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Plan B for particle physics: finding long lived particles at CERN

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Chapter 6

Searching for new physics with the SHiP neutrino detector (iSHiP)

6.1 Light dark matter at the iSHiP

6.1.1 Production of DM particles

Light dark matter (LDM) is a weakly interacting massive particle (WIMP) with the mass below the Lee-Weinberg bound. The original idea for WIMPs was first proposed in the paper [278]. In this paper, it was assumed that a new weakly interacting stable particle χ interacting with the SM particles through neutral weak interactions (so-called “heavy neutrino”), which can play the role of DM. These particles were in thermal equilibrium in the early Universe. They keep the equilibrium number density via annihilation $\chi + \bar{\chi} \leftrightarrow \text{SM} + \text{SM}$. During the Universe expansion, the density of DM drops and hence the annihilation rate decreases.

At some moment, the annihilation rate is insufficient to maintain the equilibrium number density and therefore χ degree of freedom freezes out. WIMP “remembers” the density of the Universe at the time of freeze-out. It is given by

$$\Omega_\chi h^2 \sim \frac{[3 \cdot 10^{-27}] \text{cm}^3/\text{sec}}{\langle \sigma_{ann} v \rangle}, \quad (6.1.1)$$

where $\langle \sigma_{ann} v \rangle \sim G_F^2 m_\chi^2 N_{\text{channels}}$ is the annihilation rate at the time of freeze-out. For a “heavy neutrino” mass $m_\chi \sim \mathcal{O}(1)$ GeV, annihilation into the SM channels leads to a too small cross-section, which leads to too large DM abundance. Requiring that (6.1.1) does not exceed the present number density of the Universe, it was obtained in [278] that the lower bound $m_\chi > 5$ GeV.

To increase the annihilation rate we need a new light mediator $m_{\text{mediator}} \ll m_W$ with a sizeable coupling to the SM sector,

$$G_F \rightarrow G_F^{\text{mediator}} = \frac{4\pi\tilde{\alpha}}{m_{\text{mediator}}^2}. \quad (6.1.2)$$

One of possible mediators is a scalar mediator. The Lagrangian of the interaction of DM with a scalar is (1.6.1).

There are three χ particles production mechanisms which are relevant to proton beam dump experiments [279]:

- Production in deep inelastic proton-proton scattering (DIS).
- Coherent proton-nucleus and proton-proton collisions.
- Decays of secondary particles — kaons, D and B mesons.

The first two channels remain opened for very wide range of χ masses, while the third channel closes for $m_\chi \gtrsim m_B/2 \simeq 2.5$ GeV.

6.1.1.1 DIS production

DIS channel is a production of $\chi\bar{\chi}$ pairs through scattering of partons inside the protons, namely gluons and u -, d -, s - quarks. This is relevant because of the high proton-proton CM energy, $\sqrt{s_{pp}} = 28.4$ GeV. Using the couplings to quarks and gluons, one can draw the diagrams of DIS productions, see Fig. 6.1.

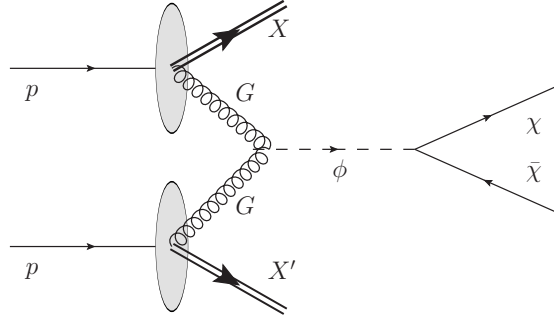


Figure 6.1: The production of the $\chi\bar{\chi}$ pairs in DIS.

The “hard” cross-sections for the parton (which can be either G or q) in region of parameters $m_\phi < 2m_\chi$ are:

$$\sigma_{GG \rightarrow \chi\bar{\chi}}(s_{GG}) = \alpha_{\phi\chi\chi} \frac{\alpha_s^2(s_{GG}) F_G^2 \sin^2(\theta) \left(1 - \frac{4m_\chi^2}{s_{GG}}\right)^{\frac{3}{2}}}{256\pi^3 v_H^2 \left(1 - \frac{m_\phi^2}{s_{GG}}\right)^2}, \quad (6.1.3)$$

$$\sigma_{q\bar{q} \rightarrow \chi\bar{\chi}}(s_{qq}) = \frac{\alpha_{\phi\chi\chi} y_q^2 \left(1 - \frac{4m_\chi^2}{s_{qq}}\right)^{3/2}}{4s_{qq} \left(1 - \frac{m_\phi^2}{s_{qq}}\right)^2}, \quad (6.1.4)$$

where $s_{PP} = x_1 x_2 s_{pp}$ is an invariant mass of two partons, and x is the momentum fraction of one of the partons defined as $p_{P_i}^\mu \approx x_i p_{p_i}^\mu$, F_G is effective coupling constant

to gluons, y_q is Yukawa coupling of the quark q and v_H is the vacuum expectation value of the Higgs field.

