Imperial College London

SHiP
Search for Hidden Particles

Optimisation of the SHiP muon shield

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IoP APP/HEPP

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The current state of physics

"We know there is new physics,..."

Dark matter, baryon asymmetry and neutrino masses are direct experimental evidence that we're missing something.

"... We don't know where it is..."

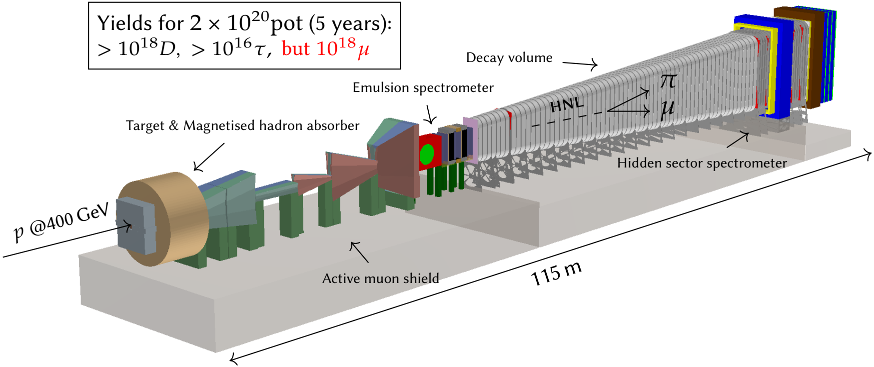
We do not know which energy scale to target: Very weakly coupled new physics could be hiding in plain sight — at energies already accessible!

"... We need to be as broad as possible in our exploratory approach"

— *Fabiola Gianotti*

Overview of the Search for Hidden Particles

Yields for 2×10^{20}pot (5 years):
$> 10^{18} D$, $> 10^{16} \tau$, but $10^{18} \mu$



Two signatures:

1. Via decay to visible particles in hidden sector spectrometer
2. Via scattering in nuclear emulsion

} Generic signatures predicted by many new physics models

Zero Background **crucial to study hidden sector decays**

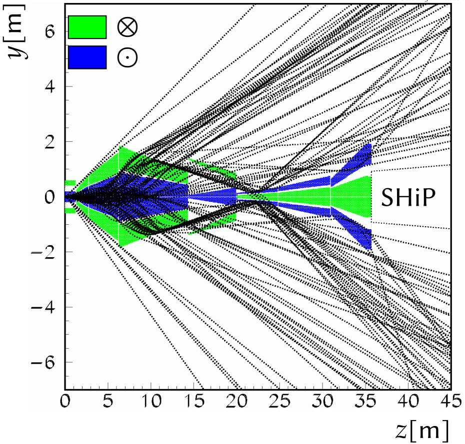
Crucial challenge: Zero background

- Passive hadron absorber
- Active muon shield that has to reduce muon flux by at least 6 orders of magnitude
- kinematic range of muons up to $p \sim 350\,\mathrm{GeV}$
- kinematic range of muons up to $p_T \sim 8\,\mathrm{GeV}$

The muon shield is the critical component to optimise to maximise the experimental acceptance

- A measurement of the muon spectrum for the SHiP target at the H4 test-beam at CERN's SPS is planned for this summer
  - Obtain 10^{11} protons on target, c.f. 10^{10} currently available in simulation

[2017 JINST 12 P05011]



Goals & Challenges of the muon shield optimisation

Goal: Optimisation using *full simulation* with `FairShip` framework for every evaluation to *optimise performance vs. cost* and *provide robustness by optimising for a lower field strength*.

