Majorana field for γ_5-anomaly cancelation and the β-function coincides with the β-function of the previous model. For the model with scalar LDM for the creation of nonzero dark photon mass in a gauge invariant form we have to introduce additional scalar field with the charge $Q_S = 1$ and one-loop β-function is equal to $\beta(\alpha_D) = \alpha_D^2/3\pi$. From the condition $\Lambda \geq 1$ TeV we find that $\alpha_D \leq 0.2$ for pseudo-Dirac and Majorana fermions and $\alpha_D \leq 0.8$ for charged scalars. Note that α_D is the effective coupling constant at the scale $\mu = m_{A'}$, i.e. $\alpha_D = \bar{\alpha}_D(m_{A'})$. In the assumption that the dark photon model is valid up to Planck scale, i.e. $\Lambda = M_{PL} = 1.2 \times 10^{19}$ GeV, we find that $\alpha_D \leq 0.05$ for pseudo-Dirac and Majorana fermions and $\alpha_D \leq 0.2$ for the charged scalars.

Dark photon A' can decay into the SM particles (visible modes), for instance,

$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, ...$$

or into LDM particles(invisible modes)

$$A' \to \chi\bar{\chi}.$$

Invisible and visible decay width of the dark photon into fermion LDM particles and into e^+e^- pair are given by the formulae

$$\Gamma(A' \to \chi\bar{\chi}) = \frac{\alpha_D}{3} m_{A'}(1 + \frac{2m_\chi^2}{m_{A'}^2})\sqrt{1 - \frac{4m_\chi^2}{m_{A'}^2}}\,, \tag{10}$$

$$\Gamma(A' \to e^+e^-) = \frac{\epsilon^2\alpha}{3} m_{A'}(1 + \frac{2m_e^2}{m_{A'}^2})\sqrt{1 - \frac{4m_e^2}{m_{A'}^2}}\,. \tag{11}$$

Here $\alpha = \frac{e^2}{4\pi} = 1/137$. [1]

There are two types of experiments on the search for dark photon and LDM [4,5]. In the first type visible decays of dark photon $A' \to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$... are looked for. The reactions $e^+e^- \to \gamma A'$, $eZ \to eZA'$ are used for the dark photon production. Also A' could be produced in $\pi^0, \eta \to A'\gamma$ decays.

For the case with the dominant dark photon decay into LDM particles the reactions $eZ \to eZ(A' \to \chi\bar{\chi})$ and $e^+e^- \to \gamma(A' \to \chi\bar{\chi})$ could be used for the search for LDM. Here the identification of LDM is probed by the measurement of large missing energy. For instance BaBar collaboration used the reaction $e^+e^- \to \gamma(A' \to \chi\bar{\chi})$ [4, 5]. The momenta of e^+, e^- and γ

[1] For the scalar LDM particles invisible dark photon decay width is given by the formula $\Gamma(A' \to \chi\chi^*) = \frac{\alpha_D}{12} m_{A'}(1 - 4\frac{m_\chi^2}{m_{A'}^2})\sqrt{1 - \frac{4m_\chi^2}{m_{A'}^2}}$.

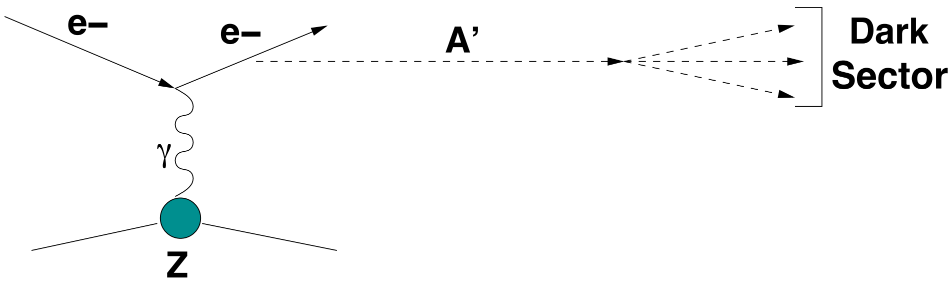

Fig. 1. The Feynman diagram illustrating the A'-boson production in the reaction $eZ \to eZA'$ with the subsequent invisible decay $A' \to invisible$.

