Decaying light particles on board the SHiP (I):
Signal rate estimates for hidden photons

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I. INTRODUCTION: THE EXPERIMENT AND THE MODEL TO BE TESTED

Unsolved phenomenological problems — neutrino oscillations, dark matter phenomena, baryon asymmetry of the Universe — definitely ask for an extension of the Standard model of particle physics (SM). It is natural to find the corresponding new particles at a mass scale not much higher than the electroweak scale. Otherwise the hierarchy problem arises in the scalar sector: quantum corrections of heavy particles push the SM Higgs boson mass up to their mass scale. While LHC scrutinizes thoroughly the (sub)TeV scale, there is a logical possibility to have so far elusive new physics at (much) lower scale. The absence of any direct evidence of the new physics may be attributed to the weakness of interaction between known and new particles. In search for such new physics the superior are experiments operating on the high intensity frontier.

An example of this type of experiments is SHiP (Search for Hidden Particles [1]), the recently proposed [2] new fixed target experiment at CERN SPS 400 GeV proton beam. The original motivation [3] was to search for O(1) GeV sterile neutrinos of νMSM: one of the most economic extensions of the SM capable of explaining all the three aforementioned phenomenological problems with only three new fields (singlet with respect to SM gauge groups fermions) added to the SM, see [4] for review. Mixing between singlet fermions and active neutrinos is responsible for both the singlet production in decays of heavy mesons (generated by protons on target) and subsequent singlet decays into SM particles (the main signature for the SHiP detector), see [5] for details. The flux of secondary particles from proton scatterings is suppressed by the very dense (tungsten) dump placed downstream. The main idea is to have detector large (5×5 m²×50 m [2]) and place it as close to the target as possible (at a distance of about 60 m [2]) in order to maximize the number of potential singlet decays within the detector fiducial volume and still have the background under control. This makes SHiP a universal tool to probe any new physics which introduces sufficiently light and long-lived particles produced by protons on target and then decaying into the SM particles.

In this paper we consider one of the examples of such new physics providing with long-lived light particles to be searched for at SHiP: models with massive hidden photons. The SM Lagrangian $\mathcal{L}_{SM}$ is extended in the following way:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'_{\mu} A'^{\mu},$$

where $A'_\mu$ is a massive gauge field of a new (dubbed dark) $U'(1)$ group, $F'_{\mu\nu} \equiv \partial_{\mu} A'_{\nu} - \partial_{\nu} A'_{\mu}$, and $\epsilon$ is the parameter of kinetic mixing. This mixing provides effective coupling between massive photon $A'$ and pairs of the SM charged particles, which determines the model phenomenology. Hidden photon may be a messenger of the hidden sector, that is responsible for (some of) the unsolved problems we started with (see e.g. [6] for dark matter). Present phenomenological limits on $\epsilon$ and $m_{A'}$ are shown in Fig. 1.

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FIG. 1. Present limits on the hidden photon model parameter space, see [7], [8], [9] for details. Red shaded region shows the expected limits from SHiP, see Sec. IV.
hidden photon decays inside the SHiP detector. This is the first step towards the estimate of the SHiP sensitivity to the models with light hidden photons, that in order to be completed requires fixing the experiment layout, understanding the detection efficiency and calculating the expected background.

II. PRODUCTION MECHANISMS

Hidden photons can be produced directly, via proton (quark) or lepton bremsstrahlung, and indirectly, in meson decays. The relevant leptons and mesons are secondary particles produced either at proton scattering off target or when the initiated by scattering hadron and lepton cascades propagate in the dump material.

