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Sgoldstino rate estimates in the SHiP

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Abstract. For supersymmetric extensions of the Standard Model with light sgoldstinos—scalar and pseudoscalar superpartners of goldstinos—we estimate the signal rate anticipated at the recently proposed fixed target experiment SHiP utilizing a CERN Super Proton Synchrotron beam of 400 GeV protons.

1 Introduction

Low energy supersymmetry (SUSY) is perhaps the most developed extension of the Standard Model of (SM) of particle physics [1, 2]. While, inherent in supersymmetry, a technically natural solution to the gauge hierarchy problem implies the SM superpartners are at or below the TeV energy scale, other and much lighter new particles can exist as well. In particular, if supersymmetry is spontaneously broken at not very high energy scales, the particles from the SUSY breaking sector may show up at quite low energies. Their effective couplings to the SM particles are anticipated to be rather weak; therefore a high intensity beam is required to test the model via production of the new particles. The CERN Super Proton Synchrotron (SPS) provides us with a high intensity beam of 400 GeV protons, and the recently proposed beam-dump Search for Hidden Particles (SHiP) experiment can perform the task. We estimated the signal rate expected at the SHiP experiment in supersymmetric models with sufficiently light particles of the Goldstino supermultiplet. The latter contains Goldstino (the Nambu–Goldstone field, fermion) and its superpartners, scalar and pseudoscalar sgoldstinos. While goldstinos are R odd, sgoldstinos are R even and hence can be singly produced in scatterings of the SM particles and can subsequently decay into the SM particles. Interaction of the Goldstino supermultiplet with other fields is suppressed by the parameter F. To the leading order in $1/F$, sgoldstino coupling to SM gauge fields [photons $F_{\mu\nu}$, gluons $G^a_{\mu\nu}$, where the index $a = 1, ...8$ runs $SU(3)$ color group] and matter fields (leptons f_L, up and down quarks f_U and f_D) at the mass scale above Λ_{QCD} but below electroweak symmetry breaking reads

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$$\mathcal{L}_{eff} = -\frac{1}{2\sqrt{2}F}\Big(m_S^2 S\bar{\tilde{G}}\tilde{G} + im_P^2 P\bar{\tilde{G}}\gamma_5\tilde{G}\Big) - \frac{1}{2\sqrt{2}}\frac{M_{\gamma\gamma}}{F}SF^{\mu\nu}F_{\mu\nu} + \frac{1}{4\sqrt{2}}\frac{M_{\gamma\gamma}}{F}P\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} -$$
$$-\frac{1}{2\sqrt{2}}\frac{M_3}{F}SG^{\mu\nu\, a}G^a_{\mu\nu} + \frac{1}{4\sqrt{2}}\frac{M_3}{F}P\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma} - \frac{\tilde{m}^{LR\,2}_{D_{ij}}}{\sqrt{2}F}S\bar{f}_{D_i}f_{D_j} - i\frac{\tilde{m}^{LR\,2}_{D_{ij}}}{\sqrt{2}F}P\bar{f}_{D_i}\gamma_5 f_{D_j} -$$
$$-\frac{\tilde{m}^{LR\,2}_{U_{ij}}}{\sqrt{2}F}S\bar{f}_{U_i}f_{U_j} - i\frac{\tilde{m}^{LR\,2}_{U_{ij}}}{\sqrt{2}F}P\bar{f}_{U_i}\gamma_5 f_{U_j} - \frac{\tilde{m}^{LR\,2}_{L_{ij}}}{\sqrt{2}F}S\bar{f}_{L_i}f_{L_j} - i\frac{\tilde{m}^{LR\,2}_{L_{ij}}}{\sqrt{2}F}P\bar{f}_{L_i}\gamma_5 f_{L_j}\,. \quad (1)$$

Here M_3 is the gluino mass, $M_{\gamma\gamma} = M_1\sin^2\theta_W + M_2\cos^2\theta_W$ with M_1 and M_2 being $U(1)_Y$- and $SU(2)_W$-gaugino masses and θ_W the weak mixing angle, and $\tilde{m}^{LR\,2}_{U_{ij}}$ and $\tilde{m}^{LR\,2}_{D_{ij}}$ are left-right up- and down- squark soft mass terms. Sgoldstino decays into two electrically charged SM particles yield the signature well recognizable at SHiP: two charged tracks from a single vertex supplemented with a peak in the invariant mass of outgoing particles. Sgoldstino couplings to the SM fields are inversely proportional to the parameter of the order of the squared scale of SUSY breaking in the whole model. This unique feature of the Goldstino supermultiplet allows us to probe the SUSY breaking scale by hunting for the light sgoldstinos.