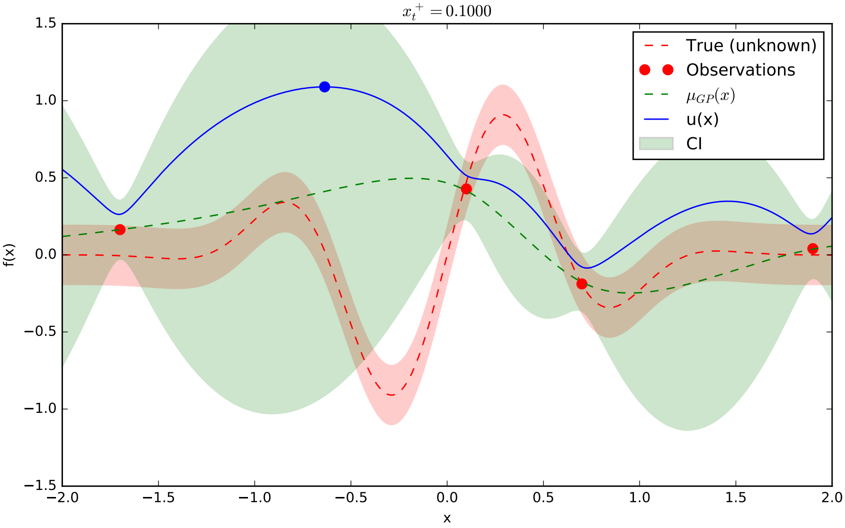
Challenges

- Doubly statistically limited
  - Not enough simulation
  - Not enough computing power to use entire simulation for optimisation
- Underlying physics inherently stochastic
  - Nearly identical configurations may have very different performance
  - With a different random seed entirely different muons pass the shield

→ Evaluation of points very expensive, gradient information not available and can not be approximated

- Even with a simple parametrisation we have ~50 free parameters (lengths), each varying from cm to m

Introduction to Bayesian Optimisation using a 1D example*



*Based on scikit-optimize documentation

How we use Bayesian Optimisation

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Not quite as simple as this example:

- Bayesian optimisation does not scale well for high-dimensional problems.
- Computing model imposes additional constraints.
  - 1600 cores available at YANDEX[†]
  - Make up to 100 guesses at once (with 16 nodes parallelising every function evaluation)
- Use `scikit-optimize` implementation of Bayesian optimisation DOI 10.5281/zenodo.1170575.
- Use Gaussian processes and random forests as surrogate models.
- Reduce muon sample by factor ~40 to speed up evaluation and even out coverage of phase space:
  - Currently:
    1. study the importance of different regions of the phase-space
    2. reduce and re-weight manually
  - Evaluating importance sampling and other options

[†]Russian internet company which contributes to LHCb, COMET, CMS and SHiP with its machine learning expertise and computing power

Loss function

$$f(W,\chi_\mu) = \begin{cases} 10^8 & \text{if } W > 3\,\text{kt} \\ (1 + \exp(10 \times (W - W_0)/W_0)) \times (1 + \sum_\mu \chi_\mu(x_\mu)) & \text{otherwise,} \end{cases}$$

where:

- W weight of the muon shield
- W_0 weight of the baseline
- χ_μ weighted position of muon μ passing a sensitive plane at position x_μ.

Note:

- Penalise muons entering the acceptance
- Length optimised implicitly via the weight
- Weight cut-off as regularisation

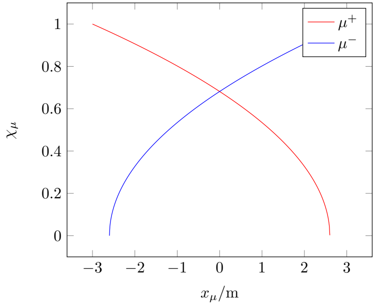
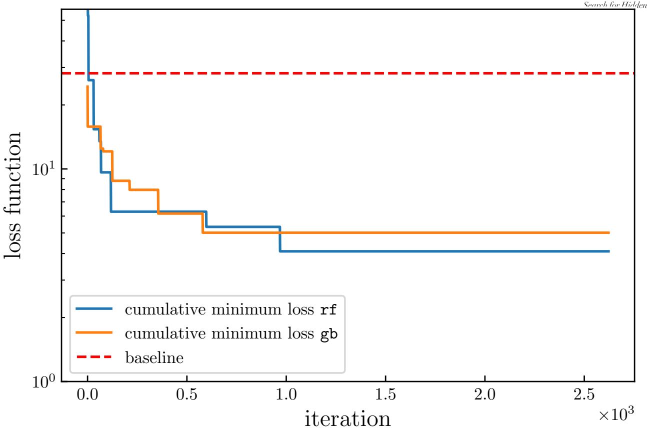


