Modification of dark photon model

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Introduction

This talk is based on my paper

N.V.K., Phys.Lett. B854(2024)138747

Outline

1. Introduction
2. Dark photon model with modification
3. Conclusions

1. Introduction

The main motivation in favor of BSM physics is dark matter.

There are a lot of dark matter models.

For many years SUSY with R-parity was the most popular dark matter model.

However LHC failed to discover SUSY.

Other models became popular now.

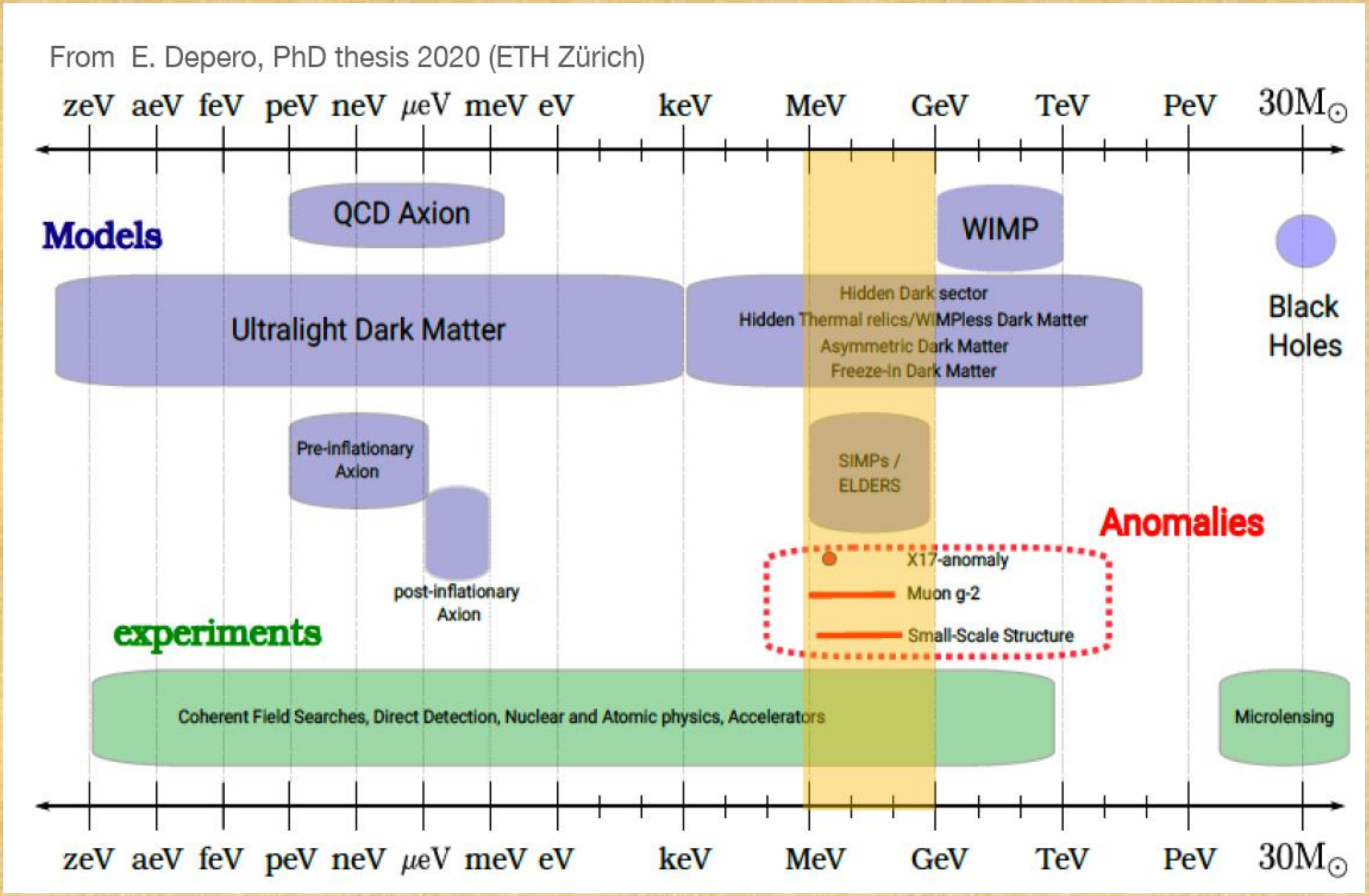
We know that dark matter exists and it is cold (nonrelativistic) or warm

