Search for hidden particles with the SHiP experiment

DPG Frühjahrstagung 2017 – Münster

Daniel Bick

SHiP
Search for Hidden Particles

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

March 29, 2017

Physics Motivation

SM very successful, however. . .

Strong Evidence for BSM Physics

- neutrino masses and oscillations
- the nature of non-baryonic Dark Matter
- excess of matter over antimatter in the Universe
- cosmic inflation of the Universe

Shortcoming of Theory

- gap between Fermi and Planck scales
- Dark Energy
- connection to gravity
- . . .

New/extended models needed

Where to find new physics

- Unsolved problems → new particles
- Why haven't we seen them, yet?
    - Too heavy or too weakly interacting

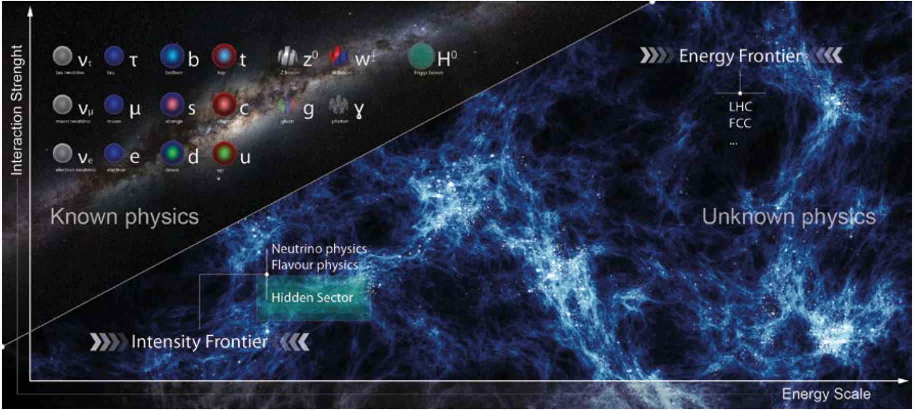


Image: CERN Courier 2/2016

How to Explore Hidden Sector?

- Phenomenologies of hidden sector models share a number of unique and common physics features

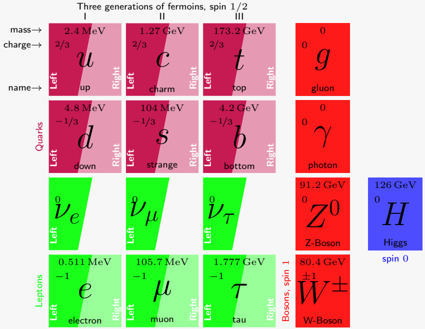
Models	Final States
Neutrino portal, HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}$
Vector, scalar, axion portals, SUSY sgoldstino	$e^{+}e^{-}$, $\mu^{+}\mu^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}$, $K^{+}K^{-}$
Neutrino portal, HNL, SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$

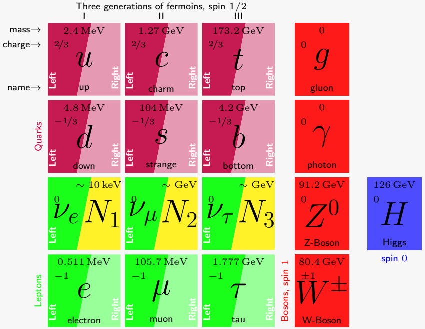
- Production through meson decays (π, K, D, B)
- Production and decay rates are strongly suppressed relative to SM
  - production branching ratios $\mathcal{O}(10^{-10})$
  - long-lived objects $\mathcal{O}(\mu s)$
  - travel unperturbed through ordinary matter

νMSM

Minimal approach, extends SM by three neutral particles

→ T.Asaka, M.Shaposhnikov **PLB 620** (2005) **17**

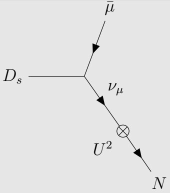


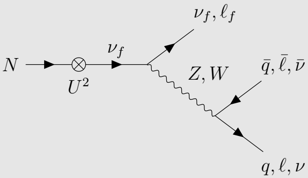


- N_i: 3 Heavy Neutral Leptons (HNL)
- N_1: $\sim 10\,\mathrm{keV}$
  - DM candidate
- N_2, N_3: $\sim$ GeV region
  - neutrino masses
  - baryon asymmetry of the Universe

