Search for Hidden Particles

SHiP

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Particle physics: now what's the matter?

- Higgs @ 125 GeV in agreement with the Standard Model
- Couplings as predicted by SM
- No direct observation of BSM particles
- No significant deviations from SM in Flavour Physics

But...

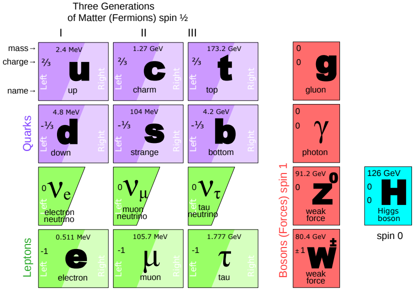
- NP @ TeV scale needed to recover naturalness
- m_H, m_t close to stability bound
- Hierarchy
- Baryogenesis (matter-antimatter asym.) not explained by CKM
- Neutrino masses and oscillations not explained by SM
- What is dark matter?

νMSM

i.e. How to fix most SM problems w/o introducing new physic principles [2]

Leptons and quarks get their mass through the Yukawa interaction:

$$\mathcal{L} = m\,\psi_L^\dagger\,h\,\psi_R + c.c.$$



Neutrinos need a right-handed partner to get their masses like the other SM fermions!

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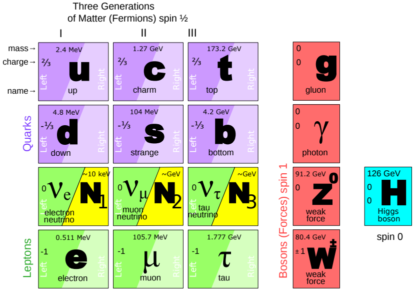


Neutrinos need a right-handed partner to get their masses like the other SM fermions!

Three extra N field could exist (*sterile neutrinos*). They would be $SU(2)$ singlets, as they are still unobserved.

Sterile neutrinos would mix to $\nu_{e,\mu,\tau}$ with very small couplings $U^2_{e,\mu,\tau}$.

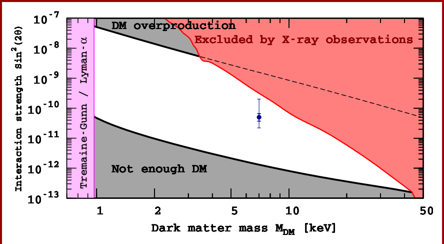
νMSM

i.e. How to fix most SM problems w/o introducing new physic principles [2]

Suitable values of m_N and U_f^2 [2] allow to simultaneously explain:

- ν oscillation: two massive states N_2, N_3 give mass to active νs through the Seesaw mechanism
- dark matter: N_1, likely to have mass in the keV region, could have a lifetime greater than the age of the Universe
- matter-antimatter asymmetry: baryogenesis induced by leptogenesis if N has a Majorana mass term [10].

Two recent observations provide hints of the **existence of a 7** keV **dark matter (**N_1**?) candidate** [8, 9].



A new dedicated experiment

Search for Hidden Particles

Small hints of a 7 keV DM candidate are not enough to confirm or rule out the νMSM: need to look for N_2, N_3! $\longrightarrow$ SHiP project [6, 7]. The proposed facility enables the investigation of a wide range of BSM models.

- collaboration rapidly growing
- working on the technical proposal

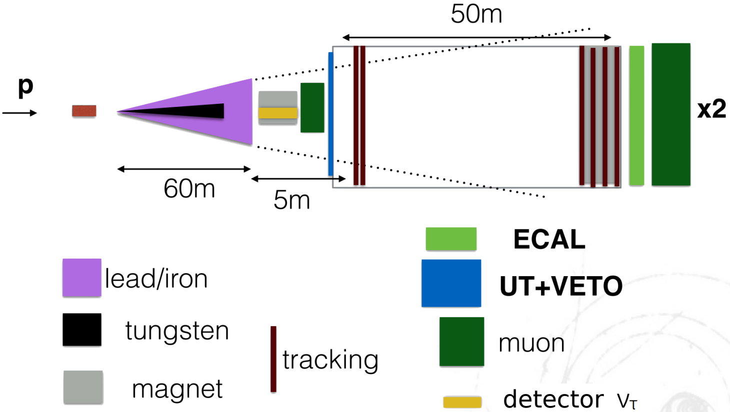
SHiP

My contribution

- investigate SHiP's physics reach in the parameter space of νMSM sterile neutrinos N_2, N_3
- determine SHiP's discovery potential in the "Vector Portal"

A proposed fixed-target experiment at the SPS (400 GeV protons) aimed at the study of long-lived weakly interacting particles [6, 7].

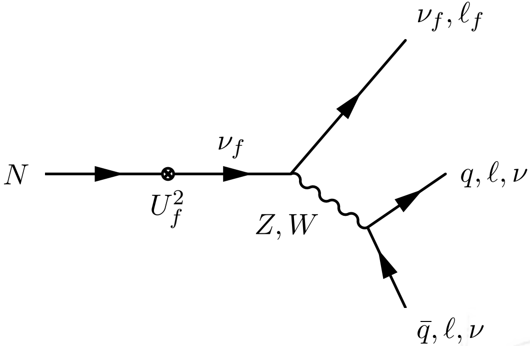
- $\times 10\,000$ statistical sensitivity to Heavy Neutral Leptons & co.
- $\times 200$ statistical sensitivity to ν_τ



HNL mixing to Standard Model

i.e. How to detect sterile neutrinos

HNLs can be produced in decays where a ν is replaced by a N (kinetic mixing, low $\mathcal{BR}$). Main neutrino sources in SHiP: c and b mesons.



