ShiP: Searh for Hidden Particles

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Structure of the Standard Model

Standard Model is the theory describing three of the four known fundamental forces in the universe. It was created in the mid-1970s. It is consistent up to very high scales.

Before the Higgs discovery the structure of the Standard Model was predicting where to expect new physics. We searched for new particles without which our explanation of all the previous experiments would become inconsistent

- We knew that something shall be found at energies below $E < G_{\text{Fermi}}^{-1/2}$
- Without the top quark the Standard Model would be **non-unitary**
- Without the Higgs boson the Standard Model would be **non-unitary**

Higgs boson was the last predicted but unseen particle

- **Where do we need to look for something else?**

Problem of Fermi Theory

- Fermi theory predicts how neutrinos scatter of protons and electrons:

$$e + \nu_e \rightarrow e + \nu_e$$

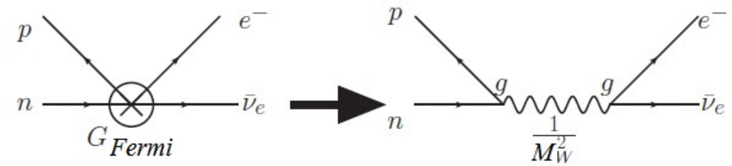
- Fermi coupling $[G_F] = GeV^{-2}$ – dimension of inverse energy squared
- On dimensional grounds, the cross-section σ is

$$\sigma \sim (coupling)^2 \times (Energy)^{somepower} \rightarrow G_F^2 E^2$$

- Cross-section (i.e. probability) grows with energy – Unitarity Violation
- As compared with e.g. QED where $\sigma \sim \frac{\alpha}{E^2}$, which does not lead to unitarity violation at any energy

From β-decay to weak interactions. Fast forward

- Prediction of massive vector bosons – weak interaction is **mediated** by some particle (as all other interactions)



- New particle (**W-boson**) explained Fermi interactions led to verifiable predictions
- creates more questions that required introduction of new particles?

Should we believe that new particles exist?
Physics **Beyond** the Standard Model

Neutrino masses and oscillations

What makes neutrinos disappear and then re-appear in a different form? Why do they have mass?

- Neutrino oscillations do not tell us what is the scale of new physics
- It can be **anywhere** between sub-eV and 10^{15} GeV

Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Physics on the **very different scales** can be responsible for it

Dark matter

What is the most prevalent kind of matter in our Universe?

- Physics at **high scales** (10^{12} GeV for axion-like particles), at **intermediate scales** (TeVs for WIMPs) or at **low scales** (keV-ish sterile neutrino, physics below electroweak scale) can be responsible for this

Questions about the evolution of the Universe as a whole

Cosmological inflation:

What sets the initial conditions for all the structure that we see in the Universe? (possibly Higgs field)

Dark Energy:

What drives the accelerated expansion of the universe now (possibly this is just Λ-term)

Deep theoretical questions

- Strong CP problem
- Why Planck scale 10^{19} GeV is much higher than the electroweak scale (100 GeV)?
- How to describe gravity quantum mechanically?

Unsolved problems mean that new particles probably exist

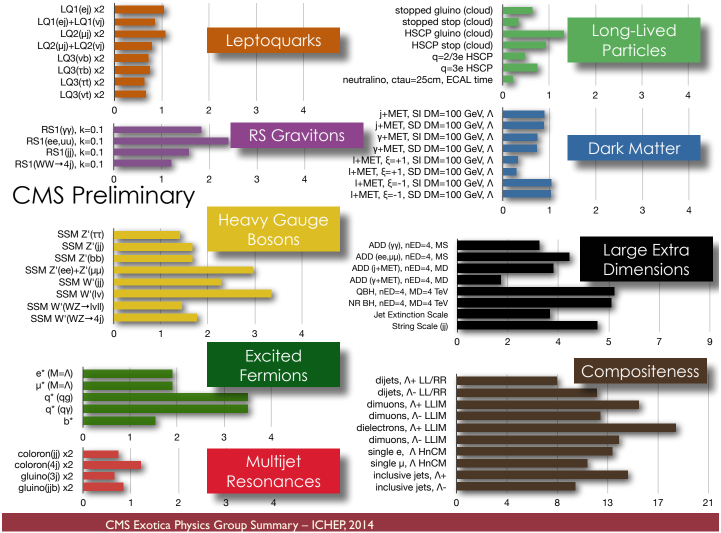
We did not detect them because

they are **heavy**

OR

they are light but
very weakly interacting

Heavy particles: active LHC searches



Probed scale

$\ll 10^{19}$ GeV

Can there be new particles lighter than M_W?

Three possibilities exist

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

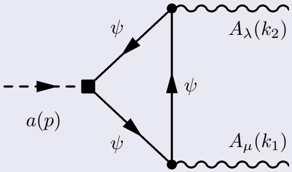
Why some of the new particles can be light?

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:

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



Why some SUSY particles can be light?

Gravitino

- Superpartner of graviton ⇒ Massless at tree level
- Roughly speaking

$$m_{\text{gravitino}} = \frac{(\text{SUSY breaking scale})^2}{M_{\text{Planck}}} \ll \text{Other SUSY particles}$$

Sgoldstino

- spontaneous SUSY breakin ⇒ the existence of spin 1/2 Goldstone particle **goldstino**
- Superpartner to goldstino – **Sgoldstino**
- Massless at tree level
- Mass via loop corrections

Can we classified new hidden light particles from different theoretical extension of the SM in some a way?