Experimental Concept

Example for HNLs

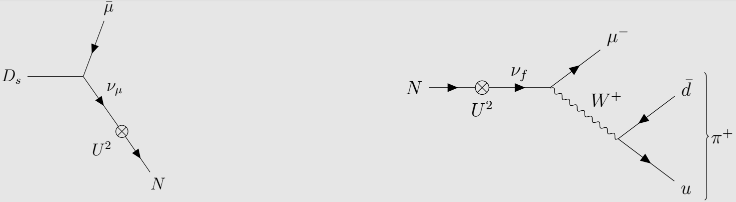




- typical lifetimes $> 10\,\mu\mathrm{s}$ for $m_{N_{2,3}} \sim 1\,\mathrm{GeV}$
- decay distance $\mathcal{O}(\mathrm{km})$

- Detection of hidden particles through their decay in SM particles
- Detector must be sensitive to as many decay modes as possible
- ▷ Full reconstruction essential to minimize model dependence
- Branching ratios suppressed compared to SM couplings $\mathcal{O}(10^{-10})$
- ▷ challenging background suppression → estimated $\mathcal{O}(0.01)$ needed

Example for HNLs



- typical lifetimes $> 10\,\mu\text{s}$ for $m_{N_{2,3}} \sim 1\,\text{GeV}$
- decay distance $\mathcal{O}(\text{km})$

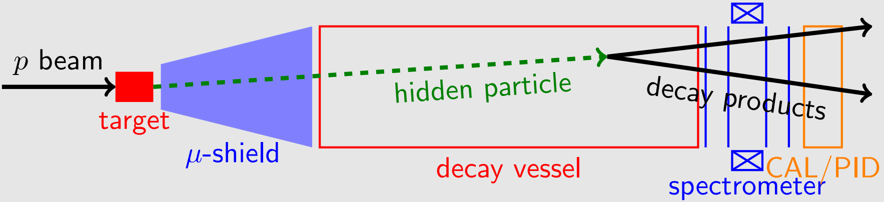
- Detection of hidden particles through their decay in SM particles
- Detector must be sensitive to as many decay modes as possible
- ▷ Full reconstruction essential to minimize model dependence
- Branching ratios suppressed compared to SM couplings $\mathcal{O}(10^{-10})$
- ▷ challenging background suppression → estimated $\mathcal{O}(0.01)$ needed

- SHiP is a new proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to $\mathcal{O}(10)\,\mathrm{GeV}$ and extremely weak couplings down to 10^{-10}.

Decay of hidden particles

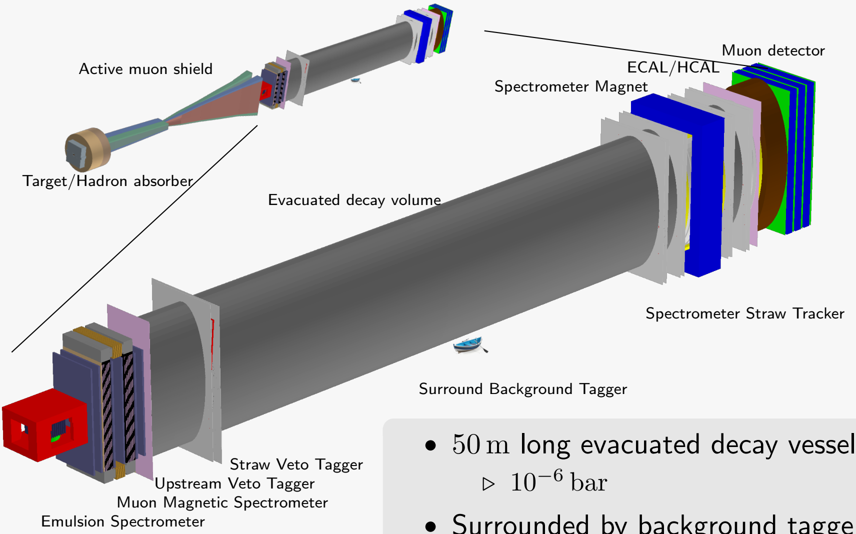
- SHiP is a new proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to $\mathcal{O}(10)\,\mathrm{GeV}$ and extremely weak couplings down to 10^{-10}.

