Plan B for particle physics: finding long lived particles at CERN
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Chapter 2

Scalar portal

In this Chapter we will discuss the implications of introducing a light scalar particle S into the standard model. As a first step we extend the renormalizable Lagrangian of the Standard model with a CP-even scalar particle coupled to the Higgs doublet. We calculate the (small) mixing angle of the Higgs and S fields so as to be able to write a first-order approximation of the extended standard-model Lagrangian. We then apply this result to the calculation of the production mechanisms for the light scalar particle, namely through a direct channel and through the decay of hadrons. The direct channel effectively involves just a single process which has been studied in [182].

The hadronic decay channel is much richer involving many mesonic (11) and baryonic (13) paths. Here, following Refs. [182, 200], we focus on the mesonic channels and calculate branching ratios for 2-body meson decay as well as 3-body meson decay, each involving the production of one light scalar particle. The values of the branching ratios vary by 12 orders of magnitude.

In an experiment one not only wants to produce the light scalar particles but also detect them. In the final part of this Chapter I present my calculations of their decay widths. I explore the decay into leptons and into hadrons, where, again, the hadronic channel is more rich. The results are presented as a function of the, hitherto unknown, mass of the light scalar particle.

2.1 Scalar portal effective Lagrangian

The general renormalizable SM Lagrangian with a new (CP-even) scalar particle added to the Standard Model (SM) is given by

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S + (\alpha_1 S + \alpha S^2)(H^\dagger H) + \lambda_2 S^2 + \lambda_3 S^3 + \lambda_4 S^4, \qquad (2.1.1)$$

where S is the new light scalar particle coupled to the Higgs doublet H with coupling constants α_1, α, and $\lambda_2, \lambda_3, \lambda_4$ are self-interaction coupling constants of the scalar S.

There are two main properties of the Lagrangian (2.1.1) that make it noticeable from the point of view of connection to the hidden sector. Firstly, it contains only renormalizable terms, which means that its phenomenological relevance is not suppressed by the energy scale of the new physics. Secondly, as dark matter seems to be not charged under SM interactions, the singlet scalar gives a simple possibility to directly connect dark matter to SM trough this portal.

After the spontaneous symmetry breaking, the Higgs doublet chooses the following vacuum,

$$H = \begin{pmatrix} 0 \\ \dfrac{v+h}{\sqrt{2}} \end{pmatrix}, \tag{2.1.2}$$

where v is the vacuum expectation value and h is the Higgs boson field. Thus, substituting it into the initial Lagrangian (2.1.1) we get,

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{\alpha_1}{2} S h^2 + \frac{\alpha}{2}(S^2 h^2 + 2v S^2 h) + \alpha_1 v S h + \frac{\alpha_1 v^2 S + (\alpha v^2 + 2\lambda_2) S^2}{2} + \ldots. \tag{2.1.3}$$

The last term can be written in a form of a mass term as

$$\frac{\alpha_1 v^2 S + (\alpha v^2 + 2\lambda_2) S^2}{2} = \frac{\alpha v^2 + 2\lambda_2}{2} \tilde{S}^2 + c = -\frac{m_S^2}{2} \tilde{S}^2 + c, \tag{2.1.4}$$

where $m_S^2 = -(\alpha v^2 + 2\lambda_2)$ is the mass of S field, the $\tilde{S} = S + \frac{\alpha_1 v^2}{2(\alpha v^2 + 2\lambda_2)}$ is a redefined field, and c is some constant. Henceforth, we will use S instead of $\tilde{S}$.

The mass Lagrangian of the Higgs field and S field is

$$\mathcal{L}^{h,S}_{mass} = -\frac{M_h^2 h^2}{2} - \frac{m_S^2}{2} S^2 + \alpha_1 v S h. \tag{2.1.5}$$

If $\alpha_1 = 0$ (for example because of Z_2 symmetry $S \to -S$) the phenomenology is significantly different from the case when α_1 is not equal to zero [110]. We will not discuss this special case and concentrate on the most general $\alpha_1 \neq 0$ possibility.