They can then decay again to SM particles through mixing (U^2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a Z^0 or $W^\pm$ boson [11].

Estimating SHiP's physics reach

HNL production × Experimental acceptance

- Number of detected HNL events:

$$\Phi(p.o.t) \times \sigma(pp \to NX) \times \mathcal{P}_{vtx} \times \mathcal{BR}(N \to visible) \times \mathcal{A}$$

with

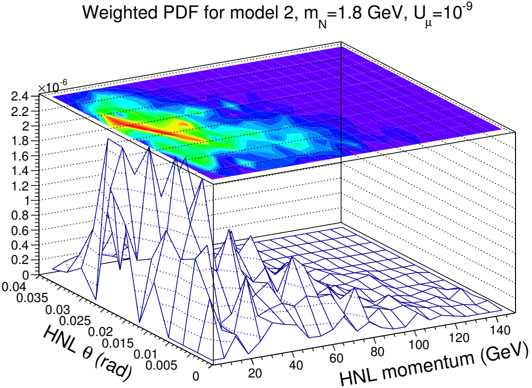
$$\sigma(pp \to NX) \propto \chi_{cc}, \chi_{bb}, U_f^2$$
$$\mathcal{BR}(N \to visible) \propto U_f^2$$

- HNL production:
  - χ_{cc}, χ_{bb} from simulations
  - $\mathcal{BR}(m_N, U_f^2)$ parametrised according to theory [11]
- Now we only need to compute the daughters acceptance $\mathcal{A}$:
  - HNLs kinematics obtained from simulation
  - every decay channel with detectable daughters is simulated

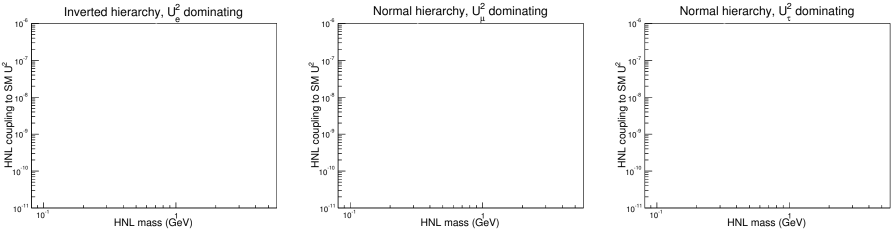
Estimating SHiP's physics reach

$\Phi(p.o.t) \times \mathcal{BR}(pp \to NX) \times \mathcal{P}_{vtx} \times \mathcal{BR}(N \to visible) \times \mathcal{A}$

- Pythia8 used to retrieve the spectrum of c and b mesons in SHiP. Heavy neutrinos produced in kinematically-allowed decay chains.
- HNL spectra are re-weighted by the probability that HNLs decay with a vertex inside SHiP's tracking volume: $\mathcal{P}_{vtx} \sim \int_{SHiP} e^{-l/c\gamma\tau} dl$



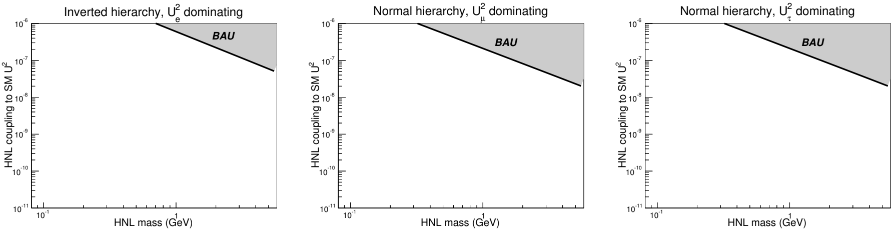
The parameter space of the νMSM



Results must be interpreted according to the hierarchy of ν masses and to the relative strenght of the U_e^2, U_μ^2 and U_τ^2 couplings.

Three “extreme” benchmark models [11] will be shown.

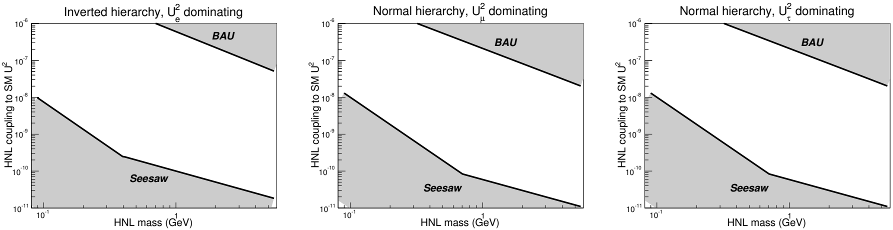
The parameter space of the νMSM



The cosmologically interesting parameter space is limited by physical constraints [11]:

1. by the requirement that sterile neutrinos explain the matter-antimatter asymmetry (baryogenesis induced by leptogenesis)

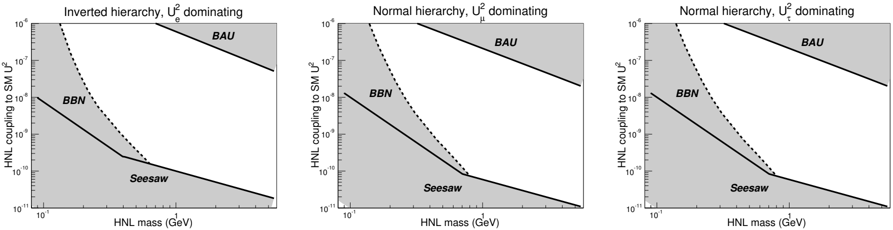
The parameter space of the νMSM



The cosmologically interesting parameter space is limited by physical constraints [11]:

