Ideas on neutrino physics beyond the SM

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SWAPS 2014

In-spite of the fact that the Standard Model is consistent with LHC experiments and can be a valid effective field theory all the way up to the Planck scale, it cannot be an ultimate theory of nature.

Experimental evidence for new physics

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe

Theoretical evidence for new physics

- Hierarchy problem
- Cosmological constant problem
- Flavour
- Gravity
- ...

Where is new physics?

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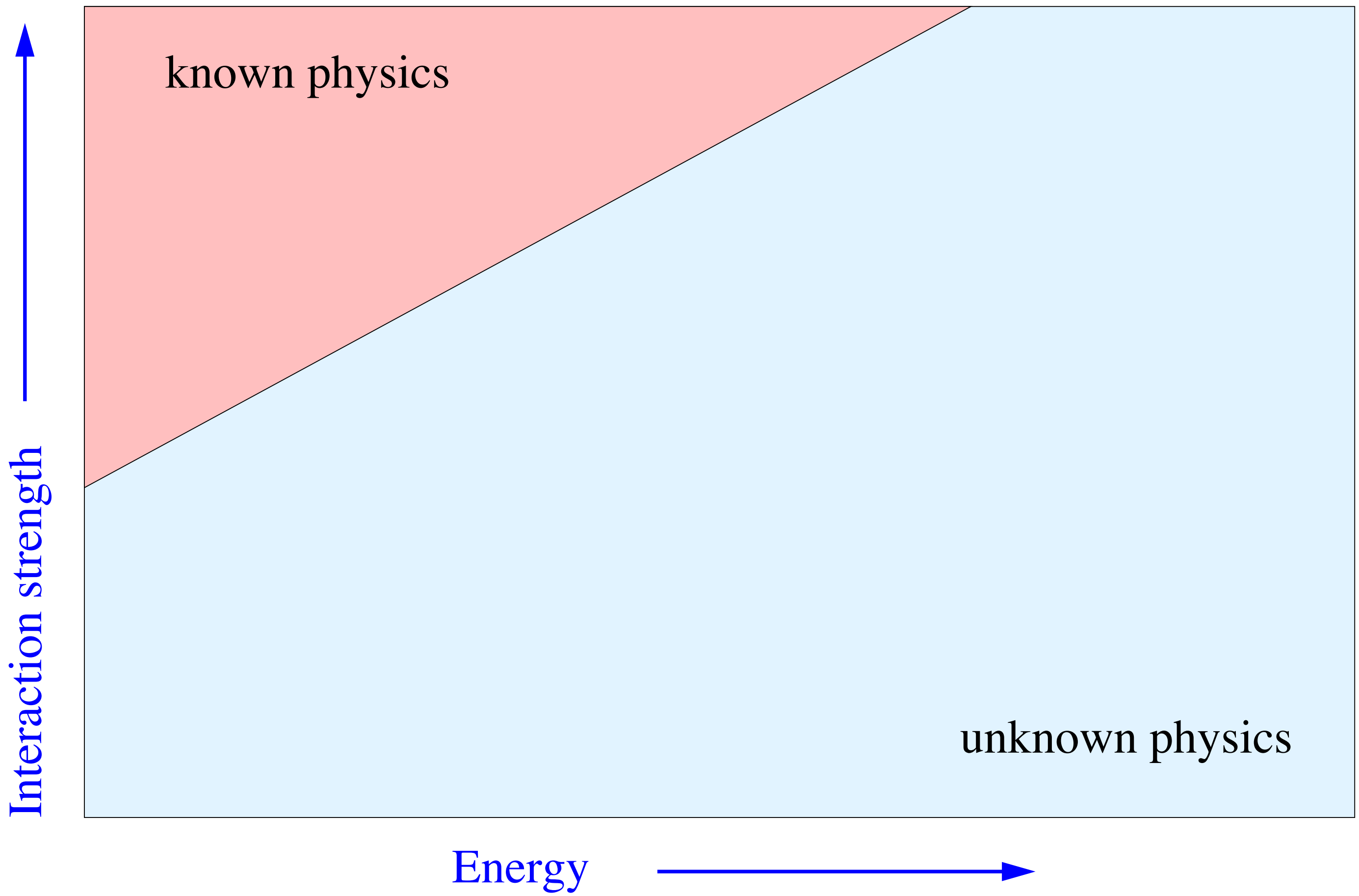

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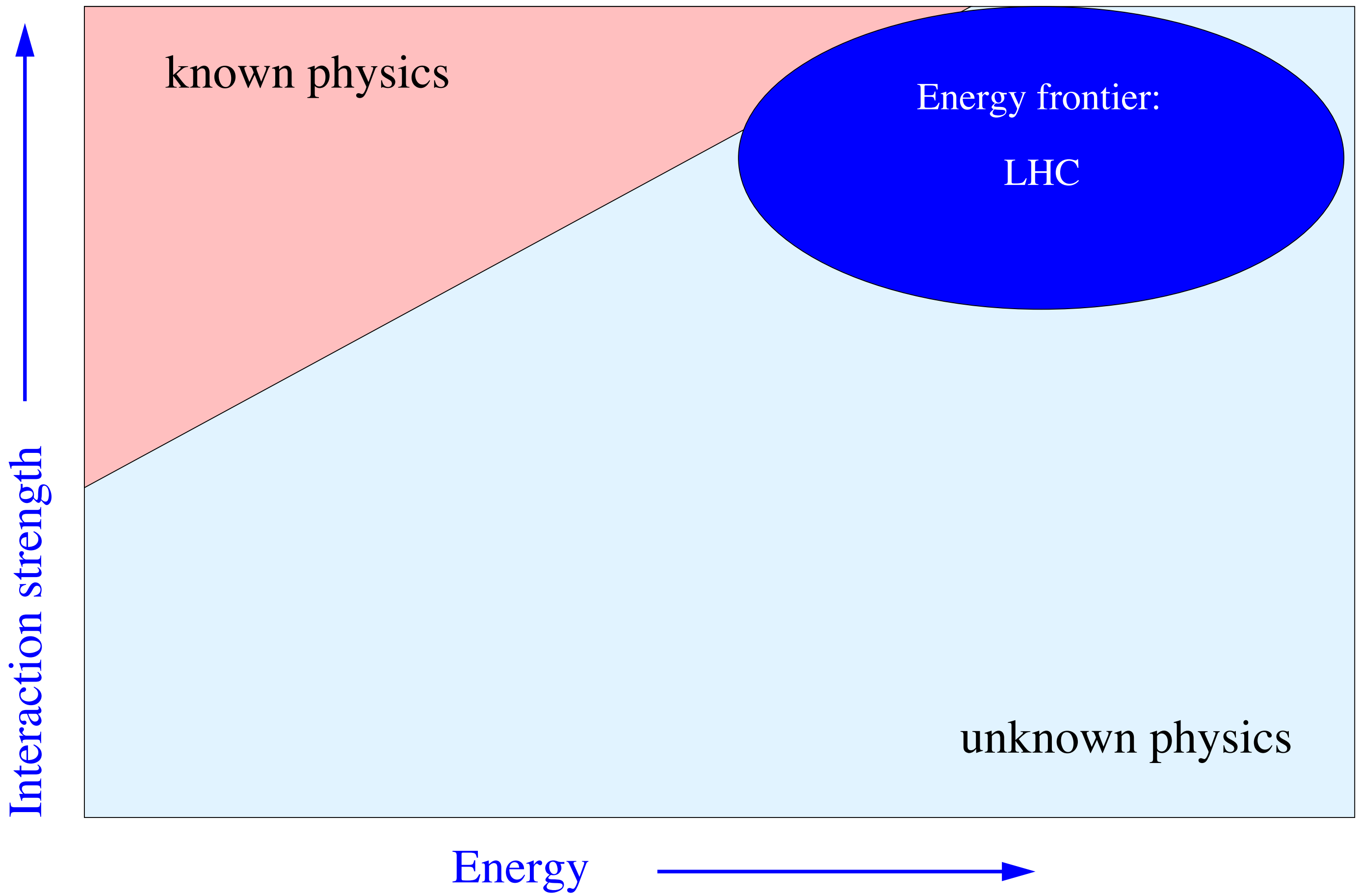

