# Beam dump experiments

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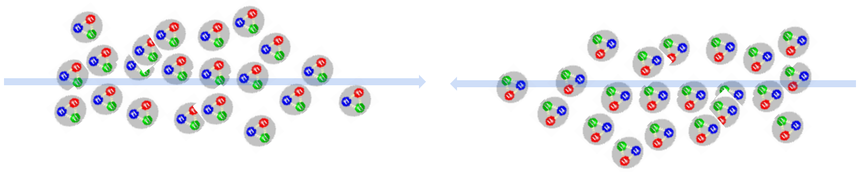
Future Colliders for Early-Career Researchers,
CERN 27/09/2023

# Beam dump experiments

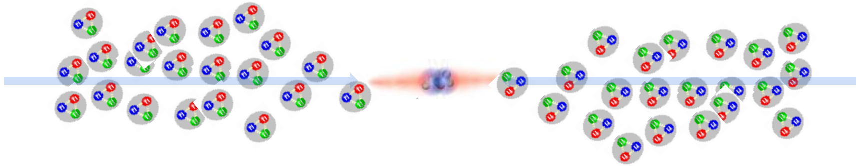
Colliders experiments



Fixed – target experiments

# Beam dump experiments

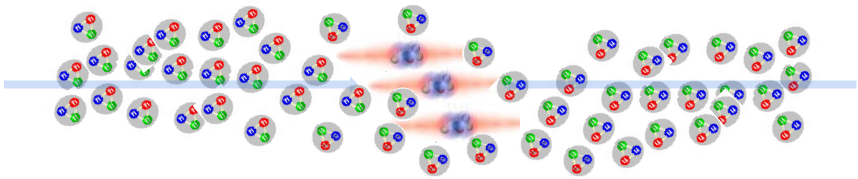
Colliders experiments



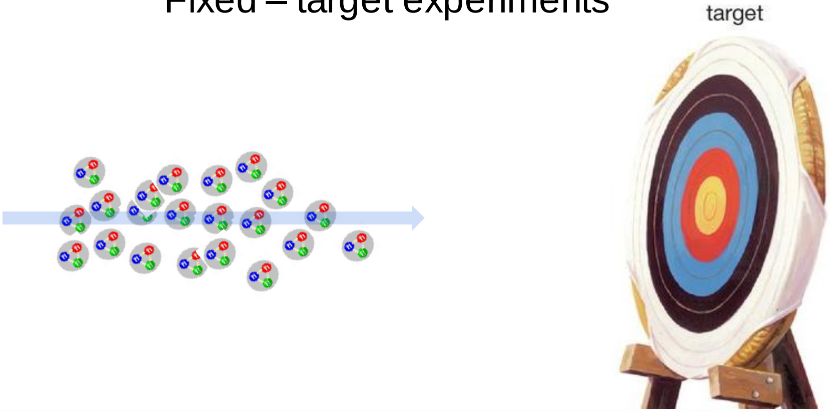
Fixed – target experiments

# Beam dump experiments

Colliders experiments

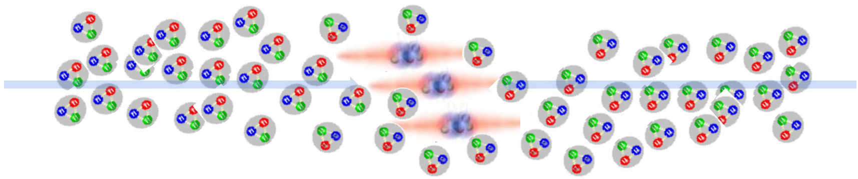


Fixed – target experiments

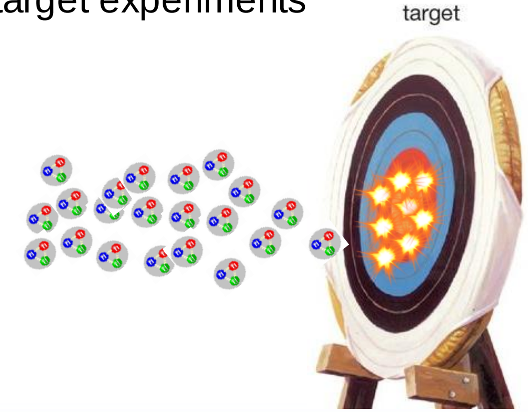


# Beam dump experiments

Colliders experiments

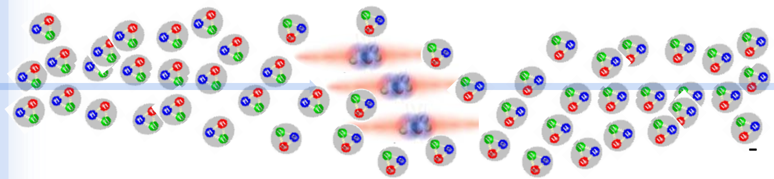


Fixed – target experiments



# Beam dump experiments

## Colliders experiments

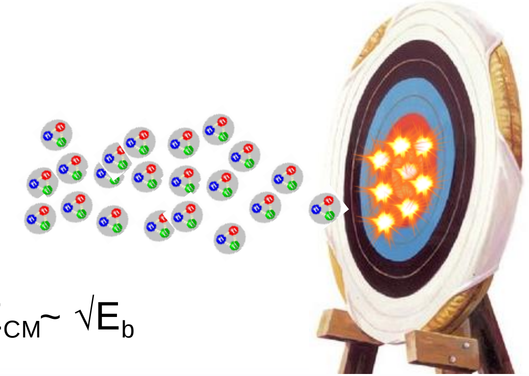


$E_{CM} \sim 2E_b$

- The energy available for the generation of new particles is twice as high as the beam energy.
- The same bending magnets and focusing magnets can be used to accelerate and control the two beams.

- The luminosity is low compared to experiments with fixed targets.
- It is technically difficult to focus the beams to a size small enough to achieve maximum luminosity

## Fixed – target experiments



$E_{CM} \sim \sqrt{E_b}$

- The event rate can be very high
- Compared to colliding beams, experiments are relatively easy to arrange.

- The energy available to generate new particles is a small fraction of the beam energy.

# Beam dump experiments

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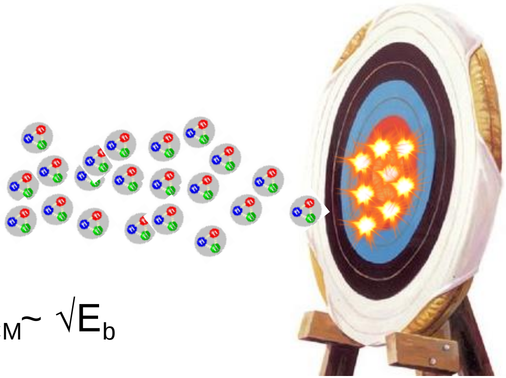
Fixed – target experiments



$E_{CM} \sim \sqrt{E_b}$

# Beam dump experiments

a beam is dumped into a dense block of heavy material to absorb the hadronic cascade as fast as possible.

