Sensitivity of the SHiP experiment to a light scalar particle mixing with the Higgs

G. Lanfranchi

1Laboratori Nazionali di Frascati, INFN

Abstract

This conceptual study shows the ultimate sensitivity of the SHiP experiment for the search of a light scalar particle mixing with the Higgs for a dataset corresponding to 5-years of SHiP operation at a nominal intensity of $4 \times 10^{13}$ protons on target per second. The sensitivity as a function of the length of the vessel and of its distance from the target as well as a function of the background contamination is also studied.
1 Introduction

Additional scalars are required to exist in various extensions of the Standard Model (SM) [1–12]. Speculations regarding a possible Higgs portal coupling to new, weakly-coupled 'hidden' scalar particles have intensified after the discovery of the Higgs boson. Recently a light scalar field has been introduced to solve the hierarchy problem in a different way with respect to the common lore [13]. The SHiP experiment [24], has the potential to probe this portal provided that the new states connected to it are light with masses of \( \mathcal{O}(\text{GeV}/c^2) \). The purpose of this note is to survey the SHiP sensitivity to a light hidden scalar particle \( S \), which mixes with the SM Higgs with a parameter \( y^2 = \sin^2 \theta \) and which decays only to SM particles with a coupling constant \( y^2 = \sin^2 \theta \) compared to the SM Higgs.

Figure 1 shows the currently excluded regions and sensitivities of planned experiments for the search for a light dark scalar in the \( \sin^2 \theta \) versus mass plane. Existing limits are shown as shaded areas and come from rare \( B \) meson decays \( B \to K S \) from \( B \)-factory experiments and from LHCb, with \( S \) decaying in the dilepton channel [16–18] and, for \( B \)-factories’ experiments only, in the invisible channel [19, 20]. The sensitivity contour for \( S \to e^+e^-, \mu^+\mu^- \) final states obtained by the CHARM experiment [21] is also shown. The blue line marked as \( K \to \pi + X \) is an interpretation [22] of the results of the E949 experiment [23]. Constraints from the Super Novae 1987a (SN1987a) and Big Bang Nucleo-synthesis (BBN) cover the region of low-couplings, low-mass values in the plot. Future sensitivities from NEWS [25], super CDMS [26], and SeaQuest [27] are shown as dotted lines.

2 Basic theory framework

In the lagrangian of the SM a complex scalar doublet with four degrees of freedom generates the \( W/Z \) and the Higgs. A natural extension of the SM predicts the existence of an extra real singlet scalar that couples with the Higgs with a coupling constant \( \sin^2 \theta \) or \( y^2 \). The production of the light hidden scalars therefore is linked to the production of the Higgs particle. At low energy, this is expected to occur mostly via meson decays, as shown in Figure 2 Depending on the meson involved, the CKM contribution to the amplitude is given by:

\[
\begin{align*}
\Gamma(K \to \pi S) & \sim (m_t^2 |V_{td}^* V_{td}|)^2 \propto m_t^4 \lambda^5 \\
\Gamma(D \to \pi S) & \sim (m_b^2 |V_{ub}^* V_{ub}|)^2 \propto m_b^4 \lambda^5 \\
\Gamma(B \to K S) & \sim (m_b^2 |V_{tb}^* V_{tb}|)^2 \propto m_b^4 \lambda^2.
\end{align*}
\] (1)

Given the CKM structure, the main contribution to the scalar production arises from \( B \) and \( K \) decays, being the \( D \) decays highly suppressed.
Figure 1: Sensitivity contours for a light scalar particle mixing with the Higgs in the plane $\sin^2 \theta$ versus mass. Shaded areas are already excluded parameters regions by past experiments, dotted lines are sensitivities of planned experiments.

