SHADOWS
Search for Hidden And Dark Objects With the SPS

INFN-LNF
INFN-Ferrara
INFN-Bologna
University of Bologna
CERN
Royal Holloway London
University of Mainz (excellence cluster)
University of Heidelberg
Karlsruhe Institute of Technology
University of Freiburg
INFN-Naples
INFN- Rome3
Charles University, Prague
University of Groningen, The Netherland

+ the invaluable support of the CBWG, NACONS team, and CERN-DT Depart.

SPSC Open Session – November 2022
The Collaboration has doubled in a few months

PS: since the submission (4 Nov) one more group joined: INFN-Roma1
Introduction to the Physics Case
Evidence for New Physics

Atoms

In Energy chart they are 4%.
In number density chart $\sim 5 \times 10^{-10}$ relative to $\gamma$

We have no idea about DM number densities. (WIMPs $\sim 10^{-8}$ cm$^{-3}$; axions $\sim 10^9$ cm$^{-3}$. Dark Radiation, Dark Forces – Who knows!).

Lack of precise knowledge about nature of dark matter leaves a lot of room for existence of dark radiation, and dark forces – dark sector in general.

New IR degrees of freedom = light (e.g. sub-GeV) BSM states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out:

\[ L_{\text{SM+BSM}} = -m_H^2 (H^+_\text{SM}H_{\text{SM}}) + \text{all dim 4 terms } (A_{\text{SM}}, y_{\text{SM}}, H_{\text{SM}}) + \]
\[ (W.\text{coeff.} / L^2) \times \text{Dim 6 etc } (A_{\text{SM}}, y_{\text{SM}}, H_{\text{SM}}) + \ldots \]
\[ \text{all lowest dimension portals } (A_{\text{SM}}, y_{\text{SM}}, H, A_{\text{DS}}, y_{\text{DS}}, H_{\text{DS}}) \times \text{portal couplings} \]
\[ + \text{dark sector interactions } (A_{\text{DS}}, y_{\text{DS}}, H_{\text{DS}}) \]

SM = Standard Model
DS – Dark Sector

Golden rule of any EFT approach: first look at low-dim operators!
The Portal Framework

Expand the SM with the minimal set of operators of lowest dimension
gauge-invariant and renormalizable (all but the pseudo-scalar).
This guarantees that the theoretical structure of the SM is preserved and
any NP is just a simple (natural?) extension of what we already know.

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Photon, $A_\mu$</td>
<td>$-\frac{e}{2\cos \theta_W} F^\mu_\nu B^{\mu\nu}$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Axion, $a$</td>
<td>$\frac{a}{f_a} F_{\mu \nu} E^\mu_\nu$, $\frac{a}{f_a} G_i, \mu \nu \tilde{G}^{\mu \nu}<em>i$, $\frac{\delta</em>{\mu a}}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>

The full set of allowed renormalizable interactions for dark sector with SM, consistent with SM Gauge invariance (plus one notable generalization)

They are representative of broad classes of models:
Each may predict distinct texture of New Physics interactions:
From the portals, the PBC picked up 11 notable benchmark models now widely used

What are Feebly-Interacting Particles (FIPs)?

**Very roughly:**
any NP with (dimensional or dimensionless) effective couplings $\ll 1$

[The smallness of the couplings can be generated by an approximate symmetry almost unbroken, and/or a large mass hierarchy between particles (as data seem to suggest)]

**Fully complementary to high-energy searches.**
Naturally long-lived.
European Strategy for Particle Physics recommendations

"4. Other essential scientific activities for particle physics:

- a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics.

- This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles.

- There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy.
What FIPs can provide us: A notable example

1) Thermal DM candidates that extend the WIMP paradigm in the MeV-GeV range
2) Ultra-light non thermal DM candidates;
3) The simplest theories to explain the origin of CP-symmetry in strong interactions
4) Candidates to explain the origin of neutrino masses and the matter/anti-matter asymmetry in the Universe;

and:
Candidates to address the electro-weak hierarchy problem, possible answers to the flavor puzzle, answers to many astrophysical anomalies,.....

DM available mass range ~ 80 orders of magnitude.
Direct Detection DM searches below a few GeV: A vibrant field.

