Search for Hidden Particles
Ulrik Egede, on behalf of SHiP collaboration

UCL, 28 May 2014
A contradiction?

The Standard Model seems perfect and can exist without corrections to the Planck scale

But the same Standard Model can't explain dark matter, neutrino masses and baryogenesis.

I will propose a set of possible ways out of this
Introduction

Outline

- The physics landscape
- Hidden sector theories
- The neutrino minimal Standard Model
- Design of a new beam-dump experiment
- Sensitivity and future plans
Proposal to Search for Heavy Neutral Leptons at the SPS

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The triumph of the Standard Model

Boson consistent with the SM-Higgs has been found!

ATLAS : $M_H = 125.5 \pm 0.2$ (stat) $+0.5-0.6$ (syst) GeV/$c^2$

CMS : $M_H = 125.7 \pm 0.3$ (stat) $\pm 0.3$ (syst) GeV/$c^2$
The triumph of the Standard Model

Mass value important for the stability of the vacuum:

- \( M_H < 175 \text{ GeV} \)
  - SM weakly coupled up to the Plank energies!
- \( M_H > 111 \text{ GeV} \)
  - EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (JHEP 1208 (2012) 098)
The limitations of the Standard Model

But we still have a number of significant problems

Theory

Radiative corrections to Higgs mass
fine-tuning

Experiment

Matter anti-matter asymmetry in the Universe
Neutrino masses and oscillations
Non-baryonic dark matter
Dark Energy
## Introduction

**ATLAS SUSY Searches** - 95% CL Lower Limits

*Status: Moriond 2014*

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**Inclusive Searches**

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**Plot of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.**
... and indirect searches

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

\[ \sim 1 \quad \text{tree/strong + generic flavor} \quad \Lambda \gtrsim 2 \times 10^4 \text{ TeV} \ [K] \]
\[ \sim 1/(16\pi^2) \quad \text{loop + generic flavor} \quad \Lambda \gtrsim 2 \times 10^3 \text{ TeV} \ [K] \]
\[ \sim (y_t V_{ti}^* V_{tj})^2 \quad \text{tree/strong + “alignment”} \quad \Lambda \gtrsim 5 \text{ TeV} \ [K \ & B] \]
\[ \sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \quad \text{loop + “alignment”} \quad \Lambda \gtrsim 0.5 \text{ TeV} \ [K \ & B] \]
A hidden sector?

Rather than being heavy, could new particles be light but very weakly interacting?

- A new, light “hidden sector” of particles
- Singlets with respect to gauge group of the SM

How could we have missed it?

- Key is that it only interacts with SM particles through some kind of mixing through a “portal” particle
A hidden sector?

Several possibilities for renormalisable singlet operators

Vector portal, $U(1) B_{\mu\nu}$
- Massive vector photon (paraphoton, secluded photon… )
- Mixing with regular photon $\rightarrow \varepsilon B_{\mu\nu} F^{\mu\nu}$

Higgs portal
- Scalar field $\chi$, $(\mu\chi + \lambda\chi^2) H^\dagger H$

Axial portal
- Pseudo Nambu-Goldstone bosons
- Axion like vector field, $(a/F) G_{\mu\nu} G^{\mu\nu}$, $(\partial_{\mu} a/F) \psi^\dagger \gamma_\mu \gamma_5 \psi$

Neutrino portal
- Heavy neutral leptons (HNL), $YH^T N' L$

Low energy SYSY
Vector Portal

Exploit mixing between a virtual photon and the dark photon

No other interactions with SM particles - “light-shining-through-a-wall” experiments

[arXiv:1311.3870]

[arXiv:1406.2980]
Higgs Portal

Example of inflaton

Together with Higgs, generates inflation of the early Universe
Model has a 7 keV (warm) DM candidate and respects constraints from BICEP2 and Planck
Interesting mass region $0.3 \text{ GeV} < m_\chi < 1 \text{ GeV}$

Little experimental exploration of interesting region…
Neutrino Portal

The neutrino Minimal Standard Model (uMSM) aims to explain

Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter

Adds three right-handed, Majorana, Heavy Neutral Leptons (HNL), $N_1$, $N_2$ and $N_3$
Neutrino Portal

$N_1$

Mass in keV region, (warm) dark matter candidate

$N_{2,3}$

Mass in 100 MeV – GeV region

Generate neutrino masses via see-saw and produce baryon asymmetry of the Universe
See-saw for v mass

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
See-saw for $\nu$ mass

The scale of the active neutrino mass is given by the see-saw formula, $m_\nu = m_D^2 / M$

Typical value of the Dirac mass term is linked to the Yukawa coupling of the $I$-th neutrino by $m_D \sim Y_{I\alpha} \nu$
Constraints on $N_1$ as DM