To illustrate the sensitivity of the SHiP experiment to sgoldstino couplings, in the next sections we present numerical results for the set of values of MSSM parameters (the benchmark point in the MSSM parameter space) shown in Table 1. It is an arbitrary choice, except we suppose that all the

M_1, GeV	M_2, GeV	M_3, GeV	μ, GeV	$\tan\beta$
100	250	1500	1000	6
m_A, GeV	A_l, GeV	m_l, GeV	A_Q, GeV	m_Q, GeV
1000	2800	1000	2800	1000

Table 1. MSSM benchmark point.

model parameters take experimentally allowed values and the lightest Higgs boson mass is 125 GeV. Trilinear soft supersymmetry breaking parameters $A_{l,Q}$ are defined by the relations $\tilde{m}^{LR\,2}_{D_{ii}} \equiv m_{D_i}A_Q$, $\tilde{m}^{LR\,2}_{U_{ii}} \equiv m_{U_i}A_Q$, $\tilde{m}^{LR\,2}_{L_{ii}} \equiv m_{L_i}A_l$, where we use SM fermion masses m_{D_i,U_i,L_i}; m_A, m_Q, m_l are CP-odd Higgs boson, squark and slepton masses, correspondingly.

2 Scalar sgoldstino

In this section we consider two different production mechanisms of the scalar sgoldstino relevant for the SHiP setup. The first one is the direct production via hard gluon fusion in proton scatterings off the target material. The second one is the production in decays of mesons emerging due to the proton scattering.

2.1 Gluon fusion

If the sgoldstino is much heavier than the QCD energy scale of 100 MeV, it can be produced directly via gluon fusion. The relevant parts of the sgoldstino interaction Lagrangians (1), read

$$\mathcal{L}_{Sgg} = \Big(\theta\, g^{one-loop}_{hgg}(m_S) - \frac{\alpha_s(m_S)\beta(\alpha_s(M_3))}{\beta(\alpha_s(m_S))\alpha_s(M_3)}\frac{M_3}{2\sqrt{2}F}\Big)SG^{\mu\nu\, a}G^a_{\mu\nu}, \quad (2)$$

where the first term, associated with Higgs-sgoldstino mixing (**??**), is proportional to the Higgs effective coupling to gluons (appearing at one-loop level via virtual quark exchanges) [3]. Note that both terms in Eq. (2) are inversely proportional to supersymmetry breaking parameter F. To obtain a reliable estimate of the direct scalar sgoldstino cross section $\sigma_{pp\to S}$, we properly rescale the results of Ref. [4], where a coupling similar to Eq. (2) is responsible for the light inflaton production at the fixed target experiment with a 400 GeV proton beam. For the MSSM parameters from Table 1 we find the following numerical approximation to the cross section as a function of the sgoldstino mass and supersymmetry breaking parameter,

$$\log_{10}\left(\frac{\sigma_{pp\to S}}{\sigma_{pp,\text{total}}}\right) = -15.8666 - 0.93934\times\left(\frac{m_S}{1\text{GeV}}\right) + 0.02025\times\left(\frac{m_S}{1\text{GeV}}\right)^2 + 0.00052\times\left(\frac{m_S}{1\text{GeV}}\right)^3 - \\ - 4\log_{10}\left(\frac{\sqrt{F}}{100\text{TeV}}\right), \quad (3)$$

where $\sigma_{pp,\text{total}}$ is the total pp cross section for the 400 GeV proton beam. This approximation is illustrated in Fig. 1 (left) for two reference values of $\sqrt{F}$. Given the number of protons on target