We need to diagonalize the Lagrangian (2.1.5) to get the proper mass for the Higgs and scalar fields as we have terms $\propto Sh$, of which we have to get rid. The standard procedure is the following: find such orthogonal matrix O for which the mass matrix M will be diagonal $O^T M O = \mathrm{diag}(m_1, m_2)$. The matrix O could be chosen as a rotation matrix,

$$O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \tag{2.1.6}$$

From the Lagrangian (2.1.3) the mass matrix is,

$$M = \begin{pmatrix} -\frac{1}{2}M_h^2 & \frac{1}{2}\alpha_1 v \\ \frac{1}{2}\alpha_1 v & -\frac{1}{2}m_S^2 \end{pmatrix}. \tag{2.1.7}$$

Therefore, the mass matrix will be diagonalized if the condition

$$\tan 2\theta = \frac{2\alpha_1 v}{M_h^2 - m_S^2} \tag{2.1.8}$$

is valid. For small mixing angle $\theta \ll 1$ and assuming that the scalar particle is much lighter than the Higgs boson $m_S \ll M_h$ we obtain the condition,

$$\boxed{\theta \approx \frac{\alpha_1 v}{M_h^2}}. \tag{2.1.9}$$

Thus, the Higgs and scalar field should be transformed as,

$$h \to h + \theta S, \tag{2.1.10}$$
$$S \to S - \theta h. \tag{2.1.11}$$

Looking at the interaction Lagrangian for the Higgs field with the SM particles, one can see that after the transformations (2.1.10) and (2.1.11) we have the interaction of the scalar particle S with the SM particles

$$\mathcal{L}_{SM}^{h+\theta S} = -\sum_f \frac{m_f}{v}(h+\theta S)\bar{f}f + \frac{2M_W^2}{v}(h+\theta S)W^+W^- + \frac{M_Z^2}{v}(h+\theta S)Z^2 + \\ + \frac{M_W^2}{v^2}(h+\theta S)^2 W^+W^- + \frac{M_Z^2}{2v^2}(h+\theta S)^2 Z^2 - \frac{M_h^2}{2v}(h+\theta S)^3 - \frac{M_h^2}{8v^2}(h+\theta S)^4, \tag{2.1.12}$$

where f, $W^\pm$, Z are fields of the SM fermions, W-boson and Z-boson respectively and m_f, M_W, M_Z are their masses. Using (2.1.12) we obtain the Lagrangian of interaction, to first order in θ, of the S-particle with SM particles, in the unitary gauge:

$$\mathcal{L}_{SM,partial}^{S} = \boxed{-\sum_f \theta \frac{m_f}{v} S\bar{f}f} + 2\theta\frac{M_W^2}{v}SW^+W^- + \theta\frac{M_Z^2}{v}SZ^2 + \\ + 2\theta\frac{M_W^2}{v^2}ShW^+W^- + \theta\frac{M_Z^2}{v^2}ShZ^2 - 3\theta\frac{M_h^2}{2v}Sh^2 - \theta\frac{M_h^2}{2v^2}Sh^3. \tag{2.1.13}$$

2.2 Light scalar production

The scalar particle S could be produced in primary p-p collisions or in the decay of produced hadrons.

2.2.1 Direct production

The examples of the processes where the light scalar particle could be produced in a direct p-p collision in the deep inelastic scattering (DIS) are given in Fig. 2.1. This production channel for the case of proton fixed-target experiment was studied in [182]. It was found that the main contribution to this type of production comes from gluon fusion with a top quark in the loop because of the large Yukawa coupling of the top quark. The production probability of this channel is shown in Fig. 2.2. The production probability is small because it competes with QCD processes.

