Search for hidden particles at SHiP. Lecture 4. Scalar sector. Number of created particles. Distribution functions.

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Strategy to construct sensitivity domain in the SHiP experiment

1. Find most effective channel of S-particle production in SHiP.
2. Find number of S-particles that can be produced within SHiP
3. Find number of S-particles that can get into vacuum tank of SHiP.
4. Find number of S-particles that can decay into SM particles in the vacuum tank of SHiP.
5. The number of S-particles that can be registered within SHiP
6. To construct sensitivity domain (in the plane coupling constant and mass of S-particle) in that particle must be detected in the SHiP experiment in 5 years of its operation in the minimum required amount.

Number of produced mesons

The number of mesons h produced at the SHiP target can be estimated as

$$N_h = 2 \times fh \times X_{q\bar{q}} \times N_{PoT}$$

where $X_{q\bar{q}}$ represents the $q\bar{q}$ production rate, fh is the meson h production fraction and expected number of protons on target $N_{PoT} = 2 \cdot 10^{20}$.

- the proton-nucleon cross section is $\sigma(pN) \simeq 10.7$ mbarn.
- $X_{ss} \approx 1/7$
- $\sigma(cc) = 18$ μbarn and the fraction $X_{cc} = 1.7 \times 10^{-3}$
- $\sigma(bb) = 1.7$ nbarn and the fraction $X_{bb} = 1.6 \times 10^{-7}$

To calculate meson production fraction the simulation is needed. It should take into account the properties of the target (materials, geometry) and the cascade processes (birth of the excited meson states like D^* and its decay into D).

Number of produced mesons

Meson	fh	N_h
K	—	$5.7 \cdot 10^{19}$
$D^{\pm}$	0.207	$1.4 \cdot 10^{17}$
D^0	0.632	$4.3 \cdot 10^{17}$
D_s	0.088	$6.0 \cdot 10^{16}$
J/ψ	0.01	$6.8 \cdot 10^{15}$
$B^{\pm}$	0.417	$2.7 \cdot 10^{13}$
B^0	0.418	$2.7 \cdot 10^{13}$
B_s	0.113	$7.2 \cdot 10^{12}$

Table: Production fraction and expected number of different mesons in SHiP.

Number of the produced S-particles

$$N_S = \text{BR}(h \to Sh') \cdot N_h \cdot P$$

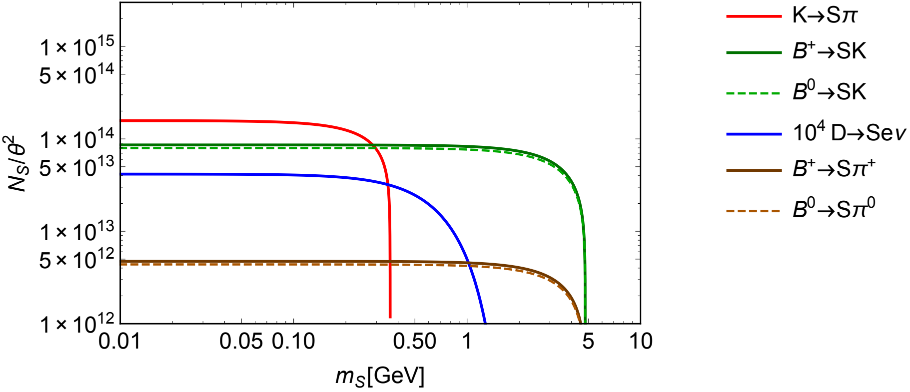


Figure: The expected number of the produced light scalars at SHiP.

Most effective channel of S-particle production

CERN experiment NA62 has more possibilities to find S-particle in K-mesons decay, so the most effective channel of S-particle production in SHiP

