Searching for Hidden Particles

From proposal to realisation *or* the SHiP of Theseus

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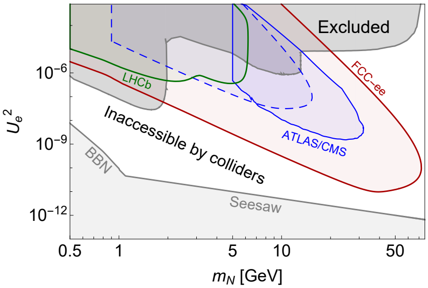
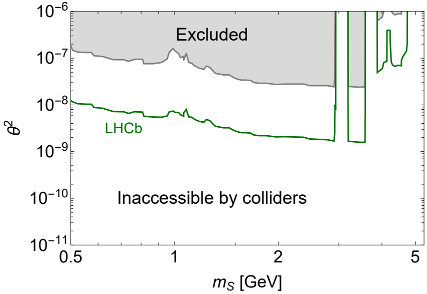
2025-01-15 RAL PPD Seminar

Sensitivity frontier

Many mysteries beyond the Standard Model remain, and at the GeV-scale there are plenty of areas, where New Physics could by hiding from collider experiments





SHiP is designed to explore these blank spots on the map!

Portal formalism

If there is super weakly coupled new physics, there generally is a portal that mediates between the standard model and one or more hidden particles, i.e. the hidden sector (HS):

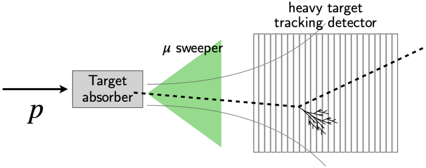
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{HS}}$$

There are four possible types of portal:

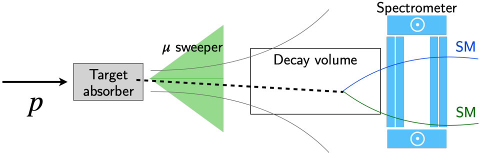
- Scalar (e.g. dark scalar, dark Higgs) $(H^\dagger H)\phi$
- Vector (e.g. dark photon) $\epsilon F_{\mu\nu} F'_{\mu\nu}$
- Fermion (e.g. heavy neutral lepton (HNL)) $H^\dagger \overline{N} L$
- Axion-like particle (ALP) $a F^{\mu\nu} \tilde{F}^{\mu\nu}$

Signal signatures

Scattering



Displaced vertexes in decay



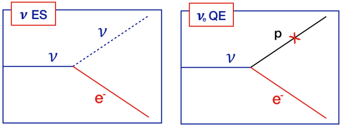
For decay, both fully and partially reconstructed events are considered

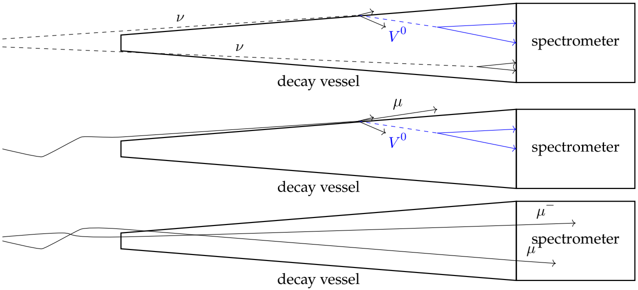
- fully reconstructed better as smoking gun for discovery, identification of signal
- partially reconstructed important for full sensitivity reach

Need to redundantly reduce backgrounds to zero for both

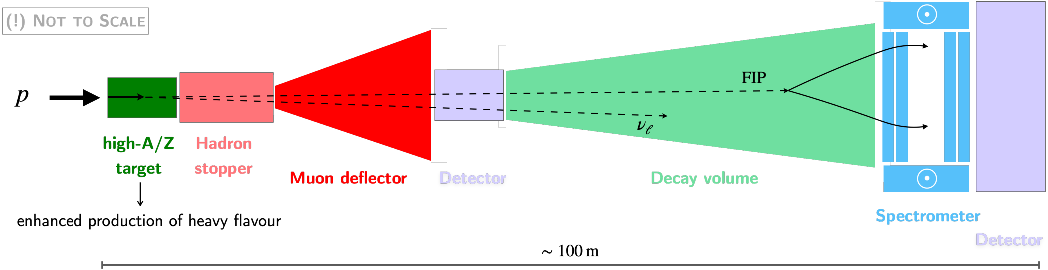
Backgrounds

- Decay signatures see combinatorial, muon DIS and neutrino DIS backgrounds
- Scattering signatures have irreducible background from neutrino events quasi-elastic and elastic scattering on electrons





A sketch of the detector concept



SHiP aims to be the world-leading experiment for hidden sector searches and tau-neutrino measurements

A brief summary of a long journey (ECN4)

2013 Expression of Interest SPSC-EOI-010

2015 Technical Proposal SPSC-P-350 and Physics Proposal SPSC-P-350-ADD-1, beginning of Comprehensive Design Study

2019 Comprehensive Design Study Report, input to ESPPU, my PhD thesis `CERN-THESIS-2019-157`

2020 ESPPU, start of search for alternative locations

A brief summary of a long journey (ECN3)

2022 Study of alternative locations for the SPS Beam Dump Facility
CERN-SPSC-2022-009

2023 Proposal for ECN3 [SPSC-P-369], decision originally foreseen for December

2024 Approval to go to TDR in March 2024

Approval and beyond

Potential of SHiP physics case recognised by CERN, with the HI-ECN3 facility being the only major new programme at CERN until the next collider in 20+ years, first to outlast the LHC

- SHiP sole user of the facility (parasitic experiments possible)
- 60 MCHF committed by CERN to development of facility, designed to run at least 15 years
- If no new heavy particles are discovered at the HL-LHC, SHiP best hope for direct evidence of new physics at CERN
- TDRs for all subsystems expected by 2027, construction 2029 for commissioning in 2033

