Search for Hidden Particles (SHiP): an experimental proposal at the SPS

ship.web.cern.ch/ship
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On behalf of the ShiP collaboration
The Standard Model and beyond

- All SM particles have been directly observed so far (apart from anti-$\nu_\tau$)
- Despite some anomalies, no compelling evidence of new physics found so far
- Higgs mass points to a meta-stable universe
- The SM could be valid to the Plank scale
- Naturalness only a problem if we assume new particles between EW and Plank scales
- Apart from naturalness, we do not understand:
  - Barion Asymmetry of the Universe
  - Dark Matter (indications are for cold, non-barionic)
  - The pattern of masses and mixings
  - Inflation

- Limits to masses of new particles being pushed in the TeV scale by the LHC.
  $\rightarrow$ “protection” against a small Higgs mass getting weaker
The “hidden sector” approach to new physics

- Searches for new particles at the LHC so far unsuccessful, maybe new physics has a very small coupling?
- If an additional, weakly interacting, term to the Lagrangian could lead to particles very difficult to observe, but contributing to dark matter.

Particle content of SM made symmetric by adding 3 HNL: $N_1$, $N_2$, $N_3$

With $M(N_1) \sim$ few KeV, it is a good DM candidate (or DM can be generated outside of this model through decay of inflaton)

With $M(N_2, N_3) \sim$ GeV, could explain Barion Asymmetry of Universe (via bariogenesis), and generate neutrino masses through see-saw.

HNL production and decay modes

Interaction with Higgs vev leads to mixing with active neutrinos, resulting in a behaviour similar to oscillation to the HNL and back into a virtual neutrino, that produces a muon and a W (→ hadrons, eg pions)

Exact branching fractions depend on flavor mixing

Due to small couplings, ms lifetimes, decay paths O(km)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{2,3} \rightarrow \mu, e + \pi$</td>
<td>$0.1 - 50%$</td>
</tr>
<tr>
<td>$N_{2,3} \rightarrow \mu-/e- + \rho^+$</td>
<td>$0.5 - 20%$</td>
</tr>
<tr>
<td>$N_{2,3} \rightarrow \nu + \mu + e$</td>
<td>$1 - 10%$</td>
</tr>
</tbody>
</table>
How to explore these phenomena? an experiment in practice

Use protons from CERN's SPS: 500 kW is 4x1E13 protons/7 s ->2E20 in 5y
Slow (ms → 1s) and uniform extraction to reduce detector occupancy and combinatorics

- HS particles produced by mesons (mainly charm) decays; need to absorb all SM decay products to minimise BG
  - heavy material thick target, with wide beam to dilute energy deposition (different from neutrino facility)
- Muons cannot be absorbed by target
  - active muon shield
- Long vacuum (or helium) decay tunnel away from external walls to minimise rescattering of muons and neutrinos close to detector

- Hidden sector detector with good PID and resolutions
- An additional emulsion detector for tau neutrino studies
The SHiP proposal

- Proposal for a new experiment at the CERN SPS accelerator:
  - hidden sector detector
  - Emulsion spectrometer for DM searches and $\nu_\tau$
- 235 experimentalists from 45 institutes and 15 countries + CERN
- Technical Proposal submitted in April last year (arXiv:1504.04956)
- Physics Proposal signed by 80 theorists (arXiv:1504.04855)
- SPSC has given the green light to the next stage, a Comprehensive Design study, to be submitted in about 3 years
- SHiP recommended by the CERN research board
The SHiP detector

Example of creation of long-lived neutral particles ($N_{2,3}$):

Target/hadron absorber → Active muon shield

Hidden Sector decay volume

Spectrometer

Particle ID

Emulsion spectrometer

It is designed as a background-free experiment → need for lots of background veto systems
A zero-background experiment

- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:
\[ \leq 0.1 \text{ bkg} / 5 \text{ y} \]