The total cross section is obtained by integrating the “hard” cross-section with two parton distribution functions of two gluons $f_{p/G}(x, Q^2)$, where $Q^2 = s_{GG}$ is the “soft”/“hard” fragmentation scale. Namely, one has

$$\sigma_{\text{DIS}} = \int_0^1 dx_1 \int_0^1 dx_2 f_{p/P}(x_1, s_{PP}) f_{p/P}(x_2, s_{PP}) \sigma_{PP \rightarrow \chi \bar{\chi}}(s_{PP}). \quad (6.1.5)$$

The corresponding DIS branching fractions

$$\text{Br}_{\chi \bar{\chi}}^{\text{DIS}} = \frac{\sigma_{\text{DIS}}}{\sigma_{p+p \rightarrow \text{all}}}, \quad (6.1.6)$$

where $\sigma_{p+p \rightarrow \text{all}} \approx 100 \text{ GeV}^{-2}$ for the SHiP center-of-mass energy [222]. Examples of DIS production of χ particles for different proton beam energies are shown in Fig. 6.2.

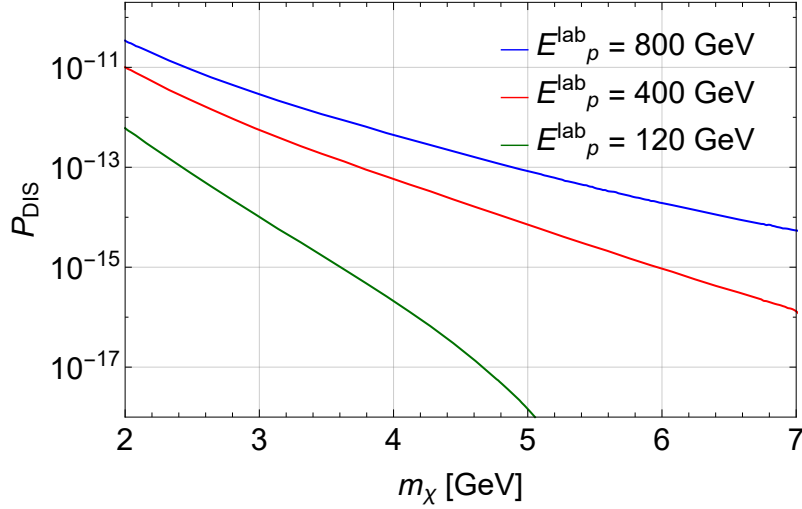


Figure 6.2: Production probability of χ particles in DIS for different proton beam energies.

6.1.1.2 Coherent production

Other direct production channels are coherent proton-nucleus scattering $p + Z \rightarrow p + Z + \chi + \bar{\chi}$. Scattering goes through Spp and $S\gamma\gamma$ vertices. The leading order diagrams for direct production are shown in Fig. 6.3.

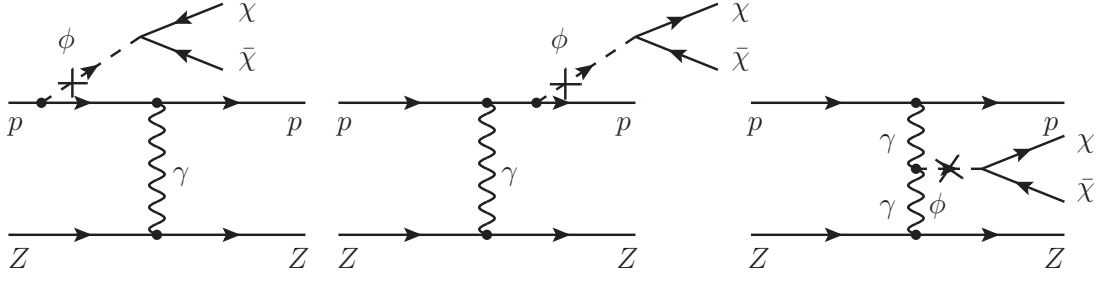


Figure 6.3: Diagrams of production of the $\chi\bar{\chi}$ pairs in coherent pZ scattering.

The corresponding branching ratios are

$$\text{Br}_{p+Z \rightarrow p+Z+\chi+\bar{\chi}} = \frac{\sigma_{p+Z \rightarrow p+Z+\chi+\bar{\chi}}}{\sigma_{p+Z \rightarrow \text{all}}}, \quad \text{Br}_{p+p \rightarrow p+p+\chi+\bar{\chi}} = \frac{\sigma_{p+p \rightarrow p+p+\chi+\bar{\chi}}}{\sigma_{p+p \rightarrow \text{all}}}, \quad (6.1.7)$$

where $\sigma_{p+p \rightarrow \text{all}} \approx 100 \text{ GeV}^{-2}$ and $\sigma_{p+Z \rightarrow \text{all}} \approx 53 A^{0.77} \text{ mb} \approx 4400 \text{ GeV}^{-2}$ [222] (for Molybdenum) are calculated in the forthcoming paper [236]. Here we will give only the main results. The upper bounds on the cross-sections valid for light DM pairs are

$$\sigma_{p+Z \rightarrow p+Z+\chi+\bar{\chi}} \lesssim \frac{\alpha_{\text{EM}}^2 Z^2 y_N^2}{4\pi m_p^2} \ln \left(\frac{E_{p.o.t.}^2}{4m_\chi^2} \right) \alpha_{\phi\chi\chi} \sin^2(\theta) \simeq 10^{-3} \alpha_{\phi\chi\chi} \sin^2(\theta) \text{ GeV}^{-2}. \quad (6.1.8)$$

For light χ particles, the proton coherent production branching ratio is in Z times suppressed in comparison with the nucleus coherent production. However, heavy χ particles require a large transferred momenta, which strongly suppress coherent production from nucleus, and thus the proton production becomes the dominant one.

