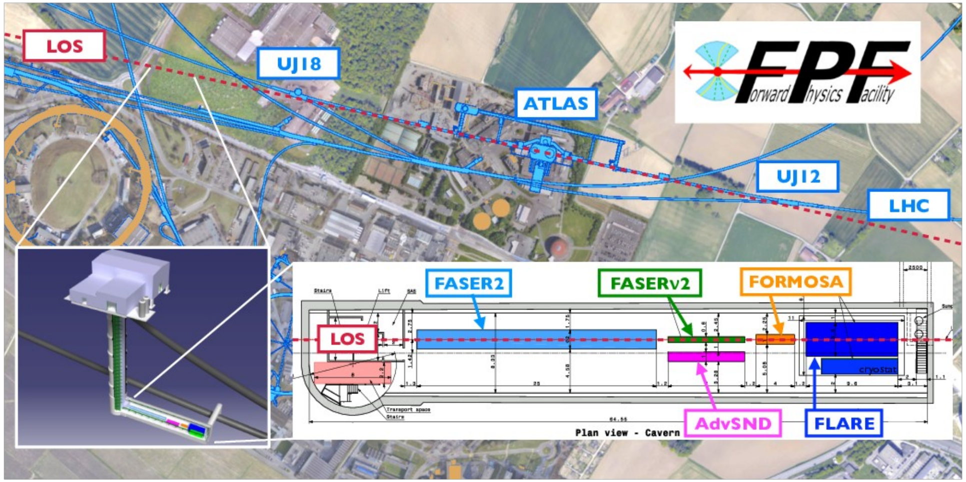
Hidden sector searches for Physics Beyond Colliders: the SPS and Forward Physics Facility

Mario Campanelli (UCL)



Outlook

NA62 in dump mode: dark photon searches

The future of the ECN3 experimental area:

- HIKE and SHADOWS
- SHiP

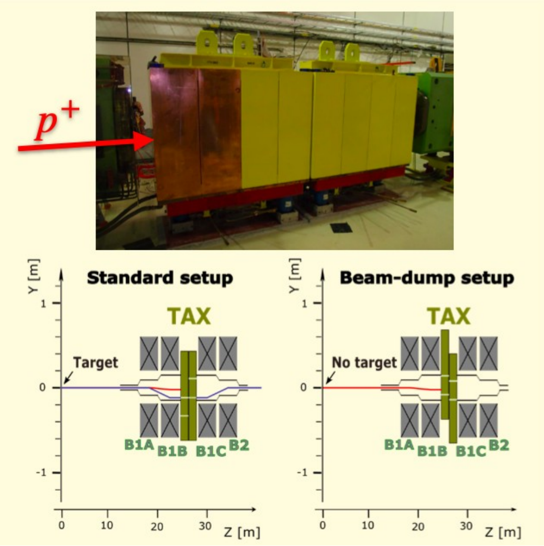
Forward Physics Facility

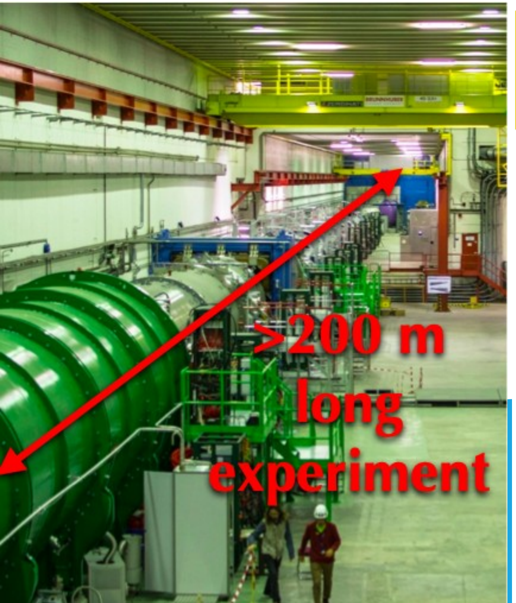
The NA62 Kaon experiment in beam dump mode