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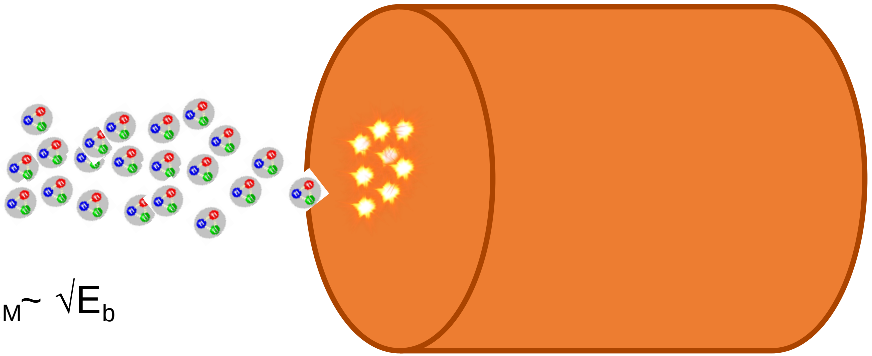
Fixed – target experiments

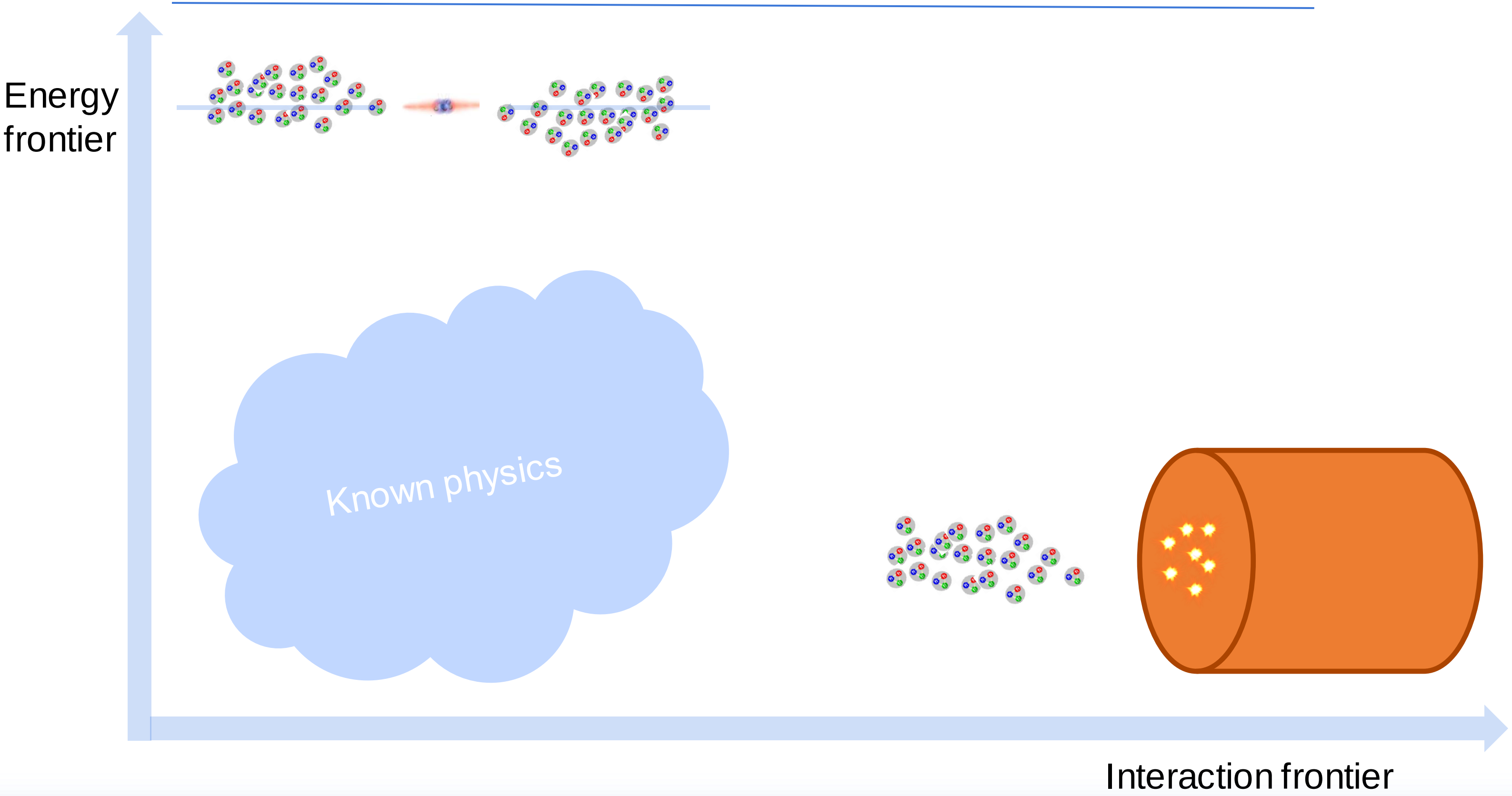


$E_{CM} \sim \sqrt{E_b}$

**∀ Beam dump == Fixed Target**

**∀ Fixed Target ≠ Beam dump**

# Where is new physics?



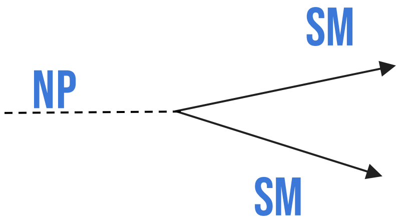
# Where is new physics?

Energy frontier

## What can we know about new particles?

- Their decay rates can be strongly suppressed compared to Standard Model.
- New particles can be long-lived objects.
- They should interact feably with matter.