A. Proton bremsstrahlung

In a fixed target experiment particles $A'$ are generated by scattering protons through a process analogous to ordinary photon bremsstrahlung. Consider a proton of mass $m_p$ with initial 3-momentum $P$ and initial energy $E_p$. Let $E_{A'}$ be the energy of $A'$ and $z$ denote fraction of the momentum $P$ carried away by $A'$ in the direction of incoming proton. Thereby $P_z = p_{z|}$, $p_{||}$ and $P_{\perp}$ are longitudinal and transverse components of $A'$ 3-momentum $P_{A'}$. Differential $A'$-production rate per proton interaction, calculated in the Weizsäcker-Williams approximation, reads [9]:

$$\frac{dN}{dz dp_{\perp}^2} = \frac{\sigma_{pA}(s')}{\sigma_{pA}(s)} \frac{w_{ba}(z, p_{\perp}^2)}{2\pi H},$$

(2)

where $s' = 2m_p(E_p - E_{A'})$, $s = 2m_pE_p$ and

$$w_{ba}(z, p_{\perp}^2) = \frac{\alpha_{\text{QED}}^2}{2\pi H} \left[ 1 + (1 - z)^2 \right] - 2z(1 - z) \left( \frac{2m_p^2 + m_{A'}^2}{H} - z^2 \frac{2m_p^4}{H^2} \right) + 2z(1 - z) (z + (1 - z)^2) \frac{m_p^2 m_{A'}^2}{H^2} + 2z(1 - z)^2 \frac{m_{A'}^4}{H^2} \right]$$

with $H(p_{\perp}^2, z) = p_{\perp}^2 + (1 - z)m_{A'}^2 + z^2 m_p^2$ and fine structure constant $\alpha_{\text{QED}} \approx 1/137$. The hadronic cross section is factorized and related to the proton-proton scattering cross section $\sigma_{pp}$ as $\sigma_{pA}(s) = f(A)\sigma_{pp}(s)$ with function $f(A)$ depending only on atomic number $A$. Thus it drops out in expression for event rate (2). For inelastic proton-proton cross section we use the fit from [10].

Equation (2) was originally derived [11] under a set of specific conditions. For a beam-dump type experiments these conditions could be summarized as follows [9]:

$$E_p, E_{A'}, E_p - E_{A'} \gg m_p, m_{A'}, \sqrt{p_{\perp}^2}.$$  

(3)

Another restriction comes from our treatment of scattering proton as entire particle and not the bunch of partons: we consider proton, but not quark, bremsstrahlung at high energies. To ensure dealing with the entire proton we restrict proton-nuclei momentum transfer: $(P - P_{f} - P_{A'})^2 \ll \Lambda_{\text{QCD}}^2$, where $P_f$ denotes the 3-momentum of outgoing proton. Then, we also require 3-momentum of produced $A'$ to be inside a cone determined by a detector geometry (see Sec. IV A). We have checked numerically that the latter two restrictions guarantee the fulfillment of conditions (3). These two restrictions are summarized in the following function:

$$f(z, p_{\perp}^2) = \theta (\Lambda_{\text{QCD}}^2 - (P - P_{f} - P_{A'})^2) : f_{\text{fiducial}}.$$  

(4)

with $f_{\text{fiducial}}$ referring to the restriction from the detector geometry. Finally, to obtain a number of $A'$ which trajectories cross the fiducial volume of detector one integrates eq. (2) with factor (4).

Provided our restrictions we arrive at the conservative lower limit on the hidden photon flux.

B. Secondary particles bremsstrahlung

Hidden photons can be created by secondary particles in the beam dump (tungsten, lead, etc.). $A'$-production cross section in the electron bremsstrahlung process was calculated in [12] in the Weizsäcker-Williams approximation. For incoming electron of energy $E_0$ the differential cross section to produce $A'$ of energy $E_{A'} \equiv xE_0$ is

$$\frac{d\sigma}{dx d\cos\theta_A} \approx \frac{8Z^2\alpha_{\text{QED}}^3e^2E_0^2x}{U^2} \frac{\chi}{Z^2} \left[ (1 - x + x^2/2) - x(1 - x)m_{A'}^2E_0^2x \theta_A^2 \right],$$

(5)

where $\theta_A$ is the angle in the lab frame between the emitted $A'$ and the incoming electron, $Z$ is atomic number of the dump atoms,

$$U = U(x, \theta_A) = \frac{E_0^2x}{U} \frac{\theta_A^2 + m_{A'}^2}{x} + m_{e}^2x,$$