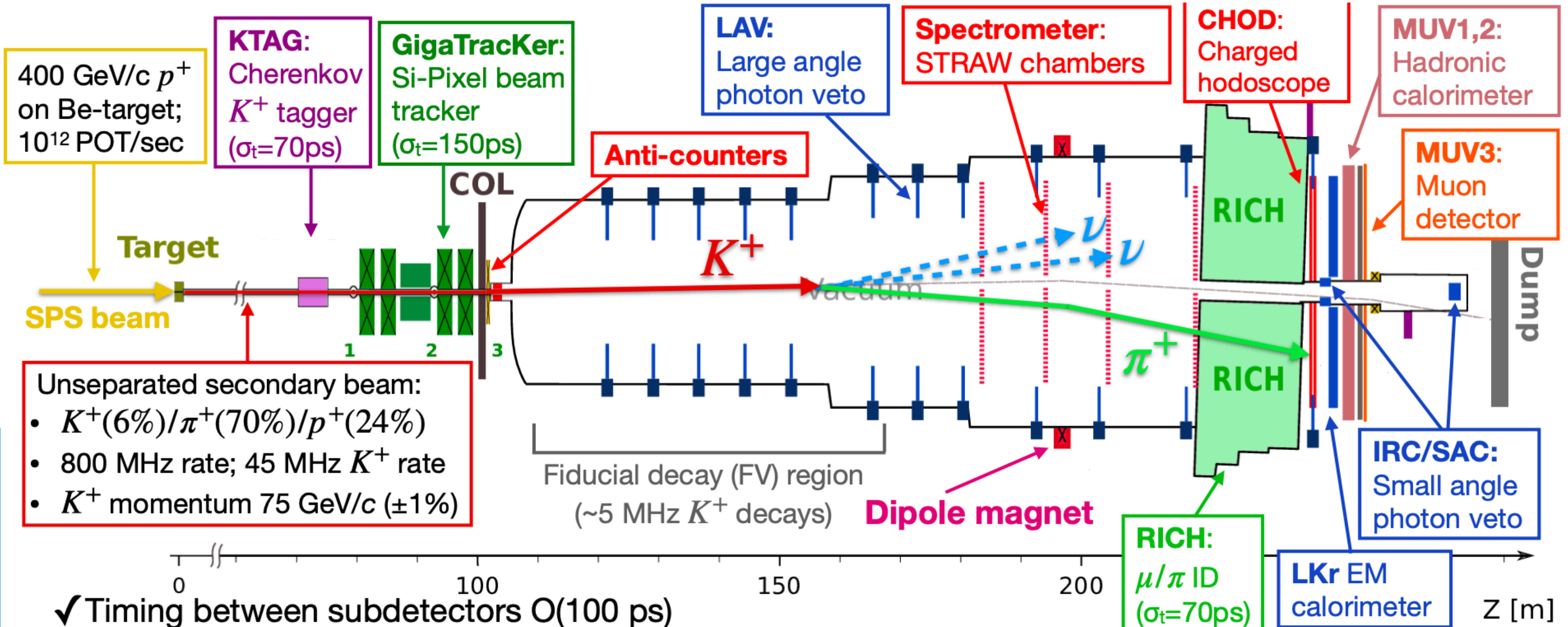
Running from 2007, NA62 is the latest of CERN's Kaon decay-in-flight technique experiments (NA31, NA48), and dedicated to measurement of rare decays (in particular, $K^+ \rightarrow \pi^+ \nu\nu$)

In 2021, Be target removed from beam, and collimators were closed to act as a beam dump. With magnets to swipe away halo muons, only neutrinos and possible FIPs could reach fiducial volume.

1.4E17 PoT collected in 10 days.



