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

Bondarenko, K.

Citation

Bondarenko, K. (2018, November 15). *Plan B for particle physics: finding long lived particles at CERN*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/67089

Author: Bondarenko, K.
Title: Plan B for particle physics: finding long lived particles at CERN
Issue Date: 2018-11-15

Chapter 4

Description of experiments

4.1 SHiP

SHiP is a dedicated beam-line experiment extracted from the super proton synchrotron (SPS) based at CERN [110] (see FIG. 4.2). It will fire a 400 GeV proton beam at a Molybdenum and Tungsten target, with a center-of-mass energy $E_{\mathrm{CM}} \approx 27$ GeV. There will be approximately a total of $2 \cdot 10^{20}$ proton-target collisions (PoT) in 5 years of operation.

The target is followed by a 5 m long hadron stopper, intended to stop all $\pi^{\pm}$ and K mesons before they decay. After the hadron absorber there is a so-called active muon shield, a system of magnets constructed to sweep muons away from the fiducial decay volume. For sweeping of 350 GeV muons active muon shield contains a 18 m long magnet with a magnetic field $B \approx 1.8$ T [244]. The entire active muon shield system has a length of 34 m.

After the muon shield, there is the SHiP neutrino detector, called iSHiP. This is schematically shown in Fig. 4.1. The iSHiP consists of a magnetized target with

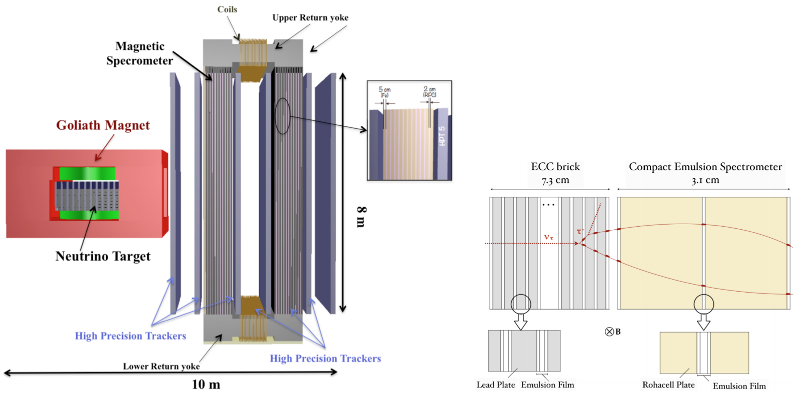

Figure 4.1: Construction of the the iSHiP detector [245]

the length of $l_{\mathrm{iSHiP}} \simeq 5$ m with a modular structure. Each module consists of walls of emulsion cloud chambers (ECC) and a compact emulsion spectrometer (CES).

ECC bricks are plates of high atomic number passive material (e.g. lead) interleaved with thin nuclear emulsion foils. Electronic trackers provide time stamping for each event and are located between the target walls. They allow the reconstructed tracks to be connected between the emulsion target and those measured in the spectrometer downstream. This layout has already proven to be effective in detecting all ν flavors. For example it is possible to separate the ν_τ via the decay of the τ lepton in the muon channel by measuring the electric charge of the muon in the spectrometer. This can be further optimized by adopting a magnetized target which would allow the separation of ν_τ through the decay of the τ lepton in the hadronic channel. The emulsion spectrometer (CES) is made of a sequence of very low-density layers and emulsion foils that measures the electric charge and momentum of particles.

There is an upstream tagger, that together with the muon spectrometer of the neutrino detector, will detect and veto charged particles produced outside of the main decay volume. The fiducial decay volume begins approximately 63.8 m downstream from the primary target and is contained within a cylindrical vacuum tank 50 m long with an elliptical cross-section of 12.5 m^2.

A straw tagger is placed in a vacuum 5 m downstream from the entrance lid of the vacuum tank to help reduce the background arising from interactions in the material upstream of the decay volume. An additional background tagger surrounds the fiducial decay volume, the walls of which enclose 30 cm of liquid scintillator.

The tracking system aimed to measure the decay products of hidden particles is located at the end of the decay volume. It consists of 5 m long straw tubes organized in to 4 stations, with a magnetic field of 1 T between the second and third station. The high-accuracy timing information provided by a dedicated detector following the straw tracker will be used to discriminate the combinatorial background.

The particle identification system is placed outside the vacuum tank, and features an electromagnetic and a hadronic calorimeter, followed by a muon system made of four active layers interlaced with iron.

4.1.1 Production of heavy flavor at the SHiP

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

$$N_h = 2 \times fh \times X_{q\bar{q}} \times N_{PoT}, \tag{4.1.1}$$

where $X_{q\bar{q}}$ represents the $q\bar{q}$ production rate, fh is the meson h production fraction[1] and expected number of protons on target $N_{PoT} = 2 \cdot 10^{20}$. The following cross sections have been used for the estimates:

---

[1] fh is equal to the number of h mesons divided by the number of corresponding quarks.

