AXINO PRODUCTION IN $e^+e^-$ AND $\gamma\gamma$ COLLISIONS

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Abstract

Production of axinos and photinos in $e^+e^-$ and $\gamma\gamma$ collisions is calculated and estimated. It is shown that there is an upper limit of the cross section for the process $e^-e^+ \rightarrow \tilde{a}\tilde{\gamma}$ dependent only on the breaking scale. For the process $\gamma\gamma \rightarrow \tilde{a}\tilde{\gamma}$, there is a special direction in which axinos are mainly produced. Behaviour of cross section for this process is also analysed. Based on the result a new constraint for $F/N$ is derived: $\frac{F}{N} \geq 10^{12}$ GeV.

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December 2000

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Axinos - supersymmetric partners of axions [1–3] are predicted in low-energy supersymmetry and the Peccei-Quinn (PQ) solution. The axino is an electrically and color neutral particle with mass highly dependent of the models [4–6]. In a large class of supersymmetric axion models [5] the mass of axino is predicted in the region $m_a \leq O(1)$ keV, which is cosmologically harmless [6] (if axinos are heavier than a few keV they have to decay fast enough not to upset any standard prediction of big-bang cosmology). In these models the axino $a$ is the lightest supersymmetric particle (LSP), which is stable and may contribute to the present mass density of the Universe, as dark matter. There are good reasons to suspect that most of the mass of the Universe is in some exotic and hitherto unknown dark form (the dark matter and dark energy) contribute about $80 \pm 20\%$ of the critical density [7]. Thus axinos are very strongly motivated.

The possible consequences of the presence of axino is a subject of this study. In this paper we consider the processes in which the axinos are mainly produced in, namely in $e^+e^-$ and in $\gamma\gamma$ collisions. In our opinion, the considered collision is one of the many promising processes which can be studied in the exiting collider project CLIC designed at the CERN with operating energy at a range of 3 TeV.

As usual, we start with a piece

$$\left( \phi \overline{W}_\alpha W^\alpha \right)_{\theta\theta} + \left( \phi^* \overline{W}^\alpha W_{\alpha} \right)_{\theta\theta},$$

where $\phi = \sigma + ia + \sqrt{2}\theta a + \theta^2 F_\phi$. Here $a$ denotes an axion, $\sigma$ a saxion, and $\bar{a}$ an axino. Then a relevant Lagrangian of axino - photino - photon coupling is given [6,8]

$$\mathcal{L}_{\bar{a}\gamma\gamma} = \frac{\alpha N}{8\pi F} \left[ \bar{\chi} \gamma^\mu \gamma^\nu (1 - \gamma_5) \bar{a} F_{\mu\nu} + h.c. \right],$$

where $N$ is a number of inequivalent vacua [9] (for type I (KSVZ) models [2], $N = 1$, while for type II (DFSZ) models [3], $N = 6$) and $F$ is the PQ breaking scale. Collider and astrophysics constraints require roughly [10]

$$\frac{F}{N} \geq 10^9 \text{ GeV.}$$

The above couplings are valid at energy scales between the PQ symmetry breaking scale $F$ and the electroweak symmetry breaking scale.

From (2) we get an axino - photino - photon vertex as follows.
With the help of this vertex, an axino can be produced in pair with an antiphotino ($\tilde{\gamma}^c$) in the $e^+e^-$ collision through s-channel photon exchange. A pair of axino - antiaxino ($\tilde{a}\tilde{a}^c$) can be produced in the $\gamma\gamma$ scattering via $t$-channel photino exchange.

Now let us first consider a process in which the initial state contains the electron and the positron and in the final state there are the axino and the antiphotino:

$$e^-(p_1) + e^+(p_2) \rightarrow \tilde{a}(k_1) + \tilde{\gamma}^c(k_2),$$

in which the letters in parentheses stand for the momenta of the particles. This process proceeds through the s-channel photon exchange.

Amplitude for this process is given by

$$\mathcal{M}(e^-e^+ \rightarrow \tilde{a}\tilde{\gamma}^c) = \left(\frac{\epsilon\alpha N}{4\pi F q^2}\right) \bar{\psi}(p_2)\gamma_\mu u(p_1)\bar{u}(k_1)(1 + \gamma_5)\gamma^\mu - k_1^\mu - k_2^\mu]v(k_2),$$

where $q = p_1 + p_2$.