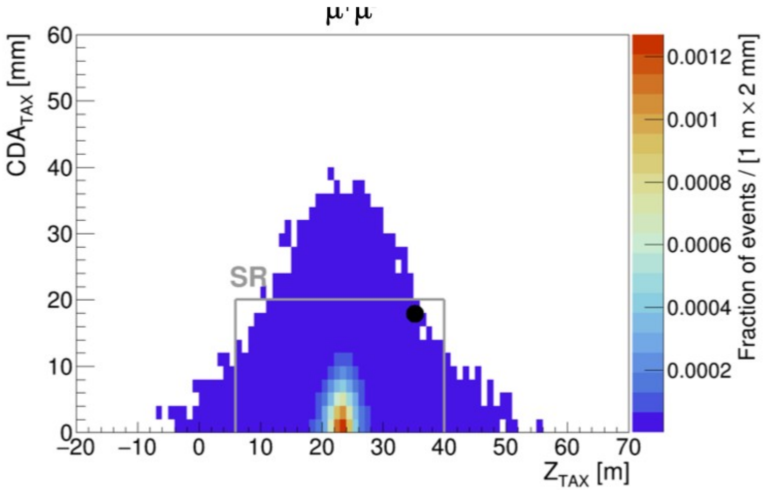




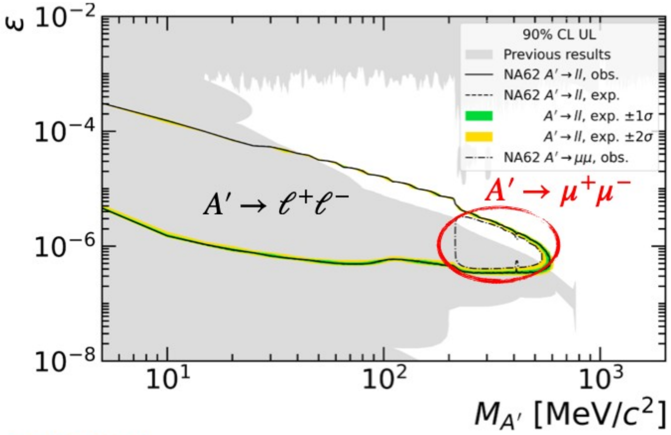
Search for dark photons in NA62

Opposite-charge electron or muon pairs in decay volume, for M_A < 700 MeV
Signal and control regions defined in a 2D plane of the two variables

- Distance of closest approach between output tracks and the beam path
- Longitudinal position of decay vertex



Zero candidates in near CR and in electron SR, but:
1 candidate found at the edge of the muon SR (0.025 BG events expected overall)



Some improvements on previous limits despite the unexpected event
More analysis ongoing on that dataset

The future of the ECN3 area

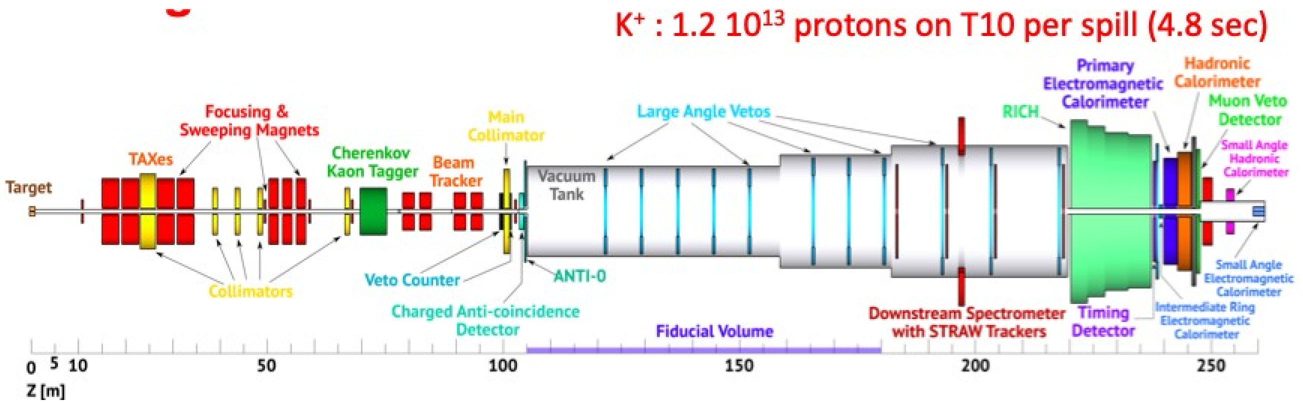
The NA62 program will finish at the end of 2025. With the termination of the CNGS line, the North Area will have an intensity upgrade, and two possibilities are open:

- Continue with the rare Kaon program, with some runs in beam-dump mode
  - HIKE and SHADOWS detectors

- Build instead a dedicated Hidden Sector + neutrino detector
  - SHiP

- The two options have been extensively discussed, and the SPSC will take a decision this march, after having asked in December for more time and information