Yes !!!

It can be done with help of few portals !

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 $\varepsilon^{\mu\nu\sigma\rho}X_\mu V_\nu \partial_\sigma V'_\rho$)

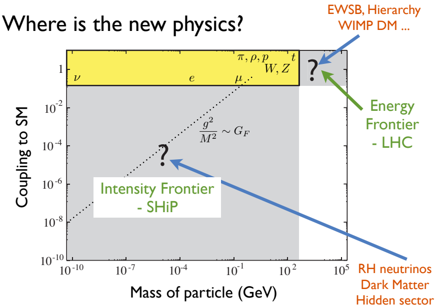
$$\frac{C_Y}{\Lambda_Y^2}\cdot X_\mu(\mathfrak{D}_\nu H)^\dagger H B_{\lambda\rho}\cdot\epsilon^{\mu\nu\lambda\rho} + \frac{C_{SU(2)}}{\Lambda_{SU(2)}^2}\cdot X_\mu(\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H\cdot\epsilon^{\mu\nu\lambda\rho} + h.c.$$

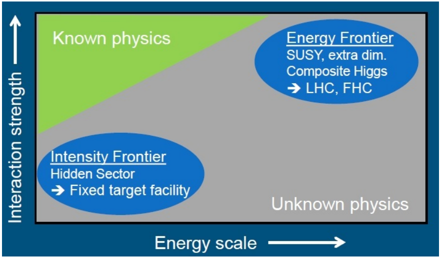
$$c_z\epsilon^{\mu\nu\lambda\rho}X_\mu Z_\nu\partial_\lambda Z_\rho + c_\gamma\epsilon^{\mu\nu\lambda\rho}X_\mu Z_\nu\partial_\lambda A_\rho + c_w\epsilon^{\mu\nu\lambda\rho}X_\mu W_\nu^-\partial_\lambda W_\rho^+$$

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

Intensity frontier searches for feebly interacting particles

Where is the new physics?





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

Intensity frontier searches for feebly interacting particles

Proposals for Intensity frontier experiments are of great interest now!

Proposals at the PS beam lines

- REDTOP

Proposals at the SPS beam lines:

- NA64++
- NA62++
- LDMX
- AWAKE
- KLEVER
- SHiP

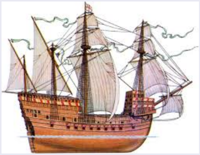
Proposals at the LHC interaction points:

- FASER
- MATHUSLA
- CODEX-b

What is SHiP?

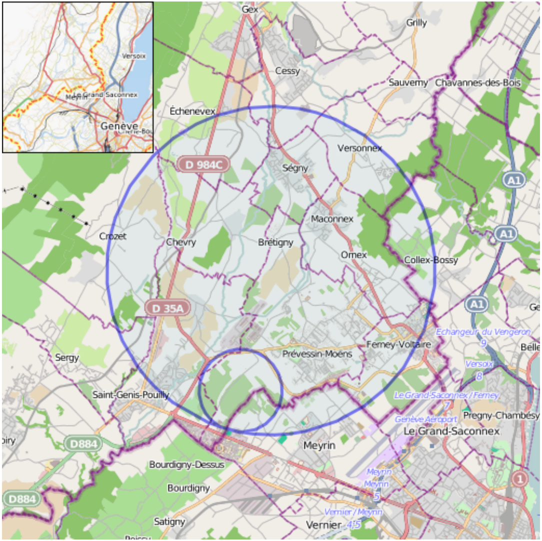
http://ship.web.cern.ch/ship

SHiP is not a usual ship:



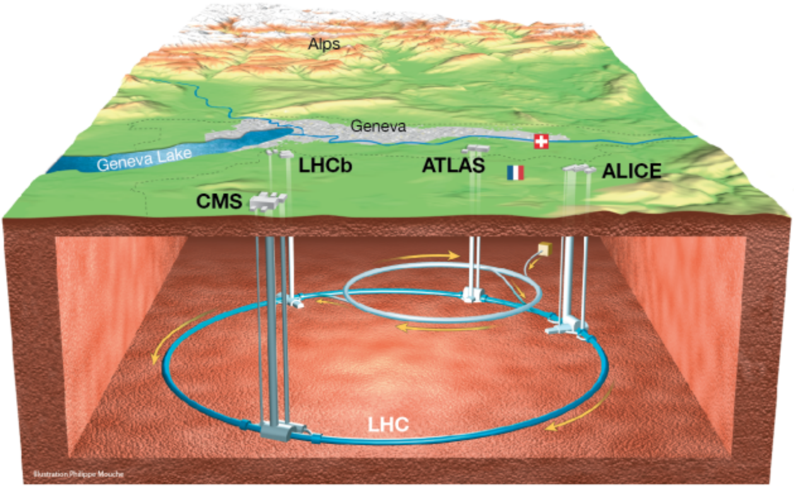
The SHiP (*Search for Hidden Particles*) Experiment is a new general-purpose beam dump facility at the SPS to search for very weakly interacting long lived particles including Heavy Neutral Leptons, vector, scalar, axion portals to the Hidden Sector, and light supersymmetric particles. Moreover, the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