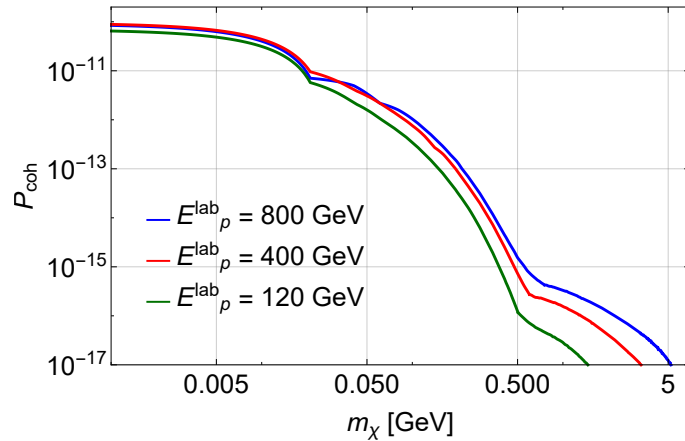


Figure 6.4: The production probability of $\chi\bar{\chi}$ pairs in coherent scattering for different proton beam energies.

6.1.1.3 Production from mesons

Let us discuss $\chi\bar{\chi}$ pairs production from heavy flavored mesons. The relevant processes, mediated by the Lagrangian 2.1.12, are $M \rightarrow M' + \chi + \bar{\chi}$, where M, M' are different mesons. We'll calculate the production fractions for the processes

$$K \rightarrow \pi + \chi + \bar{\chi}, \quad D \rightarrow K + \chi + \bar{\chi}, \quad B \rightarrow K + \chi + \bar{\chi} \quad (6.1.9)$$

The diagram for production of $\chi\bar{\chi}$ pairs from mesons is shown on Fig. 6.4.

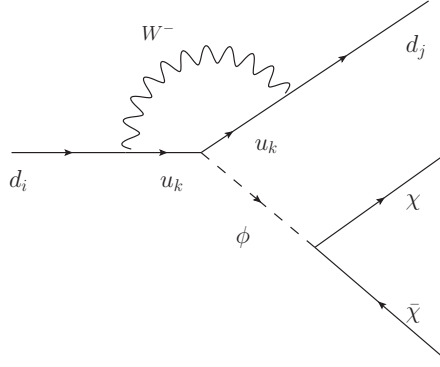


Figure 6.5: Diagrams of production of the $\chi\bar{\chi}$ pairs from mesons decays

At SHiP experiment there will be produced $N_{K^+} \approx 3.4 \cdot 10^{16}$, $N_{B^+} \approx N_{B^0} \approx 5.6 \cdot 10^{13}$ mesons¹ see discussion in Sec. 2.2.2. D production channel is suppressed in comparison with B production channel and is not relevant. The reasons are following:

- for D meson decay loop the heaviest quark running in the loop is b quark, while for B meson it is t quark
- for D meson decay loop the CKM matrix elements are much smaller than the CKM matrix elements for B meson decay

6.1.1.4 Summary

Amounts of DM pairs produced by each of these channels are given on Fig. 6.6.

¹The number of kaons include $\sim 10^{-3}$ suppression due to their absorption inside the wall because of scatterings

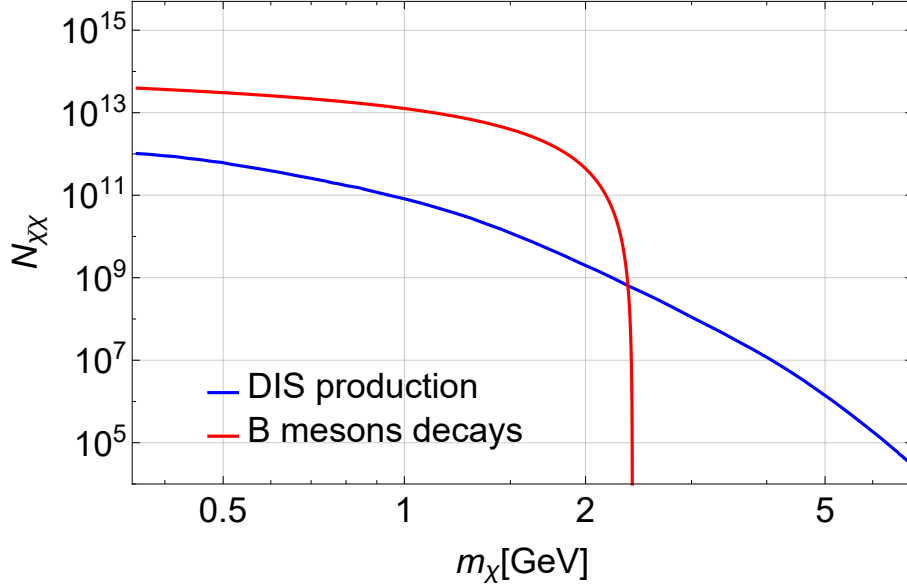


Figure 6.6: Number of produced $\chi\bar{\chi}$ pairs for different channels: DIS of quarks and gluons, mesons decays $B^{+0} \rightarrow K + \chi + \bar{\chi}$, $K \rightarrow \pi + \chi + \bar{\chi}$, and coherent scattering on nuclei and protons, $p + Z/p \rightarrow p + Z/p + \chi + \bar{\chi}$. Amounts are evaluated for $m_S = m_\chi/3$

For masses $2m_\chi \lesssim m_B$ the dominant production channels are mesons decays: kaons decays for $2m_\chi \lesssim m_K - m_\pi$, and B^+ , B^0 mesons decays for masses $m_K - m_\pi \lesssim 2m_\chi < m_B - m_K$, while for larger masses the dominant channel is DIS. Coherent production channel is always sub-dominant and doesn't present on Fig. 6.6.