HIKE for HS searches

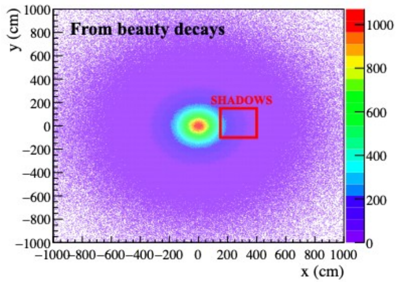


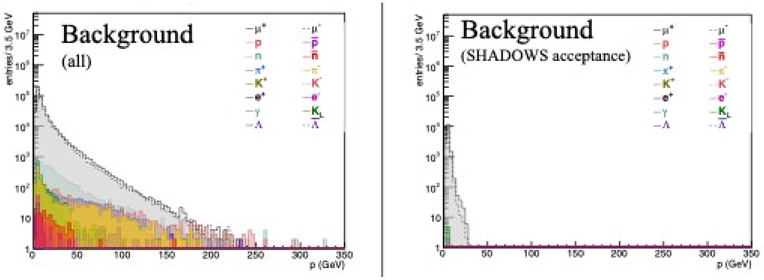
Similar design to NA62
Aims at precision measurement of
$K^+ \rightarrow \pi^+ \nu\nu$
And BSM modes like
$K^+ \rightarrow \pi^+ l^+ l^-$

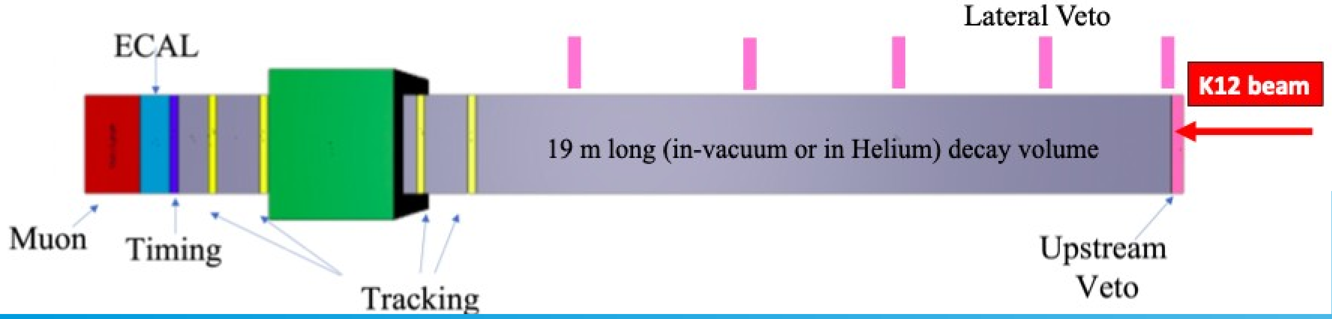
FIP searched in:
kaon decays for HS particles below the K mass:
$K^+ \rightarrow l^+N$, $K^+ \rightarrow \pi^+X$
beam-dump
all main portals
assume 5E19 PoT in dump mode over 4 years, with 2E13 PoT over 4.8s
HIKE searches complemented by a dedicated off-axis detector to search for HS in beam dump mode: SHADOWS

The SHADOWS detector

Off-axis but close to the dump to optimise HS signals with very small BG from muons and neutrinos







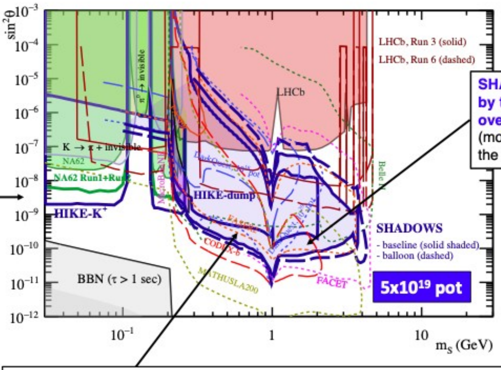
19 m-long decay volume followed by a spectrometer able to measure and identify leptons, pions and kaons

SHADOWS

Physics sensitivity: Light Dark Scalar mixing with the Higgs

(mediator of sub-GeV DM interacting with SM particles; candidate for relaxion mechanism, etc.)

SHADOWS is fully complementary to HIKE-phase 1 in kaon mode, that improves by about one order of magnitude below the kaon mass.



SHADOWS can improve by three orders of magnitude over the existing bounds (mostly from LHCb) between the di-muon threshold and ~4 GeV.

Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

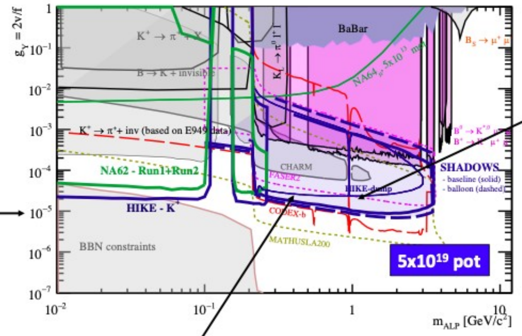
SHADOWS can cover a larger area in the (still uncharted) parameter space **than: DarkQuest; LHCb Run3 & Run 4 (upgrade 1); LHCb Run 6 (upgrade 2); CODEX-b; FASER2** at the Forward Physics Facility.