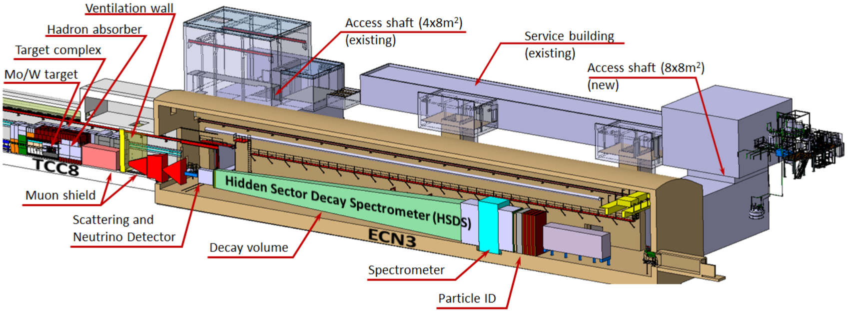
Configuration discussed today

- Since approval, we have taken several important decisions on the way to the TDRs, all on the basis of studies with full simulation
  - The decay volume will be filled with helium instead of being under vacuum (with possible upgrade path)
  - The SND detector will be integrated into the muon shield

This latest configuration is the one I will focus on, see also Progress Report 2024 SPSC-SR-354

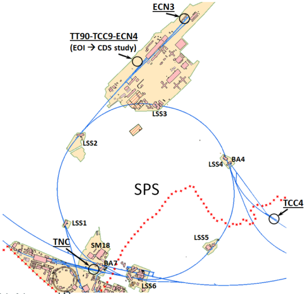
BDF and SHiP from bow to aft

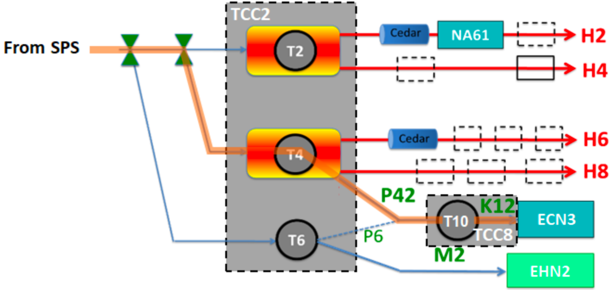
[SPSC-P-369]



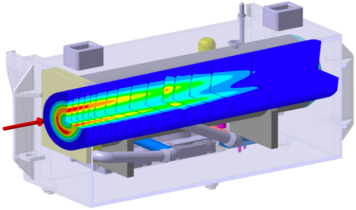
SPS

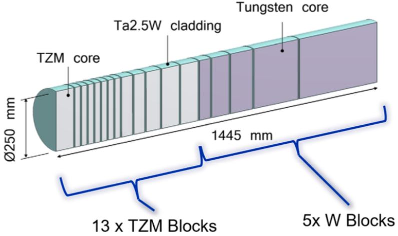
- Upgrade of existing beamline to TCC8 for HI-ECN3 facility to deliver 4×10^{19} PoT per year 400 GeV
- Slow extraction over 1 s, spread and spiralled over target
- The BDF facility is designed to exploit the full available intensity of SPS
- Plan for 15 years of running → $6 \times 10^{20}\ \mathrm{PoT}$





Target



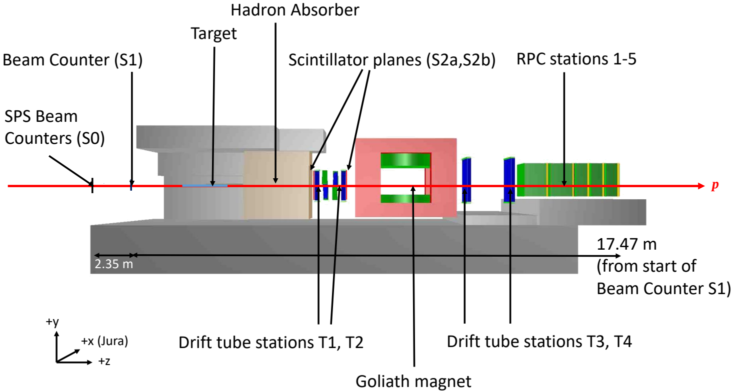


- In the $12\ \lambda$ SHiP target, reinteractions of particles are non-negligible
  - Increases signal yield ($\times 2.3$ for D, $\times 1.7$ for B)
  - Reduces neutrino interactions due to reinteractions of pions and kaons before leptonic decay
- Annually, 2×10^{17} charmed hadrons, 1.4×10^{13} beauty hadrons, 2×10^{15} tau leptons and $\mathcal{O}\left(10^{20}\right)$ photons above $100\ \mathrm{MeV}$, as well as unprecedented sample of ν_τ

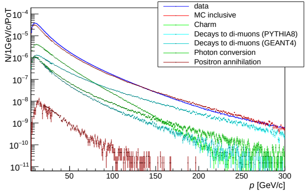
Muon flux measurement

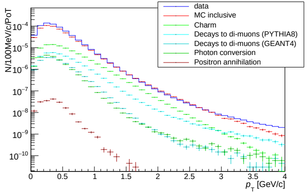
[SHiP-EOI-016]

Stand-alone experiment to measure the flux of the SHiP target to cross-check simulation



[10.1140/epjc/s10052-020-7788-y]

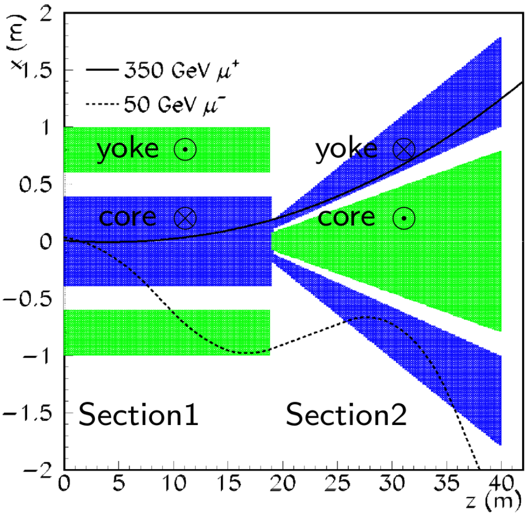




Muon shield: Idea

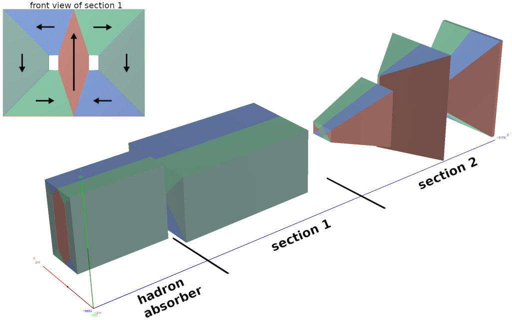
- In order to have a zero-background environment as close to the target as possible, active shielding from muons is needed
- At least two magnets are required to deflect the continuous muon spectrum

