Searches for heavy neutral leptons at SHiP

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Rencontres du Vietnam: 3 ν and beyond

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Why HNL?

As mentioned many times already, HNL could clarify the origin of

- Baryon asymmetry
- neutrino masses

Several models including HNL can also offer dark matter candidates (e.g. the νMSM)

Practical considerations

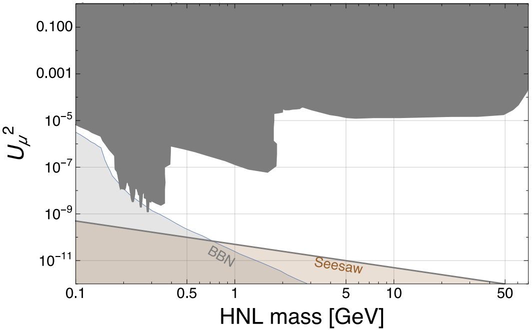
› Models with $M_N > \mathcal{O}(\text{GeV})$ can generate Baryon asymmetry via leptogenesis while also offering a dark matter candidate

› HNL can take part in any (kinematically allowed) process containing active neutrinos with suppression factor of $\left|U_{\{e,\mu,\tau\}}\right|^2$

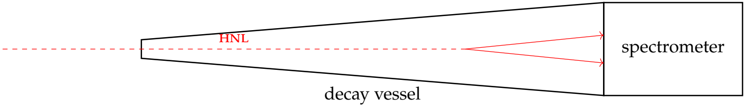
  › Can be produced in SM processes

  › Can decay to SM particles

› Parameter space (see J.Klaric's talk) bounded on 3 sides: lower bound gives us something to aim for

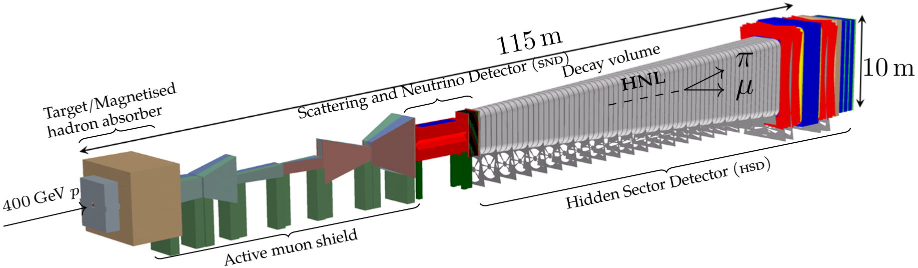


Signature & Implications for experiment



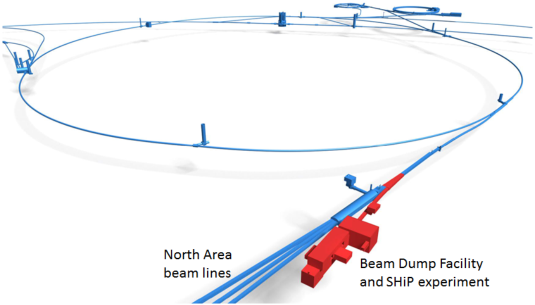
- Common signature (vertex of visible SM particles)
  - SM background needs to be suppressed
  - reliable particle identification to identify exclusive decays
- Macroscopic flight distance: $c\gamma\tau$ of interest in range metre to tens of kilometres
  - detector distance from target $\sim$ lower boundary of $c\gamma\tau$
  - detector size determines upper boundary of $c\gamma\tau$
- Production via weak decays of heavy flavour
  - maximise heavy flavour production

[SPSC-SR-248, CERN-SPSC-2015-016, CERN-SPSC-2015-040, Rept.Prog.Phys. 79 (2016) no.12, 124201, JINST 14 (2019) no.03, P03025]



- Designed for **discovery and measurement** of super-weakly interacting new particles
- **Decay** and **scattering** signatures give complementary access to new physics models
- Ultra-low background environment (< 0.1 candidates/5 years) for hidden sector decays

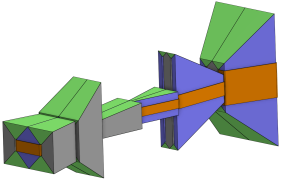
- The beam dump facility (BDF) at the CERN SPS is a unique facility, complementing existing and future collider experiments:
  - 400 GeV
  - 5 years of BDF @ SPS (2×10^{20} protons on target):
    - 10^{18} charm mesons
    - 10^{14} beauty mesons
    - 10^{16} τ leptons
- No conflict with HL-LHC data taking
- BDF could also host τFV parasitically upstream of SHiP