SHADOWS

Physics sensitivity: ALPs with fermion couplings

Axions/ALPs in the MeV-GeV range are possible solution to the strong-CP problem

SHADOWS is complementary to HIKE-phase 1 in kaon mode, that can improve by about one order of magnitude the current bound below the K mass, and fill the gap down to BBN.



SHADOWS can improve by two orders of magnitude over the existing experimental bounds (LHCb) between the di-muon threshold and ~ 4 GeV.

Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

SHADOWS can cover a larger area than: FASER2 at the Forward Physics Facility; and is very similar to CODEXb with the full data set at the end of the HL-LHC (3 ab^{-1}).

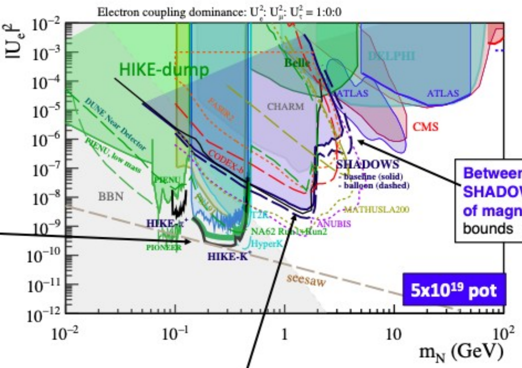
Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715

SHADOWS

Physics sensitivity: HNL with electron couplings

Possible solution to the origin of the neutrino masses and matter-antimatter asymmetry

Fully complementary with HIKE phase 1 and BD Below the K and above the B threshold. Synergistic Between K and D thresholds.



Between D and B thresholds SHADOWS improves by about one order of magnitude over the existing experimental bounds (Belle & CMS)

Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

Between K and D thresholds SHADOWS improves by about four orders of magnitude over the existing experimental bounds (Belle)

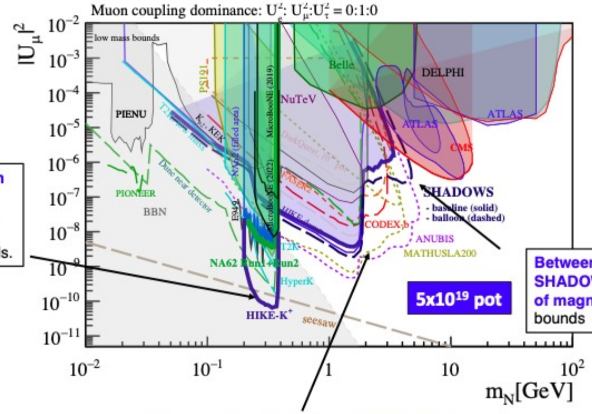
Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715,

SHADOWS

Physics sensitivity: HNL with muon couplings

Possible solution to the origin of the neutrino masses and matter-antimatter asymmetry

Fully complementary with HIKE phase 1 and BD below the K and above the B threshold. Synergistic between K and D thresholds.



Between D and B thresholds SHADOWS improves by about one order of magnitude over the existing experimental bounds (CMS)

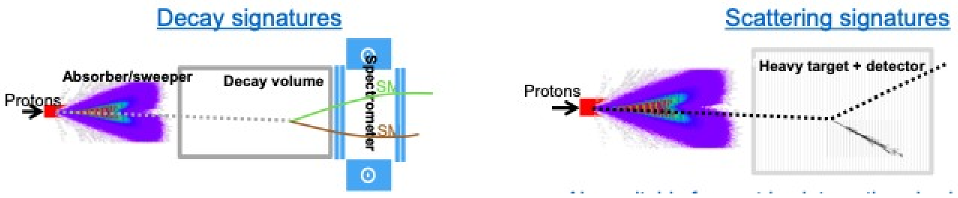
Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