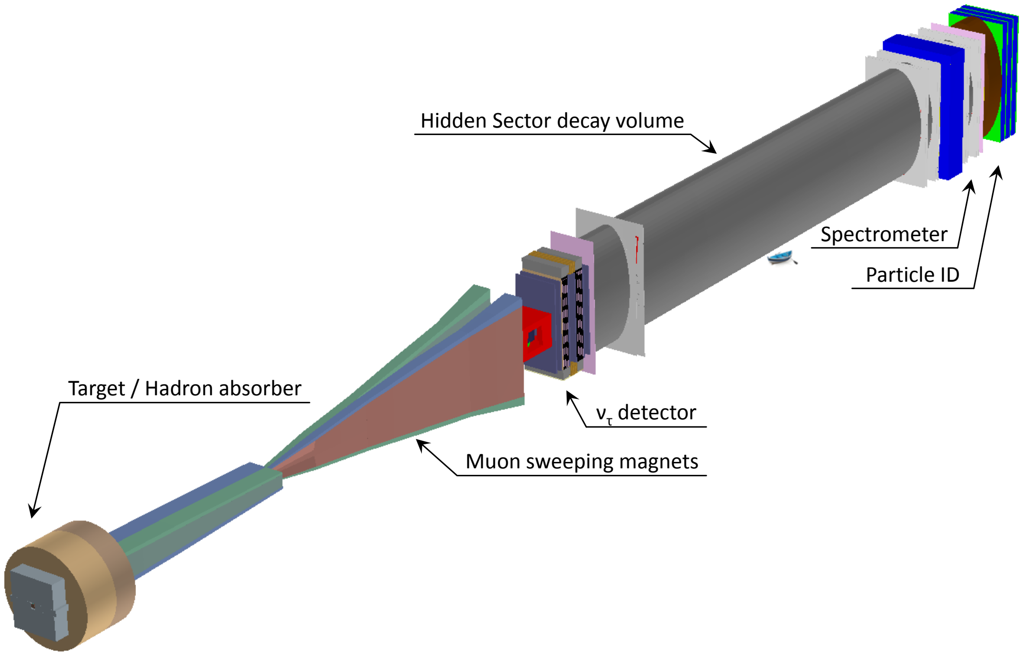

Figure 4.2: Scheme of the SHiP experimental setup with indication of its main parts.

- The proton-nucleon cross section is $\sigma(pN) \simeq 10.7$ mbarn;
- $X_{ss} \approx 1/7$ [218];
- $\sigma(cc) \approx 41.4$ μbarn [246] and the fraction $X_{cc} = 9 \times 10^{-3}$;
- $\sigma(bb) = 2.9$ nbarn [246] and the fraction $X_{bb} = 2.7 \times 10^{-7}$.

Simulation is needed to calculate the meson production fraction. It should take into account the properties of the target (e.g. materials, geometry) and the cascade processes (e.g. birth of the excited meson states like D^* and its decay into D). The values of fh for the case of the SHiP experiment were calculated in the paper [221]. These values with the number of different mesons are given in the Table 4.1. For kaons, we do not divide them into species.

The expected number of τ leptons for $N_{PoT} = 2 \times 10^{20}$ is $N_\tau = 3 \times 10^{15}$.

4.1.2 Kaon decay fraction at the SHiP

In this section, we calculate the fraction of kaons that decay before scattering on the absorber material. We assume that scattered kaons fly in a random direction and their products do not hit the detector.

Meson	fh	N_h
K	$-$	$5.7 \cdot 10^{19}$
$D^{\pm}$	0.207	$3.2 \cdot 10^{17}$
D^0	0.632	$9.9 \cdot 10^{17}$
D_s	0.088	$1.4 \cdot 10^{17}$
J/ψ	0.01	$6.8 \cdot 10^{15}$
$B^{\pm}$	0.417	$4.6 \cdot 10^{13}$
B^0	0.418	$4.6 \cdot 10^{13}$
B_s	0.113	$1.2 \cdot 10^{13}$

Table 4.1: Production fraction and expected number of different mesons at the SHiP.

The cross section for kaon-nucleon scattering is (see "Plots of cross sections and related quantities" review in Particle Data Group [222])

$$\sigma_{KN} = 20 \text{ mb} = 2 \cdot 10^{-26} \text{ cm}^2. \tag{4.1.2}$$

The number density for nucleons in the SHiP absorber (iron)

$$n_N = 4.8 \cdot 10^{24} \text{ cm}^{-3}. \tag{4.1.3}$$

Therefore, the mean free path of the kaon in the absorber is

$$l = \frac{1}{\sigma_{KN} n_N} = 10 \text{ cm}. \tag{4.1.4}$$

The mean distance before the kaon decay is

$$d = \gamma c \tau, \tag{4.1.5}$$

where γ is the gamma factor and τ is the lifetime. In our estimation, we take $\gamma \sim 15$, which is corresponds to the gamma factor between center-of-mass and laboratory frame of the colliding protons.