Goal: Reduce the muon flux by $\mathcal{O}(10^6)$ in under 35 m



Muon shield: Three complementary parts

[SPSC-P-369]



Hadron absorber Warm

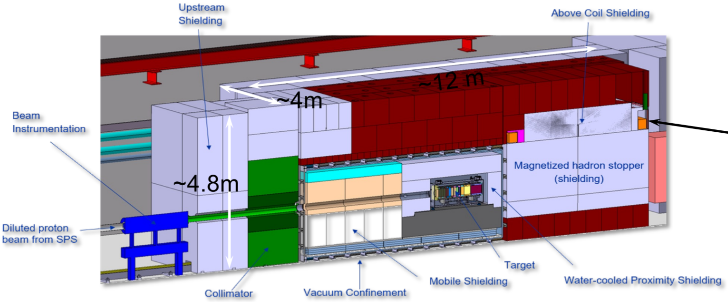
Section 1 Superconducting

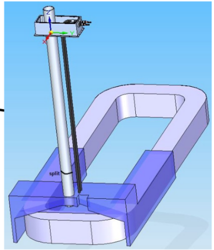
Section 2 Warm

- Magnetised hadron absorber
- In the baseline, the muon shield combines superconducting and warm magnets
- Fully warm option shown to work for CDS, and is available as fallback, decision point this year

Magnetised hadron absorber

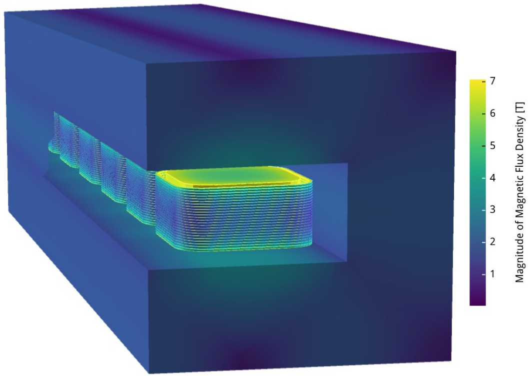
- Approx. 5 m of shielding necessary after target to contain radiation and absorb hadrons
- In order to start separating the muon flux as early as possible, magnetise the hadron absorber using a coil ready for remote handling
- Design of coil and integration with BDF target complex thanks to RAL-TD groups





Muon shield: HTS

- An array of square HTS coils provide an approx. 5 T field over 7 m
- Operating temperature 30 K
- 125 km of ReBCO tape
- Prototyping planned and starting, decision point 2025

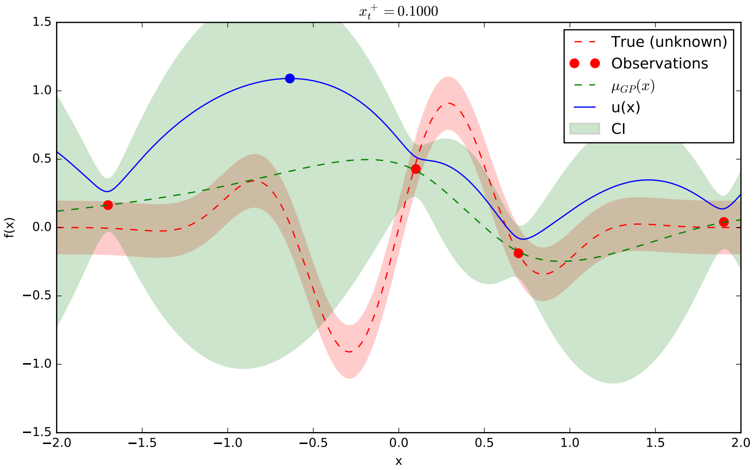


Muon shield optimisation

CERN-THESIS-2019-157, J.Phys.Conf.Ser. 934 (2017) 1, 012050, 2002.04632 10.25560/95975]

- The muon shield is critical to reaching SHiP's physics goals, needs to be optimised for performance and robustness to uncertainties of muon flux
  - Only a fraction of a spill available in full simulation
  - Computationally prohibitive to optimise with much larger samples
- Optimisation of muon shield in the past performed using approximate fields and Bayesian optimisation
  - 54 (34) parameters for warm (hybrid) configuration
  - Noisy, black-box optimisation, no gradient available
  - Full simulation using `Geant4` for each configuration
  - 100 configurations tested in parallel

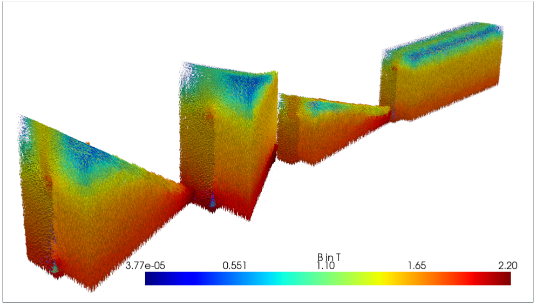
Introduction to Bayesian Optimisation in one slide [1]



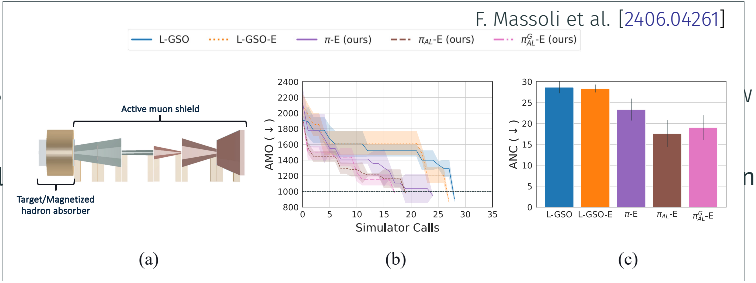
[1] Based on `scikit-optimize` documentation