## How can we find them?



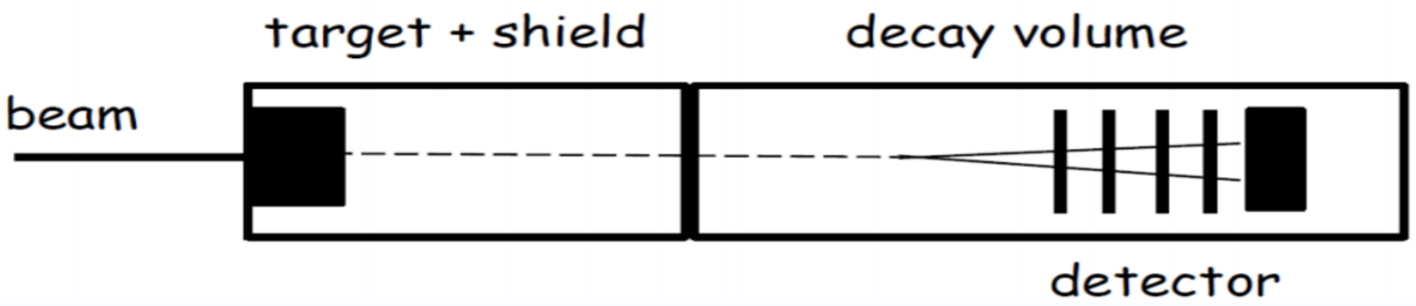

Hidden Sector particles can be explored through their interactions to SM particles

Interaction frontier

# Experimental requirements

**What requirements does it put on us experimentally?**

- High rates of Heavy Flavour Decays
  - High intensity beam
  - Heavy target
- Minimize the flux of SM particles in the detector
  - Hadrons
    - Heavy target
    - Iron stopper to absorb hadrons
  - Muons
    - Muon sweeper



# Beam dump experiments

- **Proton beam dump**
  high fluxes of protons on an appropriate target could produce the Hidden Sector particles in meson decays

| Existing | Proposed |
| --- | --- |
| NA62-BD, MiniBooNE-DM, SeaQuest-BD | SHiP, SHADOWS, RedTop, SBND |

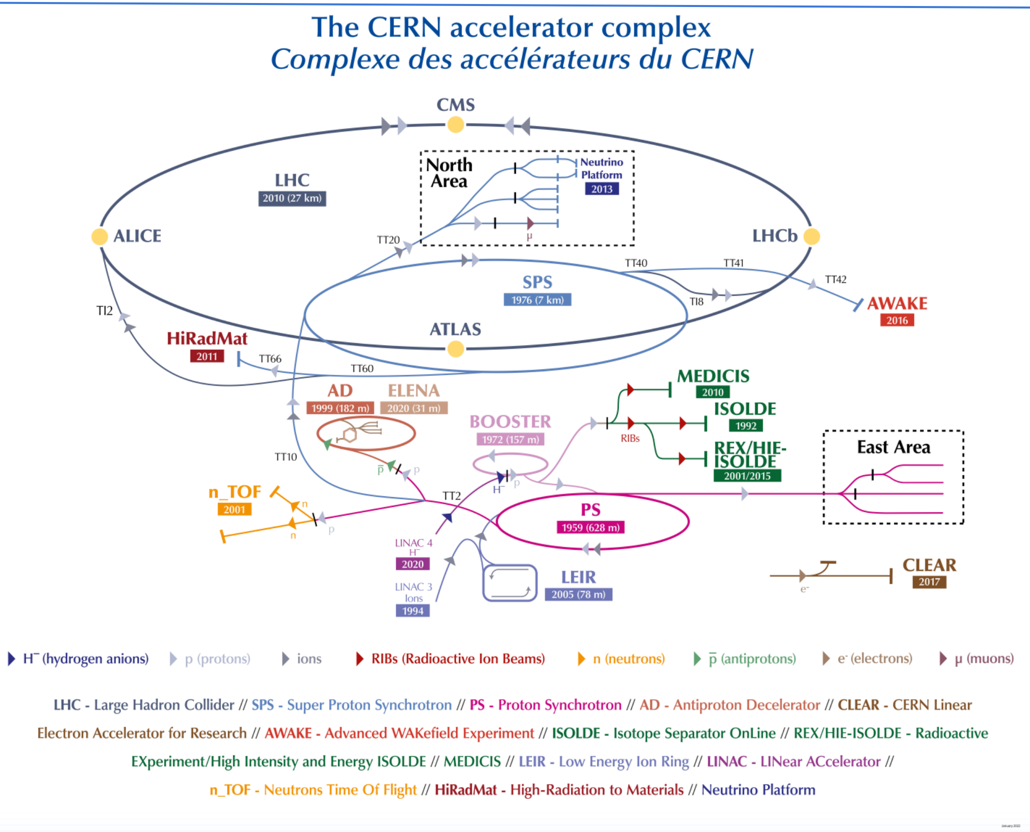
- **Electron beam dump**
  high-intensity multi-GeV electrons impinging on the dump produce, potentially, dark matter candidates

| Existing | Proposed |
| --- | --- |
| NA64e | LDMX, BDX |

- **Muon beam dump**
  the high energy muon beam is 'dumped' into a dense material possibly producing the dark photon and $L_\mu - L_\tau$ gauge boson directly in the target

| Existing | Proposed |
| --- | --- |
| NA64μ | beam dump experiment at the future muon collider μC |