Figure 2: Main diagram driving the light scalar production in mesons decays.
The branching fractions of $B$ and $K$ decays into a scalar as computed in Ref. [1][28] are the following:

\[
\begin{align*}
BR(K^+ \rightarrow \pi^+ S) & \simeq \sin^2 \theta \times 0.002 \times \frac{2|\vec{p}_S|}{m_K} \\
BR(K_L \rightarrow \pi^0 S) & = \frac{BR(K^+ \rightarrow \pi^+ S)}{\Gamma_K} \\
BR(B^+ \rightarrow K^+ S) & \simeq \sin^2 \theta \times 0.5 \times \frac{2|\vec{p}_S|}{m_B} \times F(q^2) \\
F(q^2) & = 0.33/(1 - q^2/38 \text{ GeV}^2), \quad q^2 = m_S
\end{align*}
\]

where $|\vec{p}_S|$ is the momentum of the scalar particle in the centre-of-mass frame, the $\Gamma_K$ and $\Gamma_{K_L}$ are the total decay widths of the $K^+$ and $K_L$, respectively, and $F(q^2)$ is a form factor. The partial decay width of the new light scalar into muon pairs is given by:

\[
\Gamma(S \rightarrow \mu\mu) = \frac{\sin^2 \theta m^2_S m_S}{8\pi v^2} \beta^3_{\mu}
\]

where $m_S$ is the mass of the scalar particle, $v \sim 246$ GeV is the Higgs condensate, and $\beta_{\mu} = \sqrt{1 - 4m^2_{\mu}/m^2_S}$ is a kinematic factor.

Following the prescription in Ref. [1], the relations for the partial decay widths are as follows:

\[
\begin{align*}
\Gamma_{\mu\mu} : \Gamma_{\pi\pi} : \Gamma_{KK} : \Gamma_{\eta\eta} : \Gamma_{DD} : \Gamma_{gg} = m^2_\mu \beta^3_\mu : 3(m^2_u + m^2_d)\beta^3_\mu : 3 \frac{9}{13} m^2_s \beta^3_K : 3 \frac{4}{13} m^2_s \beta^3_\eta : m^2_c \beta^3_D : m^2_t \beta^3_\tau.
\end{align*}
\]

from which is possible to compute the scalar total decay width for a given mass. Figure 3 (left) shows the total branching fraction in two-body final state as a function of the mass of the scalar particle in the mass range interesting for SHiP. Figure 3 (right) shows the $c\tau$ values for different $y^2$ values. For example, a scalar particle produced with $p = 35$ GeV/c, $m = 1$ GeV/c$^2$, $y^2 = 10^{-8}$ has an average decay path length of $L \sim 350$ m.

For $m_S < 2m_{\mu}$, the light scalar decays almost exclusively to $e^+ e^-$. Above $2m_{\mu}$, the decay $S \rightarrow \mu^+ \mu^-$ takes over until the $2m_{\pi} \simeq 280$ MeV/c$^2$ threshold. For scalars produced in $b$-hadrons decays, additional decay channels are open ($\pi\pi$, $KK$, $\eta\eta$, $\tau\tau$, $DD$, ..). Currently there are significant theoretical uncertainties in the computation of their rates [29][32]. In this note we will follow the prescriptions of Ref. 29.
Figure 3: Left: branching fractions of the dark scalar to $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$ final states. The sum of these branching fractions is also shown. Right: $c\tau$ of the dark scalar as a function of the mass and for different $y^2 = \sin^2\theta$ values.

3 The scalar’s production mechanism at SHiP

At a fixed target (or beam dump) experiment the production of light hidden scalars is given by [2]:

$$N_S \simeq N_{pot} \cdot (2\cdot \chi_s \cdot f_{S1} \cdot 0.5 \cdot BR(K^\pm \rightarrow \pi^0 S) + 2\cdot \chi_s \cdot f_{S2} \cdot 0.25 \cdot BR(K_L \rightarrow \pi^0 S) + 2\cdot \chi_b \cdot BR(B \rightarrow X_s S))$$

(5)

where:

- $N_{pot}$ is the total number of protons on target;
- $\chi_s = \sigma_{pp \rightarrow sX}/\sigma_{pp \rightarrow Y} = 0.147$ and $\chi_b = \sigma_{pp \rightarrow bX}/\sigma_{pp \rightarrow Y} = 1.6 \times 10^{-7}$ are the ratios of the production cross sections of $s$ and $b$ quarks with respect to the total $pp$ cross section;
- $f_{S1} = 0.2\%$ and $f_{S2} = 0.02\%$ are the fractions of $K^+$ and $K_L$ that decay before being absorbed in the target;
- $BR(K^\pm \rightarrow \pi^\pm S)$, $BR(K_L \rightarrow \pi^0 S)$, $BR(B \rightarrow X_s S)$ are the branching fractions of $K^\pm$, $K_L$ and $B$ into the scalar particle, as described in Eq. 2.