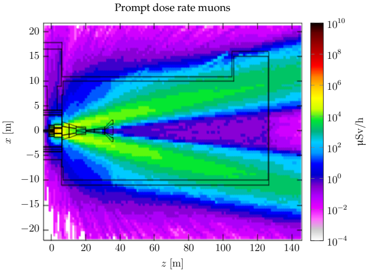


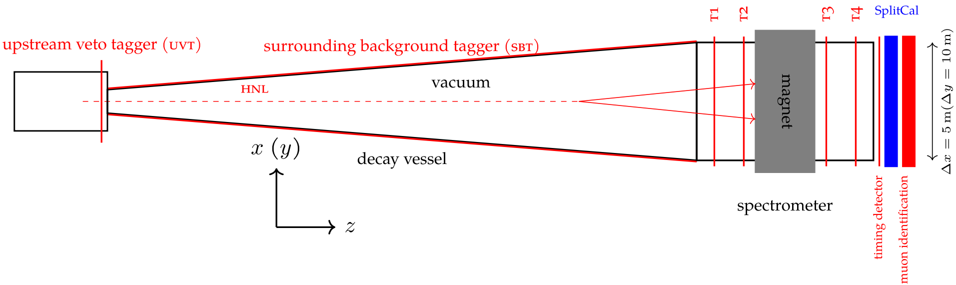
[JINST 14 (2019) no.03, P03025]
[CERN-PBC-REPORT-2018-001]

Target facility and the muon shield

- Heavy target $(12X_0)$
  - Fully absorbs the beam
  - Reabsorbs pions and kaons before decay
  - **Enhanced production of heavy flavour** through a cascade of interactions ($\times$2.3 for D, $\times$1.7 for B)
- Magnetised hadron absorber separates muon polarities
- Active muon shield bends muons out of experimental acceptance $10^{11} \to 25 \times 10^{3}$ [JINST 12 (2017) no.05, P05011]
  - Optimised using machine learning techniques & full simulation
  - Expected muon flux validated using dedicated experiment in 2018
  - Can turn off for calibration, alignment and data driven background studies







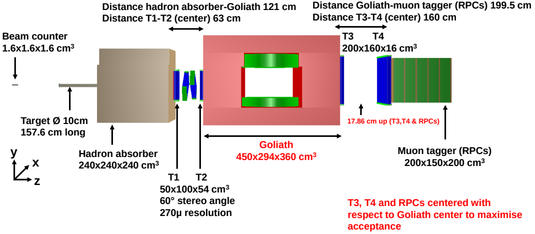
- < 0.1 background events expected → 3 candidates sufficient for discovery
- Can measure decay vertex, invariant mass, impact parameter of signal candidate
  - mass, charge and flavour of new particles measurable
  - redundant background rejection (+background tagger, timing,...)

Simulation and validation

- **Mature software framework** using Pythia6, Pythia8, Genie, Geant4
  - **Cascade production** of heavy flavour implemented [CERN-SHiP-NOTE-2015-009]
  - Validation of simulation with data from NA62 and Hyperon [SPSC-SR-248]
- HNL of given $M_N, U_{\{e,\mu,\tau\}}$ produced using Pythia8 from pre-production of heavy flavour mesons
- Backgrounds all evaluated in **full software framework**

- Validated using 2 dedicated experiments in summer 2018 at SPS
  - **Muon flux measurement with target replica at SPS** accumulated 10^{11} PoT →
  - **Charm cross-section measurement** with an instrumented target (prototype for longer measurement after LS2 [SPSC-EOI-017])

[SPSC-EOI-016]



Minimal HNL benchmark model

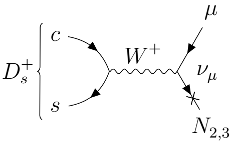
For each HNL 4 parameters:

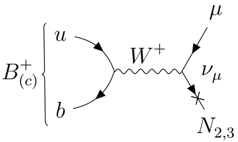
- M_N: mass
- $U_{\{e,\mu,\tau\}}$: mixing with active neutrino flavours

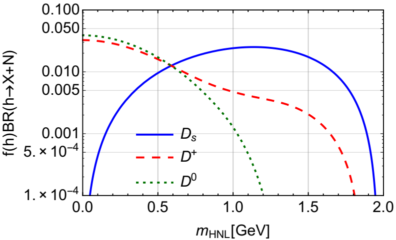
Most physically motivated models include two (or more) HNL.

