Search for hidden particles at SHiP. Lecture 2. Hidden sectors. Portals. SHiP experiment

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Unsolved problems mean that new particles probably exist

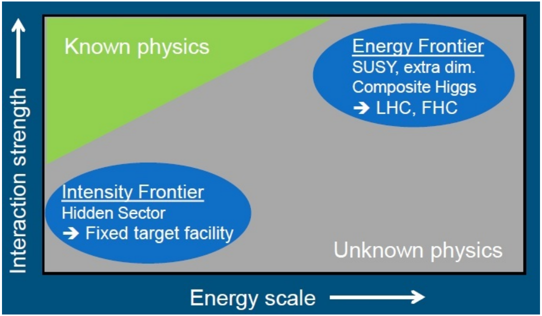
We did not detect them because

they are **heavy**

OR

they are light but
very weakly interacting

Intensity frontier searches for feebly interacting particles



Intensity frontier has been paid much less attention in the recent years:

- **PS 191**: neutrino oscillation, early 1980s
- **CHARM**: semi-leptonic neutral current processes and muon polarization produced in neutrino and antineutrino interactions, 1980s
- **NuTeV**: search neutral heavy lepton, 1990s
- **DONUT**: tau neutrino interactions, late 1990s – early 2000

Can there be new particles lighter than M_W?

Three possibilities exist

1. Standard Model plus some light particles is valid up to very high energies.
   No new physics between Fermi and Planck scale

2. There is a wider theory with a new, experimentally reachable energy scale (SUSY scale, large extra dimensions) but **there are light particles in the spectrum**

   Examples: pseudo-Goldstone bosons of high energy symmetries. Axion with big mass, gravitino, sgoldstino, ...

3. There is a theory with very high ($E \gg 1$ TeV) energy scale (GUT scale, small extra dimensions, new strong dynamics, etc) but **there are light particles in the spectrum**

   Examples: Chern-Simons portal, axion with small mass, ...

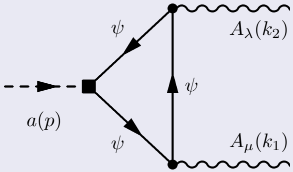
Why some of the new particles can be light?

Example: axion

- Heavy fermions Ψ interact with a heavy scalar $\Phi = |\Phi| e^{i\theta}$
- The theory possesses U(1) symmetry **spontaneously broken** at high energies $E \sim g_{\phi\gamma\gamma} \gg \mathrm{TeV}$
- Spontaneously broken symmetry leaves behind a **Goldstone boson** ϕ
- if the symmetry was not exact these (pseudo)-Goldstone bosons will be massive. But generically light

Heavy fermions in the loops induce interactions between light particles:

$$\mathcal{L}_{\text{axion}} = \frac{\phi}{g_{\phi\gamma\gamma}} F\tilde{F}$$



Renormalization Theory Analysis

Dimension of the field function

Action is dimensionless: $[S] = \int [d^4x][\mathcal{L}] = [m]^0$. So $[\mathcal{L}] = [m]^4$.

$$\mathcal{L} = \frac{1}{2}\partial^\mu \varphi \partial_\mu \varphi - \frac{m^2}{2}\varphi^2, \quad \text{so} \quad [\varphi] = [m]^1,$$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{m^2}{2}A^\mu A_\mu, \quad \text{so} \quad [A_\mu] = [m]^1,$$

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi, \quad \text{so} \quad [\psi] = [m]^{3/2}$$

Dimension of the coupling constant

$$[\mathcal{L}] = [g] + N_{boz} + \frac{3}{2}N_{fer} + \delta = 4$$

$$[g] = 4 - N_{boz} - \frac{3}{2}N_{fer} - \delta$$

Renormalization Theory Analysis

Theory is renormalizible only if $[g] \geq 0$!!!

$$\mathcal{L}_{int} = g\varphi^3, \quad [g] = 1, \quad \text{good theory},$$
$$\mathcal{L}_{int} = g\varphi^4, \quad [g] = 0, \quad \text{good theory},$$
$$\mathcal{L}_{int} = g\bar{\psi}\gamma^\mu\psi A_\mu, \quad [g] = 0, \quad \text{good theory},$$
$$\mathcal{L}_{int} = g\bar{\psi}\psi\varphi, \quad [g] = 0, \quad \text{good theory},$$
$$\mathcal{L}_{int} = gF^{\mu\nu}F_{\mu\nu}, \quad [g] = 0, \quad \text{good theory},$$

$$\mathcal{L}_{int} = g\bar{\psi}\psi\,\bar{\psi}\psi, \quad [g] = -2, \quad \text{NOT good theory},$$
$$\mathcal{L}_{int} = g\bar{\psi}\psi\,\partial^\mu A_\mu, \quad [g] = -1, \quad \text{NOT good theory},$$
$$\mathcal{L}_{int} = g\bar{\psi}\partial_\mu\varphi\gamma^\mu\psi, \quad [g] = -1, \quad \text{NOT good theory}.$$