DM in the MeV-GeV range: a blooming field

DM direct detection experiments are pushing the exploration down to the neutrino floor in the MeV-GeV range. **MeV-GeV range is accessible also by accelerator-based experiments.**
Light DM with thermal origin with a new light Vector Mediator
(with new forces/interactions the Lee-Weinberg bound can be evaded)

Accelerator-based experiments
Production of DM at accelerators (via SM (electron/proton/..) particles)

DM Direct detection experiments
DM scattering with e/protons

$\sigma(DMe^- \rightarrow DMe^-) \sim 3.7 \cdot 10^{-22} \text{cm}^2 \times \left( \frac{10 \text{ MeV}}{m_{DM}} \right)^4 \times y$

Astroparticle, cosmology
Direct DM annihilation (main process to get the thermal relic abundance)

$\Omega_{DM} h^2 \sim \frac{10^9 \text{GeV}^{-1}}{M_{pl}} \frac{1}{\langle \sigma v \rangle}$
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Dataset assumed for sensitivities, beams</th>
<th>Tentative Timescale</th>
<th>References</th>
<th>Benchmarks</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA64-e</td>
<td>3x10^{12} eot, electrons, 100 GeV</td>
<td>&lt; LS3 (2025) (approved)</td>
<td>CERN-SPSC-2018-004 ; SPSC-P-348-ADD-2.</td>
<td>BC1, BC2, BC9</td>
<td>Extrapolation from data</td>
</tr>
<tr>
<td>FASER</td>
<td>150 fb^{-1}, pp@13 TeV</td>
<td>&lt; LS3 (2025) (approved)</td>
<td>arXiv:1812.09139 ; CERN-LHCC-2018-036</td>
<td>BC1, BC9, BC11</td>
<td>Full simulation ? Bkg included?</td>
</tr>
<tr>
<td>NA62-dump</td>
<td>10^{18} pot, protons 400 GeV</td>
<td>&lt; LS3 (2025) (approved)</td>
<td>CERN-SPSC-2019-039 ; SPSC-P-326-ADD-1</td>
<td>BC1, BC4, BC5, BC6, BC7, BC8, BC9, BC10, BC11</td>
<td>Full simulation, bkg from data</td>
</tr>
<tr>
<td>milliQan</td>
<td>3 ab^{-1}</td>
<td>First run: 2022</td>
<td></td>
<td>BC3</td>
<td></td>
</tr>
<tr>
<td>nTOF</td>
<td>6x10^{17} pot, protons, 20 GeV</td>
<td>2022-2023</td>
<td>INTC-I_233</td>
<td>BC1</td>
<td>New experiment</td>
</tr>
<tr>
<td>SHADOWS</td>
<td>Phase1: 10^{19} pot, protons, 400 GeV</td>
<td>LS3 &lt; run &lt; LS4 (2031) LS4 &lt; run &lt; LS5 (2035)</td>
<td>EoI: 2110.08025</td>
<td>BC4, BC5, BC6, BC7, BC8, BC10, BC11</td>
<td>Fast simulation, bkg being estimated using dump data in ECN3</td>
</tr>
<tr>
<td></td>
<td>Phase2: 5 10^{19}, protons, 400 GeV</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