The number of protons on target collected in one year at full intensity by the SHiP experiment is expected to be:

$$N_{pot} = 4 \cdot 10^{13} p/s \cdot 10^7 s (100 \text{ days}) \cdot 20\% (\text{SPS duty cycle}) \cdot 60\% (\text{SPS efficiency}) \simeq 4 \cdot 10^{19},$$

(6)

which corresponds to $N_{pot} = 2 \cdot 10^{20}$ assuming five years of data taking. This number of protons has been considered in the sensitivity studies of this note.
For a proton beam-dump experiment the dominant production process of light scalar particles is via $b$-hadrons decays, being most of the kaons absorbed by the dump before decaying. The $b$-hadrons can be originated by primary protons, and by all the secondary products of the hadronic shower in the dump, as protons, neutrons, and pions. The composition of the shower and the kinematics of the $b$-hadrons have been studied by simulating with Pythia [33] the 400 GeV/c proton beam on $\sim 11 \lambda_I$ Mo-W based target [34], [35].

The momentum and transverse momentum distributions of the particles that produce the $b$-hadrons in the shower are shown in Figure 4. The production of $b\bar{b}$ pairs is due to primary protons and secondary particles, eg. protons, pions, and neutrons generated in the shower. The momentum, transverse momentum and polar angle distributions of the $b$-hadrons produced in the shower are shown in Figure 5, for $b-$hadrons originating from primary and secondary interactions, separately. The $b\bar{b}$ pairs produced by interactions of secondary particles are $\sim 74\%$ of those produced by the interactions of the primary protons. They have on average a softer momentum spectrum and are less boosted in the forward direction. The momentum, transverse momentum and polar angle distributions of the scalar are shown in Figure 6 for primary and secondary interactions, separately.

![Figure 4: Momentum and transverse momentum distributions of the particle that produces the $b$-hadrons in the shower.](image)

The kinematic distributions of light scalar particles originated in the decays $B \to K S$ depends on the mass of the scalar itself. This is shown in Figure 7 where the momentum, transverse momentum and polar angle of the scalar are shown for different values of the mass, $m_S = 1, 2, 3 \text{ GeV}/c^2$. Only scalars produced in primary interactions are considered here. The more the scalar is heavy the more it takes away most of the energy of the system and thus the more is boosted in the forward direction.

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1Primary protons are defined as protons with $p = 400 \text{ GeV}/c$ and $p_T < 10^{-5}$.
Figure 5: Momentum, transverse momentum, and polar angle distributions of the $b$-hadrons in the shower, separately for primary and secondary interactions.
Figure 6: Momentum, transverse momentum, and polar angle distributions of the scalar produced in $b$-hadrons decays, for $b$-hadrons produced in primary and secondary interactions.

Figure 7: Momentum, transverse momentum, and polar angle distributions of the scalar produced in $b$-hadrons decays for three values of the mass of the scalar.
4 The SHiP acceptance

The SHiP detector \cite{24} can reconstruct all the final states with two charged tracks. As an example, in this note we compute the SHiP sensitivity to light scalar particles decaying to two-body final states, $S \rightarrow X^+ X^-$ where $X = e, \mu, \pi, K$.