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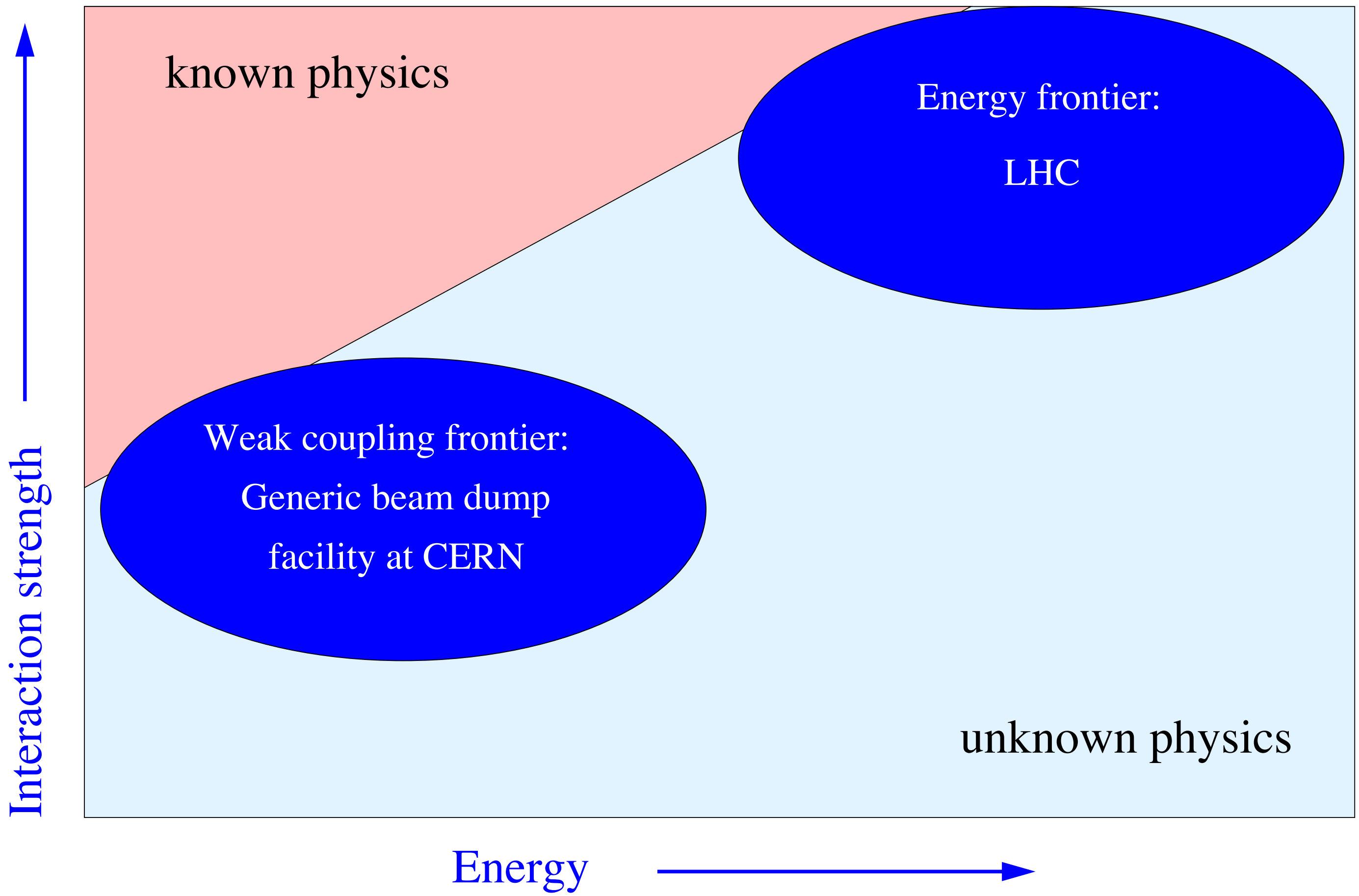

Portals to the hidden sectors

If new hidden particles are light, they must be singlets with respect to the gauge group of the SM (possible exception - milli-charged particles). 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 - massive vector (paraphoton, secluded 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

$$(\mu\chi + \lambda\chi^2) H^\dagger H$$

- 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,

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

Outline

- Neutrino portal
- Experimental setup of SHIP
- Conclusions

Neutrino portal

Motivations

Minkowski, Yanagida, Gell-Mann, Ramond, Slansky, Glashow, Mohapatra, G. Senjanovic + too many names to write, the whole domain of neutrino physics

Most general renormalizable (see-saw) Lagrangian

$$L_{see-saw} = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c.,$$

Assumption: all Yukawa couplings with different leptonic generations are allowed.

$I \leq \mathcal{N}$ - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with $\mathcal{N}$ to see if having some number of HNLs is good for something

- $\mathcal{N} = 1$: Only one of the active neutrinos gets a mass

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- $\mathcal{N} = \mathbf{3}$: All active neutrinos get masses: all neutrino experiments, can be explained (LSND with known tensions). The theory contains 6 new CP-violating phases: baryon asymmetry of the Universe can be understood. If LSND is dropped, dark matter in the Universe can be explained. The quantisation of electric charges follows from the requirement of anomaly cancellations (1-3-3, 1-2-2, 1-1-1, 1-graviton-graviton).

