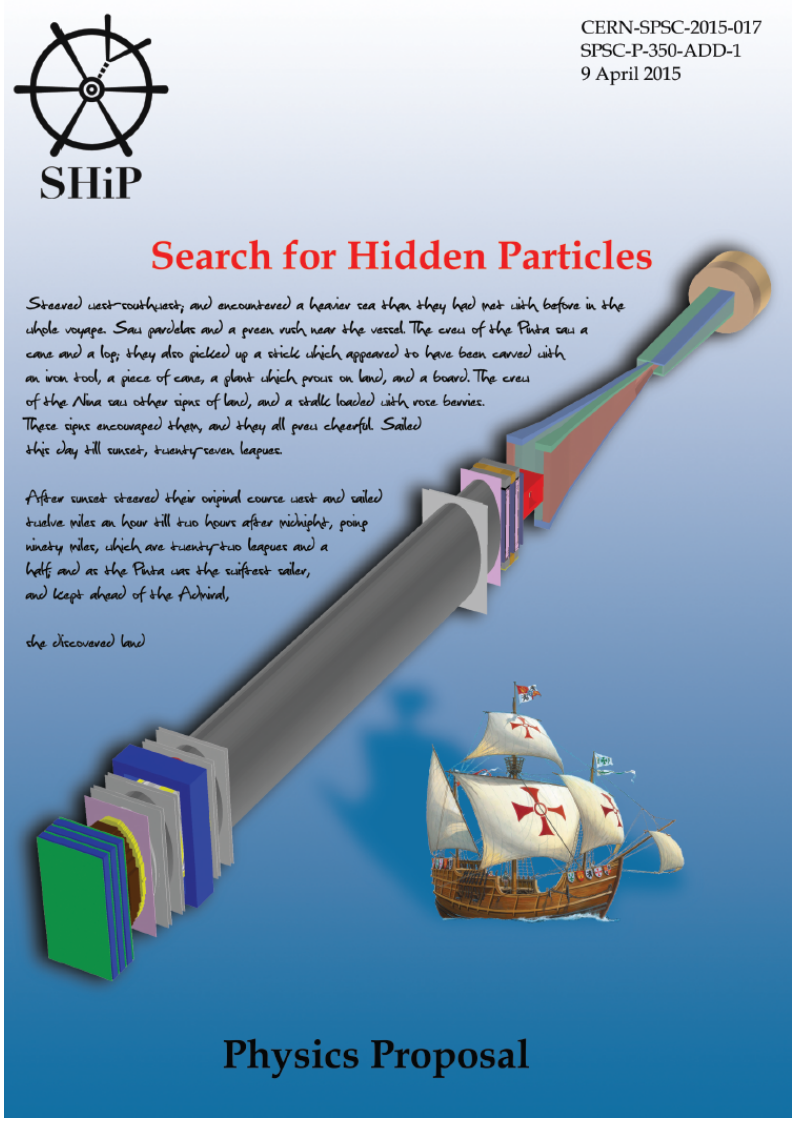
On behalf of the SHiP theory: The hidden sector Mikhail Shaposhnikov/EPFL



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

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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

Search for Hidden Particles: Physics Proposal, written by 85 authors from 65 Institutes, submitted to IOP review journal : Reviews on Progress in Physics (ROPP).

Outline:

- Scale of new physics
- Portals to the hidden sectors
- Vector portal
- Higgs portal
- Neutrino portal
- Axion portal
- SUSY
- Conclusions

In-spite of the fact that after the discovery of the Higgs boson at the LHC the Standard Model is complete and can be a consistent effective quantum field theory up the the Planck energies $\sim \mathbf{10^{19}}$ GeV it suffers from a number of experimental and theoretical problems.

Experiment:

- Neutrino masses and oscillations, absent in the SM
- Dark matter, absent in the SM
- Baryogenesis, absent in the SM
- Different anomalies: muon magnetic moment, LSND,...

Theory:

- Most importantly : hierarchy problem - “Why the Fermi scale is so much smaller than the Planck scale?"
- Probably, related problem: “Why the cosmological constant is so tiny?”
- Strong CP, flavour, ...

What does it mean for the energy scale of new physics?

Is there any new particle physics scale between the Fermi and Planck scales?

If yes

- proton decay yes (?)

$$\tau_p \sim \frac{\Lambda_{new}^4}{m_p^5}$$

  Current limit $\tau_p > 10^{32}$ years;

- new physics at LHC yes (?)

  Electroweak scale solution to the hierarchy problem - stability of the weak scale against quantum radiative corrections. Supersymmetry, composite Higgs boson, large extra dimensions, etc. Scale of new physics hundreds of GeV.

If yes

- searches for Dark Matter Weakly Interacting Massive Particles (WIMPS) yes (?)
  SUSY relic - neutralino
- searches for Dark Matter annihilation yes (?)
  SUSY relic - neutralino
- searches for axions yes (?)
  Axion is a hypothetic particle used for solution of the strong CP problem

If no

- proton decay no
  $\tau_p \simeq 10^{45}$ years for $\Lambda_{new} \simeq M_P$
- Higgs and nothing else at LHC
- searches for Dark Matter Weakly Interacting Massive Particles (WIMPS) no
- searches for Dark Matter annihilation no
- searches for axions no
  Interacts too weakly if $\Lambda_{new} \simeq M_P$

Can we get with certainty the energy scale of new physics from experiment or theory?