Stability
- Must have a lifetime larger than that of the Universe

Production
- Created in the early Universe in reactions $l^+l^- \rightarrow \nu N_1$, $qq \rightarrow \nu N_1$ etc.
- Need to provide correct DM abundance

Structure formation
- Should be heavy enough to not erase non-uniformities at small scales

Decay
- Should not produce decays we have already excluded!
**N\textsubscript{1} – dark matter candidate**

Small Yukawa couplings mean that N\textsubscript{1} can be very stable

\[
\tau_{N_1} = 10^{14}\text{ years} \cdot \left( \frac{10\text{ keV}}{M_N} \right)^5 \left( \frac{10^{-8}}{\theta_1^2} \right) \quad \theta_1 = \frac{m_D}{M_N}
\]

Main decay mode $N \rightarrow 3\nu$, clearly unobservable

Subdominant radiative decay $N \rightarrow \nu\gamma$ would give a monoenergetic photon with $E_\gamma = M_N/2$
$N_1$ allowed parameter space

- Too much Dark Matter
  - Excluded by X-ray observations with Chandra, Suzaku, XMM-Newton, INTEGRAL
- Small galaxies do not exist
- Not enough Dark Matter

Interaction strength $u^2$ vs. Dark matter mass $M_{DM}$ [keV]
New line in galaxy spectrum?

ArXiv:1402.4119

An unidentified line in the x-ray spectrum of the Andromeda galaxy and Perseus galaxy cluster $E_\gamma \approx 3.5$ keV

ArXiv:1402.2301

Detection of an unidentified emission line in the stacked x-ray spectrum of galaxy clusters $E_\gamma \approx 3.56$ keV

Astro-H will be able to check these claims with better energy resolution
Generating the baryon asymmetry

CP is not conserved in the vMSM:
- 6 new CP-violating phases in lepton sector

Process for Baryon asymmetry
- HNL are created in the early Universe
- CPV in the interference of HNL production and decay
- Lepton number asymmetry goes from HNL to active neutrinos
- Asymmetry transferred to baryons via “sphaleron processes”
**N\(_{2,3}\) production and decay**

M(N\(_{2}\)) \approx M(N\(_{3}\)) \sim \text{a few GeV} \rightarrow \text{can dramatically increase amount of CPV to explain Baryon Asymmetry of the Universe (BAU)}

- Explanation of DM with N\(_{1}\) reduces number of free parameters, need degeneracy to ensure sufficient CPV

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

- Typical lifetimes >10 ms for (N\(_{2,3}\)) \sim 1 \text{ GeV} \rightarrow \text{decay distance O(km)}
- Too large U erases any BAU

\[ \tau = \frac{U^2 G_F M_N^5}{86 \pi^3} \]
**N_{2,3} production and decay**

Production in charm decays…

... and decays to lighter SM particles

For what follows will focus on $N \rightarrow \mu^- \pi^+$ decay, BF~0.1-50%  
Similar BF for $N \rightarrow \mu^- \rho^+$,  
BF($N \rightarrow \nu \mu e$) ~ 1-10%
Experimental and cosmological constraints

BAU, See-saw and Big Bang Nucleosynthesis (BBN) constraints indicate that previous experiments probed the interesting region only below the kaon mass:

- Previous searches:
  - PS191('88)@PS 19.2 GeV
    - $1.4 \times 10^{19}$ pot, 128 m from target
  - CHARM('86)@SPS 400 GeV, $2.4 \times 10^{18}$ pot, 480 m from target
  - NuTeV('99)@Fermilab 800 GeV, $2.5 \times 10^{18}$ pot, 1.4 km from target

BBN, BAU and Seesaw give stronger constraints than experimental searches for $M_N > 400$ MeV
Experimental and cosmological constraints

BAU, Seesaw and Big Bang Nucleosynthesis (BBN) constraints indicate that previous experiments probed the interesting region only below the kaon mass:

Mixing at both production and decay

- \( \text{BF}(D \rightarrow NX) \) around \( 10^{-8} - 10^{-12} \)
- Lifetime can give further factor \( 10^{-4} \)

Need \( \geq 10^{16} \) D mesons!
Where to produce charm?

$\bar{c}c$ cross-section:

LHC ($\sqrt{s} = 14$ TeV)
- $1 \text{ ab}^{-1}$ (i.e. 3-4 years), $\sim 2 \times 10^{16}$ in $4\pi$

SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV)
- $2 \times 10^{20}$ pot (i.e. 3-4 years): $\sim 2 \times 10^{17}$

Fermilab: 120 GeV, 10× smaller $\sigma_{\bar{c}c}$, 10×pot by 2025 for LBNE
Could mass range be extended?

Would neutrinos from B-decays extend the mass range for $N_{2,3}$ upwards?