Muon shield optimisation: new approaches

- Moving Bayesian optimisation to GPUs and redesign of optimisation workflow now allow us to test $\mathcal{O}(100\,000)$ muon shield configurations per day
- **On-the-fly calculation of field maps** becomes plausible by integrating with `Sn∞.py` FEM solver



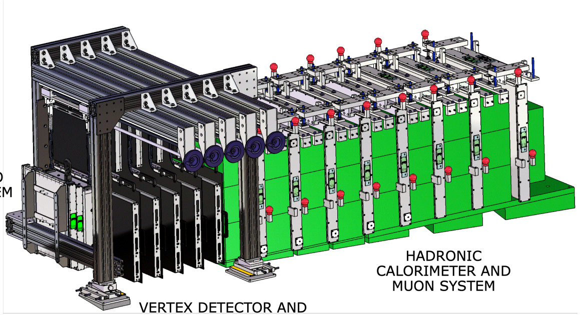
Muon shield optimisation: new approaches



- Moving B … now allow us to test $\mathcal{O}$ …
- **On-the-fl** … n∞.py FEM solver

- **Local Generative Surrogates** (L-GSO) allow us to simulate fewer configurations with full simulation, drastically speeding up optimisation https://arxiv.org/abs/2002.04632
- **Reinforcement learning** shows promise to further improve on Bayesian Optimisation and L-GSO

SND@LHC and AdvSND



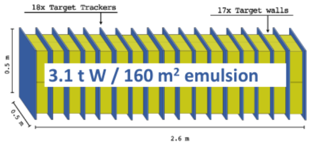
Technical Proposal LHCC-P-016, detector paper JINST 19 (2024) 05, P05067

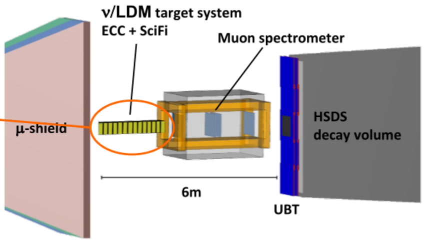
- First observation of collider neutrinos (ν_μ) Phys. Rev. Lett. 131, 031802
- Observation of 0μ neutrino interactions 2411.18787

- Valuable test of SHiP technologies at the LHC since 2022
- Upgrade planned adding magnet and replacing nuclear emulsions with silicon strip trackers

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. $10^6\ \nu_e$, $10^7\ \nu_\mu$, $10^5\ \nu_\tau$ → no longer statistically limited)

SND@SHiP: Silicon

[AdvSND LoI: LHCC-I-040]

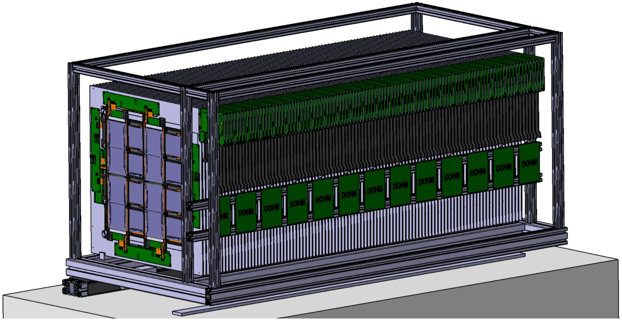
Inspired by SND@LHC upgrade for the HL-LHC

Advantages

- Real time readout allows full integration with other detectors
- Unique signatures accessible

Challenges

- Vertex resolution of emulsions impossible to equal
- Reconstruction of "double-kink" challenging

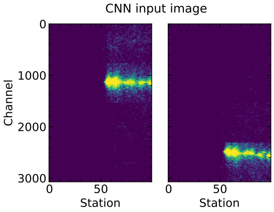


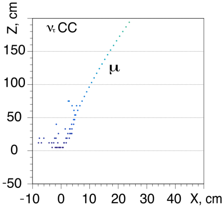
- CMS TOB modules baseline for AdvSND, sensor options for SHiP under study
- Technical Proposal in February

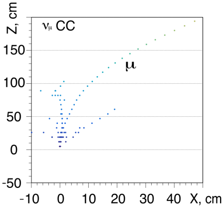
Electronic SND reconstruction challenges

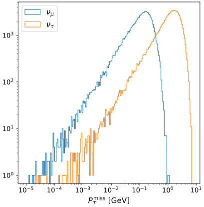
AdvSND

SND@SHiP





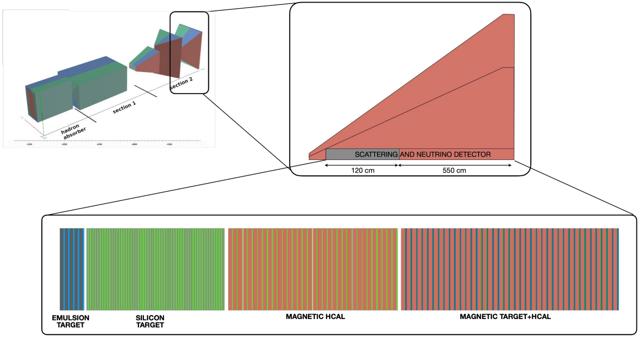




- Combinatorial background negligible, but very high occupancy around primary and secondary vertices
- Only isolated particles can be tracked using silicon strips
- With a student in Bergamo I currently study the use of CNNs and CVTs for the energy reconstruction and classification of neutrino events for the AdvSND TP

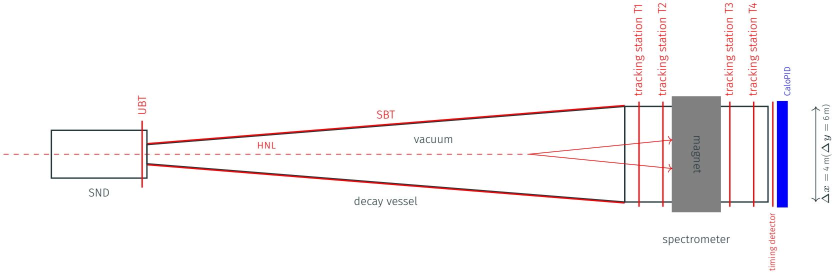
Integration of SND in muon shield

Integrating one or several SND technology directly in the muon shield saves space, obviates additional magnet



