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DARK MATTER FERMION PRODUCTION AT LEPTON COLLIDERS VIA PHOTON - DARK PHOTON - PHOTON EXCHANGE

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Abstract. The dark matter fermion production has studied at lepton colliders via photon-dark photon-photon exchange, the results show that, the $\bar{\chi}\chi$ production cross-section at e^+e^- collider is the same as at $\mu^+\mu^-$ collider when the initial beams are unpolarized or both the initial beams are left- or right-polarized. In case of mix between both the initial beams are left-polarized with both the initial beams are right-polarized, the $\mu^+\mu^- \to \bar{\chi}\chi$ cross-section is very much bigger than the $e^+e^- \to \bar{\chi}\chi$ cross-section, and the cross-section strongly depends on the polarization of initial beams.

Keywords: Dark matter fermion, dark photon, unpolarized, polarized.

1. Introduction

Dark matter (DM) is a special matter kind. The total amount of dark matter should be around five times bigger than that of ordinary matter. Currently, there are many dark matter models, such as the Cold Dark Matter model with a cosmological constant (ΛCDM) [1] and the vector-fermion dark matter model [2].

The dark photon is a hypothetical hidden sector particle, proposed as a force carrier potentially connected to DM [3]. This new force can be introduced by extending the gauge group of the SM with a new abelian U(1) gauge symmetry.

In this paper, we study the process $l^+l^- \to \bar{\chi}\chi$ via the exchange of photon-dark photon-photon when beams l^+, l^- are unpolarized and polarized, where l^+l^- are e^+e^- and $\mu^+\mu^-$; and χ is dark matter fermion. Specifically, we evaluate the contribution of dark photon on the cross-sections when the initial beams are polarized and unpolarized.

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2. Content

2.1. Interaction Lagrangian

The effective interaction Lagrangian of photon (γ) and dark matter fermion (χ) was given by [4]:

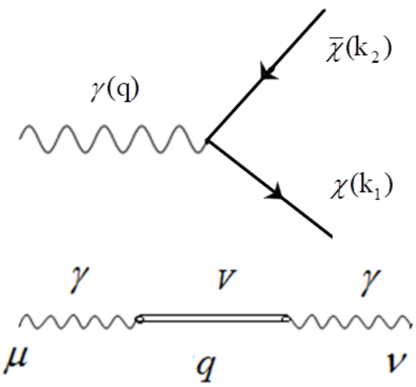
$$L_{\text{int}} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mu_\chi + \gamma_5 \mathrm{d}_\chi)\chi F^{\mu\nu}, \tag{1}$$

where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$, and $\mu_\chi, \mathrm{d}_\chi$ correspond to the magnetic dipole moment, and the electric dipole moment of the DMF χ.

The effective interaction Lagrangian for the dark photon (V) and photon (γ) with respective field strengths $V_{\mu\nu}$ and $F_{\mu\nu}$ is [5]:

$$L_{\text{int}} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{em}^\mu A_\mu, \tag{2}$$

The corresponding Feynman rules are



$$-i(\mu_\chi + \gamma_5 d_\chi)(\hat{q}\gamma^\nu - q^\nu)$$

$$\frac{-i\varepsilon^2}{q^2 - m_V^2}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{m_V^2}\right)$$

Figure 1. Feynman rules for the photon couplings with DMF and $\gamma - V - \gamma$ propagator

2.1. The cross-section of the $l^+l^- \to \bar{\chi}\chi$ collision

The corresponding Feynman diagrams for the pair production of dark matter fermion in l^+, l^- collision via $\gamma - V - \gamma$ exchange are shown in Figure 2.