Decay of hidden particles



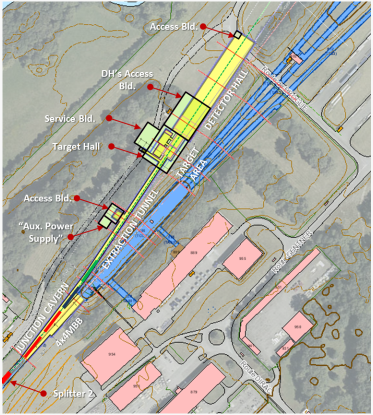
- large decay volume followed by spectrometer, calorimeter, PID
- shielding from SM particles: hadron absorber and veto detectors

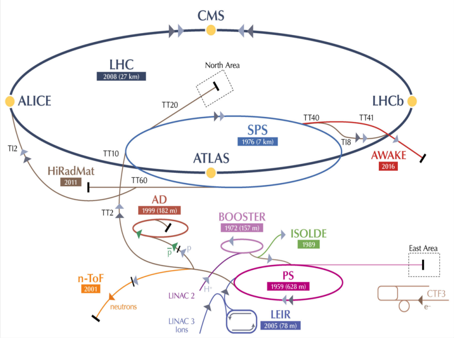
Detector Layout



- $50\,\mathrm{m}$ long evacuated decay vessel
  - ▷ $10^{-6}\,\mathrm{bar}$
- Surrounded by background taggers
- Active shield for μ-free environment

Fixed Target Facility @ SPS North Area





- $400\,\mathrm{GeV}$ protons
- $4 \cdot 10^{13}$ pot/spill (every $7\,\mathrm{s}$)

▷ $2 \cdot 10^{20}$ pot in 5 years

Target

- $58\,\mathrm{cm}$ Mo $(4\,\lambda)$, $58\,\mathrm{cm}$ W $(6\,\lambda)$

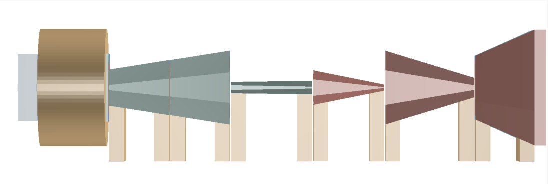
▷ Optimized for heavy meson production

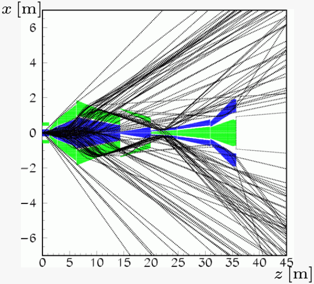
- Followed by hadron stopper

Magnetic Sweeper

Deal with 10^{10} muons/spill

- active magnetic muon shield and passive absorber
- less than 100k μ/spill remaining

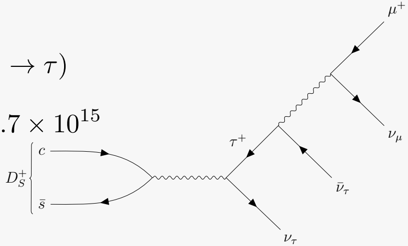




SM Physics

- The facility is also ideally suited for studying ν_τ and $\bar{\nu}_\tau$ properties and testing lepton flavor universality by comparing interactions of μ and τ neutrinos.

