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TESTING STERILE NEUTRINOS WITH NEW FIXED TARGET EXPERIMENT AT CERN SPS

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We discuss the recently proposed new fixed target experiment at CERN with SPS beam of 400 GeV protons aimed at searches for sterile neutrinos produced in charmed hadron decays. The three sterile neutrinos introduced to the Standard Model can explain the active neutrino masses and mixings by means of seesaw type I mechanism, baryon asymmetry of the Universe by making use of leptogenesis via sterile-active neutrino oscillations in the primordial plasma, and dark matter phenomenon due to a relic component of the lightest sterile neutrino. The new beam-dump with detector placed as close to the target as possible will allow one to test many other extensions of the Standard Model with new unstable yet long-lived particles at GeV mass scale.

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1. MAIN MOTIVATION: NEUTRINO PHYSICS

So far neutrino oscillations provide the only direct and convincing evidence for a hidden structure beyond the Standard Model of particle physics (SM). Phenomenological explanation of the observed oscillations is achieved by introducing two neutrino mass differences (so-called solar, $\Delta m^2_{\rm sol}$, and atmospheric, $\Delta m^2_{\rm atm}$, neutrino mass squared) and three angles to describe mixing between gauge (flavor) and mass eigenstates.

The combined analysis of T2K and Daya Bay data shows some hint of nonzero CP-phase [1], more chances to probe it come with Novae experiment. The masses themselves are not fixed by the present experiments. Naturally, one expects three nonzero masses. The hierarchy between the two observed mass differences, $\Delta m^2_{\rm sol} \ll \Delta m^2_{\rm atm}$, implies a hierarchical pattern in neutrino mass eigenstates, m_i, $i = 1, 2, 3$: normal or inverted, see Fig. 1, *a*. Determining the type of neutrino mass hierarchy in oscillation experiment is a challenge. Combined analysis of cosmological data exhibits higher sensitivity to the neutrino

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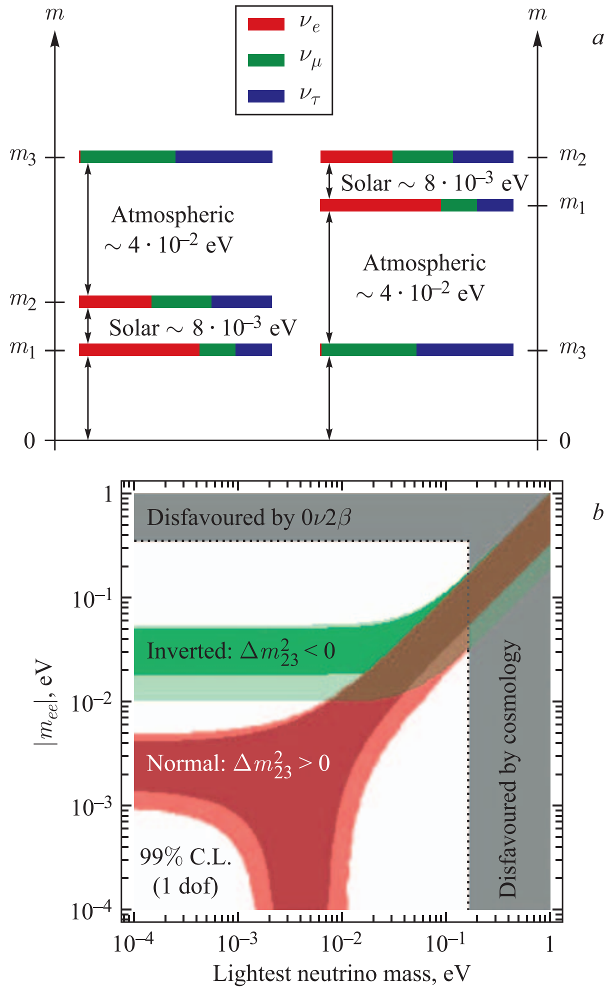

Fig. 1. *a*) Mass hierarchies in neutrino sector. *b*) Limits on neutrino sector parameters from cosmology and searches for neutrinoless double β-decays [2]

masses, limiting sum of neutrino mass $\sum_i m_i \lesssim 0.5$ eV, see Fig. 1, *b*. The final release of Planck experiment may exclude the inverted hierarchy scenario. Future galaxy surveys, e.g., provided by EUCLID, extend the sensitivity of cosmological experiments to the normal hierarchy case [3]. Finally, if lepton number is violated in neutrino sector, there are two Majorana phases, to which oscillation experiments are blind. The Majorana nature of neutrino masses may be tested by neutrinoless double β-decay experiments, sensitive to $|m_{ee}| = \left|\sum\limits_i U_{ei}^2 m_i\right|$ (see Fig. 1, *b*), where U_{ei} stand for the elements of neutrino mixing matrix.