But we don’t know:

1. Spin of dark matter particles
2. Mass of dark matter particles
3. SM – DM interactions

In SUSY with R-parity conservation LSP is gaugino with $s = ½$ and $m = O(100\ \text{GeV})$ as a rule

Dark matter mass range



WIMP

The most popular mass interval from LHC

point of view between O(1) GeV and

O(1) TeV   -> WIMP = weakly interacting massive particles

Also mass interval between O(1) MeV and

O(1) GeV is popular for fixed target experiments like NA64, BELLE, SHIP, …

So called light dark matter

Typical models

At LHC bounds depend on particular model. There are a lot of models.

Simplified models:

A. Models with vector mediator

B. Models wth scalar mediator

Dark Matter: scalar, fermion, Majorana, vector Spin 1.

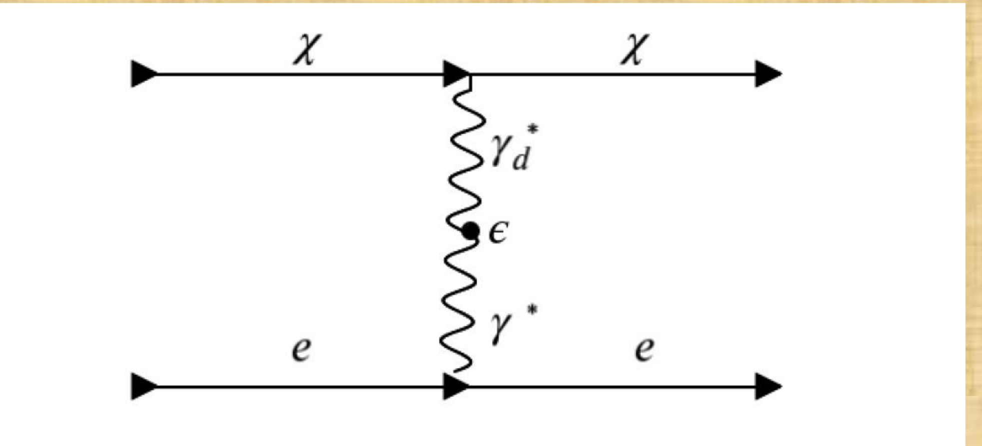
Underground experiments

Direct detection of DM using the elastic scattering reaction

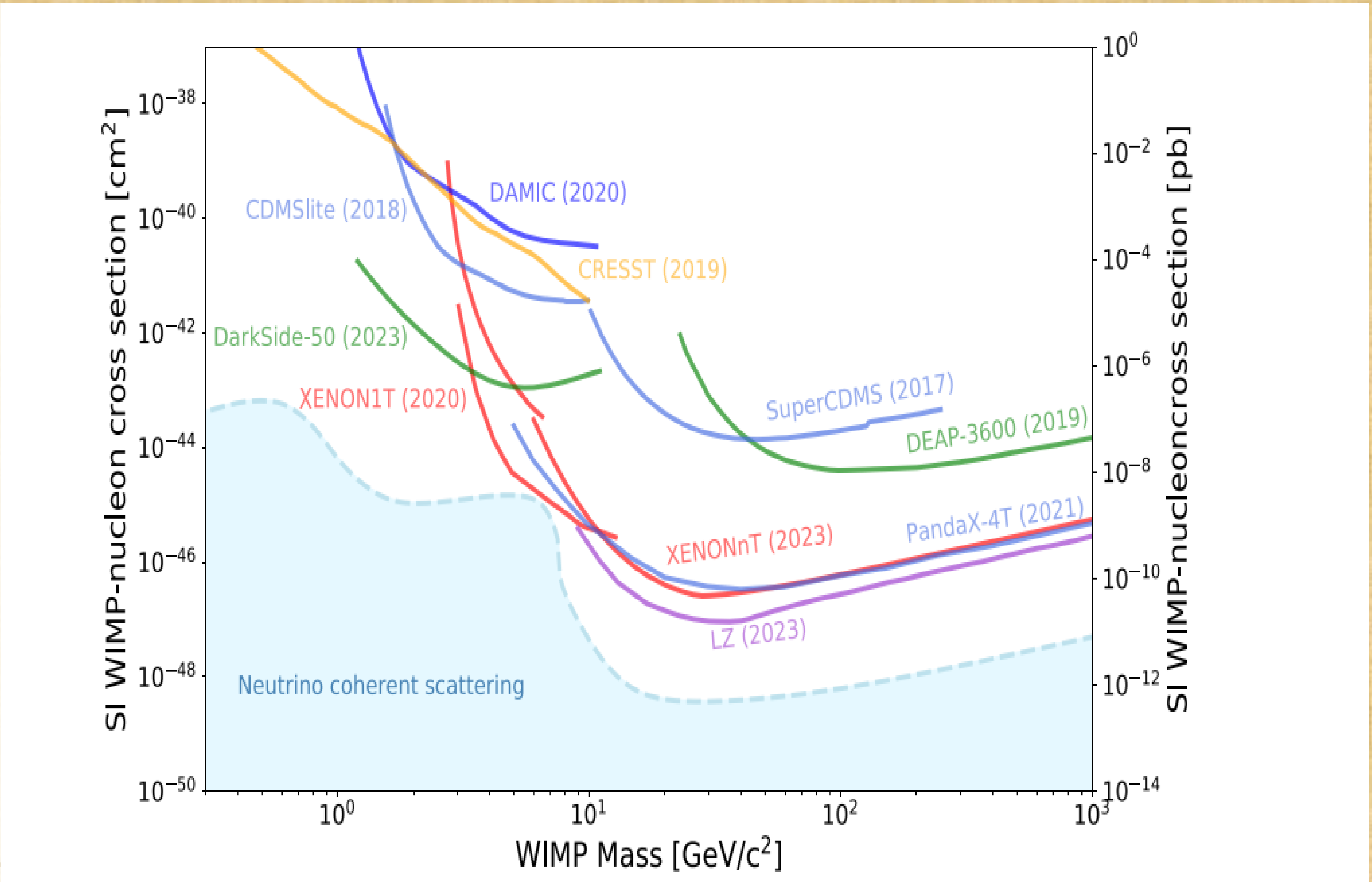
DM + (electron)nucleon -> DM + (electron)nucleon

For instance for model with additional vector (B-L) interaction nucleon DM cross section is

$$\sigma(DM\ +\ nucleon \to DM\ +\ nucleon) = \mu_{\chi N}^2 \frac{g_{B-L}^2 g_\chi^2}{\pi m_{Z'}^4},$$



Elastic DM nucleon cross sections bounds . Bounds from underground experiments. Particle data