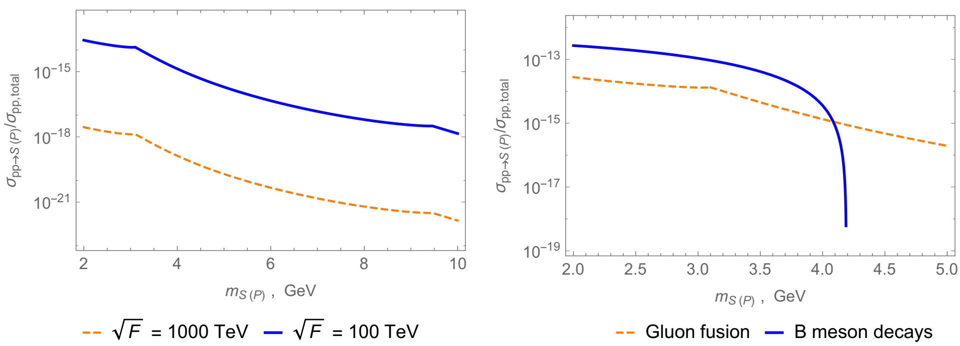


Figure 1. Cross sections of scalar and pseudoscalar sgoldstino production in gluon fusion as functions of sgoldstino mass. No difference between scalar and pseudoscalar cases is expected (on the left panel). And cross sections of scalar sgoldstino production in gluon fusion and in B-meson decays for the model with $\sqrt{F} = 100$ TeV (on the right panel).

expected at SHiP, about 2×10^{20} [5], one concludes from Fig. 1 (left) that the direct production can provide us with sgoldstinos only in the models with a supersymmetry breaking scale below 1000 TeV, if the MSSM superpartner scale is in the TeV range.

2.2 *B* meson decays

Scalar sgoldstinos of masses in the GeV range are dominantly produced by decays of heavy mesons appearing by proton scattering off target. In the context of the SHiP experiment the main source of sgoldstinos is decays of B mesons. Decays of charmed mesons are suppressed as compared to beauty meson decays due to the smallness of the CKM (Cabibbo – Kobayashi – Maskawa) matrix element in the corresponding amplitude. The process is described by the triangle diagram with a t quark and W bosons running in the loop. The sgoldstino is emitted by the virtual t quark through sgoldstino-top-top coupling (1) and sgoldstino-Higgs mixing (the latter dominates for the values shown in Table 1).

Adopting the same logic as used in [4] for the light inflaton, we calculate the branching ratio of B-meson decay into S,

$$\mathrm{Br}(B \to X_s S) = 0.3 \times (\frac{m_t}{m_W})^4 \left(1 - \frac{m_S^2}{m_b^2}\right)^2 (A_Q v + F\theta)^2 \left(\frac{100\ \mathrm{TeV}}{\sqrt{F}}\right)^4 , \tag{4}$$

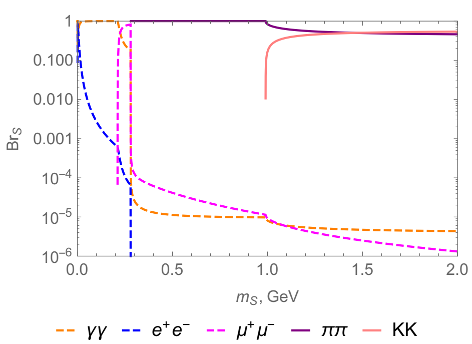
where X_s stands for the strange meson channel mostly saturated by a sum of pseudoscalar and vector kaons; m_b, m_t and m_W stand for b, t quarks and $W^\pm$ boson masses, correspondingly. The scalar sgoldstino production cross section is then a product of the branching ratio above and the beauty cross section evaluated at the SHiP energy scale as $1.6 \times 10^{-7} \times \sigma_{pp,\mathrm{total}}$ [5]. In Fig. 1 (right) we compare the sgoldstino production cross sections provided by the direct and the indirect mechanisms for the same value of the supersymmetry breaking parameter, $\sqrt{F} = 100$ TeV. One can observe from Eqs. (3) and (4) that both cross sections scale as $\propto 1/F^2$. Thus, we conclude from the plot in Fig. 1 (right) that the meson channel dominates sgoldstino production when the kinematics allows. In what follows we concentrate on this case and comment on prospects of searches for the heavier sgoldstinos, $M_{S(P)} \gtrsim 4$ GeV, (available only via the direct production) in due course.

2.3 Sgoldstino decay pattern

The sgoldstino is R even and can decay into pairs of SM particles, if it is kinematically allowed. For the sgoldstino of the (sub-)GeV mass-range, the main decay channels are $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\pi^0\pi^0$, $\pi^+\pi^-$, K^+K^-, $K^0\bar{K}^0$ (see Ref. [6] for details).