- Produced with factor 20-100 smaller cross-section
- Dominant semi-leptonic decay $B \rightarrow D \mu \nu$
  
  Similar limit for neutrino mass

- Charmless $B \rightarrow \pi \mu \nu$ heavily Cabibbo suppressed

B decays are not at all competitive

Decays from $Z \rightarrow \nu N$ neither competitive
  
  Lifetime too long to contain
Experimental design

Propose a beam dump experiment at the CERN SPS with a total of $\sim 2 \times 10^{20}$ protons on target

Crucial design parameters:

- Minimise residual neutrino and muon fluxes
  - Can produce $K^0$ that decay in detector and mimic signal events
- Short-lived resonances generate $10^9$ muons/spill
  - Muon shield
- Neutrinos from light meson decays
  - Dense target/hadron absorber
- Prevent neutrino interactions from mimicking HNL decay
  - Evacuate decay volume
Beamline
**Target**

- **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

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- **Future SHIP Extension Area**
- **SHIP AREA on the French CERN Site in Prévessin**
- **Access Bld. ~ 20m wide**
- **Service Bld. ~ 15m wide**
- **Bypass tunnel**
- **“Aux. Power Supply”**
- **TDC2**
- **TCC2**
- **810**
- **811**
- **812**

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**28 May 2014**

J. Osborne, M. Manfredi, GS-SE-FAS
Target

Compact tungsten target to minimise neutrinos from kaon and pion decays

Significant (but achievable) requirement on cooling and radiation protection.
Timeline for civil engineering

The LS2 of the LHC is critical for building the new extraction point from the SPS

This is what drives the aggressive schedule for a Technical Proposal

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GS-SE Resources

- Engineer
- Technician/Fellow
- Draughtman
Experimental design

HNLs produced in charm decays have significant $p_T$

Detector must be close to target to maximise geometrical acceptance

Shielding for muons must be as short as possible
Secondary beam line

Initial reduction of beam induced backgrounds

- Heavy target (50 cm of W)
- Hadron absorber
- Muon shield: optimization of active and passive shields is underway

Acceptable occupancy <1% per spill of $5 \times 10^{13}$ p.o.t.

- spill duration 1s $\leq 5 \times 10^6$ muons
- spill duration 10ms $\leq 5 \times 10^3$ muons
- spill duration 10us $\leq 500$ muons

Generic setup, not to scale!
Muon Shield

Without μ-filter: $5 \times 10^9$/ spill ($5 \times 10^{13}$ pot)

Idea to reduce background from μ-interactions to below ν-background

Acceptable rate $\sim 10^5 \mu / 2 \times 10^{20}$ pot

Main sources of muons simulated using PYTHIA

Two alternatives for shield:

Passive: i.e. use high Z material: need 54 m of W to stop 400 GeV μ

Active (+passive): need 40 Tm to deflect 400 GeV μ outside acceptance
Neutrino backgrounds

Neutrino interactions in the decay volume:
- After shield expect $2 \times 10^4$ per $2 \times 10^{20}$ pot at atmospheric pressure
- Negligible at 0.01 mbar

Neutrino interactions in the final part of the muon shield:
- Use GEANT and GENIE to simulate the CC and NC neutrino interactions
- CC(NC) rate of $\sim 6(2) \times 10^5$ per interaction length per $2 \times 10^{20}$ pot
- Use veto-station to suppress short lived
- $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu \pi \nu$ main background
- Requiring $\mu$-id. for one of the two decay products
- $\rightarrow 150$ two-prong vertices in $2 \times 10^{20}$ pot
Neutrino backgrounds

Neutrino interactions in the decay volume

~10% of neutrino interactions in the muon shield just upstream of the decay volume produce $\Lambda$ or $K^0$
Detector Concept

Aim to reconstruct HNL decays into the final states: $\mu^-\pi^+$, $\mu^-\rho^+$, $e^-\rho^+$

Require long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter
Detector Concept

5 m diameter, 50 m length vacuum vessel
10 m long magnetic spectrometer with 0.5 Tm dipole magnet and four tracking chambers
Detector Technologies

Dipole magnet

- Magnet similar to LHCb design required, but with ~40% less iron and 3× less power
- Free aperture of ~16 m²
- Field integral ~ 0.5 Tm over 5 m length

Vacuum tank and straw tracker

- NA62 has $10^{-5}$ mbar pressure, only $10^{-2}$ mbar here
- Have demonstrated gas tightness of straw tubes with 120 µm spatial resolution and 0.5% $X^0$ material budget in long term tests
Detector Technologies

Electromagnetic calorimeter

Shashlik technology used in LHCb would provide economical solution with good energy and time resolution

Muon detector

Scintillator strips with WLS fibres and Silicon Photomultiplier (SiPM) an attractive option