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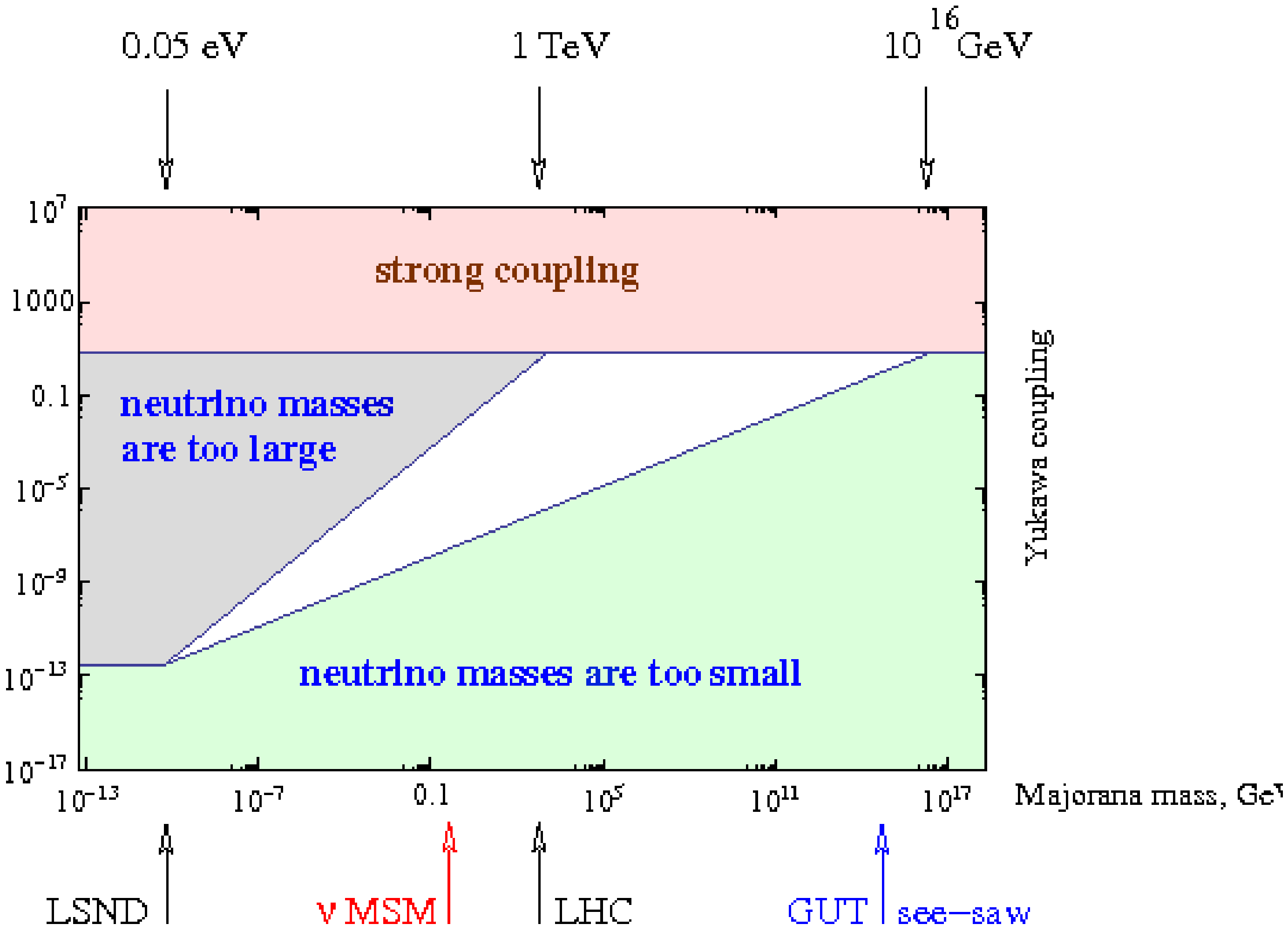
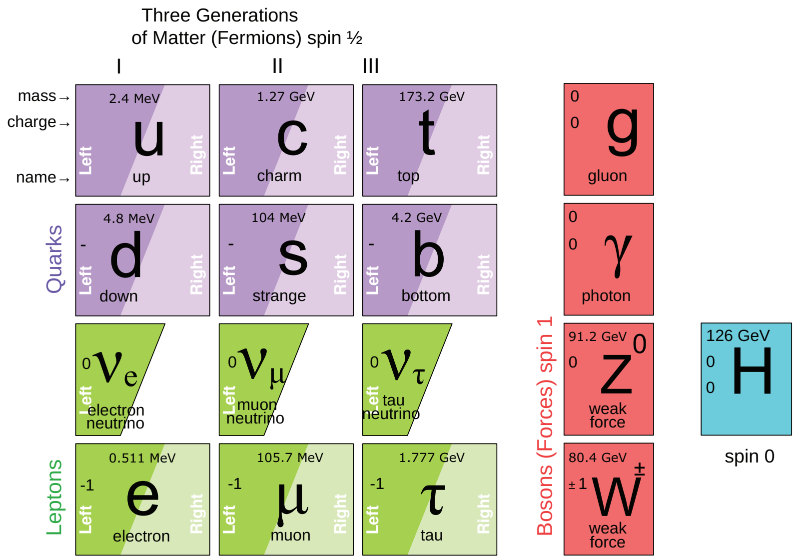
- $\mathcal{N} > \mathbf{3}$: Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.

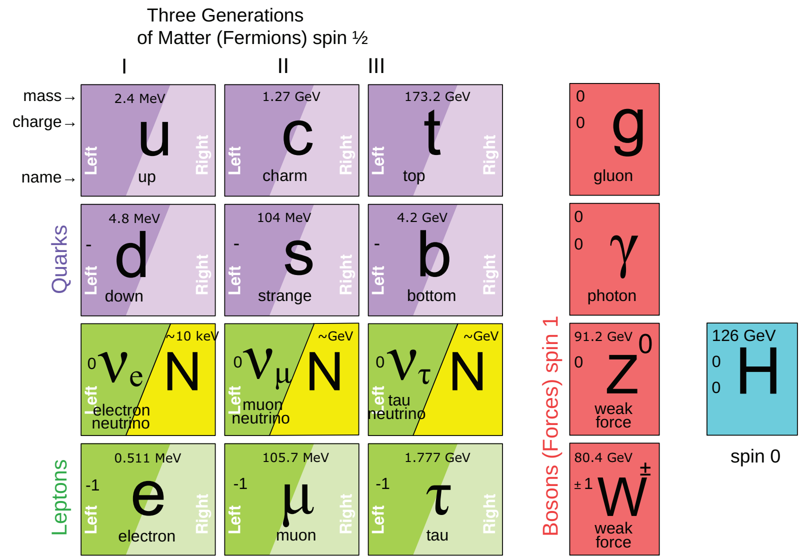
New mass scale and Yukawas

$$Y^2 = Trace[F^\dagger F]$$



$\mathcal{N} = 3$ with $M_I < M_W$: the νMSM





N = Heavy Neutral Lepton - HNL

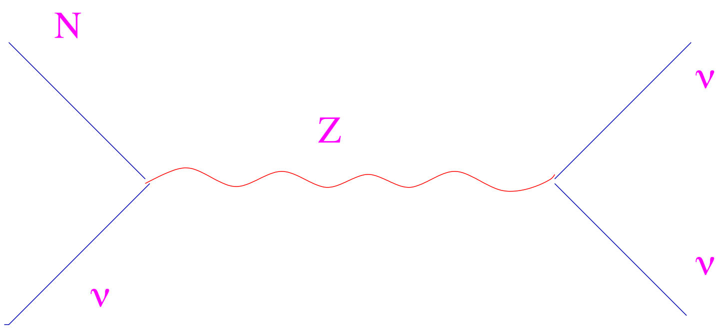
Role of N_1 with mass in keV region: dark matter (has been discovered in X-rays? $M_1 \simeq 7$ keV, Bulbul et al., Boyarsky et al)

Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

HNL Dark Matter

Dark Matter candidate: N_1

Yukawa couplings are small $\rightarrow$ N can be very stable.



Main decay mode: $N \rightarrow 3\nu$.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

For one flavour:

$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\ \text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

$$\theta_1 = \frac{m_D}{M_N}$$

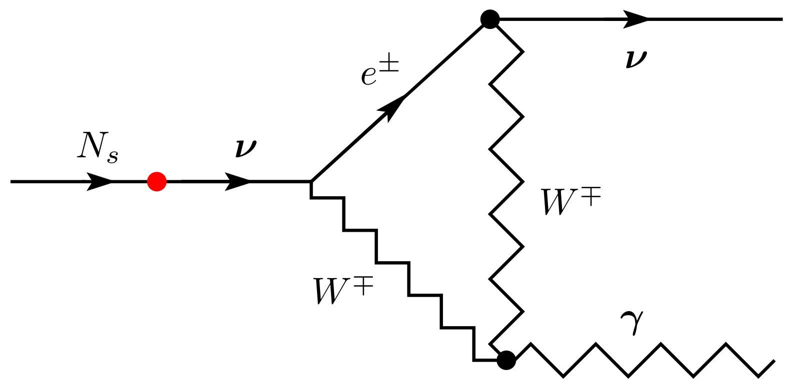
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \to 3\nu$ is not observable.