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  - the masses of right-handed see-saw neutrinos can vary from 1 eV to 10^{15} GeV

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  - the masses of DM particles can be as small as 10^{-22} eV (super-light scalar fields) or as large as 10^{20} GeV (wimpzillas, Q-balls)

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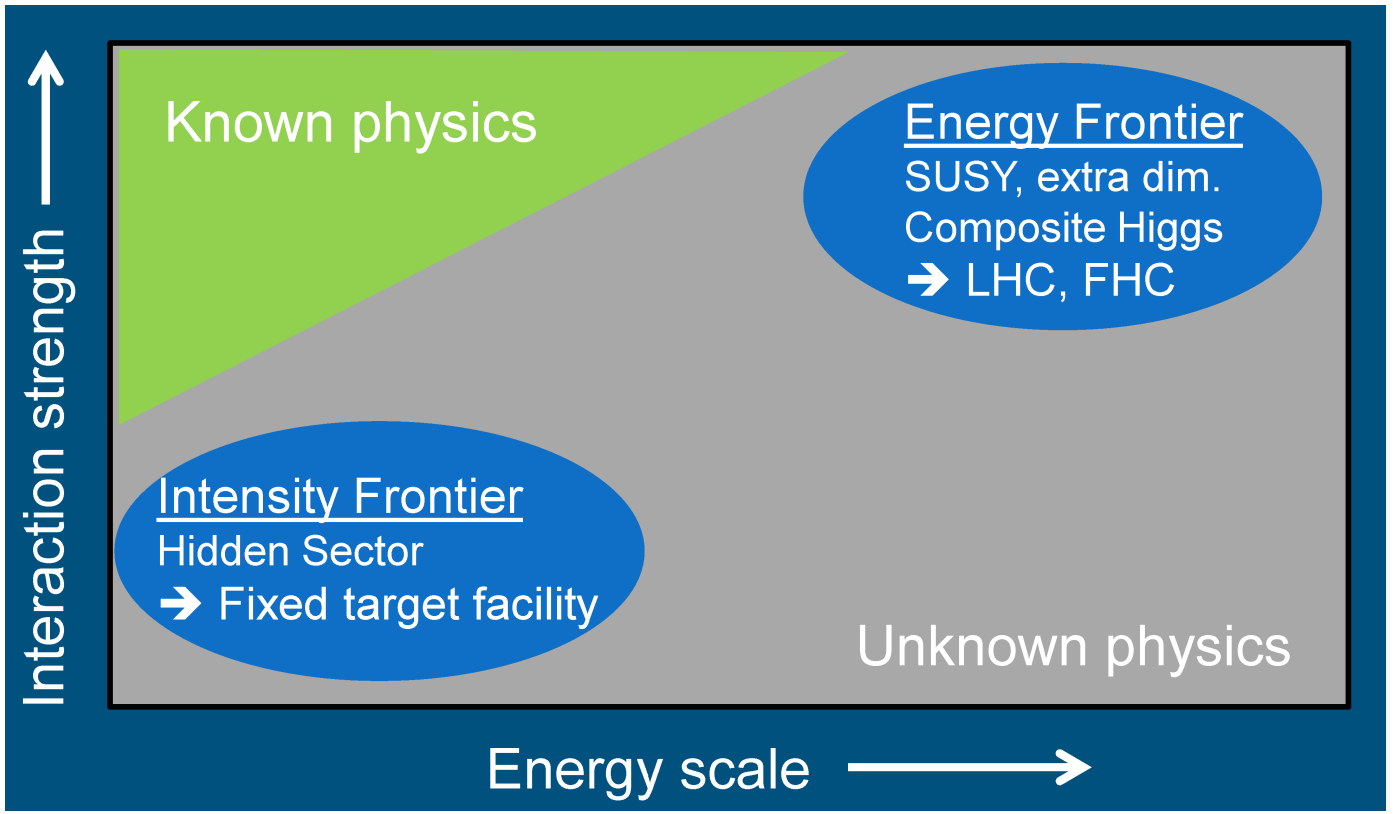
- Higgs mass hierarchy
  - BSM models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale , whereas the BSM models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

Where is new physics?



Systematic approach to Hidden Sector Particles

If new hidden particles are light, they must be singlets with respect to the gauge group of the SM. So, they may couple to different singlet composite operators (portals) of the SM

- dim 2: Hypercharge U(1) field, $B_{\mu\nu}$: vector portal. New particle - dark photon; renormalisable coupling - kinetic mixing

$$\epsilon B_{\mu\nu} F'^{\mu\nu}$$

- dim 2: Higgs field, $H^\dagger H$: Higgs portal. New particle - “dark” scalar; renormalisable couplings

$$(\alpha_1 S + \alpha S^2) H^\dagger H$$

- dim $2\frac{1}{2}$: Higgs-lepton, $H^T L$: neutrino portal. New particles - Heavy Neutral Leptons, HNL; renormalizable couplings

$$Y H^T \bar{N} L$$

- dim 4: New particles - ALPs (axion like particles), pseudo-scalars: axion portal. Non-renormalizable couplings,

$$\frac{a}{f_A} G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad \frac{a}{f_A} \partial_\mu J^\mu, \quad etc$$

J_μ - some SM current

- ...

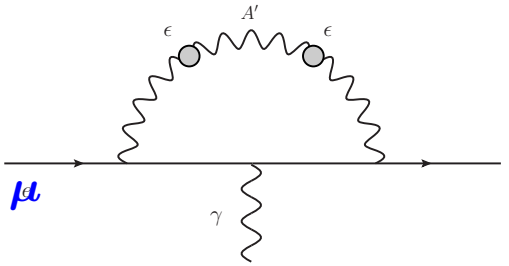
Vector portal

Okun, Voloshin, Holdom, Ellis, Schwarz, Tyupkin, Kolb, Seckel, Turner, Georgi, Ginsparg, Glashow, Foot, Volkas, Blinnikov, Khlopov, Gninenko, Ignatiev, ... + authors of PP

New vector particles: motivations

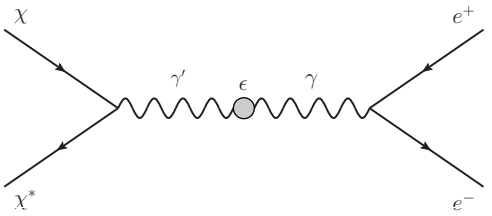
- Structure of the SM gauge group SU(3)×SU(2)×U(1) may descend from a larger (e.g. GUT) group, and low energy theory symmetric under SU(3)×SU(2)×[U(1)]^n is possible. Examples: gauging of the $B - L$ "accidental" global symmetry of the SM;
- Left-right symmetric models $[SU(3) \times SU(2) \times U(1)]_{our} \times [SU(3)' \times SU(2)' \times U(1)']_{mirror}$: spontaneous parity violation. Messenger between left and right mirror particles .
- Dark matter hidden sector may have complicated structure, not associated with ideas of mirror symmetry. A possible bridge between hidden and and our world can be the vector portal.

