Prospects of models with light sgoldstino in electron beam dump experiment at CERN SPS

K. O. Astapov1,2,* and D. V. Kirpichenkov1,†

1 Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia
2 Physics Department, Moscow State University, Vorobievy Gory, Moscow 119991, Russia

We discuss phenomenology of light scalar sgoldstino in context of CERN electron beam dump experiment NA64. We calculate sgoldstino production rate for this experiment taking into account sgoldstino mixing with the Higgs boson and find a region in the model parameter space which can be tested in NA64.

I. MOTIVATION

Supersymmetry is a promising extension of the Standard Model [1, 2]. However according to experimentally observed absence of superpartners at low energies, SUSY models imply supersymmetry to be spontaneously broken at some scale. The breaking mechanism is provided by underlying microscopic theory. The breaking can happen when a hidden sector dynamics results in a nonzero vacuum expectation value $F$ to an auxiliary component of the superfield $\Phi$ and $\sqrt{F}$ is SUSY breaking scale. According to supersymmetric analog of the Goldstone theorem [4] there should exist a massless fermionic degree of freedom, goldstino.

In the simplest case this fermion belongs to a chiral multiplet, dubbed goldstino supermultiplet. Apart from goldstino, it contains scalar - sgoldstino and an auxiliary field acquiring nonzero vacuum expectation value $F$, which trigger spontaneous SUSY breaking. The quantity $\sqrt{F}$ is supersymmetry breaking scale. Couplings of sgoldstino to SM fields are suppressed by $\frac{1}{F}$ and expected to be quite small. Being included into supergravity framework goldstino becomes longitudinal component of gravitino with mass related to the scale of supersymmetry breaking $\sqrt{F}$ as follows $m_{3/2} = \frac{F}{\sqrt{3}M_{pl}}$, where $M_{pl}$ is the Planck mass [5]. In the present work we consider the mass of sgoldstino to be light (less than 1 GeV) as phenomenologically interesting case; therefore a high intensity beam is required to test the model via production of sgoldstino. Beam dump experiment can perform the task. A preliminary estimate of the search for sgoldstino at beam dump experiment SHiP for sgoldstino production and decay mechanisms can be found in Ref. [6]; here we complete that study by considering production of sgoldstino in electron-proton collisions.

The purpose of the present paper is to estimate the signal rate of sgoldstino decays expected to detect at the NA64 electron beam-dump experiment in context of present model (see Refs. [7–9] for description of the experiment in context of the search for Dark photon). We consider the case when mostly the sgoldstino decays into electron-positron pairs as searching signature.

The paper is organized as follows. In section II we present effective interaction Lagrangian of sgoldstino to SM particles and set of chosen values of parameters of MSSM. Section III contains calculation of sgoldstino production cross section. In section IV we discuss sgoldstino decay channels and calculate its lifetime for given model parameters. In Secs. V we calculate NA64 sensitivity to the SUSY breaking scale and put new limits on the model parameters. We conclude in Sec. VI by summarizing the results obtained.

II. LAGRANGIAN AND PARAMETERS

To the leading order in $1/F$, sgoldstino couplings to SM gauge fields - photons $F_{\mu\nu}$, gluons $G_{\mu\nu}$ and matter fields - leptons $l_a$, up and down quarks $u_a$ and $d_a$, where index $a$ runs over three generations at the mass scale above $\Lambda_{QCD}$ but below electroweak symmetry breaking reads as [10, 11]

$$
\mathcal{L}_{\text{eff}}^s = -\frac{M_{\gamma\gamma}}{2\sqrt{2}F}sF_{\mu\nu}F_{\mu\nu} - \frac{M_2}{\sqrt{2}F}sW_{\mu\nu}W_{\mu\nu} - \frac{M_{ZZ}}{2\sqrt{2}F}sZ_{\mu\nu}Z_{\mu\nu} - \frac{M_3}{2\sqrt{2}F}s\text{Tr}G_{\mu\nu}G_{\mu\nu} - \frac{A_{U}^{\mu\nu}}{\sqrt{2}F}s\text{Tr}u_{a}u_{b} - \frac{A_{D}^{\mu\nu}}{\sqrt{2}F}s\text{Tr}d_{a}d_{b} - \frac{A_{L}^{\mu\nu}}{\sqrt{2}F}s\text{Tr}l_{a}l_{b}
$$