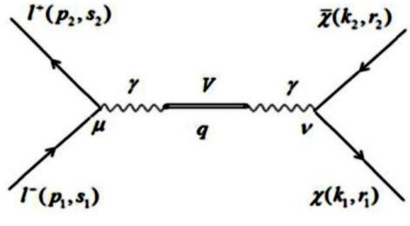


Figure 2. The Feynman diagrams for the process $l^+l^- \to \bar{\chi}\chi$ via $\gamma - V - \gamma$ exchange

For unpolarized l^+, l^- beams, the square of matrix element is given by:

$$|M|^2 = \left(\frac{e\varepsilon^2}{q^2 - m_V^2}\right)^2 2\left(4(p_1k_2)(p_2q) + 4(p_1q)(p_2k_2) - \frac{4(qp_2)q^2(p_1k_2)}{m_V^2}\right.$$

$$-\frac{4(qp_2)(p_1q)(k_2q)}{m_V^2} - \frac{4(qp_1)q^2(p_2k_2)}{m_V^2} - \frac{4(qp_1)(k_2q)(p_2q)}{m_V^2}$$

$$\left.+4\left(\frac{2(qp_1)(qp_2)}{m_V^4} - [(\mathrm{p_1p_2}) + m_l^2]\left(-\frac{2}{m_V^2} + \frac{q^2}{m_V^4}\right)\right)q^2(k_2q) - 4[(\mathrm{p_1p_2}) + m_l^2](k_2q)\right)$$

$$\times[8(\mu_\chi^2 + d_\chi^2)(qk_1) - 4(\mu_\chi^2 + d_\chi^2)(k_1q)]$$

$$+\left(4(p_1p_2) + 4(p_1p_2) - \frac{4(qp_2)(qp_1)}{m_V^2} - \frac{4(qp_2)(qp_1)}{m_V^2} - \frac{4(qp_1)(q\ \ p_2)}{m_V^2} - \frac{4(qp_1)(qp_2)}{m_V^2}\right.$$

$$\left.+4\left(\frac{2(qp_1)(qp_2)}{m_V^4} - [(\mathrm{p_1p_2}) + m_l^2]\left(-\frac{2}{m_V^2} + \frac{q^2}{m_V^4}\right)\right)q^2 - 4[(\mathrm{p_1p_2}) + m_l^2]4\right)$$

$$\times[-8(\mu_\chi^2 + d_\chi^2)(qk_1)(k_2q)+[4(\mu_\chi^2 + d_\chi^2)q^2(k_2k_1) - 4(\mu_\chi^2 - d_\chi^2)\mathrm{m}_\chi^2q^2]$$

$$+2\left(4(p_1k_2)(p_2k_1) + 4(p_1k_1)(p_2k_2) - \frac{4(qp_2)(p_1k_2)(qk_1)}{m_{\gamma'}^2}\right.$$

$$-\frac{4(qp_2)(p_1k_1)(qk_2)}{m_V^2} - \frac{4(qp_1)(p_2k_2)(qk_1)}{m_V^2} - \frac{4(qp_1)(p_2k_1)(qk_2)}{m_V^2}$$

$$\left.+4\left(\frac{2(qp_1)(qp_2)}{m_V^4} - [(\mathrm{p_1p_2}) + m_l^2]\left(-\frac{2}{m_V^2} + \frac{q^2}{m_V^4}\right)\right)(qk_2)(qk_1) - 4[(\mathrm{p_1p_2}) + m_l^2](k_1k_2)\right)[-4(\mu_\chi^2 + d_\chi^2)q^2]$$

$$+2\left(4(p_2k_1)(p_1q) + 4(p_1k_1)(p_2q) - \frac{4(qp_2)(qk_1)(p_1q)}{m_V^2}\right.$$

$$-\frac{4(qp_2)(p_1k_1)q^2}{m_V^2} - \frac{4(qp_1)(qk_1)(p_2q)}{m_V^2} - \frac{4(qp_1)q^2(p_2k_1)}{m_V^2}$$

$$\left.+4\left(\frac{2(qp_1)(qp_2)}{m_V^4} - [(\mathrm{p_1p_2}) + m_l^2]\left(-\frac{2}{m_V^2} + \frac{q^2}{m_V^4}\right)\right)q^2(qk_1) - 4[(\mathrm{p_1p_2}) + m_l^2](qk_1)\right)[4(\mu_\chi^2 + d_\chi^2)(k_2q)]$$

