Dark Matter Polarization Operator in the Generalized Yukawa Model

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The dark matter particle candidates are searched on various modern colliders, but nothing has been found, yet. The possible reason for this is considered in this work. In the on-resonance search method of the new particle, the latter is identified with the resonant peak in the cross-section of some scattering process. The resonance position coincides with the mass of the particle, and its width is defined as peak width on the half of its height. It is assumed in the experimental data treatment that the new resonance is narrow, namely its width is up to 3% of its mass. If it is wider, such state could be missed in the data as a noise. We consider different scenarios in which dark matter candidate acquires bigger width, and identify the new particle parameters at which it happens.

We conduct our research in the framework of the generalized Yukawa model, where dark matter is presented as a scalar field χ and a Dirac fermionic field Ψ. The model also contains the sector of visible matter particles, which consists of scalar field ϕ and Dirac fermionic fields ψ_1 and ψ_2. The lagrangian of the model reads:

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu\phi)^2 - \mu^2\phi^2 + (\partial_\mu\chi)^2 - \Lambda^2\chi^2\right] - \lambda\phi^4 - \rho\phi^2\chi^2 - \xi\chi^4 +$$
$$+ \sum_{a=1;2}\bar{\psi}_a\left(i\gamma^\mu\partial_\mu - m_a - g_\phi\phi - g_\chi\chi\right)\psi_a + \bar{\Psi}\left(i\gamma^\mu\partial_\mu - M - G_\chi\chi\right)\Psi.$$

Width of the χ particle is defined generally by the imaginary part of its polarization operator $\Pi_{\chi\chi}(p^2)$ taken at the point $p^2 = \Lambda^2$. Here p^2 is the squared momentum transferred through the virtual bosonic state. $\Pi_{\chi\chi}(p^2)$ is found analytically. Hence, the width ρ of the χ resonance, as a fraction of mass Λ, reads:

$$\rho = \frac{\Im\Pi_{\chi\chi}(\Lambda^2)}{\Lambda^2} = \frac{g_\chi^2}{8\pi}\left[\left(1 - \frac{4m_1^2}{\Lambda^2}\right)^{\frac{3}{2}} + \left(1 - \frac{4m_2^2}{\Lambda^2}\right)^{\frac{3}{2}}\right] + \frac{G_\chi^2}{\Lambda^2}\left(1 - \frac{4M^2}{\Lambda^2}\right)^{\frac{3}{2}}. The lagrangian also introduces the mixing of scalar field$

$loop level. That is, two-point Green function \langle 0|T\phi(x_1)\chi(x_2)|0\rangle$ becomes non-zero due to the loop correction from the ψ_1 and ψ_2, which connects ϕ and χ lines on the corresponding diagram. The magnitude of such mixing is defined by the corresponding mixing angle θ_{mix}. We define this angle from the diagonalization of the bosonic mass matrix, which is given by the effective potential of the scalar fields. Hence, θ_{mix} reads:

$$\tan 2\theta_{mix} = 2g_\phi g_\chi F\left[\frac{4\pi^2}{3}\left(\Lambda^2 - \mu^2\right) + \left(g_\phi^2 - g_\chi^2\right)F - G_\chi^2 M^2\ln\frac{M^2}{\kappa^2}\right]^{-1}, F = m_1^2\ln\frac{m_1^2}{\kappa^2} + m_2^2\ln\frac{m_2^2}{\kappa^2},$$

where κ is an arbitrary renormalization parameter.

From the explicit analytical expression, we find areas of the model parameters space where $\rho \cdot 100\% > 3\%$. We find that the limit of 3% can be exceeded in many cases. In the framework of our model, the conditions for that are the following. There should be $\Lambda > \mu$, so DM particle is heavier than the visible one. Additionally, interactions in the visible sector should be weaker than that of between the dark and visible particle or between the particles in the dark sector only. That is, if either $g_\chi \gg g_\phi$ or $G_\chi \gg g_\phi$. Finally, there exists an upper bound for the mixing angle – in our model, it should be $|\theta_{mix}| \leq 10^{-5}$. We find that until mixing between visible and dark bosons is small and two resonances are located far enough one from another, the parameters of visible particle resonance are independent of the characteristics of the dark sector. In this case dark resonance is both wide and does not interfere with the resonance of visible ϕ. The presence of the upper limit on θ_{mix} is qualitatively important.

The self-interaction of the bosonic particles does not affect their widths, being canceled in the renormalization procedure.

The considered Yukawa model gave a possibility for analyzing the role of the masses and couplings of particles. Other aspects of the problem such as group symmetry of the extended model and, hence, the content of the states remain behind it. However, we have obtained the set of conditions which have to be taken into account when searches for the DM particles are carried out. In general, to avoid the problem of wide resonance states we have to apply additionally non-resonant methods to detect these new states of matter.

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