Neutrino oscillations can be described with the SM field content by introducing nonrenormalizable dimension-5 term

$$\mathcal{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda} \bar{L}_\alpha \tilde{H} H^\dagger L_\beta^C + \text{h.c.} \tag{1}$$

to the model Lagrangian. Here L_α are SM leptonic doublets, $\alpha, \beta = e, \mu, \tau$, $\tilde{H}_a = \epsilon_{ab} H_b^*$, where H_a is the SM Higgs doublet and ϵ_{ab} is antisymmetric matrix, $a, b = 1, 2$, hereafter upper index C denotes charge conjugated quantity; Λ is the high-energy scale, where the interaction (1) appears, $F_{\alpha\beta}$ are dimensionless parameters. When the Higgs field gets nonzero vacuum expectation value $\langle H^T \rangle = \left(0, v/\sqrt{2}\right)$, $v = 246$ GeV, Eq. (1) yields neutrino mass term

$$\mathcal{L}_{\nu\nu}^{(5)} = \frac{v^2 F_{\alpha\beta}}{4\,\Lambda} \frac{1}{2} \bar{\nu}_\alpha \nu_\beta^C + \text{h.c.} = m_{\alpha\beta} \frac{1}{2} \bar{\nu}_\alpha \nu_\beta^C + \text{h.c.} \tag{2}$$

In Eq. (1) parameter Λ refers to the energy scale of new dynamics giving rise to this effective interaction at low energies. The model has to be UV-completed at this scale. Parameters $F_{\alpha\beta}$ reflect the strength of new dynamics. Neutrino masses fix only ratio of $F_{\alpha\beta}$ and Λ, see Eq. (2). Given this degeneracy, there are two options for the model parameters. First, one can take the *natural values of coupling constants*, $F_{\alpha\beta} \sim 1$, then Eq. (2) yields

$$\Lambda \sim 3 \cdot 10^{14}\ \text{GeV} \left(\frac{3 \cdot 10^{-3}\ \text{eV}^2}{\Delta m_{\text{atm}}^2} \right)^{1/2},$$

which implies a huge hierarchy between the electroweak scale $\Lambda_{\text{EW}} \sim 100$ GeV and the new dynamics scale Λ. In particular, one expects then quantum corrections to the SM Higgs boson mass of order Λ. One may invoke the supersymmetry to cure the model, however no signal of superpartners at LHC and absence of non-SM contributions in flavor physics make it questionable. Second, one can take $\Lambda \lesssim \Lambda_{\text{EW}}$ and hence *hierarchical values of coupling constants*, $F_{\alpha\beta} \ll 1$. This option suggests a new physics below the electroweak scale, which we have not recognized by now because it is tiny coupled to SM fields. This is precisely the physics to be tested directly at a fixed target experiment.

As an example of phenomenologically viable model of this type, we consider the seesaw type I scheme [4], where to the SM one adds three massive Majorana fermions N_I, $I = 1, 2, 3$, singlets with respect to the SM gauge group. One can introduce renormalizable interactions between SM fields and the singlets, which provide mass mixing between the latter and SM neutrinos. Consequently, the singlets are called *sterile neutrinos*, while the SM neutrinos are *active neutrinos*.

Mass eigenvectors in the active neutrino sector are naturally rotated with respect to gauge basis, that yields masses and mixing needed to explain neutrino oscillations. The scheme is rather attractive: (i) only 6 new degrees of freedom (3 Majorana fermions) are exploited, (ii) the model is renormalizable (hence valid up to the Planck scale), (iii) adjusting the model parameters, one can explain the baryon asymmetry of the Universe via leptogenesis, (iv) lightest of the sterile neutrino can serve as dark matter particle. Sterile fermions play the role of right-handed components in the neutrino sector making it completely similar to the quark sector, where both left-handed and right-handed components are present.