Portal operators — the gate to new physics

A part of BSM phenomena can be resolved by introducing relatively light new particles only (νMSM).

Alternatively, some of the new particles, responsible for the resolution of the BSM puzzles, can be heavy or do not interact directly with the SM sector! These "hidden sectors" may nevertheless be accessible to the intensity frontier experiments via few sufficiently light particles, which are coupled to the Standard Model sectors either via renormalizable interactions with small dimensionless coupling constants ("portals") or by higher-dimensional operators suppressed by the dimensionfull couplings Λ^{-n}, corresponding to a new energy scale of the hidden sector.

Alekhin, S. et al. (2016). A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case. Rept. Prog. Phys., 79(12):124201, 1504.04855.

Portal operators — the gate to new physics

Light messengers couple Standard Model to "hidden sectors" via portals

- **Scalar** portal (new particles are neutral singlet scalars, S_i that couple the Higgs field: $(\lambda_i S_i^2 + g_i S_i)(H^\dagger H)$)
- **Vector** portal (new particles are Abelian fields, A'_μ with the field strength $F'_{\mu\nu}$, that couple to the hypercharge field $F_Y^{\mu\nu}$ via $F'_{\mu\nu} F_Y^{\mu\nu}$)
- **Neutrino** portal (the singlet operators $(\bar{L} \cdot \tilde{H})$ couple to new neutral singlet fermions N_I $F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{\Phi}) N_I$)

- **Chern-Simons*** portal: 6-dimensional operator (coupling of SM vectors to new vector X through the interaction of form $\varepsilon^{\mu\nu\sigma\rho} X_\mu V_\nu \partial_\sigma V'_\rho$)

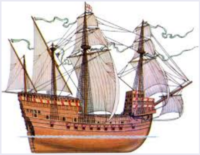
$$\frac{C_Y}{\Lambda_Y^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger H B_{\lambda\rho} \cdot \epsilon^{\mu\nu\lambda\rho} + \frac{C_{SU(2)}}{\Lambda_{SU(2)}^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.$$

- **Axion-like*** portal: 5-dimensional operator (couplings of pseudo Nambu-Goldstone bosons a, associated with the breaking of approximate global symmetries: $a F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$)

What is SHiP?

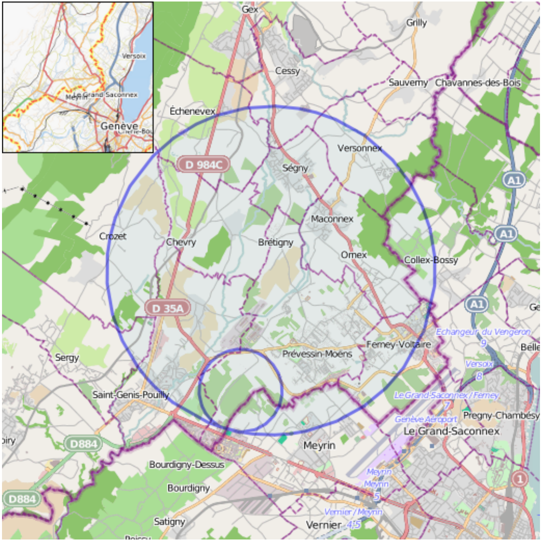
http://ship.web.cern.ch/ship

SHiP is not a usual ship:



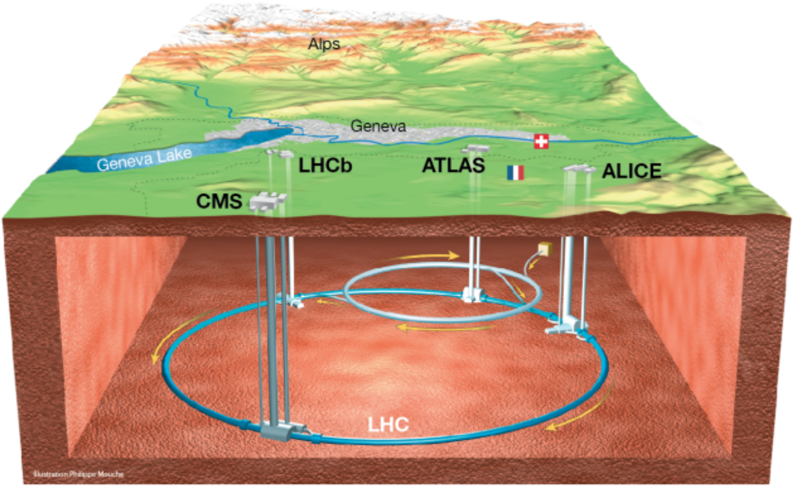
The SHiP (*Search for Hidden Particles*) Experiment is a new general-purpose beam dump facility at the SPS to search for very weakly interacting long lived particles including Heavy Neutral Leptons, vector, scalar, axion portals to the Hidden Sector, and light supersymmetric particles. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

Where will the experiment SHiP take place?

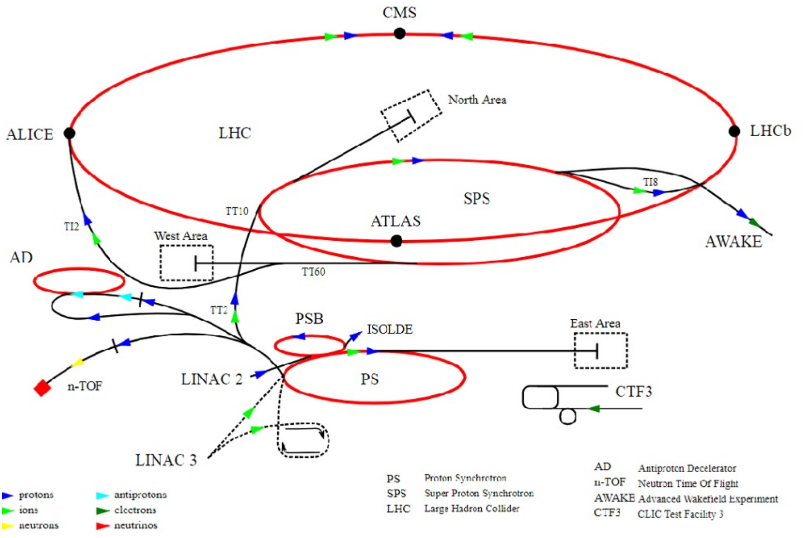


Accelerator complex is located between France and Switzerland. LHC uses the 27 km circumference circular tunnel. The tunnel is located 100 metres underground.

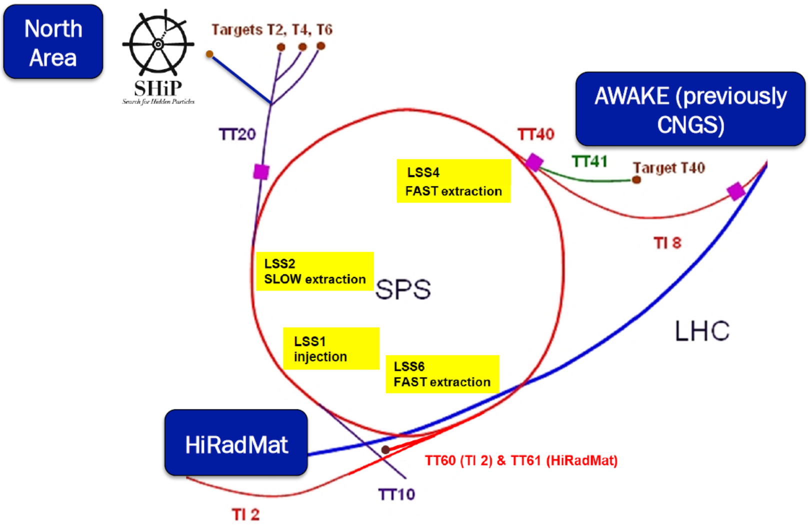
Where will the experiment SHiP take place?



Where will the experiment SHiP take place?



Where will the experiment SHiP take place?



The SHiP experiment is designed to be installed next to the SPS North Area.

What is main idea of SHiP functioning?