# Beam dump at CERN



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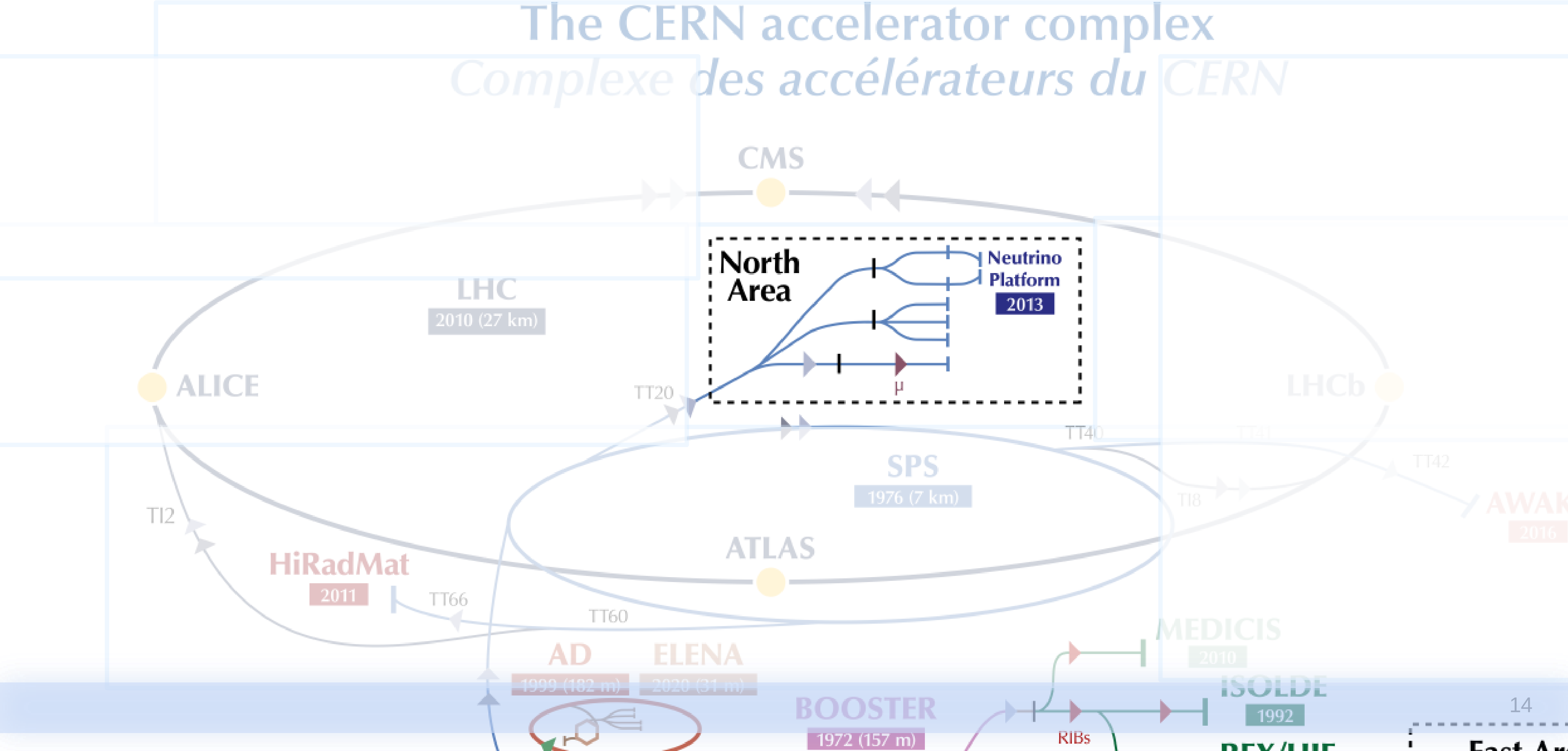
# Beam dump at CERN

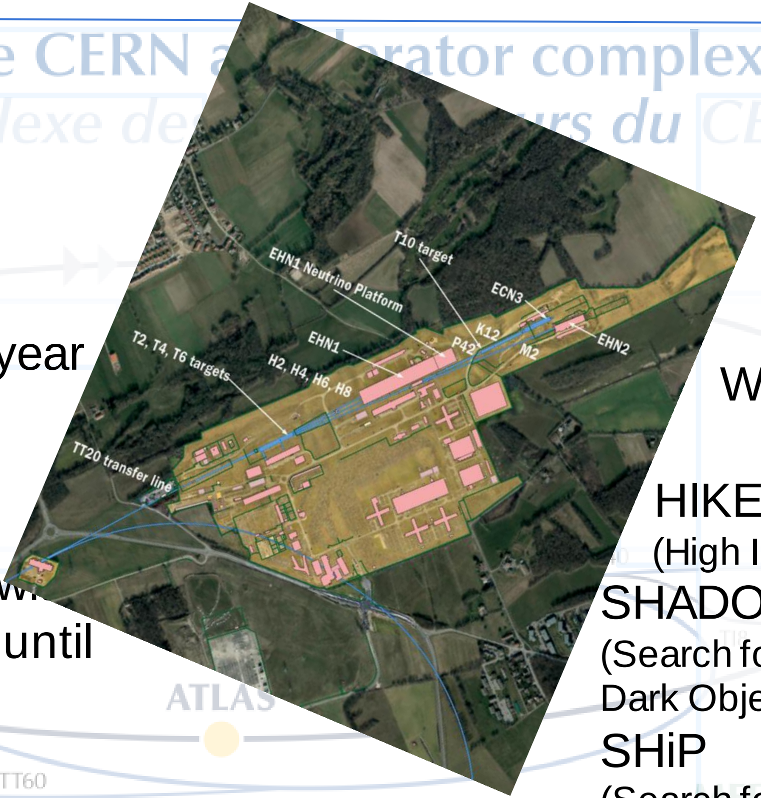


# Beam dump at CERN

- ECN3 - part of the SPS NA
- 400 GeV
- high intensity up to $10^{19}$ pot/year
- high duty cycle

Currently :

the NA62 experiment w... an approved program until LS3.



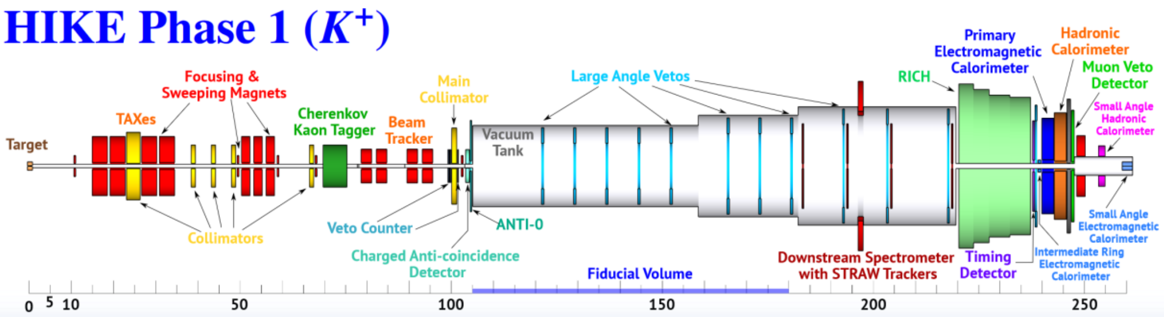

What is after LS3?

HIKE
(High Intensity Kaon Experiment)
SHADOW
(Search for Hidden And Dark Objects With the SPS)
SHiP
(Search for Hidden Particles)