2. by the Seesaw mechanism: adding an extra singlet neutrino field allows to extend the Lagrangian with a Majorana mass term. The active and sterile neutrino masses are then inversely proportional

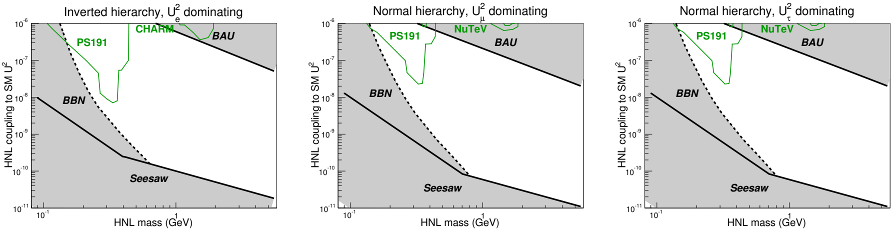
The parameter space of the νMSM



The cosmologically interesting parameter space is limited by physical constraints [11]:

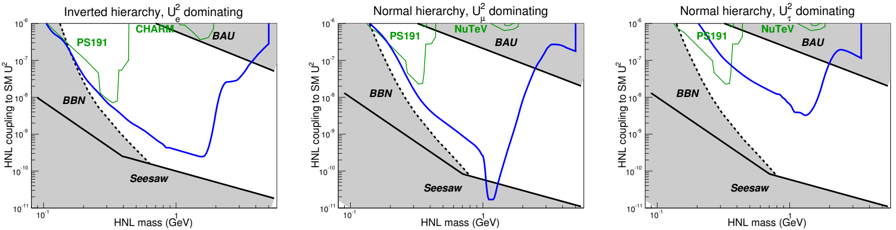
3. at low M_N, by Big Bang Nucleosynthesis constraints (observations of the relative abundance of primordial nuclei)

The parameter space of the νMSM



Searches already performed by e.g. PS191, CHARM, NuTeV, but most of the parameter space is still unexplored!

The parameter space of the νMSM



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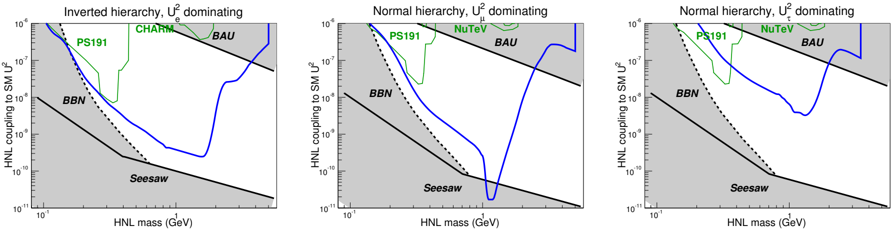
Blue lines: area of the νMSM parameter space that can be ruled out if no event is observed in SHiP (90% C.L.).

The parameter space of the νMSM



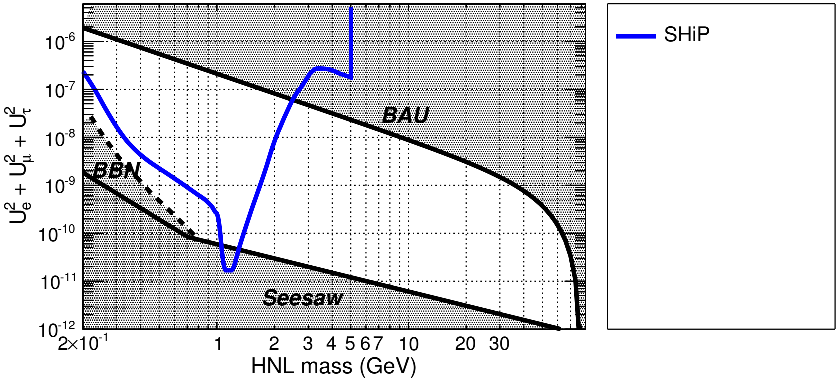
Blue lines: area of the νMSM parameter space that can be ruled out if no event is observed in SHiP (90% C.L.).

- the remaining area below $m_N \simeq 350$ keV can be covered by NA62.
- what about $m_N \gg 1$ GeV?

Yet another reason to build a Z^0 factory

i.e. How to close the HNL parameter space

- Possible N sources for $m_N \gg 1$ GeV: $W^{\pm}$, Z^0



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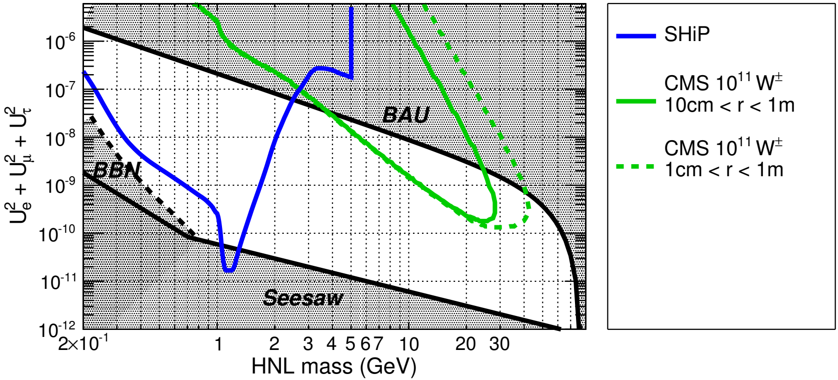
- Possible N sources for $m_N \gg 1$ GeV: $W^{\pm}$, Z^0
- $W \to \ell N$ at LHC: extremely large BG, difficult triggering/analysis.