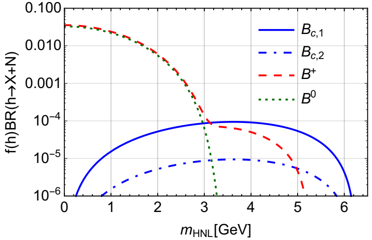
Sensitivities for arbitrary HNL models can be derived from the sensitivity matrix made available by the SHiP collaboration (see later)

- Production via heavy flavour decay dominant (below Z-pole)
- For masses $\lesssim$ 500 MeV, production via K dominant, but K reabsorbed in SHiP target before decay, so not considered here
- $|V_{cb}|^2 / |V_{ub}|^2 \sim 10^2$ → B_c contribution important, even for small fractions of b-quarks hadronising to B_c



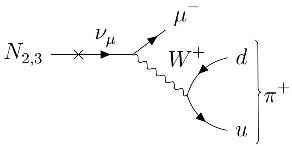






Decay

- SHiP can reconstruct exclusive decays and identify final state (including charge)



Distinguish between

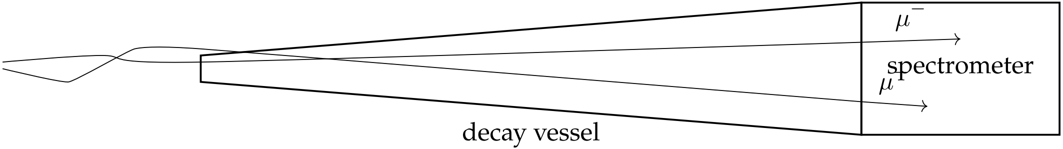
- **Fully reconstructed final states:**
  - All final state particles reconstructed by spectrometer (e.g. $N \to \ell^\mp \pi^\pm$)
  - Strict pointing to target can be required (impact parameter to target $<$ 10 cm)
  - Mass can be accurately and precisely reconstructed
- **Partially reconstructed final states:**
  - Some invisible particles in the final state are not reconstructible (e.g. $N \to \ell^\pm \ell^\mp \nu_\ell$)
  - Looser selection to maintain high signal efficiency (impact parameter to target $<$ 250 cm)

Signature and selection

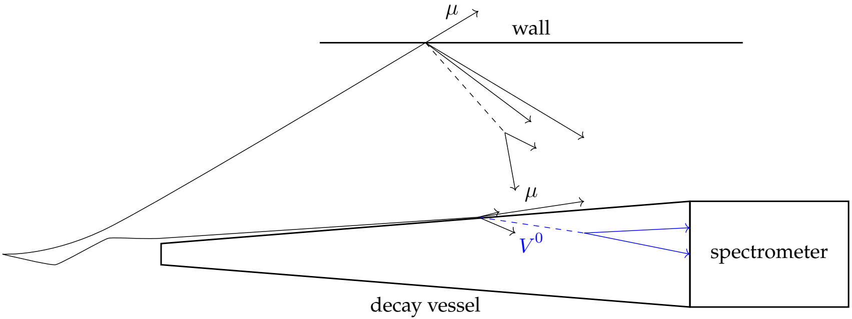
Selection cut	Value
Track momentum	> 1.0 GeV/c
DOCA	< 1 cm
Fiducial cut on vertex position	> 5 cm from vessel wall
IP w.r.t. target (fully reconstructed)	< 10 cm
IP w.r.t. target (partially reconstructed)	< 250 cm

- Selection redundantly suppresses background while maintaining high signal efficiency
- In case of discovery, final state can be fully reconstructed (mass, charge, flavour) to identify particular models
- Sufficient to reduce **partially reconstructed candidates** from background to < 0.1

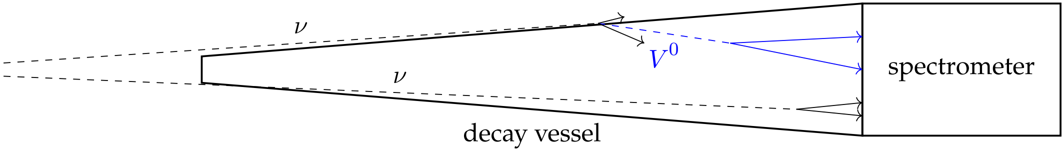
Backgrounds: muon combinatorial



- Timing detector and selection redundantly reject: 4.2×10^{-2} **partially reconstructed candidates** over 5 years at 90 % CL
- Limited by simulation statistics → planning to produce larger samples using GAN technique (paper in preparation)



