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Probing axino LSP from diphoton events with large missing transverse energy

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ABSTRACT

In a supersymmetry model with an axino as the lightest supersymmetric particle (LSP) and a Bino as the next LSP (NLSP), supersymmetric particle production ends up with including two Binos, followed by each Bino's decaying into a photon and an axino. Final states are diphoton with large missing energy. In a benchmark scenario, we have comprehensively studied the implication of $\gamma\gamma + \not{E}_{(T)}$ data from the ALEPH, CDF II, ATLAS and CMS experiments. No excess over the standard model backgrounds can be explained in this model if the Bino NLSP decays outside the detector. Long life time of the Bino is possible because of high Peccei–Quinn symmetry breaking scale f_a. The ALEPH and CDF II data put a very strong bound on f_a for light Bino case with $m_{\widetilde{B}} \lesssim 150$ GeV: the narrow hadronic axion window around $f_a \sim 10^6$ GeV is completely closed. The recent ATLAS and CMS data show very interesting bound on $f_a \gtrsim 10^5$ GeV for the Bino mass below 700 GeV. This is already stronger than the previous laboratory bounds.

Impressive performance of the LHC in its early operation escalates our expectation to reveal the secrets of the universe. One of the most profound mysteries is the identity of the dark matter (DM). In particle physics, the DM is usually explained by a weakly interacting stable particle with a well-motivated symmetry for new physics beyond the standard model (SM). If this DM particle is produced at a high energy collider, it escapes detection and leaves the signal of missing energy. In order to obtain the missing energy information, we need to measure the four-momenta of accompanying SM particles. An isolated photon is a good candidate for this role.

Recently the ATLAS and CMS Collaborations have reported the search for diphoton events with large missing transverse energy $\not{E}_T$ based on the LHC data at $\sqrt{s} = 7$ TeV [1–4]. No excess above the SM backgrounds has been found. Together with the previous results from LEP2 [5–7] and CDF II [8,9], these events constrain new physics models which predict $\gamma\gamma + \not{E}_T$ signal. One good example is the minimal supersymmetric standard model (MSSM) with the gauge mediated supersymmetry breaking (GMSB). In this model, the light gravitino $\widetilde{G}$ is the lightest supersymmetric particle (LSP). A supersymmetric (SUSY) particle eventually decays into the next-LSP (NLSP), and the NLSP sequentially decays into a gravitino and a SM particle. In most parameter space, the NLSP is the Bino, and the Bino decays almost exclusively into a photon and a gravitino. With R parity conservation, SUSY particles are always produced in pairs. Therefore all the SUSY final states include two photons plus missing energy carried by two gravitinos. In this regard, the experiments of Refs. [1–9] provide bounds on the lifetime and mass of the Bino in the GMSB models [10–12].

Another interesting new physics model for the diphoton events plus large $\not{E}_T$ is the SUSY model with axino LSP [13]. This model is motivated in order to solve the strong CP problem. It introduces an axion superfield with the Peccei–Quinn (PQ) symmetry. In addition to the MSSM particle contents, we have an axion and its superpartner axino. This axino can be very light with mass about 10 MeV [14,15]. Then as in the GMSB model, the NLSP Bino decays into an axino and a photon. The final states include two photons with missing energy. The $\gamma\gamma + \not{E}_T$ data can have significant implications on this axino-LSP and Bino-NLSP model. This is our main goal.

Let us begin with a brief review on the axion field. The strong CP problem arises from the strong CP odd term of

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^a_{\mu\nu}, \qquad (1)$$

where $G^a_{\mu\nu}$ is the field strength of a gluon. The absence of neutron electric dipole moment leads to extremely small value of θ: $|\theta| \lesssim 0.7 \times 10^{-11}$ [16]. It requires to be explained by some symmetry argument. One way is replacing θ as a dynamical field $\theta(x) = a(x)/f_a$, where $a(x)$ is an extremely weakly interacting pseudoscalar field, called an axion, and f_a is the axion decay constant. The effective Lagrangian for the axion field is

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\left(\frac{g_s^2}{32\pi^2} G^{a\mu\nu}\widetilde{G}^a_{\mu\nu} + C_{a\gamma}\frac{e^2}{32\pi^2} F^{\mu\nu}\widetilde{F}^{\mu\nu}\right), \qquad (2)$$

where $|C_{a\gamma}| \sim 1$ is a model-dependent parameter.