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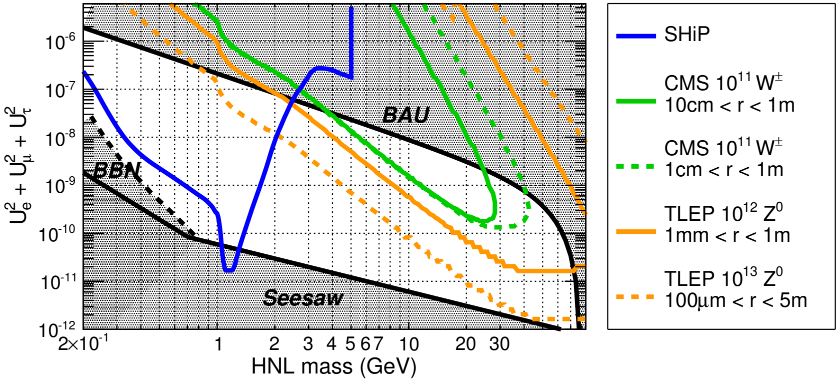
- Possible N sources for $m_N \gg 1$ GeV: $W^{\pm}$, Z^0
- $W \to \ell N$ at LHC: extremely large BG, difficult triggering/analysis.
- $Z \to \nu N$ at e^+e^- collider [3]: clean signature, low BG.



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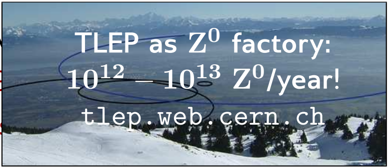
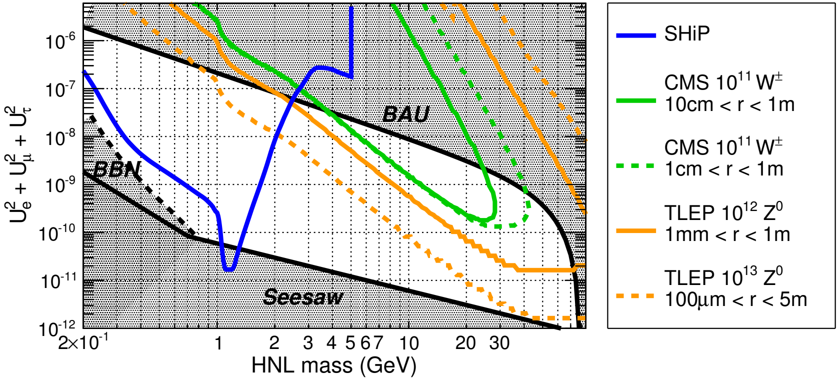
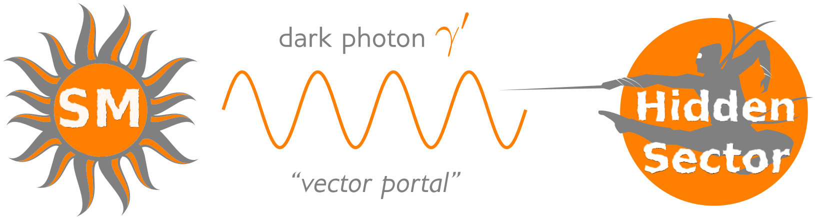


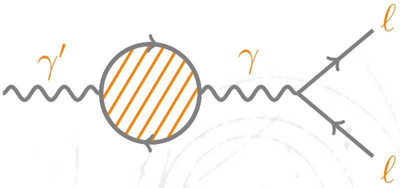


The vector portal to the hidden sector

Most BSM models predict a set of SM-neutral unobserved particles that do not interact with SM except through a "messenger" particle.

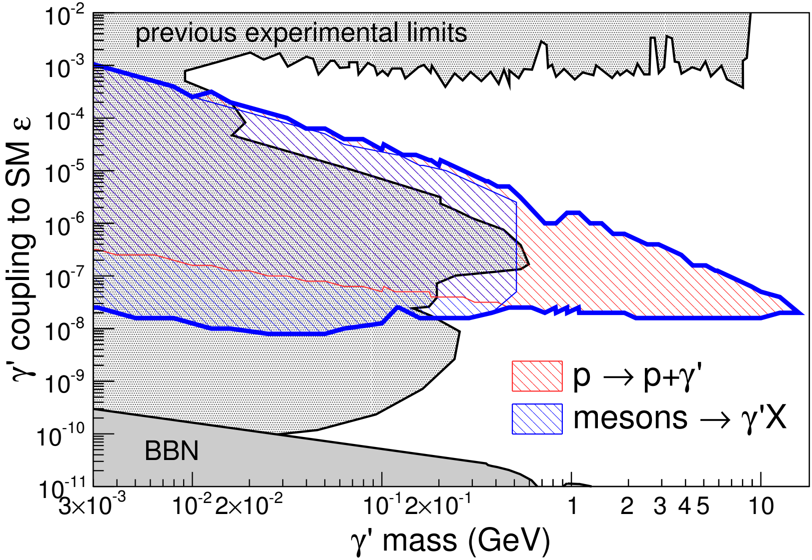


Sensitivity to γ' investigated as for HNLs: γ' mixes to γ through loops of particles charged under both the SM and HS. Extra production mode: proton bremsstrahlung [1, 5].