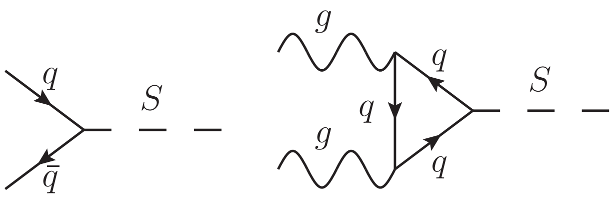

Figure 2.1: Deep inelastic scattering production channels of scalar particle: quark-antiquark fusion (left) and gluon fusion (right).

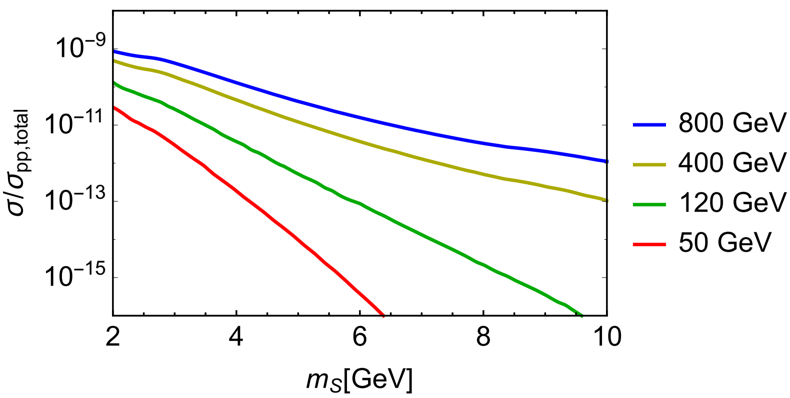

Figure 2.2: Production probability of S particle from gluon fusion at proton fixed-target experiments for different energies of proton beam.

2.2.2 Production from hadrons

In light scalar production from hadron decays, the main contribution comes from the lightest hadrons in each flavor.[1] The list of the main hadron candidates is as

[1]Indeed, if X is the lightest hadron in the family, it can decay *only* through weak interaction, so it has a small decay width Γ_X (in comparison to hadrons that could decay through electromagnetic or

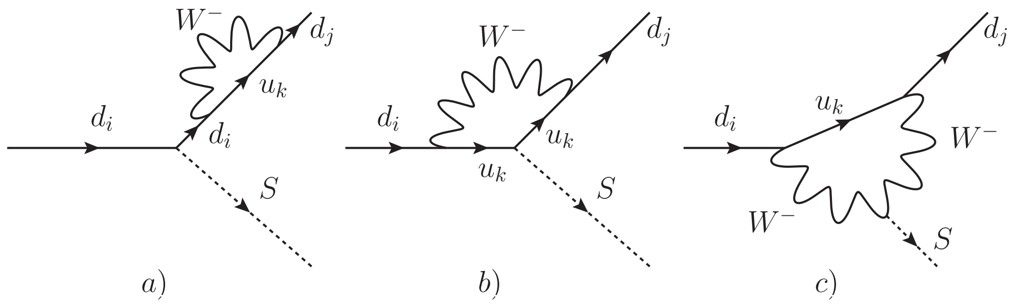

Figure 2.3: Diagrams of S particle production: flavor changing quarks transitions in unitary gauge.

follows (the information is given in the format "Hadron name(quark contents, mass in MeV)")

Mesons

- s-mesons $K^-(s\bar{u}, 494)$, $K^0_{S,L}(s\bar{d}, 498)$;
- c-mesons $D^0(c\bar{u}, 1865)$, $D^+(c\bar{d}, 1870)$, $D_s(c\bar{s}, 1968)$, $J/\psi(c\bar{c}, 3097)$;
- b-mesons $B^-(b\bar{u}, 5279)$, $B^0(b\bar{d}, 5280)$, $B_s(b\bar{s}, 5367)$, $B_c(b\bar{c}, 6276)$, $\Upsilon(b\bar{b}, 9460)$;