Between these mass ranges, where $m_s \approx 1.2 - 4$ GeV, neither description method is reliable where some heavy mesons, as well as multimeson final states, enter the game. However, comparing contributions for relevant hadronic modes calculated within these two approaches, we observe that deviations do not exceed an order of magnitude. Thus, we conclude that order-of-magnitude estimates of the sgoldstino lifetime for the mass interval 1.2 – 4 GeV can be obtained by some extrapolation of the chiral theory approach.

The branching ratios of the scalar sgoldstino decays for the values of MSSM soft parameters chosen in Table 1 are shown in Fig. 2 (left). Hadronic channels, $\pi\pi$, KK, naturally dominate (if kinematically allowed), while $\gamma\gamma$ and $\mu^+\mu^-$ give small but noticeable contributions.



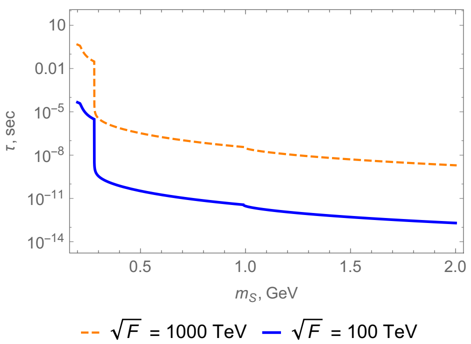


Figure 2. Branching ratios of a scalar sgoldstino (on the left panel). And Lifetime of a scalar sgoldstino as a function of its mass (on the right panel).

The sgoldstino lifetime for a set of values of F is presented in Fig. 2 (right). To reach the main detector of the SHiP experiment, the sgoldstino has to cover a distance of about 100 meters [5]. The results in Fig. 2 (right) suggest that SHiP can be sensitive mostly to the models with supersymmetry breaking scale of about 100 TeV and higher. The lifetime scales as $\tau \propto F^2$ and as $\tau \propto 1/M_3^2$ since the hadron channel dominates.

2.4 Sgoldstino signal event rate at SHiP

Now we collect all the ingredients required to achieve the main goal of this article, the estimate of the number of sgoldstino decay events inside the fiducial volume of the SHiP experiment. The SHiP construction is outlined in Ref. [5]. The 400 GeV proton beam fueled by the SPS hits the target and produces bunches of mesons, which can decay into new particles (sgoldstinos in the case at hand). The latter can also appear directly from the proton-proton collisions (through gluon fusion). The detector is placed at a distance of $l_{sh} = 63.8$ m from the target. The vacuum vessel length is about $l_{det} = 60$ m. It forms a cylinder along the beam axis with an elliptical base of 5 m×10 m. The trajectories of electrically charged particles emerging from the new particle decays can be traced in the detector volume and their energies and types can be determined by the registration system utilizing devices arranged at the far end of the detector.

Number of signal events as

$$N_{\text{signal}} = \frac{N_{\text{POT}}}{\sigma_{pp,\text{total}}} \int w_{det} \frac{d\sigma_{pp\to S(P)}}{dp d\theta_p d\phi_p} d^3\vec{p}\,, \tag{5}$$

where the expected number of protons on the target is $N_{\text{POT}} = 2 \times 10^{20}$ [7] and w_{det} denotes the probability for the sgoldstino to decay inside the fiducial volume of the detector,

$$w_{det}(E_{S(P)}, m_{S(P)}, \sqrt{F}) = \exp(-l_{sh}/\gamma c\tau_{S(P)}) \left[1 - \exp(-l_{det}/\gamma(E_{S(P)}) c\tau_{S(P)})\right], \tag{6}$$

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

In Fig. 3 we indicate the region in the model parameter space $(m_{S(P)}, 1/\sqrt{F})$, where the number of sgoldstino decays inside the SHiP fiducial volume exceeds 3, $N_{\text{signal}} > 3$. That is, if no events were observed (the background for the two-body decays into charged SM particles is zero [5]) the region is excluded at the confidence level of 95%, in accordance with the Poisson statistics. The upper boundary in Fig. 3 is the region where the sgoldstino coupling constants $\propto 1/F$ are large enough to initiate very fast decay of the sgoldstino before it reaches the detector. The lower boundary in Fig. 3 is the region where the couplings are so small that sgoldstinos escape from the detector without decay. The number of signal events here scales with the model parameters as $N_{\text{signal}} \propto M_3^2\mu^6/F^4$. The region in Fig. 3 of the heaviest sgoldstino reachable at SHiP, $m_S \approx 3.6$ GeV, is the meeting point of the lower and the upper boundaries. Here, the sgoldstino decay length is about 100 m, which is the scale of both the SHiP detector length and the distance from the target, $\gamma c\tau \sim l_{det} \sim l_{sh}$. In this case the number of signal events scales as $N_{\text{signal}} \propto \mu^6/F^2$. The scalings of the signal events imply that models with a higher (as compared to that presented in Fig. 3) scale of supersymmetry breaking can be tested if MSSM parameters μ, M_3 are appropriately bigger (as compared to those presented in Table 1).