SHiP's contribution to the vector portal

Sensitivity to dark photons



Conclusions

- Three fundamental questions left open by the Standard Model can be answered by the νMSM, with no need for new physic principles
  - searches for N_2, N_3 are necessary to confirm or rule out the νMSM
  - design of the dedicated SHiP experiment
- SHiP's discovery potential was investigated
  - most of the parameter space can be covered by SHiP ($m_N < 2-3$ GeV) and by future Z factories ($m_N > 3$ GeV)
- SHiP can be used to look for signatures of other BSM physics
  - SHiP's physics reach into the vector portal determined

Thanks!

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Spare slides

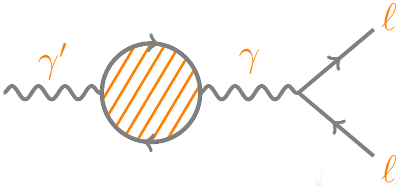
Backgrounds

- **SHiP:** it is designed to be a zero-BG experiment: evacuated decay volume, veto chambers, event topology... Active or passive muon shielding.
- **CMS:** every event with either three leptons or one lepton and two jets in the final state!
- **TLEP:** W^*W^*, Z^*Z^* and $Z^*\gamma^*$ backgrounds suppressed by displacement of the secondary vertex.

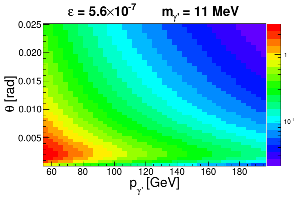
Dark photons in short

The vector portal [5]

- Extra $U(1)'$ symmetry with gauge boson γ' (*dark photon*)
- $U(1)'$ broken by Higgs-like mechanism $\rightarrow$ non-zero $m_{\gamma'}$
- Mix to γ through kinetic mixing to particles charged under both $U(1)$ and $U(1)'$: $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{hidden} + \frac{\varepsilon}{2} A'_{\mu\nu} F^{\mu\nu}$



Estimating SHiP's physics reach

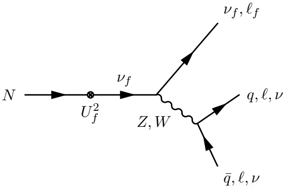


1. Production: 10^{20} *p.o.t.*

HNL: $D_s \to \ell N$, $D \to K \ell N$

γ': $p \to p\gamma'$, meson decays $\to \gamma' X$

2. (p, θ)-PDF weighted with the probability that the particle decays inside the SHiP volume ($\mathcal{P}_{vtx}$)
3. Vertex acceptance: $\int_{SHiP} e^{-l/c\gamma\tau} dl$
4. Simulate decays and compute daughters acceptance ($\mathcal{A}$)



5. Count the number of events:

$$N = \Phi(p.o.t) \times BR_{prod} \times U_f^2 \times BR_{visible} \times \mathcal{P}_{vtx} \times \mathcal{A}$$

where U_f^2 is the mixing angle to SM particles.

HNL reach at TLEP: $Z^0 \to \nu N$, similar procedure.

HNL lifetime

and branching ratios

For a given N mass, its lifetime was computed on the basis of the widths of its kinematically allowed decay channels, according to the formulas in [11]. I included all the main N decay channels:

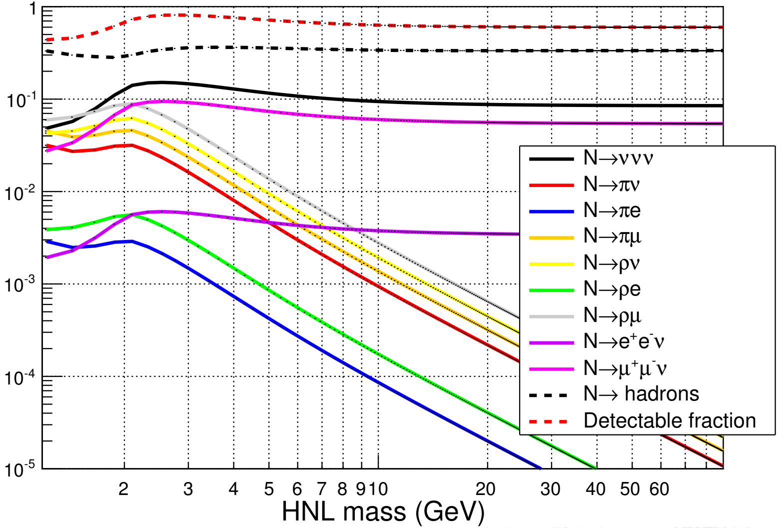
- $N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
- $N \to H^\pm \ell^\mp$, with $H = \pi, \rho$
- $N \to 3\nu$
- $N \to \ell_i^\pm \ell_j^\mp \nu_j$
- $N \to \nu_i \ell_j^\pm \ell_j^\mp$

The formulas in [11] are valid **up to** $m_N \simeq 1$ GeV. For $m_N \gg \lambda_{QCD}$, the two quarks do no longer hadronise together and should be considered free. In this regime ($m_N \geq 2$ GeV) I extrapolated the three-body leptonic formulas to the quark case to compute the total hadronic decay width.

HNL lifetime

and branching ratios

Branching ratios for HNL (model: U^2 = [6.25e-10, 1e-08, 2.5e-09])



HNL lifetime

and branching ratios

All decay channels into ≥ 2 charged particles were taken to be visible.

Decay chains such as $N \to \rho^0 \nu$ followed by $\rho^0 \to \pi^+ \pi^-$ were taken into account, with the pion pair as final state particles.