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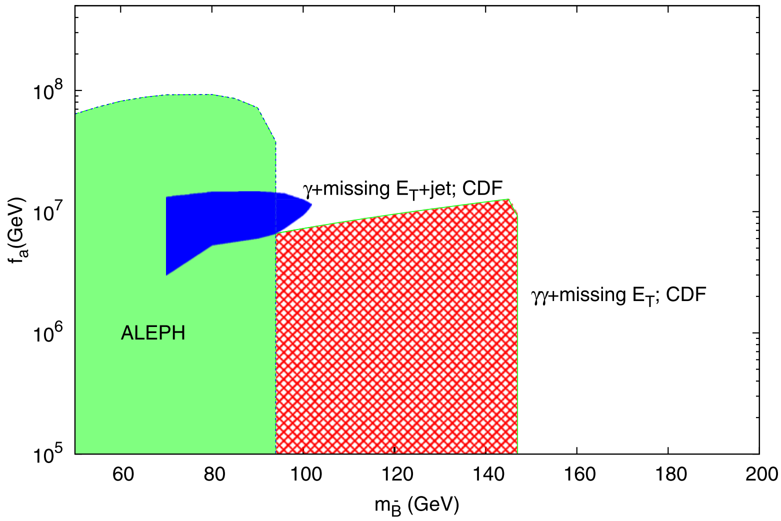

Fig. 1. Excluded region in the parameter space of $(m_{\tilde{B}}, f_a)$ by ALEPH $\gamma\gamma + \not{E}_T$, CDF $\gamma\gamma + \not{E}_T$ and CDF $\gamma + \not{E}_T +$ jet data. We set $C_{aY} = 5/3$ and the benchmark scenario in Eq. (11).

After the QCD phase transition, the axion acquires the mass of

$$m_a = \frac{\sqrt{z}}{1+z}\frac{f_\pi m_\pi}{f_a}, \tag{3}$$

where $z = m_u/m_d$, f_π is the pion decay constant, and m_π is the pion mass. The axion–photon interaction can be rewritten as

$$L_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu}, \tag{4}$$

where $g_{a\gamma\gamma} = \alpha C_{a\gamma}/(2\pi f_a)$.

In the literature, there are two popular models for a very light and weakly interacting axion, the hadronic axion model [17,18] and the DFSZ axion model [19,20]. Current laboratory bound on the axion decay constant is $f_a \gtrsim 10^4$ GeV. Much stronger bound comes from the astrophysical and cosmological searches such that 10^9 GeV $\lesssim f_a \lesssim 10^{12}$ GeV [16,21]. Below this cosmological bound, still survives a very narrow but interesting range around $f_a \sim 10^6$ GeV, called the hadronic axion window [22].

We consider the hadronic axion model with supersymmetry [23]. In our model, the axion interaction is described by the following superpotential:

$$W = y\Phi Q_1 Q_2, \tag{5}$$

where $\Phi = \phi + \sqrt{2}\chi\theta + F_\Phi\theta\theta$ is the axion superfield, and $Q_{1,2}$ are $SU(2)_L$ singlet heavy quark superfields. The vacuum expectation value $\langle\phi\rangle = f_a/\sqrt{2}$ is the PQ symmetry breaking scale. The complex field ϕ consists of the real-scalar saxion field s and the pseudo-scalar axion field a. The axino field is

$$\tilde{a} = \begin{pmatrix} \chi \\ \bar{\chi} \end{pmatrix}. \tag{6}$$

The mass of axino is model-dependent. An interesting possibility connected with the DM is that the axino can be significantly lighter than other SUSY particles, and becomes the LSP [24,25]. In the no-scale supergravity model, for example, the axino mass is generated through one-loop diagrams:

$$m_{\tilde{a}} \simeq \frac{1}{16\pi^2} y^2 m_{\text{SUSY}}, \tag{7}$$

where m_{SUSY} is the induced SUSY breaking soft mass. If $y \simeq 0.1$ and $m_{\text{SUSY}} \simeq 100$ GeV, we have $m_{\tilde{a}} \sim 10$ MeV. If the axino is the LSP, then the NLSP will decay into an axino and a SM particle. Hereafter we consider the case where the axino is the LSP and the Bino is the NLSP.