Trigger and DAQ

Requirements on both are very modest due to low data rate
Spectrometer resolution

Arrange spectrometer such that multiple scattering and spatial resolution of straw tubes give similar contribution to the overall $\Delta p/p$

For $m(N_{2,3}) = 1$ GeV, 75% of $\mu^-\pi^+$ decay products have $p < 20$ GeV

For 0.5 Tm field integral $\sigma(\text{mass}) \sim 40$ MeV for $p < 20$ GeV

Good discrimination between high mass tail from small number of residual $K_L \rightarrow \mu^-\pi^+\nu$ and 1 GeV HNL
Residual Backgrounds

$K_L$ produced in the final part of the muon shield have very different pointing to the target compared to signal events

Use Impact Parameter (IP) to further suppress $K_L$ background

IP < 1 m is 100% efficient for signal and leaves only a handful of background events

The IP cut will also be used to reject backgrounds induced in neutrino interactions in the material surrounding the detector
Expected event yield

Integral mixing angle $U^2$ is given by $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$

Make a conservative estimate of the sensitivity by only considering the decay $N_{2, 3} \rightarrow \mu^-\pi^+$ – probes $U_\mu^2$

Expected number of signal events then,

$$N_{\text{signal}} = n_{\text{pot}} \times 2\chi_{cc} \times \text{BR}(U_\mu^2) \times \varepsilon_{\text{det}}(U_\mu^2)$$

Strongest experimental limit for $M_N \sim 1$ GeV at $U_\mu^2 = 10^{-7}$

Would then expect $\tau_N = 1.8 \times 10^{-5}$ s and $\sim 12k$ fully reconstructed $N \rightarrow \mu^-\pi^+$

For cosmologically favoured region $U_\mu^2 = 10^{-8}$ ($\tau_N = 1.8 \times 10^{-4}$ s)

Would expect 120 fully reconstructed events
Expected sensitivity

For $M_N < 2$ GeV the proposed experiment has discovery potential for the cosmologically favoured region with $10^{-7} < U_\mu^2 < \text{a few } \times 10^{-9}$

Limit from decay channels with electromagnetic not studied yet.

Will extend search on $U^2$ and limit on $U_e^2$
Status of the SPSC review


SPSC assigned four referees – provided answers to their questions [http://ship.web.cern.ch/ship/EOI/SPSC-EOI-010_ResponseToReferees.pdf]

SPSC discussed our proposal Jan 2015, official feedback

"The Committee received with interest the response of the proponents to the questions raised in its review of EOI010.
The SPSC recognises the interesting physics potential of searching for heavy neutral leptons and investigating the properties of neutrinos.

Considering the large cost and complexity of the required beam infrastructure as well as the significant associated beam intensity, such a project should be designed as a general purpose beam dump facility with the broadest possible physics programme, including maximum reach in the investigation of the hidden sector.

To further review the project the Committee would need an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration."
A strengthening collaboration

SHIP - Search for Hidden Particles
CERN, Universität Zürich, EPFL Lausanne, INFN Cagliari, Università Federico II and INFN Napoli, Imperial College London

We propose a new fixed-target experiment at the CERN SPS accelerator to search for hidden particles. In particular, to search for Heavy Neutral Leptons (HNLs) produced in charm decays. HNLs are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations, and provide a Dark Matter candidate.

SHIP is a collaboration of six institutes: CERN, Universität Zürich, École Polytechnique Fédérale de Lausanne, INFN Sezione di Cagliari, Università Federico II and INFN Napoli, Imperial College London. Groups interested in joining should contact Andrey Golutvin and Jaap Parman. The extension of the collaboration will be discussed at the First SHIP Workshop that will be take place in Zürich the 10-12 June 2014.
First SHiP Workshop, 10-12th June 2014

Around 100 people met in Zurich and discussed

- Physics reach of SHiP detector
- Detector requirements and technologies

A proto collaboration is now in place ...

Theoretical Overview (10th June)
Review of heavy neutral leptons, with discussions about leptogenesis and cosmological constraints

Theory review (11th June Morning)
Discussion of theoretical status and present experimental constraints

Facility and Experiment (11th June Afternoon)
Discussion on the primary beam line, target and detector design for the SHiP experiment

Tau neutrinos and SHiP detector (12th June Morning)
Discussion on the electronics and DAQ system for the SHiP experiment and on the detector for tau neutrinos

Summary and discussion (12th June Afternoon)
Conclusions

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.

Ongoing discussion of the beam line with CERN experts.

The discovery of a HNL would have enormous impact – could solve several of the significant problems of the SM.

The origin of the baryon asymmetry of the Universe
The origin of neutrino mass

The results of this experiment, together with cosmological and astrophysical data, could be crucial to determine the nature of Dark Matter.

Wide range of other hidden sector physics under investigation.