Baryons

- light baryons $\Lambda^0(uds, 1116)$, $\Sigma^+(uus, 1189)$, $\Sigma^-(dds, 1197)$, $\Xi^0(uss, 1315)$, $\Xi^-(dss, 1322)$, $\Omega^-(sss, 1672)$;
- c-baryons $\Lambda_c(udc, 2287)$, $\Xi^+_c(usc, 2468)$, $\Xi^0_c(dsc, 2480)$;
- b-baryons $\Lambda_b(udb, 5619)$, $\Xi^0_b(usb, 5792)$, $\Xi^-_b(dsb, 5795)$, $\Omega_b(ssb, 6071)$.

The light scalar S can be produced from the hadron through two-body decay via the flavor changing quark transitions (see diagrams in Fig. 2.3). In the Ref. [182] only production channels from K, D and B mesons were considered as the most effective ones. We will follow their approach.

The flavor changing amplitude was calculated using different techniques in many papers [201–204]. To be specific, the result for the amplitude $b \to s + S$ is:

$$M_{fi} = \frac{3\theta g^2}{64\pi^2 M_W^2 v} \sum_{i=u,c,t} V^*_{is} V_{ib} m^2_{u_i} \left[m_b \bar{s}_L b_R + m_s \bar{s}_R b_L\right] \approx$$
$$\approx |m_b \gg m_s| \approx \frac{3\theta g^2}{64\pi^2 M_W^2 v} \sum_{i=u,c,t} V^*_{is} V_{ib} m^2_{u_i} m_b \bar{s}_L b_R. \quad (2.2.1)$$

strong interactions). The probability of light scalar production from hadron is inversely proportional to the hadron decay width thus the light scalar production from the lightest hadrons is the most efficient.

Generalizing this result (2.2.1) and taking into account that the mass of every next quark generation is much larger than for previous ones, one can write the effective Lagrangian of flavor changing quark interactions with S particle as

$$\mathcal{L}_{eff}^{Sqq} = \theta \frac{S}{v} \sum_{\substack{i,j=1 \\ i<j}}^{3} \left(\xi_d^{ij} m_{d_j} \bar{d}_i P_R d_j + \xi_u^{ij} m_{u_j} \bar{u}_i P_R u_j + h.c. \right). \tag{2.2.2}$$

Here m_{d_j} and m_{u_j} are masses of up and down quarks, P_R is a projector on the right chiral state, V_{ij} are the elements of the CKM matrix, G_F is the Fermi constant, and

$$\xi_d^{ij} = \frac{3G_F\sqrt{2}}{16\pi^2} \sum_{k=u,c,t} V_{ki}^* m_k^2 V_{kj}, \qquad \xi_u^{ij} = \frac{3G_F\sqrt{2}}{16\pi^2} \sum_{k=d,s,b} V_{ik}^* m_k^2 V_{jk}. \tag{2.2.3}$$

Numerical values of some of the constants ξ are given in the Table 2.1.

	ξ	Value
ξ	ξ_d^{ds}	$3.3 \cdot 10^{-6}$
	ξ_u^{uc}	$1.4 \cdot 10^{-9}$
	ξ_d^{db}	$7.9 \cdot 10^{-5}$
	ξ_d^{sb}	$3.6 \cdot 10^{-4}$

Table 2.1: Values of some useful ξ constants.

The matrix element for the $h \to Sh'$ decay is [204]

$$\mathcal{M}(h \to Sh') \approx \theta \frac{M_h^2}{2v} \xi_{u/d}^{\alpha\beta}, \tag{2.2.4}$$

where h and h' are mesons, which differ from each other by replacing β with α quark.

