# Dark matter production in $e^-e^+$annihilation

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## Abstract

We propose a double extension model to describe the weakly interacting massive particles (WIMPs) or sometimes called dark particles. This extension is made adding two extra gauge group symmetry $U(1)$ to the Standard Model, one via Stueckelberg mechanism and another via minimal coupling. The Stueckelberg mechanism is one of the ways to give mass to the particles. So we get two new gauge bosons, one called $Z'$ wich is massive and the other $\gamma'$ or dark photon, wich is massless and doesn't interact with the standard model particles. Therefore we can calculate the criation process of dark particles $e^-e^+ \to \bar{\chi}\chi$, where $\chi$ is a dark fermion and the process is mediated by three bosons contributions $\gamma, Z, Z'$. Some results and perspectives are presented.

## The Lagrangian density of the model

In the present we shall study a hybrid scenario in which two new vector bosons are introduced. A first boson $C_\mu$ couples to the Standard Model (SM) by the usual minimal coupling and producing an enlarged SM. The second boson $X_\mu$ mixes with $C_\mu$ via Stueckelberg [1] coupling. The dark QED symmetry group is defined by $\mathcal{G}_{\rm dQED} = U(1)_C \otimes U(1)_X$. The dark QED lagrangian (dQED) defines the dark sector

$$\begin{aligned}\mathcal{L}_{\rm dQED} &= -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{1}{2}\Lambda_\mu\Lambda^\mu \\ &\quad + i\bar{\chi}\left(\gamma^\mu D_\mu^X - m_\chi\right)\chi\,, \end{aligned} \tag{1}$$

with

$$D_\mu^X = \partial_\mu + ig_x Q_X X_\mu. \tag{2}$$

The new $U(1)$ bosons in the dark sector define the field tensors $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ and $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$. The third term in (1) is the Stueckelberg mixing term between the two boson fields $C_\mu$ and $X_\mu$ via an axial pseudo-scalar $\sigma$ field given by

$$\Lambda_\mu = \partial_\mu\sigma + m_1\,C_\mu + m_2\,X_\mu\,. \tag{3}$$

The $\sigma$ field is unphysical and decouples from all fields after gauge fixing. The last term in (1) is a fermion singlet term of the dark sector. This type of model was first proposed by [2], but with just one dark field, and was applied as well in [3]. In present, the $C_\mu$ of the dQED interacts with the SM fields by

$$D_\mu = \partial_\mu + i\,g_2\,\frac{\tau^3}{2}W_\mu^3 + i\,g_Y\,\frac{Y_1}{2}\,B_\mu + i\,g_c\,\frac{Y_2}{2}\,C_\mu\,, \tag{4}$$

where in (4) only the relevant part, that couples the vector bosons, is presented. The model lagrangian density that represents them is a sum of

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dQED}\,. \tag{5}$$

Using this full Lagrangian (5) and taking into account just the terms that contribute to the vector bosons masses, we write the relevant term that corresponds to the squared mass matrix and after diagonalizing it, we obtain 4 mass eigenvalues:

$$\begin{aligned} m_{Z'}^2, m_Z^2 &= \frac{1}{8}\left[v^2\,g_{s1}^2 + 4m_1^2 + 4m_2^2 \pm \Delta\right] \\ m_\gamma^2 &= 0 \quad ; \quad m_{\gamma'}^2 = 0. \end{aligned} \tag{6}$$

where

$$\Delta = \sqrt{8m_1^2\,(4m_2^2 - v^2\,g_{s2}^2\,) + (v^2 g_{s1}^2 - 4m_2^2)^2 + 16m_1^4}\,,$$

with $g_{s1}^2 = g_2^2 + g_c^2 + g_y^2$ and $g_{s2}^2 = g_2^2 - g_c^2 + g_y^2$. A first qualitative fact one extracts from this result is that, $m_{Z'} > m_Z$ which is consistent with the idea that the SM particles could couple to the dark sector in higher energies. In similar studies explict estimations for the $Z'$ mass was obtained [2].

## Annihilation cross section

Now we are interested in the interaction part of the Lagrangian. The full Model's interaction Lagrangian can be written as

$$\mathcal{L}_{int} = i\bar{\chi}\gamma^\mu D_\mu^X\chi + i\bar{\Psi}\gamma^\mu D_\mu\Psi. \tag{7}$$

The process of interest is $e^-e^+ \to Z', Z, A \to \chi\bar{\chi}$. Therefore, the amplitude for the process is

$$\mathcal{M} = \left[\bar{u}_\chi(p')\gamma_\mu v_\chi(k')\right]\left[\bar{u}_e(k)\gamma^\mu\Pi\,v_e(p)\right], \tag{8}$$