$$+\left(8(p_1q)(p_2q) - \frac{8(qp_2)q^2(p_1q)}{m_V^2} - \frac{8(qp_1)q^2(p_2q)}{m_V^2}\right.$$

$$+4\left(\frac{2(qp_1)(qp_2)}{m_V^4}-[(\mathrm{p_1p_2})+m_l^2]\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)\right)q^4-4[(\mathrm{p_1p_2})+m_l^2]q^2\Bigg)$$

$$\times[-4(\mu_\chi^2+d_\chi^2)(k_2k_1)+4(\mu_\chi^2-d_\chi^2)\mathrm{m}_\chi^2$$

$$-4(\mu_\chi^2+d_\chi^2)(k_2k_1)+4(\mu_\chi^2-d_\chi^2)m_\chi^2+4(\mu_\chi^2+d_\chi^2)(k_2k_1)-4(\mu_\chi^2-d_\chi^2)m_\chi^2]\,. \qquad (3)$$

In case of both the l^+ and l^- beams are polarized, we have

$$|M_{LL}|^2=|M_{RR}|^2=\left(\frac{e\varepsilon^2}{q^2-m_V^2}\right)^2\times\Bigg(4(p_1k_2)(p_2q)+4(p_1q)(p_2k_2)-\frac{4(qp_2)q^2(p_1k_2)}{m_V^2}$$

$$-\frac{4(qp_2)(p_1q)(k_2q)}{m_V^2}-\frac{4(qp_1)q^2(p_2k_2)}{m_V^2}-\frac{4(qp_1)(k_2q)(p_2q)}{m_V^2}$$

$$+4\left(\frac{2(qp_1)(qp_2)}{m_V^4}-(\mathrm{p_1p_2})\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)\right)q^2(k_2q)-4(\mathrm{p_1p_2})(k_2q)\Bigg)[8(\mu_\chi^2+d_\chi^2)(qk_1)-4(\mu_\chi^2+d_\chi^2)(k_1q)]$$

$$+\Bigg(4(p_1p_2)+4(p_1p_2)-\frac{4(qp_2)(qp_1)}{m_V^2}-\frac{4(qp_2)(qp_1)}{m_V^2}-\frac{4(qp_1)(q\ p_2)}{m_V^2}-\frac{4(qp_1)(qp_2)}{m_V^2}$$

$$+4\left(\frac{2(qp_1)(qp_2)}{m_V^4}-(\mathrm{p_1p_2})\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)\right)q^2-4(\mathrm{p_1p_2})4\Bigg)$$

$$\times[-8(\mu_\chi^2+d_\chi^2)(qk_1)(k_2q)+[4(\mu_\chi^2+d_\chi^2)q^2(k_2k_1)-4(\mu_\chi^2-d_\chi^2)\mathrm{m}_\chi^2q^2]$$

$$+2\Bigg(4(p_1k_2)(p_2k_1)+4(p_1k_1)(p_2k_2)-\frac{4(qp_2)(p_1k_2)(qk_1)}{m_V^2}$$

$$-\frac{4(qp_2)(p_1k_1)(qk_2)}{m_V^2}-\frac{4(qp_1)(p_2k_2)(qk_1)}{m_V^2}-\frac{4(qp_1)(p_2k_1)(qk_2)}{m_V^2}$$

$$+4\left(\frac{2(qp_1)(qp_2)}{m_V^4}-(\mathrm{p_1p_2})\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)\right)(qk_2)(qk_1)-4(\mathrm{p_1p_2})(k_1k_2)\Bigg)\times[-4(\mu_\chi^2+d_\chi^2)q^2]$$

$$+2\Bigg(4(p_2k_1)(p_1q)+4(p_1k_1)(p_2q)-\frac{4(qp_2)(qk_1)(p_1q)}{m_V^2}$$

$$-\frac{4(qp_2)(p_1k_1)q^2}{m_V^2}-\frac{4(qp_1)(qk_1)(p_2q)}{m_V^2}-\frac{4(qp_1)q^2(p_2k_1)}{m_V^2}$$