- DIS in vessel walls can be tagged by background taggers
- DIS in experimental hall negligible compared to vessel walls
- Assuming factorisation of background tagger inefficiency and selection cuts: $< 6 \times 10^{-4}$ **partially reconstructed candidates** over 5 years at 90 % CL

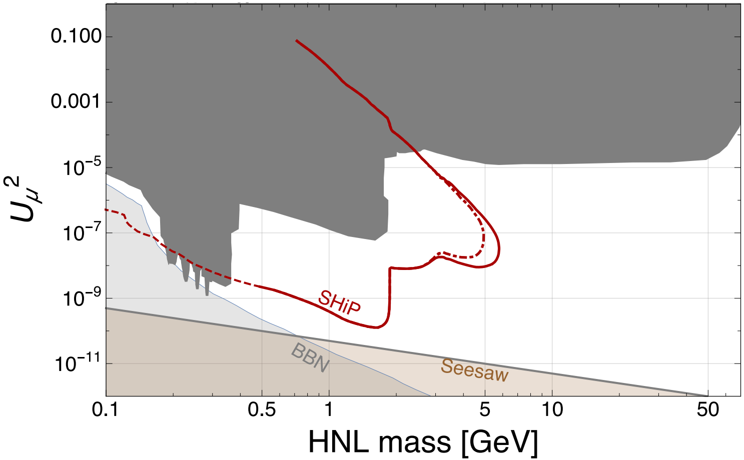


- Evacuated decay vessel → dominated by interactions in the vessel walls
  - Usually taggeable and/or reconstructed vertex too close to the walls
- < 1 **partially reconstructed candidates** over 5 years at 90 % CL (limited by simulation statistics)

- Showing case

$$U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$$

- B_c-contribution not knownat SHiP energy → showing upper and lower limits
- Covering large parts of the cosmologically interesting parameter space up to B threshold



Dedicated paper: [JHEP 1904 (2019) 077]

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- B_c-contribution not knownat SHiP energy → showing upper and lower limits
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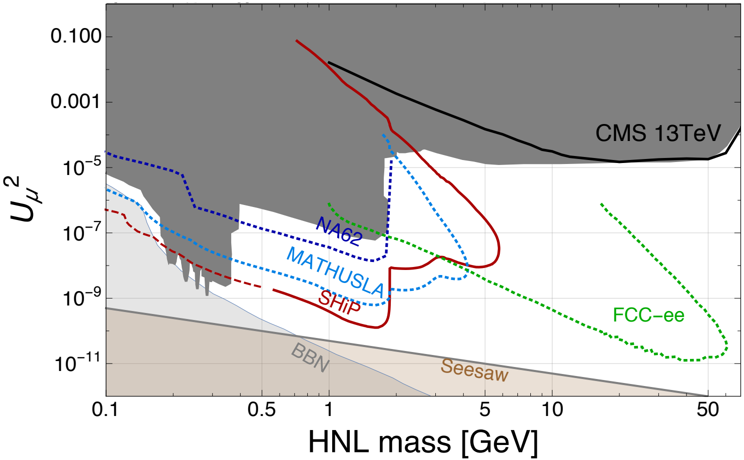
- Complementary to



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For arbitrary patterns of mixing with the active neutrinos, a model-independent sensitivity matrix[1] and tools are available:

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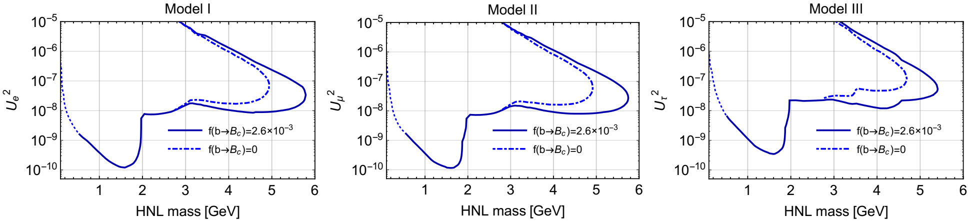
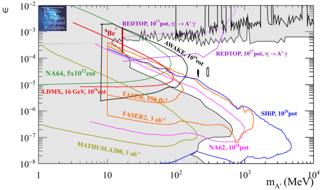
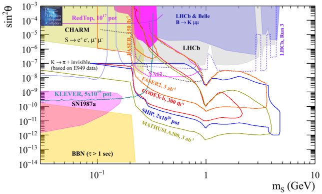


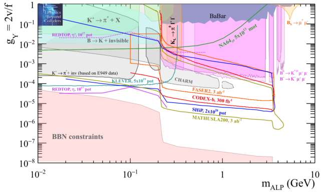
[1] Dependence on flavour mixing and masses factorise, so only a handful of simulations are needed instead of full $4D$ scan of the parameter space.