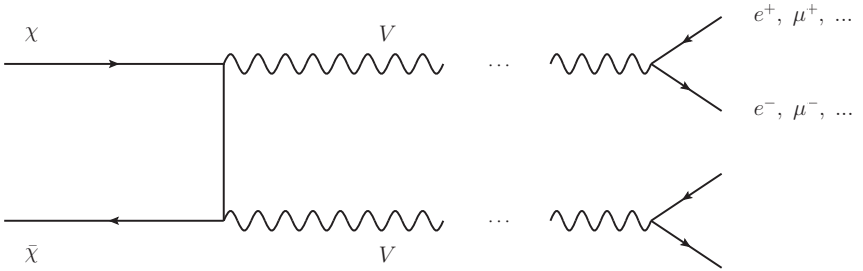
- Possible solution of muon $g-2$ discrepancy



- Mediator of interaction with Dark matter

  - Light dark matter with M as small as few MeV: increase of annihilation cross-section of DM particles. Used for DM explanations of the positron excess;





  - Self-interacting dark matter: core-cusp problem in dwarf galaxies, too-big-to-fail problem (excess of massive sub-halos in N-body simulations of Milky Way type galaxies)

Vector portal: phenomenology

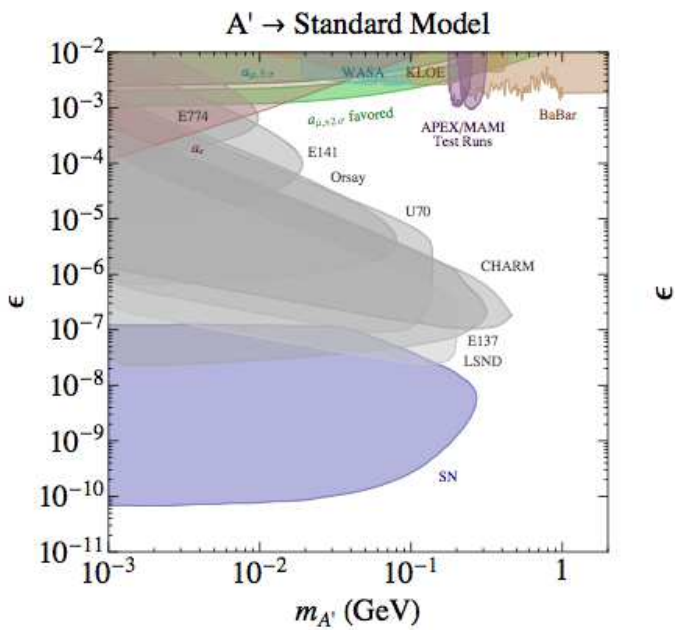
Production

- Meson decays, such as $\eta,\ \rho,\ \pi, \ldots \to \gamma A'$; Bremsstrahlung processes $pp \to ppA'$; Direct QCD production $q\,\bar{q} \to A',\ q\,g \to A'\,q$

Decays

- $A' \to l^+l^-,\ \ A' \to \mathbf{hadrons},\ \ A' \to \chi\bar{\chi}$

Example of constraints



Scalar portal

Patt, Wilczek, Schabinger, Wells, No, Ramsey-Musolf, Walker, Khoze, Ro, Choi, Englert, Zerwas, Lebedev, Mambrini, Lee, Everett, Djouadi, Falkowski, Schwetz, Zupan, Tytgat, Gunion, Haber, Kane, Dawson,...+ authors of PP

New scalars: motivations

- LHC: fundamental scalar boson exists in nature. There are many quarks, leptons, vector bosons. Why the Higgs boson should be unique?
- Hierarchy problem: SUSY and extended SUSY, mirror world with twin Higgs, neutral naturalness
- Composite Higgs boson: extra scalar states
- Large extra dimensions: KK scalar modes
- Pseudo-Nambu-Goldstone bosons (PNGB) of a spontaneously broken symmetry
- Flavour problem: familons

- Hidden Valley scenario: low mass hidden sector coupled to the SM through mediators of different nature
- Inflation is most probably driven by a scalar field
- Candidate for dark matter
- Messenger between the visible and dark matter sectors
- Electroweak baryogenesis (new scalar can make the EW phase transition of the first order, resulting in thermal non-equilibrium)
- Neutrino masses: type II see-saw

Scalar portal: phenomenology

Typical Lagrangian:

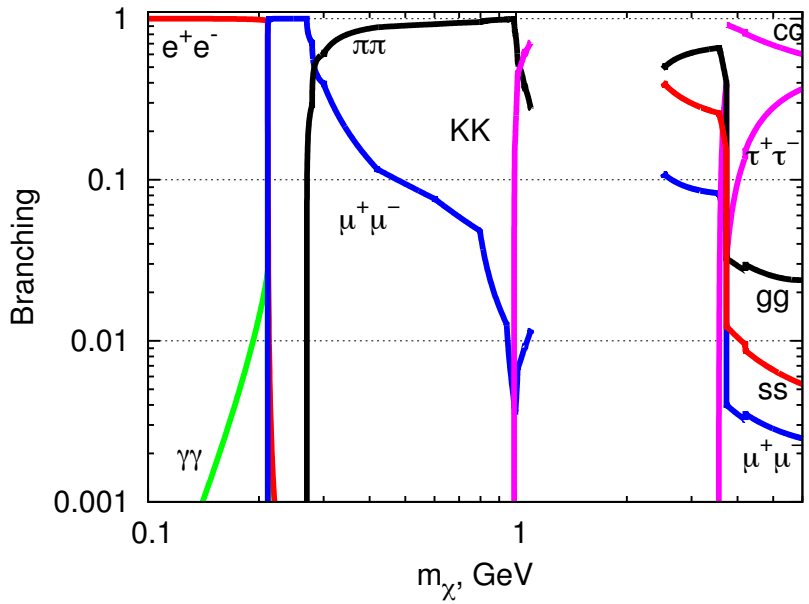
$$(\alpha_1 S + \alpha S^2) H^\dagger H + L_{SM} + L_{hidden}$$

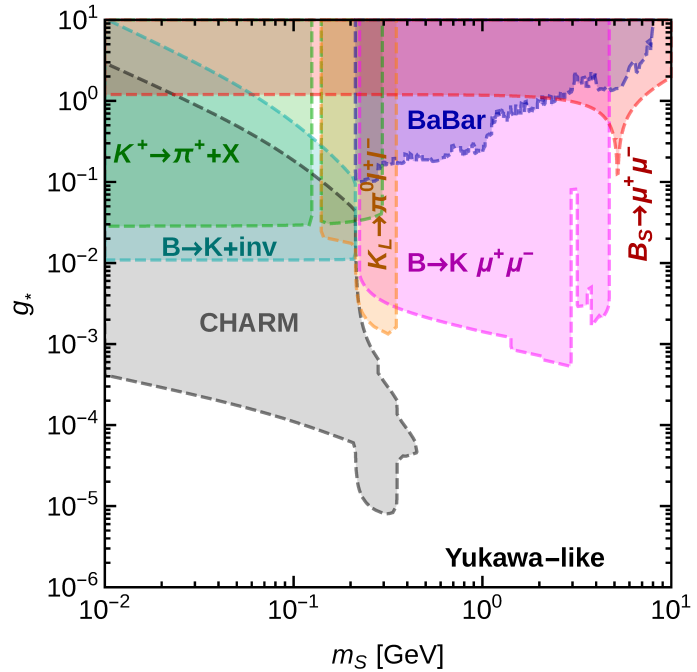
Production

- Direct production $p + \mathrm{target} \to S + \ldots$
- Production via intermediate (hadronic) state
  $p + \mathrm{target} \to \mathrm{mesons} + \ldots$, and then $\mathrm{hadron} \to S + \ldots$.

Decays

- Subsequent decay of S to SM particles





Through mixing with Higgs

Example of constraints,

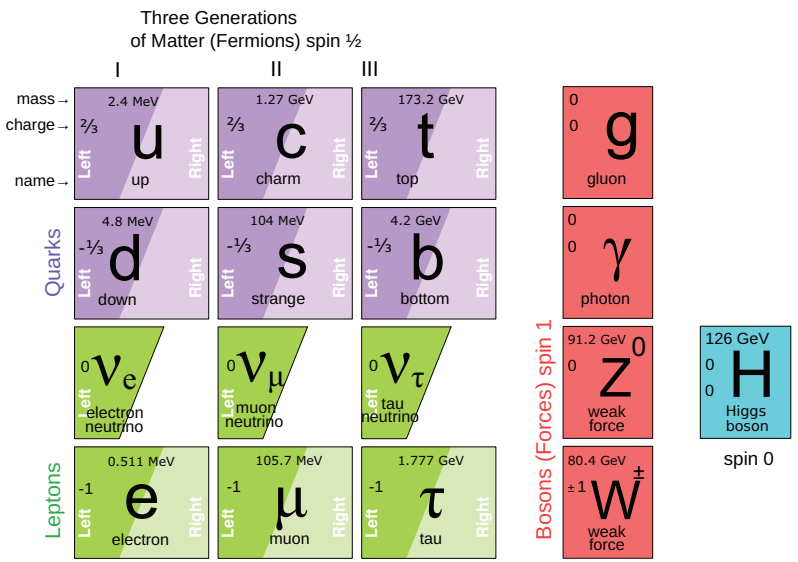
$$g_* = \alpha_1 V/m_h^2$$

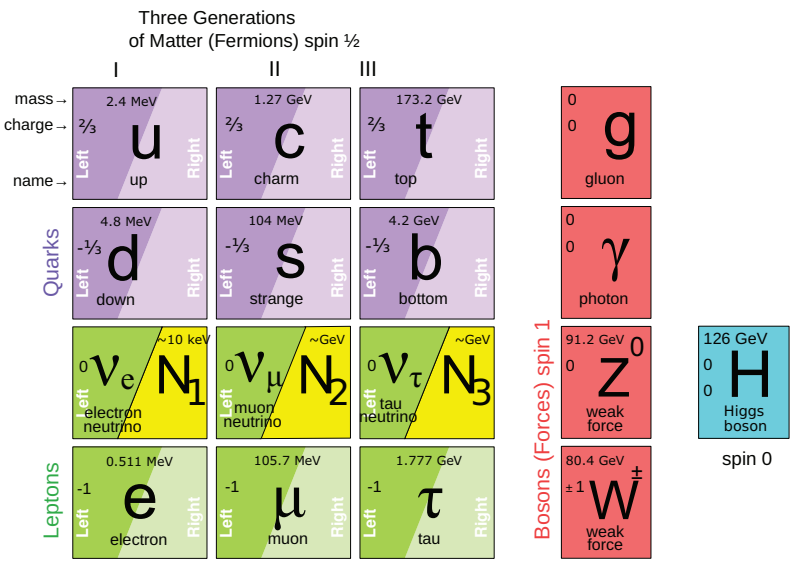
Neutrino portal

Minkowski, Yanagida, Gell-Mann, Ramond, Slansky, Glashow, ... the whole domain of neutrino physics + authors of PP