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$

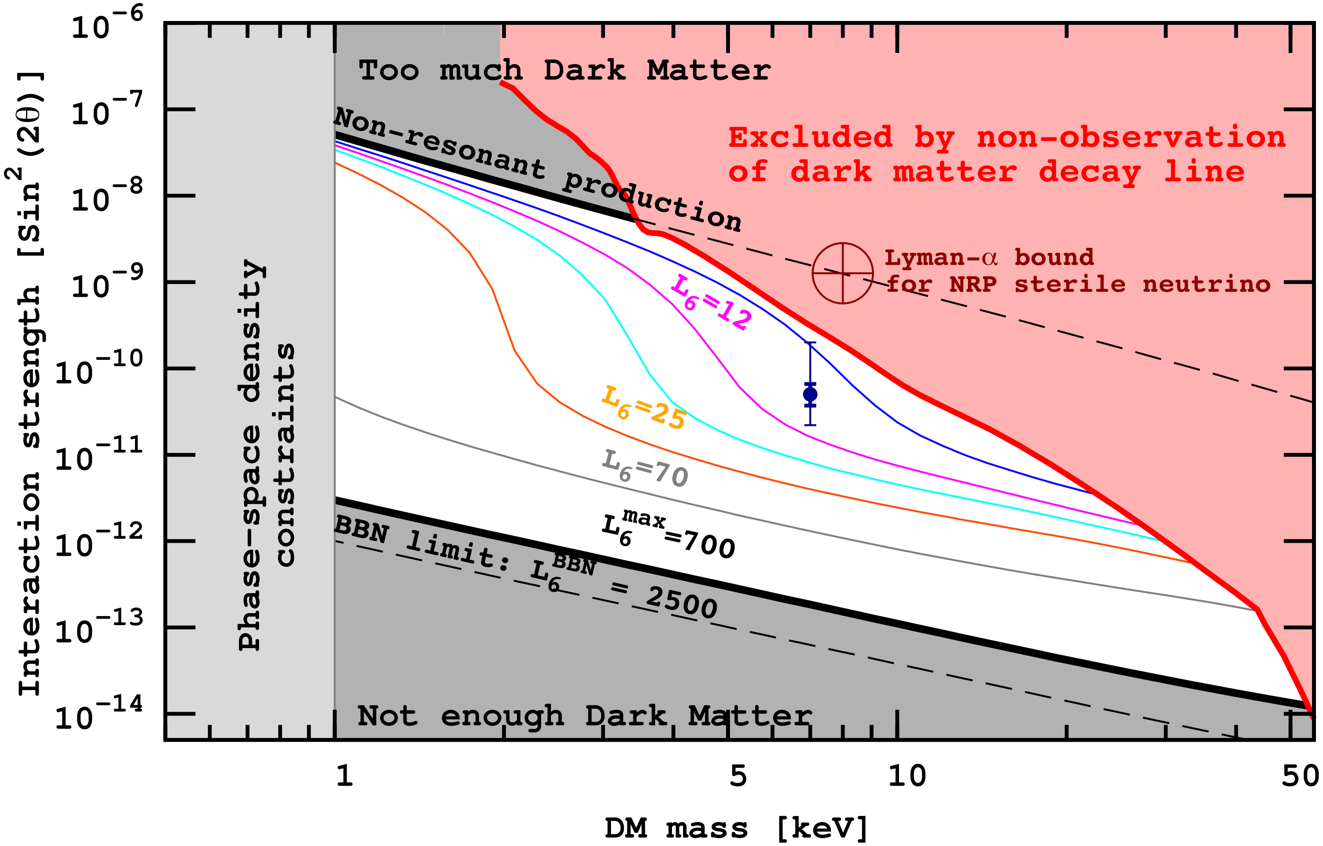


Radiative decay width:

$$\Gamma_{\mathbf{rad}} = \frac{9\,\alpha_{\mathrm{EM}}\,G_F^2}{256 \cdot 4\pi^4}\ \sin^2(2\theta)\,M_s^5$$

Constraints on DM HNL N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). seen yet



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

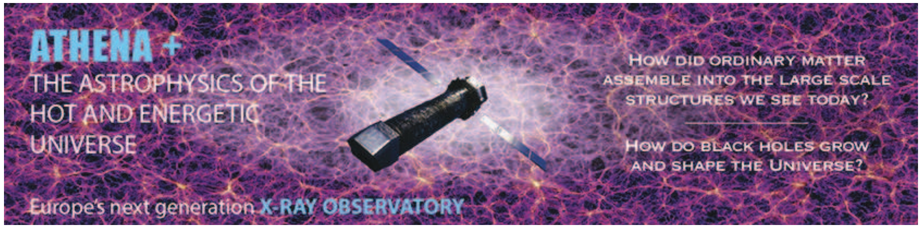
Searches for HNL in space

- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)
- Proposed/planned X-ray missions with sufficient spectral resolution:

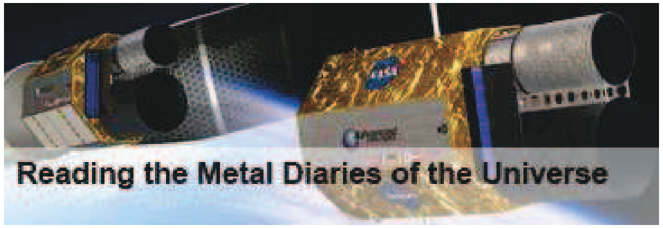
Astro-H

LOFT

Athena+



Origin/Xenia



Baryon asymmetry

- CP-violation - OK due to new complex phases in Yukawa couplings
- Lepton number violation - OK due to HNL couplings and due to Majorana masses
- Deviations from thermal equilibrium: OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Note:

- there is no electroweak phase transition for the Higgs mass 126 GeV
- For masses of N in the GeV region they decay at temperatures ~ 1 GeV. These decays cannot be used for baryogenesis, as they occur below the sphaleron freeze-out temperature

Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.

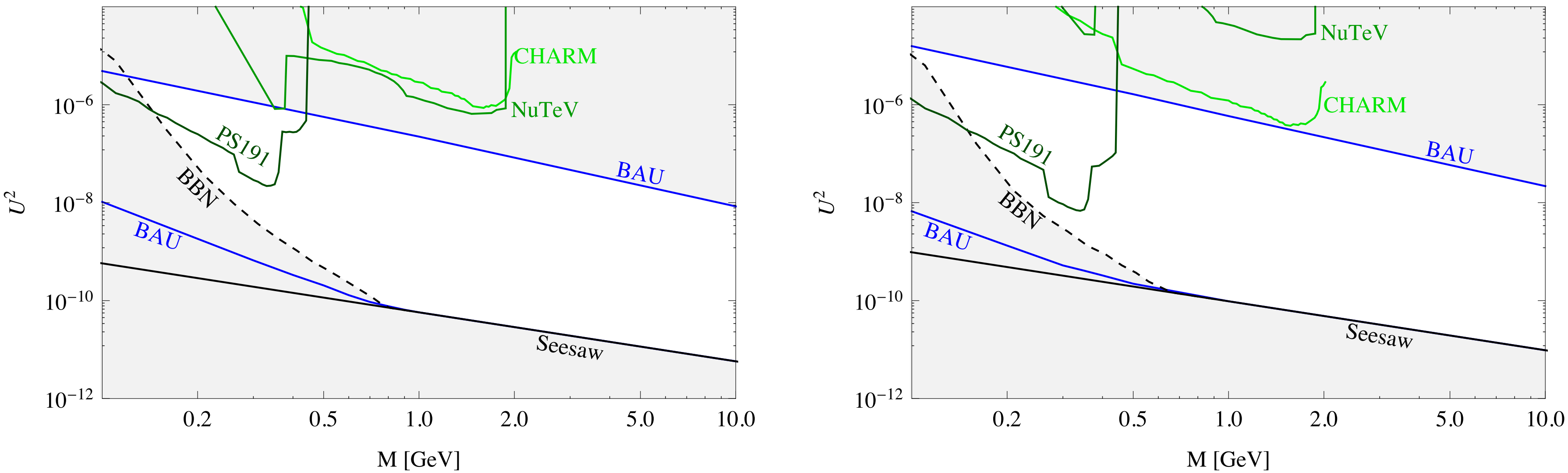
Qualitatively:

- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen



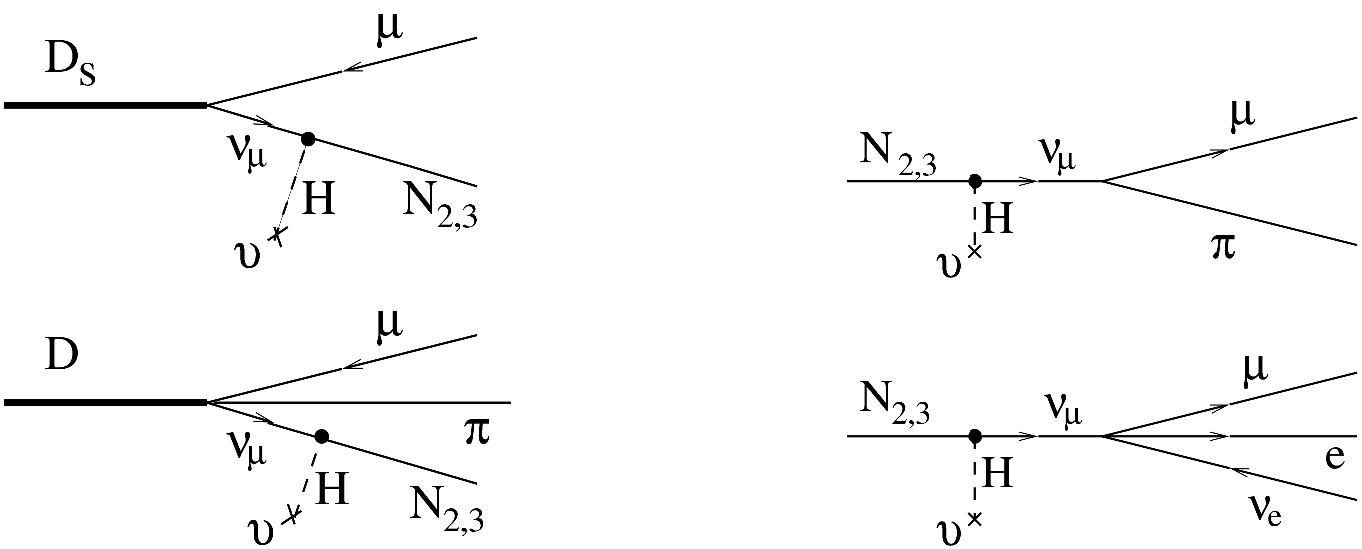
Constraints on $\boldsymbol{U^2}$ coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS).

Phenomenology of the Neutrino portal

- Production via intermediate (hadronic) state

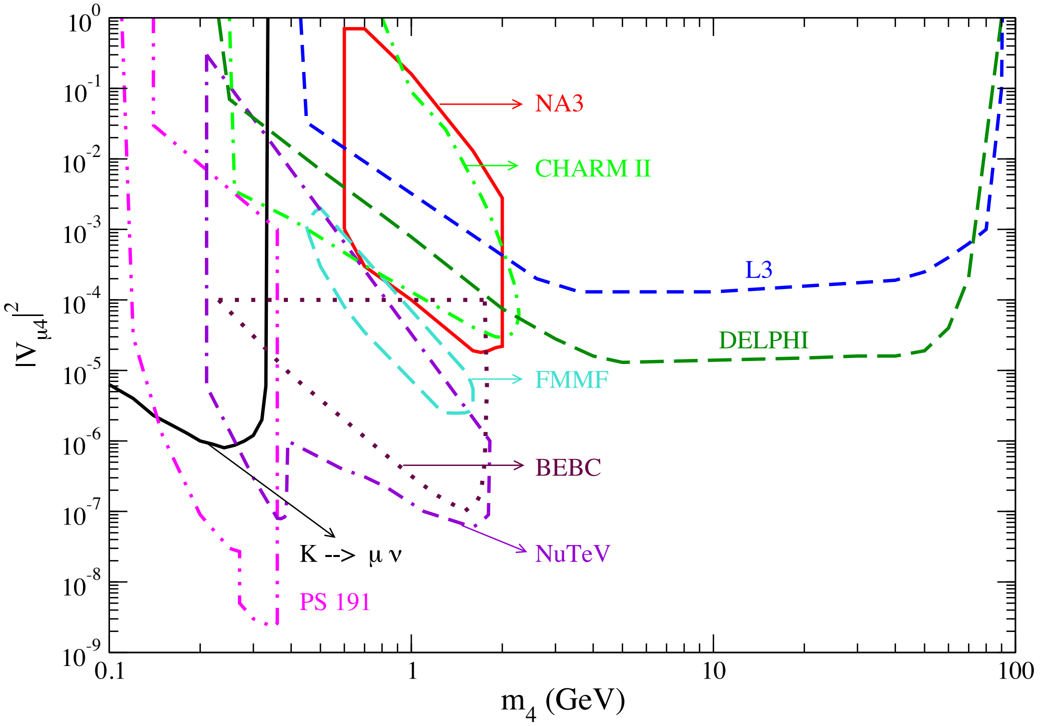
  $p + \textbf{target} \to \textbf{mesons} + ...$, and then hadron$\to N + ...$

- Subsequent decay of N to SM particles



Similar phenomenology - light neutralino $\tilde{\chi}$ in some SUSY models with R-parity violation Dedes, Dreiner, Richardson: $D \to l\tilde{\chi}, \ \ \tilde{\chi} \to l^+ l^- \nu$

Survey of constraints



From arXiv:0901.3589, Atre et al

The experimental constrains on N can be greatly improved by SHIP, see below.

How to improve the bounds or to discover light very weakly interacting hidden sector?

Dedicated experiments

Common features of all the hidden particles :

- Can be produced in decays of different mesons (π, K, charm, beauty)
- Can decay to SM particles (l^+l^-, $\gamma\gamma$, $l\pi$, etc)
- Can be long lived

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)
  - Have the detector as large as possible to increase the probability of hidden particle decay inside the detector
  - Have the detector as empty as possible to decrease neutrino and other backgrounds

Most recent dedicated experiment - 1986, Vannucci et al

Volume 166B, number 4 PHYSICS LETTERS 23 January 1986

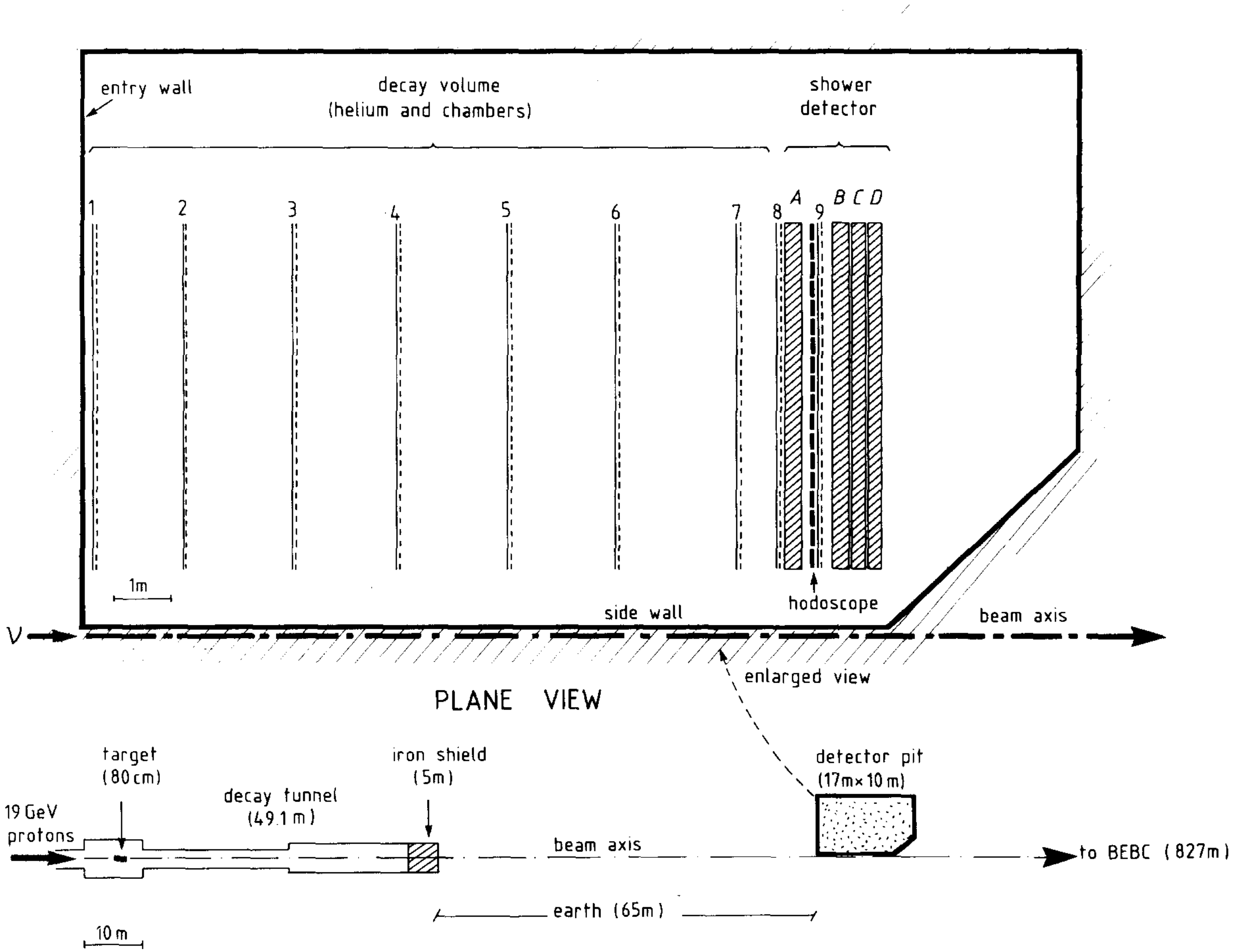


Fig. 1. Beam and layout of the detector.