$$B^{\pm} \to S + K^{\pm}, \quad B^{0} \to S + K^{0}$$

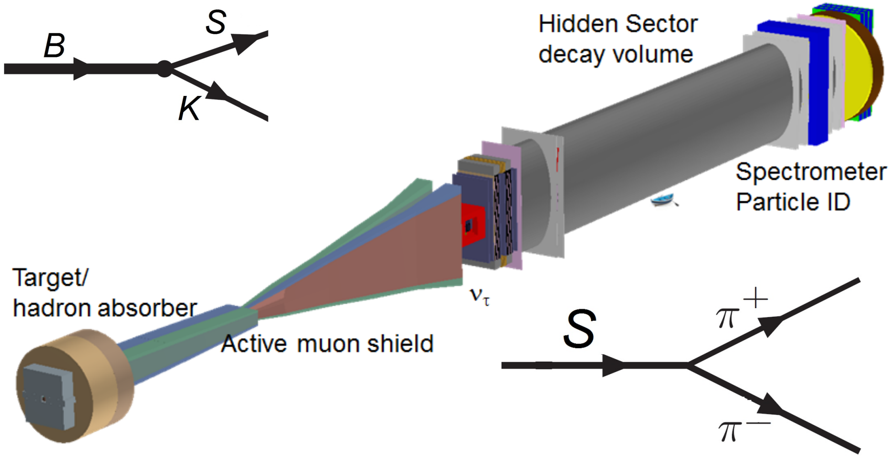
$$M_S^{min} < M_S < M_S^{max}$$
$$M_S^{min} = M_K - M_\pi \approx 0.37 \text{ GeV.}$$
$$M_S^{max} = M_B - M_K \approx 4.78 \text{ GeV}$$

$$N_S^{reg} = \sum_i N_{B^i} Br(B^i \to SK^i) P_{geom} P_{decay} \simeq 4 N_B Br(B \to SK) P_{geom} P_{decay}.$$

P_{geom} is a probability of the produced S-particle to move towards the detector.
P_{decay} is a probability of the produced S-particle to decay in the volume of the vacuum tank before the detectors.

SHiP (*Search for Hidden Particles*) experiment

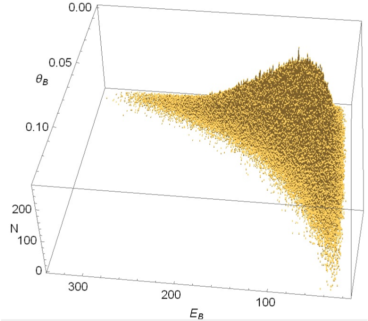
Step by step overview



P_{geom} – probability to move towards the detector. Distribution functions.

Kinematic parameters of S-particle depend on kinematic parameters of initial B-mesons. Through the use of **Monte-Carlo method** one can get a distribution of kinematic parameters of S-particles from the distribution of the produced B-mesons (simulation data from program packages *Pythia* and *Geant*).

We assumed, that in the own reference frame of B-meson the production of S-particle is isotropic.



Distribution of B-meson production (627074 events) in energy and polar angle

P_{geom} – probability to move towards the detector. Distribution functions.

Probability density functions (PDFs) $f(x)$, $Xmin < x < Xmax$.

Probability that quantity x will be in domain (a, b) is $P(x \in (a,b)) = \int_a^b f(y)dy$.

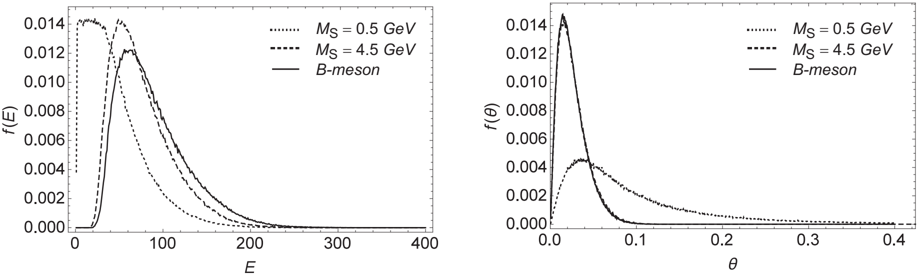
Cumulative distribution functions (CDFs) is just $F(x) = \int_{Xmin}^{x} f(y)dy$.

CDFs is the probability that X will take a value less than or equal to x.

The most probable value (mean value) x^* is found condition $F(x^*) = 1/2$!

What is the average amount of money in visitors of a pub, if the billionaire went there?

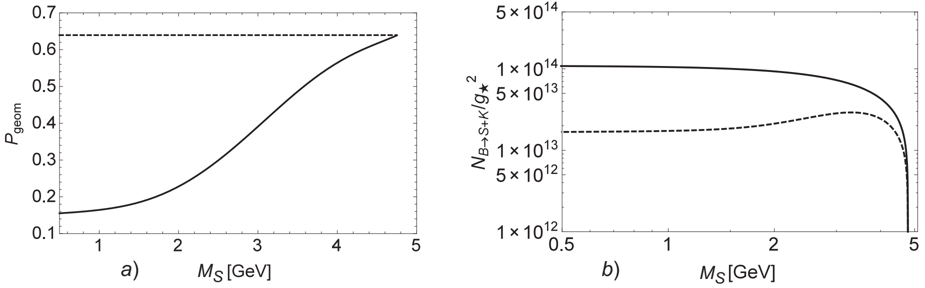
P_{geom} – probability to move towards the detector. Distribution functions.