- Background and integration studies in full swing, focus of Naples engineering groups

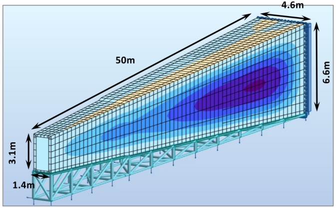
The SHiP hidden sector detector

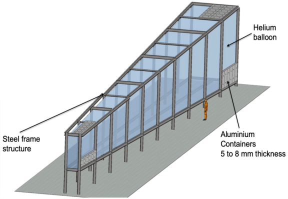


- Full spectrometer allows measurement of
  - invariant mass, impact parameter, decay vertex of signal candidate
  - distinguish between signal models using PID of decay products
- If LLPs are discovered, detector can perform precision measurements of LLPs
- Background taggers (MRPC and liquid scintillator) and timing detector (scintillating bars) allow identification of residual background

Decay volume

- To suppress neutrino interactions, the decay volume originally as designed to be under 1 mbar vaccum
- 1 bar helium reduces interactions sufficiently for residual events to be rejected using selection and background taggers

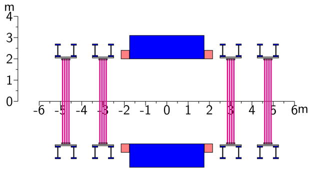


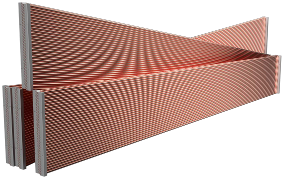


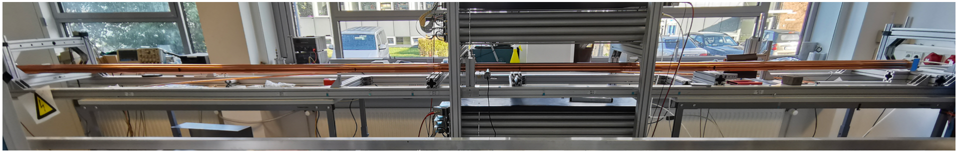
- Reduction of material, cost, easier construction due to reduced mechanical requirements

Spectrometer tracker

- Ultralight mylar straw tubes provide tracking for momentum and vertex reconstruction, crucial for the determination of signal properties and rejection of background
- Replacement of Mylar with Al considered, clear advantages but also trade-offs
- Tracker aperture $4 \times 6\ \mathrm{m}^2$, $20\ \mathrm{mm}$ diameter
- Prototyping well advanced, mechanical stiffness main challenge
- Optimisation of track reconstruction ongoing

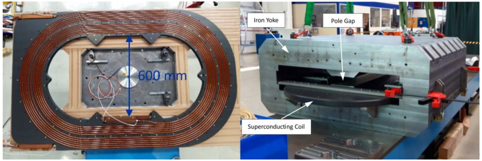


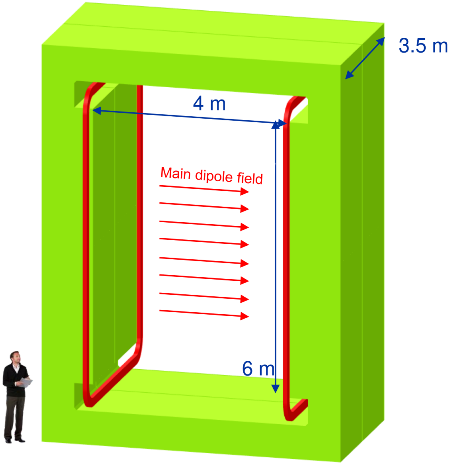




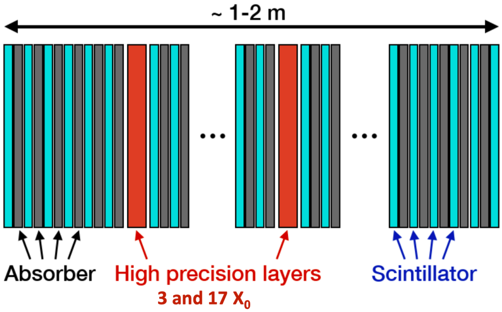
Spectrometer magnet

- Bending field $\sim 0.6\text{–}0.8\ \mathrm{Tm}$, nominal on axis $\sim 0.15\ \mathrm{T}$
- Integrated field more important than field uniformity (~5-10%)
- Field mapping in-situ important
- New Energy-efficient superferric dipole technology, resulting in much lower power consumption [10.1109/TASC.2024.3355872]