(*)

astapov@ms2.inr.ac.ru
Here $M_3$ is the gluino mass, $M_{\gamma\gamma} = M_1 \sin^2 \theta_W + M_2 \cos^2 \theta_W + M_{ZZ} = M_1 \cos^2 \theta_W + M_3 \sin^2 \theta_W$ with $M_1$ and $M_2$ being $U(1)_Y$- and $SU(2)_W$-gaugino masses and $\theta_W$ the weak mixing angle, and $A_{\alpha\beta}^u$, $A_{\alpha\beta}^d$ and $A_{\alpha\beta}^e$ are soft trilinear coupling constants. Lagrangian (1) includes only single-sgoldstino interaction terms; considered in Refs. [11–14], double-sgoldstino terms are suppressed by $1/F^2$ and are not probable for testing at the NA64 experiment.

In general sgoldstino also mixes with neutral Higgs bosons as discussed in Refs. [10, 15–17]: the scalar sgoldstino $S$ mixes with neutral light $h$ and heavy $H$ Higgs bosons, while pseudoscalar $P$ mixes with their axial partner $A$. We account for the mixing with $h$ only, since the other two do not change light scalar sgoldstino phenomenology at NA64 for considered set of parameters of the model. Mixing of the scalar sgoldstino and the lightest MSSM Higgs boson (SM-like Higgs) $h$ can be written as [10]

$$L_{\text{mixing}} = \frac{X}{F} S h,$$

where the mixing parameter $X$ is

$$X = 2 \mu^3 v \sin 2\beta + \frac{1}{2} v^3 (g_1^2 M_1 + g_2^2 M_2) \cos 2\beta,$$

here $\mu$ is Higgsino mixing mass parameter, $v = 174$ GeV is the Higgs vacuum expectation value (vev), $\tan \beta$ is describing the Higgs vev ratio, and $g_1$ and $g_2$ are $SU(2)_W$ and $U(1)_Y$ gauge coupling constants.

Since we are considering sgoldstino $S$ mass to be less than 1 GeV (much lighter than the SM-like Higgs boson of mass $m_h \approx 125$ GeV) all the Higgs-like couplings of scalar resonanse are suppressed by the mixing angle

$$\theta = -\frac{X}{F m_h^2}.$$

In Table I we set numerical values for parameters of the MSSM so that $h$ acquire its experimentally observed value of 125 GeV by loop corrections from squark masses and trilinear couplings; and $H$ along with $A$ fields acquire heavy masses over 1 TeV to not to contribute into mixing with scalar and pseudoscalar sgoldstinos. In this arbitrary choice we suppose that all the model parameters take experimentally allowed values.

| $M_1$, GeV | $M_2$, GeV | $M_3$, GeV | $\mu$, GeV | $\tan \beta$ |
|------------|------------|------------|------------|-------------|
| 100        | 250        | 1500       | 1000       | 6           |
| $m_A$, GeV | $A_t$, GeV | $m_{\tilde{t}}$, GeV | $A_{\tilde{t}}$, GeV | $m_{\tilde{g}}$, GeV |
| 1000       | 2800       | 1000       | 2800       | 1000        |

TABLE I. MSSM benchmark point.

† kirpich@ms2.inr.ac.ru

In the table we denoted $A_{\alpha\beta}^u$, $A_{\alpha\beta}^d$ as $A_Q$ and $A_{\alpha\beta}^e$ as $A_t$, all the off-diagonal $A_{\alpha\beta}^{U,D,T}$ are set to zero.