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau)$$
$$= 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$



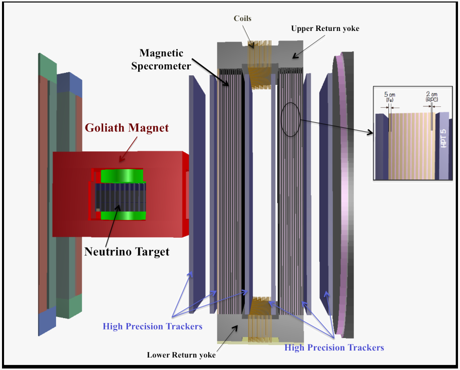
ν-production @ p-target

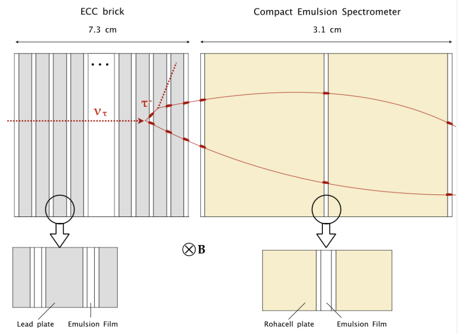
- $5.7 \cdot 10^{15}$ ν_τ and $\bar{\nu}_\tau$
- $5.7 \cdot 10^{18}$ ν_μ and $\bar{\nu}_\mu$
- $3.7 \cdot 10^{17}$ ν_e and $\bar{\nu}_e$

Interactions @ ν-target

	$< E >$ (GeV)	Number of ν
ν_μ	30	$2.3 \cdot 10^6$
ν_e	46	$3.4 \cdot 10^5$
ν_τ	58	$7.1 \cdot 10^3$
$\bar{\nu}_\mu$	27	$9.5 \cdot 10^5$
$\bar{\nu}_e$	46	$1.4 \cdot 10^5$
$\bar{\nu}_\tau$	58	$3.6 \cdot 10^3$

Emulsion Spectrometer





- $9.6\,\mathrm{tons}$ emulsion/lead target in magnetic field:
- 11 walls of 14×6 ECC-bricks, replaced every 6 months for scanning
- ▷ Total number of bricks: $924 \rightarrow 6930\,\mathrm{m}^2$ emulsion films
- Each brick is followed by a compact emulsion spectrometer
- Resolution of $1\,\mu\mathrm{m}$

ν_τ Physics and more...

Direct measurements of tau neutrino CC-interaction fairly recent

- DONUT: 9 ± 1.5 events
  - no distinction between ν_τ and $\bar{\nu}_\tau$
- OPERA: 5 events
  - only ν_τ

SM Physics opportunity for SHiP

- $\mathcal{O}(4000)$ $\nu_\tau/\bar{\nu}_\tau$ interactions
- ▷ Study the properties and cross-section
- ▷ First observation of $\bar{\nu}_\tau$

- Light Dark Matter search
- Extraction of F_4 and F_5 structure functions
- Measure the s-content of the nucleon

Background in Hidden Particle Detector

Background sources and rejection strategies

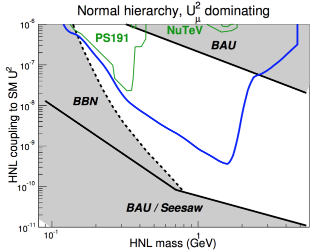
- ν- and μ-induced backgrounds
  - e.g inelastic ν-interactions in the surroundings of the HP detector
  - ▷ Reconstructed momentum must point back to proton target
  - ▷ Veto upstream the decay volume
  - ▷ Reconstructed vertex must be in decay volume
- Random combination of tracks
  - Rate at spectrometer: $7\,\mathrm{kHz/spill}$
  - ▷ Timing veto with a precision of $\mathcal{O}(100\,\mathrm{ps})$
  - ▷ Surround background tagger and upstream veto detector
- Cosmic muons
  - Scattering/DIS on cavern and vessel walls
  - ▷ Surround background tagger and upstream veto detector
  - ▷ Event topology, pointing of momentum

- Backgrounds have been investigated in extensive MC studies.