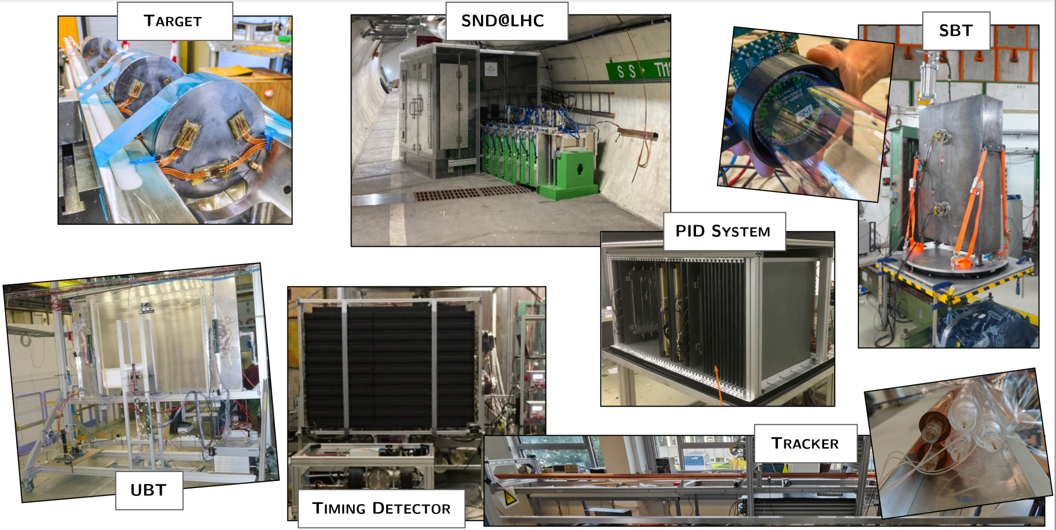
SplitCal and PID



Longitudinally segmented $\sim 20\ X_0$ with high-resolution layers provides

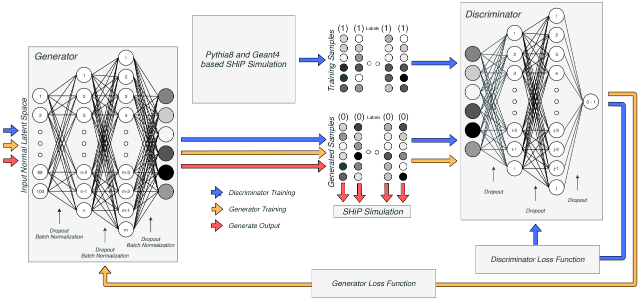
- e/γ separation and energy measurement
- μ/π discrimination
- Shower angular resolution of $\sim 5\ \mathrm{mrad}$ to $\mathrm{ALP} \to \gamma\gamma$

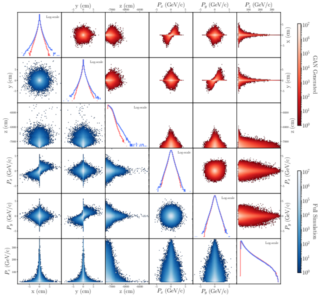
Proven in practice



Fast simulation

- Design intensity many orders of magnitude beyond what is possible with full simulation
  - GANs allow us to increase statistics for muon-induced backgrounds [JINST 14 (2019) P11028]
  - For the muon shield optimisation, DNNs are being tested for gradient-based optimisation to approximate `Geant4` output, alongside fast histogram-based lookup method





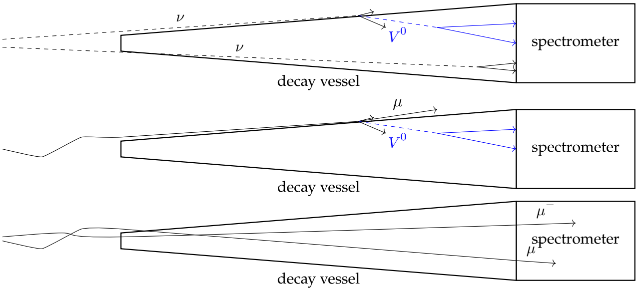
Reconstruction

- Tracking for electronic detectors currently performed using `GenFit`, with Artificial Retina pattern matching for track findings, and home-made vertexing
- For analysis of emulsions, particularly far light dark matter, several ML techniques are being studied (including GNN) [J.Phys.Conf.Ser. 1085 (2018) 4, 042025][J.Phys.Conf.Ser. 1525 (2020) 1, 012087]
- Reconstruction of electronic SND very challenging due to large multiplicity and very high material budget, experiments using CNNs and other techniques ongoing
  - Electromagnetic shower energy measurement in SND@LHC using CNN [CERN-LHCC-2021-003]
  - A lot of studies ongoing as part of AdvSND proposal
- How can we be sensitive to unknown unknowns? → anomaly detection using variational auto-encoders [WiP]

Backgrounds

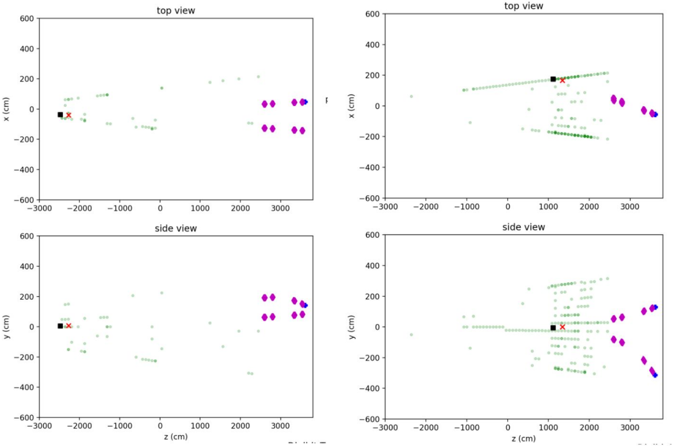
[See Proposal for full details]

- Minimal selection common to all signal channels sufficient
- Optimised selections per channel will further reduce backgrounds in future
- Biasing, factorisation allow background estimates for 15 years

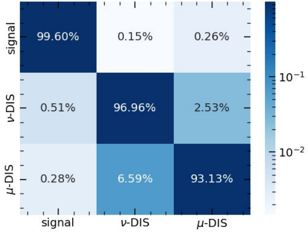


Background source	Expected events in 15 years
Neutrino DIS	< 0.1 (fully)/< 0.3 (partially)
Muon DIS (factorisation)	$< 5 \times 10^{-3}$ (fully) / < 0.2 (partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

Advanced veto



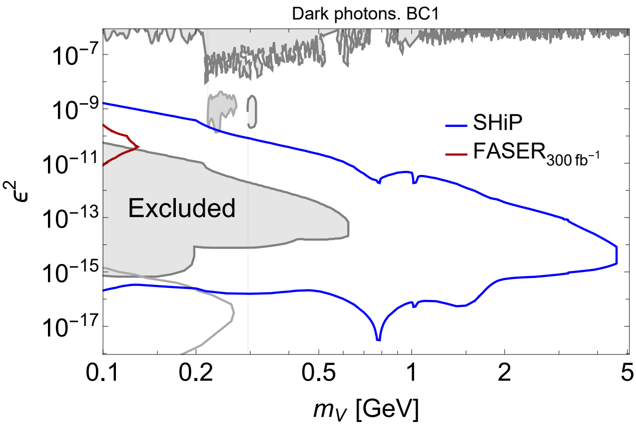
A graph-neural network allows us to tag background with high efficiency while not falsely rejecting signal