The number of events of $S \rightarrow X^+ X^-$ reconstructed in the SHiP detector is given by:

$$N_{\text{obs}} = N_S \sum_{X = e, \mu, \pi, K} BR(S \rightarrow f) \times A(f) \times \varepsilon(f)$$

(7)

where $N_S$ is the number of scalars produced in kaon and $b$-hadrons decays, as shown in Eq. 5 and $BR(S \rightarrow f)$ is the branching fraction of the scalar in a given final state $f$. The acceptance $A(f)$ for a light scalar particle of a given mass $m_S$, coupling parameter $\sin^2 \theta$ and decaying into a final state $f = X^+ X^-$ is given by the product of the probability that the light scalar particle decays inside the fiducial volume and of the probability $P(X^+ X^-)$ that the two charged tracks in the final state are reconstructed in the magnetic spectrometer. The efficiency $\varepsilon(f)$ is the product of the trigger, reconstruction and selection efficiencies for the final state. This has been assumed for the time being 40% below the $2 \cdot m_\mu$ threshold and 70% above this threshold, following simulation studies with FairSHiP as documented in Ref. \cite{14}.

We assume in the following the baseline geometry of the SHiP detector as described in the Technical Proposal \cite{24}. A schematic layout is shown in Figure 8. In order to be within the acceptance of the SHiP detector, an event has to satisfy the following requirements:

1. the position of the decay vertex of the scalar is required to be between $D_{\text{min}} = (63.8 + 5)$ m and $D_{\text{max}} = (D_{\text{min}} + L_{\text{FV}} - 8.4)$ m, where $L_{\text{FV}} = 60$ m is the length of the fiducial volume and 8.4 m is the distance between the end of the fiducial volume and the center of the dipole magnet of the downstream spectrometer\footnote{All the distances refer to the production point defined by the target position, unless explicitly stated.};

2. the decay vertex of the scalar is required to be in the transverse plane within a ellipse of 2.5 m and 5 m horizontal and vertical semi-axes, respectively;

3. the decay products are required to cross the spectrometer dipole magnet, thus to be within the same trasverse elliptical area requested for the decay vertex.

The impact of these three requirements on the decay length distribution of a scalar of mass $m = 1 \text{ GeV}/c^2$ and coupling $y^2 = 10^{-10}$ is shown in Figure 9, left. The decay length distributions for three different mass values are shown in Figure 9 (right).
Figure 8: Schematic layout in the $xz$ view of the SHiP geometry as defined in the Technical Proposal.

Figure 9: Left: decay length distribution of a scalar of mass $m = 1$ GeV/$c^2$ and coupling $y^2 = 10^{-10}$ for different requirements on the position of the vertex and acceptance of the decay products. Right: same distribution for three different values of the scalar mass, $m=1,2,3$ GeV/$c^2$. 
The acceptance is a function of the mass and the coupling parameter of the scalar. This is shown in Figure 10 for primary and secondary interactions. This dependence is due to two reasons: the lifetime (and thus the probability for the scalar to decay in the fiducial volume) depends on the mass and the coupling $y^2$; the transverse momenta of the decay products (and thus the probability to be within the spectrometer acceptance) depend on the mass of the scalar. The acceptance is lower for secondary interactions due to the fact that the $b$ spectrum is softer and, therefore, the scalar and its decay products are less boosted in the forward direction and miss the spectrometer.

It is interesting to note that the acceptance does not change sizeably for different final states. This is shown in Figure 11 where the acceptance curve as a function of the scalar mass for a given coupling ($y^2 = 10^{-10}$) is shown for $S \to K^+K^-$ and $S \to \mu^+\mu^-$ final states.

The acceptance as a function of $c\tau$ for different values of the scalar mass is shown in Figure 12 left. The three acceptance curves corresponding to three values of the scalar mass tend to superimpose once they are plotted as a function of $c\tau/m$, as shown in Figure 12 right. This (almost) universal curve can be used to optimize the geometry of the decay volume.

We use as figure of merit the width of the $c\tau/m$ region where the acceptance is above 0.5%. With the nominal geometry this region ranges from $c\tau/m = 30$ cm/GeV to $c\tau/m = 6000$ cm/GeV. Assuming fixed the transverse dimensions of the decay vessel (which are essentially cost-driven), only two other parameters can be optimized: the length of the
Figure 11: Acceptance as a function of the scalar mass for $y^2 = 10^{-10}$ for two different final states, $S \rightarrow \mu^+\mu^-$ and $S \rightarrow K^+K^-$. 