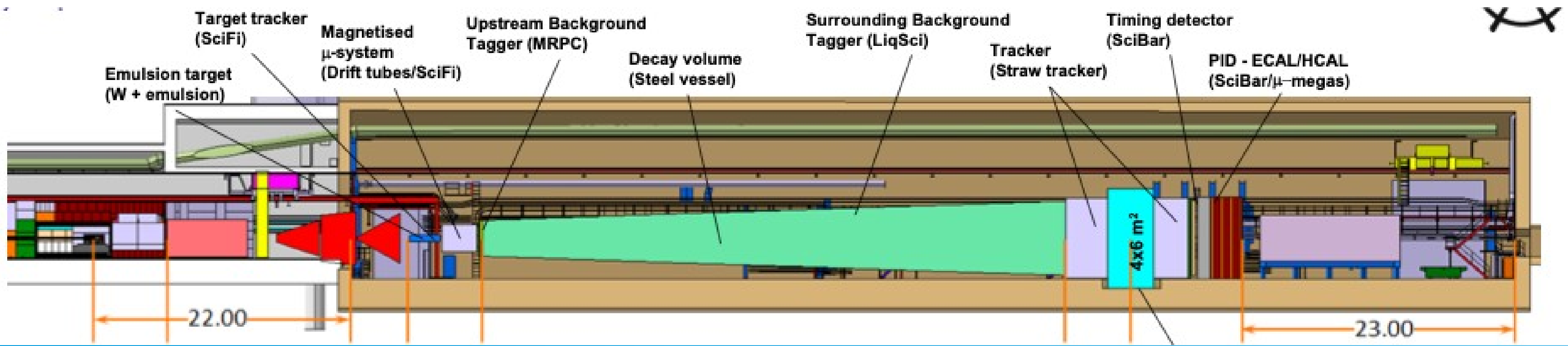
Between K and D thresholds SHADOWS improves by about one order of magnitude over the existing experimental bounds (NuTeV)

Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715, accepted by EPJC

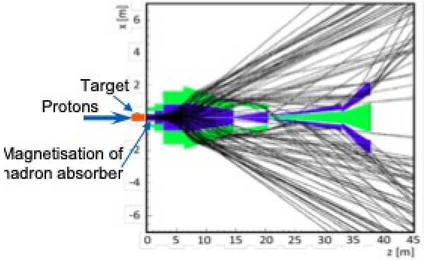
The SHiP detector

SHiP is the result of a decade of optimisation to produce the best sensitivity to GeV-range FIP
Initially proposed to another beamline that will not be built, the proposal has been adapted to ECN3 with almost no loss of sensitivity
FIP searches in a background-free environment in decay mode and low BG in scattering mode



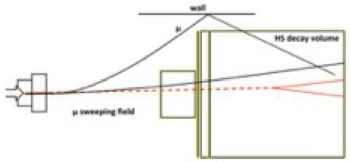


Background control in SHiP

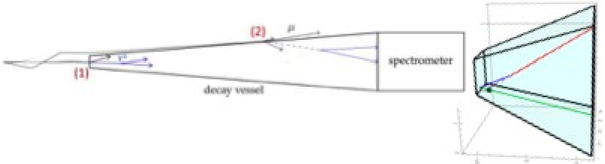


Active muon shield with Normal Conducting or NC/SuperConducting magnets reduce rate to 70 or 10 kHz in tracker

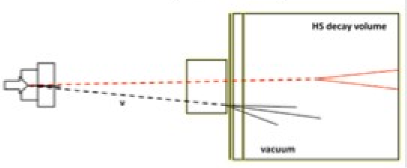
Muon combinatorial



Muon DIS



Neutrino DIS



Residual flux of muons and neutrinos dominated by combinatorics.
Using data-driven techniques, BG can be reduced to < 1 event for 6E20 PoT (15 years)

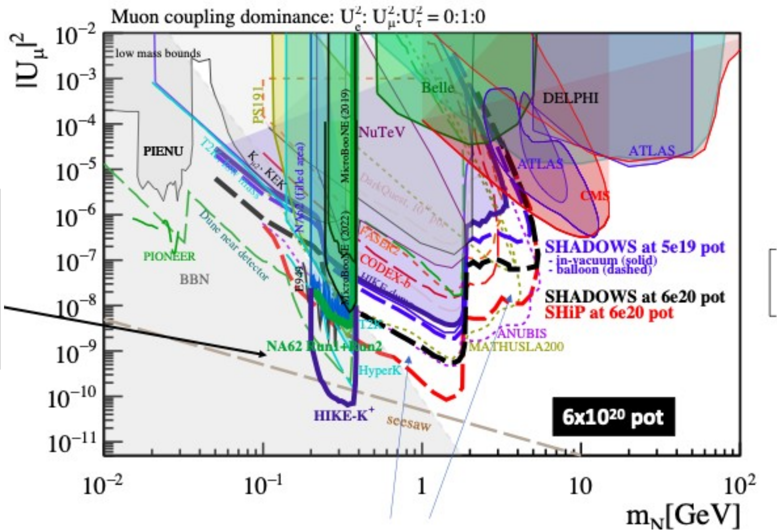
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/< 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / < 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