In green: already approved
In black: under consideration
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Dataset assumed for sensitivities, beams</th>
<th>Tentative Timescale</th>
<th>References</th>
<th>Benchmarks</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLEVER/NA62</td>
<td>A few 10^{19} pot/year</td>
<td>After LS4 ?</td>
<td>1901.03199</td>
<td>BC4, BC9, ....</td>
<td>Full simulation, bkg evaluated but not included in results?</td>
</tr>
<tr>
<td>high intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CODEX-b</td>
<td>300 fb^{-1}, pp@14 TeV</td>
<td>2038 (end of HiLumi)CODEX-beta could start after LS3</td>
<td>EOI: 1911.00481</td>
<td>BC4, BC5, BC6, BC7, BC8, BC10, BC11</td>
<td>Fast simulation, background evaluated but not included in results?</td>
</tr>
<tr>
<td>MATHUSLA</td>
<td>3 ab^{-1}</td>
<td>2038 (end of HiLumi)</td>
<td>Physics case: 1806.07396</td>
<td>BC4, BC5, BC6, BC7, BC8, BC10, BC11</td>
<td>Fast simulation, no bkg (bkg being evaluated with data)</td>
</tr>
<tr>
<td>FLArE@FPF</td>
<td>3 ab^{-1}</td>
<td>2038 (end of HiLumi)</td>
<td>2109.10905</td>
<td>DM via scattering (BC2)</td>
<td>Fast simulation, no bkg</td>
</tr>
<tr>
<td>FASER-2@FPF</td>
<td>3 ab^{-1}</td>
<td>2038 (end of HiLumi)</td>
<td>2109.10905</td>
<td>BC1, BC4, BC5, BC6, BC7, BC8, BC9, BC10, BC11</td>
<td>Fast simulation, no bkg</td>
</tr>
<tr>
<td>FORMOSA@FPF</td>
<td>3 ab^{-1}</td>
<td>2038 (end of HiLumi)</td>
<td>2109.10905, 2010.07941</td>
<td>BC3</td>
<td>Fast simulation, no bkg</td>
</tr>
<tr>
<td>Gamma Factory</td>
<td>Laser on stripped ions (LHC)</td>
<td>Still undefined.. PoP crucial to understand.</td>
<td>2105.10289 (DP)</td>
<td>BC1, BC6</td>
<td>Fast simulation, no bkg</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Experiment</th>
<th>LAB</th>
<th>Dataset assumed for sensitivities, beam</th>
<th>Timescale</th>
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</tr>
</thead>
<tbody>
<tr>
<td>DarkQUEST</td>
<td>FNAL</td>
<td>$10^{18}$ pot, protons, 120 GeV</td>
<td>2022-2023</td>
<td>BC1, BC4, BC5</td>
<td>Depends on the situation of SpinQUEST (QCD)</td>
</tr>
<tr>
<td>LDMX</td>
<td>SLAC</td>
<td>$4 \times 10^{14}$ eot, electrons 4 GeV</td>
<td>2024-2031</td>
<td>Mostly BC2</td>
<td>Full simulation</td>
</tr>
<tr>
<td>SUBMET</td>
<td>JPARC</td>
<td>$10^{22}$ pot, T2K beam, 30 GeV, protons</td>
<td>First run: 2022-2023</td>
<td>BC3</td>
<td>0.5 M$ already secured from KOREA; status of simulation?</td>
</tr>
<tr>
<td>LUXE</td>
<td>DESY</td>
<td>XFEL, 16.5 GeV e-, 1.5x10^9 e-/burst; 40 (350) TW optical laser</td>
<td>2025-2026</td>
<td>BC1, BC9, BC10</td>
<td>Fast simulation, no bkg</td>
</tr>
<tr>
<td>mu3e</td>
<td>PSI</td>
<td>Muons, 29 MeV, 10^8 $\mu$/sec (10^{10} $\mu$/sec)</td>
<td>Phase-1: 2023 Phase-2: 2029</td>
<td>BC1, ….</td>
<td>Phase-I and phase-II</td>
</tr>
<tr>
<td>PADME</td>
<td>LNF</td>
<td>$e^+, 500 \text{ MeV}$</td>
<td>running</td>
<td>BC1, BC2, BC9</td>
<td>data</td>
</tr>
<tr>
<td>Belle II</td>
<td>KEK</td>
<td>$e^+ e^- \ (Y(4S)); 220 \text{ fb}^{-1} \text{ collected, } 1 \text{ ab}^{-1} \text{ by 2024, } 50 \text{ ab}^{-1} \text{ by 2031++}$</td>
<td>running</td>
<td>BC1, BC2, BC64, BC5, BC6, BC7, BC8, BC9, BC10</td>
<td>data</td>
</tr>
<tr>
<td>T2K ND280</td>
<td>KEK</td>
<td>30 GeV proton beam</td>
<td>running</td>
<td>BC6, BC7, BC8</td>
<td>data</td>
</tr>
<tr>
<td>microBooNE</td>
<td>FNAL</td>
<td>Protons, 8 GeV, $10^{21}$ pot</td>
<td>running</td>
<td>BC2 (DM scattering), others?</td>
<td>data</td>
</tr>
<tr>
<td>Dark MESA</td>
<td>Mainz</td>
<td>e-, 155 MeV, 150 uA</td>
<td>2031+++?</td>
<td>BC1, ….</td>
<td>Full simulation?</td>
</tr>
</tbody>
</table>
FIP related experiments/projects @ accelerators: beyond PBC

<table>
<thead>
<tr>
<th>Experiment</th>
<th>LAB</th>
<th>Dataset assumed for sensitivities, beam</th>
<th>Timescale</th>
<th>Benchmarks</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>CERN</td>
<td>50 fb$^{-1}$ (phase I), 300 fb$^{-1}$ (phase II)</td>
<td>&lt; 2031 (phase I) &lt; 2038 (phase II)</td>
<td>BC1, BC4, BC5</td>
<td>Mass range: $2m(\mu)$ – $B$ (mass). Sensitive mostly to large couplings.</td>
</tr>
<tr>
<td>ATLAS/CMS</td>
<td>CERN</td>
<td>Up to 3 ab$^{-1}$</td>
<td>Now – 2038++</td>
<td>BC1, BC4, BC5, BC6, BC7, BC7, BC9, BC10</td>
<td>Mostly sensitive above 10 GeV and large couplings. Below 10 GeV very limited sensitivity.</td>
</tr>
<tr>
<td>Moedal/MAPP</td>
<td>CERN</td>
<td>Up to 3 ab$^{-1}$</td>
<td>Now – 2038++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FACET</td>
<td>CERN</td>
<td>Up to 3 ab$^{-1}$</td>
<td>HiLumi</td>
<td></td>
<td>Under consideration within CMS</td>
</tr>
<tr>
<td>HyperK near detectors</td>
<td>KEK</td>
<td>??</td>
<td>BC6, BC7, BC8</td>
<td></td>
<td>As T2K-ND280 but larger sample</td>
</tr>
<tr>
<td>DUNE near detectors</td>
<td>FNAL</td>
<td>$10^{22}$ pot (11 years of data taking)</td>
<td>2040++</td>
<td>BC6, BC7, BC8</td>
<td>Several estimates done by theorists.</td>
</tr>
</tbody>
</table>