New neutral leptons: motivations

- Left-right symmetry
- Quantisation of electric charges without Grand Unification, as a consequence of requirement of anomalies cancellations
- Natural completion of the Standard Model in neutrino sector





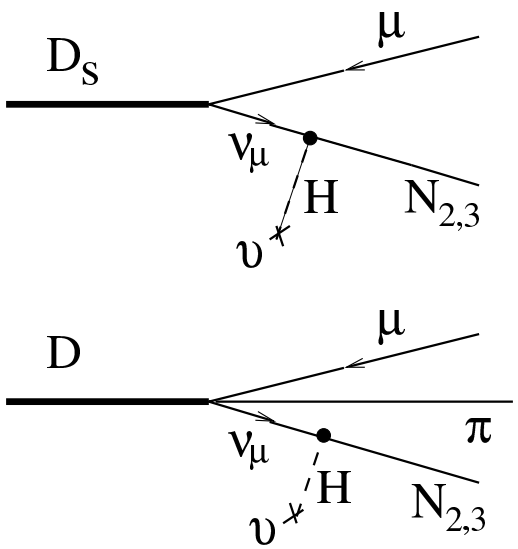
- Origin of active neutrino masses via type I see-saw (requires at least 2 HNL)
- Dark matter candidate (requires 1 HNL)
- Baryon asymmetry of the Universe (requires at least 2 HNL)
- Neutrino anomalies (LSND, MiniBOONe, reactor), requires HNL with eV scale mass

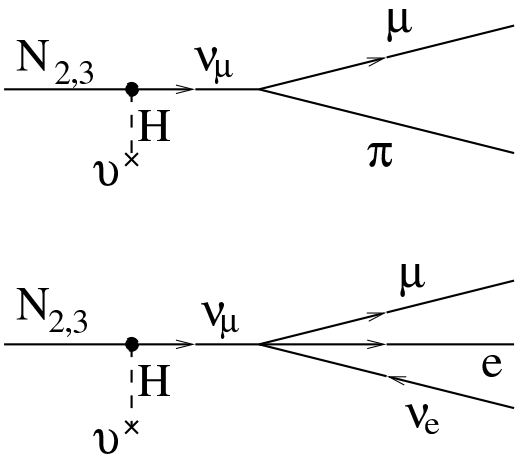
Neutrino portal: phenomenology

- Production via intermediate (hadronic) state

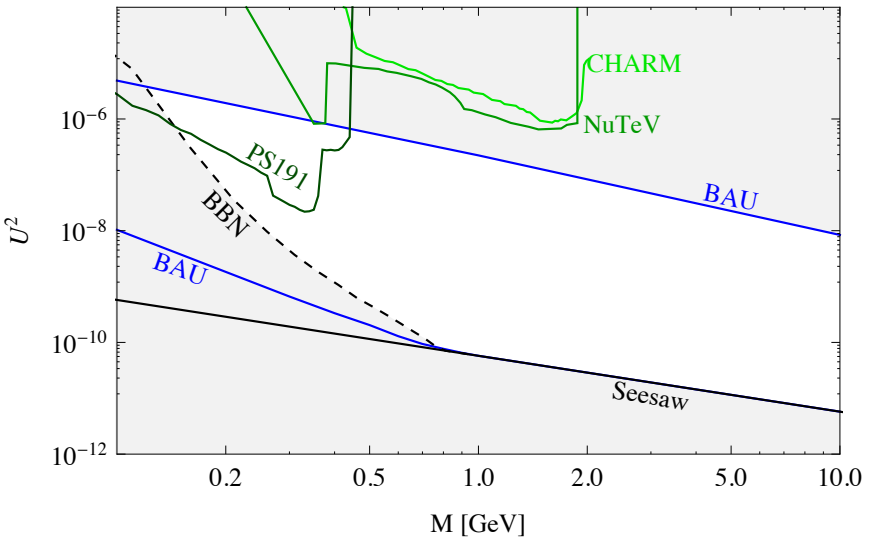
  $p + \text{target} \to \text{mesons} + \ldots$, and then $\text{hadron} \to N + \ldots$.

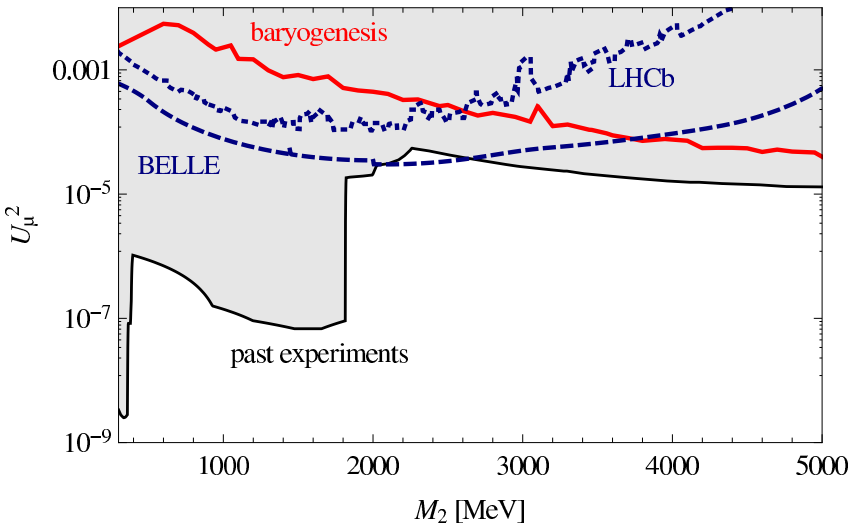
- Subsequent decay of N to SM particles





Neutrino portal: cosmological and experimental constraints





Constraints on mixing angle U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches.