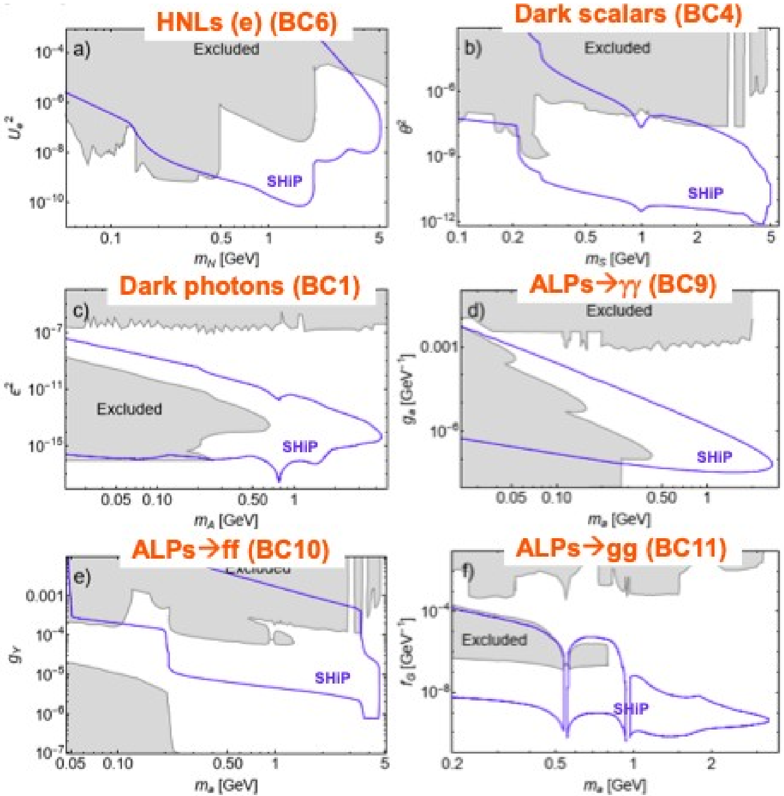
Neutrino interactions in the SND (very similar to current SND@LHC experiment) lead to high-precision neutrino measurements

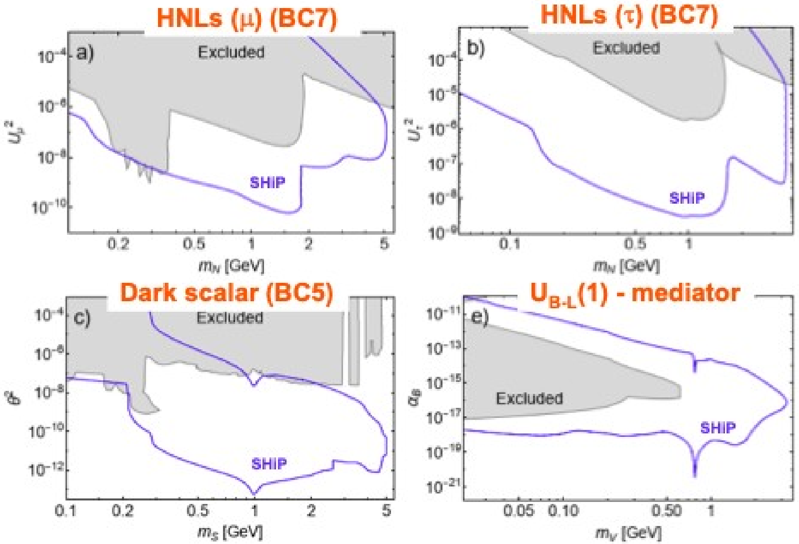
	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	63	2.8×10^6
N_{ν_μ}	2.6	5.4×10^{18}	40	8.0×10^6
N_{ν_τ}	9.0	2.6×10^{16}	54	8.8×10^4
$N_{\bar{\nu}_e}$	6.6	3.6×10^{17}	49	5.9×10^5
$N_{\bar{\nu}_\mu}$	2.8	3.4×10^{18}	33	1.8×10^6
$N_{\bar{\nu}_\tau}$	9.6	2.7×10^{16}	74	6.1×10^4