- Proceedings of the 2020 edition (FIPs 2020) :
Back to SHADOWS.....
Why the ECN3 area?

- Because ECN3/TCC8 has the best 400 GeV primary extracted proton beam line at CERN (and worldwide) and a plethora of hidden sector particles can emerge from interactions of a high-energy proton beam with a dump.
  - NA62 nominal intensity is $3 \times 10^{12}$ ppp with 4.8s pulse duration: $\sim 10^{12}$ pot/sec, up to $2 \times 10^{18}$ pot/year.

- K12 beam intensity proposed to be increased by a factor x6-7 for high intensity K beams and SHADOWS up to $1.2 \times 10^{19}$ pot/year.

<table>
<thead>
<tr>
<th>Physics Experiment</th>
<th>Proton Momentum</th>
<th>3SPS Cycle [s]</th>
<th>Proton / pulse</th>
<th>2Pulses / day</th>
<th>Days / year</th>
<th>POT/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIKE–Phase1</td>
<td>400 Gev/c</td>
<td>4.8 / 14.4</td>
<td>$1.2 \times 10^{13}$</td>
<td>3000</td>
<td>200</td>
<td>$0.72 \times 10^{19}$</td>
</tr>
<tr>
<td>HIKE–Phase2</td>
<td>2.0 $\times 10^{13}$</td>
<td>3000</td>
<td>200</td>
<td>$1.2 \times 10^{19}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIKE–Phase3</td>
<td>2.0 $\times 10^{13}$</td>
<td>3000</td>
<td>200</td>
<td>$1.2 \times 10^{19}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIKE-Dump Mode</td>
<td>400 Gev/c</td>
<td>4.8 / 14.4</td>
<td>$3.2-4 \times 10^{13}$</td>
<td>3000</td>
<td>200</td>
<td>$4.5 \times 10^{19}$</td>
</tr>
<tr>
<td>SHADOWS</td>
<td>400 Gev/c</td>
<td>4.8 / 14.4</td>
<td>$2.0 \times 10^{13}$</td>
<td>3000</td>
<td>200</td>
<td>$1.2 \times 10^{19}$</td>
</tr>
<tr>
<td>BDF/SHiP</td>
<td>400 Gev/c</td>
<td>1.2 / 7.2</td>
<td>$4.0 \times 10^{13}$</td>
<td>5000</td>
<td>200</td>
<td>$4.0 \times 10^{19}$</td>
</tr>
</tbody>
</table>

SHADOWS can collect $5 \times 10^{19}$ pot in ~4 years of data taking starting after LS3 (~2028).
SHADOWS in TTC8/ECN3

On the other side of the NA62 blue wall – in the target area (supervised zone)
**Preliminary Conceptual Layout**
A spectrometer of about 2.5x 2.5 m$^2$ transverse area
~1 m off-axis from beam line
20 m long decay volume,
starting ~10 m downstream of the K12-dump (TAXes)
SHADOWS detector components:
20 m long, in vacuum decay volume, Muon Veto, Tracking System with a (warm) dipole magnet, Timing layer, Electro-magnetic calorimeter, Iron filter and four Muon Stations. Transversal size: 2.5x2.5 m².
SHADOWS can operate when K12 beam line runs in dump-mode.

T10 target is lifted and the 400 GeV primary p beam is sent onto the dump.

The NA62 dump system:

~ 3.2 m, Cu-Fe based

NB: TAX to be replaced in the high-intensity ECN3 era.
Why “off-axis” works: Signal

HNL → πμ illumination @ first SHADOWS tracking station

FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs,...) at the SPS energy are produced with a large polar angle
Why “off-axis” works: Background

Most of the residual background emerging from TAXes are muons and neutrinos that are mostly produced forward (and miss SHADOWS acceptance).

NB: muon deep-inelastic scattering IS simulated in SHADOWS MC
SHADOWS Main Idea: Stay close & stay off-axis!