are measured with the accuracy $O(10^{-2})$ that allows to restore the missing mass $m_{mis} = \sqrt{(p_{e^+} + p_{e^-} - p_\gamma)^2}$ with a good accuracy. The A'-boson is searched for as a resonance in the distribution of the missing mass m_{mis}. However there are experiments in which the measurement of initial or final momenta is impossible. For instance the NA64 experiment uses the reaction $eZ \to eZA'; A' \to \chi\bar{\chi}$ (see Fig.1) for the search for invisible A' decays and NA64 measures only the energies of ongoing and outgoing electrons. Here typical signature for the search for invisible A' boson decays is the large missing energy in the detector. High hermiticity of the NA64 detector allows to suppress backgrounds at the level $O(10^{-12})$, that is extremely important for the search for A'. The number of signal events in the NA64 experiment is proportional to the square of the mixing parameter ϵ^2.

In proton beam-dump experiments the LDM particles are produced mainly in the decays $\pi^0, \eta, \eta' \to \gamma A'(A' \to \chi\bar{\chi})$ or in the reaction $pZ \to pZA'(A' \to \chi\bar{\chi})$ + ... of direct production and they are detected by the use of the reactions $\chi e \to \chi e$, $\chi N \to \chi N$ in the far detector. The beam-dump experiments probe the LDM particles twice and the number of signal events is proportional to $\epsilon^2 \cdot \epsilon^2 \alpha_D$. Therefore the large number proportional to $1/\epsilon^4$ of initial particles on target is nesessary.

In the modified Williams-Weitzecker (IWW) approximation the differential and full cross-sections for the reaction (**??**) at $m_{A'} \gg m_e$ have the form [14]

$$\frac{d\sigma^{A'}_{WW}}{dx} = (4\alpha^3\epsilon^2\chi_{eff})(1 - x + x^2/3)(m^2_{A'}\frac{1-x}{x} + m^2_e x)^{-1}\,, \tag{12}$$

$$\sigma^{A'}_{WW} = \frac{4}{3}\frac{\epsilon^2\alpha^3}{m^2_{A'}} \cdot log(\delta^{-1}_{A'})\,, \tag{13}$$

$$\delta_{A'} = max[\frac{m^2_e}{m^2_{A'}},\ \frac{m^2_{A'}}{E^2_0}]\,, \tag{14}$$

where χ_{eff} is the effective photon flow

$$\chi_{eff} = \int_{t_{min}}^{t_{max}} dt \frac{t - t_{min}}{t^2}[G^{el}_2(t)\ +\ G^{inel}_2(t)]\,, \tag{15}$$

$x = \frac{E_{A'}}{E_o}$. Here $t_{min} = m_{A'}^4/4E_0^2$, $t_{max} = m_{A'}^2 + m_e^2$ and $G_2^{el}(t)$, $G_2^{inel}(t)$ - are elastic and inelastic formfactors. For NA64 experiment energy $E \leq 100$ GeV elastic formfactor $G_2^{el}(t)$ dominates. The expression for the elasic formfactor can be represented in the form [14]

$$G_2^{el} = (\frac{a^2 t}{1 + a^2 t})^2 (\frac{1}{1 + t/d})^2 Z^2 \,, \tag{16}$$

where $a = 111 Z^{-1/3}/m_e$, $d = 0.164$ GeV$^2 A^{-2/3}$ and A is the atomic number of the nuclei. Here we consider quasi elastic reaction (**??**) therefore we can neglect inelastic formfactor $G_2^{inel}(t)$. Numerically $\chi_{eff} = Z^2 \cdot Log$ and the function $Log \sim (5 \;-\; 10)$ depends rather weekly on the nuclei.

The simplest LDM model with dark photon as a messenger between the SM world and the dark sector depends on four unknown parameters ϵ, α_D, $m_{A'}$ and m_χ. From the condition that LDM model reproduces observable dark matter density of the Universe we can eliminate one parameter and our predictions will depend on three unknown parameters. Consider for example dark photon model with charged scalar LDM. The annihilation cross section in the nonrelativistic approximation [1]

$$\sigma(\chi\bar{\chi} \to e^- e^+) v_{rel} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha \alpha_D m_\chi^2 v_{rel}^2}{(m_{A'}^2 - 4m_\chi^2)^2} \,. \tag{17}$$