Final-state π^0s were taken not to be detectable, even if the photon pair could be reconstructed with a high-granularity calorimeter.
For decay chains like $N \to \rho^\pm \ell$ with $\rho^\pm \to \pi^\pm \pi^0$, the requirement that the two photons fall into the acceptance of a toy detector of radius 2.5 m decreases the final-state detection efficiency to ~27%, while it is ~37% for a $(\pi^\pm, \ell)$ final state.

How to estimate the number of expected events

For SHiP

1. Charm mesons are the main source of HNLs in SHiP
2. Simulate protons on target $\Longrightarrow$ store an ntuple of charm mesons with their secondary vertices
3. Fix the model (fix the U_f^2) and the HNL mass m_N
4. According to the dominating U_f^2, simulate the $D_s \to \ell N$ and $D^{\pm,0} \to K^{0,\mp} \ell^{\pm} N$ decays or the $D_s \to \tau\nu_\tau$, $\tau \to \mu\nu N$ decay chain
5. Momentum and angle of the outgoing N are stored in a binned bi-dimensional PDF
6. Each bin of the PDF is weighted with the probability that a N with that kinematics decays into SHiP's fiducial volume, and the total probability $\mathcal{P}_{vtx}$ is computed as the integral of the weighted PDF

How to estimate the number of expected events

For SHiP

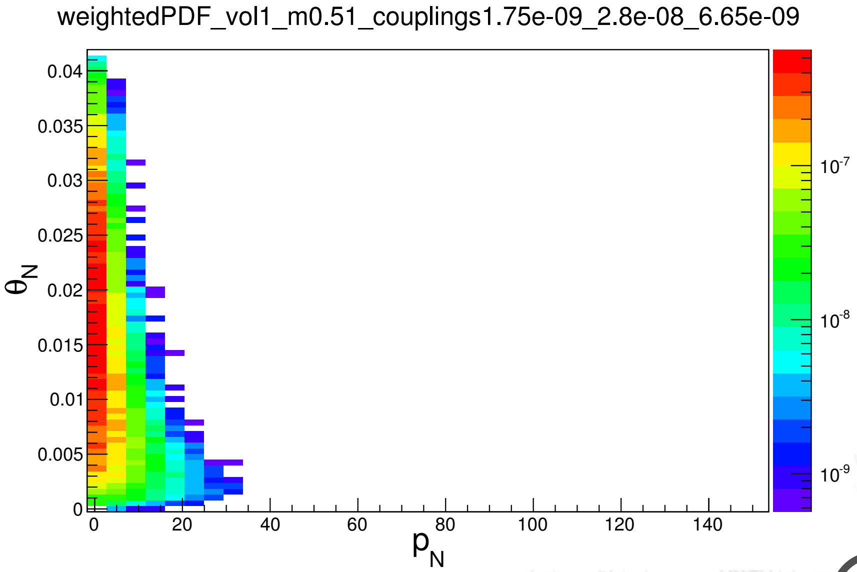
7. For each of the kinematically allowed decays into detectable daughters, decays inside SHiP's fiducial volume are simulated to compute SHiP's acceptance to the daughters ($\mathcal{A}$). Decaying N are sampled from the weighted PDF. The total branching ratio $BR\,(visible)$ into detectable particles is computed.
8. For each of the two fiducial volumes, the number of expected events is computed as:

$$N_{events} = N_{p.o.t.} \times 2\chi_{cc} \times BR\,(production, f) \times U_f^2 \\ \times \mathcal{P}_{vtx} \times BR\,(visible) \times \mathcal{A}$$

It depends on the three mixing angles U_f^2 and on m_N.

How to estimate the number of expected events

For SHiP



How to estimate the number of expected events

For TLEP, assuming running as Z^0 factory

The expected statistic is $10^{12} - 10^{13}$ Z^0/year. The following considerations is applicable to any e^+e^- collider capable of producing a large quantity of Z^0 bosons.

The only production channel considered is $Z^0 \to \nu\bar{\nu}$, with one neutrino mixing to N. An onion-like detector is assumed.

1. Fix the model (fix the U_f^2) and the HNL mass m_N
2. The Z^0 decays in place to νN. The boost to the N is then:

$$\gamma = \frac{m_Z}{2\,m_N} + \frac{m_N}{2\,m_Z}$$

How to estimate the number of expected events

For TLEP, assuming running as Z^0 factory

3. Compute the N lifetime τ. Compute the probability $\mathcal{P}_{vtx}$ that it decays inside the tracking volume:

$$\mathcal{P}_{vtx} = \frac{1}{c\gamma\tau} \int_{R_{min}}^{R_{max}} e^{\frac{r}{c\gamma\tau}} dr$$

   where R_{min} corresponds to the minimum SV displacement ($\sim$ inner tracker resolution)