Probability density functions of produced B-mesons and S-particles (with masses $M_S = 0.5$ GeV and $M_S = 4.5$ GeV) in the SHiP experiment: *a*) – PDFs on energy E (the number of events with energy values that lie in successive bins of width $\Delta E = 1$ GeV); *b*) – PDFs on polar angle θ (the number of events with angle values that lie in successive bins of width $\Delta\theta = 5 \cdot 10^{-4}$).

P_{geom} – probability to move towards the detector

P_{geom} – probability of the produced S-particles to move towards the detector ($\theta_S^{lab} < \theta_{detector}$) is just cumulative distribution functions on polar angle at point $\theta_{detector}$: $P_{geom}^S(M_S) = F_{S,\theta}(M_S, \theta_{detector})$.
We can also find probability of the B-meson to move in direction of the detector (to have angle $\theta_B^{lab} < \theta_{detector}$): $P_{geom}^B = F_{B,\theta}(\theta_{detector}) \simeq 0.6395$



Probability of a particle survival

$\tau = 1/\Gamma$ – life time of the particle for unmoved particle

$\tau' = \frac{\tau}{\sqrt{1-\beta^2}} = \gamma\tau$ – life time of the moving particle ($\beta = v/c$)

$P = e^{-t_0\Gamma/\gamma} = e^{-t_0\Gamma M/E}$ – probability of existence particle during time t_0 (probability of not decaying particle during time t_0)

$L = \tau\gamma v = \tau|\vec{p}|/M$ – the distance a particle travels before decay

$P = e^{-x_0\Gamma/(v\gamma)} = e^{-x_0\Gamma M/|\vec{p}|} = e^{-x_0/L}$ – probability of not decaying particle during a travel a distance L

P_{decay} – probability to decay inside the vacuum tank

$$P_{decay} = e^{-\frac{L\Gamma}{\gamma\beta}} - e^{-\frac{(L+\Delta L)\Gamma}{\gamma\beta}} =$$

$$e^{-\frac{g_\star^2}{c\sqrt{\gamma^2-1}}\left(\frac{L}{1m}\right)\left(\frac{1s}{\tau}\right)} - e^{-\frac{g_\star^2}{c\sqrt{\gamma^2-1}}\left(\frac{L+\Delta L}{1m}\right)\left(\frac{1s}{\tau}\right)},$$

where $L = 63.8$ m is a distance from the target to the vacuum tank, $\Delta L = 60$ m is the length of the vacuum tank, $\gamma = E_S^{lab}/M_S$, $\beta = \sqrt{1-\gamma^{-2}}$ and $\Gamma = 1/\tau$ is the decay width of S-particle.

We very need decay width of the new scalar !!!

Scalar decay into leptons

Full decay width is sum of decay width over all decay channel!
We need to know all decay channel!

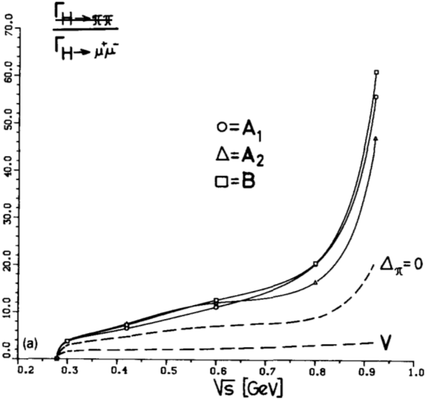
$$\Gamma = \sum_i \Gamma_i$$

For any mass of the scalar m_S the decay width for S particle into **lepton** is

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

Scalar decay into hadrons $2m_\pi < M_S < 1$ GeV

If $m_S > 2m_\pi$, then the decay into pions is possible. The calculation can be made up to $M_S \sim 1$ GeV using **chiral perturbation theory**



The ratio of the decay widths of the Higgs boson (S-particle) into pions and muons.