For the small distance dx, the probability of scattering is equal to $P_{\text{scat}} = \dfrac{dx}{l}$, and the probability of the decay is $P_{\text{decay}} = \dfrac{dx}{d}$. Thus, the ratio between the number of scattered and decayed kaons is equal to

$$\frac{N_{\text{scat}}}{N_{\text{decay}}} = \frac{d}{l}, \tag{4.1.6}$$

and the full number of the decayed kaons is

$$N_{\text{decay}} = N_0 \frac{l}{l+d}, \tag{4.1.7}$$

where N_0 is the initial number of kaons. So, the probability of the kaon decay P_{decay} before scattering is

$$P_{decay} = \frac{N_{decay}}{N_0} = \frac{l}{l+d}. \tag{4.1.8}$$

Meson	P_{decay}
K_L^0	$4 \cdot 10^{-4}$
$K^{\pm}$	$1.7 \cdot 10^{-3}$
K_s^0	$2 \cdot 10^{-1}$

Table 4.2: The decay probability for kaons in the SHiP absorber.

4.2 MATHUSLA

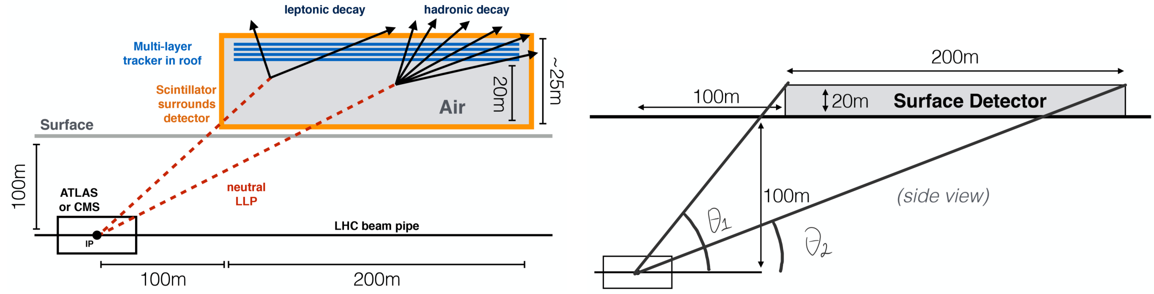

Figure 4.3: The proposed design for the MATHUSLA experiment (left) [113] and the main experimental dimensions, adapted from [247].

The MATHUSLA (MAssive Timing Hodoscope for Ultra Stable neutraL pArticles) is a proposed experiment [113, 114] that consists of 20 m×200 m×200 m surface detector, installed above the ATLAS or CMS detectors (see Fig. 4.3). The long-lived particles, created during the LHC collisions, travel 100+ meters of rock and decay within a large decay volume (8×10^5 m^3) of the detector. A multi-layer tracker on the detector's roof will catch the charged tracks, originating from the particle decays. The ground between the ATLAS/CMS and the MATHUSLA detector would serve as a passive shield, significantly reducing the Standard Model background (with the exception of neutrinos, muons, and K_L^0 created near the surface). Assuming the isotropic angular distribution of a given particle traveling to the MATHUSLA, the average distance that it should travel to reach the MATHUSLA detector is equal to

$$\bar{l}_{\text{tar-det}} \equiv \left\langle \frac{L_{ground}}{\sin\theta} \right\rangle = 192.5 \text{ m}, \tag{4.2.1}$$

where $L_{\text{ground}} = 100$ m. The average distance where a particle travels inside the detector, $\bar{L}_{\text{det}}$, is given by

$$\bar{l}_{\text{det}} \equiv \left\langle \frac{20 \text{ m}}{\sin\theta} \right\rangle = 38.5 \text{ m}. \tag{4.2.2}$$

Geometrical parameters of the MATHUSLA experiment are summarized in Table 4.3. Relevant parameters of mesons at the experiment are provided by FONLL program [248, 249]. They are summarized in Table 4.4.

Parameter	θ_1	θ_2	η_1	η_2	$\bar{l}_{\text{tar-det}}$, m	$\bar{l}_{\text{det}}$, m	$\Delta\phi$
Value	44.3°	22.9°	0.9	1.6	192.5	38.5	$\pi/2$

Table 4.3: Parameters of the MATHUSLA experiment [247]. For the definition of angles $\theta_{1,2}$ see Fig. 4.3, and $\Delta\phi$ is the azimuthal size of the MATHUSLA.

Parameter	$N_{c\bar{c}}$	$\langle p_D \rangle$	$N_{b\bar{b}}$	$\langle p_B \rangle$, GeV
Value	3.6×10^{14}	5.1	3.6×10^{13}	12.2

Table 4.4: Parameters of mesons production at the MATHUSLA experiment.