(6)

and an effective flux of photons (emitted by rapidly moving atom in the rest frame of incoming electron) is defined as follows:

$$\chi \equiv \int_{t_{\text{min}}}^{t_{\text{max}}} dt \frac{t - t_{\text{min}}}{t^2} G_2(t),$$

(7)

where $t_{\text{min}} = (m_{A'}^2/2E_0)^2$, $t_{\text{max}} = m_{A'}^2$, and $G_2(t) = G_{2,\text{el}}(t) + G_{2,\text{in}}(t)$ is a general electric form factor, sum of elastic and inelastic parts, see [12] for details. To simplify numerical integration we neglect $x$- and $\theta_A$-dependences of $t_{\text{min}}$ in (7). This can lead [13] to an overestimate of the cross section by $\sim 30\%$, which affects only insignificantly our results for the SHiP discovery potential.
C. Production in meson decays

Hidden photon \( A' \) can emerge in meson electromagnetic decays (if kinematics admits) due to mixing with photon. For the corresponding branching ratio of \( \pi^0 \) meson decay one has the following estimate [14]:

\[
\text{Br}(\pi^0 \to A' \gamma) \approx 2e^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \text{Br}(\pi^0 \to \gamma\gamma). \quad (8)
\]

There is a similar expression for \( \eta^0 \)-meson with obvious replacement \( \pi^0 \leftrightarrow \eta^0 \) in (8).

For branching ratios of vector meson \( V \) (e.g. \( V = \rho^\pm, \rho^0, \omega \)) decays into \( A' \) and pseudoscalar meson \( P \) (e.g. \( P = \pi^\pm, \pi^0, \pi^0 \)) one finds:

\[
\text{Br}(V^\pm \to PA') \approx e^2 \times \text{Br}(V^\pm \to P\gamma) \times \frac{(m_V^2 - m_{A'}^2 - m_P^2)^2 \sqrt{(m_V^2 - m_{A'}^2 + m_P^2)^2 - 4m_{V^*}^2m_P^2}}{(m_V^2 - m_{A'}^2)^3},
\]

where \( m_V \) is mass of the decaying vector meson and \( m_P \) is mass of the pseudoscalar meson.

We are interested only in the mesons with the sufficient decay branching ratio. Another obvious requirement is that the very mesons should be produced in sufficient amount in the SHiP setup. Therefore, in what follows we account only for \( \pi^0 \) and \( \eta^0 \) contributions.

III. HIDDEN PHOTON DECAY PATTERN

Photon-paraphoton mixing \( \epsilon \) is responsible for hidden photon decays into pairs of charged SM particles. Partial decay width into a lepton pair is given by [9]

\[
\Gamma_{A'}^{l+l-} = \frac{1}{3} \alpha_{\text{QED}} m_{A'} e^2 \sqrt{1 - \frac{4m_l^2}{m_{A'}^2}} \left(1 + \frac{2m_l^2}{m_{A'}^2}\right),
\]

where \( m_l \) is the lepton mass. Partial decay width into hadrons can be estimated as

\[
\Gamma_{A'}^{\text{hadrons}} = \frac{1}{3} \alpha_{\text{QED}} m_{A'} e^2 \cdot R(m_{A'}),
\]

where

\[
R(\sqrt{s}) = \frac{\sigma(e^+ e^- \to \text{hadrons})}{\sigma(e^+ e^- \to \mu^+ \mu^-)}.
\]

is the energy \( \sqrt{s} \) dependent ratio [10]. Resulting branching ratios for the three relevant channels are shown in Fig.2.