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 $(6 \times 10^{20}\ \mathrm{PoT})$

Sensitivity: Dark photons to visible fermions (BC1)

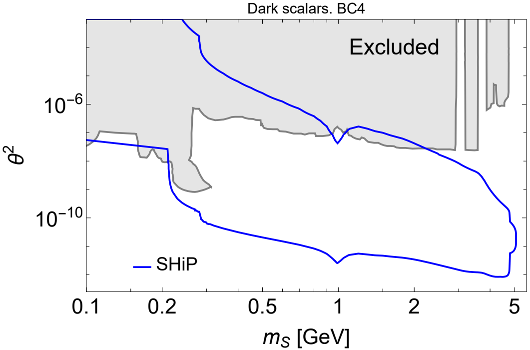


- Implemented in full simulation
- Production taken into account via:
  - Bremsstrahlung
  - Meson decay
  - QCD

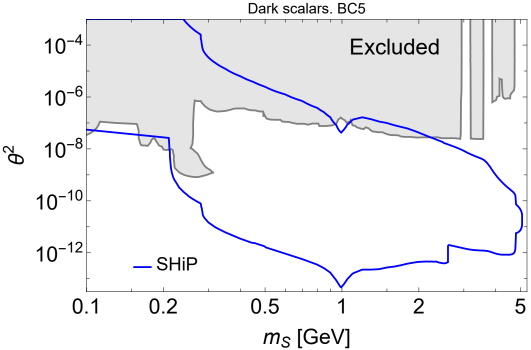
Detailed study for ECN4: Eur.Phys.J.C 81 (2021) 5, 451

Sensitivity: Dark Scalars

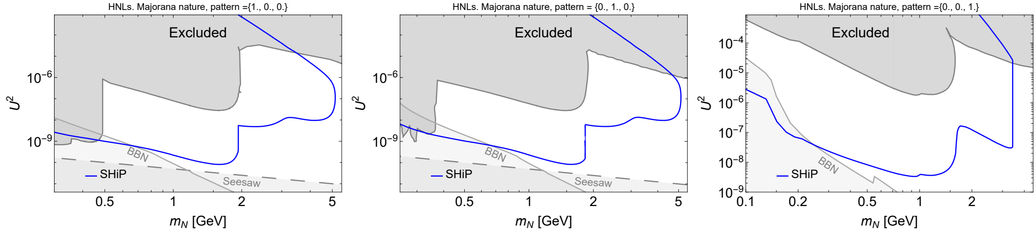
BC 4



BC 5



Sensitivity: HNL



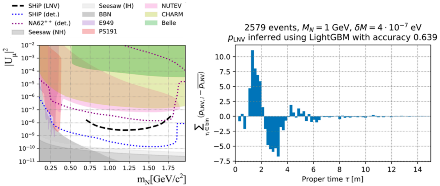
- Arbitrary coupling ratios implemented in full simulation
- Production from charm and beauty hadrons considered
- Cosmological limits within grasping distance

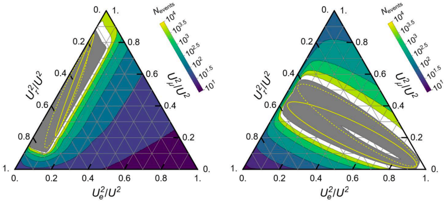
Detailed study for ECN4: JHEP 04 (2019) 077

Measurement of HNL properties

- SHiP could do more than just discover HNL:
  - Are neutrinos Majorana or Dirac?
  - What is their mass splitting? → HNL oscillations!
  - What is the mass ordering of active neutrinos?

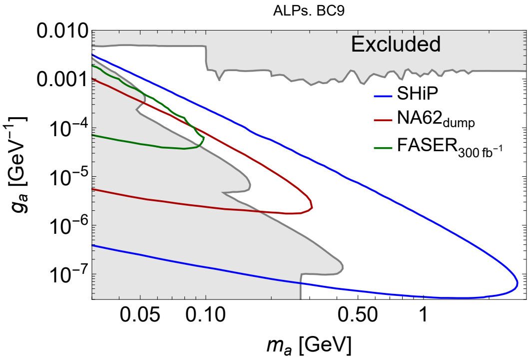
[JHEP 04 (2020) 005]

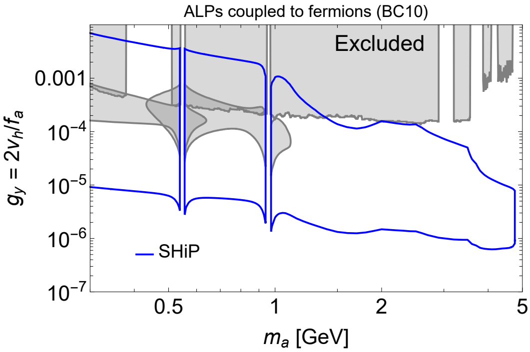




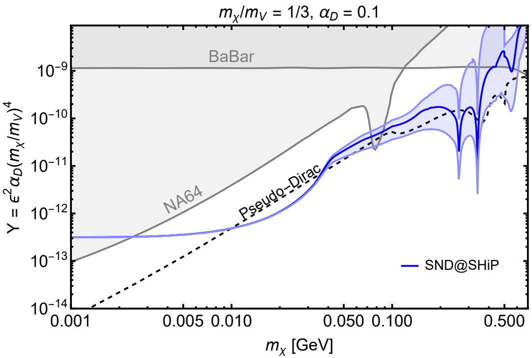
[2312.05163]

Sensitivity: ALPs





Light Dark Matter



- Detailed study for ECN4: JHEP 04 (2021) 199
- Preliminary results indicate at least as good at ECN3, but currently undergoing optimisation as part of the SND integration in the muon shield
- Potential for LAr TPC after SHiP to further increase reach, see JHEP 02 (2024) 196