The reason for this is the following. $\chi\bar{\chi}$ pairs production channels compete with SM production channels. For the direct production, the main SM production channels are mediated by strong and EM interactions, while for the mesons decays the main channels are mediated by weak interactions. Therefore direct production channels are strongly suppressed in comparison with mesons channel (even taking into account that one needs to produce mesons first).

6.1.2 Number of scattering events

6.1.2.1 Effective interaction with nucleons

Effective low-energy coupling g_{SNN} to the nucleons N , which is defined by the Lagrangian

$$\mathcal{L}_{SNN} = g_{SNN} \sin(\theta) S \bar{N} N, \quad (6.1.10)$$

can be related to the interaction $\mathcal{L}_{Sff}$ by the expression

$$g_{SNN} \equiv \frac{1}{v_H} \lim_{p \rightarrow p'} \langle N(p) | \sum_q m_q \bar{q} q | N(p') \rangle \equiv \frac{1}{v_H} \langle N | \sum_q m_q \bar{q} q | N \rangle, \quad (6.1.11)$$

where the shorthand notation $\langle N | .. | N \rangle \equiv \lim_{p \rightarrow p'} \langle N(p) | .. | N(p') \rangle$ was used. Numerical result for the coupling is [280]

$$g_{SNN} = \frac{2}{9} \frac{m_N}{v_H} \sin(\phi) \left(1 + \frac{7}{2} \sum_{q=u,d,s} \frac{m_q}{m_N} \langle N | \bar{q}q | N \rangle \right) \approx 1.2 \cdot 10^{-3} \quad (6.1.12)$$

6.1.2.2 Scattering

χ particles are stable and therefore can't be detected by their decay. They can be, however, detected by their scattering on the target. We'll consider two scattering channels:

- elastic χN scattering;
- deep inelastic scattering (DIS) on gluons

The diagrams corresponding to these channels are given on Fig. 6.7.

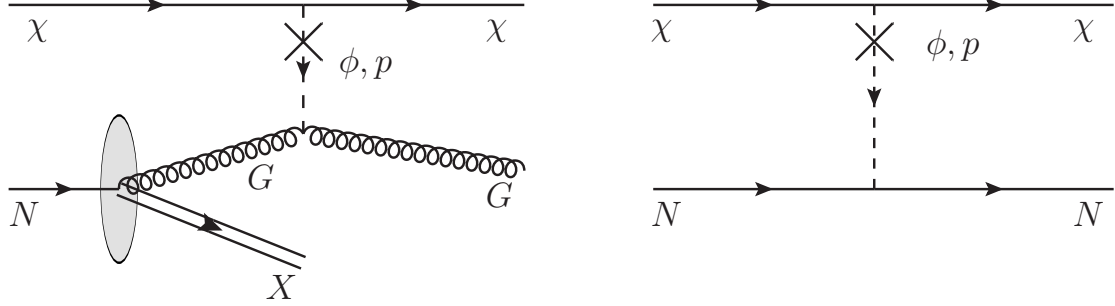


Figure 6.7: Scattering of the χ particle inside the detector. Left: DIS on gluons. Right: elastic scattering on nucleons

Elastic scattering on the nucleons, i.e. the process $\chi + N \rightarrow \chi + N$, occurs due to SNN coupling (6.1.11). Because of the scalar mediator propagator the cross-section crucially depends on the minimal detectable transferred momentum $p_{\min}$. Namely, for $m_\chi \simeq 1$ GeV one has approximate formula

$$\sigma_{\chi N \rightarrow \chi N} \simeq \frac{m_N^2 m_\chi^2}{4 (E_{\chi N}^{\text{CM}})^2 p^2 \max(p_{\min}^2, m_S^2)} g_{\phi NN}^2 \alpha_{\phi \chi \chi} \sin^2(\theta), \quad (6.1.13)$$

where $E_{\chi N}^{\text{CM}}$ is χN CM frame energy and p is χ CM frame momentum.

The cross-section increases with increasing the ratio m_χ/m_ϕ , being maximal for $m_\chi \gg p_{\min} > m_\phi$. Taking the energy of χ particle at nucleon's lab frame to be $E_\chi = 12$ GeV, one obtains

$$\sigma_{\chi N \rightarrow \chi N} \approx 10^{-5} \left(\frac{m_\chi}{1 \text{ GeV}} \right)^2 \left(\frac{50 \text{ MeV}}{p_{\min}} \right)^2 \alpha_{S\chi\chi} \sin^2(\theta) \text{ GeV}^{-2} \quad (6.1.14)$$

Another contribution in the scattering is the *deep inelastic scattering* of the χ particles on gluons inside the nucleons. Using the Lagrangian 2.1.1 and introducing the modulus of the Mandelstam invariant $Q^2 = -t$, for the differential cross-section of the process one has

$$\frac{d\sigma_{\text{DIS}}}{dQ^2} = \frac{\alpha_s(Q^2)}{128\pi^4 v_H^2} \frac{|F_G(Q^2)|^2 Q^4 (2m_\chi^2 + Q^2)}{(m_S^2 + Q^2)^2 s_{\chi G}(x)}, \quad (6.1.15)$$

where $s_{\chi G}$ is χG invariant mass expressed in terms of χp invariant mass $s_{\chi p}$ and amount x of the proton energy carried by gluon as $s_{\chi G}(x) = m_\chi^2(1-x) + xs_{\chi p}$.