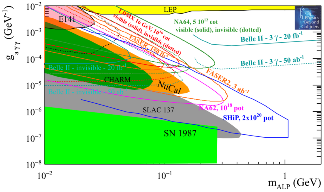
Not only a HNL experiment:

- Hidden sector detector sensitive to many types of long-lived neutral particles (e.g. dark photons, ALPs, dark scalars)
- Can distinguish between models based on the final state







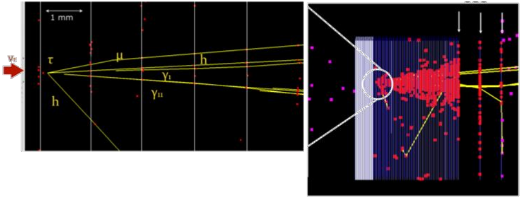


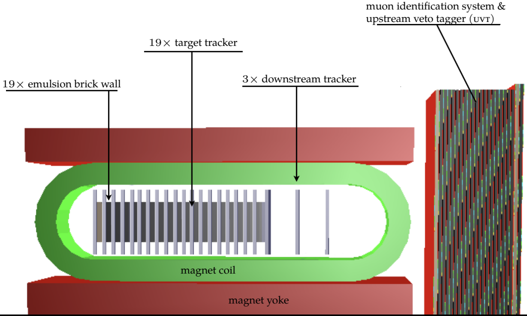
[CERN-PBC-REPORT-2018-007]

- Can distinguish all neutrino flavours, their charge
  - First direct observation of $\bar{\nu}_\tau$
  - Precision neutrino physics (e.g. form factors, ν_τ...)

	$\langle E \rangle$ /GeV	# CC DIS
ν_e	59	1.1×10^6
ν_μ	42	2.7×10^6
ν_τ	52	3.2×10^4
$\bar{\nu}_e$	46	2.6×10^5
$\bar{\nu}_\mu$	36	6.0×10^5
$\bar{\nu}_\tau$	70	2.1×10^4

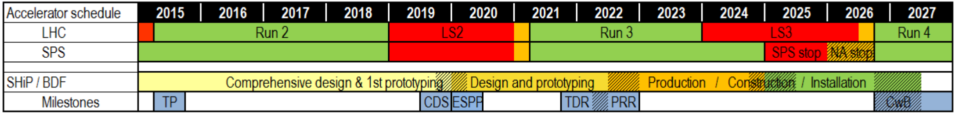
- Also ideal for scattering of hidden sector particles, e.g. light dark matter





Project status

- Strong collaboration: 297 authors, 54 Institutes, 18 countries
- Completed comprehensive design study (report in preparation) including detailed sensitivity studies, good progress towards TDR [SPSC-SR-248]



- Part of the Physics Beyond Colliders study group at CERN
- Submitted input to the update of the European Strategy for Particle Physics

Detector and infrastructure R&D

- BDF very mature, developed by a dedicated CERN team [CERN-PBC-REPORT-2018-001]
  - CERN Machine Development runs in summer 2018 with an instrumented target [SPS-LJ-EC-0012]
  - Detailed engineering plans for target bunker and experimental hall
- During comprehensive design study (2016–2019), all subdetectors underwent [SPSC-SR-248]
  - Extensive R&D, simulation studies, concretisation of engineering designs (CAD, FEA)
  - Phase 1 prototyping
  - Dedicated tests with and without beam
- Phase 2 prototyping ongoing, several beam tests planned for 2019–2021, including full run of the charm cross-section measurement at the SPS

Prototypes & test beams

Conclusion

- SHiP designed to discover HNL and other super-weakly interacting new particles:
  - High intensity beam dump facility at the SPS
  - **Redundant background rejection** for ultra-low background environment
  - **Full reconstruction** of final state, allowing us to study specifics of HNL model
  - Complementary **decay** and **scattering** signatures
- SHiP can improve current HNL limits by several orders of magnitude up to $\mathcal{O}(10\ \mathrm{GeV})$
- Can test cosmologically interesting parameter space, approaching theoretical bounds
- Could discover origin of neutrino masses and of baryon asymmetry of the universe