The axino field has the interaction vertices with $\tilde{g}g$ and $\widetilde{B}\gamma$ at one-loop level, mediated by two $SU(2)_L$ singlet heavy quarks U and D in a simple model. The electromagnetic charges of U and D are $2/3$ and $-1/3$ respectively. The effective Lagrangian is

$$\mathcal{L}_{\tilde{a}\tilde{g}g} = \frac{\alpha_s}{8\pi f_a}\bar{\tilde{a}}\gamma_5\sigma^{\mu\nu}\tilde{g}^a G^a_{\mu\nu},$$
$$\mathcal{L}_{\tilde{a}\widetilde{B}B} = \frac{\alpha}{8\pi\cos^2\theta_W}\frac{C_{aY}}{f_a}\bar{\tilde{a}}\gamma_5\sigma_{\mu\nu}\widetilde{B}\left[\cos\theta_W F^{\mu\nu} - \sin\theta_W Z^{\mu\nu}\right], \tag{8}$$

where $C_{aY} = 5/3$ if the number of U quarks is the same as that of D quarks [21,23], and θ_W is the electroweak mixing angle.

At the LHC, axinos are produced as decay products of gluinos and Binos. However the decay rate $\Gamma(\tilde{g} \to g\tilde{a})$, which is proportional to $m^3_{\tilde{g}}/f^2_a$, is extremely suppressed by large value of $f_a \gtrsim 10^4$ GeV. Other decay channels of the gluino through strong and/or electroweak interactions have much larger decay rates, and thus make $\text{Br}(\tilde{g} \to \tilde{a}g)$ negligible.

The Bino NLSP is different. Only allowed is its decay into an axino: no matter how small its decay rate is, the branching ratio of $\text{Br}(\widetilde{B} \to \tilde{a}\gamma)$ is almost 100%. The decay width of $\widetilde{B} \to \tilde{a}\gamma$ is given by

$$\Gamma(\widetilde{B} \to \tilde{a}\gamma) = \frac{\alpha^2}{128\pi^3}\frac{C^2_{aY}}{f^2_a\cos^2\theta_W} m^3_{\widetilde{B}}, \tag{9}$$

which leads to the lifetime of Bino as

$$\tau_{\widetilde{B}} \simeq 0.038\left(\frac{100\ \text{GeV}}{m_{\widetilde{B}}}\right)^3\left(\frac{f_a/C_{aY}}{10^6\ \text{GeV}}\right)^2\ \text{ns}. \tag{10}$$

In the axino-LSP and Bino-NLSP scenario, therefore, SUSY particle production leads to the final states of diphoton and missing E_T, accompanied by SM particles. This process is phenomenologically identical to that of the GMSB model.

As comprehensively summarized in Figs. 1 and 2, we study the implications of the diphoton events plus missing energy by the ALEPH, CDF, ATLAS and CMS experiments. All of the results are consistent with the SM backgrounds. There are two interpretations for this null result. First is that the new physics scale is too high to yield an excess over the backgrounds. The new physics cross section is too small. An alternative interpretation is possible in our