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<table>
<thead>
<tr>
<th>Background source</th>
<th>Stat. weight</th>
<th>Expected background (UL 90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$-induced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2.0 &lt; p &lt; 4.0 \text{ GeV/c}$</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>$4.0 &lt; p &lt; 10.0 \text{ GeV/c}$</td>
<td>2.5</td>
<td>0.9</td>
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<tr>
<td>$p &gt; 10 \text{ GeV/c}$</td>
<td>3.0</td>
<td>0.8</td>
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<tr>
<td>$\bar{\nu}$-induced</td>
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<tr>
<td>$p &gt; 10 \text{ GeV/c}$</td>
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<td>Muon inelastic</td>
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<td>Muon combinatorial</td>
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<td>Cosmics</td>
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<td></td>
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<tr>
<td>$p &gt; 100 \text{ GeV/c}$</td>
<td>1600</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Sensitivity to HNL

New development:
B-L gauge symmetry model
(enhanced HNL production)

(Batell et al. 1604.06099)

Just an example; many more recent papers and accessible regions of phase-space:

Drewes et al. (2016)
Hernandez et al. (2016)
Hernandez (2015)
Etc...
Sensitivity to dark photons

- Decays of $\pi^0 \rightarrow V\gamma$, $\eta \rightarrow V\gamma$, $\omega \rightarrow V\pi^0$
- Proton bremsstrahlung and parton bremsstrahlung above $\Lambda(QCD)$
- Decay into pair of SM particles
- SHiP will have a unique sensitivity for low couplings

Planned and future experiments
**Hidden scalars**

- Can mix with the SM Higgs, with angle $\theta$
- Mainly produce in penguin B and K decays
- Displaced vertex for decays into pairs of SM particles ($e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$, $K^+K^-$, ....)
Neutrino physics

- An OPERA-like tau neutrino emulsion detector
- Current status of tau neutrino measurements:
  - DONUT observed 9 events (from charm), OPERA 5 events (from oscillations)
- Ship can increase by 200 the current tau neutrino sample, discover tau antineutrinos, measure structure functions and constrain strange PDFs (with $\nu_\mu$)
Light dark matter

Theoretically, DM could be as light as 10-22 eV, but most of the searches focus on WIMPs with masses above 10 GeV: little sensitivity below

However, sub-GeV DM predicted by SUSY, hidden sector, extra dimension models...
Direct detection of DM in SHiP

- Light dark matter can be produced in a beam dump, as a decay product eg. of a dark photon

  LDM particles detected from their scattering on the emulsion spectrometer

- Studies still ongoing (need further reduction of neutrino BG), but sensitivity goes beyond relic density in a minimal hidden photon model
SHiP at CERN and timeline

From Fabiola’s June presentation to the CERN staff:

**Funding for neutrino activities**, through CERN Neutrino Platform, now covers commitments to US LBNF project described in the previous MTP (~ 20 MCHF were missing). No new commitments made.

**Beam dump facility at the North Area**: small funding included in the accelerator R&D budget to complete key technical feasibility studies in time for the ESPP. SHiP experiment recommended by the Research Board to prepare comprehensive design study as input to the ESPP.

- **future opportunities of diversity programme** (new): "Physics Beyond Colliders" Study Group

**Addendum to the TP**: SPSC-P-250

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talk from A. Golutvin at the PBC kick-off meeting

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Figure 4.2: New baseline project schedule for the facility and SHiP experiment with WP1 in LS3 and adapted to latest accelerator schedule MTP 2016-2020 V1.

Figure 4.3: Overall cost profile for the construction of the facility in MCHF in the new baseline schedule with WP1 in LS3, as shown in Figure 4.2.
Conclusions

- Light hidden-sector particles can solve many problems of the SM, and SHiP is the only dedicated detector to discover them.
- Two complementary detectors:
  - Long decay volume with spectrometer for long-lived particles
  - Emulsion spectrometer for neutrinos and direct DM
- Despite its uniqueness and innovative potential, it relies on existing technologies.
- Unique discovery potential due to design and SPS characteristics; complementary to high-energy LHC searches.