Left panel - normal hierarchy, 2HNL+1 DM HNL; right panel - 3 HNL .

Axion portal

Weinberg, Wilczek, Witten, Conlon, Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, Cicoli, Goodsell, Lazarides, Shafi, Choi, Harnik, Kaplan, Espinoza, Quiros, Hooper, Feng...+ authors of PP

Axion-like particles and PNGB: motivations

Well known example: axion to solve strong CP-problem (different mass region, cannot be searched at SHiP)

- String theory compactifications: axiverse with ALPs with masses taking values distributed across every scale of energy
- Pseudoscalars in extended Higgs sectors (e.g. NMSSM)
- Large extra dimensions with relatively small fundamental Planck scale
- PNGBs of spontaneously broken global flavour symmetries : familons
- Dark matter - mediation of interactions between SM and DM particles

Typical interaction:

$$\frac{a}{f_A} G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad \frac{\partial_\mu a}{f_A}\bar{\psi}\gamma_\mu\gamma_5\psi, \quad etc$$

Axion portal: phenomenology

Production

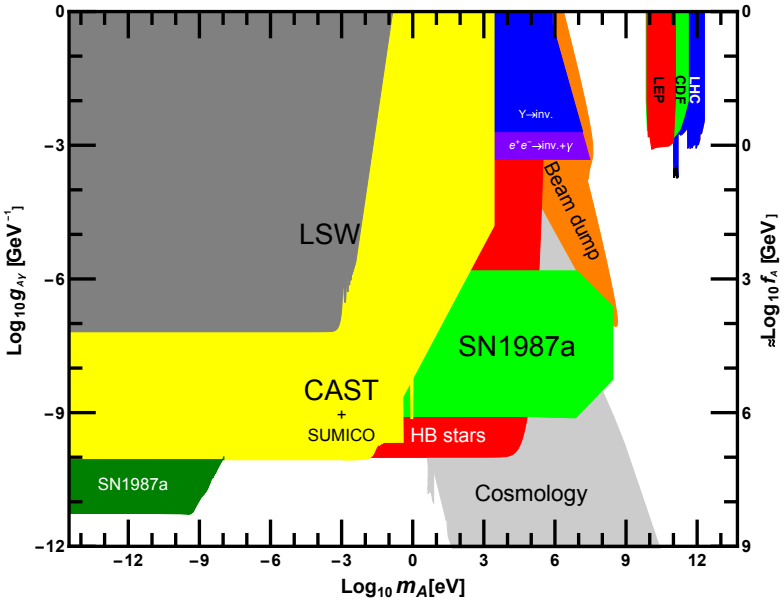
- Drell-Yan production of photon $q\bar{q} \to \gamma^*$, followed by Primakoff production of ALPs $\gamma^* \to a\gamma$
- meson decays, e.g. $B \to Ka$

Decays

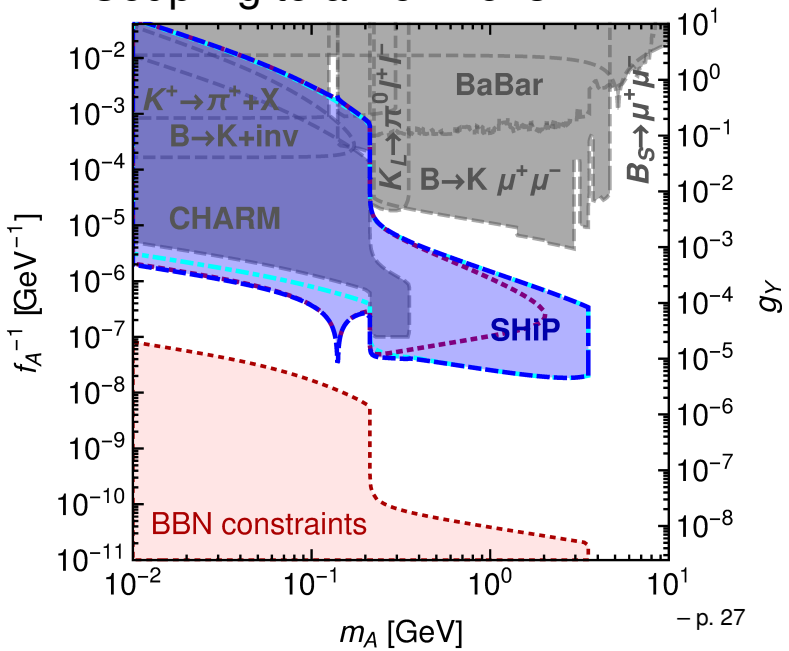
- $a \to \gamma\gamma, \;\; a \to l^+l^-$, etc

Example of constraints

Coupling to 2 photons, $g_{A\gamma} \propto 1/f_A$



Coupling to all fermions



SUSY

too many names to write + authors of PP

Light SUSY particles: motivations

SUSY: general framework for addressing hierarchy problem and Grand Unification. The prejudice that SUSY particles are heavy comes from the minimal models such as MSSM or CMSSM

- Unstable neutralino in models with R-parity breaking (then DM candidates - axino or axion)
- Scalar and pseudoscalar sgoldstinos coming from SUSY breaking (e.g. no-scale SUGRA)
- Pseudo Dirac gauginos χ_1, χ_2: dark matter candidate χ_1
- SUSY partners of axion: axino and saxion
- SUSY partners of dark photons: hidden photinos $\tilde{\gamma}, \tilde{\gamma}', \ldots$ (string theory compactifications)