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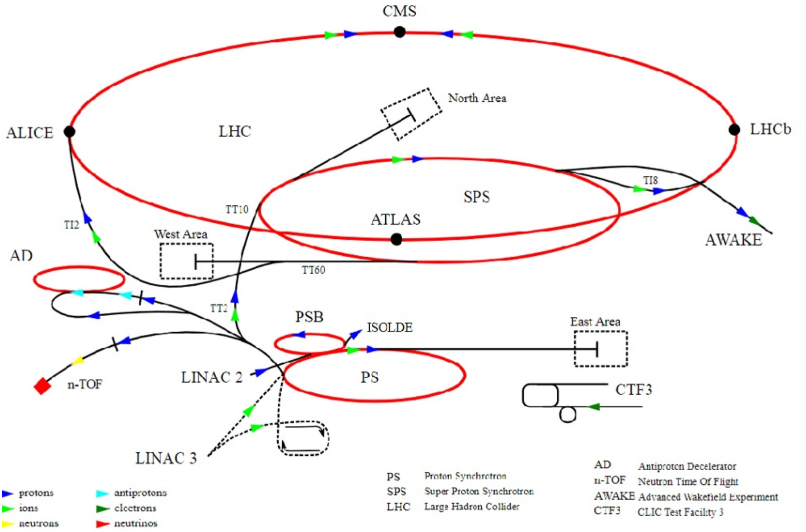

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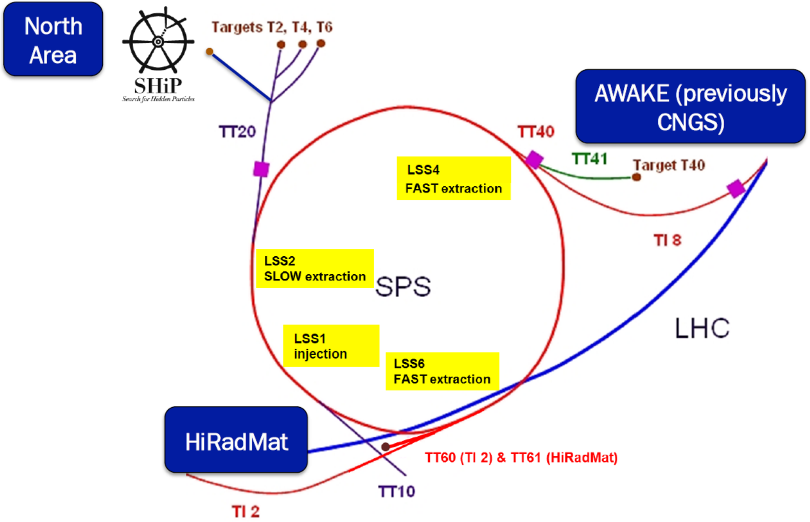


The SHiP experiment is designed to be installed next to the SPS North Area.

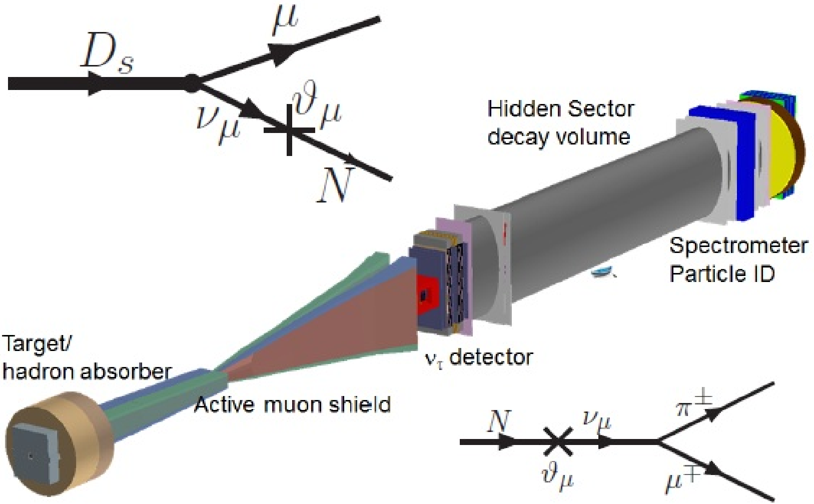
What is main idea of SHiP functioning?

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



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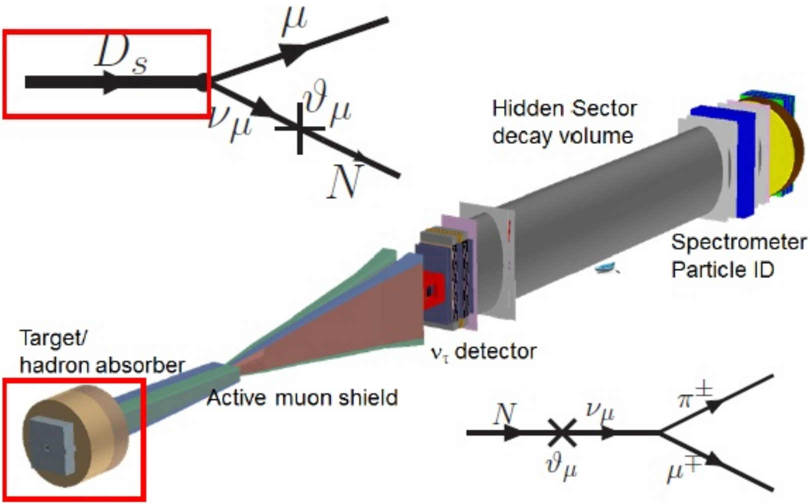