The sterile neutrino Lagrangian reads

$$\mathcal{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^C N_I + \text{h.c.}, \tag{3}$$

where M_{N_I} are Majorana masses and $f_{\alpha I}$ are Yukawa couplings. When the Higgs field gains nonzero vacuum expectation value, the mass terms appear in the joint neutrino sector:

$$\mathcal{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^C N_I + \text{h.c.} =$$

$$= \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^C\right)\begin{pmatrix} 0 & v\,\dfrac{\hat{f}}{\sqrt{2}} \\ v\,\dfrac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^C\,, N_I\right)^T + \text{h.c.}$$

Then for $M_N \gg \hat{M}_D = v\,\dfrac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues in sterile and active subsectors:

$$\simeq \hat{M}_N \quad\text{and}\quad \hat{m}^\nu = -\hat{M}_D\frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\frac{v^2}{M_N} \propto \frac{M_D^2}{M_N^2}\,M_N \lll M_N,$$

which nicely illustrates how the seesaw mechanism works: the active neutrino masses are double suppressed by small parameter M_D/M_N, thus explaining the smallness of active neutrino masses. The active neutrino flavor state (eigenvector in the gauge basis) is a linear combination of mass eigenstates

$$\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I}N_I,$$

where $U_{\alpha i}$ is the PMNS matrix describing mixing in the active neutrino sector, so that $U^T\hat{m}^\nu U = \text{diag}\,(m_1\,, m_2\,, m_3)$. In the seesaw framework the active-sterile mixing is small,

$$\theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1.$$

Integrating out the heavy sterile neutrinos, one can obtain from (3) the effective interaction (1) suited for describing the processes with energy transfer smaller than sterile neutrino masses, $|Q^2| \ll M_N^2$. At the sterile neutrino mass scale, one has the following matching condition:

$$\frac{\hat{F}}{\Lambda} = \hat{f}^T \hat{M}_N^{-1} \hat{f}.$$

2. νMSM: 3 IN 1 (NEUTRINO OSCILLATIONS, DARK MATTER, BARYON ASYMMETRY OF THE UNIVERSE)

Lagrangian (3) contains 18 independent physical parameters, 9 of which describe masses and mixing in active neutrino sector. The rest (3 sterile neutrino masses, 3 sterile-active mixing angles and 3 CP-violating phases) may be chosen at will. One can use this choice to explain phenomenological problems coming from cosmology and astrophysics: baryon asymmetry of the Universe and dark matter. With sterile neutrino mass scale *below electroweak scale*, one can solve both the problems [5].

Majorana mass term in (3) breaks lepton symmetry, which allows one to produce lepton asymmetry in the early Universe. Oscillations between sterile and active neutrinos in primordial plasma result in redistribution of lepton charge between active and sterile neutrinos [6]. The former participate in gauge interactions, and electroweak sphaleron processes operating at plasma temperature $T > 100$ GeV transfer part of lepton asymmetry from neutrino sector to baryon asymmetry in quark sector [7]. With relatively light sterile neutrinos, $M_N < 100$ GeV, sterile-active mixing $\theta \propto fv/M_N$ is naturally small, given the smallness of active neutrino masses $m^\nu \propto \theta^2 M_N$. This prevents sterile neutrino equilibrating in plasma and washing out the lepton asymmetry. For the three sterile neutrinos mixing strength is enough to produce the required amount of baryon asymmetry [8]. With only two sterile neutrinos involved into oscillations, one needs to fine tune model parameters: sterile neutrinos must be degenerate in mass, $\Delta M_N \ll M_N$, to generate enough lepton asymmetry and save it from washing out due to thermalization [9]. In this case the third sterile neutrino may be utilized to explain the dark matter phenomena [5]. Its mixing with active neutrino must be sufficiently small to avoid thermalization in the early Universe: otherwise sterile neutrino decouples from plasma being relativistic and forms *too hot* dark matter component inconsistent with presence of dwarf galaxies, see, e.g., [10]. Sterile neutrino dark matter must be produced non-thermally: in decays of inflaton [11] or through the neutrino oscillations in primordial plasma as explained below.