Light SUSY particles: phenomenology

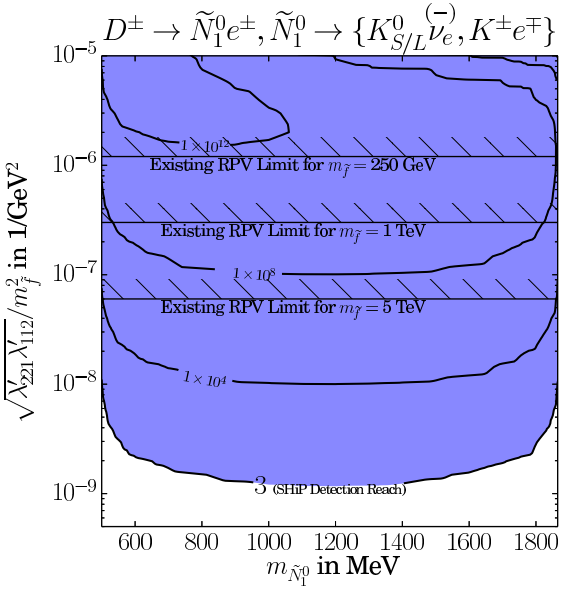
- Neutralino: similarity with HNL
- Sgoldstino: similarity with ALPs
- Pseudo Dirac gauginos: $pp \to \chi_2 + \chi_{1,2}, \quad \chi_2 \to \chi_1 + l^+ l^-$
- Photinos: $B \to K\tilde{\gamma}\tilde{\gamma}, \quad \tilde{\gamma} \to \tilde{\gamma}' + l^+ l^-$
- Saxions: similarity with ALPs
- Axinos: similarity with neutralino

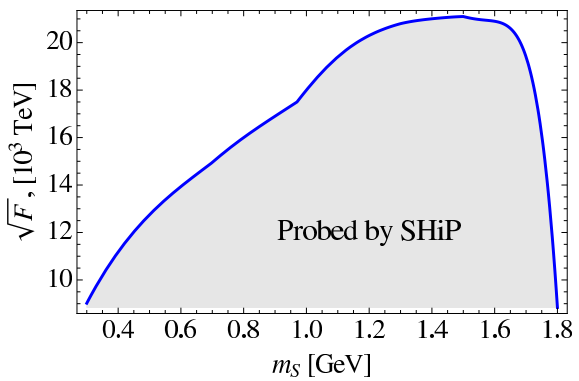
Examples of constraints

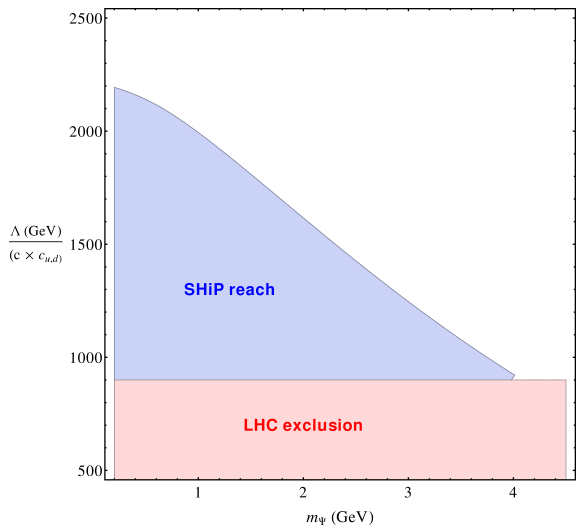
SUSY breaking scale

as a function of

sgoldstino mass







RPV neutralinos

λ- amplitude of RPV

Pseudo-Dirac fermion

$1/\Lambda^2$ - interaction

with SM fields

Conclusions

The SHiP 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 LHC. It can test

- the ideas on light messengers between the SM and heavy sectors such as SUSY, extra dimensions, new strong dynamics
  Examples: dark photon, light scalars, pseudo-Goldstone bosons of high energy symmetries, RPV neutralino, sgoldstino, . . .
- the ideas on the absence of new particle thresholds between the Fermi and Planck scales Example: heavy neutral leptons.

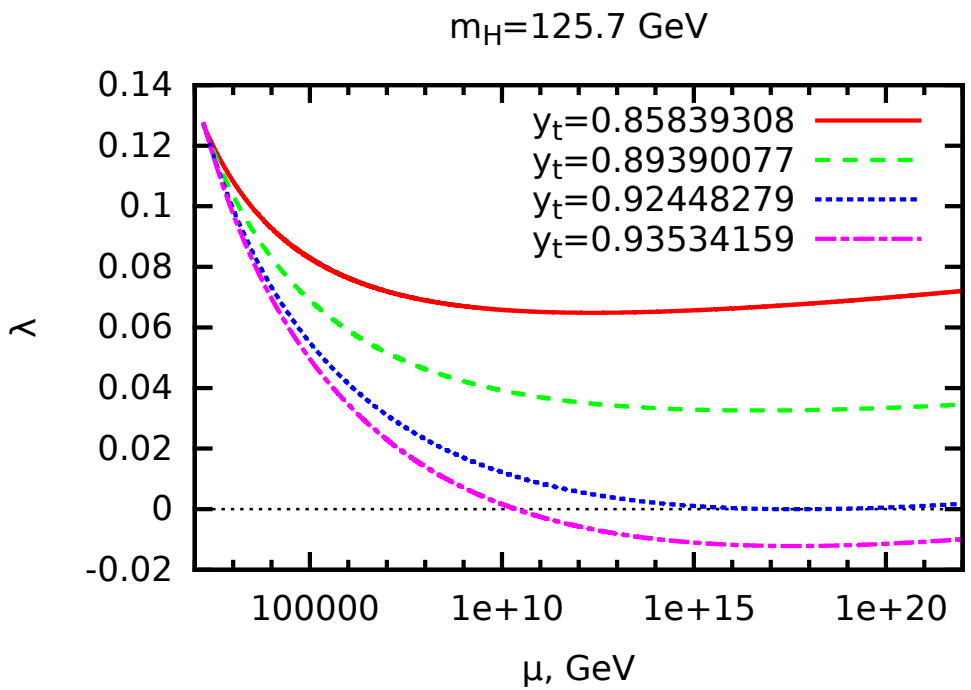
It can probe different solutions of BSM problems:

- Dark matter
- Neutrino masses
- Baryon asymmetry of the Universe
- Inflation
- Hierarchy
- Flavour

Tau neutrino physics and precision measurements

- τ-neutrino charged current cross section ($\sim few \times 10^3$ events) (present situation: 9 events in DONUT and 5 events in OPERA).
- Discovery of $\bar{\nu}_\tau$
- Determination of $\nu_\tau, \ \bar{\nu}_\tau$ DIS structure functions F_4 and F_5.
- Update of DIS of muon (~ 2 Mio events) and electron neutrinos (~ 1 Mio events)
- α_s measurement via Gross-Llewellin Smith sum rule
- EW parameters $\sin^2 \theta_W$
- Charmed pentaquark searches
- Tau neutrino magnetic moment (cross section of elastic scattering on electron)
- Lepton flavour violation, $\tau \to 3\mu$ (current limit 2×10^{-8}, improvement to $\simeq 10^{-10}$)

BACK UP SLIDES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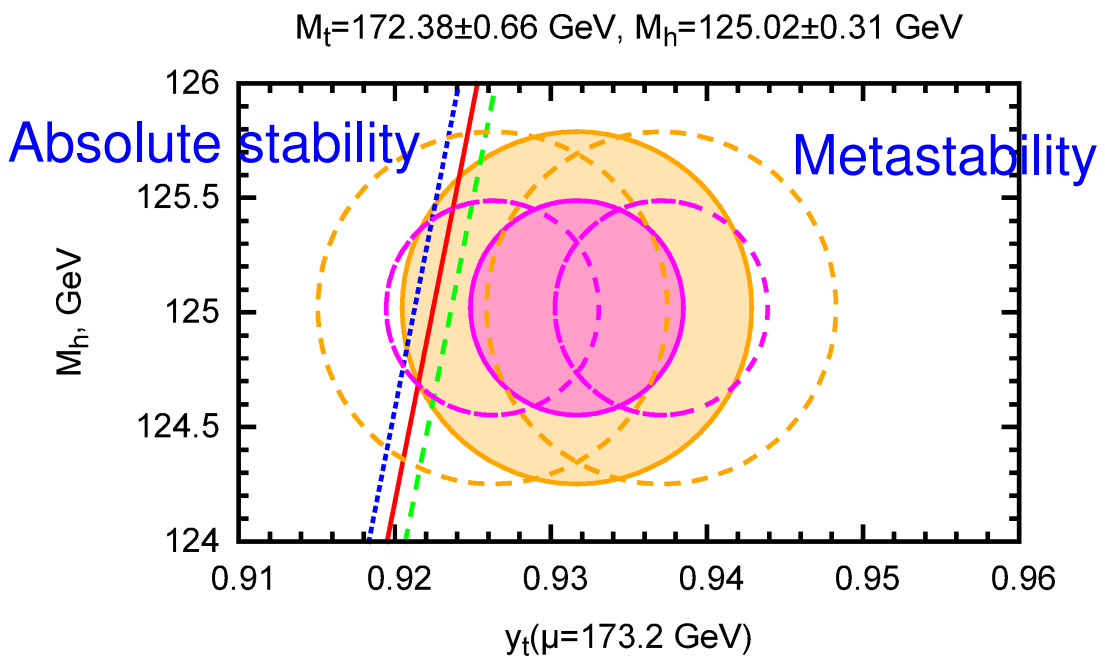
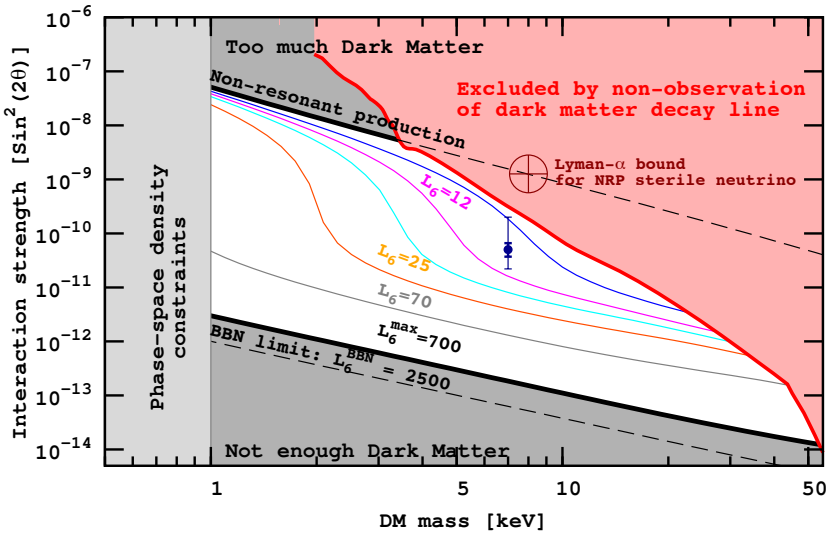
y_t=0.85839308
y_t=0.89390077
y_t=0.92448279
y_t=0.93534159
λ
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
100000
1e+10
1e+15
1e+20
μ, GeV


M_t=172.38±0.66 GeV, M_h=125.02±0.31 GeV
Absolute stability
Metastability
M_h, GeV
126
125.5
125
124.5
124
0.91
0.92
0.93
0.94
0.95
0.96
y_t(μ=173.2 GeV)

Dark Matter HNL: $N_1 \to \nu\gamma$



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119