Figure 12: Right: acceptance of the scalar as a function of $c\tau$ for three different values of the scalar mass. Right: acceptance of the scalar as a function of $c\tau/m$ for the same three values of the mass. This (almost) universal curve can be used to optimize the SHiP geometry.

decay vessel and the distance of the vessel from the target. Figure 13 shows how the acceptance as a function of $c\tau/m$ changes for three different values of the vessel length, $L=60, 40, \text{and } 30 \text{ m}$. A loss of about $50 - 70\%$ of events with $c\tau/m > 1000 \text{ cm/GeV}$ is observed for reduction of the decay length of the vessel from 60 m to 30 m while tiny losses are expected for $c\tau/m < 100 \text{ cm/GeV}$. 

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Figure 13: Acceptance as a function of $c\tau/m$ for three different values of the vessel length, $L=60, 40,$ and $30$ m.

The variation of the acceptance as a function of the distance of the decay vessel from the target is shown in Figure 14 for the nominal length of the decay vessel ($60$ m) and three distances with respect to the target, 68.8, 33.8 and 20 m. A large gain is observed by placing the decay vessel near the target, as a consequence of the relatively short average decay length of the scalar at the SPS energy. The $c\tau/m$ range where the acceptance is above 0.5% passes from:

$$30 \text{ cm/GeV} < c\tau/m < 6000 \text{ cm/GeV}$$

to:

$$3 \text{ cm/GeV} < c\tau/m < 20000 \text{ cm/GeV}$$

On the same plot the acceptance for a distance of 20 m and a length of the vessel of 40 m (instead of 60 m) is shown: the loss in acceptance in this case is fully negligible with respect to the cost saving due to a reduced length of the decay volume.
Figure 14: Acceptance as a function of $c\tau/m$ for different distances of the decay vessel from the target, $D_{\text{min}} = 68.8, 33.8$ and 20 m and for the nominal length of the vessel $L = 60$ m. For $D_{\text{min}} = 20$ m the acceptance is computed also for $L = 40$ m.
5 SHiP sensitivity to light scalar particles

Toy Monte Carlo techniques are used to assess the sensitivity contours in the mass-coupling parameter space. This is done by generating light scalar particles with different masses and different values of the coupling parameter, letting them decay in the chosen final states, and computing the corresponding acceptance. The sensitivity contour obtained using the geometry of the SHiP Technical Proposal is shown in Figure 15. This plot shows the exclusion limit at 90% CL in case no event is observed. The range of the accessible $y^2$ values is determined in the lower part of the curve by the number of available protons on target, and on the higher part by the distance of the decay volume from the target. The range of the accessible values of the mass is defined in the left-hand side by the $e^+e^-$ threshold and in the right-hand side by the kinematical limit set by the decay $B \rightarrow KS$.

Figure 16 shows the difference in sensitivity due a reduced distance (28.8 m) of the vessel from the target with respect to the baseline geometry (68.8 m), for the same value of the vessel length (60 m). An increase of about a factor 2 is observed in the high-range of the coupling parameter, where the distance with respect to the target is the driving parameter.

Between the $m_K - m_\pi$ mass and $\sim 5$ GeV, SHiP can put a limit few orders of magnitude better than the world best results obtained by LHCb in that mass range. The sensitivity plots have been obtained in the assumption of zero background events. The impact of background events will be discussed in the next section.

6 Impact of the background in the sensitivity plot

The final state that suffers the most from background contamination is the $S \rightarrow \mu^+\mu^-$ channel. In fact, random combinations of the residual muon flux from proton interactions in the target can mimic the signal if they form a fake vertex in the fiducial volume. The residual muon flux has been estimated in the Technical Proposal to be about 30 kHz (7 kHz) in the SHiP acceptance for muons with momentum greater than 1 (3) GeV/c for $4 \times 10^{13}$ pot/spill, 1 s spill, beam intensity. These muons are spread along the full length of the spill and thus they can be effectively rejected using a short time coincidence.