In case of oscillation mechanism there are two options: normal and resonant productions. The first option refers to the dark matter production rate proportional

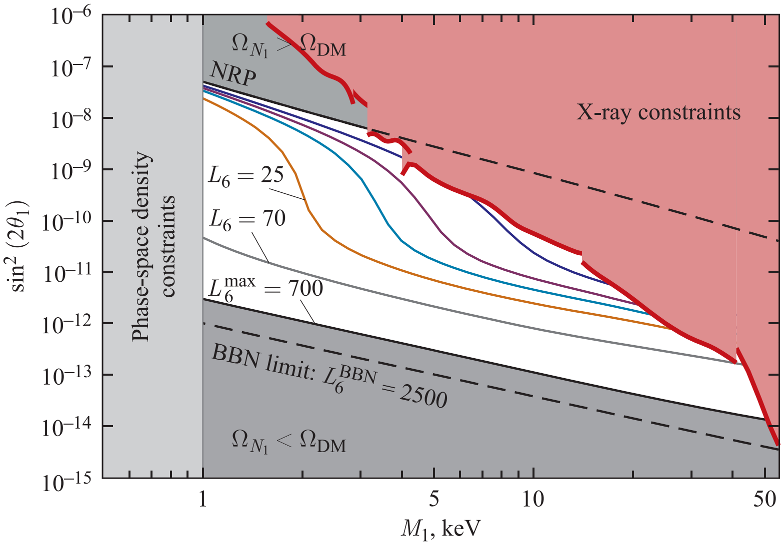

Fig. 2. Region of masses and mixing angles for sterile neutrino to be dark matter [5]: at solid line (NRP) one obtains right amount via oscillations in primordial plasma, if lepton asymmetry is present (L_6 indicates lepton asymmetry in units 10^{-6}), the right amounts are for parameter values along the corresponding thin lines. There are also limits from orbital X-ray telescope searches for anomalous lines, and a conservative limit from studies of dark matter phase-space density. In the region indicated as $\Omega_{N_1} < \Omega_{\rm DM}$ other than oscillations mechanism of dark matter production must be exploited (e.g., inflaton decays)

to the mixing squared angle, which we denote as θ_1. Hence, for a particular sterile neutrino mass the mixing is fixed, if sterile neutrino forms the dominant component of dark matter, see Fig. 2. The same mixing is responsible for the instability of the dark matter neutrino: it decays into three active neutrinos. Neutrino lifetime must exceed the age of the Universe, which places an upper limit on sterile-active mixing. Yet more severe constraints come from searches for two-body decay of sterile neutrino into active neutrino and photon emerging at one-loop level due to virtual W boson and charged lepton. Its rate is [5]

$$\Gamma_{N\to\nu\gamma} \simeq 5.5\cdot 10^{-22}\theta_1^2 \left(\frac{M_1}{1\,\text{keV}}\right)^5 \text{s}^{-1}.$$

There must be a photon monochromatic line in the sky at energy $E_\gamma = M_N/2$, its relative width is about 10^{-3} associated with typical dispersion in velocities of galactic dark matter particles. The present limits on mixing are presented in Fig. 2.

The second option refers to the oscillations in lepton-asymmetric plasma [12]. There for a narrow width of neutrino momentum the effective mixing in plasma becomes of order one similar to MSW-effect in the Sun. Hence the (vacuum) mixing may be smaller than in the normal case, and still enough to generate required amount of dark matter, see Fig. 2. The required amount of lepton asymmetry must be produced after electroweak phase transition, at temperatures $T < 100$ GeV. It may be achieved with two heavier sterile neutrinos, but with much stronger degeneracy, $\Delta M_N \sim 10^{-7}$ eV [13]. This minimal model with three sterile neutrinos is known as νMSM (neutrino minimal extensions of the SM), see details in [5].

At small mass range, primordial sterile neutrinos are too hot to explain small scale structures, the conservative limit is $M_N > 1$ keV [14]. Confronting the phase-space density evolution with observation of dwarf galaxies of the highest dark matter population places stronger lower limit, so that for non-resonant production one obtains $M_N > 5.7$ keV [15], which excludes this mechanism given the limits from X-rays, see Fig. 2.

3. NEW EXPERIMENT ON DIRECT SEARCHES AT SPS

Sterile neutrinos of masses at GeV scale may be searched for in meson decays, e.g., $B \to \mu N$, $D \to \mu\pi N$, etc., see Fig. 3. Sterile neutrinos responsible for the active neutrino masses via seesaw type I mechanism are unstable and decay into SM particles, see Fig. 3. They may be searched for in a beam-dump experiment, where sterile neutrinos produced in the heavy meson decays escape dump and subsequently decay into SM particles in a detector empty volume, see Fig. 4.