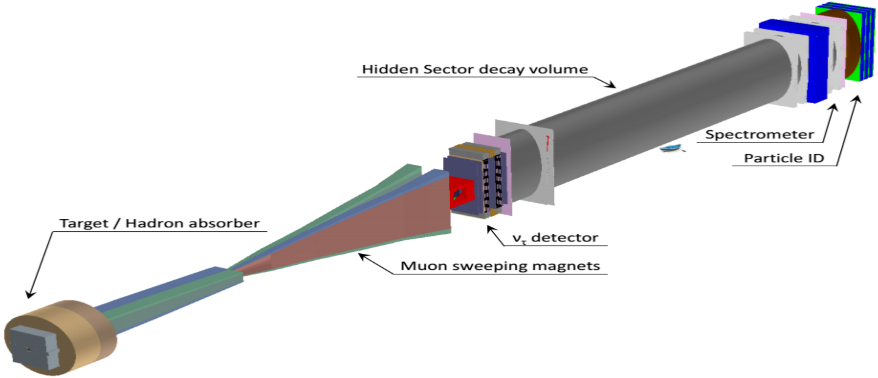
http://ship.web.cern.ch/ship

- Take the highest Energy/Intensity proton beam of the world
- ...dump it into a target ...
- ...followed by the closest, longest and widest possible and technically feasible decay tunnel!
- Aim: background free detector
- Any event would mean new particles

How does the SHiP work?

http://ship.web.cern.ch/ship

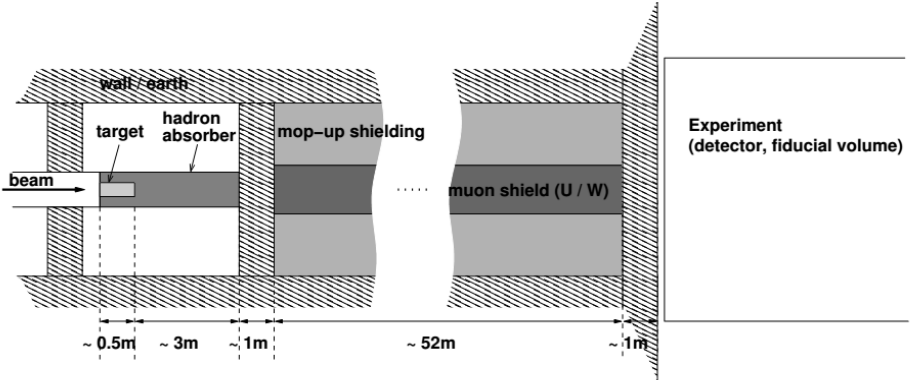
General configuration



How does the SHiP work?

http://ship.web.cern.ch/ship

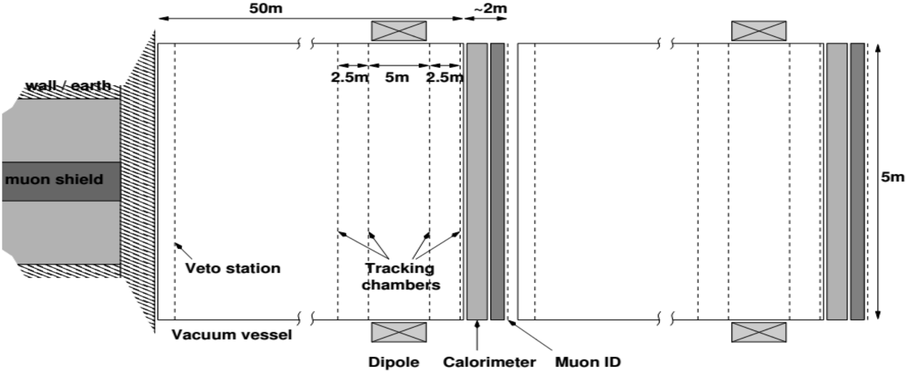
First aim is to stop (or exclude) all SM particles!



How does the SHiP work?

http://ship.web.cern.ch/ship

Second aim is to detect New Physics!



What is SHiP characteristics?

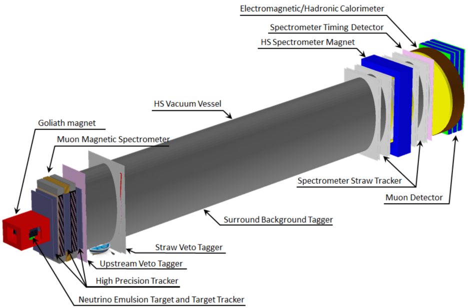
http://ship.web.cern.ch/ship

A dedicated beam line extracted from the SPS will convey a 400 GeV/c proton beam at the SHiP facility. The beam will be stopped in a Molybdenum and Tungsten target, at a center-ofmass energy $E_{CM} = 27$ GeV. Approximately $2 \cdot 10^{20}$ proton-target collisions are foreseen in 5 years of operation.