Neglecting possible invisible decay modes (e.g. those associated with decay into hidden sector particles if exist) one has for the total decay width:

\[
\Gamma_{A'}^{\text{tot}} = \Gamma_{A'}^{l+l-} + \Gamma_{A'}^{\mu^+\mu^-} + \Gamma_{A'}^{\text{hadrons}}.
\]

Thus \( A' \) decay length reads (see also Fig.2):

\[
\gamma c\tau_{A'} = \frac{c\gamma}{\tau_{A'}},
\]

with \( \gamma \)-factor in laboratory frame \( \gamma = E_{A'}/m_{A'} \).

IV. SIGNAL EVENT RATE

A. hidden photon decays inside the SHiP detector

Probability for \( A' \) to decay inside the fiducial volume of the detector reads:

\[
w_{\text{det}} \equiv w_{\text{det}}(E_{A'}, m_{A'}, \epsilon) = \exp\left(-\frac{l_{\text{sh}}}{\gamma(E_{A'}) c\tau_{A'}}\right) \times \left[1 - \exp\left(-\frac{l_{\text{det}}}{\gamma(E_{A'}) c\tau_{A'}}\right)\right],
\]

where \( l_{\text{sh}} \) is the muon shielding length (60 m for SHiP [2]) and \( l_{\text{det}} \) is the length of the detector fiducial volume (50 m).

Proposed fiducial volume of the SHiP detector is 50 m length cylindrical vacuum vessel of 5 m diameter. To estimate expected number of events we use more conservative volume that is the cone with the vertex in a target pointing to the 5 m diameter circle at the end of the fiducial volume. Thus we select \( A' \)-s with momenta inside
that cone, which means:

\[
\frac{|p_\perp|}{p_\parallel} < \frac{2.5}{60 + 50} = \theta_0. \tag{14}
\]

We apply this cut to the momenta of hidden photons produced via bremsstrahlung. The corresponding restriction on momentum space refers to \( f_{\text{fiducial}} \) in (4).

For the proton channel one integrates differential flux (2) with \( w_{\text{det}} \) over the region limited by (14). The number of \( A' \) decays in the detector is then given by:

\[
N_{\text{sig}} = N_{\text{POT}} \frac{\sigma_{\text{pp}}(\theta)}{\sigma_{\text{pp}}(\theta')} \int \! dz dp_\perp^2 w_{\text{ba}}(z, p_\perp^2) w_{\text{det}} f(z, p_\perp^2). \tag{15}
\]

where \( f(z, p_\perp^2) \) is defined in eq. (4). We assume that total number of protons on target will be \( N_{\text{POT}} = 10^{20} \). Expected number of events is shown in Fig. 3 (left panel). Feature at 0.8 GeV is due to \( \omega \)-meson peak in ratio (11).

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{\( \log_{10} \) of expected number of \( A' \) in the detector fiducial volume: proton bremsstrahlung (left panel) and meson decays (right panel).}
\end{figure}

To roughly estimate contribution of secondary protons we assume that their average energy is (400 GeV/multiplicity) and apply the same procedure described above.

\section*{B. Monte-Carlo simulation}

Proton hitting the target initiates a shower of secondary particles inside the target and muon dump. To precisely account for energy and angular distributions of secondaries we simulate both hadronic and electromagnetic component of showers. We use Geant4 simulation toolkit [15] for this purpose.

Since SHiP muon dump design is under discussion we chose the most simple geometry for the proton target and muon dump: rectangular parallelepiped of 40 \( \times \) 40 cm\(^2\) front section and 60 m length, made of tungsten. Protons of 400 GeV are directed to the target.

We set Geant4 standard options for particle lists and electromagnetic processes. The only essential choice is selection of inelastic hadronic processes generator. We applied 2 recommended options—FTFP_BERT (FRITIOF model) and QGSP_BIC (quark gluon string model)—and found significant difference in both proton interaction cross-section and energy-angular dependence of produced secondary particles. We compared inclusive cross-section with ref. [16] and accepted usage of QGSP_BIC model.