# HIKE

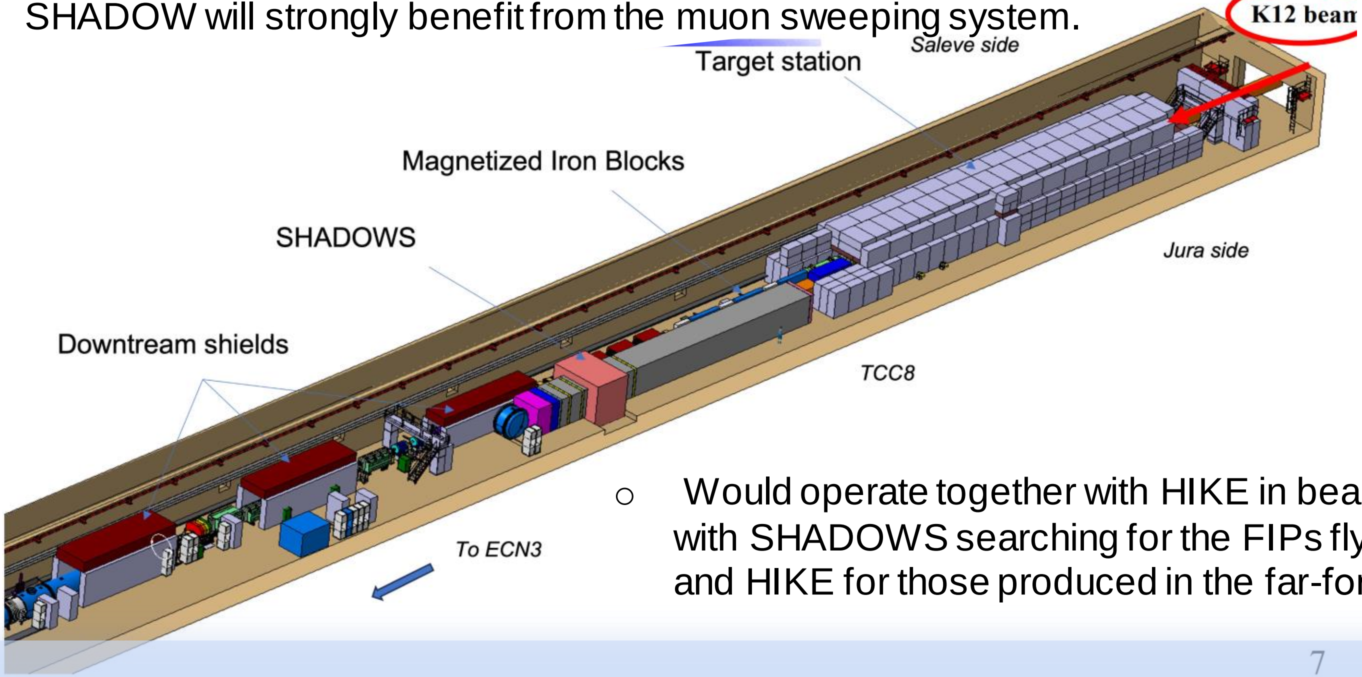
1. The NA62 High Intensity experiment is expected to reach its goal of a 10 % measurement of the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
2. KLEVER aims to measure the branching ratio of $K_L \rightarrow \pi^0 \nu \nu$ to a precision of around 20%, supplementing the $K^+ \rightarrow \pi^+ \nu \nu$ measurement currently being performed by NA62.
3. Operate in beam-dump mode for FIP physics. In this mode, the kaon target is moved aside to let the proton beam of the same intensity be directly dumped on the absorber.

small solid angle coverage -> sensitivity mainly to dark photons and ALPs with photon coupling.



# SHADOW

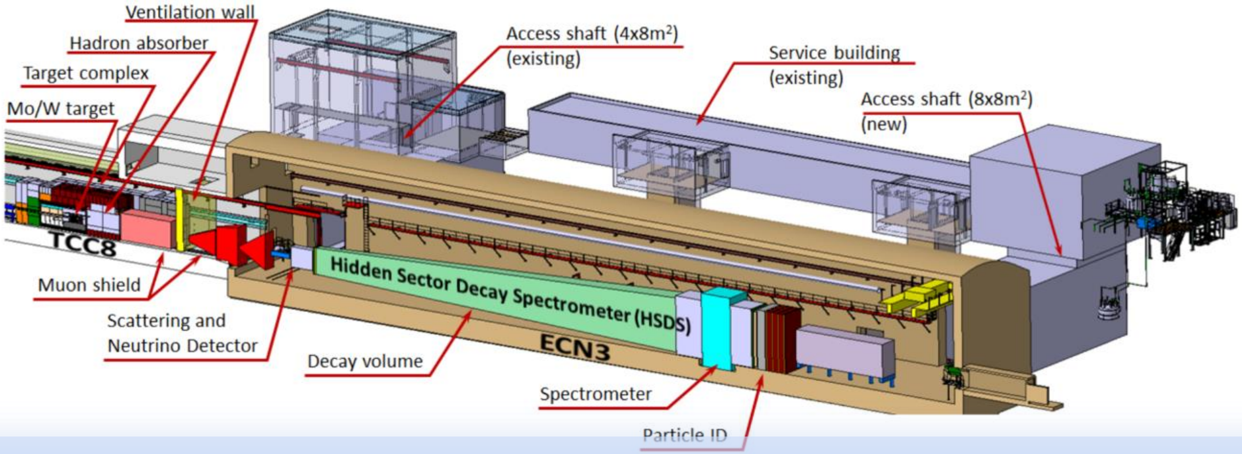
- Off-Axis experiment
- Focus on the search for feebly interacting particles shortly after the beam dump.
- Strong synergies are expected between the two beam dump experiments, where SHADOW will strongly benefit from the muon sweeping system.




- Would operate together with HIKE in beam-dump mode, with SHADOWS searching for the FIPs flying off-axis and HIKE for those produced in the far-forward region.

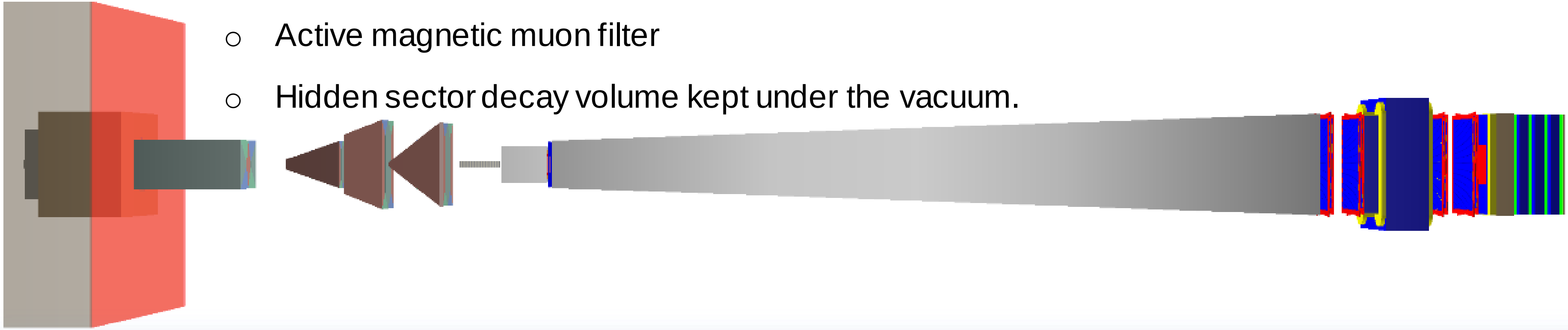
# SHiP

- The experiment was desined and advanced studied for the ECN4 location.
- ESPP concluded that BDF/SHiP as one of the front-runners among the larger scale new facilities investigated within CERN PBC.
- But the project could not be recommended due to financial challenges associated with the other recommendations.
- Relocation in ECN3 and re-optimization studied to reduce the overall BDF/SHiP cost