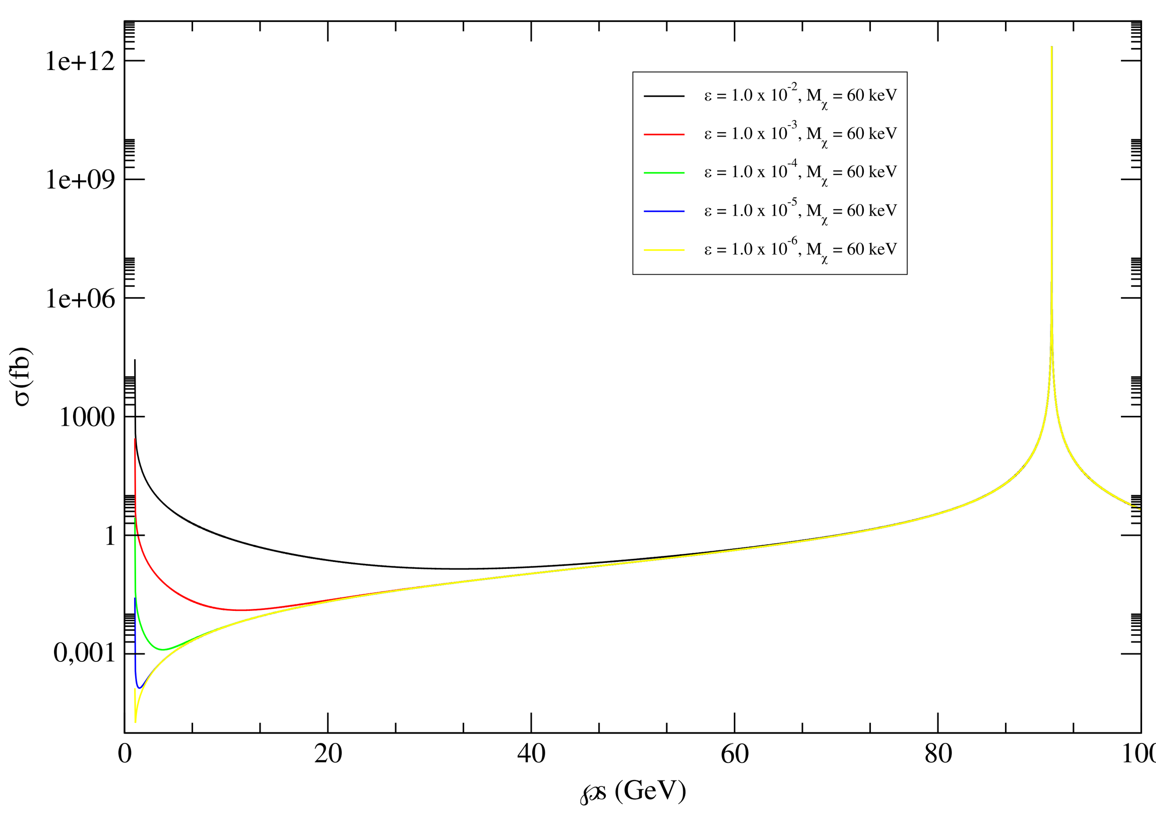
where $\Pi = \lambda_L P_L + \lambda_R P_R$ and $P_{L,R} = \frac{1}{2}(1 \mp \gamma^5)$, with

$$\lambda_{L,R} = \frac{\epsilon e^2}{s} + \frac{\epsilon_z^\chi \epsilon_z^{f_{L,R}}}{s - m_z^2} + \frac{\epsilon_{z'}^\chi \epsilon_{z'}^{f_{L,R}}}{s - m_{z'}^2}. \tag{9}$$

Here we use the values $m_Z = 91.1876$GeV [4] and $m'_Z = 250$GeV wich is used in [2, 3]. The cross section for this amplitude becomes

$$\begin{aligned}\frac{d\sigma}{d\cos\theta} &= \frac{1}{32\pi s}\frac{\beta_\chi}{\beta_e}\left\{\left(\lambda_L^2 + \lambda_R^2\right)\left[\left(t - m_e^2 - m_\chi^2\right)^2 + \left(u - m_e^2 - m_\chi^2\right)^2\right.\right. \\ &\quad + \left.\left. m_\chi^2\left(s - 2m_e^2\right)\right] + 4\lambda_R\lambda_L m_e^2\left(s - 2m_\chi^2\right)\right\}. \end{aligned} \tag{10}$$

We find two boundaries involving $\sqrt{s}$, where $s$ is square of the center-of-masss energy. The first is $s > 4m_e^2$ and the second is $m_\chi < \frac{\sqrt{s}}{2}$.




In the figure we can see there are six diferent values for the fraction of electric charge $\epsilon$, and as low as is the $\epsilon$ value, lower is the cross section. The cross section behavior is tipcal for this kind of calculation. We fixed the dark fermion mass in $m_\chi = 60$keV, as an agreement with a result obtained in a work we have been doing and that will be published soon. The next steps are to calculate the relic density and compare with the known data from INTEGRAL and PAMELA [5].

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