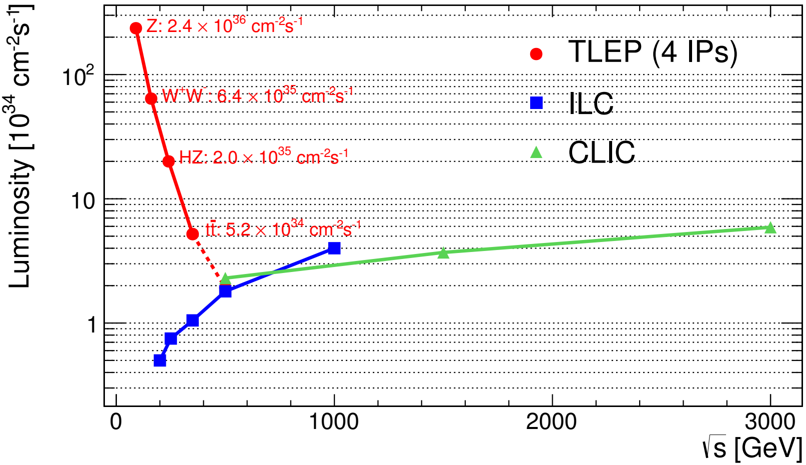
4. Compute the total branching ratio $BR\,(visible)$ into lepton pairs (ee, $\mu\mu$ and $e\mu$). The detector efficiency is assumed to be 100%
5. The number of expected events is computed as:

$$N_{events} = N_{Z^0} \times BR\left(Z^0 \to 2\nu\right) \times 2 \times \sum_f U_f^2$$
$$\times \mathcal{P}_{vtx} \times BR\,(visible)$$

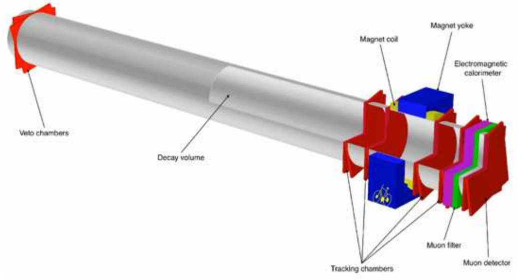
How to estimate the number of expected events

For TLEP, assuming running as Z^0 factory

Expected luminosity is large at the Z^0 mass [4]:



Decay Volume



- Vacuum tank (similar to NA62) with 1e-2 mbar (instead of 1e-5 mbar)
- NA62-like straw chambers, 120um resolution and 0.5% X0/X
- LHCb-like magnet 0.5Tm over 5m
- LHCb-like shashlik calorimeter
- Veto chambers at the entrance of the vacuum tank to veto muons and strangeness from surroundings

Geometry

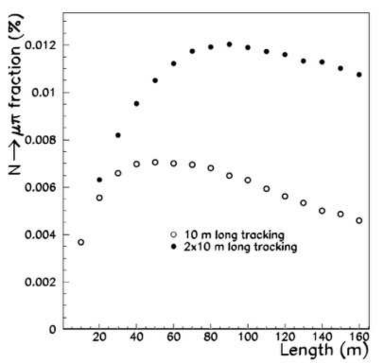


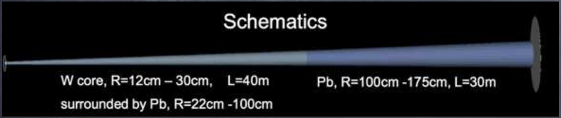
Figure 8: Fraction of HNL in the detector acceptance as a function of the length of the fiducial volume. Open circles: a single spectrometer following a fiducial volume of a given length. Full circles: two spectrometers in series, each following a fiducial volume of half the given length. The spectrometer length is fixed to 10 m.

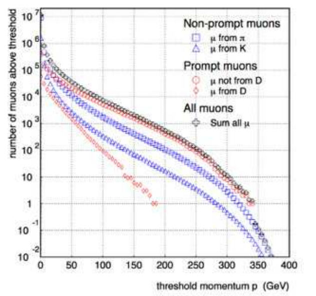
Muon Shield

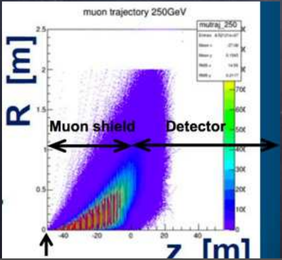
N. Serra, Flavour Physics Conference, Vietnam, 01.08.2014

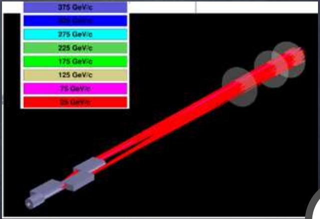
Muon rate 5×10^9 muons/spill

- Acceptable rate $< 10^5$ muons per spill
- Main source of muons from η, η', ω, etc...
- Studying solution with passive or active filter



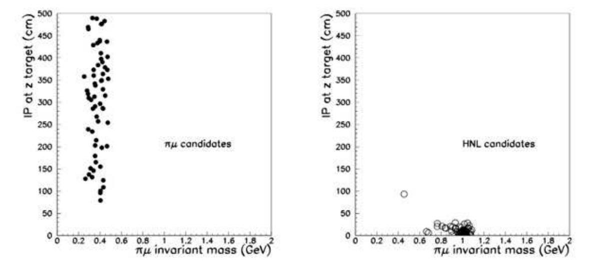






Background rejection

- 2×10^4 neutrino interactions per 2×10^{20}POT in the decay volume at atmospheric pressure, negligible at 10^{-2}mbar
- K_L production from $\nu + A \rightarrow K_L(\rightarrow \mu\nu\pi)X$
- 10% ν interactions produce Λ and K^0 in acceptance
- Majority of the decays in the first 5m of the decay volume
- Muon filter to reduce background from muon DIS to a negligible level



Fighting hard to design a zero background experiment


Underground Structures (Tunnel/Cavern/Hall)
Surface or Partially Underground Structures (Target Hall/SB/Access Building)
Shafts + Tunnel access
Access Area + Car Park
New SHIP Beamline
Future SHIP Extension Area
DETECTOR HALL ~20 m wide
810
811
812
~120 m
Access Bld. ~20m wide
~38 m
25 m
Filter Tunnel
50
Service Bld. ~15m wide
Bypass tunnel
TARGET HALL ~20m wide
10
20
Technical Gallery
~140 m
Existing Technical Gallery GT801
Access Bld. ~15m wide
15 m
Tunnel
"Aux. Power Supply"
TCC2
~170 m
Extraction
TDC2
JUNCTION CAVERN
~85 m
Splitter 2
SHIP extraction MSSB2117 Splitters
TDC2
~100 m
new access road