Donoghue, J. F., Gasser, J., and Leutwyler, H. (1990), Nucl. Phys., B343:341-368

Scalar decay into hadrons with $M_S > 2$ GeV

The decay width of S-particle with $M_S > 2$ GeV into quarks and gluons can be calculated in **perturbative QCD !!!**

The decay width of S-partile into **gluons** (with QCD corrections)

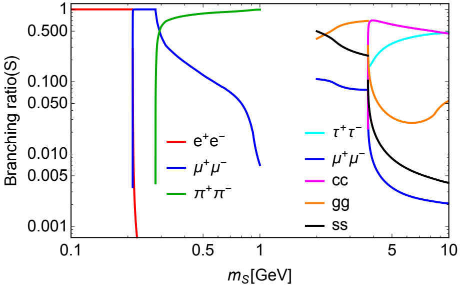
$$\Gamma(S \to gg) = |F|^2 \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\theta^2 m_S^3}{8\pi v^2} \left(1 + \frac{m_t^2}{8v^2\pi^2}\right)$$

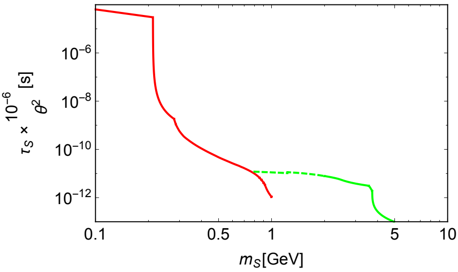
The decay width of S-partile into **quarks** with QCD corrections

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

Bezrukov, F. and Gorbunov, D. (2010). Light inflaton Hunter's Guide. JHEP, 05:010.
Spira, M. (1998). QCD effects in Higgs physics. Fortsch. Phys., 46:203284.

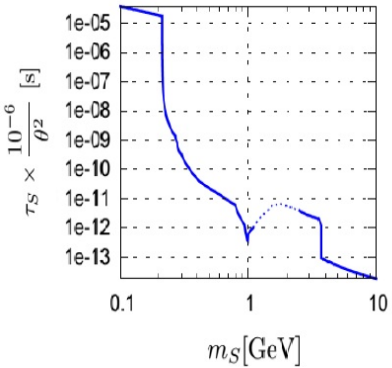
Scalar decay

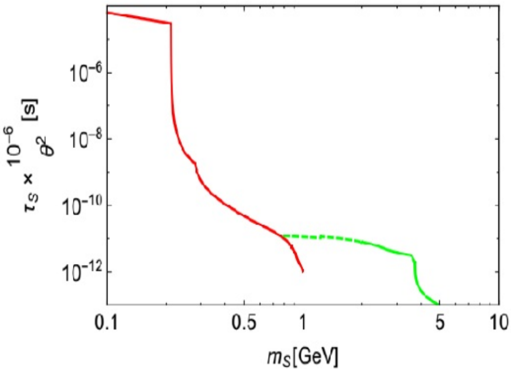




- At low mass $m_S < 2m_\pi$ decay to leptons dominates
- Using perturbative QCD one can calculate decays into quarks and gluons for $m_S > 2$ GeV
- Region in between has large theoretical uncertainty because of the resonant decay into pions and kaons Boyarsky,Monin,Ruchayskiy *to appear*. They are the main decay channels in this region, even taking into account the uncertainty

Theoretical predictions in S-particle life time

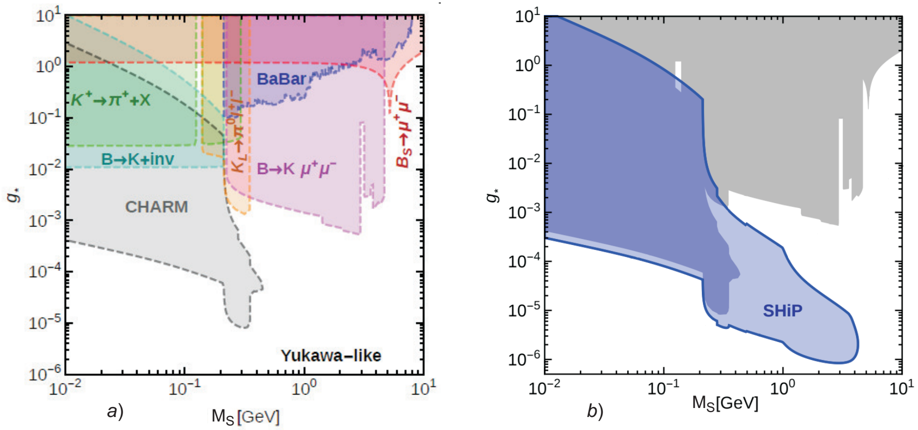




F. Bezrukov and D. Gorbunov, inflaton after LHC8 and WMAP9 results, JHEP 1307 (2013) 140, [arXiv:1303.4395];
A. Boyarsky, K. Bondarenko (unpublished)

The depth of the valley is unknown!