### III. PRODUCTION MECHANISM

In this section we describe scalar sgoldstino production in electron-proton collisions as 100 GeV electron beam hitting heavy nuclei lead ($Z = 82$) target. We take into account interactions of sgoldstino with nuclei and electrons. Feynman diagrams of the process are presented on Fig. 2. We denote the four-momenta of the initial beam and scattered electrons by $k_e = (E_e, \vec{k}_e)$ and $k'_e = (E'_e, \vec{k}'_e)$; the four-momenta of the initial and final target state by $k_N = (E_N, k_N)$ and $k'_N = (E'_N, k'_N)$; for outgoing sgoldstino particle $k = (E, \vec{k})$. Expressions for corresponding diagrams read as:

$$i\mathcal{M}^{(b)} = \frac{M_{\gamma\gamma}}{2\sqrt{2} F} \frac{(-ie)^2}{(k_p - k'_p)^2} \frac{i}{(k_e - k'_e)^2} \times$$

$$\times \left[ -2(k_e - k'_e, k_p - k'_p) g^{\alpha\beta} + (k_e - k'_e)^{\alpha}(k_p - k'_p)^{\beta} (k_e - k'_e)^{\gamma}(k_p - k'_p)^{\alpha} \right] j^e_{\alpha} j^N_{\beta},$$

where leptonic and hadronic currents read as

$$j^e_{\alpha} = \bar{u}_e(k_e) \gamma_\alpha u(k_e)$$

and

$$j^N_{\alpha} = Z F(Q_t)(k_p + k'_p)\alpha$$

correspondingly. Here $F(Q)$ is the nuclear charge form factor [18]. Note, that we did not consider diagrams similar to (a), (b) and (c) but with $Z^0$-boson exchange, since they are suppressed by $Z^0$ mass.

Leptonic tensor:

$$L_{\alpha} = \bar{u}_e(k_e) \left( \gamma^\alpha \frac{-(k'_e - \vec{k}) + m_e}{(k_e - k)^2 - m_e^2} + \frac{-(\vec{k} + k'_e) + m_e}{(k + k'_e)^2 - m_e^2} \gamma^\alpha \right) u(k_e).$$

Therefore full amplitude of the process reads as

$$i\mathcal{M} = i\mathcal{M}^a + i\mathcal{M}^b + i\mathcal{M}^c$$

The differential cross section of $2 \rightarrow 3$ process for $m_S = 100$ MeV is presented on Fig.1.
IV. DECAY CHANNELS

For (sub-)GeV mass-range sgoldstino decay channels into pairs of SM particles, if kinematically allowed are: $\gamma\gamma, e^+e^-, \mu^+\mu^-, \pi^0\pi^0, \pi^+\pi^-$. Decay width of sgoldstino into photons:

$$\Gamma(S \to \gamma\gamma) = \left( \frac{\alpha(m_S)\beta(M_{\gamma\gamma})}{\beta(\alpha(m_S))\alpha(M_{\gamma\gamma})} \right) \frac{m_S^3 M_{\gamma\gamma}^2}{32\pi F^2}.$$  \hspace{1cm} (8)

Here the dimensionless multiplicative factor accounts for the renormalization group evolution of the photonic operator at different mass scales. Lepton channels are:

$$\Gamma(S \to l^+l^-) = \frac{m_S^3 A_l^2}{16\pi F^2} \frac{m_S^2}{m_{l\ell}^2} \left( 1 - \frac{4m_{\pi^0}^2}{m_S^2} \right)^{3/2}.$$  \hspace{1cm} (9)

Decay into light mesons is provided with gluonic operator at a low energy scale.

$$\Gamma(S \to \pi^0\pi^0) = \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))} \frac{\pi m_S m_S^2 M_3^2}{4 F^2} \left( 1 - \frac{4m_{\pi^0}^2}{m_S^2} \right)^2.$$  \hspace{1cm} (10)

See Ref.[6] for notations for above formulas.

Sgoldstino decay branching ratios for the values of MSSM parameters given in Table I are shown in Fig. 3. Hadronic channel $\pi\pi$ dominate when it is kinematically allowed, while $\gamma\gamma$ and $\mu^+\mu^-$ give small but noticeable contributions.

