Why should we search for Heavy Neutral Leptons
**Theoretical motivation**

- Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model
  The SM may work successfully up to Planck scale!

- SM is unable to explain:
  - Neutrino masses
  - Excess of matter over antimatter in the Universe
  - The nature of non-baryonic Dark Matter

- All three issues can be solved by adding three new fundamental fermions, right-handed Majorana Heavy Neutral Leptons (HNL): \( N_1, N_2 \) and \( N_3 \)

**νMSM**: T. Asaka, M. Shaposhnikov PL **B620** (2005) 17

- The nature of non-baryonic Dark Matter
- Excess of matter over antimatter in the Universe
- Neutrino masses

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[Diagram showing three generations of matter fermions with masses and charges, along with leptons and bosons.]

- **Leptons**:
  - Electron (\( e^- \)),Muon (\( \mu^- \)), Tau (\( \tau^- \))
  - Masses: 0.511 MeV, 105.7 MeV, 1.777 GeV

- **Bosons** (forces) spin 0:
  - Weak force: 80.4 GeV ± 11
  - Higgs boson: 126 GeV

- **Quarks**:
  - Mass change:
    - \( u \), \( c \), \( t \) - up, charm, top
    - \( d \), \( s \), \( b \) - down, strange, bottom
  - Masses: \( 2.4 \) GeV, \( 1.27 \) GeV, 173.2 GeV
  - Charges: \( \frac{2}{3} \), \( \frac{1}{3} \), \( \frac{1}{3} \)

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The structure and interactions within the Standard Model are illustrated through these fundamental fermions and forces, highlighting the theoretical and experimental breakthroughs in understanding particle physics.
- Boson found consistent with SM-Higgs.
- Atlas: $M_H = 125.5 \pm 0.2_{\text{stat}}^{+0.5}_{-0.6_{\text{syst}}} \text{GeV}$
- CMS: $M_H = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{syst}} \text{GeV}$
No sign of New Physics seen

What is not found..
No sign of New Physics seen

What is not found..

Summary of CMS RPV SUSY Results*

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*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit.

CMS Preliminary

EJPHEP 2013

Prompt LSP decays

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 8$ TeV

Mass scales [GeV]
Bounds on the scale of New Physics

Most stringent limits come from observables in $B\bar{B}$ mixing

$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP} \frac{1}{\Lambda^2}$$

- $c_{NP}$
  - $\sim 1$ (tree/strong + generic flavor) $\Lambda \gtrsim 2 \times 10^4$ TeV
  - $\sim 1/(16\pi^2)$ (loop + generic flavor) $\Lambda \gtrsim 2 \times 10^3$ TeV
  - $\sim (y_t V_{ti}^* V_{tj})^2$ (tree/strong + “alignment”) $\Lambda \gtrsim 5$ TeV
  - $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2)$ (loop + “alignment”) $\Lambda \gtrsim 0.5$ TeV

68% CL contours ($\Delta \log L = 1.15$):

- LHCb
- CDF 9.6 fb$^{-1}$ + D0 8 fb$^{-1}$ + ATLAS 4.9 fb$^{-1}$

HFF April 2013
Theoretical motivation

- **SM is unable to explain:**
  - Neutrino masses & oscillations
  - Excess of matter over antimatter in the Universe
  - The nature of non-baryonic Dark Matter

- All three issues can be solved by adding three new fundamental fermions, right-handed Majorana Heavy Neutral Leptons (HNL): $N_1$, $N_2$ and $N_3$
See-saw generation of neutrino masses

Most general renormalisable Lagrangian of all SM particles (+3 singlets wrt the SM gauge group):

\[ L_{\text{singlet}} = i \bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha^c - M_I \bar{N}_I^c N_I + \text{h.c.}, \]

Yukawa term: mixing of \( N_I \) with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

The scale of the active neutrino mass is given by the see-saw formula:

\[ m_\nu \sim \frac{m_D^2}{M} \]

where \( m_D \sim Y_{I\alpha} v \) - typical value of the Dirac mass term

**Example:**

For \( M \sim 1 \text{ GeV} \) and \( m_\nu \sim 0.05 \text{ eV} \) it results in \( m_D \sim 10 \text{ keV} \) and Yukawa coupling \( \sim 10^{-7} \)
The $\nu$MSM model

$N = \text{Heavy Neutral Lepton - HNL}$

Role of $N_1$ with mass in keV region: dark matter

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

Role of the Higgs: give masses to quarks, leptons, $Z$ and $W$ and inflate the Universe.
**Masses and couplings of HNLs**

- $N_1$ can be sufficiently stable to be a DM candidate, $M(N_1) \sim$ a few keV
  - Can decay to $3\nu$ (unobservable) or sub-dominantly to $\nu\gamma$

- $M(N_2) \approx M(N_3) \sim$ a few GeV $\Rightarrow$ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)
  - Very weak $N_{2,3}$-to-$\nu$ mixing ($\sim U^2$) $\Rightarrow$ $N_{2,3}$ are much longer-lived than the SM particles