The solution of the Boltzmann equation

$$\frac{dn_D}{dt} + 3H(T) n_D = - < \sigma v_{rel} > (n_D^2 - n_{D,eq}^2) \tag{18}$$

for LDM density n_D allows to estimate $\epsilon^2 \alpha_D$, namely

$$\epsilon^2 \alpha_D \sim 0.04 \cdot 10^{-11} \cdot (\frac{m_\chi}{MeV})^2 (\frac{m_{A'}^2}{m_\chi^2} - 4)^2 \,. \tag{19}$$

For often used values $m_{A'} = 3m_\chi$ and $\alpha_D = 0.1$ we find that

$$\epsilon^2 \sim 10^{-10} \cdot (\frac{m_\chi}{MeV})^2 \,. \tag{20}$$

3. NA64 experiment

The NA64 experiment [8]- [11] at the CERN employs the electron beam from the H4 beam line in the North Area (NA). The beam delivers $\approx 10^6$ electrons per SPS spill of 44.8 s produced by the primary 400 GeV proton beam with an intensity of a few 10^{12} protons on target. The NA64 experiment is a fixed target experiment searching for dark sector particles at the CERN

[1] Here we assume that $m_\chi \gg m_e$

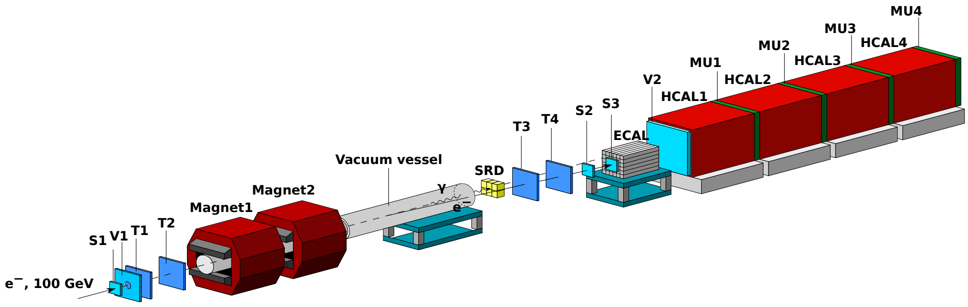

Fig. 2. The schematic illustration of the NA64 detector used for the search for invisible A' decays produced in the reaction $eZ \to eZA'$ in the electromagnetic calorimeter.

Super Proton Synchrotron(SPS) by using active beam dump technique combined with missing energy approach. If new light boson A' exists it could be produced in the reaction of high energy electrons scattering off nuclei. Compared to the traditional beam dump experiment the main advantage of the NA64 experiment is that its sensitivity is proportional to the ϵ^2. While for the classical beam dump experiments the sensitivity is proportional to the $\epsilon^2 \cdot \epsilon^2$, where one ϵ^2 comes from new particle production in the dump and another ϵ^2 is from the LDM interaction in far detector. Another advantage of the NA64 experiment is that due to the higher energy of the incident beam, the centre of mass system is boosted relative to the laboratory system. This boost leads to enhanced hermeticity of the detector providing a nearly full solid angle coverage.

The NA64 method of the search can be illustrated by considering the search for the dark photon A' production with invisible A' decays $A' \to \chi\bar{\chi}$ into LDM particles. A fraction f of the primary beam energy $E_{A'} = fE_0$ is carried away by LDM particles, which penetrate the target and detector without interactions resulting in zero energy deposition. The remaining part of beam energy $E_e = E_0 - fE_0$ is deposited in the target by the scattered electron. The occurrence of the A' production via the reaction $eZ \to eZA'$; $A' \to \chi\bar{\chi}$ would appear as an excess of events with a signature of a single isolated electromagnetic (e-m) shower in the active dump with energy E_e accompanied by a missing energy $E_{miss} = E_{A'} = E_0 - E_e$ above those expected from backgrounds. Here we assume that LDM particles χ traverse the detector without decaying visibly. The NA64 detector is schematically shown in Fig.2.

4. The main results

In this section we briefly present the main results of the experiments including NA64 experiment on the search for LDM in dark photon model. The current situation with the search for visible A' decays, mainly $A' \to e^+e^-, \mu^+\mu^-$ decays is presented in Fig.3.