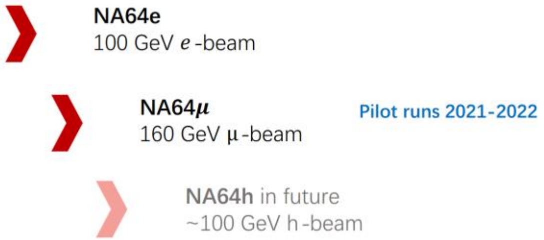
# SHiP

- A dedicated on-axis experiment with the detector located as close as possible to a compact target station housing a target of molybdenum/tungsten that is optimised for FIP physics.
- All the SHiP sub-detectors have undergone at least a first level of prototyping and measurements with the prototypes in test beam
- Spectrometer for DM decays
- High-precision spectrometer for DM scattering and $\nu_\tau$ physics
- Active magnetic muon filter
- Hidden sector decay volume kept under the vacuum.



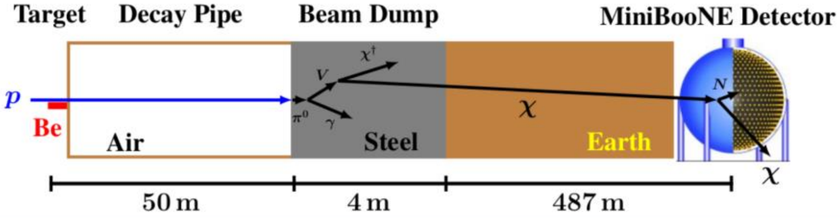
# Another beam dump at CERN: NA64(e,µ, h)

- NA64 experiment on H4 beamline performs a competitive dark photon search with high purity 100 GeV electron beam searches in an active dump
- Search for Dark Sector physics in missing energy events from electron/positron, hadrons, and muon scattering off nuclei.
- In addition to extending the accessible mass range for the light dark matter searches, exploiting muon beams would enable the search for a possible light gauge boson, which would couple predominantly to muons and/or taus.
- The NA64µ program started in 2021 with two pilot runs at the M2 beam-line using the unique CERN 160 GeV/c muon beam.
- In the 2022 beam-time, 1 day of data taking dedicated to accumulate $\sim 2 \times 10^9$ pions on target in order to understand the potential of NA64 to explore dark sectors coupled predominantly to quarks using the missing energy technique.



# Beam dump outside CERN

- The Short-Baseline Neutrino Program at Fermilab built to measure properties of neutrinos, specifically how the flavor of a neutrino changes as it moves through space and matter:
  - SBND, the near detector, 110 m away
  - ICARUS, the far detector, 600 m away
  - MicroBooNE, the detector in-between, 470 m away
- All three SBN Program detectors are Liquid Argon Time Projection Chambers
- Neutrinos & antineutrinos provided by 8 GeV wide band proton beam.
- In 2014 a special beam dump run which suppressed neutrino produced backgrounds while enhancing the search for sub-GeV dark matter via neutral current scattering, resulting in new significant sub-GeV dark matter limits.
- New dedicated beam dump target station -> greater than an order of magnitude increase in search sensitivity for dark matter relative to the recent MiniBooNE beam dump search



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# Beam dump outside CERN

CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

## MAIN BEAM DUMP PROJECTS OUTSIDE CERN

| EXPERIMENT | PERIOD | BEAM | PARTICLES ON TARGET | SIGNATURE | MODELS |
|---|---|---|---|---|---|
| **BDX @JLAB** | ~2024-25 | e 11 GeV | $\sim 10^{22}$ | recoil e | DP, ALPs |
| **LDMX @SLAC** | < 2030 | e 4-8 GeV | $2\ 10^{16}$ | invisible | DP, ALPs |
| **SBND @FNAL** | < 2030 | p 8 GeV | $6\ 10^{20}$ | recoil Ar | DP |
| **DarkQuest @FNAL** | 2024 | p 120 GeV | $10^{18} \rightarrow 10^{20}$ | visible $e^+e^-$ | DP, DS, HNL |
| **LBND @FNAL** | < 2040 | p 120 GeV | $\sim 10^{21}$ | recoil e, N | DP, DS, HNL |

***Recent dedicated experiments demonstrate a regain of interest for beam dumps***

**Flavour factories (BELLE II, …) have also some sensitivity from exotic decays**

Slide is taken from Claude Vallée

# Summary

- Beam-dump experiments are gaining interest again because they can investigate the physics of hidden particles in different ways
- Different beam dump facilities are proposed at different levels
- The SPS provides near-optimal parameters for a state-of-the-art beam-dump facility with unique long range reach
- A decision on the beam dump program at ECN3 should be made by the end of the year
- Exciting times are ahead!

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# BEAM DUMP PROJECTS AT CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

| EXPERIMENT | PERIOD | BEAM | PARTICLES ON TARGET | SIGNATURE | MODELS |
|---|---|---|---|---|---|
| **NA64(e)** | ongoing | e 100 GeV | ~5 $10^{12}$ | invisible & visible $e^+e^-$ | DP, ALPs |
| **NA62-BD** | 2022-25 | p 400 GeV | $10^{18}$ | visible | DP, ALPs |
| **HIKE/SHADOWS** | 2030-40 | p 400 FeV | 5 $10^{19}$ | visible | DP, DS, HNL, ALPs |
| **BDF/SHiP** | 2030-50 | p 400 GeV | 6 $10^{20}$ | recoil & visible | DP, DS, HNL, ALPs |
| **NA64(μ,h)** | > 2024 | μ,h > 100 GeV | 2 $10^{13}$ | invisible | $DZ_{\mu}$ , ALPs |

| | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 |
|---|---|---|---|---|---|---|---|---|---|---|
| HIKE | Detector / Beam Commissioning | | K+ BD | K+ BD | | K+ BD | K+ BD | K+ BD | K+ BD | K+ BD |
| SHADOWS | Installation & Detector / Beam Commissioning | | BD | BD | LS4 | BD | BD | BD | BD | BD |
| SHiP/BDF | Installation & Detector / Beam Commissioning | | BD | BD | | BD | BD | BD | BD | BD |

| | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 | 2046 | 2047 | 2048 |
|---|---|---|---|---|---|---|---|---|---|---|
| HIKE | | K+ BD | K+ | Installation & Detector / Beam Commissioning | K0 | K0 | K0 | K0 | K0 | K0 |
| SHADOWS | LS5 | BD | | | | | | | | |
| SHiP/BDF | | BD | BD | Extension & Detector / Beam Commissioning | BD | BD | BD | BD | BD | BD |