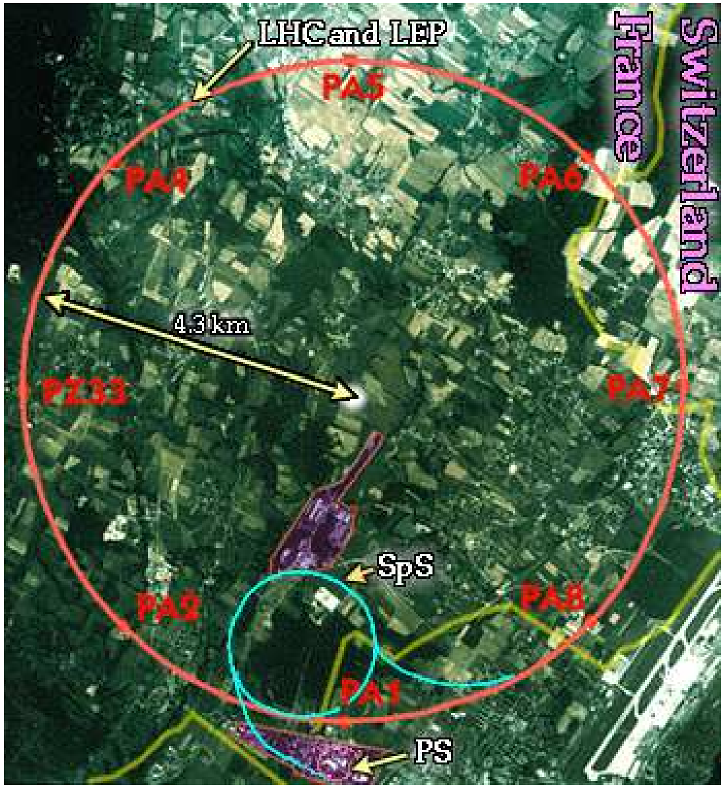
No new particles are found with mass below K-meson, the best constraints are derived

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

$$\Downarrow$$

General beam dump facility: Search for HIdden Particles



Energy: 400 GeV, power: 750 kW

$\mathbf{4.5 \times 10^{13}}$ protons per pulse (upgrade to $\mathbf{7 \times 10^{13}}$), every 6 s

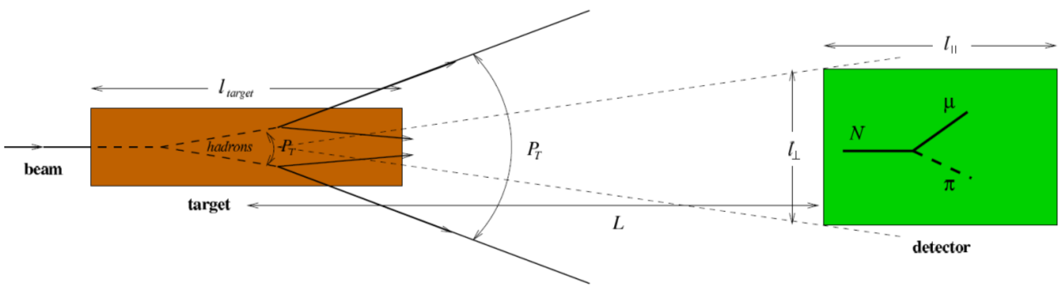
CNGS: $\mathbf{4.5 \times 10^{19}}$ protons on target per year (200 days, 55% machine availability, 60% of the SPS supercycle

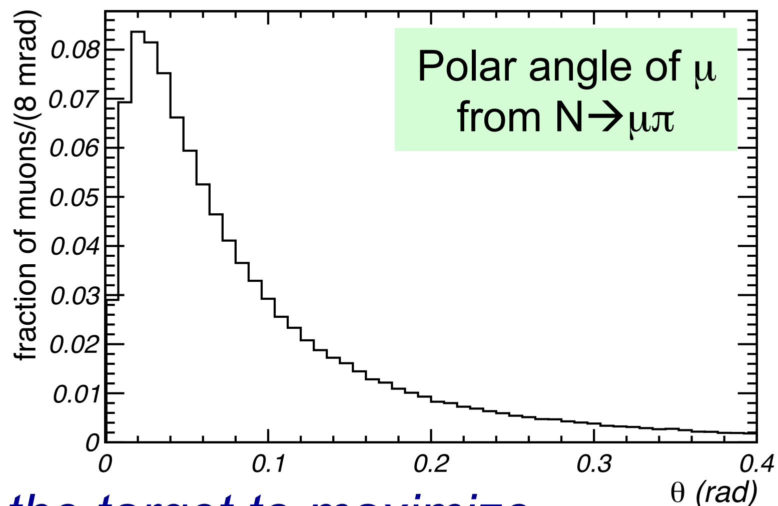
Experimental requirements

- *Example – Neutrino portal : search for HNL in Heavy Flavour decays*

→ *Beam dump experiment at the SPS with a total of 2×10^{20} protons on target (pot) to produce large number of charm mesons*

- *HNLs produced in charm decays have significant P_T*





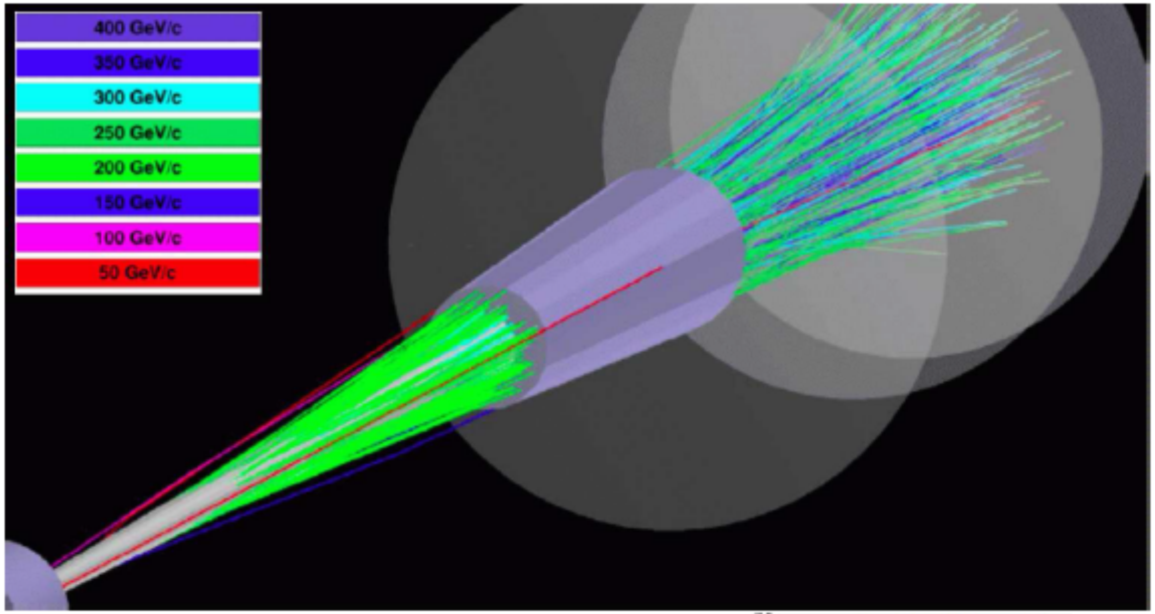
→ *Detector must be placed close to the target to maximize geometrical acceptance*