- **Stay close to the dump:**
  to maximise acceptance for signals with a relatively small detector

- **Stay off-axis with respect to the beam line:**
  to minimize acceptance for backgrounds (mostly peaked forward)
The beam-induced background: the name of the game
Beam-induced background after the dump

Layout of the K12 beamline around the dump

Muons
- neutrinos

Muon illumination after the dump
Muon illumination as a function of the position along the beamline

Entrance decay volume
First Tracking station
Last muon station

Target and TAXes area
NA62 experimental area
The sweeping system: the Magnetized Iron Blocks (MIB)

400 GeV protons

SHADOWS detector

MIB Stage 1

MIB Stage 2
Muon Illumination with the Sweeping System (MIB)
Muon Illumination with the Sweeping System (MIB) at first tracking chamber

<table>
<thead>
<tr>
<th></th>
<th>$\mu^+ + \mu^-$</th>
<th>$\mu^+$</th>
<th>$\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>rate before MIB</td>
<td>100 MHz</td>
<td>50 MHz</td>
<td>50 MHz</td>
</tr>
<tr>
<td>MIB reduction factor</td>
<td>$\sim 120$</td>
<td>$\sim 110$</td>
<td>$\sim 150$</td>
</tr>
<tr>
<td>rate after MIB</td>
<td>0.8 MHz</td>
<td>0.5 MHz</td>
<td>0.3 MHz</td>
</tr>
</tbody>
</table>

$N_{pot} = 10^9$

$N_{pot} = 10^{10}$
Validation of the simulated muon flux with NA62 data

Monte Carlo simulation has been compared against data collected by NA62 in October 2021, when the experiment was successfully operated in beam-dump mode for about 1 week at about 150% the nominal NA62 beam intensity. In this period NA62 collected about 1.5 x10^{17} pot

Excellent agreement in shape, the rate is about 3 times lower in MC than in data. MC rates corrected by this factor.
1. Background: Muon Combinatorial

Muon rate without MIB: 100 MHz in acceptance from NA62 data and MC. MIB reduces it to 0.8 MHz (0.5 MHz $\mu^+$ ad 0.3 MHz $\mu^-$).

$N(\mu \mu) = 0.7$ events in $5 \times 10^{19}$ pot

<table>
<thead>
<tr>
<th>$N_{\mu \mu}/$spill</th>
<th>requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>timing (T)</td>
</tr>
<tr>
<td>$1.2 \times 10^{-2}$</td>
<td>UV</td>
</tr>
<tr>
<td>$2.4 \times 10^{-5}$</td>
<td>CDA&lt;10 mm</td>
</tr>
<tr>
<td>$2.4 \times 10^{-7}$</td>
<td>IP&lt;30 mm</td>
</tr>
</tbody>
</table>

$N_{\mu \mu}/5 \cdot 10^{19}$ pot

0.7 events T & UV & CDA & IP
2. Background: Muon inelastic interactions in dump, MIB and beamline elements

These interactions give signal in the Upstream Veto (UV), form a vertex very close to the boundaries of Decay Volume and do not point back to the impinging point of the proton beam onto the dump. This will not be the dominant background…. 

$N(\mu \text{ inel. Int. }) = \text{no event in acceptance in } 10^9 \text{ pot}$
3. Background: Neutrino inelastic interactions in decay volume

Number of inelastic interactions in 20 m long decay volume filled by air at atmospheric pressure, for $< E_\nu > \sim 5 \text{ GeV}$:

$$N_{\nu, \bar{\nu}_{\text{inel.int.}}(N_{\text{pot}} = 5 \times 10^{19})} = N_{\nu, \bar{\nu}} \times \varepsilon_{\text{acc}} \times P_{\text{inel.int.}} \sim 1.5 \cdot 10^{16} \times 2 \cdot 10^{-15} \sim 30$$

1 mbar vacuum reduces them to < 1 event in $5 \times 10^{19}$ pot

$\text{N}(\nu + \bar{\nu}, \text{inel. int. in decay volume}) < 1 \text{ event in } 5 \times 10^{19} \text{ pot}$

NB: Neutrino DIS with detector+beamline material still to be evaluated.
SHADOWS physics sensitivity for some standard PBC benchmarks

Validation of toy kinematic distributions with SHADOWS full MC (only Geant hit now, no reconstruction yet)
Light Dark Scalar mixing with the Higgs (BC4)

SHADOWS sensitivity to standard PBC benchmarks

5x10^{19} \text{pot}

SHADOWS covers about 4 orders of magnitude in coupling in the mass range 2 M_{\mu} - M_{b}