$$+4\left(\frac{2(qp_1)(qp_2)}{m_V^4}-(\mathrm{p_1p_2})\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)\right)q^2(qk_1)-4(\mathrm{p_1p_2})qk_1\Bigg)\times[4(\mu_\chi^2+d_\chi^2)(k_2q)]$$

$$+\Bigg(8(p_1q)(p_2q)-\frac{8(qp_2)q^2(p_1q)}{m_V^2}-\frac{8(qp_1)q^2(p_2q)}{m_V^2}$$

$$+4\left(\frac{2(qp_1)(qp_2)}{m_V^4}-(\mathrm{p_1p_2})\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)\right)q^4-4(\mathrm{p_1p_2})q^2\Bigg)$$

$$\times[-4(\mu_\chi^2+d_\chi^2)(k_2k_1)+4(\mu_\chi^2-d_\chi^2)\mathrm{m}_\chi^2$$

$$-4(\mu_\chi^2+d_\chi^2)(k_2k_1)+4(\mu_\chi^2-d_\chi^2)m_\chi^2+4(\mu_\chi^2+d_\chi^2)(k_2k_1)-4(\mu_\chi^2-d_\chi^2)m_\chi^2],$$

$$M_{\mathrm{RR}}^+M_{LL}=\left(\frac{e\varepsilon^2}{q^2-m_V^2}\right)^2\times 4\left(-m_l^2\left(-\frac{2}{m_V^2}+\frac{q^2}{m_V^4}\right)q^2(k_2q)-m_l^2(k_2q)\right)$$

$$[8(\mu_\chi^2+d_\chi^2)(qk_1)-4(\mu_\chi^2+d_\chi^2)(k_1q)]$$

$$+4\left(-m_l^2\left(-\frac{2}{m_{\gamma'}^2}+\frac{q^2}{m_{\gamma'}^4}\right)q^2-m_l^2\right)[-8(\mu_\chi^2+d_\chi^2)(qk_1)(k_2q)+[4(\mu_\chi^2+d_\chi^2)q^2(k_2k_1)-4(\mu_\chi^2-d_\chi^2)\mathrm{m}_\chi^2q^2]$$

$$+2\times 4\left(-m_l^2\left(-\frac{2}{m_{\gamma'}^2}+\frac{q^2}{m_{\gamma'}^4}\right)(qk_2)(qk_1)-m_l^2(k_1k_2)\right)[-4(\mu_\chi^2+d_\chi^2)q^2]$$

$$+2\times 4\left(-m_l^2\left(-\frac{2}{m_{\gamma'}^2}+\frac{q^2}{m_{\gamma'}^4}\right)q^2(qk_1)-m_l^2(qk_1)\right)[4(\mu_\chi^2+d_\chi^2)(k_2q)]$$

$$+4\left(-m_l^2]\left(-\frac{2}{m_{\gamma'}^2}+\frac{q^2}{m_{\gamma'}^4}\right)q^4-m_l^2q^2\right)[-4(\mu_\chi^2+d_\chi^2)(k_2k_1)+4(\mu_\chi^2-d_\chi^2)\mathrm{m}_\chi^2$$

$$-4(\mu_\chi^2+d_\chi^2)(k_2k_1)+4(\mu_\chi^2-d_\chi^2)m_\chi^2+4(\mu_\chi^2+d_\chi^2)(k_2k_1)-4(\mu_\chi^2-d_\chi^2)m_\chi^2] \qquad (4)$$

and $\quad |M_{LR}|^2=|M_{RL}|^2=M_{LR}^+M_{RL}=0$.

From the square of matrix elements above, we evaluate the differential cross section (DCS) as a function of $\cos\theta$ by the expression:

$$\frac{d\sigma}{d\cos\theta}=\frac{1}{64\pi s}\frac{|\vec{k}_1|}{|\vec{p}_1|}|M|^2. \qquad (5)$$

The results are shown in Figure 3 for $e^+e^-\to\bar{\chi}\chi$.