As we see from Fig.3 current experimental data give upper bound on mix-

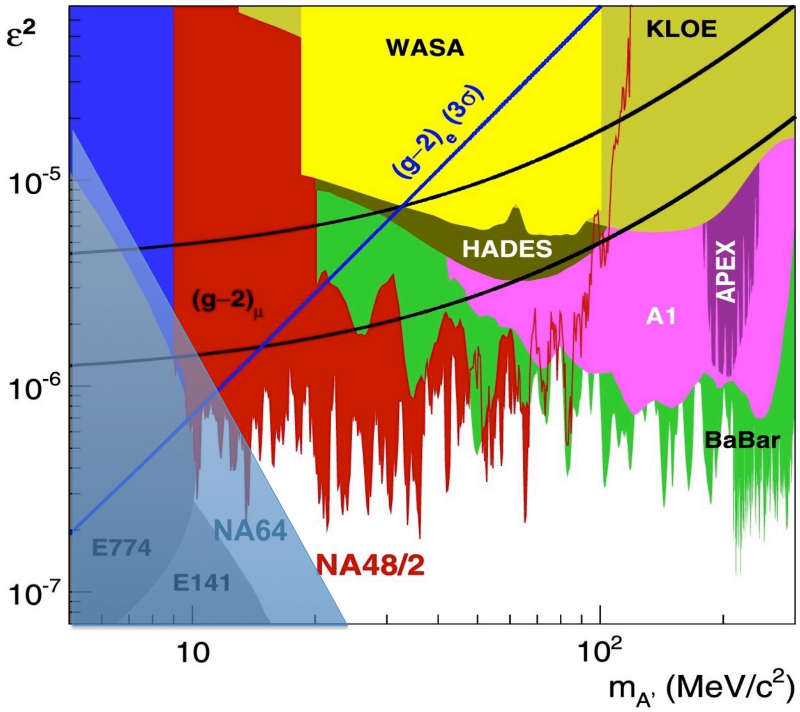

Fig. 3. The limits on ϵ^2 parameter as a function of the A'-boson mass for visible A' decays, taken from Ref. [15].

ing parameter ϵ^2 at the level $\epsilon^2 \leq O(10^{-6})$ and exclude possible explanation of muon g-2 anomaly in visible scenario due to one loop contribution of dark photon to muon anomalous magnetic moment.

Also very interesting is the search for dark photon and LDM in the invisible scenario with the dominant dark photon decay into LDM particles. A lot of experiments searched for dark photon in invisible scenario (as a review see for example [4, 5]). In the NA64 experiment the signature with large missing energy in electromagnetic calorimeter and small activity in the hadron calorimeter is used. The events with large missing energy could be realized as the production of dark photon with the subsequent decay into LDM particles. The SM backgrouns for this signature are extermely small and this signature is background free. The bounds on ϵ parameter are presented in Fig.4. The implications of obtained ϵ bounds for LDM dark photon models are presented in Fig.5.

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5. Conclusion

The LDM models are renormalizable extensions of the SM. The LDM models can explain the observable dark matter density in the Universe by the introduction of new interaction (messenger) between the SM world and dark sector. The LDM models predict the interaction strength of the messenger with the SM particles reasonable for the search for LDM at the fixed target