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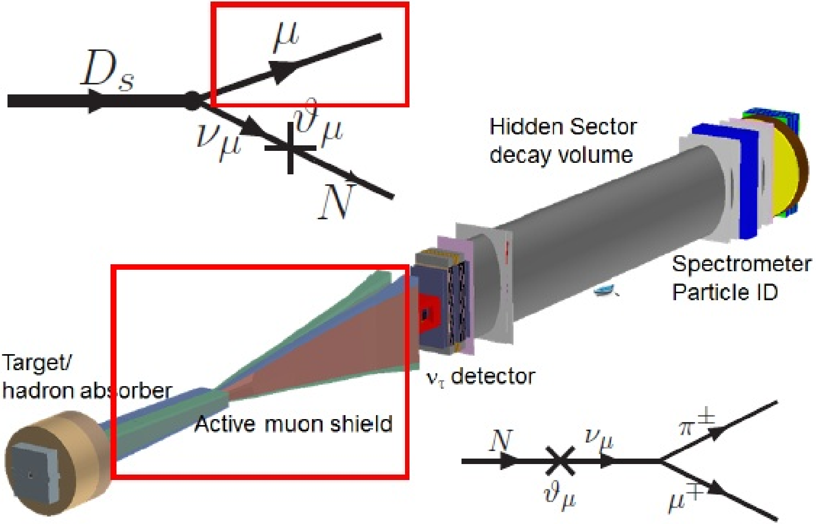

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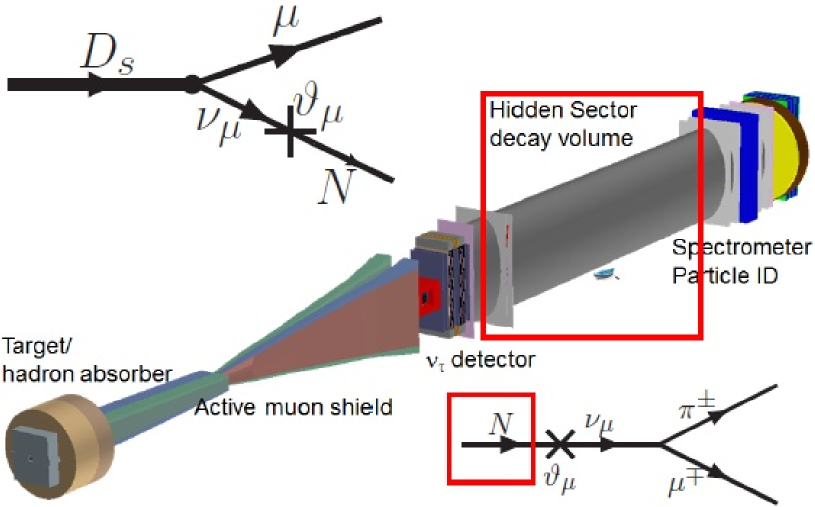

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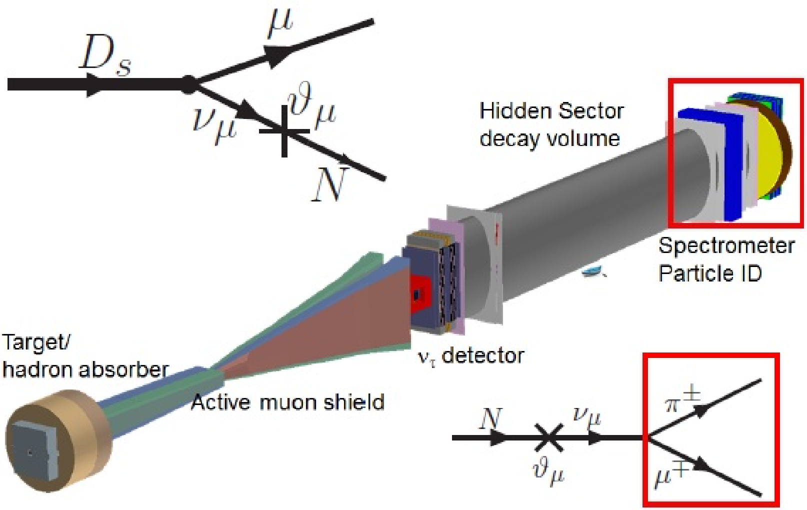
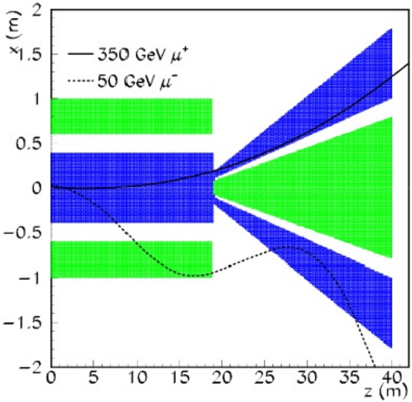


Muon Shield



Polarity of the magnetic field is indicated by the blue/green colour of the iron poles of the magnets. The trajectories of a 350 GeV/c muon and 50 GeV/c muon are shown with a full and dashed line, respectively.
SHiP collaboration: *The active muon shield in the SHiP experiment*, 2017_JINST_12_P05011

What is SHiP characteristics?