In particular, estimates for s, c and b mesons are:

$$\mathcal{M}(K \to S\pi) \approx \theta \frac{M_K^2}{v} \frac{1}{2} \frac{3G_F\sqrt{2}}{16\pi^2} \sum_{i=u,c,t} V_{is}^* m_i^2 V_{id} \approx 1.7 \cdot 10^{-9} \cdot \theta \text{ GeV}; \tag{2.2.5}$$

$$\mathcal{M}(D \to S\pi) \approx \theta \frac{M_D^2}{v} \frac{1}{2} \frac{3G_F\sqrt{2}}{16\pi^2} \sum_{i=d,s,b} V_{ic}^* m_i^2 V_{iu} \approx 1.0 \cdot 10^{-11} \cdot \theta \text{ GeV}; \tag{2.2.6}$$

$$\mathcal{M}(B \to S\pi) \approx \theta \frac{M_B^2}{v} \frac{1}{2} \frac{3G_F\sqrt{2}}{16\pi^2} \sum_{i=u,c,t} V_{ib}^* m_i^2 V_{id} \approx 4.5 \cdot 10^{-6} \cdot \theta \text{ GeV}; \tag{2.2.7}$$

$$\mathcal{M}(B \to SK) \approx \theta \frac{M_B^2}{v} \frac{1}{2} \frac{3G_F\sqrt{2}}{16\pi^2} \sum_{i=u,c,t} V_{ib}^* m_i^2 V_{is} \approx 2.0 \cdot 10^{-5} \cdot \theta \text{ GeV}. \tag{2.2.8}$$

The matrix element for the D meson decay is suppressed compared to K or B for two reasons:

- The heaviest quark in the intermediate state for the D decay is the b quark, that is much lighter than the t quark in K and B mesons.
- CKM elements for the D decay are much smaller than for K and B mesons.

Using this information, we estimate the branching ratio for mesons into the scalar S and some other meson h' as

$$\mathrm{BR}(h \to Sh') = \frac{1}{\Gamma_{tot}(h)} \frac{|\mathcal{M}(h \to Sh')|^2}{16\pi M_h} \frac{2|p_S|}{M_h}, \tag{2.2.9}$$

where p_S is the momentum of the scalar S,

$$|p_S| = \frac{\sqrt{(M_h^2 - (m_S + m_h')^2)(M_h^2 - (m_S - m_h')^2)}}{2M_h}. \tag{2.2.10}$$

The results for different reactions are given in the Table 2.2.

Meson	$\mathrm{BR}(h \to SX) / \left(\frac{2\|p_S\|}{M_h}\theta^2\right)$
$K^\pm \to S\pi^\pm$	$1.8 \cdot 10^{-3}$
$K_L^0 \to S\pi^0$	$7.4 \cdot 10^{-3}$
$K_s^0 \to S\pi^0$	$1.3 \cdot 10^{-5}$
$D^\pm \to S\pi^\pm$	$3.0 \cdot 10^{-12}$
$B^\pm \to SK^\pm$	4.5
$B^0 \to SK^0$	4.2
$B^\pm \to S\pi^\pm$	0.22
$B^0 \to S\pi^0$	0.20

Table 2.2: Branching ratios of the 2-body meson decay.

The branching ratio of the $D \to S\pi$ decay is very small and it turns out that three-body decay is more probable [205, 206],

$$\mathrm{BR}(h \to Se\nu) = \frac{\sqrt{2}G_F M_h^4}{96\pi^2 m_\mu^2 (1 - m_\mu^2/M_h^2)^2} \times \mathrm{BR}(h \to \mu\nu) \left(\frac{7}{9}\right)^2 f\left(\frac{m_S^2}{M_h^2}\right), \tag{2.2.11}$$

where $f(x) = (1 - 8x + x^2)(1 - x^2) - 12x^2 \ln x$. The numerical values of the $h \to Se\nu$ decay for D, K and B mesons are given in the Table 2.3.