| ECN3 High Intensity - Indicative Schedule & Constraints | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Machine/Facility/Experiments | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 |
| EHN1+2 NA-CONS | Preparation & YETS Implementation Phase | | | LS3 Deployment | | | Commissioning + Operation | | |
| ECN3 HI TT20/TCC2/TDC2/TTs | Engineering Preparation & Implementation Phase | | | Installation (LS3) | | Commissioning | | | |
| ECN3 HI TCC8 Target Complex | Engineering Design Phase | | | Final Opt. & PRR | Preparation, Dismantling | Procurement / Assembly | Procurement/Installation | Installation/ Commissioning | |
| HIKE Experiment | Proposal | TDR | TDR | TDR/PRR | Prototyping | Prototyping & Production | Production | Installation & Detector / Beam Commissioning | |
| SHIP Experiment | Proposal | TDR | TDR | TDR/PRR | Production / ECN3 Dismantling | Construction | Installation & Detector / Beam Commissioning | | |
| SHADOWS Experiment | Proposal | TDR | TDR | TDR/PRR | Production/ Area preparation | Production | Production / Installation | Installation & Detector / Beam Commissioning | |

Figure 20: Preliminary implementation schedule of the ECN3 High Intensity facility.

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DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Leptor
ALP = Axion-Like Particle

## MAIN PAST BEAM DUMP PROJECTS

| EXPERIMENT | PERIOD | BEAM | PARTICLES ON TARGET | SIGNATURE | MODELS |
|---|---|---|---|---|---|
| **E137 @SLAC** | 80's | e 20 GeV | $2\ 10^{20}$ | recoil e | DP, ALPs |
| **E141 @SLAC** | 80's | e 9 GeV | $2\ 10^{15}$ | visible $e^+e^-$ | DP, ALPs |
| **E774 @FNAL** | 80's | e 275 GeV | $5.2\ 10^{9}$ | visible $e^+e^-$ | DP |
| **NuTeV @FNAL** | 90's | p 800 GeV | $2\ 10^{18}$ | visible $\mu$ | HNL |
| **NUCAL @Serpukhov** | 80's | p 70 GeV | $1.7\ 10^{18}$ | visible $\gamma\gamma$, $e^+e^-$, $\mu^+\mu^-$ | DP, DS, ALPs |
| **PS191 @CERN** | 80's | p 19 GeV | $0.8\ 10^{19}$ | visible | HNL |
| **CHARM @CERN** | 80's | p 400 GeV | $2.4\ 10^{18}$ | visible $\gamma\gamma$, $e^+e^-$, $\mu^+\mu^-$ | DP, DS, HNL |

***NB: most past beam dumps were "cheap" by-products of other experiments***

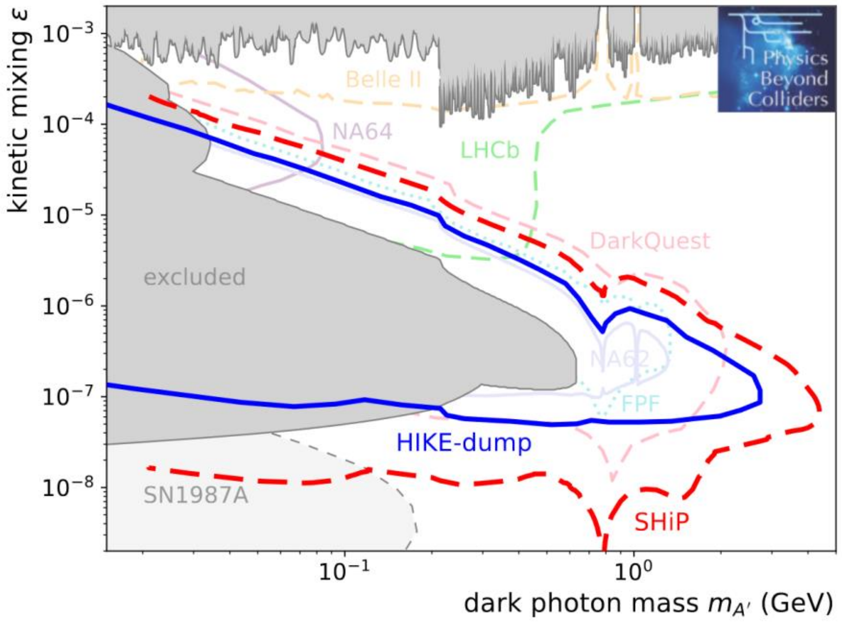


Figure 22: Sensitivity projections for the FIP Physics Centre (FPC) benchmark BC1 (dark photons with kinetic mixing).

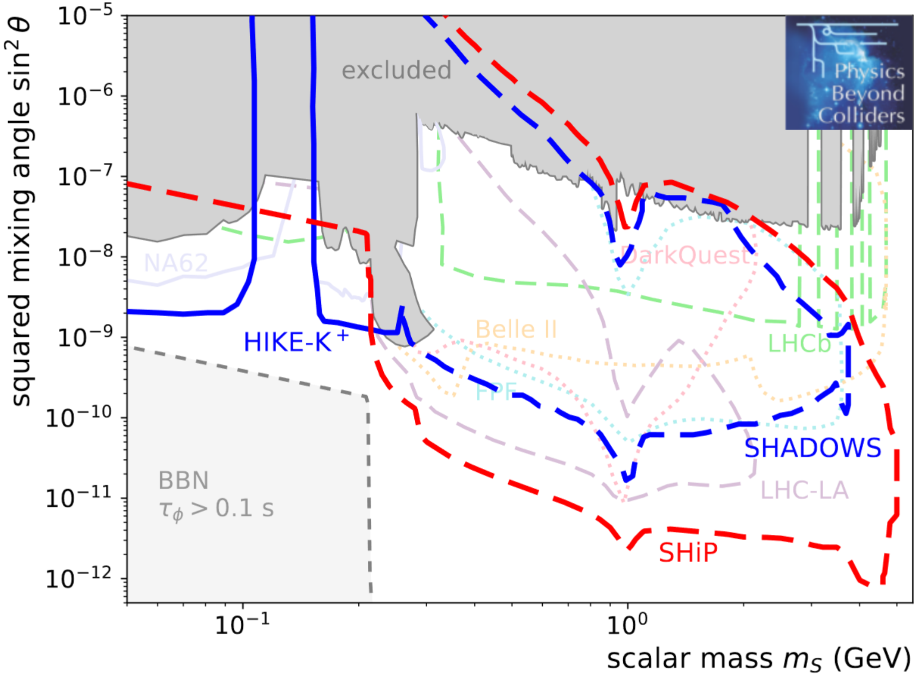


Figure 24: Sensitivity projections for the FPC benchmark BC4 (dark scalars with Higgs mixing). The inclusive branching ratio for $B \to S + X$ is calculated following the appendix of [179], while the decay kinematics are taken from the decay $B^+ \to K^+ S$.