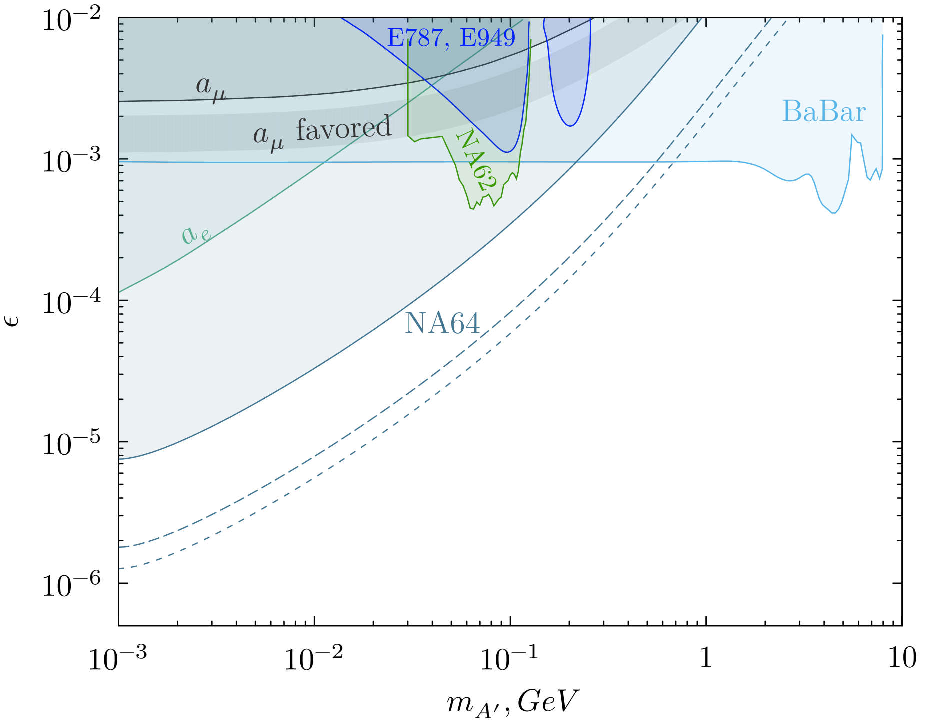

Fig. 4. The limits on ϵ parameter as a function of the A'-boson mass for invisible dark photon decays. Also shown the expected NA64 bounds for the statistics 5×10^{12} and 10^{13}. Taken from Ref. [11].

experiments. At present the most popular LDM model is the model with dark photon. In this model the interaction of dark photon with the SM world is an effect of nonzero mixing of dark photon and $U(1)$ gauge field of the SM. There are a lot of experiments on the search for dark photon. The experiments use both visible and invisible dark photon decays. At present the NA64 experiment obtained the most stringent bound on the mixing parameter ϵ for dark photon masses $1\ MeV \leq m_{A'} \leq 200\ MeV$ for invisible mode. In future the NA64 experiment will be able to improve statistics by factor $O(10)$ and to test the most interesting LDM scenario.

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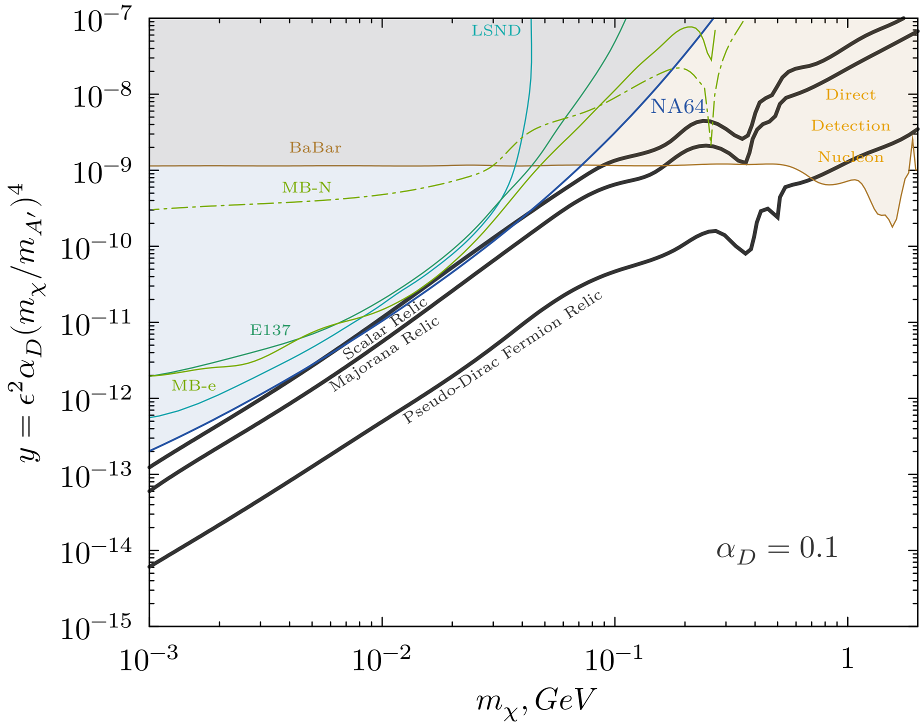

Fig. 5. The limits on $y \equiv \epsilon^2\alpha_D(\frac{m_\chi}{m_{A'}})^4$ parameter for $\alpha_D = 0.1$ and $m_{A'} = 3m_\chi$ as a function of LDM mass m_χ in comparison with the predictions of the dark photon models with the scalar, Majorana and pseudo-Dirac LDM particles. Taken from Ref. [11]

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