The total cross-section is

$$\sigma_{\text{DIS}} = \int_0^1 dx \int_{s_{\chi G}-2m_\chi^2}^{s_{\chi G}-m_\chi^2} dQ^2 \frac{d\sigma_{\text{DIS}}}{dQ^2} f_{N/G}(x, Q^2) \theta(s_{pG}(x) - Q^2), \quad (6.1.16)$$

where $f_{N/G}$ is the DIS of the gluon inside the nucleon. Unlike the case of elastic scattering (6.1.14), for the DIS cross-section there is no p_{min} dependence, since it occurs only for kinematic range

$$Q^2 \gtrsim r_N^{-2} \simeq 1 \text{ GeV}^2, \quad (6.1.17)$$

for which the scattering probes the internal structure of the nucleon. Due to this reason the cross-section is almost independent on the nucleon mass and has the form

$$\sigma_{\text{DIS}} \approx \eta \cdot \left(\frac{\alpha_s(1 \text{ GeV}^2)}{4\pi v_H} \right)^2 \sin^2(\theta) \alpha_{S\chi\chi} \simeq 5 \cdot 10^{-8} \sin^2(\theta) \alpha_{S\chi\chi} \text{ GeV}^{-2}, \quad (6.1.18)$$

where $\eta \simeq 10^{-1}$ is the additional suppression coming from the kinematic range (6.1.17). One sees that for $m_\chi > m_S$ the elastic cross-section (6.1.14) dominates.

The mass dependence of total scattering cross-section given by the sum of cross-sections (6.1.14), (6.1.16) is presented on Fig. 6.8.

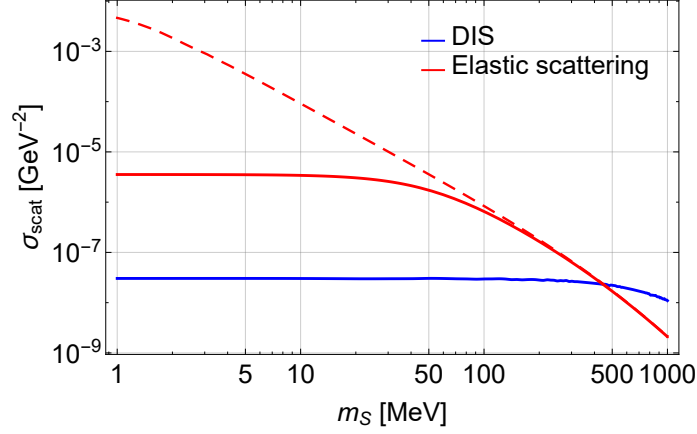


Figure 6.8: Dependence of scattering cross-sections of DM in iSHiP on scalar mediator mass for fixed DM mass $m_\chi = 1\text{ GeV}$. For elastic scattering it is assumed that $p_{\min} = 50\text{ MeV}$ (solid line) and $p_{\min} = 1\text{ MeV}$ (dashed line)

For the given scattering events detector of length l_{detector} , with target of nuclear number density n and mass number A , the scattering probability is

$$P_{\text{scat}} \approx l_{\text{detector}} \cdot A \cdot n \cdot \sigma_{\text{scat}} \quad (6.1.19)$$

Normalizing A and n on lead², for the domain $m_\chi > m_S$ we have

$$P_{\text{scat}} \approx 1.4 \cdot 10^{-8} \frac{l_{\text{detector}}}{5\text{ m}} \cdot \frac{A \cdot n}{7 \cdot 10^{24}\text{ cm}^{-3}} \left(\frac{m_\chi}{\max[m_S, p_{\min}]} \right)^2 \quad (6.1.20)$$

6.1.2.3 Summary

From Fig. 6.6 we see that in the region $m_\chi \lesssim 2\text{ GeV}$ the main production channel of χ particles is the decay $B^\pm \rightarrow K^\pm + \chi + \bar{\chi}$. For $m_\chi \simeq 1\text{ GeV}$ the number of $\chi\bar{\chi}$ pairs is

$$N_{\chi\bar{\chi}} \approx 2 \cdot N_{B^+ \rightarrow \chi\bar{\chi}} \approx 2 \cdot 10^{12} \alpha_{S\chi\chi} \sin^2(\theta) \quad (6.1.21)$$

Using (6.1.20) one finds that the total number of scatterings is

$$N_{\text{scat}} = 2N_{\chi\bar{\chi}} \cdot P_{\text{scat}} \approx 6 \cdot 10^4 \left(\frac{m_\chi}{\max[m_S, p_{\min}]} \right)^2 \alpha_{S\chi\chi}^2 \sin^4(\theta) \quad (6.1.22)$$

In dependence on the ratio $m_\chi/\max[m_\phi, p_{\min}]$ the number of scattering events varies from $6 \cdot 10^4 \alpha_{S\chi\chi}^2 \sin^4(\theta)$ (for $m_\chi \simeq m_S$) to $6 \cdot 10^{10} \alpha_{S\chi\chi}^2 \sin^4(\theta)$ (for $m_S < p_{\min} \simeq 1\text{ MeV}$). However, using the LHC constraint $\sin^2(\theta) \alpha_{S\chi\chi} \lesssim 10^{-5}$ and CHARM constraint

²The number density for lead can be estimated as $n = \rho N_A / M$, where $\rho = 11.34\text{ g/cm}^3$ is mass density, $M = 207\text{ g/mol}$ is molar mass and $N_A = 6.02 \cdot 10^{23}$ is Avogadro's number

$\sin^2(\theta) \lesssim 10^{-6}$ for $m_S \lesssim m_K - m_\pi$, one obtains the upper bound

$$N_{\text{scat}} \lesssim 10^{-2} \quad (6.1.23)$$

One sees that the SHiP experiment doesn't have the sensitivity to χ scatterings.