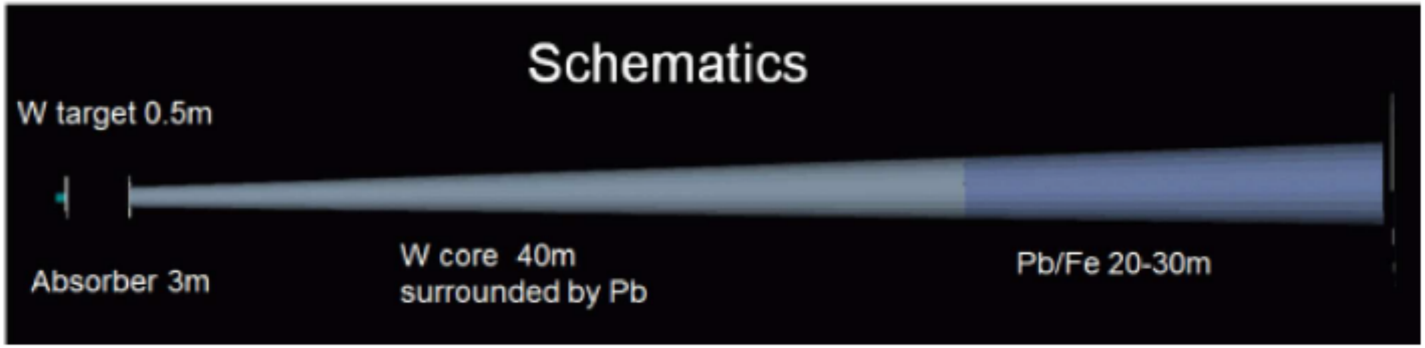
→ *Effective (and "short") muon shield is essential to reduce muon-induced backgrounds (mainly from short-lived resonances accompanying charm production)*

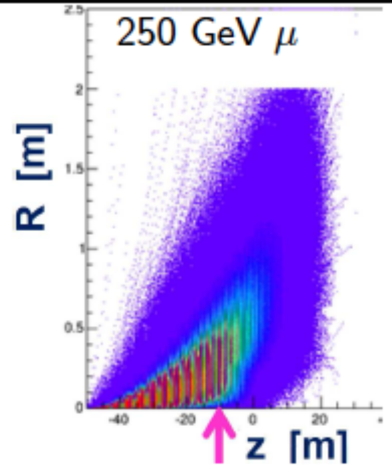
Muon shield optimization

Passive μ-filter

- Geant studies to estimate flux.
- MS and €: limit W-length to 40 m.
- High-p at small θ: W⌀12-50 cm
- +20-30 m of Pb/Fe :
- reduction of 10^7 possible
- Robust/easy to operate



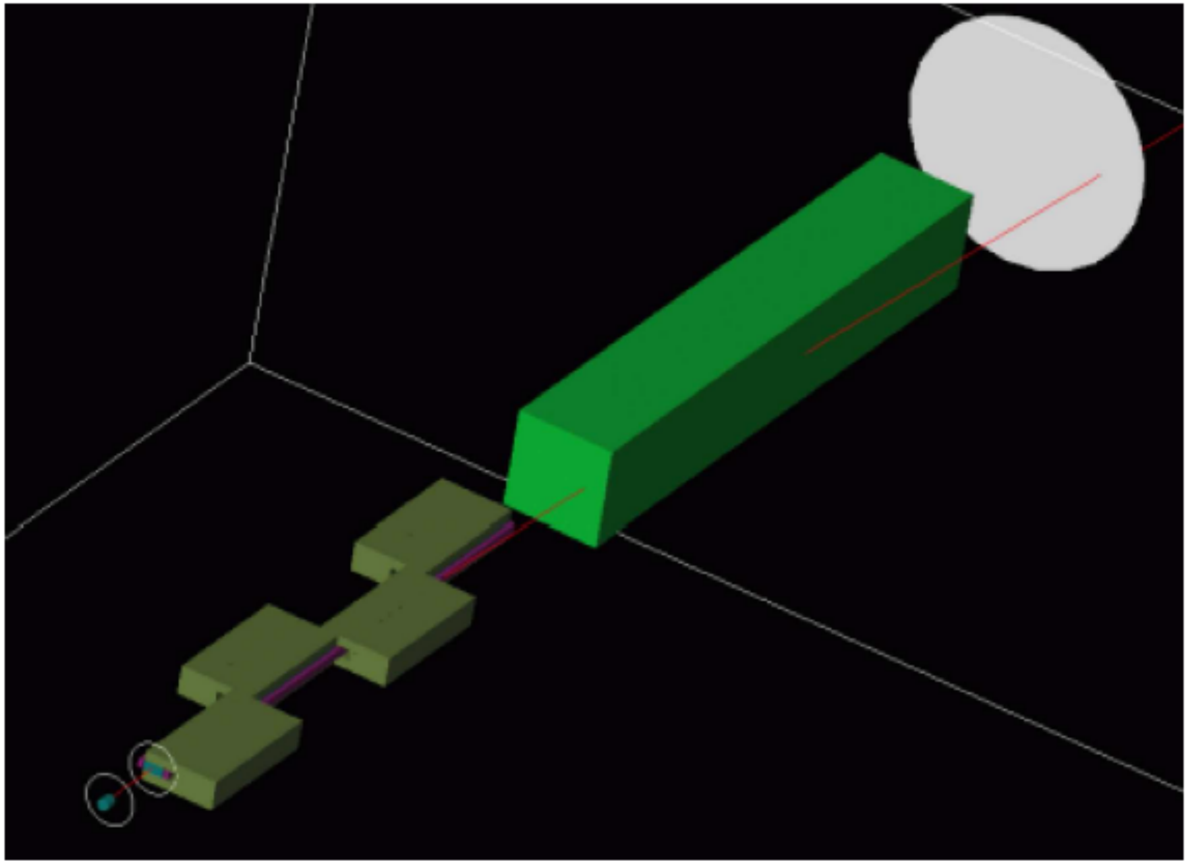




Muon shield optimization

Alternative: Active (+passive) μ-filter

- Use 6 m long C-shaped magnets.
- Produces 40 Tm total field with 4 magnets: high-p swept out.
- Problem: return-B of low-p μ:
  - alternate return-B left/right
  - Add passive Fe-shield
- reduction of 10^7 possible