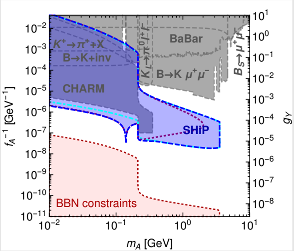
▷ Overall expected background: less than 0.1 events in 5 years

Some Sensitivities

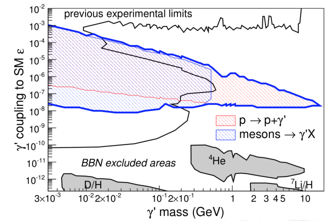
Neutrino Portal



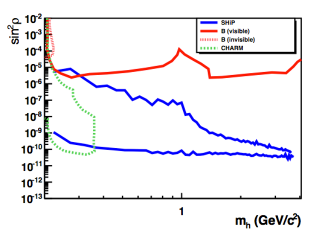
Axion Portal



Vector Portal



Scalar Portal



The People behind SHiP

Technical Proposal


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

arXiv:1504.04956v1 [physics.ins-det] 20 Apr 2015

Technical Proposal

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

The SHiP Collaboration[1]

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

[1] Authors are listed on the following pages.

arXiv:1504.04956v1

$\sim$ 250 physicists from 47 institutions and 15 countries

Physics Proposal


CERN-SPSC-2015-017 (SPSC-P-350-ADD-1)

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

arXiv:1504.04855v1 [hep-ph] 19 Apr 2015

Sergey Alekhin,[1,2] Wolfgang Altmannshofer,[3] Takehiko Asaka,[4] Brian Batell,[5] Fedor Bezrukov,[6,7] Kyrylo Bondarenko,[8] Alexey Boyarsky⋆,[8] Nathaniel Craig,[9] Ki-Young Choi,[10] Cristóbal Corral,[11] David Curtin,[12] Sacha Davidson,[13,14] André de Gouvêa,[15] Stefano Dell'Oro,[16] Patrick deNiverville,[17] P. S. Bhupal Dev,[18] Herbi Dreiner,[19] Marco Drewes,[20] Shintaro Eijima,[21] Rouven Essig,[22] Anthony Fradette,[17] Björn Garbrecht,[20] Belen Gavela,[23] Gian F. Giudice,[5] Dmitry Gorbunov,[24,25] Stefania Gori,[3] Christophe Grojean§,[26,27] Mark D. Goodsell,[28,29] Alberto Guffanti,[30] Thomas Hambye,[31] Steen H. Hansen,[32] Juan Carlos Helo,[11] Pilar Hernandez,[33] Alejandro Ibarra,[20] Artem Ivashko,[8,34] Eder Izaguirre,[3] Joerg Jaeckel§,[35] Yu Seon Jeong,[36] Felix Kahlhoefer,[27] Yonatan Kahn,[37] Andrey Katz,[5,38,39] Choong Sun Kim,[36] Sergey Kovalenko,[11] Gordan Krnjaic,[3] Valery E. Lyubovitskij,[40,41,42] Simone Marcocci,[16] Matthew Mccullough,[5] David McKeen,[43] Guenakh Mitselmakher ,[44] Sven-Olaf Moch,[45] Rabindra N. Mohapatra,[46] David E. Morrissey,[47] Maksym Ovchynnikov,[34] Emmanuel Paschos,[48] Apostolos Pilaftsis,[18] Maxim Pospelov§,[3,17] Mary Hall Reno,[49] Andreas Ringwald,[27] Adam Ritz,[17] Leszek Roszkowski,[50] Valery Rubakov,[24] Oleg Ruchayskiy⋆,[21] Jessie Shelton,[51] Ingo Schienbein,[52] Daniel Schmeier,[19] Kai Schmidt-Hoberg,[27] Pedro Schwaller,[5] Goran Senjanovic,[53,54] Osamu Seto,[55] Mikhail Shaposhnikov⋆,§,[21] Brian Shuve,[3] Robert Shrock,[56] Lesya Shchutska§,[44] Michael Spannowsky,[57] Andy Spray,[58] Florian Staub,[5] Daniel Stolarski,[5] Matt Strassler,[39] Vladimir Tello,[53] Francesco Tramontano§,[59,60] Anurag Tripathi,[59] Sean Tulin,[61] Francesco Vissani,[16,62] Martin W. Winkler,[63] Kathryn M. Zurek[64,65]

Abstract: This paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (*Search for Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau \to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

⋆Editor of the paper
§Convener of the Chapter

arXiv:1504.04855v1

$\sim$ 85 theorists, more than 250 pages

German Contributions to SHiP

HU Berlin

- Liquid Scintillator Surround Background Tagger
  - ▷ Studies of wavelength shifting optical modules