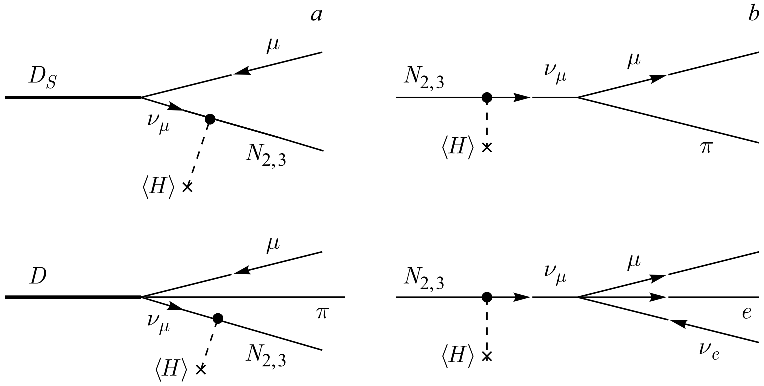

Fig. 3. Sterile neutrino phenomenology in examples: production in meson decays (*a*), decay into SM light particles (*b*)

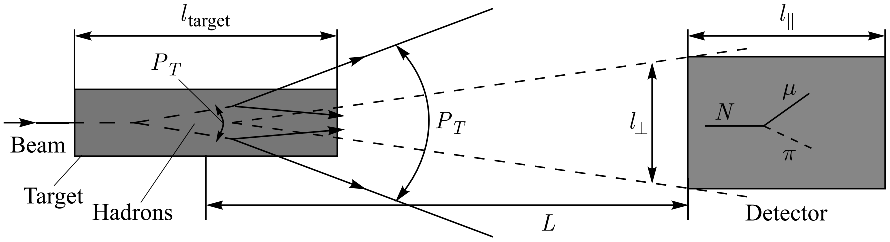

Fig. 4. Sketch of the beam-dump experiment dedicated to searches for the sterile neutrinos of GeV mass scale [16]

The experimental setup has been proposed in [16]. It is based on the estimates [17] of meson branching ratios into sterile neutrinos and sterile neutrino lifetime and branching ratios into SM particles obtained within νMSM assuming sterile neutrino masses are below 5 GeV. The estimates for the overall sterile-active mixing strength U^2 (typical squared mixing angle) and sterile neutrino lifetime are presented in Fig. 5. One concludes that for the interesting region of parameter space sterile neutrinos of GeV-scale mass cover a distance of hundreds of meters before decay. Then a hundred meter scale detector may be used to search for their decay signal. Since neutrinos are produced in the heavy meson decays as explained above, they have transverse momentum of the order of meson mass, so that sterile neutrino trajectories diverge. The detector must be placed as close to the target as possible to trace all the trajectories.

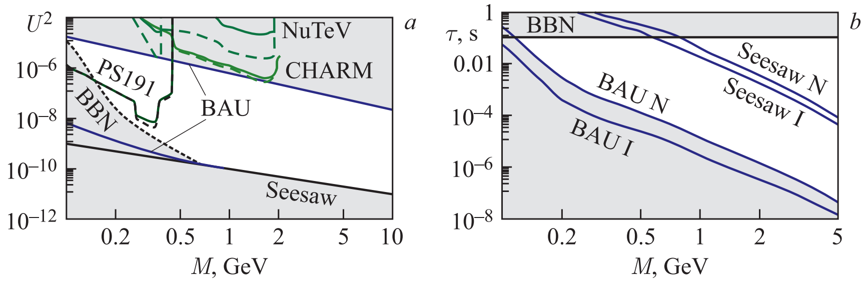

Fig. 5. Viable region of sterile neutrino parameter space within νMSM [16]: overall squared mixing U^2 for inverted hierarchy (*a*) and corresponding sterile neutrino lifetime for normal (N) and inverted (I) hierarchy cases (*b*). “BBN” marks the limit from Big Bang Nucleosynthesis (late decay of sterile neutrino can destroy primordial nuclei), “BAU” indicates the region where baryon asymmetry of the Universe can be explained with two degenerate sterile neutrinos by neutrino oscillations in the primordial plasma, curves with label “Seesaw” outline the region where sterile-active neutrino mixing is strong enough to explain the masses and mixing in active neutrino sector via seesaw type I mechanism. There are lines illustrating constraints from direct searches for sterile neutrinos performed by experiments PS191, CHARM and NuTeV