The straightforward calculation yields the following differential cross section (DCS) in the center-of-mass frame

$$\frac{d\sigma(e^-e^+ \rightarrow \tilde{a}\tilde{\gamma}^c)}{d\cos \theta} = \frac{\alpha^3 N^2}{32\pi^2 F^2 s^{3/2}} \left[ s^2 + \frac{\sqrt{s}}{2} (m_\gamma^2 - m_\tilde{a}^2)(E_1 - E_2) - s(E_1 E_2 + k^2 \cos^2 \theta) \right],$$

where $\theta$ is the angle between $\vec{p}_1$ and $\vec{k}_1$, $k = |\vec{k}_1| = |\vec{k}_2|$. $E_1$ and $E_2$ are energy of the initial electron and of the final axino and antiphotino, respectively. The value $k$ can be expressed in terms of the usual variable $s \equiv q^2$ as follows

$$k = \sqrt{\frac{1}{s} \left[ \frac{1}{4}(s - m_\tilde{a}^2 - m_\gamma^2)^2 - m_\tilde{a}^2 m_\gamma^2 \right]}. $$

The momentum of outgoing particle vanishes at threshold

$$s_c = (m_\gamma + m_\tilde{a})^2.$$
Figure 2: DCS for $e^-e^+ \rightarrow \tilde{\chi} \tilde{\chi}$ (the solid curve) and reduced $e^-e^+ \rightarrow \mu^-\mu^+$ in QED (the dashed curve) as a function of $\cos \theta$ at $\sqrt{s} = 200$ GeV.

Figure 3: Cross section $\sigma(e^-e^+ \rightarrow \tilde{\chi} \tilde{\chi})$ as a function of $\sqrt{s}$. The solid curve refers to photino mass equal to 100 GeV, the dashed curve - 200 GeV.

For the sake of certainty, hereafter in our estimation, mass of the axino is assumed to be 0.5 GeV and $F/N = 10^{10}$ GeV. In figure 2 we plot the DCS by $\cos \theta$ (the solid curve). To see the difference, we also plot the reduced by $10^{21}$ cross section for $e^-e^+ \rightarrow \mu^-\mu^+$ in the QED framework (the dashed curve). As we can see from the figure, our curve is a downward parabola (maximum at $\cos \theta = 0$), while the QED value is an upward parabola (minimum at $\cos \theta = 0$).

After integration over $\cos \theta$ the total cross section takes a form

$$\sigma(e^-e^+ \rightarrow \tilde{\chi} \tilde{\chi}) = \frac{\alpha^2N^2}{32\pi^2F^2} \frac{k}{s^{5/2}} \left[ s^2 + \sqrt{s}(m_2^2 - m_3^2)(E_1 - E_3) - s \left( 2E_1E_2 + \frac{2k^2}{3} \right) \right]. \quad (9)$$

It must be emphasized that if $\sqrt{s}$ tends to infinity the QED cross section tends to zero, while from Eq. (9) we get an upper limit

$$\lim_{\sqrt{s} \rightarrow \infty} \sigma(e^-e^+ \rightarrow \tilde{\chi} \tilde{\chi}) = \frac{\alpha^2N^2}{192\pi^2F^2} \approx 2.1 \times 10^{-6} \text{bar for } F/N = 10^{10} \text{ GeV.} \quad (10)$$

Behaviour of $\sigma(e^-e^+ \rightarrow \tilde{\chi} \tilde{\chi})$ as a function of $\sqrt{s}$ is shown in figure 3. It should be noted that when $\sqrt{s}$ tends to zero, the cross section tends to an upper limit but not zero as in the QED. This upper limit is independent of both axino and photino masses. Taking into account of negative searches and the present experimental limit ($\sigma^{exp} = 5 \times 10^{-5} \text{nb}$) based on the following
Figure 4: $d\sigma(\gamma\gamma \to \tilde{a}\tilde{a}^c)/d\cos \theta$ as a function of $\cos \theta$ at $\sqrt{s} = 100$ GeV. The left figure refers $\cos \theta \in [0 \pm 0.93]$, the right figure for $\cos \theta \in [0 \pm 1]$.

data: luminosity $\simeq 10^{31}$ (of LEP I), 5 events per year ($1 \text{ year} \sim 10^7 \text{ s}$). As we can see from figure 3, in order to be consistent with present collider constraints the value $\delta_N$ has to be bigger than $10^{14}$ GeV. With the CLIC luminosity designed to be $10^{33}$, should the collider experiment show the negative result then $F/N$ has to be bigger than $10^{15}$ or so.

Now we turn to the second process

$$\gamma(p_1) + \gamma(p_2) \to \tilde{a}(k_1) + \tilde{a}^c(k_2).$$

(11)

Process (11) is mediated by a virtual photino in the $t$-channel.