6.1.3 Other experiments

Apart from SHiP there are other proton beam dump experiments which could provide compatible sensitivity to DM. Examples of such experiments are MiniBooNE [281], DUNE (previously known as LBNE) [106] and T2K [282]. Their parameters are given in Table 6.1.

Experiment	$N_{p.o.t.}$	$E_{p.o.t.}$, GeV	E_{pp}^{CM} , GeV	Detector length, m
SHiP	$2 \cdot 10^{20}$	400	28.3	5
MiniBooNE	$2 \cdot 10^{20}$	8	4.2	12
T2K-Super K	10^{22}	30	7.9	$\simeq 40$
DUNE	$\simeq 10^{22}$	60-120	11.04-15.5	7

Table 6.1: Parameters of different experiments

Let's briefly estimate their sensitivity to heavy DM with the mass $2m_\chi \gtrsim m_K - m_\pi$. For this region, the DM pairs are produced mainly by B mesons decay. The number of B mesons can be calculated as³

$$N_{B^+} \approx N_{p.o.t.} \times \frac{\sigma_{pp \rightarrow b\bar{b}}(E_{\text{CM}})}{\sigma_{p+p \rightarrow \text{all}}(E_{\text{CM}})} \times f_{b \rightarrow B^+}, \quad (6.1.24)$$

where $f_{b \rightarrow B^+} \simeq 0.4$ is fragmentation fraction of b quark into B^+ meson. The total pp cross-section $\sigma_{p+p \rightarrow \text{all}}$ is widely independent on beam energy and is approximately $\sigma_{pp \rightarrow \text{all}} \approx 40$ mb [222]. The $b\bar{b}$ pair production cross-section, however, strongly depends on energy E_{pp}^{CM} . For $E_{p.o.t.} = 28.3$ GeV (SHiP) and $E_{p.o.t.} = 15.5$ GeV (DUNE) we compared the simulated cross-sections with [110] and [218]. It was found that the predictions agrees well. The values of cross-section for the energies from Table 6.1 are given in Table 6.2.

³Within this estimation, it was neglected the number of B mesons produced by scatterings of secondary particles. For SHiP experiment the number of such B mesons is 74 percents of the number of primary particles (see [report](#)), while for experiments with lower beam energy this amount is expected to be suppressed

$E_{pp}^{\text{CM}}, \text{ GeV}$	28.3 (SHiP)	15.5 (DUNE)	11 (DUNE)	7.9 (T2K)	4.2 (MiniBooNE)
$\sigma_{pp \rightarrow b\bar{b}+X}, \text{ pb}$	$1.6 \cdot 10^3$	2.4	$8 \cdot 10^{-4}$	0	0
$\sigma_{pp \rightarrow b\bar{b}+X} / \sigma_{pp \rightarrow \text{all}}$	$4 \cdot 10^{-8}$	$6 \cdot 10^{-11}$	$2 \cdot 10^{-14}$	0	0

Table 6.2: Average values of $b\bar{b}$ production cross-section in dependence on the proton pair CM energy

Using these results, one finds that T2K and MiniBooNE experiments won't produce B mesons, while for SHiP and DUNE one has

$$\frac{N_{b\bar{b}}^{\text{SHiP}}}{N_{b\bar{b}}^{\text{DUNE}}} \simeq \frac{N_{p.o.t.}^{\text{SHiP}}}{N_{p.o.t.}^{\text{DUNE}}} \times \frac{\sigma_{pp \rightarrow b\bar{b}+X}^{\text{SHiP}}}{\sigma_{pp \rightarrow b\bar{b}+X}^{\text{DUNE}}} \simeq 7 \quad (6.1.25)$$

Since the lengths of near detector at DUNE and iSHiP detector are comparable (see Table 6.1), we conclude that the sensitivity of DUNE experiment will not be better than that of SHiP.

6.2 Axions at the iSHiP

6.2.1 Axion portal

Axion-like particle (ALP) portal introduces a pseudo-scalar particle a interacting with the density of Chern-Simons charge of the electromagnetic field:

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2 a^2}{2} - \frac{g_\gamma}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}, \quad (6.2.1)$$

where g_γ is a coupling constant with the dimension GeV^{-1} . There is a wide class of models for which ALPs emerge as a Goldstone boson of some underlying spontaneously broken global symmetry [283–286]. Then, the mass of a is generated if there is some symmetry breaking interactions. If the underlying symmetry scale is very large, while symmetry breaking effects occur at small scales, the mass of the ALP is naturally small. One of the example of such a model is a QCD axion, for which $U(1)$ symmetry first becomes spontaneously broken at some large scale Λ , and then becomes broken explicitly by QCD effects at the scale Λ_{QCD} . The axion mass is then $m_a \simeq \Lambda_{\text{QCD}}^2 / \Lambda_{\text{PQ}} \ll \Lambda_{\text{QCD}}$.

Therefore, ALPs are good candidates for searching at intensity frontier experiments and in particular at the SHiP.