Sgoldstinos of masses 3.6–4.2 GeV, which can be produced through B-meson decays (see Figs. 1 (right) and 3), seem to be beyond the SHiP's grip for our choice of MSSM parameters presented in Table 1. However, the signal scaling with model parameters explained above suggests that sgoldstinos of masses above 3.6 GeV can be tested at SHiP in models with a higher scale of SM superpartners. Finally, from the results presented in Figs. 1 (right) and 2 (right) one can conclude that sgoldstinos

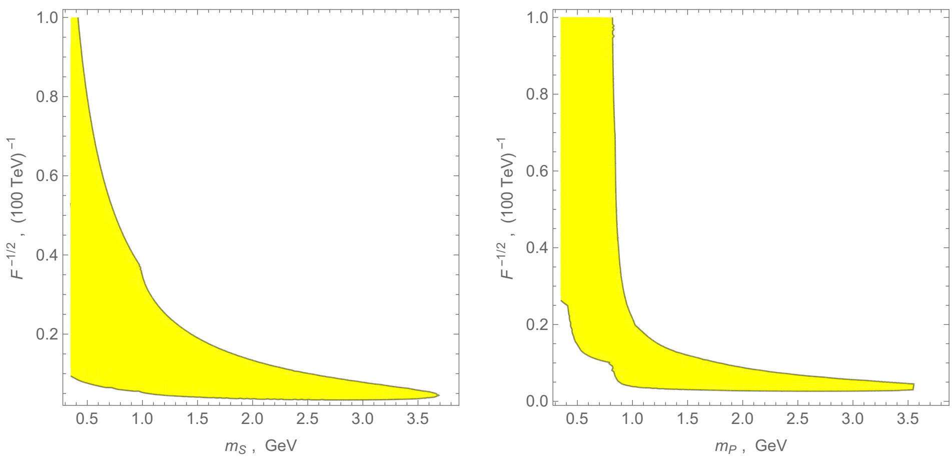


Figure 3. The shaded region will be probed at the SHiP experiment. Left plot is for probing scalar sgoldstino and right is for pseudoscalar.

of masses above 4 GeV, which can appear only via direct production, cannot be tested at SHiP. Both sgoldstino production and decay are governed by the same ratio M_3^2/F^2, and the sgoldstino lifetime $\tau \propto 1/m_S^3$ is too short for the reasonably high sgoldstino production. One needs much higher intensity of the proton beam at SPS to probe this region of model parameter space.

3 Pseudoscalar sgoldstino

If parity is (strongly) violated in the sfermion sector of the MSSM, sgoldstino couplings to the SM fermions violate it, too. Then, scalar and pseudoscalar sgoldstinos are very similar as regards the SHiP phenomenology. However, if sgoldstino couplings conserve parity (that takes place, e.g., in left-right extensions of the MSSM), the phenomenology of pseudoscalar and scalar sgoldstins is different in some aspects (see Refs. [6, 8] for details). In this section we investigate SHiP sensitivity to the pseudoscalar sgoldstino couplings.

The pseudoscalar sgoldstino P can be directly produced via the gluon fusion with the same cross section as the scalar sgoldstino; hence, Fig. 1 is valid for both cases. However, its production through the meson decays is somewhat different from that of the scalar sgoldstino because of the absence of mixing with the light MSSM Higgs.[1]

The light pseudoscalar can be produced in B-meson decays. The corresponding one-loop diagram is very similar to that in the case of the scalar sgoldstino discussed in Sec. 2.2, but only the sgoldstino-top-top pseudoscalar coupling (1) contributes. Given the pseudoscalar nature of P, for the two-body decay it is accompanied by the vector kaon K^*. The decay rate can be obtained by properly replacing the coupling constants in the result presented in Ref. [9] for the case of decay into the axion. In contrast to the scalar S, the pseudoscalar sgoldstino P does not decay into a meson pair. However, it mixes with pseudoscalar mesons π and η, as explained in Ref. [6]. Since mesons exhibit four-meson coupling, the pseudoscalar sgoldstino can decay into three mesons through the virtual meson state, $P \to \pi^{0^*}/\eta^* \to 3$ mesons.