(Interesting synergy with HIKE-K^+ which dominates below K threshold)
Light Dark Scalar mixing with the Higgs (BC4)

SHADOWS covers about 4 orders of magnitude in coupling in the mass range $2 \, M_\mu - M_b$

(Interesting synergy with HIKE-$K^+$ which dominates below $K$ threshold)

SHADOWS sensitivity to standard PBC benchmarks

ALPs with fermion couplings (BC10)

SHADOWS (5x10^{19} pot) better than FASER2 (3 ab^{-1}), and comparable to CODEX-b (300 fb^{-1}).
HNL with electron coupling (BC6)

HNL – single lepton dominance:

**Between K and D:** SHADOWS is better than CODEX-b and FASER2 with their full dataset.

**Between D and B:** SHADOWS expands by two-three orders of magnitude wrt current bounds (Belle)

Interesting synergy with HIKE-K+ that dominates below K-mass and with HIKE-dump that covers the part forward.
SHADOWS sensitivity to standard PBC benchmarks

HNL – single lepton dominance:

**Between K and D:** SHADOWS is better than CODEX-b and FASER2 with their full dataset.

**Between D and B:** SHADOWS expands by two-three orders of magnitude wrt current bounds (Belle)
Interesting synergy with HIKE-K+ that dominates below K-mass and with HIKE-dump that covers the part forward.
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Derived from F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered).

SHADOWS (5x10^{19} pot) competitive with DUNE for small couplings and extends the mass range towards heavier ALPs and larger couplings.
SHADOWS sensitivity to standard PBC benchmarks


Derived from F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered).

ALPs with W-couplings

\[ C_{BB} = C_{gg} = 0 \]

\[ 5 \times 10^{19} \text{ pot} \]

ALPs with gluon-couplings

\[ C_{gg} = C_{WW} = C_{BB} \]

\[ 5 \times 10^{19} \text{ pot} \]

SHADOWS (5x10^{19} pot) competitive with DUNE for small couplings and extends the mass range towards heavier ALPs and larger couplings.
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @ SHADOWS!

- **SHADOWS**
- **NaNu = North Area Nu detector**

- **K12 beam**

---

**Estimated Muon Background for 4x10^19 POT**

**Muon illumination at NaNu position**

**Neutrinos illumination at NaNu position**

**Predicted Neutrino Kinematics**

\[
p (400 \text{ GeV}) + p (0 \text{ GeV})
\]

Pythia8 QCD Processes

**Arbitrary Units**

Position Y [m]

Position X [m]
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @SHADOWS!

NaNu = North Area Nu detector

NaNu layout

NaNu Magnet (already available at CERN)
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @SHADOWS!

\( \nu_t \) interaction events in NaNu (including BRs and efficiencies)

<table>
<thead>
<tr>
<th></th>
<th>( \tau \to e )</th>
<th>( \tau \to \mu )</th>
<th>( \tau \to h(\pi^\pm) )</th>
<th>( \tau \to 3h(3\pi^\pm) )</th>
<th>( \bar{\tau} \to e )</th>
<th>( \bar{\tau} \to \mu )</th>
<th>( \bar{\tau} \to h(\pi^\pm) )</th>
<th>( \bar{\tau} \to 3h(3\pi^\pm) )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BR</strong></td>
<td>0.17</td>
<td>0.18</td>
<td>0.46</td>
<td>0.12</td>
<td>0.17</td>
<td>0.18</td>
<td>0.46</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Geometrical</strong></td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Decay search</strong></td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>PID</strong></td>
<td>1.0</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total Events</strong></td>
<td>50</td>
<td>50</td>
<td>150</td>
<td>40</td>
<td>30</td>
<td>30</td>
<td>100</td>
<td>30</td>
</tr>
</tbody>
</table>

Geant4 simulated \( \nu \)-interactions in NaNu
Detector design:
requirements & survey of technology options
SHADOWS Conceptual Design: a standard spectrometer (NA62-like)

SHADOWS detector components:
20 m long, in vacuum decay volume, an Upstream Veto, a Tracking System with a (warm) dipole magnet, Timing layer, Electro-magnetic calorimeter, a filter and four Muon Stations.
Transversal size: 2.5x2.5 m².
SHADOWS Upstream (Muon) Veto: MicroMegas

Requirements:
1. efficiency: 99.5%
2. time resolution: o(10 ns) (to allow matching with the other detectors)
3. position resolution: o(cm) (match the backward extrapolation of tracks)
4. rate capability: up to several kHz/cm²

Proposal: **double layer of MicroMegas.**
Interest from groups who built the ATLAS New Small Wheels (P. Iengo, M. Iodice, & collaborators)
SHADOWS Dipole Magnet and Decay Vessel:

Requirements:
- Dipole Magnet: about 1 Tm (warm)
- Decay vessel: 125 m³ in vacuum (1 mbar)

Dipole Magnet design quite advanced.
NA62 magnet-like but:
- Bending power increased by x2
- Power consumption decreased by x10.