6.2.2 Probing ALPs at the iSHiP

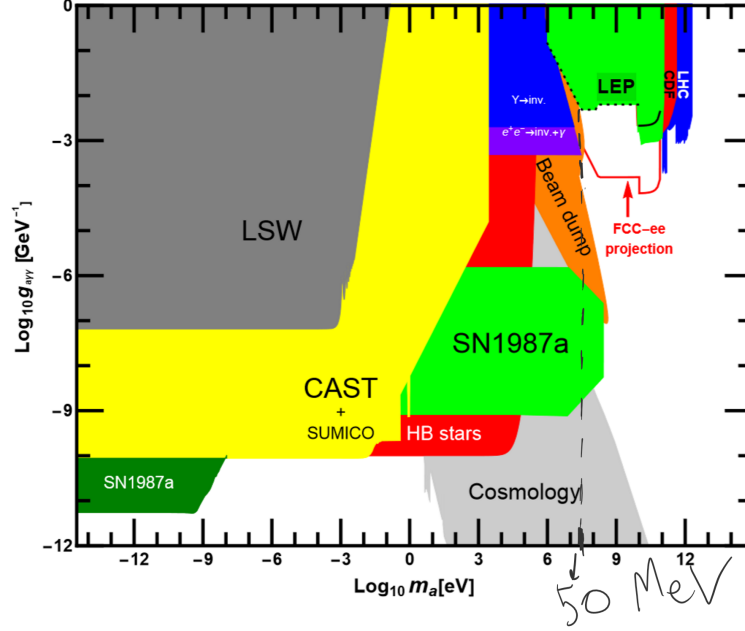


Figure 6.9: Bounds on an ALP model provided by laboratory experiments and cosmology [287].

Using the current bounds on ALP models, see Fig. 6.9, we can divide ALP models that are not excluded on two classes: light ALPs, with $m_a \lesssim 1$ eV, $g_\gamma \lesssim 10^{-10}$ GeV $^{-1}$ and heavy ALPs $m_a \gtrsim 50$ MeV, $g_\gamma \lesssim 10^{-1}$ GeV $^{-1}$. Before discussing the probing of ALPs at the iSHiP, let us talk about production at the SHiP experiment.

6.2.2.1 Production

At the SHiP experiment, ALPs can be produced in the following processes:

- Conversion of secondary produced photons to ALPs $\gamma \rightarrow a$ in the magnetic field of the active muon shield.
- Primakov conversion $\gamma + e \rightarrow a + e$ inside the muon active shield magnetic field.
- Coherent proton-nucleus scattering.

B



Figure 6.10: ALP production from conversion in the magnetic field.

Magnetic field conversion Consider $\gamma \rightarrow a$ conversion of secondary produced photons in the magnetic field B of the muon shield. Conversion probability is [288]

$$P_{\text{conv.}}^{\text{magn}} = \frac{4B^2 E_\gamma^2 g_\gamma^2}{m_a^4} \sin^2 \left(\frac{m_a^2 l}{4E_\gamma} \right), \quad (6.2.2)$$

where l is a radiation length in the iron medium of the shield and E_γ is the energy of converted photon. It is almost energy-independent for $E_\gamma > 1$ MeV and equal to $l_{\text{rad}} \simeq \mathcal{O}(1 \text{ cm})$, see [222].

There are two different production regimes through the magnetic field conversion. The first regime is for small masses $m_a \ll 10 \text{ eV} \left(\frac{E_\gamma}{1 \text{ MeV}} \frac{1 \text{ cm}}{l_{\text{rad}}} \right)^{1/2}$ and the production probability is

$$P_{\text{conv.}}^{\text{magn}} \approx (Blg_\gamma)^2/4 \simeq 10^{-22} \left(\frac{B}{1 \text{ T}} \frac{l_{\text{rad}}}{1 \text{ cm}} \frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2. \quad (6.2.3)$$

The second regime is for masses $m_a \gg 10 \text{ eV} \left(\frac{E_\gamma}{1 \text{ MeV}} \frac{1 \text{ cm}}{l_{\text{rad}}} \right)^{1/2}$. The production probability is

$$P_{\text{conv.}}^{\text{magn}} \approx \frac{2B^2 E_\gamma^2 g_\gamma^2}{m_a^4} \simeq 10^{-30} \left(\frac{B}{1 \text{ T}} \frac{E_\gamma}{1 \text{ MeV}} \frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2 \left(\frac{100 \text{ eV}}{m_a} \right)^4. \quad (6.2.4)$$

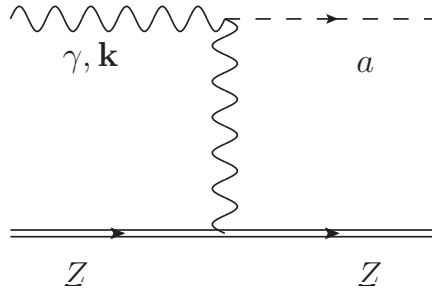


Figure 6.11: ALP production from the Primakov conversion.