Here we choose $m_e=0$, 0 G ; $m_\mu=0{,}1068MeV$; $m_\chi=30MeV$; $m_V=10^{-3}GeV$; $\mu_\chi=\frac{1}{\lambda_\mu}$, $\lambda_\mu=2{,}3.10^{10}GeV$; $d_\chi=\frac{1}{\lambda_d}$, $\lambda_d=2{,}26.10^{10}GeV$ [4]; $\varepsilon=10^{-12}$ [5], $\sqrt{s}=3000GeV$ (CLIC).

We see that the DCS is unchanged when $\cos\theta$ changes from -1 to 1 in the cases of the e^+,e^- beams are unpolarized, and as well as left-polarized or right-polarized. Therefore, the direction to collect $\bar{\chi},\chi$ is the same for direction to the e^+,e^- beams.

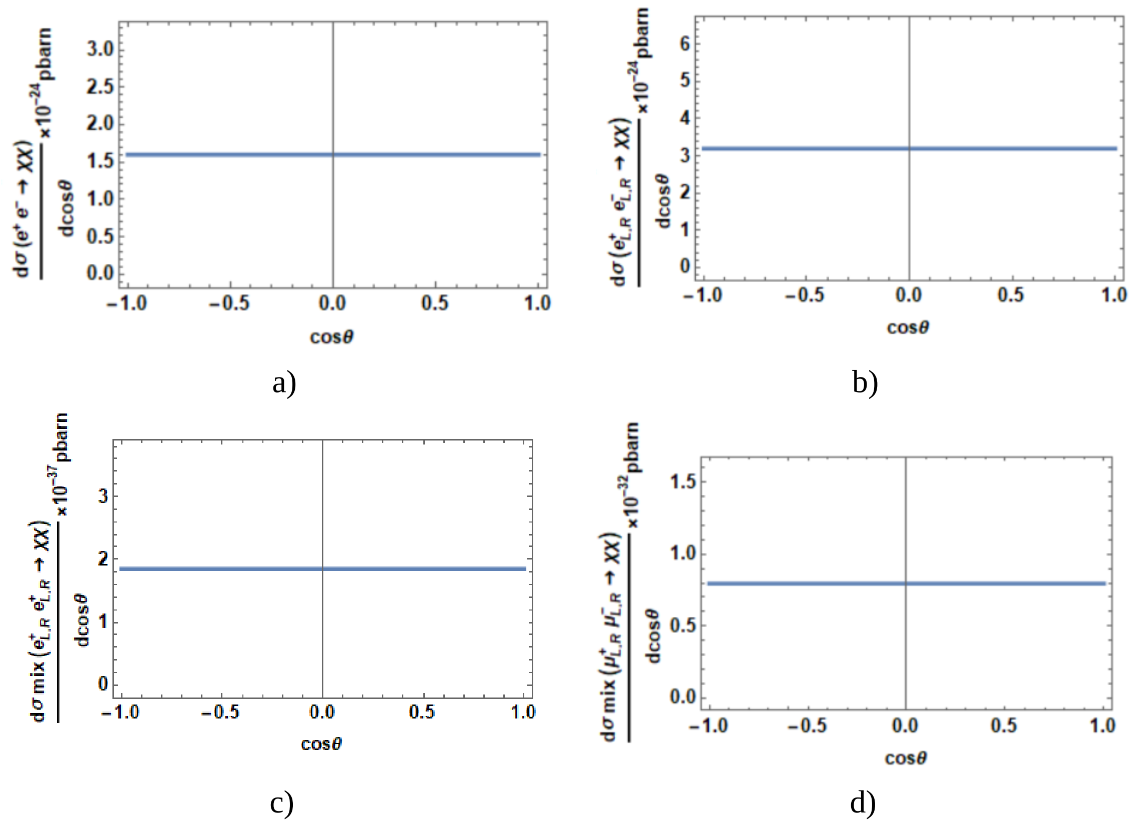


Figure 3. The DCS as a function of $\cos\theta$

Next, we proceed to evaluate the total cross section of these colliders as function of mass center energy $\sqrt{s}$, it is shown in Figure 4.