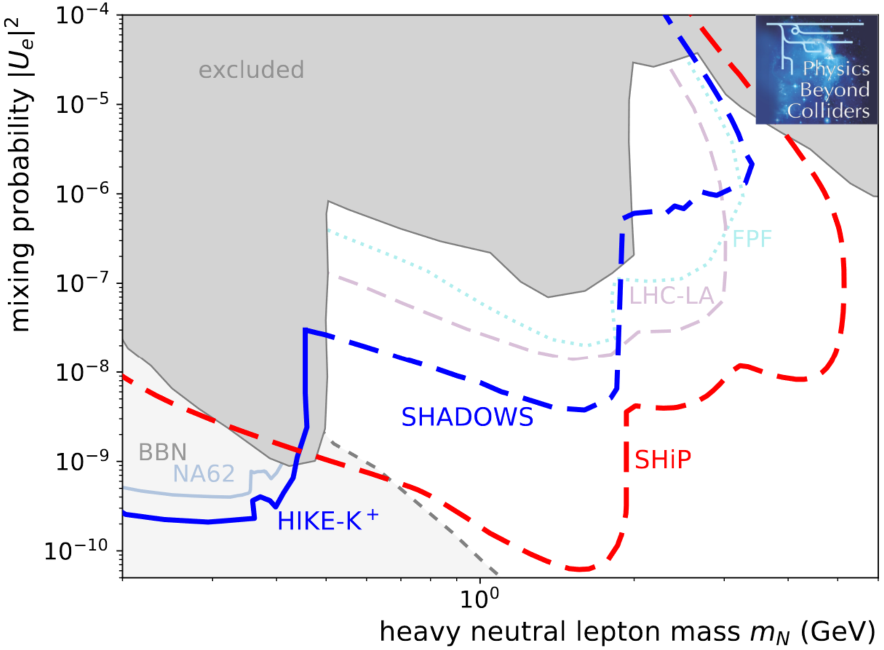


Figure 25: Sensitivity projections for the FPC benchmark BC6 (heavy neutral leptons with electron mixing).

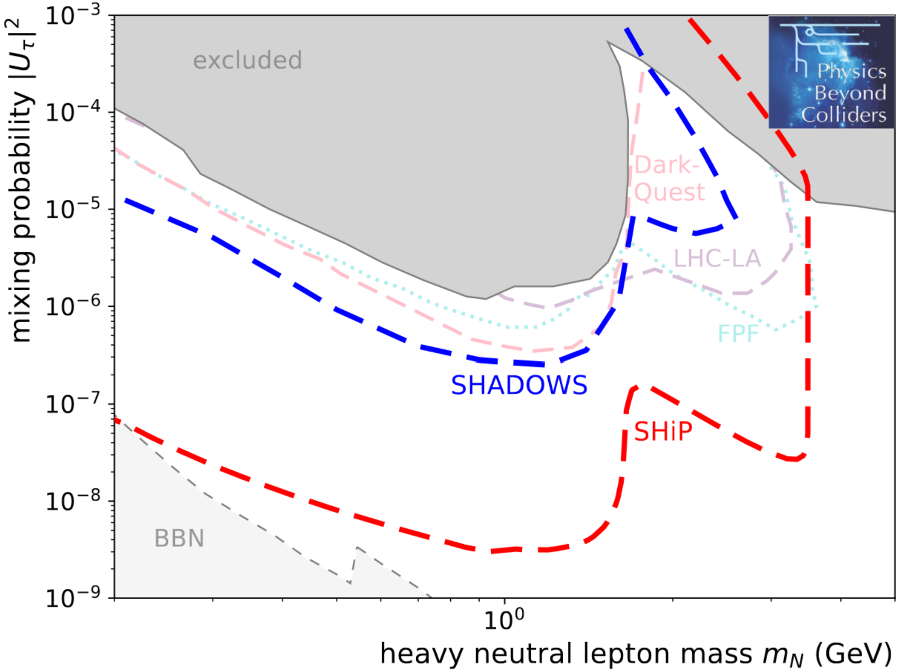


Figure 26: Sensitivity projections for the FPC benchmark BC8 (heavy neutral leptons with tau mixing).

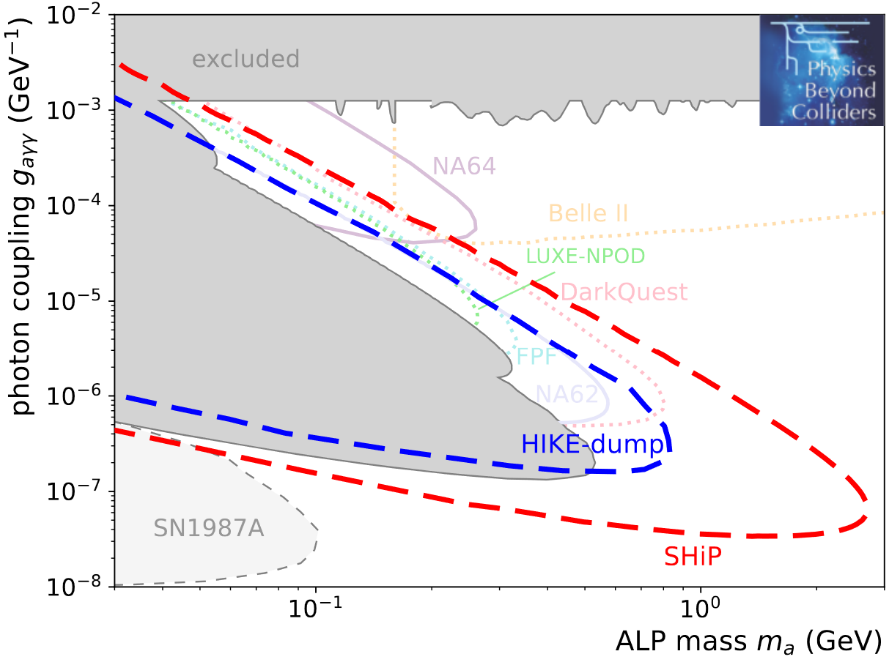


Figure 27: Sensitivity projections for the FPC benchmark BC9 (axion-like particles with photon couplings). The SN1987A constraint is taken from Ref. [180].