Introduction

Implications from underground and accelerator experiments for different

DM models are contained in recent review:

M.Lindner et al., arXiv:2403.15860

A lot of models at the level of exclusion

The most popular light dark matter model – model with additional U(1) gauge field

A’ – dark photon model (Holdom, Okun)

Dark photon connects our world and dark matter world due to nonzero kinetic mixing between dark photon and ordinary photon

THERMAL ORIGIN

We assume that in the early Universe dark matter is in equilibrium with the SM matter

Today DM density tells us about annihilation cross-section. Correct DM density corresponds to $<\sigma_{an} v> \sim O(1)$ pb*c

Dark matter dark photon model depends on four unknown parameters

1. Mixing ε

2. Fine coupling constant for dark sector $\alpha_D = e^2_D/4\pi$

3. Dark photon mass $m_{A'}$

4. Dark matter mass m_χ

Thermal origin condition → $<\sigma_{an}v> \sim O(1)$ pb*c

As a consequence: 3 independent parameters

$$\sigma(\chi\bar{\chi} \to e^- e^+)v_{rel} = \frac{16\pi\epsilon^2\alpha_D m_\chi^2}{(m_{A'}^2 - 4m_\chi^2)^2}$$

$$\varepsilon^2\alpha_D = F(m_{A'}, m_\chi)$$

Dark photon model generalization with a additional vector massive field (N.V.K., Phys.Lett. B854(2024)138747)