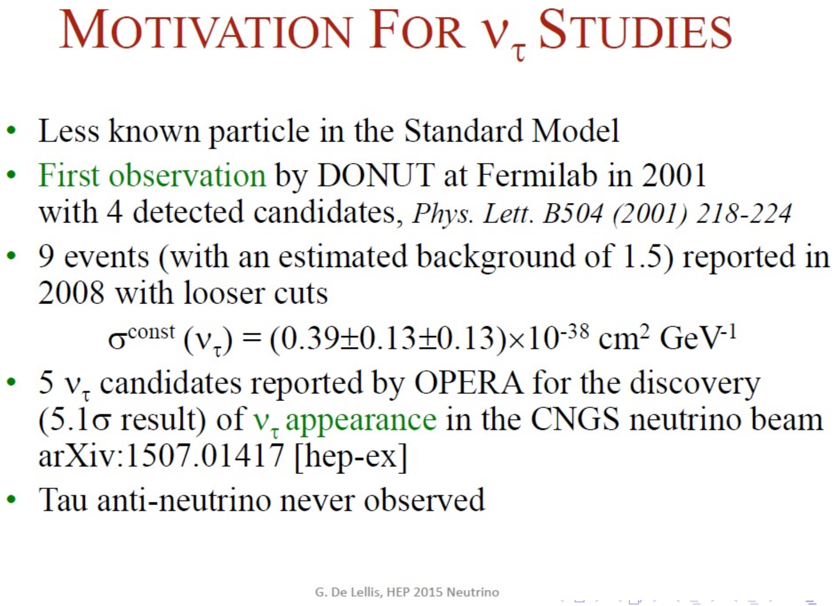
http://ship.web.cern.ch/ship

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



MOTIVATION FOR ν_τ STUDIES

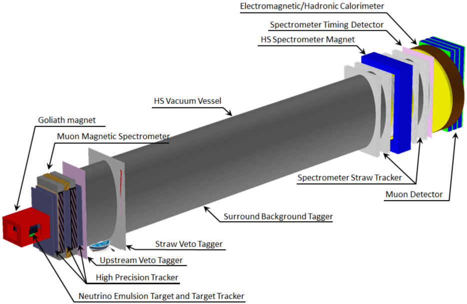
- Less known particle in the Standard Model
- First observation by DONUT at Fermilab in 2001 with 4 detected candidates, *Phys. Lett. B504 (2001) 218-224*
- 9 events (with an estimated background of 1.5) reported in 2008 with looser cuts

$$\sigma^{\text{const}}(\nu_\tau) = (0.39\pm0.13\pm0.13)\times10^{-38}\ \text{cm}^2\ \text{GeV}^{-1}$$

- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam arXiv:1507.01417 [hep-ex]
- Tau anti-neutrino never observed

G. De Lellis, HEP 2015 Neutrino

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**
- About 250 people (53 institutions from 18 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 16 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`

Time Line

- Approval by CERN – 2020
- Data taking – 2026

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

Technical proposal [1504.04956]

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

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

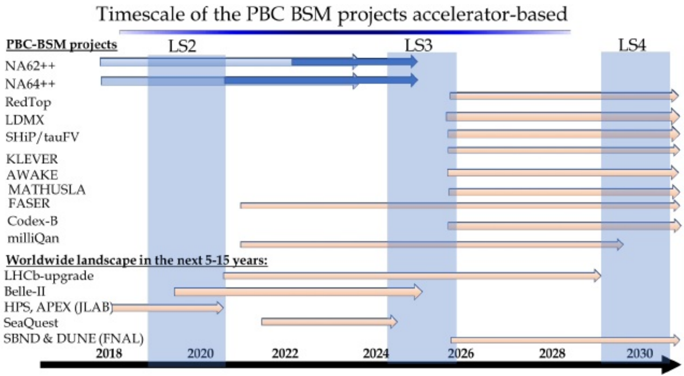
Technical Proposal

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

The SHiP Collaboration[1]

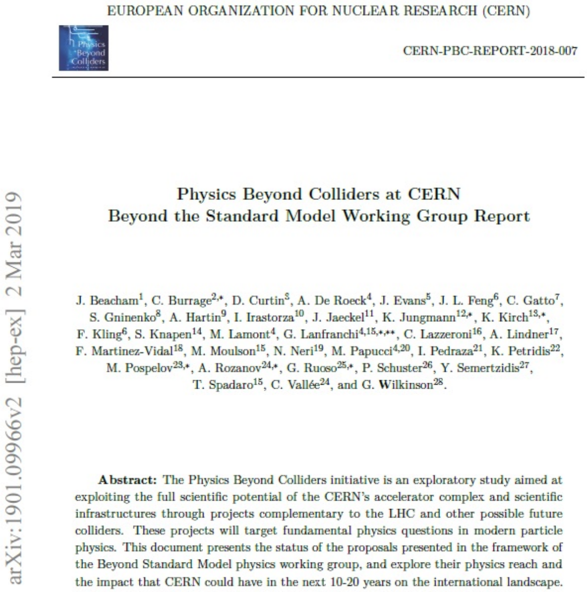
BSM problems at Intensity Frontier

- Today the landscape of opportunities is wide and Intensity Frontier experiments are a significant part of it
- Proposal of the SHiP experiment opened a path for many other brilliant ideas
- A special Physics Beyond Collider working group was created at CERN



Timescale of the PBC BSM projects accelerator-based

Beyond the Standard Model Working Group Report



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PBC-REPORT-2018-007

arXiv:1901.09966v2 [hep-ex] 2 Mar 2019

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7],
S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*],
F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17],
F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22],
M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27],
T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

Abstract: The Physics Beyond Colliders initiative is an exploratory study aimed at exploiting the full scientific potential of the CERN's accelerator complex and scientific infrastructures through projects complementary to the LHC and other possible future colliders. These projects will target fundamental physics questions in modern particle physics. This document presents the status of the proposals presented in the framework of the Beyond Standard Model physics working group, and explore their physics reach and the impact that CERN could have in the next 10-20 years on the international landscape.