For kaons, we need to take into account that a large number of them will be scattered in the hadron absorber before decay. The scattered kaons are effectively lost to the light scalar production process. In Appendix 4.1.2, a simple estimate is made of the probability of the kaon decay P_{decay} before scattering using the lifetime and the cross section for the kaon in the material of the hadron absorber. The results are given in the Table 2.4.

Meson	$\mathrm{BR}(h \to Se\nu)/f(x)\,\theta^2$
$D \to Se\nu$	$5.2 \cdot 10^{-9}$
$K \to Se\nu$	$4.1 \cdot 10^{-8}$
$B \to Se\nu$	$< 7.4 \cdot 10^{-10}$

Table 2.3: Branching ratios of the 3-body meson decay. From the experimental data, we have only the upper bound on the $\mathrm{BR}(B \to \mu\nu)$, thus we put an upper bound on the $B \to Se\nu$ decay.

Meson	P_{decay}	$\mathrm{BR}(K \to S\pi) \times P_{decay}/\left(\theta^2 \frac{2\|p_S\|}{M_K}\right)$
$K^{\pm}$	$1.7 \cdot 10^{-3}$	$3.1 \cdot 10^{-6}$
K^0_L	$4 \cdot 10^{-4}$	$3.0 \cdot 10^{-6}$
K^0_s	0.2	$2.6 \cdot 10^{-6}$

Table 2.4: The decay probability for kaons in the SHiP absorber and the effective branching ratios.

We expect to produce the following number of mesons at SHiP for the 5 years of experiment: $N_K = 5.7 \cdot 10^{19}$ of kaons, $N_D = 6.8 \cdot 10^{17}$ of D mesons and $N_B = 6.4 \cdot 10^{13}$ of B mesons (see Sec. 4.1.1 for more details). Production from B mesons is 10^4 times more efficient than from D mesons. The expected number of light scalars is given in Fig. 2.4.

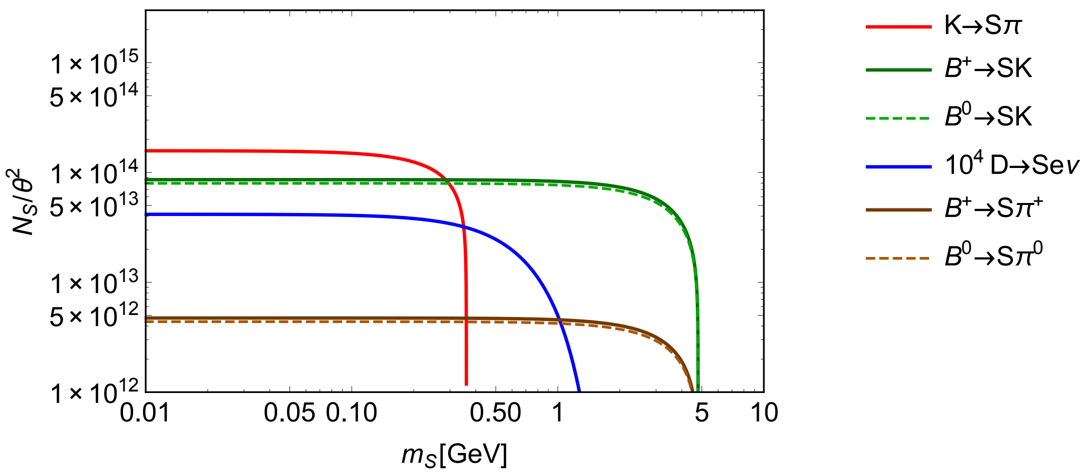

Figure 2.4: The expected number of produced light scalars at SHiP as a function of the mass of the scalar particle.

2.3 Decay widths of a scalar particle

The light scalar particle S interacts with the SM particles due to mixing with the Higgs boson, and its branching ratios coincide with the light Higgs branching ratios.