Direct underground experiments lead to very strong bounds on DM models. In particular, strong bounds arise for dark photon model on mixing parameter ε. The main idea is that ε parameter depends on the square of momentum transfer q^2, i.e. $\varepsilon(q^2)$ and for $\varepsilon(q^2) = cq^2$ at small q^2 direct elastic cross section is suppressed. Two possible realizations of this idea :

1. Nonlocal field theory – SM and dark sector are described by renormalizable field theory but the interaction between them

Is described by nonlocal field theory

2. The introduction of additional vector field allows realize this idea.

Suppose we have additional Z' boson interacting only with the SM fields, for instance Z' interacting with (B-L) current of the SM

Nonlocal generalization of dark photon model

In dark photon model [9] 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 DM Lagrangian [3]. At present scalar, Dirac, pseudo-Dirac and Majorana DM models are often considered. For instance for Dirac DM χ the interaction with dark photon A' has standard form For instance, for

the scalar DM the Lagrangian L_{dark} has the form

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

where χ is the charged scalar DM field.

and the tree level cross section with Dirac or scalar DM on the electron has the form [10]

$$\sigma(DM\ +\ electron \to DM\ +\ electron) = \mu_{\chi e}^2 \frac{16\pi\epsilon^2\alpha\alpha_D}{m_{A'}^4}\,, \tag{4}$$

where $\mu_{\chi e} = \frac{m_\chi m_e}{m_\chi + m_e}$ and $\alpha_D = \frac{e_D^2}{4\pi}$. The analogous formula is valid for nucleon. For $m_\chi \approx 10^3\ GeV$ experimental bounds on $\sigma(DM\ +\ nucleon \to DM\ +\ nucleon)$ are at the level $10^{-9}\ pb$ [7] that restricts rather strongly dark photon mass, namely $m_{A'} \geq 3.5\ TeV$ at $\alpha_D = 0.1$ and $\epsilon = 0.1$.

In nonlocal generalization of the dark photon model we assume that both our world and dark world are described by local renormalizable field theories while the communication between our world and dark sector is performed by

nonlocal interaction [11–15]. We propose to use nonlocal generalization for the mixing term (2), namely

$$L_{SM,dark} \to L_{SM,dark\ nonlocal} = -\frac{1}{2\cos\theta_w} B^{\mu\nu}\epsilon(-\frac{\partial^\mu\partial_\mu}{\Lambda^2})F'_{\mu\nu}\,. \tag{5}$$

As it has been proved on the example of nonlocal ϕ^4-model and nonlocal electrodynamics [11–13] nonlocal field theory is unitary and macrocausal theory provided nonlocal formfactors $V(q^2)$ are entire functions of the $\rho \geq 1/2$ growth[4]. Moreover we require that nonlocal interaction $\epsilon(\frac{q^2}{\Lambda^2})$ has to dissapear in the limit of the infinite nonlocal scale Λ, i.e. $\epsilon(\frac{q^2}{\Lambda^2}) \to 0$ at $\Lambda \to \infty$. In other worlds it means that the communication between our world and dark world switches off for infinite nonlocal scale. As a consequence we find that $\epsilon(\frac{q^2}{\Lambda^2}) = \sum_{k=1}^{\infty} c_k(\frac{q^2}{\Lambda^2})^k$. As an example we shall use the formfactor

$$\epsilon(\frac{q^2}{\Lambda^2}) = \frac{q^2}{\Lambda^2}\exp(-\frac{(q^2)^2}{\Lambda^4})\,. \tag{6}$$

Dark photon model modification

$\epsilon^2 \to \epsilon^2(\frac{4m_\chi^2}{\Lambda^2})$. For $q^2 \ll \Lambda^2$ and $m_{A'} = km_\chi$ we find that $\epsilon(\frac{m_{A'}^2}{\Lambda^2}) = \frac{k^2}{4}\epsilon(\frac{4m_\chi^2}{\Lambda^2})$. Using the formulae of the Appendix we can estimate the product $\alpha_D\epsilon^2(\frac{4m_\chi^2}{\Lambda^2})$ as a function of m_χ and $m_{A'}$.