JGU Mainz

- Pre-shower detector for ECAL
- Support of scintillator studies for the SBT

Uni Hamburg

- Straw Tube operation for the main spectrometer
  - ▷ use of straws also in emulsion spectrometer

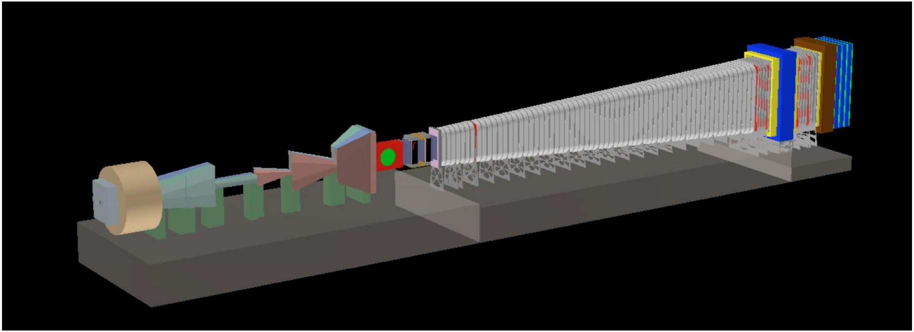
More groups welcome!!!

Summary

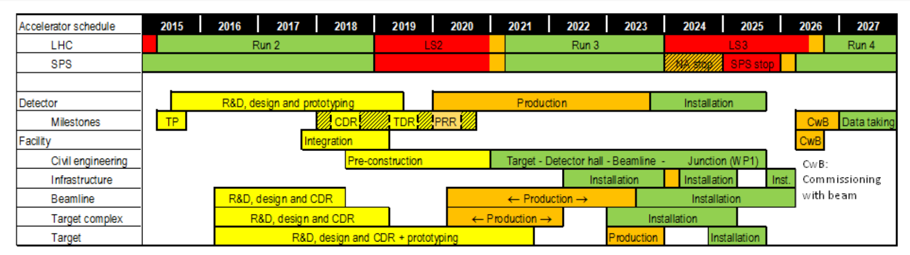
- SHiP is proposed to complement searches for new physics at CERN in the largely unexplored domain of new, very weakly interacting particles with masses $\mathcal{O}(10)\,\mathrm{GeV}$
- Also great opportunities for SM physics
  - ▷ Improve sensitivity of ν_τ-physics by $\mathcal{O}(1000)$
- Recognized as an experiment by CERN since May 2016
- Optimization ongoing

Summary

- SHiP is proposed to complement searches for new physics at CERN in the largely unexplored domain of new, very weakly interacting particles with masses $\mathcal{O}(10)\,\mathrm{GeV}$
- Also great opportunities for SM physics
  - ▷ Improve sensitivity of ν_τ-physics by $\mathcal{O}(1000)$
- Recognized as an experiment by CERN since May 2016
- Optimization ongoing



Outlook



- Currently in the conceptual design phase
- ▷ Comprehensive Design Report by the end of 2018
- ▷ recommended by the SPSC
- Input for the Update of the European Strategy for Particle Physics 2019
- Begin construction during LHC long shutdown 3
- ▷ Data taking in 2026

SHiP-related talks

Stefan Bieschke – HK 8.8, Mo, 18:45-19:00

Multicomponent drift gas mixtures for the SHiP Muon Magnetic Spectrometer

Caren Hagner – T 34.2, Di, 11:20-11:40

Gruppenbericht: Neutrino Physics within the SHiP Experiment

Maximilian Ehlert – T 68.4, Di, 17:35-17:50

WOM-Prototypen für die Auslese des Flüssigszintillator SBT im SHiP-Experiment

Paul Rosenau – T 68.5, Di, 17:50-18:05

Verspiegelung von WOMs zur Steigerung der Nachweiseffizienz

Ievgen Korol – T 78.2, Mi, 17:05-17:20

Search for hidden particles at SHiP: impact of the vertex reconstruction

Plamenna Venkova – T 78.3, Mi, 17:20-17:35

The role of the Surround Background Tagger for the SHiP experiment