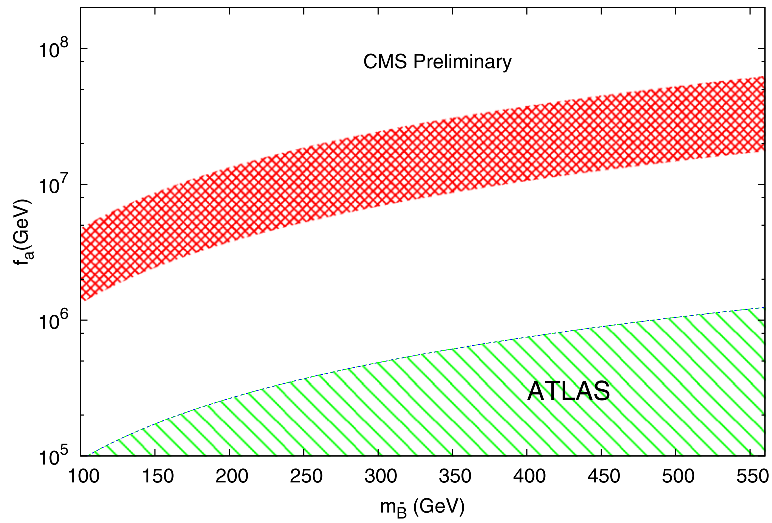

Fig. 2. Excluded region in the parameter space of $(m_{\widetilde{B}}, f_a)$ by the ATLAS $\gamma\gamma + \not{E}_T$ data and the CMS preliminary $\gamma\gamma + \not{E}_T$ + jet data. We assume that the inclusive production cross section of Bino is large enough for both ATLAS and CMS.

scenario. Binos are produced enough but they decay outside the detector so that we do not see $\gamma\gamma + \not{E}_T$ signal. This interpretation is possible because of very high scale of f_a. In this Letter, we take the second interpretation.

We specify our model in more detail. Since main production channels of the Bino pair at a hadron collider are the cascade decays from gauginos, gluinos, and squarks, the results are sensitive to their mass parameters. For simplicity, we take the following SUSY particle mass spectra:

$$m_{\widetilde{\chi}_2^0} \simeq m_{\widetilde{\chi}_1^\pm} \simeq 1.8 m_{\widetilde{B}}, \qquad m_{\widetilde{\ell}_R} \simeq 1.1 m_{\widetilde{B}}, \qquad m_{\widetilde{\ell}_L} \simeq 2.5 m_{\widetilde{B}},$$
$$m_{\widetilde{g}} \simeq 800 \text{ GeV}, \qquad m_{\widetilde{q}} \simeq 1.5 \text{ TeV}. \tag{11}$$

The second lightest neutralino $\widetilde{\chi}_2^0$ and the lightest charging $\widetilde{\chi}_1^\pm$ are assumed to be Winos. The gaugino and slepton mass relations with the Bino mass are motivated from the GMSB SPS8 slope. The gluino mass is from the recent CMS searches for the MSSM signal [26]. Note that the slepton masses do not affect the bounds from the CDF, ATLAS, and CMS experiments. One possible concern is that our benchmark scenario may have too light right-handed selectron. This could be excluded by the OPAL data on di-lepton plus missing energy, which provided, at 95% C.L., the exclusion region of the right-handed selectron mass and the LSP mass up to $m_{\widetilde{B}} = 80$ GeV [27]. Our condition of $m_{\widetilde{\ell}_R} \simeq 1.1 m_{\widetilde{B}}$ is marginally allowed.

First, the ALEPH data put a very strong bound on f_a for light Bino case. The ALEPH group searched for the GMSB reaction $e^+e^- \to \widetilde{B}\widetilde{B} \to \widetilde{G}\widetilde{G}\gamma\gamma$ at $\sqrt{s} = 189$–209 GeV with a total integrated luminosity of 628 pb^{-1} [5,7]. Crucial event selection criteria is to demand photons not originating from the primary vertex of the interaction, which is useful for longer Bino lifetime. Our benchmark scenario in Eq. (11) guarantees large enough Bino direct production, which is sensitive to the slepton mass. More general slepton masses, but still not so heavy compared to the Bino mass, result in similar results. No excess of $\gamma\gamma + \not{E}_T$ signal over the SM backgrounds can be allowed if the lifetime of the Bino is long enough. If the Bino decays within the detection reach, our scenario is not consistent with the null result, which excludes small $m_{\widetilde{B}}$ and small f_a. In Fig. 1, we show the exclusion region denoted by "ALEPH". The limited c.m. energy of the LEP2 covers the Bino mass only up to about 94 GeV. In this small Bino mass range, however, the bound on f_a is very stringent: $f_a < 10^8$ GeV is mostly excluded. The narrow hadronic axion window is completely closed for the light Bino case.