Consider at first the case of scalar LDM with $m_{A'}^2 = 5m_\chi^2$ and $\alpha_D = 0.1$. For dark photon mass $m_{A'} \le O(1)\ GeV$ the NA64 [17] and BABAR [18] experiments give the most strongest bounds on $\epsilon(\frac{m_{A'}^2}{\Lambda^2})$. As a consequence of the assumed equilibrium of the LDM with the SM particles at the early Universe one can find that

$$\epsilon(\frac{m_{A'}^2}{\Lambda^2}) \sim 0.9 \cdot 10^{-6}(\frac{m_{A'}}{MeV})\,. \qquad (7)$$

For pseudo- Dirac LDM with $m_{A'} = 3m_\chi$ and $\alpha_D - 0.1$ we find that

$$\epsilon(\frac{m_{A'}^2}{\Lambda^2}) \sim 1.5 \cdot 10^{-6}(\frac{m_{A'}}{MeV})\,. \qquad (8)$$

The obtained values (7, 8) for $\epsilon(\frac{m_{A'}^2}{\Lambda^2})$ don't contradict to experimental bounds [8], [17,18] at $m_{A'} \le 1\ GeV$. The predicted value of nonlocal scale Λ depends on dark photon mass $m_{A'}$ and it is rather small, for instance $\Lambda \sim 10\ GeV$ at $m_{A'} = 100\ MeV$.

For the mass region $m_\chi \sim O(1)\ TeV$ consider as an example fermion dark matter with $\alpha_D = 0.1$ and $m_{A'}^2 = 5m_\chi^2$. The analog of the formula (7) reads

$$\epsilon(\frac{m_{A'}^2}{\Lambda^2}) \sim 0.08(\frac{m_{A'}}{TeV})\,. \qquad (9)$$

The predicted value of nonlocal scale Λ depends on the dark photon mass $m_{A'}$, for instance $\Lambda = 7\ TeV$ at $m_{A'} = 2\ TeV$. Note that the obtained value (9) for the mixing parameter does not contradict to the LEP1 data since the mixing parameter $\epsilon(\frac{q^2}{\Lambda^2})$ strongly depends on the mass scale. In the energy region of the Z-boson we have to use $\epsilon(\frac{m_Z^2}{\Lambda^2}) = \frac{m_Z^2}{m_{A'}^2}\epsilon(\frac{m_Z^2}{\Lambda^2})$ (for $m_{A'} = 2\ TeV$ $\epsilon(\frac{m_Z^2}{\Lambda^2}) \approx 0.2 \cdot 10^{-3}$) which is suppressed by factor $\frac{m_Z^2}{m_{A'}^2}$ in comparison with $\epsilon(\frac{m_{A'}^2}{\Lambda^2})$. For often used mass relation $m_{A'} = 3m_\chi$ and $\alpha_D = 0.1$ we find that $\epsilon(\frac{m_{A'}^2}{\Lambda^2}) \sim 0.54(\frac{m_{A'}}{TeV})$ and $\Lambda = 1.4\ TeV$ at $m_{A'} = 1\ TeV$.

It should be stressed that in considered model in full analogy with DM model with pseudoscalar messenger [3] we have huge suppression factor $O(10^{-12})$

Renormalizable extension of the dark photon model with additional vector Z' boson

In dark photon model dark photon field A' interacts with DM particles due to nonzero kinetic mixing between the dark photon field A' and the $U(1)$ gauge field B of the SM model. Here we consider the extension of the dark photon model with additional $U(1)$ gauge field Z' interacting with the SM fields. As the simplest possibility we consider the interaction of the Z' with $(B-L)$ current [19–22]

$$L \supset g_{B-L} Z'_\mu \Big(\sum_{leptons} \bar{l}\gamma^\mu l - \frac{1}{3} \sum_{quarks} \bar{q}\gamma^\mu q \Big) \qquad (11)$$