Experimental status of hidden scalars



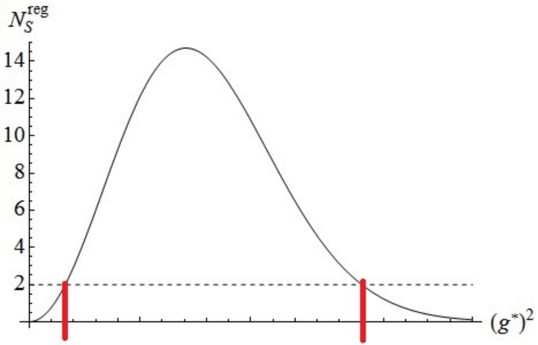
Parameter space for a light scalar with Yukawa-like couplings: *a*) – currently excluded parameter space; *b* – projected sensitivity of SHiP for a light scalar, in comparison to the existing bounds.

Calculations

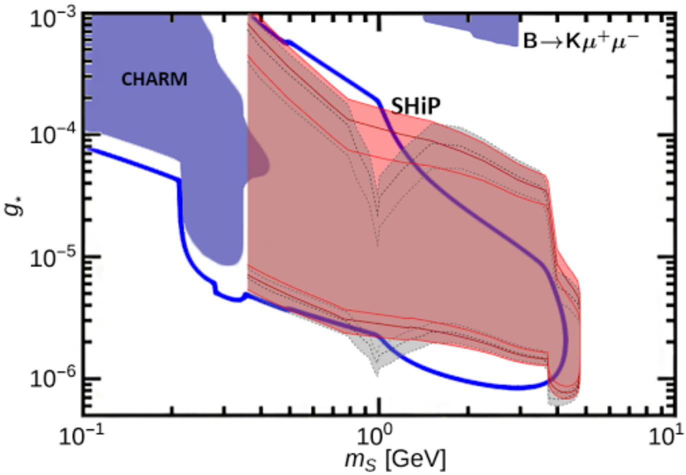
Using approximation $e^x \simeq 1 + x$, lower bound of the sensitivity region (for the coupling constant) can be analytically obtained from condition

$$N_S^{reg} \approx g_\star^4 \left(\frac{\Delta L}{1m}\right)\left(\frac{1s}{\tau}\right)\frac{1}{c}\frac{\tilde{N}_S(M_S)P_{geom}(M_S)}{\sqrt{\left(\frac{E_S}{M_S}\right)^2 - 1}} > 2$$

Upper bound of the sensitivity region can be obtained only with help of computer

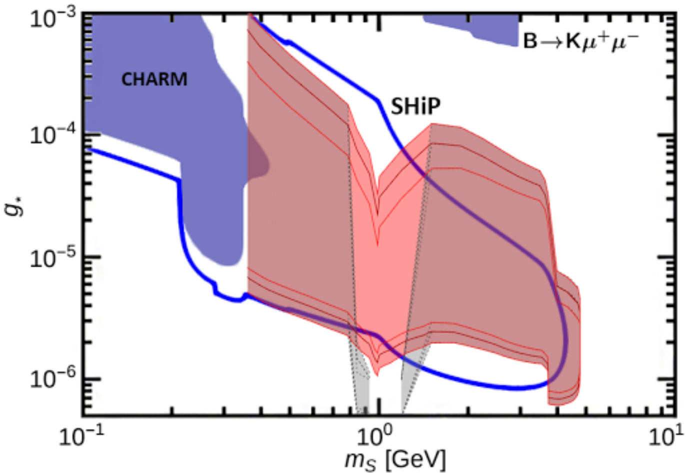


Qualitative dependence of number of the S-particles (that can be registered) on coupling constant at fixed value of particle mass:
$N_S^{reg} \sim (g^*)^2 exp[-\alpha(g^*)^2]$



Results for the sensitivity region of the SHiP experiment to find a scalar particle with Yukawa-like couplings, in comparison to the previous SHiP bounds. Presented cases of presence and absence of the valley.

Our results and constrains



Results for the sensitivity region of the SHiP experiment to find a scalar particle with Yukawa-like couplings, in comparison to the previous SHiP bounds. Presented cases of the valley and 4000 times greater valley..