- Can probe: neutrino, vector, scalar portals; axions; light SUSY particles!

Generic decay modes	Final states	Models tested
meson and lepton	$\pi l, Kl, \rho l, l = (e, \mu, \nu)$	ν portal, HNL, SUSY neutralino
two leptons	$e^+e^-, \mu^+\mu^-$	V, S and A portals, SUSY s-goldstino
two mesons	$\pi^+\pi^-, K^+K^-$	V, S and A portals, SUSY s-goldstino
3 body	$l^+l^-\nu$	HNL, SUSY neutralino

Another SHiP physical application: ν_τ physics



- From $2 \cdot 10^{20}$ protons on target is expected to produce a total $5.7 \cdot 10^{15}$ ν_τ and $\bar{\nu}_\tau$.
- $N_{\nu_e} = 5.7 \cdot 10^{18}$ and $N_{\nu_\mu} = 3.7 \cdot 10^{17}$
- **Great opportunity to study neutrino physics!**
- Expected $\sim 10^4$ ν_τ to be events detected
- **First direct observation of $\bar{\nu}_\tau$!**

SHiP collaboration

- SHiP collaboration has been **officially created on December 15, 2014**
- More than 200 people (53 institutions from 17 countries)
- There is Ukrainian group also (Quantum Field Teory and Nuclear Physics Departments, Faculty of Physics, Taras Shevchenko National University of Kyiv)
- There already were 15 collaboration meetings.
- Technical proposal & physics case papers were submitted to the SPS committee at the beginning of April 2015
- Interested groups and interested people are welcome to join!
- SHiP Physics case mailing list: `ship-theory@cern.ch`

SHiP Collaboration member institutes

1. University of Sofia, Bulgaria
2. UTFSM (Universidad Tcnica Federico Santa Maria), Valparaiso, Chile
3. NBI (Niels Bohr Institute), Copenhagen University, Denmark
4. LAL, Univ. Paris-Sud, CNRS/IN2P3, France
5. LPNHE Univ. Paris 6 et 7, France
6. Humboldt University of Berlin, Germany
7. University of Bonn, Germany
8. University of Hamburg, Germany
9. Forschungszentrum Jlich, Germany
10. University of Mainz, Germany
11. University and INFN of Bari, Italy
12. University and INFN of Bologna, Italy

...

52. Taras Shevchenko National University of Kyiv, Ukraine
53. Florida University, United States of America

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

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

Technical Proposal

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

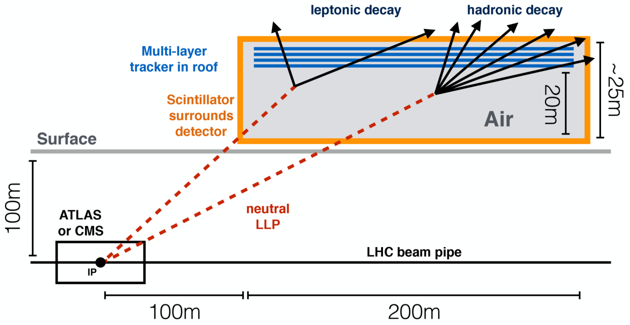
The SHiP Collaboration[1]