Figure 1: $\chi_\mu(x_\mu)$

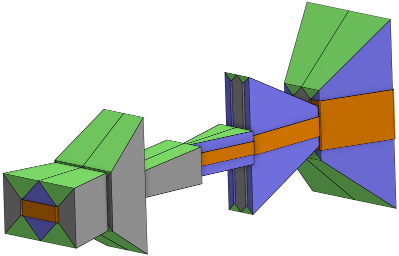
Loss function continues to evolve with technological constraints and background studies.

Optimisation convergence

- Cumulative loss: exploring points with high uncertainty part of algorithm, only cumulative loss is meaningful
- Two optimisers shown here: still evaluating different regression algorithms to determine which performs best
- Performance here is on the reduced muon sample: perform follow-up studies on the full dataset to confirm performance



Results



- Significant reduction in weight (⟶cost)
- Same performance with significantly reduced magnetic field

Configuration	length/m	weight/kt	reduced sample	full sample
baseline @1.8 T	34.60	1.72	27±5	70±15
new optimum @1.7 T	34.82	1.28	22±3	42±6

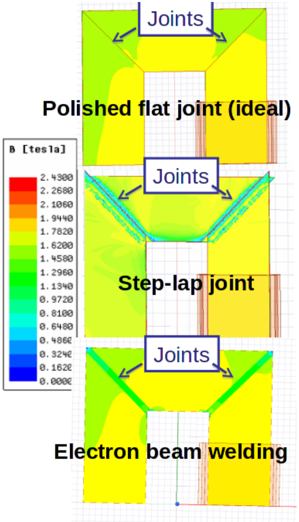
Technology & Prototyping

Grain oriented steel

- Allows to achieve fields of up to 1.8 T with warm magnets
- Manufacturing of SHiP will push the limits of the technology:
  - Scale of muon shield exceptional
  - Several techniques need to be evaluated for the joints of the magnets

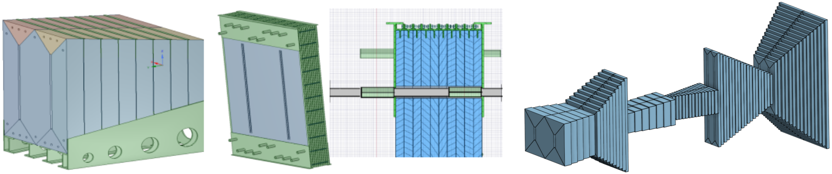
Optimise technology as well as geometry

- Several prototypes will be produced this year, and the most promising will be tested with beams at CERN ⟶ Part of the CERN/Imperial team testing the technology



Conclusion and further work

- Found new configuration for comprehensive design study.
- Have an algorithm that works and can be used as base for further improvements.
- Optimisation infrastructure is now also used for optimisation of other subsystems.



Future work

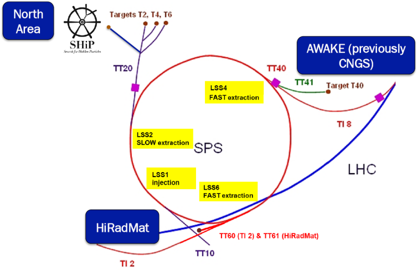
- Fully automate process, add additional constraints to loss function and improve the shield further!
- Collaboration with engineers at MISIS to progress to a detailed engineering design and prototypes.