This determines the setup of the new experiment proposed recently [18] by a joint group of theorists and experimentalists and later named SHiP (Searches for Hidden Particles) [19]. The idea is to use CERN SPS beam of 400 GeV protons to produce charmed mesons on a fixed target. Sterile neutrinos of mass below 2 GeV may be produced in D- and D_s-meson decays, while the numerous pions and kaons produced by protons on target are absorbed in the tungsten dump. Then a detector with empty volume can be placed at 50–70 m distance from the target to search for pairs of charged particles presumably originated from the sterile neutrino decays, see Fig. 3. The detector fiducial volume is almost empty to suppress the background from neutrino scattering off matter with similar signature. The distance from target is limited by the high flux of the secondary muons produced in pion and kaon decays in beam dump and rescattered off the dump and tunnel wall material. To determine the type of charged particles, a system of detectors (including electromagnetic calorimeter, tracker, and muon detector) must be installed in the back part of the decay volume. A special veto system in the front part can help to control incoming muon flux. A sketch of the relevant detector is presented in Fig. 6.

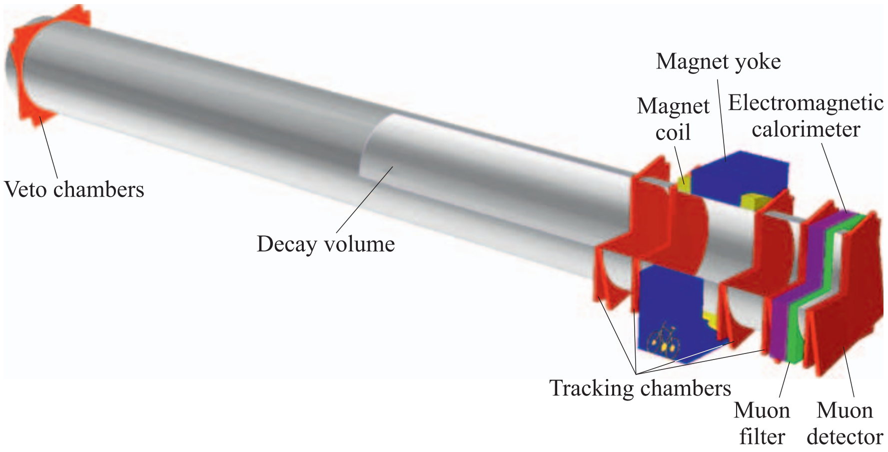

Fig. 6. Sketch of the detector to search for sterile neutrino decays in the empty volume of $5 \times 5 \times 50$ m [18]

Preliminary estimates show that with $2 \cdot 10^{20}$ protons on target (which corresponds to several years of SPS running) the proposed experiment allows one to probe the largest part of the viable region in the model parameter space presented in Fig. 5 for sterile neutrino mass below 2 GeV. To fully explore the νMSM with neutrino mass below 2 GeV, either a higher intensity proton beam (that implies a serious technical upgrade of SPS) or/and a detector of larger fiducial volume (a cluster of detectors similar to the one in Fig. 6, as proposed in [16]) are needed.

4. STATUS OF THE PROPOSAL AND PROSPECTS

The proposal was submitted to CERN SPS Scientific Committee in November 2013. A team of referees considered it later and the group answers to their questions may be found at the SHiP website [19]. The response from the Committee in January was positive. Given the time-scale, large cost and complexity of the beam infrastructure required to build the experiment, the Committee suggests that the "project should be designed as a general-purpose beam-dump facility with the broadest possible physics programme". The Committee asked for an extended proposal with further developed physics goals, more detailed technical design and preliminary list of institutes interested in the physics case to join the new Collaboration.

To follow the Committee's suggestions, the group plan to perform a special study of the sensitivity of the SHiP experiment to various models with relatively light, long-lived yet unstable particles, including paraphotons, axion- and dilaton-like particles, light neutralinos and sgoldstinos, etc. In June the group will organize a special Open Meeting to discuss the physics case, detector design and form a proto-Collaboration. The next milestone is to prepare the Technical Proposal by the Spring of 2015.