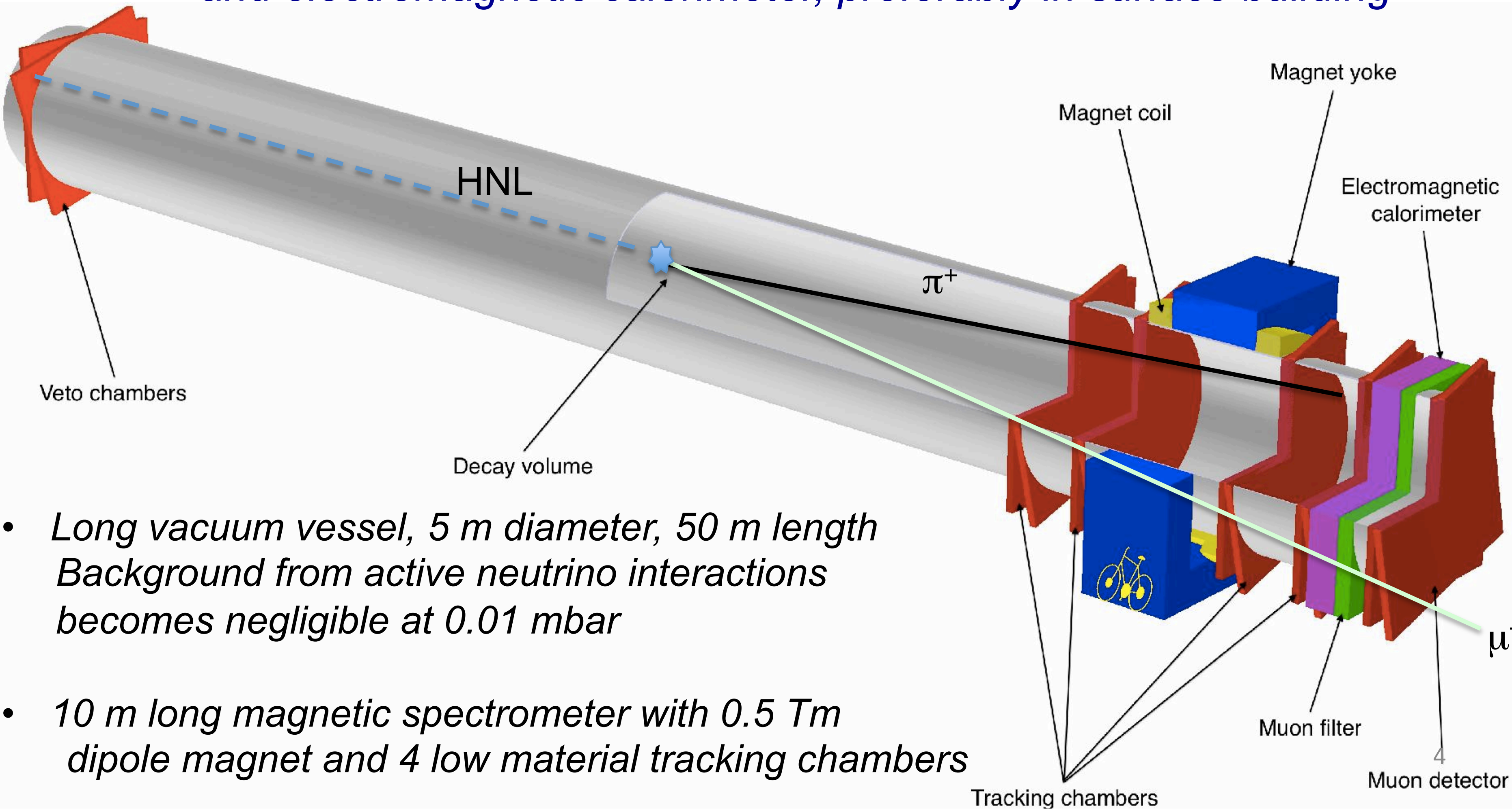


Work in progress, need to optimize together with SPS-spill length, and induced background.

Detector concept
(based on existing technologies)

- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$*

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*

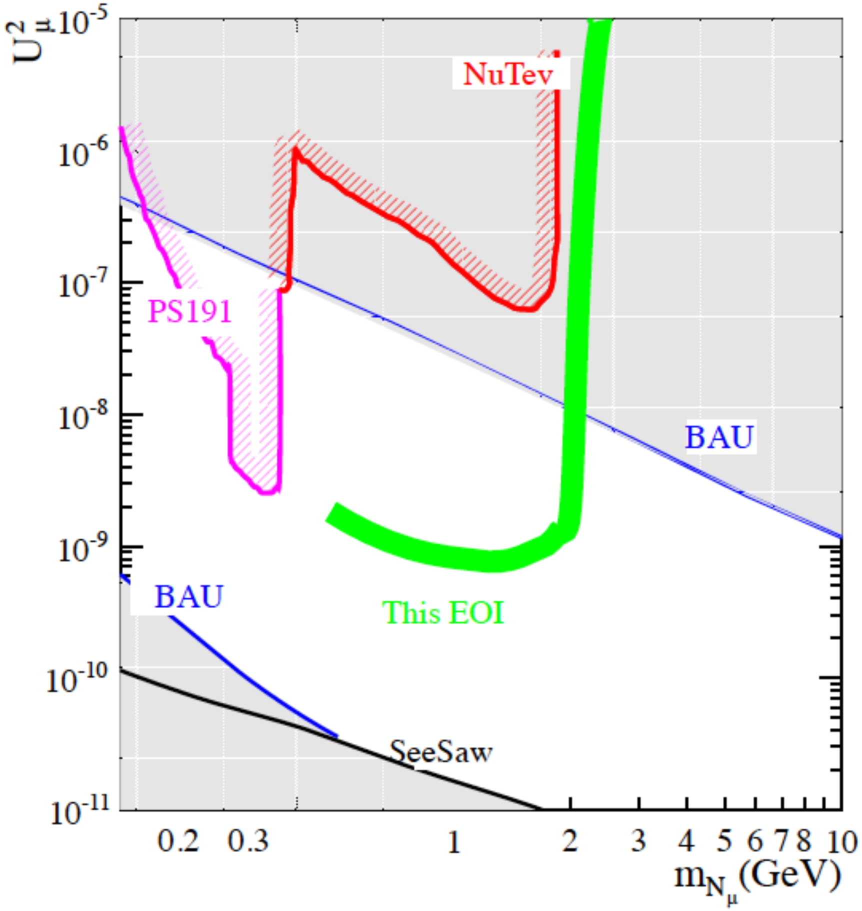


- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*

- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

Expected event yield (cont.)

Assuming $U_\mu^2 = 10^{-7}$ (corresponding to the strongest experimental limit currently for $M_N \sim 1$ GeV) and $\tau_N = 1.8\times10^{-5}$ s
~12k fully reconstructed $N \rightarrow \mu^-\pi^+$ events are expected for $M_N = 1$ GeV



120 events for cosmologically favoured region: $U_\mu^2 = 10^{-8}$ & $\tau_N = 1.8\times10^{-4}$s

First SHIP Workshop, 10-12 June 2014, Zürich

Day 1-2 (Tuesday 10 June)

Introduction

- Status of SM and BSM physics
- Overview of possible general SPS fixed target programme

Session 1: Heavy Neutral Leptons

- The scale of see-swa and models for neutrino masses
- Summary of constraints on HNL masses and mixings
- Indirect constraints on HNL from lepton number violation

Session 2: Heavy Neutral Leptons, ct

- Expectations for HNL properties from BSM physics
- Overview of vMSM
- HNLs and Baryogenesis
- HNL in astrophysics

Coffee/tea
Session 3: SUSY

- Sgoldstino
- R-parity violation and light neutralino
- Model building with R-violation

Session 4: Higgs, axion and vector portals

- Overview of portals to hidden sectors
- Scalars and pseudoscalars
- Dark photons

19:00: Dinner
21:00 - : Bar-storming discussion

Objectives of the meeting:

- *Overview of NP within the reach of SHIP*
- *Discussion on the detector requirements and technologies*

Day 2 (Wednesday 11 June)	Day 3 (Thursday 12 June)
Overall requirements to the beam dump and detector performance • Primary beam line • Target design • RP aspects • Muon shield • Design of the vacuum vessel • Magnet design (low field) • Tracking technologies • Calorimeters • Muon detector 19:00: Dinner 21:00 -: Bar-storming discussion	*09:00 - 12:00 with one cofee break for 30': Continued detector session* • Tau neutrino detector • Instrumentation of the end-part of the muon shield ("upstream tagger") • Electronics • DAQ • Computing (including simulation) 12.30-14.00 Lunch 14.00 - 16.00 *Summary session, including presentation on collaboration/structure/committments/project structure, open/guided brainstorming on topics, and summaries of specific topics, andplans.* • Collaboration matters • Summary and next steps

Conclusions

- Heavy neutral leptons can be a key to (almost all) BSM problems:
  - neutrino masses and oscillations
  - dark matter
  - baryon asymmetry of the universe
- They can be found in Space and on the Earth
  - X-ray satellites - Astro H
  - Intensity frontier experiments - SHIP