The $(B-L)$ extension of the SM is free from γ_5-anomalis only with 3 right handed neutrino. The right handed neutrinos ν_{Rk} acqure masses due to the Higgs mechanism, namely Yukawa interactions

$$L \supset \frac{1}{2} \sum_{k=1}^{3} h_k \nu_{Rk} \nu_{Rk} \Phi_{B-L} \,, \qquad (12)$$

give rise to nonzero Majorana masses $m_{\nu_{Rk}} = h_k < \Phi_{B-L} >$ for right handed neutrinos. Here Φ_{B-L} is $SU_c(3) \otimes SU_L(2) \otimes U(1)$ singlet scalar field with $B-L$ charge $Q_{B-L} = -2$. Nonzero vacuum expectation value of the Φ_{B-L} leads to both nonzero Majorana neutrino mases and to nonzero Z' boson mass $m_{z'} = 2|g_{B-L}\Phi_{B-L}|$. It should be stressed that the considered $B-L$ extension of the SM does not contain DM particles. We assume that DM particles χ don't interact with the fields of $(B-L)$ and the interaction arises due to additional massive vector field - dark photon. The dark particles χ interacts directly only with dark photon. For instance, for the Dirac fermion DM χ the interaction with dark photon A' is

$$L \supset e_D \bar{\chi}\gamma^{\mu}\chi A'_{\mu} \,. \tag{13}$$

We assume that the communication of the SM particles and DM particles is performed due to nonzero kinetic mixing of Z' with dark photon A'

$$L \supset -\frac{\epsilon_{Z'A'}}{2} A^{\mu\nu} Z'_{\mu\nu} \,, \tag{14}$$

where $A^{\mu\nu} = \partial^{\mu} A^{\nu'} - \partial^{\nu} A^{\mu'}$, $Z'_{\mu\nu} = \partial_{\mu} Z'_{\nu} - \partial_{\nu} Z'_{\mu}$. So our model is an extension of the standard dark photon model with the inclusion of additional Z' boson where the interaction between visible and dark sectors is a consequence of nonzero Z', A' kinetic mixing. Note that in the DM model with $(B-L)$ Z' vector boson interacting directly with Dirac DM the DM nucleon elastic cross section is [3]

$$\sigma(DM \ + \ nucleon \to DM \ + \ nucleon) = \mu^2_{\chi N} \frac{g^2_{B-L} g^2_{\chi}}{\pi m^4_{Z'}} \,, \tag{15}$$

Here g_χ is the coupling constant of DM with Z'. From the experimental bound $\sigma(DM + nucleon \to DM + nucleon) \leq 10^{-9}\ pb$ [7] and the formula (3) for the elastic cross section we find rather strong bound $m_{Z'} > 1.8 \cdot 10^4 \sqrt{g_{B_L} g_\chi}\ GeV$ on the Z' boson mass. In our model as a consequence of the interaction (14) and nonzero Z' boson mass we find that the tree level amplitudes with the interaction of Z' and A' bosons contain the multiplier $\frac{q^2}{q^2 - m^2_{Z'}}$, where q is the momentum transfer. Note that in dark photon model the role of the Z'-boson plays massless photon field A and the multiplier is $\frac{q^2}{q^2} = 1$. So for $|q^2| \ll m^2_{Z'}$ we have the suppression factor $\frac{q^2}{m^2_{Z'}}$ for tree level amplitudes. As it was explained in the previous section the existence of the

factor $\frac{q^2}{m^2_{Z'}}$ leads to the suppression factor $O(v^2) = O(10^{-12})$ for the tree level elastic DM nucleon(electron) cross section.

phenomenology in considered model is similar to the phenomenology of the Z'-model without dark photon. All LHC and fixed target bounds are valid for the model with additional dark photon A'. In contrast to the Z'-boson dark photon A' decays mainly into invisible modes. As a consequence the bounds on dark photon are much weaker the bounds on Z'-boson.

For the model with additional Z' boson consider two mass regions for DM. For the case of the LDM with $O(1)\ MeV \leq m_\chi \leq O(1)\ GeV$ there are rather strong bounds on coupling constant g_{B-L} for the Z' boson, see ([23]) and [24–26]. Consider as an example the scalar LDM. The annihilation cross section into electron positron pair in nonrelativistic approximation has the form

$$\sigma(\chi\bar{\chi} \to e^+e^-)v_{rel} = \frac{g^2_{B-L}e^2_D\epsilon^2_{Z'A'}m^2_\chi v^2_{rel}}{6\pi}\left(\frac{4m^2_\chi}{(4m^2_\chi - m^2_{Z'})(m^2_{A'} - 4m^2_\chi)}\right)^2 . \tag{16}$$