BSM problems at Intensity Frontier

- In order to really explore the BSM phenomena we should apply model-independent portal constraints to particular models
- For a particular model, many different constraints can be combined together and help to devise a detailed search strategy for new particles

Vector portal: dark photons

In case of the vector portal (portal of dark photons) 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

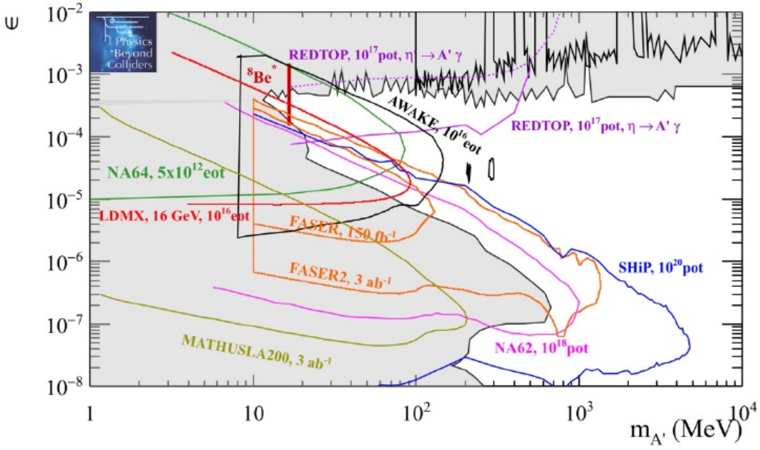
$$\mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu} \; .$$

where $m_{A'}$ is the mass of the dark photon and ϵ the coupling parameter of the Dark Photon with the standard photon, $e\epsilon$ is the coupling (*millicharge*) of the dark photon to SM particles: $\mathcal{L}_{int} \sim e\epsilon \, A'_\mu J_\mu^{\mathrm{EM}}$.

Constraints have been set depending on the assumption that the mediator can decay directly to dark matter (DM) particles (χ) (*i*nvisible decays) or has a mass below the $2 \cdot m_\chi$ threshold and therefore can decay only to SM particles (*v*isible decays).

In case of DPh with visible decays the parameter space is $(m_{A'}, \epsilon)$.
In case of DPh with invisible decays the parameter space is lager $(m_{A'}, \epsilon, \; m_\chi, \; \alpha_D \;)$, where m_χ is mass of DM particle and α_D is dark coupling of the DPh with DM. Moreover constrains depends on the properties of the DM candidate χ (boson or fermion).

Vector portal: dark photons, visible decays



Future upper limits at 90% CL for Dark Photon in *visible* decays for PBC projects on a ∼ 10-15 year timescale.

Scalar portal

The general renormalisable SM Lagrangian with a new scalar particle is

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - (\mu S + \lambda S^2)(H^\dagger H)$$

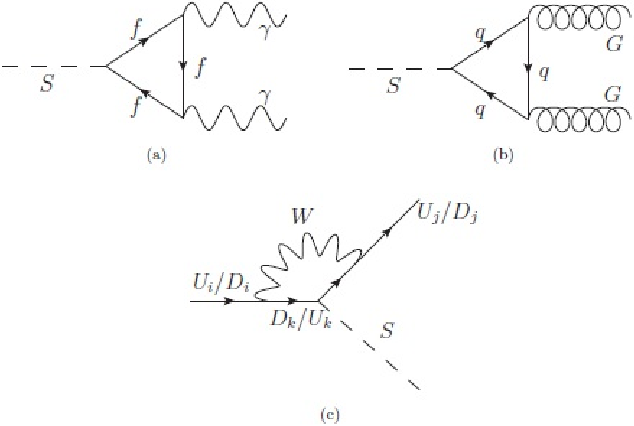
At low energies $H = (\nu + h)/\sqrt{2}$ and non-zero value of μ leads to the mixing of h and S states: $h \to h + \theta S$. In the limit of small mixing it can be written as