SHIP AREA on the French CERN Site in Prévessin

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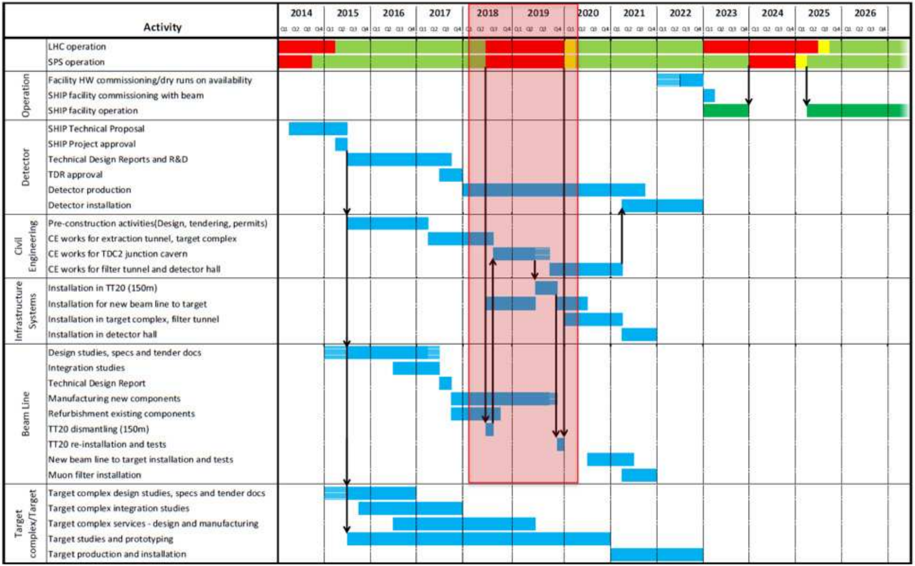

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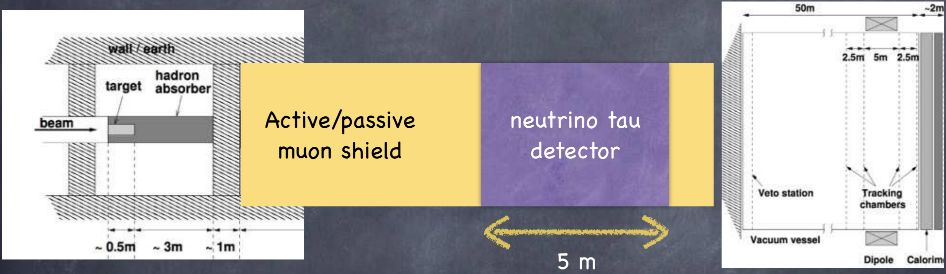
Tau neutrinos



- The same optimization for sterile neutrinos in the GeV region also maximises the flux of ν_τ
- Source of ν_τ and $\overline{\nu}_\tau$ is $D_s \to \tau\nu_\tau$
- Also high rate of ν_e from charm

Tau neutrino detector

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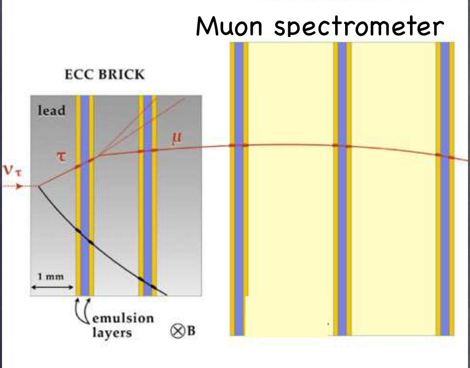

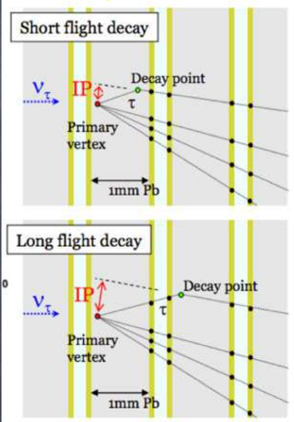

- ν_τ target: Opera-like bricks, laminated lead and nuclear emulsions (for micrometric resolution)
- 750 Opera-like bricks, to be replaced 10 times
- Muon spectrometer to measure charge and momentum and give time stamp

Working hypotheses

- Detector located ~60m from the proton target
- Charm production cross-sections in p-W affected by large uncertainties
- Compare with DONUT to extrapolate the expected numbers
- Energy dependence of σ_{cc} and ν_τ cross-section, acceptance: production ~ 0.36, detector acceptance ~ 0.2, energy dependence of the ν_τ cross-section ~0.52 → DONUT/SHIP ~ 26
- 2 x 10^{20} pot for SHIP compared to 3.6 x 10^{17} DONUT → ~ 550 in favour of SHIP
- Overall rate SHIP/DONUT ~ 20
- DONUT observed 9 events with a background of 1.5 → 7.5±3 (40% error)
- 150 events expected with the same mass (260 kg)
- Measurement of ν_τ and anti-ν_τ cross-section, including the study of structure functions sets the scale for the mass: ~ 6 tons for ~ 3400 ν_τ interactions
- Assume OPERA-like bricks (8.3 kg) and wall target structure: ~ 750 bricks