The SHiP experiment

Oliver Lantwin on behalf of the SHiP collaboration

2024-06-07
Many mysteries beyond the Standard Model remain, and at the GeV-scale there are plenty of areas, where New Physics could be hiding from collider experiments [see e.g. Andrea’s talk for a TH overview]

SHiP is designed to explore these blank spots on the map!
General purpose beam dump experiment at SPS with 400 GeV and $4 \times 10^{19}$ PoT per year

- Annually, $2 \times 10^{17}$ charmed hadrons, $1.4 \times 10^{13}$ beauty hadrons, $2 \times 10^{15}$ tau leptons and $\mathcal{O} \left( 10^{20} \right)$ photons above 100 MeV, as well as unprecedented sample of $\nu_\tau$

- Plan for 15 years of running $\rightarrow$ $6 \times 10^{20}$ PoT
Hybrid muon shield

› With robust warm fallback, baseline is now a hybrid muon shield
› A new campaign of optimisation of the different options using reinforcement learning and surrogate models kicking off

Hadron absorber  Warm

Section 1  Superconducting

Section 2  Warm

O. Lantwin (INFN Napoli)
SND@SHiP: Emulsions

- SND undergoing re-optimisation for neutrino physics and light dark matter
- Original design based on OPERA and now proven at SND@LHC

SPS offers possibilities complementary to HL-LHC, lower energy and boost, space, large (anti-)neutrino yields (approx. $10^6 \nu_e$, $10^7 \nu_\mu$, $10^5 \nu_\tau \rightarrow$ no longer statistically limited)

[see Ettore’s [I,II] and Chris’s talks for more about SND@LHC and nuclear emulsions]

O. Lantwin (INFN Napoli) 2024-06-07
SND@SHiP: Silicon

Inspired by SND@LHC upgrade for the HL-LHC

Advantages

› Realtime readout allows full integration with other detectors
› Unique signatures accessible

Challenges

› Vertex resolution of emulsions impossible to equal
› Reconstruction of “double-kink” challenging

› CMS TOB modules baseline for AdvSND, sensor options for SHiP under study

O. Lantwin (INFN Napoli)
Computing challenges at SHiP

SHiP faces unique challenges:

› Design intensity many orders of magnitude beyond what is possible with full simulation
  › GANs \textsuperscript{[JINST 14 (2019) P11028]}
› Even rarest processes need to be understood → biasing, factorisation
Computing challenges at SHiP

SHiP faces unique challenges:

- Design intensity many orders of magnitude beyond what is possible with full simulation
- GANs [JINST 14 (2019) P11028]
- Even rarest processes need to be understood → biasing, factorisation

Target/Magnetized hadron absorber
Active muon shield

- Well optimised muon-shield crucial to reach physics goals, many degrees of freedom
  - Bayesian optimisation [CERN-THESIS-2019-157]
  - L-GSO [2002.04632, 10.25560/95975]
  - Reinforcement learning [2406.04261]

- Reconstruction of scattering signatures in emulsions and Si non-trivial!
- How can we be sensitive to unknown unknowns? → anomaly detection using variational autoencoders [WiP]

F. Massoli et al. [2406.04261]

O. Lantwin (INFN Napoli) 2024-06-07
The SHiP hidden sector detector

- Full spectrometer allows measurement of
  - invariant mass, impact parameter, decay vertex of signal candidate
  - distinguish between signal models using PID of decay products
- If LLPs are discovered, detector can perform precision measurements of LLPs
- Background taggers and timing detector allow powerful background rejection
Backgrounds

› Very minimal selection common to all signal channels sufficient
› Background tagging under optimisation to improve signal efficiency while maintaining reliable background rejection