$$\theta = \frac{\mu\nu}{m_h^2 - m_S^2}.$$

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

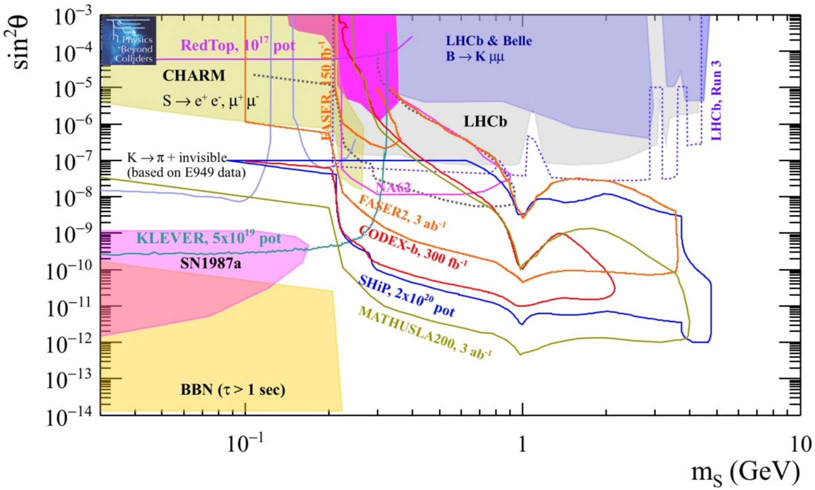
It can be Higgs-mixed scalar: in this model we assume $\lambda = 0$. The parameter space for this model is $\{\theta, m_S\}$.

Scalar portal: examples



Examples of effective interactions of the scalar with photons (a), gluons (b), and flavour changing quark operators (c).

Scalar portal: Higgs-mixed scalar



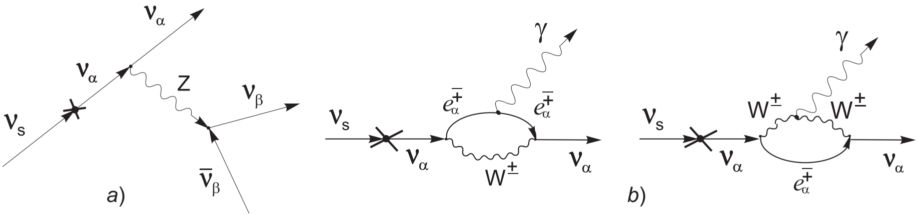
Prospects on 10-15 year timescale for PBC projects for the Dark Scalar mixing with the Higgs

Neutrino portal

In the νMSM the following terms are added to the Lagrangian of the SM:

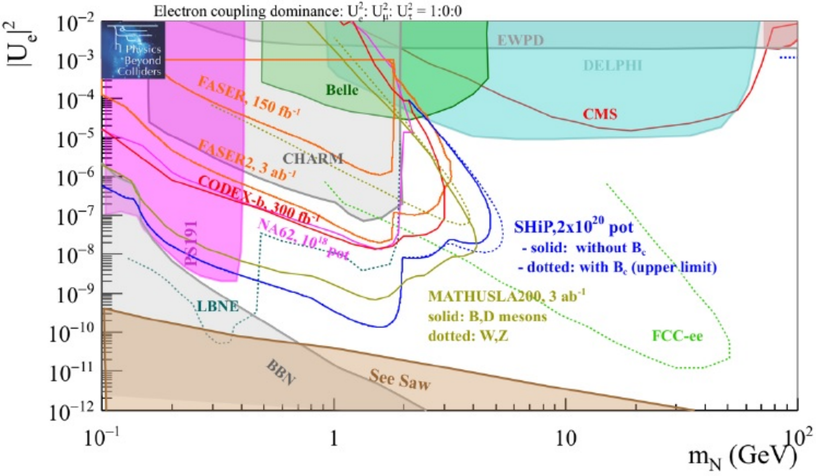
$$\mathcal{L}^{ad} = -F_{\alpha I}\bar{L}_\alpha\tilde{\Phi}\nu_{IR} - \frac{M_{IJ}}{2}\bar{\nu}^c_{IR}\nu_{JR} + h.c. =$$

$$= -\frac{h+v}{\sqrt{2}}\bar{\nu}_{\alpha L}F_{\alpha I}\nu_{IR} - \bar{\nu}^c_{IR}\frac{M_{IJ}}{2}\nu_{JR} + h.c.$$



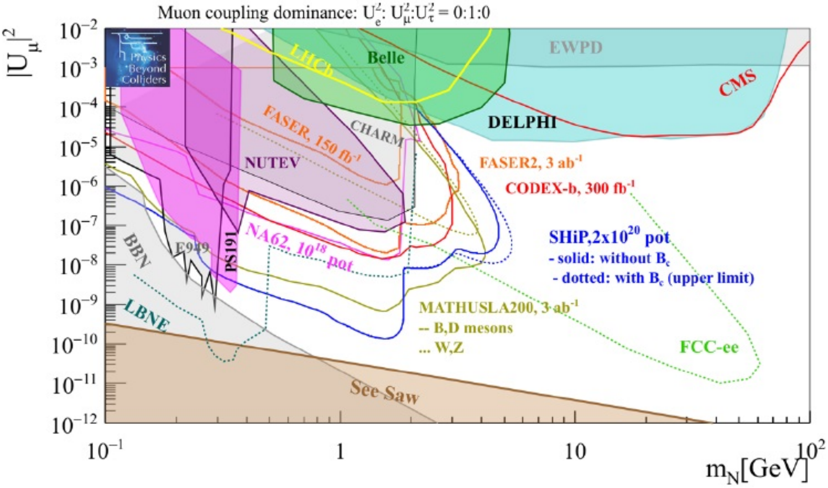
Example: decay of the lightest sterile neutrino – ν_s is the lightest sterile neutrino, ν_α is active neutrino with flavor α, $e_\alpha^\mp$ - charged lepton of the appropriate flavour.