Cases of short-lived and long-lived particles are processed differently as follows:

- for each meson produced in program we save its type \((\pi^0, \rho^0\text{ or } \eta)\), its 3-momentum \( p \), that is energy and angle to beam axis \( \theta_z \);

- for leptons we fill in the histograms with the total lengths of tracks of the particles with given energy \( E_0 \): \( L(E_0) = \sum \Delta l(E=E_0, \theta_0 \leq \theta_0) \), where sum runs over all segments \( \Delta l(E, \theta) \) of all tracks of the particles in the shower inside material. We chose binning 0...400 GeV with bin step 0.5 GeV. In this way we get four distinct histograms for \( \mu^+, \mu^-, e^+, e^- \) as shown in Fig. 4.

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Overall length of tracks of the particles with energies in a given bin. Result of 160 000 protons on target simulation.}
\end{figure}

To accelerate simulation we apply cut \( p > 0.01 \text{ GeV} \) to all particles. 160K of primary protons have been generated to estimate the dark photon rates.

\section*{C. Analysis}

Using distributions described above we calculate number of signal events inside the detector. For meson channel the number of events is simply \( N_{\text{sig}} = \sum_p N_m(p) \text{Br}(m \rightarrow A'X) w_{\text{det}} C_{\text{cut}} \), where \( p \) is meson momentum, \( m \) stands for meson type, e.g. \( \pi^0, \eta^0 \), \( N_m(p) \) is amount of mesons with given 3-momentum, Br is defined in (8), (9). Momentum dependent numerical coefficient \( C_{\text{cut}} \) accounts for the fraction of \( A' \) travelling through the fiducial volume. In \( N_m \) we count only mesons with \( \theta_z < \theta_0 \). The resulting number of signal is presented in Fig. 3.
For secondary electrons propagating in the dump medium one estimates the number of produced hidden photons as

\[ N \simeq n_a \sum_{E_0} \sigma_{\text{forward}} L(E_0), \]  

(16)

where \( n_a \) is nuclei number density, \( \sigma_{\text{forward}} \) is differential cross section (5) integrated with respect to the geometry constraint and \( E_0 \) is the electron energy.

Using this distribution we calculate number of \( A' \) decays inside the detector. Partial contributions of the proton, lepton and meson channels to the signal event number are shown in Fig. 5. At small masses meson decays dominate. Proton bremsstrahlung channel starts to dominate when \( m_{A'} > m_\rho \) since heavier \( A' \) could not be produced in meson decays in sufficient amounts. In the whole mass region lepton bremsstrahlung contribution is negligibly small and hence omitted.

To define domain of parameters \( m_{A'} \) and \( \epsilon \) where SHiP will be sensitive to hidden photon we assume that 10 events per \( 10^{20} \) POT will be sufficient access above a background. Exclusion limits are shown in Fig. 1. Solid black line represents contribution of initial and secondary protons, dotted black line represents contribution of initial protons alone. As shown in Sec. III \( A' \) lifetime is proportional to \( \epsilon^{-2} \) thus the upper border of the region in Fig. 1 corresponds to a quick decay of the \( A' \). For the values of \( \epsilon \) above the upper line the hidden photons decay within the shielding. The lower border of the region corresponds reciprocally to a slow decay.

![Graph](image)

**FIG. 5.** Partial contribution of proton, meson and electron channels to the total number of events. The kinks on the proton and electron lines near the pion mass correspond to the kinematic cut of the pion branching ratio.

V. DISCUSSION

To summarize we have estimated the hidden photon signal rate expected in SHiP experiment, and outlined the region in model parameter space, see Fig. 1, where 10 paraphoton decays in 50 m-length detector are expected for each \( 10^{20} \) protons on target. The results are rather conservative and may be improved with account of: (i) \( \rho, \omega \) and other short-lived hadron contributions to hidden photon production via decay, (ii) \( \pi^\pm \) and other long-lived hadron contributions to hidden particle production via bremsstrahlung, (iii) quark bremsstrahlung contribution. However, since the number of signal events scales with mixing as \( \epsilon^4 \), we expect no significant change of our results. As the next steps, the real experiment geometry, detection efficiency and background events must be analyzed to find the sensitivity of SHiP to the hidden photon models.

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