<table>
<thead>
<tr>
<th>Background source</th>
<th>Expected events in 15 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino DIS</td>
<td>$&lt; 0.1$ (fully)/$&lt; 0.3$ (partially)</td>
</tr>
<tr>
<td>Muon DIS (factorisation)</td>
<td>$&lt; 5 \times 10^{-3}$ (fully) / $&lt; 0.2$ (partially)</td>
</tr>
<tr>
<td>Muon combinatorial</td>
<td>$(1.3 \pm 2.1) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

O. Lantwin (INFN Napoli)
Sensitivities

› SHiP has full simulation for HNL with arbitrary coupling, dark photons and RPV SUSY, in excellent agreement with SensCalc, which is used for all other channels
› Common, minimal selecton for all channels
› Showing Physics Beyond Colliders (PBC) benchmarks here for easy of comparison: SHiP is designed to be as model-independent as possible for
  › Fully reconstructed decays to charged particles or photons
  › Partially reconstructed decays where e.g. a neutrino escapes detection
  › Diphoton vertexing possible
› All sensitivies for 15 years ($6 \times 10^{20}$ PoT)
› Lines from other experiments taken from the FIPs 2022 summary plots
Sensitivity: Dark photons to visible fermions (BC1)

- Implemented in full simulation
- Production taken into account via:
  - Bremsstrahlung
  - Meson decay
  - QCD


[LHCb downstream 2312.14016]
Sensitivity: Dark Scalars

BC 4

Dark scalars. BC4

Excluded

SHiP
LHCb downstream

0.1 0.2 0.5 1 2 5

$10^{-10}$

$m_s [\text{GeV}]$

BC 5

Dark scalars. BC5

Excluded

SHiP
LHCb downstream

0.1 0.2 0.5 1 2 5

$10^{-12}$

$m_s [\text{GeV}]$
Sensitivity: HNL

- Arbitrary coupling ratios implemented in full simulation
- Production from charm and beauty hadrons considered
- Could measure HNL oscillations in large regions of currently unexplored parameter space, see JHEP 04 (2020) 005

Detailed study for ECN4: JHEP 04 (2019) 077

O. Lantwin (INFN Napoli)
Sensitivity: ALPs

ALPs, BC9

\[ g_a [\text{GeV}^{-1}] \]

SHiP
NA62\text{dump}
FASER300 fb\text{-1}

Excluded

ALPs coupled to fermions (BC10)

\[ g_y = \frac{2v_h}{f_a} \]

SHiP
LHCb\text{downstream}
NA62\text{dump}

Excluded
BDF beyond SHiP

Several groups outside of SHiP have started evaluation concurrent uses of the BDF facility, which provides a unique spectrum of particles at very high intensity!

› TauFV upstream of BDF

Plenty of space for new ideas!
BDF beyond SHiP

Several groups outside of SHiP have started evaluation concurrent uses of the BDF facility, which provides a unique spectrum of particles at very high intensity!

- TauFV upstream of BDF
- LAr TPC for long lived particles, light dark matter and neutrinos

Plenty of space for new ideas!

[F. Resnati, JHEP 02 (2024) 196]
BDF beyond SHiP

Several groups outside of SHiP have started evaluation concurrent uses of the BDF facility, which provides a unique spectrum of particles at very high intensity!

› TauFV upstream of BDF
› LAr TPC for long lived particles, light dark matter and neutrinos
› Irradiation facility for development of radiation hard electronics (e.g. for FCC), nuclear physics and astrophysics

Plenty of space for new ideas!

[O. Lantwin (INFN Napoli) 2024-06-07]
Conclusion

› SHiP is a general-purpose beam dump experiment exploring the sensitivity frontier in decay and scatter, complementary to the LHC.
› In March 2024, SHiP/BDF at the ECN3 beamline of the SPS has been approved for the TDR phase
  › TDRs by 2026
  › Commissioning 2031

We’re ready to set sail, now the real work starts!

Plenty of room to get involved in for new groups and individuals (physics (ex and ph), hardware, software, ML...)

O. Lantwin (INFN Napoli) 2024-06-07