The sgoldstino lifetime for given $\sqrt{F} = 10$ TeV is presented in Fig. 4.
V. RESULTS

Here we estimate the number of $e^-N \to S \to e^+e^-$ events inside the fiducial volume of the NA64 experimental setup. Experimental setup is designed to search for rare decays with charged particles in the final state. Detailed setup scheme is outlined in the Ref. [7]. The experiment utilize clean high energy $e^-$ beam with less then $10^{-2}$ level of impurities and momenta of 100 GeV. Electron beam is produced by primary 400 GeV proton beam from SPS hitting the primary beryllium target. Electron beam strikes on the electron calorimeter target and produces sgoldstinos directly through the processes described in the previous sections. Target calorimeter thickness is $l_{sh} = 0.15\, m$. The vacuum vessel length is about $l_{det} = 15\, m$. It forms a cylinder along the beam axis with an circle base of 30 cm in diameter. At the back end of the vacuum vessel another electronic calorimeter serves for count of electromagnetic shower produced by subsequent sgoldstino decays into charged particles.

The number of signal events reads as

$$N_{\text{signal}} = N_{\text{EOT}} \frac{N_0 X_0}{\Lambda \int_{m_S}^{E_0-m_s} dE_S \int_{E_S+m_s}^{E_0} dE_e}$$

$$\times \int_0^T dt \left[ I_e(E_0, E_e, t) \frac{1}{E_e} \frac{d\sigma}{dx_e} \right] w_{\text{det}} BR_{\text{det}}, \quad (13)$$

where the expected number of electrons on the target is $N_{\text{EOT}} = 10^9$, $N_0$ is Avagadro’s number, $X_0$ is the unit radiation length of the target material, $\Lambda$ is atomic mass number, $E_s$ is sgoldstino energy, $E_0$ and $E_e$ are beam and initial electron energies correspondingly, $x_e = E_e/E_0$ and $w_{\text{det}}$ denotes the probability for the sgoldstino to decay inside the fiducial volume of the detector,

$$w_{\text{det}}(E_{S(P)}, m_{S(P)}, \sqrt{F}) = \exp(-l_{sh}/\gamma c t_{S(P)}) \times$$

$$\times \left[ 1 - \exp(-l_{det}/\gamma c t_{S(P)}) \right], \quad (14)$$

with the sgoldstino gamma factor $\gamma = E_{S(P)}/m_{S(P)}$.

Since electron beam with energy $E_0$ becomes degraded as electrons pass through and interact with its nucleus. Energy distribution of electrons (see Ref. [19]) after passing through material by $t$ radiation length is given by:

$$I_e(E_0, E_e, t) = \frac{1}{E_0} \left[ \ln \left( \frac{E_0}{E_e} \right) \right]^{bt-1} \Gamma(t), \quad (15)$$

where $\Gamma$ is Gamma function, $b = 4/3$, $E_0$ is initial beam energy at $t = 0$.

In Fig. 5 we indicate the region in the model parameter space $(m_S, 1/\sqrt{F})$, where the number of sgoldstino decay events inside the fiducial volume exceeds 3, $N_{\text{signal}} > 3$. That is, if no events were observed the region is excluded at the confidence level of 95%, in accordance with the Poisson statistics. The lower boundary in Fig. 5 is the region where the couplings are so small that sgoldstinos escape from the detector without decay. The upper boundary corresponds to case when couplings are so large that sgoldstinos decay before the detector. The scalings of the signal events imply that models with a higher (as compared to that presented in Fig. 5) scale of supersymmetry breaking can be tested if MSSM parameters $\mu, M_{\gamma\gamma}$ are appropriately larger (as compared to those presented in Table I).

FIG. 4. Lifetime of a scalar sgoldstino as a function of its mass.

FIG. 5. The shaded region will be probed at the NA64 experiment.
VI. CONCLUSIONS

We have estimated sensitivity of the NA64 experiment to supersymmetric extensions of the SM where sgoldstinos are light. The experiment will be able to probe the supersymmetry breaking scale $\sqrt{F}$ up to $10^4$ TeV. We have obtained exclusion regions of the scalar sgoldstino parameter space ($m_S$ vs. $1/\sqrt{F}$).

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