[1]There is a mixing with CP-odd Higgs A^0, which is negligibly small for our choice of the benchmark point in Table 1.

The pseudoscalar sgoldstino lifetime and its relevant decay branching ratios are presented in Fig. 4

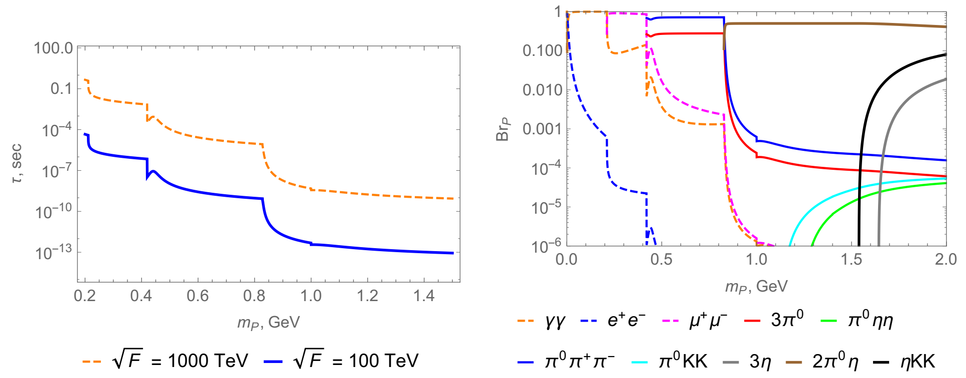


Figure 4. Pseudoscalar sgoldstino lifetime for $\sqrt{F}$ = 100, 1000 TeV (lines from bottom to top) (on the left pannel). And branchings ratios of the pseudoscalar sgoldstino (on the right panel).

Hadronic channels, mainly 3π, ηKK, $\eta\pi\pi$ and 3η, dominate sgoldstino decay. Given its geometry, the SHiP experiment is sensitive to the supersymmetry breaking scales of about $\sqrt{F} \sim 100$ TeV and above.

Performing for the pseudoscalar case the same procedure as that adopted in Sec. 2.4 for the scalar sgoldstino, we estimate the SHiP sensitivity to the pseudoscalar sgoldstino interaction. In Fig. 3 (right) we present the plot displaying the region in the parameter space $(F^{-1/2}, m_S)$ expected to be explored with the SHiP experiment. One observes that in the case of the pseudoscalar sgoldstino the SHiP is sensitive to models with a lower SUSY breaking scale $\sqrt{F}$ as compared to the scalar sgoldstino (cf. Fig.3).

References

[1] H. E. Haber and G. L. Kane, “The Search for Supersymmetry: Probing physics beyond the standard model,” Phys. Rep. **117**, 75 (1985).

[2] S. P. Martin, “A Supersymmetry primer, In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 1-153 [hep-ph/9709356].

[3] J. R. Ellis, M. K. Gaillard, D. V. Nanopoulos, and C. T. Sachrajda, Phys. Lett. B **83**, 339 (1979).

[4] F. Bezrukov and D. Gorbunov, “Light inflaton Hunter’s Guide,” JHEP **1005** (2010) 010 [arXiv:0912.0390 [hep-ph]].

[5] M. Anelli *et al.* [SHiP Collaboration], “A facility to Search for Hidden Particles (SHiP) at the CERN SPS,” arXiv:1504.04956 [physics.ins-det].

[6] D. S. Gorbunov, “Light sgoldstino: Precision measurements versus collider searches,” Nucl. Phys. B **602**, 213 (2001) [hep-ph/0007325].

[7] S. Alekhin *et al.*, “A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case,” arXiv:1504.04855 [hep-ph].

[8] D. S. Gorbunov and V. A. Rubakov, “Kaon physics with light sgoldstinos and parity conservation,” Phys. Rev. D **64**, 054008 (2001) [hep-ph/0012033].

[9] M. Freytsis, Z. Ligeti and J. Thaler, “Constraining the Axion Portal with B —> K l+ l-,” Phys. Rev. D **81**, 034001 (2010) [arXiv:0911.5355 [hep-ph]].