The cross section increases while $\sqrt{s}$ increases from $200GeV$ to $3000GeV$ for the e^+, e^- beams unpolarized, and as well as left- or right-polarized. While, the mixing cross section decreases, it can see from figure 3.3d. In addition, when the e^+, e^- beams are left - polarized or right-polarized, the cross-section is twice times as large as the cross-section when the e^+, e^- beams are unpolarized. This is shown in figure 3.3a and figure 3.3b.

For the $\mu^+\mu^- \to \bar{\chi}\chi$ cross section, we obtained the results the same for the $e^+e^- \to \bar{\chi}\chi$, the cross section when the initial beams are unpolarized or both the initial beams are left - polarized or right - polarized. In case of mix between both the initial beams are left-polarized with both the initial beams are right-polarized, from figure 3.2 c, d and figure 3.3 c, d, we can see that the $\mu^+\mu^- \to \bar{\chi}\chi$ cross-section is very much bigger than the $e^+e^- \to \bar{\chi}\chi$ cross-section.

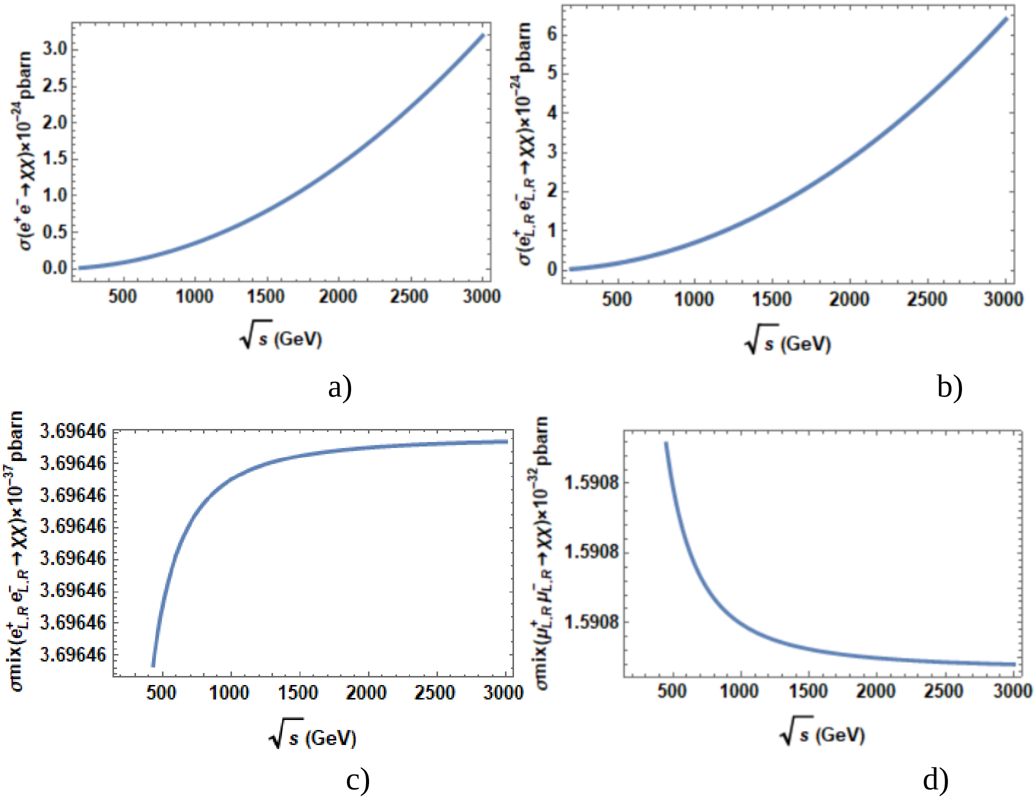


Figure 4. The cross – section as a function of $\sqrt{s}$

3. Conclusions

The cross sections of the process $l^+l^- \to \bar{\chi}\chi$ depend strongly on the polarization of initial beams. The direction to collect $(\bar{\chi},\chi)$ do not depend on the direction of the l^+,l^- beams. The cross section increases when $\sqrt{s}$ increases for left or right-polarized and unpolarized of l^+, l^- beams. The cross-section is very small, however, we maybe search for DM particles from l^+,l^- collisions if interactive energy is large enough.

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