In comparison with the $B-L$ LDM model we have additional factor $k_{ad} = \epsilon^2_{Z'A'}(\frac{4m^2_\chi}{m^2_{A'}-4m^2_\chi})^2$ for the cross section (16). For the particular case $m^2_{A'} = 3m^2_\chi$ and $\epsilon_{Z'A'} = 0.25$ the additional factor $k_{ad} = 1$ and the predictions for LDM density for both models coincide. Also the predictions of the considered model with $m^2_{A'} = 3m^2_\chi$, $m^2_{Z'} = 5m^2_\chi$, $\epsilon_{Z'A'} = 0.05$ coincide with the predictions of the $(B-L)$ model with $m_{Z'} = 3m_\chi$

For the mass region with $m_\chi = O(1)\ TeV$ the model also does not contradict to existing accelerator bounds for some parameters. Consider the model with Dirac DM. For $m_\chi = O(1)\ TeV$ the equation for the determination of the DM density leads to

$$\frac{kg^2_{B-L}e^2_D\epsilon^2_{Z'A'}m^2_\chi}{\pi}\left(\frac{4m^2_\chi}{(4m^2_\chi - m^2_{Z'})(4m^2_\chi - m^2_{A'})}\right)^2 \sim 5\cdot 10^{-9}\ GeV^{-2} , \tag{17}$$

where $k = 6.5$ for $m_\chi \gg m_{top}$. As a numerical example we use $g_{B-L} = e_D = 1$, $m_{Z'} = 3m_\chi$, $m^2_{A'} = 5m^2_\chi$. As a consequence of the equation (17) we find that $\frac{\epsilon_{Z'A'}}{m_{Z'}} \approx 2\cdot 10^{-5}\ GeV^{-1}$. From the LEP bound $\frac{m_{Z'}}{g_{B-L}} > 7\ TeV$ [27, 28][5] we find that the mixing parameter $\epsilon_{Z'A'} \geq 0.14$. As a second numerical example consider $g_{B-L} = e_D = 1$, $m^2_{Z'} = 5m^2_\chi$, $m^2_{A'} = 3m^2_\chi$. For this set of parameters we find that $\frac{\epsilon}{m_{Z'}} \approx 0.54\cdot 10^{-5}\ GeV^{-1}$ and as a consequence of the LEP bound [27, 28] $\epsilon_{Z'A'} \geq 0.038$. As in previous example at one-loop level we have the suppression factor $(\frac{g_\chi g_{B-L}\epsilon_{Z'A'}}{8\pi^2})^2 \sim O(10^{-6})$ in comparison to tree level cross section and the bound on Z'-boson mass is weaker by factor ~ 30 the corresponding bound in $(B-L)$ DM model. The Z'-boson

3.Conclusions

In this paper we have proposed two modifications of the dark photo model.

In the first case we use nonlocal generalization with

In the second case we introduce new vector Z' boson besides dark photon field A' . The dark photon field A' interacts only with DM $\epsilon(q^2) = \frac{q^2}{\Lambda^2} V\left(\frac{q^2}{\Lambda^2}\right)$

The vector field Z'(in our concrete case we use B-L model) nteracts only with the SM particles. The single interaction of our an dark world is

due to nonzero mixing term $\frac{\epsilon_{Z'A'}}{2} A^{\mu\nu} Z'_{\mu\nu}$

Both modifications predict the suppression of elastic nucleon DM cross section

Thank You for Your attention

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BACKUP

Scalar dark matter χ

$L_{dark,s} = (\partial_\mu\chi - ie_D A'_\mu\chi)^* \cdot (\partial_\mu\chi - ie_D A'_\mu\chi) - m^2_\chi \chi^*\chi - \lambda(\chi^*\chi)^2$

$-(1/4)F'_{\mu\nu}F'^{\mu\nu} + (m^2_{A'}/2)A_\mu' A'^\mu$

It is possible to use Higgs mechanism to

create dark photon mass in a gauge invariant way

Also models with Majorana fermion

$(\chi = C\chi^*)$ are often used

$L_M = (e_D/2)\chi^*\gamma_\mu\gamma_5\chi A'^\mu$

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$L_{dark,s}=(\partial_\mu\chi-ie_D A'_\mu\chi)^*\cdot(\partial_\mu\chi-ie_D A'_\mu\chi)-m^2_\chi\chi^*\chi-\lambda(\chi^*\chi)^2$

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