Figure 17 shows the number of dimuon events reconstructed and selected in $2 \cdot 10^{20}$ protons on target as a function of the residual muon flux rate in the SHiP acceptance and for different time windows of $\pm 3.29\sigma_T$, where $\sigma_T$ is the time resolution of the arrival time of the muon in the downstream detector. In the computation of the number of dimuon events we assume, as in the TP [24], a selection efficiency $\epsilon(\text{sele}) = 10^{-4}$ and an Upstream Veto efficiency for two muon tracks, $\epsilon(\text{veto}) = 10^{-4}$. The selection efficiency is based on the kinematic cuts studied in the TP [24] and reported in Table 1. For these selection requirements less than 2 background events are expected per $2 \cdot 10^{20}$ pot up to 90 kHz of muon flux in the full mass range. Current simulation [38] shows that the expected muon flux is $\sim 50$ kHz. In case of fully reconstructed events that point back to the target, as in the case of scalar’s decays, the cut in the impact parameter can be tightened from 250 cm
Figure 15: Sensitivity contours for a light scalar particle mixing with the Higgs in the plane $\sin^2 \theta$ versus mass. Shaded areas are already excluded parameters regions by past experiments, dotted lines are sensitivities of planned experiments. The SHiP sensitivity corresponding to $N_{\text{pot}} = 2 \cdot 10^{20}$ is shown as the blue dotted line.

to 10 cm, further reducing this background.

In order to study the impact of the background on the SHiP sensitivity, we assume to have one background event in each mass window of $\pm 3 \cdot \sigma_m \sim 24$ MeV/c$^2$, hence about 200 background events uniformly distributed in the full mass window. The upper limit at 90% CL without and with background is shown in Figure 15. For 2-track final states, the 200 background events uniformly distributed in the full mass range reduce the 90% CL exclusion limit to up to 40%, depending on the values of the mass and coupling parameter. The upper limit at 90% CL without background events corresponds to a 3$\sigma$ evidence for 2 signal events in presence of 0.1 background events per 24 MeV/c$^2$ mass bin. The curve for the 3$\sigma$ evidence in presence of 200 background events uniformly distributed in the mass range is also overlayed: the presence of the background reduce the 3$\sigma$ sensitivity by up to a factor of two, which is equivalent to reduce the number of protons on target by a factor four.
Figure 16: SHiP sensitivity in the $y^2$ versus $m_S$ plane for the nominal geometry ($D_{\text{min}} = 68.8$ m and $L = 60$ m, black line) and for a reduced distance of the vessel from the target ($D_{\text{min}} = 28.8$ m) (red line). The reduction of the distance of the vessel from the target by a factor of $\sim 2$ improves the sensitivity by almost the same factor in the top part of the range of couplings.

Table 1: Selection requirements for the muon combinatorial background as in the TP.

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Figure 17: Number of dimuon background events reconstructed and selected as discussed in the text, collected in $2 \times 10^{20}$ pot as a function of the residual muon rate and for a time window of $\pm 3.29 \sigma_T$. 
Figure 18: SHiP sensitivity for a light dark scalar mixing with the Higgs: 90% CL upper limit in absence of background (black solid line), 90% CL upper limit with 200 background events (red dotted line), 3 \sigma evidence with 200 background events uniformly distributed in the mass range 200 - 4800 MeV/c^2 (blue dashed line).
7 Conclusions

The SHiP experiment has a large potential to discover (or set exclusion limits for) a light scalar particle mixing with the Higgs in a still poorly covered region of the parameters space. In 5-years of operation with $2 \cdot 10^{20}$ protons on target, SHiP can improve by few orders of magnitude over the LHCb results between the $2m_\mu$ threshold and $\sim 5 \text{ GeV}$. The dependence of the sensitivity as a function of the distance of the vessel from the target and as a function of the decay vessel length has been also studied. No sizeable change in sensitivity is expected by reducing the vessel length from 60 m to 40 m, while a gain in sensitivity up to a factor of two is achieved when the distance between the target and the vessel is reduced from 68.8 m to 20 m. While SHiP has being designed to be a zero background experiment, the impact of a hypothetical background on the sensitivity has been studied. For 2-track final states, 200 background events uniformly distributed in the full mass range reduce the 90\% CL exclusion limit to up to 40\%, and the 3\(\sigma\) sensitivity curve by up to a factor of two, depending on the values of the mass and coupling parameter.
References