The CDF Collaboration also presented their analysis of $\gamma\gamma + \not{E}_T + X$ data, based on 2.6 fb^{-1} total luminosity at $\sqrt{s} = 1.96$ TeV [9]. Here X denotes other high-p_T SM particles. This search is motivated by the GMSB model. Significant improvement on the search sensitivity was made by a new photon timing system in the EM calorimeter, which measures the arrival time of photons [28]. With the tracking device measuring the position and time of the $p\bar{p}$ primary collision, this timing system probes the Bino life time $\tau_{\widetilde{B}}$ up to 2 ns.

Longer Bino lifetime region in $0 < \tau_{\widetilde{B}} < 40$ ns is also covered by CDF experiment through γ + jet + $\not{E}_T$ [8]. This final state is motivated by their reference model, the GMSB SPS8 point. Here the main Bino production channels through gaugino decays are associated with prompt taus whose decays can be identified as jets. Photon arrival time is measured by a timing system in the ECAL. Final states are a high-E_T, isolated, and *delayed* photon with large $\not{E}_T$ and a high-E_T jet. Null results with the integrated luminosity of 570 pb^{-1} have been reported.

In our benchmark scenario, gluinos and squarks are too heavy to have sizable production cross sections at the Tevatron. The produced Binos are mainly from the cascade decays of the gaugino pair production of $\widetilde{\chi}_2^0 \widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_1^+ \widetilde{\chi}_1^-$. The inclusive Bino pair production is large enough for $m_{\widetilde{B}} \lesssim 150$ GeV. If the Bino decays outside the reach of the photon timing system, our scenario is allowed. Heavier Bino case, corresponding to heavier neutral and charged Winos, leads to too small cross section: the CDF data cannot constrain the model. Based on two kinds of CDF data, we exclude the parameter space of $(m_{\widetilde{B}}, f_a)$ in Fig. 1. The CDF data put also strong bound on $f_a \lesssim 10^7$ GeV for 100 GeV $\lesssim m_{\widetilde{B}} < 150$ GeV.

The CMS and ATLAS Collaborations [1–3] have also reported their search for diphoton and missing transverse energy. With the integrated luminosity of 1 fb^{-1} at $\sqrt{s} = 7$ TeV, the ATLAS group presented their analysis of $\gamma\gamma + \not{E}_T$ final states [2]. The ATLAS search is limited for $c\tau_{\widetilde{B}} < 0.1$ mm. At the LHC, multiple collisions from high luminosity make it very challenging to measure the timing separation between the primary collision and the photon arrival. In our model with $\sqrt{s} = 7$ TeV, the gluino pair production becomes also important especially when the Bino mass is large. Following our basic interpretation, the decay of a Bino outside the reach of $c\tau_{\widetilde{B}} < 0.1$ mm is allowed. This excludes the $(m_{\widetilde{B}}, f_a)$ parameter space as in Fig. 2.

The CMS Collaboration also presented their preliminary data of $\gamma\gamma + \not{E}_T +$ jet event at integrated luminosity of 2.1 fb^{-1} [4]. The CMS group applied the photon conversion impact parameter method and searched for long-lived (2 cm $< c\tau_{\tilde{B}} <$ 25 cm) Bino decaying into a photon and a gravitino. The *transverse* impact parameter of a photon to the beam line is measured, which is a robust observable when the true primary vertex is not known because of multiple collisions. As in the CDF II delayed photon detection, this method also measures the delayed photon from long-lived Bino decay. The CMS preliminary results set the upper limits on the Bino inclusive production cross section $\sigma < (0.12 - 0.24)$ pb. In our benchmark model, gluino pair production is the main channel with the total cross section about ~ 100 fb. Based on these upper limits, we exclude the parameter space of $m_{\tilde{B}}$ and f_a, as in Fig. 2. The band structure of the exclusion region is from the limitation of the CMS photon conversion impact parameter method. The ATLAS and CMS data extend the search for larger Bino mass. The bound on f_a is quite significant, which closes a large portion of hadronic axion window $f_a \sim 10^6$ GeV especially when the Bino is heavy.