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REFERENCES

1. *Abe K. et al. (T2K Collab.).* Observation of Electron Neutrino Appearance in a Muon Neutrino Beam // Phys. Rev. Lett. 2014. V. 112. P. 061802; arXiv:1311.4750 [hep-ex].
2. *Mitra M., Senjanovic G., Vissani F.* Heavy Sterile Neutrinos and Neutrinoless Double Beta Decay. arXiv:1205.3867 [hep-ph].
3. *Basse T. et al.* Dark Energy Properties from Large Future Galaxy Surveys // JCAP. 2014. V. 1405. P. 021; arXiv:1304.2321 [astro-ph.CO].
4. *Minkowski P.* $\mu \to e\gamma$ at a Rate of One out of 1-Billion Muon Decays? // Phys. Lett. B. 1977. V. 67. P. 421.
5. *Boyarsky A., Ruchayskiy O., Shaposhnikov M.* The Role of Sterile Neutrinos in Cosmology and Astrophysics // Ann. Rev. Nucl. Part. Sci. 2009. V. 59. P. 191; arXiv:0901.0011 [hep-ph].
6. *Akhmedov E. K., Rubakov V. A., Smirnov A. Y.* Baryogenesis via Neutrino Oscillations // Phys. Rev. Lett. 1998. V. 81. P. 1359; arXiv:hep-ph/9803255.
7. *Khlebnikov S. Y., Shaposhnikov M. E.* Melting of the Higgs Vacuum: Conserved Numbers at High Temperature // Phys. Lett. B. 1996. V. 387. P. 817; arXiv:hep-ph/9607386.

8. *Drewes M., Garbrecht B.* Leptogenesis from a GeV Seesaw without Mass Degeneracy // JHEP. 2013. V. 1303. P. 096; arXiv:1206.5537 [hep-ph].
9. *Asaka T., Shaposhnikov M.* The nuMSM, Dark Matter and Baryon Asymmetry of the Universe // Phys. Lett. B. 2005. V. 620. P. 17; arXiv:hep-ph/0505013.
10. *Gorbunov D. S., Rubakov V. A.* Introduction to the Theory of the Early Universe: Hot Big Bang Theory. Hackensack, USA: World Sci., 2011. 473 p.
11. *Shaposhnikov M., Tkachev I.* The nuMSM, Inflation, and Dark Matter // Phys. Lett. B. 2006. V. 639. P. 414; arXiv:hep-ph/0604236;
    Bezrukov F., Gorbunov D. Light Inflaton Hunter's Guide // JHEP. 2010. V. 1005. P. 010; arXiv:0912.0390 [hep-ph];
    Bezrukov F., Gorbunov D. Light Inflaton after LHC8 and WMAP9 Results // JHEP. 2013. V. 1307. P. 140; arXiv:1303.4395 [hep-ph];
    Bezrukov F., Gorbunov D., Shaposhnikov M. On Initial Conditions for the Hot Big Bang // JCAP. 2009. V. 0906. P. 029; arXiv:0812.3622 [hep-ph].
12. *Shi X.-D., Fuller G. M.* A New Dark Matter Candidate: Nonthermal Sterile Neutrinos // Phys. Rev. Lett. 1999. V. 82. P. 2832; arXiv:astro-ph/9810076.
13. *Canetti L. et al.* Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos // Phys. Rev. D. 2013. V. 87. P. 093006; arXiv:1208.4607 [hep-ph].
14. *Tremaine S., Gunn J.E.* Dynamical Role of Light Neutral Leptons in Cosmology // Phys. Rev. Lett. 1979. V. 42. P. 407.
15. *Gorbunov D., Khmelnitsky A., Rubakov V.* Constraining Sterile Neutrino Dark Matter by Phase-Space Density Observations // JCAP. 2008. V. 0810. P. 041; arXiv:0808.3910 [hep-ph].
16. *Gninenko S. N., Gorbunov D. S., Shaposhnikov M. E.* Search for GeV-Scale Sterile Neutrinos Responsible for Active Neutrino Oscillations and Baryon Asymmetry of the Universe // Adv. High Energy Phys. 2012. V. 2012. P. 718259; arXiv:1301.5516 [hep-ph].
17. *Gorbunov D., Shaposhnikov M.* How to Find Neutral Leptons of the νMSM? // JHEP. 2007. V. 0710. P. 015; Erratum // JHEP. 2013. V. 1311. P. 101; arXiv:0705.1729 [hep-ph].
18. *Bonivento W. et al.* Proposal to Search for Heavy Neutral Leptons at the SPS. arXiv:1310.1762 [hep-ex].
19. Website of the SHiP experiment at CERN: http://ship.web.cern.ch.