Primakov conversion Other production mechanism is the Primakov conversion $\gamma + Z \rightarrow a + Z$ of secondary photons on the Coulomb potential of nuclei inside the wall. For the Coulomb screening radius $r_0 \simeq 20$ keV, and photons with energy in the range of MeV, and nuclei at rest frame, the cross-section is

$$\sigma_{\gamma e \rightarrow ae} \approx Z^2 g_\gamma^2 \alpha_{\text{EM}} \ln(1 + 4|\mathbf{k}|^2 r_0^2) \approx 10^{-19} \left(\frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2 \text{ GeV}^{-2}, \quad (6.2.5)$$

and the conversion probability is

$$P_{\text{conv.}}^{\text{Prim}} \approx l_{\text{rad}} \sigma_{\gamma e \rightarrow ae} n_Z \approx 10^{-24} \left(\frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2 \frac{l_{\text{abs}}}{\text{cm}}. \quad (6.2.6)$$

There is another Primakov conversion $\gamma e \rightarrow ae$ of secondary photons on electrons inside the wall (and is the main Primakov conversion when $|\mathbf{k}| \lesssim r_0^{-1}$). For keV photons the cross-section is

$$\sigma_{\gamma e \rightarrow ae} \approx g_\gamma^2 \alpha_{\text{EM}} \ln(|\mathbf{k}|/m_a) \approx 10^{-22} \left(\frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2 \text{ GeV}^{-2}, \quad (6.2.7)$$

and the conversion probability is

$$P_{\text{conv.}}^{\text{Prim}} \approx l_{\text{rad}} \sigma_{\gamma e \rightarrow ae} n_e \approx 10^{-26} \left(\frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2 \frac{l_{\text{abs}}}{\text{cm}}. \quad (6.2.8)$$

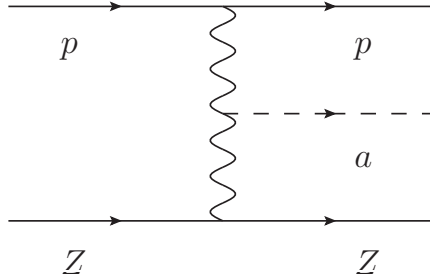


Figure 6.12: ALP coherent production.

Coherent production Consider ALP production in initial proton-nuclei interaction $p + Z \rightarrow p + Z + a$. The production probability can be estimated as

$$P_{\text{coh}} \simeq \frac{\sigma_{pZ \rightarrow pZa}}{\sigma_{pZ \rightarrow \text{all}}} \simeq 5 \cdot 10^{-10} Z^2 \alpha_{\text{EM}} \left(\frac{g_\gamma}{10^{-3} \text{ GeV}^{-1}} \right)^2 \frac{4500 \text{ GeV}^{-2}}{\sigma_{pZ \rightarrow \text{all}}} \approx 10^{-22} \left(\frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}} \right)^2, \quad (6.2.9)$$

where the rough estimation in the second line is in agreement with the exact calculations [289].

Summary Comparing the probabilities (6.2.4), (6.2.8), (6.2.9), we conclude that for the region with masses $m_a \ll 10$ eV $\left(\frac{E_\gamma}{1 \text{ MeV}} \frac{1 \text{ cm}}{l_{\text{rad}}}\right)^{1/2}$ the conversion in the magnetic field is the main production channel. For higher masses, Primakov conversion and coherent production compete with each other. The number of conversion is proportional to the number of photons that is limited by the quantity

$$N_\gamma \lesssim N_{\text{p.o.t.}} \cdot \frac{E_{\text{p.o.t.}}}{E_\gamma} \simeq 10^{25} \frac{1 \text{ MeV}}{E_\gamma}. \quad (6.2.10)$$

Therefore, the coherent production is dominated for $E_\gamma > 10$ MeV.

Using (6.2.4), the number of light ALPs produced at the SHiP can be estimated as

$$N_{\text{prod}} \leq N_{\text{magn}} \lesssim 10^3 \left(\frac{g_\gamma}{10^{-10} \text{ GeV}^{-1}}\right)^2 \frac{l}{\text{cm}} \frac{\text{MeV}}{E_\gamma}. \quad (6.2.11)$$

The number of heavy ALPs can be estimated using (6.2.9):

$$N_{\text{prod}} = P_{\text{coh}} N_{\text{p.o.t.}} \simeq 10^{14} \left(\frac{g_\gamma}{10^{-2} \text{ GeV}^{-1}}\right)^2. \quad (6.2.12)$$

We see that the number of light ALPs produced at the SHiP is strongly suppressed by the tiny coupling.

6.2.2.2 Detection

At the SHiP experiment ALPs can be detected in the following ways:

- Primakov inverse conversion $a + e \rightarrow \gamma + e$ at the iSHiP.
- Conversion to photons in the magnetic field, $a \rightarrow \gamma$, inside the iSHiP magnetic field.
- ALPs decay inside the vacuum camera.

Light ALPs are excluded at the stage of production, hence here we will consider only heavy ALPs. For such particles, the magnetic conversion is suppressed and the main detection channel at the iSHiP is the Primakov conversion process.

The ratio of detection probabilities per unit length for the Primakov conversion (scattering) and decay is

$$\frac{dP_{\text{scattering}}/dl}{dP_{\text{decay}}/dl} \sim \alpha_{\text{EM}} Z^2 \lambda_{\text{Compton}}^3 n_{\text{target}}^{\text{iSHiP}} \sim 10 \left(\frac{\lambda_{\text{Compton}}}{d_{\text{target}}^{\text{iSHiP}}}\right)^3, \quad (6.2.13)$$

where $\lambda_{\text{Compton}} = \frac{\hbar}{m_a c}$ is the Compton wave-length and the inter-atomic length $d_{\text{target}}^{\text{iSHiP}} \simeq 10^{-8} \text{ cm}$ is defined as $n_{\text{target}}^{\text{iSHiP}} \simeq (d_{\text{target}}^{\text{iSHiP}})^{-3}$. The decay detection efficiency starts to dominate for $m_a \gtrsim 30$ eV.

Therefore, the iSHiP is not effective for the detection of ALPs.