**Example:**

$N_{2,3}$ production in charm and subsequent decays

- Typical lifetimes $> 10 \mu s$ for $M(N_{2,3}) \sim 1$ GeV
  - Decay distance $O(km)$

- Typical BRs (depending on the flavour mixing):
  - $\text{Br}(N \to \mu/e/\pi) \sim 0.1 - 50\%$
  - $\text{Br}(N \to \mu/e^-/\rho^+) \sim 0.5 - 20\%$
  - $\text{Br}(N \to \nu\mu\nu e) \sim 1 - 10\%$
Searches for DM HNL \( N_1 \) in space

Radiative decays \( N_1 \rightarrow \gamma \nu \) produce a mono-line in photon galaxies spectrum

- 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
Allowed parameter space for DM HNL $N_1$
Two recent publications in arXiv:

- arXiv 1402.2301
  Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters, $E_\gamma \sim 3.56$ keV

- arXiv 1402.4119
  An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster, $E_\gamma \sim 3.5$ keV

Will soon be checked by Astro-H with better energy resolution
Masses and couplings of HNLs

- $N_1$ can be sufficiently stable to be a DM candidate, $M(N_1) \approx 10$ keV
- $M(N_2) \approx M(N_3) \sim$ a few GeV $\Rightarrow$ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)

Very weak $N_{2,3}$-to-$\nu$ mixing ($\sim U^2$) $\Rightarrow$ $N_{2,3}$ are much longer-lived than the SM particles

Example:
$N_{2,3}$ production in charm and subsequent decays

- Typical lifetimes $> 10$ $\mu$s for $M(N_{2,3}) \sim 1$ GeV
  Decay distance $O$(km)

- Typical BRs (depending on the flavour mixing):

  $Br(N \rightarrow \mu/e\pi) \sim 0.1 – 50\%$
  $Br(N \rightarrow \mu/e\rho^+) \sim 0.5 – 20\%$
  $Br(N \rightarrow \nu_{\mu}\nu_{e}) \sim 1 – 10\%$
Baryon asymmetry

Sakharov conditions:

- CP is not conserved in νMSM

  6 CPV phases in the lepton sector and 1 CKM phase in the quark sector (to be compared with only one CKM phase in the SM)

- Deviations from thermal equilibrium

  ✓ HNL are created in the early Universe

  ✓ CPV in the interference of HNL mixing and decay

  ✓ Lepton number goes from HNL to active neutrinos

  ✓ Then lepton number transfers to baryons in the equilibrium sphaleron processes

PS Explanation of DM with $N_1$ reduces a number of free parameters

$\rightarrow$ Degeneracy of $N_{2,3}$ masses is required to ensure sufficient CPV
Masses and couplings of HNLs

- $M(N_2) \approx M(N_3) \sim$ a few GeV $\rightarrow$ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU) using sphaleron lepton-to-baryon number transformation

Very weak $N_{2,3}$-to-$\nu$ mixing ($\sim U^2$) $\rightarrow$ $N_{2,3}$ are much longer-lived than the SM particles

Example:
$N_{2,3}$ production in charm

and subsequent decays

- Typical lifetimes $> 10$ $\mu$s for $M(N_{2,3}) \sim 1$ GeV
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Experimental and cosmological constraints

- **Recent progress in cosmology**
  - The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass

Strong motivation to explore cosmologically allowed parameter space

Proposal for a new experiment, SHIP, at the SPS to search for new long-lived Particles produced in charm decays (more details can be found at [http://ship.web.cern.ch/ship](http://ship.web.cern.ch/ship))
**Experimental requirements**

- **Search for HNL in Heavy Flavour decays**

  Beam dump experiment at the SPS with a total of $2 \times 10^{20}$ 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)
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 (with $2\times10^{20}$ pot)

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
Expected event yield (cont.)

- ECAL will allow the reconstruction of decay modes with $\pi^0$ such as $N \rightarrow \mu^- \rho^+$ with $\rho^+ \rightarrow \pi^+ \pi^0$, doubling the signal yield.

- Study of decay channels with electrons such as $N \rightarrow e \pi$ would further increase the signal yield and constrain $U_{e2}^2$.

In summary, for $M_N < 2$ GeV the proposed experiment has discovery potential for the cosmologically favoured region with $10^{-7} < U_{\mu2} < a few \times 10^{-9}$.
Conclusion and Next steps

• The proposed experiment will search for NP in the largely unexplored domain of new, very weakly interacting particles with masses below the Fermi scale

• Detector is based on existing technologies
  First assessment of the required beam line is ongoing

• The impact of HNL discovery on particle physics is difficult to overestimate!

• The proposed experiment perfectly complements the searches for NP at the LHC and in neutrino physics

The SHIP collaboration is currently being setup with aim for the first collaboration meeting in June. Let us know if you are interested to join!