Dipole Magnet and Decay Vessel being designed at CERN (CERN –DT) (P. Wertelaers, Burkhard Schmidt, and CERN-DT department). Overall detector integration responsibility: Alessandro Saputi (INFN-Ferrara)
SHADOWS Tracker: NA62 straws or SciFi

Requirements:
- vertex resolution over 20 m long decay volume: $\sigma_{xy} \sim 1$ cm
- impact parameter resolution at $o(30)$ m distance: $\sigma(IP) < \text{few cm}$
- must operate in vacuum (1 mbar or so).

Two options under scrutiny:
1. NA62 STRAW tubes
2. Fibre Tracker (LHCb)

[Hans Danielsson (CERN, Project leader of the NA62 Straws) and Prof. Ulrich Uwer (Heidelberg, Project leader of LHCb SciFi) are in SHADOWS]
Requirements:
- must identify electrons/photons against muons/hadrons
- $\pi^0$ reconstruction (eg: HNL $\rightarrow$ e rho $\rightarrow$ e $\pi^+\pi^0$ )
- photon directionality: Important for ALP$\rightarrow$$\gamma\gamma$
- mild energy resolution: <10% or so for E=0.5-100 GeV
- granularity defined by the minimum distance of two gammas from $\pi^0$ decays: o(5-10) cm

Options under scrutiny: Shashlik, PbWO4 (from CMS), CALICE, SplitCal
SHADOWS: Muon Detector

1 module = 16/32 tiles
1 station = 8 modules
1 tile = 15x15 cm²,
Direct SiPM readout at the corners
One analog output per tile

Requirements:
- time resolution: \( o(150) \) ps or less
- efficiency: <99% per station
- position resolution: \( o(\text{few cm}) \).
- expected rates: < 100 Hz/cm²

Efficiency > 99.5%
\( N(\text{p.e.})/\text{MIP} = 230 \)
\( \sigma(t) \sim 250 \text{ ps} \)

4-tile prototype built in INFN Bologna/LNF
Preliminary COST & TIMELINE
SHADOWS: TENTATIVE COST
(to be updated when the detector technologies will be frozen)

<table>
<thead>
<tr>
<th>Sub-detectors</th>
<th>Possible Technology</th>
<th>very preliminary) cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Veto</td>
<td>Micromegas</td>
<td>0.3 M€</td>
</tr>
<tr>
<td>Decay Vessel</td>
<td>in vacuum</td>
<td>1 M€</td>
</tr>
<tr>
<td>Dipole Magnet</td>
<td>warm</td>
<td>4-5 M€</td>
</tr>
<tr>
<td>Tracker</td>
<td>SciFi</td>
<td>4 M€</td>
</tr>
<tr>
<td>Timing Layer</td>
<td>small scintillating tiles</td>
<td>0.1-0.2 M€</td>
</tr>
<tr>
<td>ECAL</td>
<td>Shashlik</td>
<td>2-3 M€</td>
</tr>
<tr>
<td>Muon</td>
<td>scintillating tiles</td>
<td>0.4-0.5 M€</td>
</tr>
<tr>
<td>TDAQ &amp; offline</td>
<td>NA62-based</td>
<td>o(1-2) M€</td>
</tr>
</tbody>
</table>

**Total SHADOWS** 12.4-15.5 M€

**Total NaNu** 1.960 €

NB: the cost estimate is based on prices pre-Ukraine war
Jan 2022: SHADOWS EoI to SPSC
Nov 2022: SHADOWS LoI to SPSC
March 2023: decision about high-intensity beamline upgrade
Sept-Oct 2023: SHADOWS Proposal
End 2023: Decision about SHADOWS.
Conclusions

✓ SHADOWS is a proposed proton beam dump experiment for FIP physics that can be built in ECN3 and take data concurrently to HIKE (operated in beam-dump mode).

✓ SHADOWS (5x10^{19} pot) has similar/better sensitivity than CODEX-b (300 fb^{-1}) and FASER2 (3 ab^{-1}) for FIPs from charm/beauty:
  ⇒ It naturally complements HIKE-dump that is mostly sensitive to very forward objects, and HIKE-K that is mostly sensitive to FIPs below the K-mass.

✓ NaNu@SHADOWS can enrich the physics programme with active neutrino physics
  ⇒ it naturally complements FASERnu@LHC and SND@LHC covering a different region in phase space.