Backup

Crucial challenges

Maximise intensity and mass reach

- Intense proton beam from the SPS @400 GeV at the new beam dump facility (BDF) in the North Area
- Very dense target of $12 \times \lambda_{int}$
  - abundant production of heavy flavour
  - reduced neutrino production from π and K decays
- Number of protons per cycle similar to CNGS, but slow instead of fast extraction
- Operation in parallel with LHC, other beam-lines at the SPS



Sensitivity: HNL

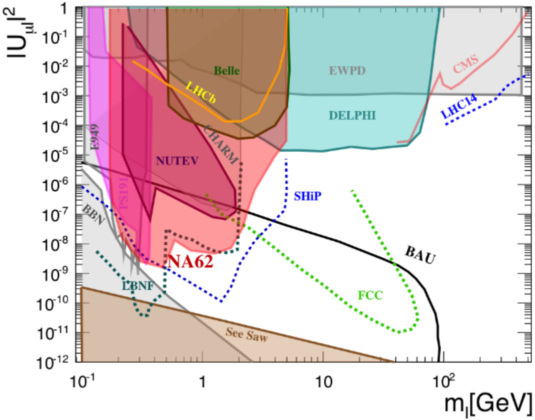


Figure 2: HNL sensitivity at SHiP for νMSM with $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$ and a normal neutrino mass hierarchy.

- Best sensitivity up to charm kinematic limit
- Significant contribution from B-decays

Theoretical limits from:

- Baryon asymmetry of the universe (BAU)
- Big bang nucleosynthesis (BBN)
- Model-independent limit for any Seesaw model

NB: Before re-optimisation

Sensitivity: Dark Scalars

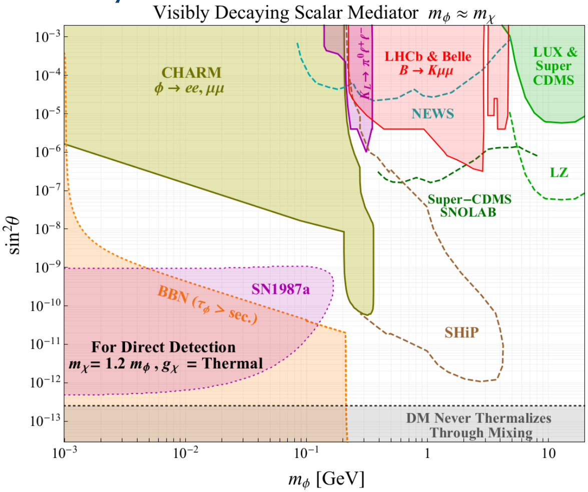


Figure 3: Dark scalar sensitivity at SHiP.

NB: Before re-optimisation

- For short lifetimes B-factories and LHCb best
- SHiP covers unique parameter space complementing other experiments
- Large contribution from B-decays at SHiP
- "Hole" at $c\tau \sim \mathcal{O}$(m), where lifetime is too short for SHiP and too long for B-experiments

Sensitivity: Dark Photons

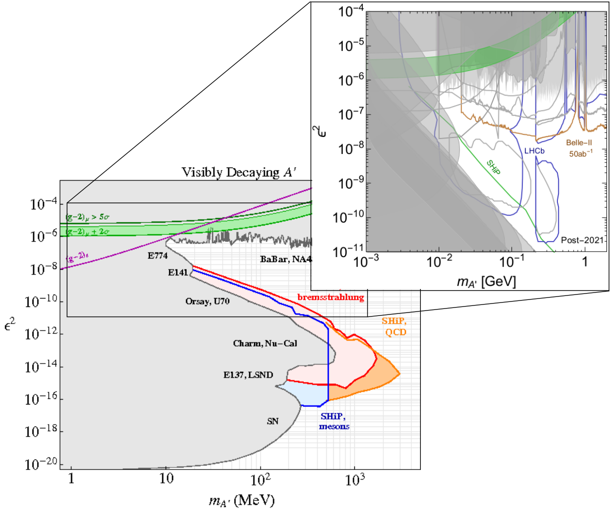


Figure 4: Dark photon sensitivity at SHiP.