Neutrino physics

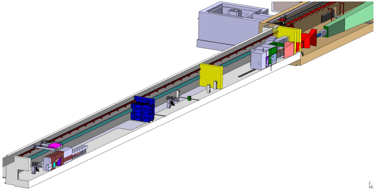
	<E> [GeV]	beam dump	<E> [GeV]	SND target acceptance	<E> [GeV]	CC DIS interactions
N_{ν_μ}	2.6	5.4×10^{18}	8.4	1.5×10^{17}	40	8.0×10^{6}
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	6.8	1.2×10^{17}	33	1.8×10^{6}
N_{ν_e}	6.3	4.1×10^{17}	30	1.3×10^{16}	63	2.8×10^{6}
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	22	9.3×10^{15}	49	5.9×10^{5}
N_{ν_τ}	9.0	2.6×10^{16}	22	1.0×10^{15}	54	8.8×10^{4}
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	32	1.0×10^{15}	74	6.1×10^{4}

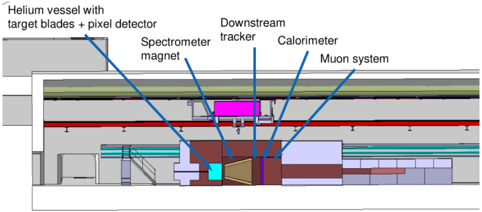
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

- Powerful detector that can identify all flavours, thousands of reconstructed neutrino events ($\sigma_{\text{stat}} < 1\,\%$)
  - LFU in neutrino interactions
  - Cross-section measurement up to 100 GeV
  - Neutrino-induced charm production to constrain nucleon strangeness content
- Unprecedented yield of $\nu\tau/\bar{\nu}_\tau$ at SHiP from D_s decays
  - First measurement of DIS structure functions F_4 and F_5 in $\sigma_{\nu-\text{CCDIS}}$ accessible only with ν_τ [NP B 84 (1975)]
  - Distinguish for the first time ν_τ and $\bar{\nu}_\tau$ in muonic channel
  - Constrain ν_τ anomalous magnetic moment

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



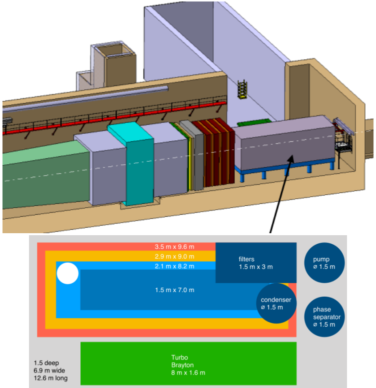


Plenty of space for new ideas!

[L. Krzempek]

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 [10.1007/JHEP02(2024)196]



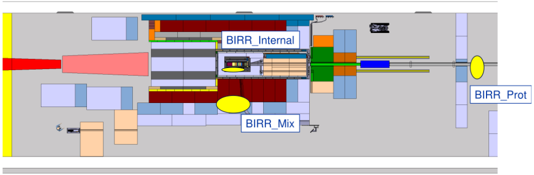
[F. Resnati, JHEP 02 (2024) 196]

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 [10.1007/JHEP02(2024)196]
- Irradiation facility for development of radiation hard electronics (e.g. for FCC), nuclear physics and astrophysics [SPSC-EOI-023]

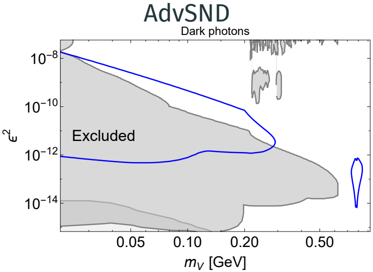


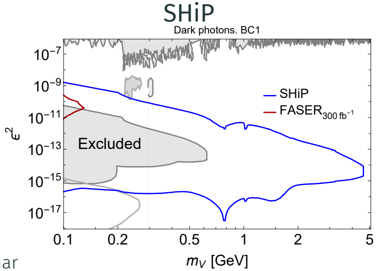
[M. Calviani]

Plenty of space for new ideas!

SHiP and FPF

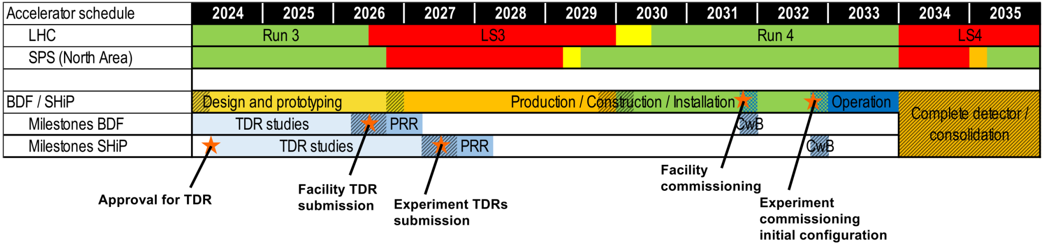
- SHiP has a much larger angular acceptance, intensity, lifetime coverage and more powerful detectors
- FPF benefits from a higher centre of mass (but benefit of being forward largest at low masses)
- For most portals, SHiP unbeatable, at high masses, FPF recovers a bit, but ANUBIS, CODEXb benefit more
- FPF has unique sensitivity to high-mass milli-charged particles and some non-minimal models such as compressed spectra, strongly interacting dark sectors
- Complementary measurements possible for neutrinos
- Timescales similar (no approval timeline for FPF yet, but before LS4 technically possible)





Collaboration strength and schedule

236 participants from 46 institutes in 19 countries + CERN, in discussion with several additional groups, including in the UK



- Aim to commission with beam before LS4, so that detector can be completed and consolidated during LS4
- TDRs for each subsystem by 2027, in order for construction to commence in 2029

SHiP in the UK

- UK-initiated and UK-led: proposed by UK physicist who's led the experiment as spokesperson since, other senior leadership positions and about 20 % of original proponents
- Currently Imperial, UCL, Bristol members of the collaboration
- So far, only direct funding from UK via RAL-TD, who also won contract for the design of the magnetised hadron absorber
- Strong involvement in muon shield, physics, computing, with potential for RAL-TD and UK industry to lead the warm section of the muon shield

Conclusion

- SHiP is a general-purpose beam dump experiment exploring the sensitivity frontier in decay and scattering, complementary to the HL-LHC.
- In March 2024, SHiP/BDF at the ECN3 beamline of the SPS has been approved for the TDR phase
  - TDRs by 2027
  - Construction 2029
  - Commissioning 2033

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...)