In conclusion, we obtain the improved bound on the axion decay constant and the Bino mass in the axino-LSP and Bino-NLSP model from the ALEPH, CDF II and early LHC data on $\gamma\gamma + \not{E}_T$ signal. We take a benchmark scenario specifying the SUSY particle masses, where the gluino mass is 800 GeV and all other squark masses are 1.5 TeV. Light Bino case with mass below about 150 GeV has a strong constraint from the ALEPH and CDF data: the region of $f_a < 10^7$ GeV is completely excluded. The hadronic axion window is almost closed in this region. The 1 fb^{-1} ATLAS data exclude a large portion of $f_a < 10^6$ GeV region up to $m_{\tilde{B}} \simeq 700$ GeV and 2.1 fb^{-1} CMS data exclude a region around $f_a \sim 10^7$ GeV. This bound is much stronger than the previous laboratory bound ($f_a > 10^4$ GeV).

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References

[1] ATLAS Collaboration, Eur. Phys. J. C 71 (2011) 1744.
[2] ATLAS Collaboration, arXiv:1111.4116 [hep-ex].
[3] S. Chatrchyan, et al., CMS Collaboration, Phys. Rev. Lett. 106 (2011) 211802.
[4] CMS Collaboration, CMS-PAS-EXO-11-067.
[5] A. Heister, et al., ALEPH Collaboration, Eur. Phys. J. C 28 (2003) 1.
[6] A. Heister, et al., ALEPH Collaboration, Eur. Phys. J. C 25 (2002) 339.
[7] J. Abdallah, et al., DELPHI Collaboration, Eur. Phys. J. C 38 (2005) 395.
[8] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. D 78 (2008) 032015.
[9] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. Lett. 104 (2010) 011801.
[10] B.C. Allanach, et al., Eur. Phys. J. C 25 (2002) 113.
[11] P. Meade, N. Seiberg, D. Shih, Progr. Theoret. Phys. Suppl. 177 (2009) 143.
[12] M. Buican, P. Meade, N. Seiberg, D. Shih, JHEP 0903 (2009) 016.
[13] T. Goto, M. Yamaguchi, Phys. Lett. B 276 (1992) 103.
[14] J. Ellis, A.B. Lahanas, D.V. Nanopoulos, K. Tamvakis, Phys. Lett. B 134 (1984) 429.
[15] A.B. Lahanas, D.V. Nanopoulos, Phys. Rep. 145 (1987) 1.
[16] J.E. Kim, G. Carosi, Rev. Mod. Phys. 82 (2010) 557.
[17] J.E. Kim, Phys. Rev. Lett. 43 (1979) 103.
[18] M.A. Shifman, A.I. Vainshtein, V.I. Zakharov, Nucl. Phys. B 166 (1980) 493.
[19] A.R. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980) 260.
[20] M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B 104 (1981) 199.
[21] A. Freitas, F.D. Steffen, N. Tajuddin, D. Wyler, JHEP 1106 (2011) 036.
[22] S. Chang, K. Choi, Phys. Lett. B 316 (1993) 51.
[23] J. Hisano, K. Tobe, T. Yanagida, Phys. Rev. D 55 (1997) 411.
[24] K. Rajagopal, M.S. Turner, F. Wilczek, Nucl. Phys. B 358 (1991) 447.
[25] E.J. Chun, J.E. Kim, H.P. Nilles, Phys. Lett. B 287 (1992) 123.
[26] S. Chatrchyan, et al., CMS Collaboration, Phys. Rev. Lett. 106 (2011) 211802; D. Nguyen, CMS Collaboration, arXiv:1110.2552 [hep-ex].
[27] G. Abbiendi, et al., OPAL Collaboration, Eur. Phys. J. C 32 (2004) 453, hep-ex/0309014.
[28] D.A. Toback, P. Wagner, Phys. Rev. D 70 (2004) 114032.