✓ ECN3 with SHADOWS+HIKE can become a “hot spot” on worldwide scale for FIP physics after LS3, fully compatible with a superb flavor programme in ECN3.
SPARES
Preliminary BDF and HIKE prompt dose rates

**BDF**

4*10^{13} p/spill every 7.2 s (355 kW)

**HIKE**

2*10^{13} p/spill every 14.4 s (90 kW)

*With current NA62 shielding*

Values averaged in \( x = [-20, 20] \) wrt. beam axis
Preliminary BDF and HIKE prompt dose rates

**BDF**

$4 \times 10^{13}$ p/spill every 7.2 s (355 kW)

**HIKE**

$2 \times 10^{13}$ p/spill every 14.4 s (90 kW)

*With preliminary shielding design as presented at PBC Annual Workshop*
The Dark Scalar:
SHADOWS vs SHiP
Comparison of sensitivity: SHADOWS (10^{19} pot, 1 year) vs SHiP (2 \times 10^{20} pot, 5 years)

Comparison between Alexey’s and Gaia’s estimate: the lower bounds agree within a factor of 2
(some difference due to Alexey’s bounds at 95% CL and Gaia’s bounds at 90% CL)
Still some mismatch in the upper bound between 1 and 2 GeV to be cross-checked.
(This region will be covered anyhow by LHCb well before SHiP/SHADOWS)
SHADOWS meeting with SHiP people May 2021

Comparison of sensitivity: SHADOWS (5x10^{19} pot, 5 years) vs SHiP (2x10^{20} pot, 5 years)

SHADOWS vs SHiP: similar area covered, just shifted.
Comparison of sensitivity: SHADOWs (5x10^{19} pot, 5 years) vs SHiP (2x10^{20} pot, 5 years)

SHiP sensitivity is dramatically changed wrt the past.

PBC workshop, Nov. 2022.
Sensitivity depends upon:

1. Underlying theory model
   (for light dark scalars, there are large non-perturbative effects in the lifetime computation that affect the sensitivity);

2. Geometry

3. Number of protons-on-dump.
Dark Scalars: Branching Fractions

Dark Scalar hadronic widths: a longstanding (non-perturbative) theoretical problem

Winkler, 1809.01876 and references therein (see also Boyarsky et al., 1904.10447)

![Graph showing branching fractions as a function of mass](image)

For Scalar, hadronic decays are dominant immediately above the 2 m(pi) threshold. Non-perturbative resonance effects around 1 GeV due to interference with 4 pi channel.
Dark Scalars: Branching Fractions

PBC recommendation: use the Donoghue et al. computation

This peak affects the lifetime that around 1 GeV becomes very short.
I did not attempt to repeat the non-perturbative calculations (of course!) but I used their findings numerically. I am not considering the $S \rightarrow \tau \tau$ channel for the time being.
Plugging together all the partial decay widths I can evaluate the lifetime…

... and I can recover Alexey’s computations…
...and I can recover Donoghue’s computations too..

**Dark Scalars: Lifetime**

![Graph showing dark scalar lifetime vs. mass](image)

- Perturbative
- Voloshin
- Higgs Hunters Guide
- Raby & West, Duchovni
- Truong & Willey
- Donoghue et al.

The graph plots the lifetime of dark scalars against the mass in GeV, with lines for different theoretical approaches.
Sensitivity depends upon:

1. Underlying theory model
   (for light dark scalars, there are large non-perturbative effects in the lifetime computation that affect the sensitivity);

2. Geometry

3. Number of protons-on-dump.
For a (relatively) short lived dark scalar, the closer to the dump you go, the more you get.
Lateral view (almost to scale): including distance from the dump

Not only because we sample the lifetime at the very beginning but because we intercept more flux…
Momentum distribution of a light dark scalar

\[ M = 0.7 \ \text{GeV} \]
\[ \sin^2 \vartheta = 10^{-8} \]

Red: light dark scalar decays between \( z_{\text{min}} \) and \( z_{\text{max}} \)
Blue: Red + at least two charged tracks in acceptance

SHiP

SHADOWS

NA62

SHADOWS acceptance selects low-p candidates, NA62 acceptance high-p (very boosted) candidates
Transverse Momentum distribution of a light dark scalar

Red: light dark scalar decays between $z_{\text{min}}$ and $z_{\text{max}}$
Blue: Red + at least two charged tracks in acceptance

SHiP

SHADOWS

NA62

SHADOWS acceptance selects high-pT candidates (off-axis), NA62 acceptance low-pT candidates (on-axis & far away)

$M=0.7\ \text{GeV}$
$\sin^2\vartheta = 10^{-8}$