- Based on $> 10^{20}\gamma$ at SHiP over 5 years
- Visible decays of dark photons
- Produced in QCD, bremsstrahlung and meson decays
- *No production via EM showers yet → Work in progress*
- Complementary to regions studied by other experiments
- Top-right edge of sensitivity determined by short lifetime

NB: Before re-optimisation

Sensitivity: Light Dark Matter

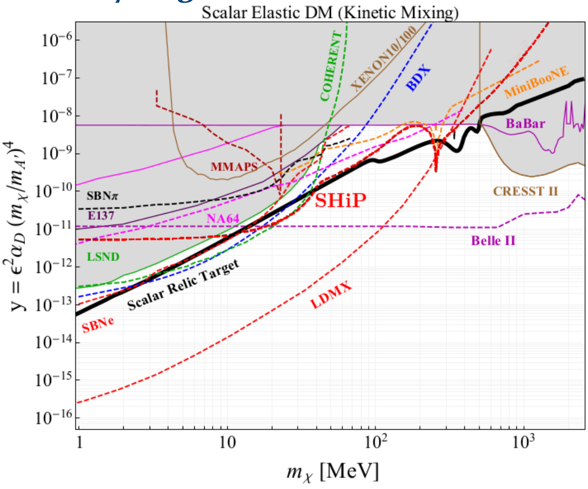


Figure 5: Light dark matter sensitivity at SHiP for $\frac{m_{A'}}{m_\chi} = 3$.

- For dark matter lighter than WIMPS "direct detection" experiments quickly lose sensitivity.

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Two approaches:

- missing mass/energy searches ($\propto U^2$)
- scattering/recoil ($\propto U^4$)

SHiP: *Indirect* detection via electron and nuclear recoil in nuclear emulsion:

- Main background for electron recoil from ν_e scattering, but differences in the kinematics can be exploited.
- *Preliminary; cascade production not yet implemented* → already best sensitivity for scattering

LDMX@SLAC:

- missing energy at electron beam

NB: Before re-optimisation

Crucial challenges

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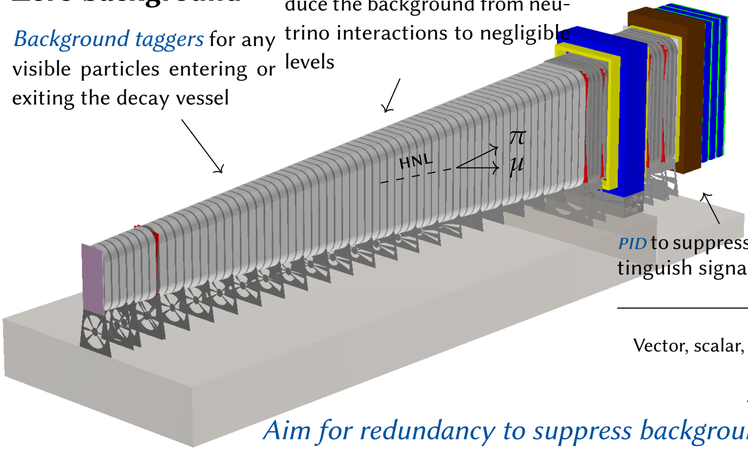
Zero background

Background taggers for any visible particles entering or exiting the decay vessel

Evacuated decay vessel to reduce the background from neutrino interactions to negligible levels



- *Timing* to suppress combinatorial background from muons
- *Tracking* for vertexing and impact parameter measurement

PID to suppress background and distinguish signal final states:

Particle	Final states
HNL, neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho$
Vector, scalar, axion portals; goldstino	$\ell^{\pm}\ell^{\mp}$
HNL, neutralino, axino	$\ell^{\pm}\ell^{\mp}\nu_{\ell}$
Axion portal, sgoldstino	$\gamma\gamma$
Sgoldstino	$\pi^{0}\pi^{0}$

Aim for redundancy to suppress background