Amplitude for the process is given

$$M(\gamma\gamma \to \tilde{a}\tilde{a}^c) = \left(\frac{\alpha N}{4\pi F}\right)^2 \frac{1}{(l^2 - m_{\tilde{a}}^2)} \epsilon_\mu(p_1)\epsilon_\nu(p_2) \bar{u}(k_1)\gamma^\mu(1 + \gamma_5)\gamma^\nu p_2 v(k_2),$$

(12)

where $l = k_1 - p_1$, and the transversality between momentum and polarization of the photons is used.

The computation is long but straightforward and gives DCS in center-of-mass frame

$$\frac{d\sigma(\gamma\gamma \to \tilde{a}\tilde{a}^c)}{d\cos \theta} = \frac{\alpha^4 N^4}{512\pi^3 F^4 (l^2 - m_{\tilde{a}}^2)^2} \left(\frac{\sqrt{s}}{2} - t \cos \theta\right)^2 \left(\frac{s}{4} - t^2 \cos^2 \theta + m_{\tilde{a}}^2\right),$$

(13)

where $t \equiv |k_1| = |k_2| = (\frac{1}{4} - m_{\tilde{a}}^2)^{1/2}$ is an absolute strength of momentum of the outgoing axino and $l^2 = m_{\tilde{a}}^2 + \sqrt{s} (t \cos \theta - \frac{s}{s})$.

It is easy to see that the DCS (13) has a single pole at

$$\cos \theta_p = \frac{1 + \frac{2}{s}(m_{\tilde{a}}^2 - m_{\tilde{a}}^2)}{\sqrt{1 + \frac{4m_{\tilde{a}}^2}{s}}}.$$  

(14)

From (14) it follows that if $\sqrt{s}$ tends to infinity the scattering angle $\theta_p$ tends to zero.

In figure 4 we plot the DCS $\frac{d\sigma(\gamma\gamma \to \tilde{a}\tilde{a}^c)}{d\cos \theta}$ as a function of $\cos \theta$ at a value $\sqrt{s} = 100 \text{ GeV}$. The solid curve corresponds to photino mass equal 100 GeV. As we can see from the figure, axinos are produced mainly at the direction determined by (14), for example $\theta \sim 0$ for $s \gg m_{\tilde{a}}^2$, $m_{\tilde{a}}^2$. 

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After taking integration over $\cos \theta$, the total cross section looks as follows

$$\sigma(\gamma \gamma \rightarrow \tilde{a} \tilde{a}) = \left( \frac{1}{3\pi} \right) \left( \frac{\alpha N}{4\pi F} \right)^4 \frac{t}{s^{3/2}} \left\{ \frac{3s^2}{4} - st^2 - 3sm_0^2 + \frac{9s}{2}m_a^2 - 9(m_a^2 - m_0^2)^2 + \frac{3}{2\sqrt{s}} \left[ 3s(m_a^2 - m_0^2)^2 - 2sm_0^2(m_a^2 - m_0^2)^2 + 4(m_a^2 - m_0^2)^3 \right] \times \log \left( \frac{s + \sqrt{st} + m_0^2}{s - \sqrt{st} + m_0^2} \right) \right\}. \quad (15)$$

In figure 5 we plot $\sigma(\gamma \gamma \rightarrow \tilde{a} \tilde{a})$ as a function of $\sqrt{s}$ at two values of the photino masses: the solid curve refers to $m_\gamma = 100$ GeV and the dashed curve - 120 GeV. As we can see from the left figure, the curves get peak at low energy region (around 2 GeV) go through the minimum value, after that smoothly increase (see the right figure).

Due to smallness of the coupling constant it seems that the tree-graph expressions are sufficient and appropriate. It is difficult to imagine practical laboratory experiments, however the considered $\gamma \gamma$ collision may play an important role in cosmology.

In summary, we have calculated the testable production of the axino and the antiphotino at high energy $e^+e^-$ colliders. We have seen that when $\sqrt{s}$ tends to infinity the total cross section has the upper bound dependent only on the value $F/N$. We have got the new limit $F/N \geq 10^{14}$ GeV, which is higher than the present estimation. In principle the considered process should be seen at the CLIC unless $F/N \geq 10^{15}$ GeV. We have also considered $\gamma \gamma \rightarrow \tilde{a} \tilde{a}$ which has an important role in cosmology. The total cross section for this process has maximum and minimum at low energy after that increases monotonously.
Acknowledgments

The authors are grateful to Prof. A. Pukhov for information on the present experimental data. They also thank the AS-ICTP for financial support and hospitality extended to them. One of them (D. V. S.) thanks the INFN for financial help. He would like to thank Prof. A. Masiero for very helpful discussions and warm hospitality at the SISSA. This work was supported in part by the Natural Science Council of Vietnam.

References