Neutrino portal: electron-flavour coupling dominance



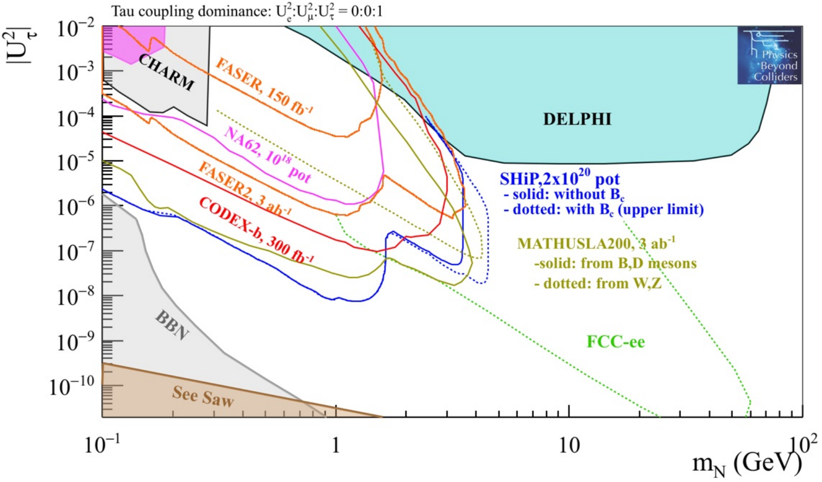
Sensitivity to Heavy Neutral Leptons with coupling to the first lepton generation only. Current bounds (filled areas) and 10-15 years prospects for PBC projects.

Neutrino portal: muon-flavour coupling dominance



Sensitivity to Heavy Neutral Leptons with coupling to the second lepton generation only. Current bounds (filled areas) and 10-15 years prospects for PBC projects.

Neutrino portal: tau-flavour coupling dominance



Sensitivity to Heavy Neutral Leptons with coupling to the third lepton generation only. Current bounds (filled areas) and 10-15 years prospects for PBC projects.

Axion-like particles portal

Historically axion was intriduced as hypothetical pseudoscalar particle in 1977 and it wasthe pseudo-Goldstone boson resulting from the spontaneous symmetry breaking of Peccei-Quinn. So, on classical level axion is massless particle.

This particle was introduced to solve strong CP-problem in the SM !

The axion mass induced by the interaction with QCD was famously computed by Weinberg and Wilczek using chiral perturbation theory:

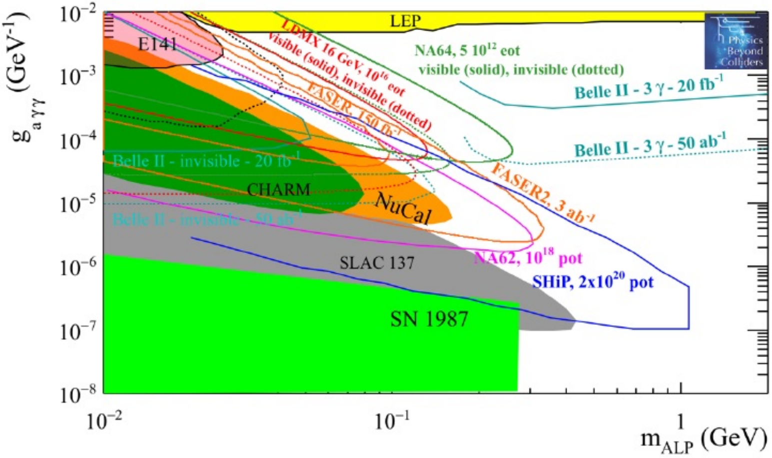
$$m_{a,\mathrm{QCD}} \approx 6 \times 10^{-6}\ \mathrm{eV}\,\frac{10^{12}\ \mathrm{GeV}}{f_a/\mathcal{C}}\,.$$

Mass of axion is expected to be in range from 10^{-5} eV to 10^{-3} eV.

There are another (not solving strong CP problem) pseudoscalar particles in the extension of SM. Such particles were called axion-like particles (ALP). Mass of ALP does not have to be small. The interactions between an ALP A and SM states are usually written in the form (after SSB of Higgs field)

$$\mathcal{L}_{\mathrm{ALPSM}} = \sum_f \frac{C_{Af}}{2\,f_a}\,\bar{f}\gamma^\mu\gamma^5 f\,\partial_\mu A - \frac{\alpha}{8\pi}\,\frac{C_{A\gamma}}{f_a}\,F_{\mu\nu}\tilde{F}^{\mu\nu}\,A - \frac{\alpha_3}{8\pi}\,\frac{C_{A3}}{f_a}\,G^b_{\mu\nu}\tilde{G}^{b\,\mu\nu}\,A$$

Axion-like particles portal



ALPs with photon coupling. Current bounds (filled areas) and prospects for PBC projects on 10-15 years timescale (solid lines).

Short Summary

- For the first time in particle physics we know that there are new particles, but we do not know where to search for them
- New feebly interacting particles lighter than $W^{\pm}$ may exist
- Intensity frontier is an underexplored possibility to discover new particles, complimentary to LHC-like experiments (but can be done on time/money scales much smaller than FCC / ILC exps.)
- Experiments like SHiP are capable to discover new particles expected from various phenomenological and theoretical directions
- It is possible that great discoveries in particle physics are right ahead