A facility to search for hidden particles (SHiP) at the SPS: the physics case

Sergey Alekhin,[1,2] Wolfgang Altmannshofer,[3] Takehiko Asaka,[4] Brian Thomas 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 Giudice,[5] Dmitry Gorbunov,[24,25] Stefania Gori,[3] Christophe Grojean§,[26,27] Mark D. Goodsell,[28,29] Elena Graverini,[30] A. Guffanti,[31] Thomas Hambye,[32] Steen H. Hansen,[33] Juan Carlos Helo,[11] Pilar Hernandez,[34] Alejandro Ibarra,[20] Artem Ivashko,[8,35] Eder Izaguirre,[3] Joerg Jaeckel§,[36] Yu Seon Jeong,[37] Felix Kahlhoefer,[27] C. S. Kim,[37] Sergey Kovalenko,[11] Gordan Krnjaic,[3] Gaia Lanfranchi,[38] Valery E. Lyubovitskij,[39,40,41] Simone Marcocci,[16] Matthew Mccullough,[5] David McKeen,[42] Sven-Olaf Moch,[43] Rabindra N. Mohapatra,[44] David E. Morrissey,[45] E. Paschos,[46] Apostolos Pilaftsis,[18] Maxim Pospelov§,[3,17] M. H. Reno,[47] Andreas Ringwald,[27] Adam Ritz,[17] Valery Rubakov,[24] Oleg Ruchayskiy⋆,[21] Jessie Shelton,[48] I. Schienbein,[49] Daniel Schmeier,[19] Kai Schmidt-Hoberg,[27] Goran Senjanovic,[27] Osamu Seto,[50] Mikhail Shaposhnikov⋆, §,[21] Brian Shuve,[3] Robert Shrock,[51] Lesya Shchutska§,[52] Michael Spannowsky,[53] Andy Spray,[54] Florian Staub,[5] Matt Strassler,[55] Francesco Tramontano,[56,57] A. Tripathi,[57] Sean Tulin,[58] Francesco Vissani,[16,59] Martin W. Winkler,[60] Kathryn M. Zurek,[61,62]

Concurrents of the SHiP experiment: MATHUSLA

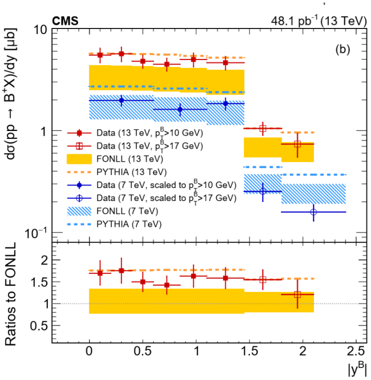
MATHUSLA – MAssive Timing Hodoscope for Ultra Stable neutraL pArticles



MATHUSLA experiment [1705.06327]

- CMS (or ATLAS) experiment is a source of weakly interacting particles
- Decay area with total volume $V \sim 20\ \text{m} \cdot 100\ \text{m} \cdot 100\ \text{m} \simeq 2 \cdot 10^5\ \text{m}^3$
- The rock as passive wall
- Multi-layer tracker at the roof

Number of B mesons in MATHUSLA



- Number of B mesons directed to Mathusla is

$$\frac{dN_B^{\text{CMS}}}{d\eta} \simeq \frac{d\sigma^{\text{measured}}_{pp\to B^+X}}{d\eta} \cdot \overbrace{\mathcal{L}_h}^{3000\ \text{fb}^{-1}} \overbrace{\frac{1}{\text{Br}_{b\to B^+X}}}^{\simeq 2}, \quad (1)$$

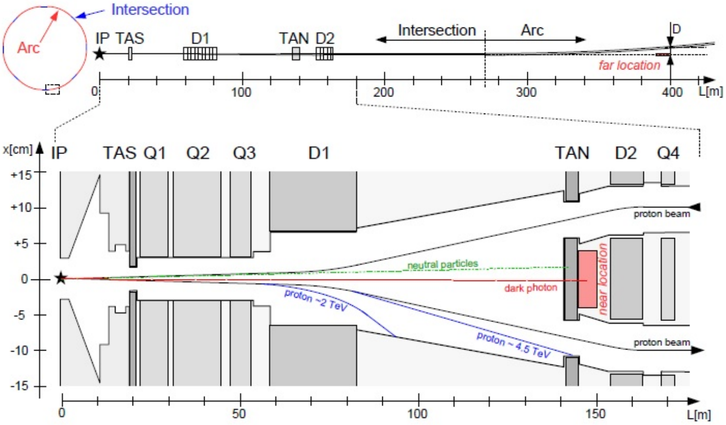
where $\text{Br}_{b\to B^+X} \approx 0.44$ [pdg]

- The estimation gives $N_B^{\text{MATHUSLA}} \approx 6\cdot 10^{12}$

Even at high luminosity LHC the number of B mesons traveling to MATUSLA's direction is slightly smaller than the number of B mesons produced at SHiP ($N_B^{\text{SHiP}} \approx 6\cdot 10^{13}$)

Concurrents of the SHiP experiment: FASER

FASER – ForwArd Search ExpeRiment at the LHC [1708.09389]



Schematic drawings of the LHC ring and the current very forward infrastructure downstream from the ATLAS and CMS interaction points, along with the representative far and near on-axis detector locations for FASER.