The main decay channels are decays into leptons and hadrons, see the paper [182]. Following this paper, we discuss separately two mass regions of the scalar S for decay into hadrons: below 1 GeV, where it is calculated using chiral perturbation theory and above 2 GeV, where it is estimated using perturbative QCD. The decay into photons is suppressed and is not be considered here.

2.3.1 Decay into leptons

The decay width for S particle into lepton is given by

$$\boxed{\Gamma(S \to l^+l^-) = \frac{\theta^2 m_l^2 m_S}{8\pi v^2}\left(1 - \frac{4m_l^2}{m_S^2}\right)^{3/2}}, \tag{2.3.1}$$

where θ is the mixing angle. This formula is valid for any mass of the scalar m_S.

2.3.2 Decay into hadrons

The scalar mass below 1 GeV If the mass of the scalar particle S is above the hadronic threshold, i.e. $m_S > 2m_\pi$, then the decay into pions is possible. The best (known to us) description of this decay is given in the paper [207], which combines chiral perturbation theory next to leading order with the method of dispersion relations. Using data on pion-pion scattering, the authors produced a prediction for the light Higgs decay width into 2 pions, see Fig. 2.5.

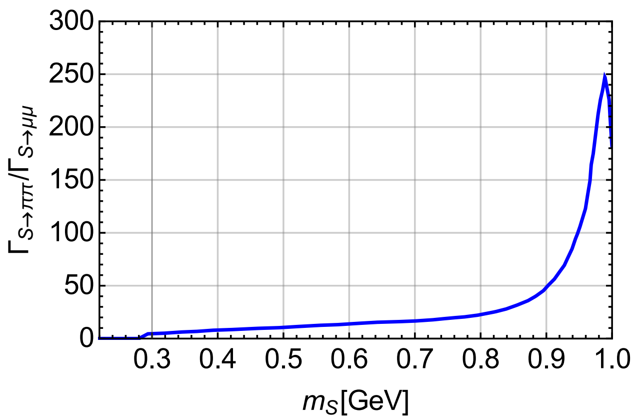

Figure 2.5: The ratio of the decay widths of the Higgs boson into pions and muons as a function of the scalar mass. Adapted from work [207].

The scalar mass above 2 GeV For this mass region, the decay width into hadrons can be estimated as the decay width into gluons and quarks. The decay width into gluons (with QCD corrections) [182, 208] is,

$$\boxed{\Gamma(S \to gg) = |F|^2\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\theta^2 m_S^3}{8\pi v^2}\left(1 + \frac{m_t^2}{8v^2\pi^2}\right)}. \tag{2.3.2}$$

Here m_t is the mass of the top quark and $F = \sum_q F_q$ is a sum of the loop contributions from quarks, which is defined as,

$$F_q = -2y_q(1 + (1 - y_q)x_q^2), \tag{2.3.3}$$

with $y_q = 4m_q^2/m_S^2$ and

$$x_q = \begin{cases} \text{Arctan}\dfrac{1}{\sqrt{y_q - 1}}, & \text{for} \quad y_q > 1, \\ \dfrac{1}{2}\left(\pi + i\log\dfrac{1 + \sqrt{y_q - 1}}{1 - \sqrt{y_q - 1}}\right), & \text{for} \quad y_q \leq 1. \end{cases} \tag{2.3.4}$$

We use the following quark masses (in GeV):

$m_u = 2.3 \cdot 10^{-3}$, $m_d = 4.8 \cdot 10^{-3}$, $m_s = 0.0924$, $m_c = 1.23$, $m_b = 4.2$, and $m_t = 173$.

Decay into quarks with the QCD corrections is calculated in the paper [208]. The decay width into quarks is basically the same as into leptons (2.3.1), multiplied by the color factor 3, and taking into account running masses for quarks and QCD corrections, namely

$$\boxed{\Gamma(S \to \bar{q}q) = 3\frac{\theta^2 m_S \overline{m}_q^2(m_S)}{8\pi v^2}\beta^3\left(1 + \Delta_{\text{QCD}} + \Delta_t\right)}, \tag{2.3.5}$$

where

$$\beta = \left(1 - \frac{4\overline{m}_q^2(m_S)}{m_S^2}\right)^{1/2}, \tag{2.3.6}$$

$$\begin{aligned} \Delta_{\text{QCD}} = 5.67\frac{\alpha_s(m_S)}{\pi} + (35.94 - 1.36N_f)\left(\frac{\alpha_s(m_S)}{\pi}\right)^2 \\ + (164.14 - 25.77N_f + 0.259N_f^2)\left(\frac{\alpha_s(m_S)}{\pi}\right)^3, \end{aligned} \tag{2.3.7}$$

$$\Delta_t = \left(\frac{\alpha_s(m_S)}{\pi}\right)^2\left(1.57 - \frac{2}{3}\log\frac{m_S^2}{m_t^2} + \frac{1}{9}\log^2\frac{\overline{m}_q^2(m_S)}{m_S^2}\right), \tag{2.3.8}$$

and the running mass [208] $\overline{m}_q(m_S)$ is given by

$$\overline{m}_q(m_S) = \overline{m}_q(Q)\frac{c(\alpha_s(m_S)/\pi)}{c(\alpha_s(Q)/\pi)}, \tag{2.3.9}$$

with the coefficient c, which is equal to,

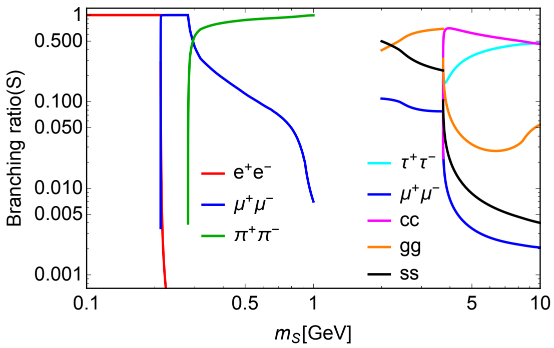

Figure 2.6: Branching ratios of the scalar S as a function of its mass.

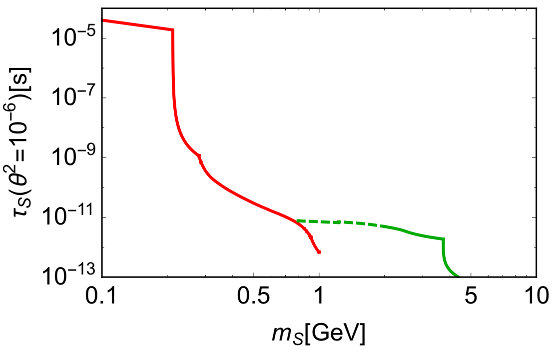

Figure 2.7: Lifetime of the scalar S as a function of its mass with the mixing angle $\theta^2 = 10^{-6}$, where the green dashed line in the middle region is calculated using perturbative QCD formulas.

$$c(x) = \left(\frac{9}{2}x\right)^{4/9}(1 + 0.895x + 1.371x^2 + 1.952x^3), \qquad \text{for } M_s < m_S < M_c, \tag{2.3.10}$$

$$c(x) = \left(\frac{25}{6}x\right)^{12/25}(1 + 1.014x + 1.389x^2 + 1.091x^3), \qquad \text{for } M_c < m_S < M_b, \tag{2.3.11}$$

$$c(x) = \left(\frac{23}{6}x\right)^{12/23}(1 + 1.175x + 1.501x^2 + 0.1725x^3), \qquad \text{for } M_b < m_S < M_t. \tag{2.3.12}$$

We use the quark masses in MS-bar scheme at $Q = 2$ TeV scale [209]: $\overline{m}_c = 1.23$ and $\overline{m}_s = 0.0924$.

The resulting branching ratios for the scalar S and its lifetime are presented in Figs. 2.6 and 2.7.