SHiP sensitivity to benchmarks

Very strong sensitivity for all benchmarks
Comparison with HIKE/SHADOW more meaningful when same number of PoT on beam dump is assumed

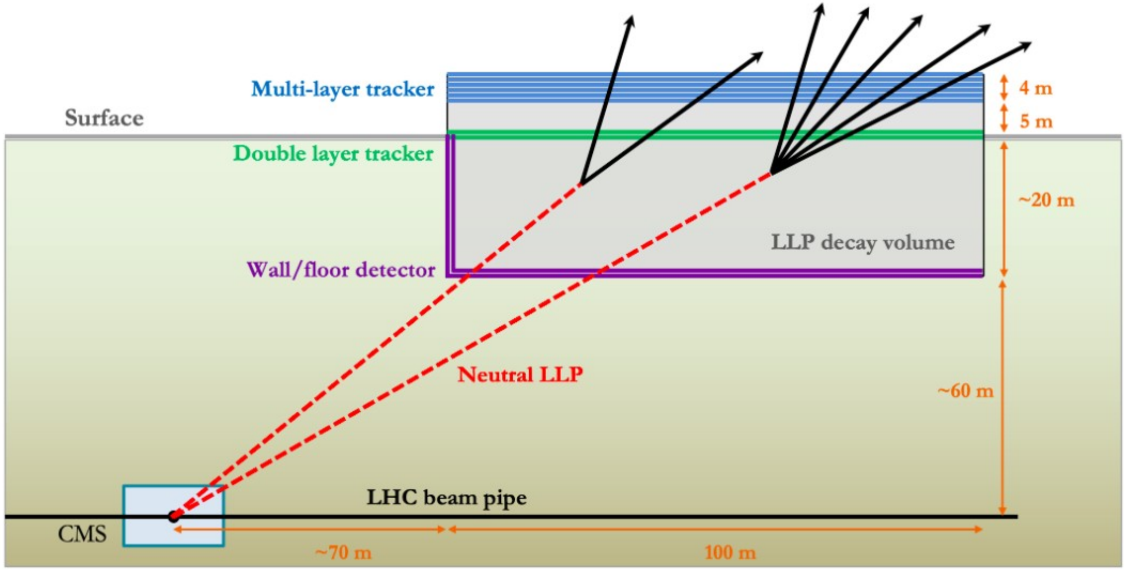




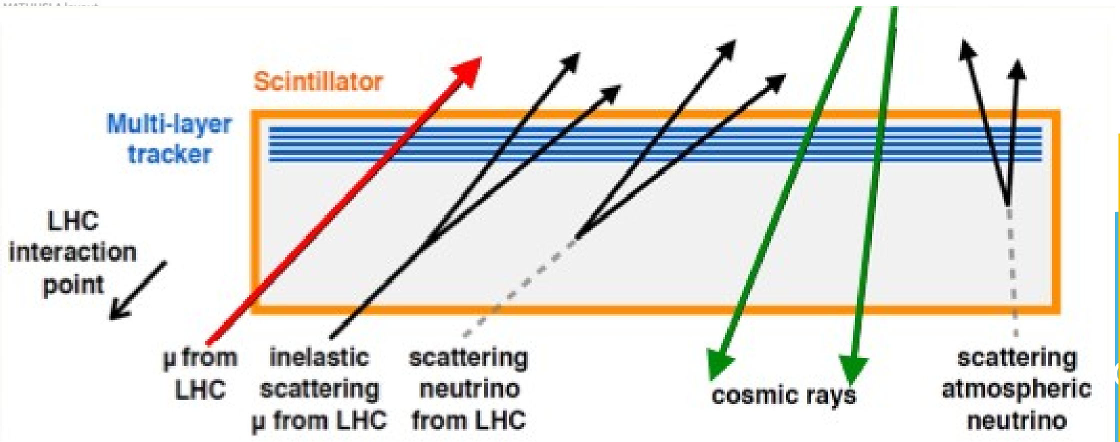


+ also SUSY-related benchmarks

Large detector, large decay length: MATHUSLA



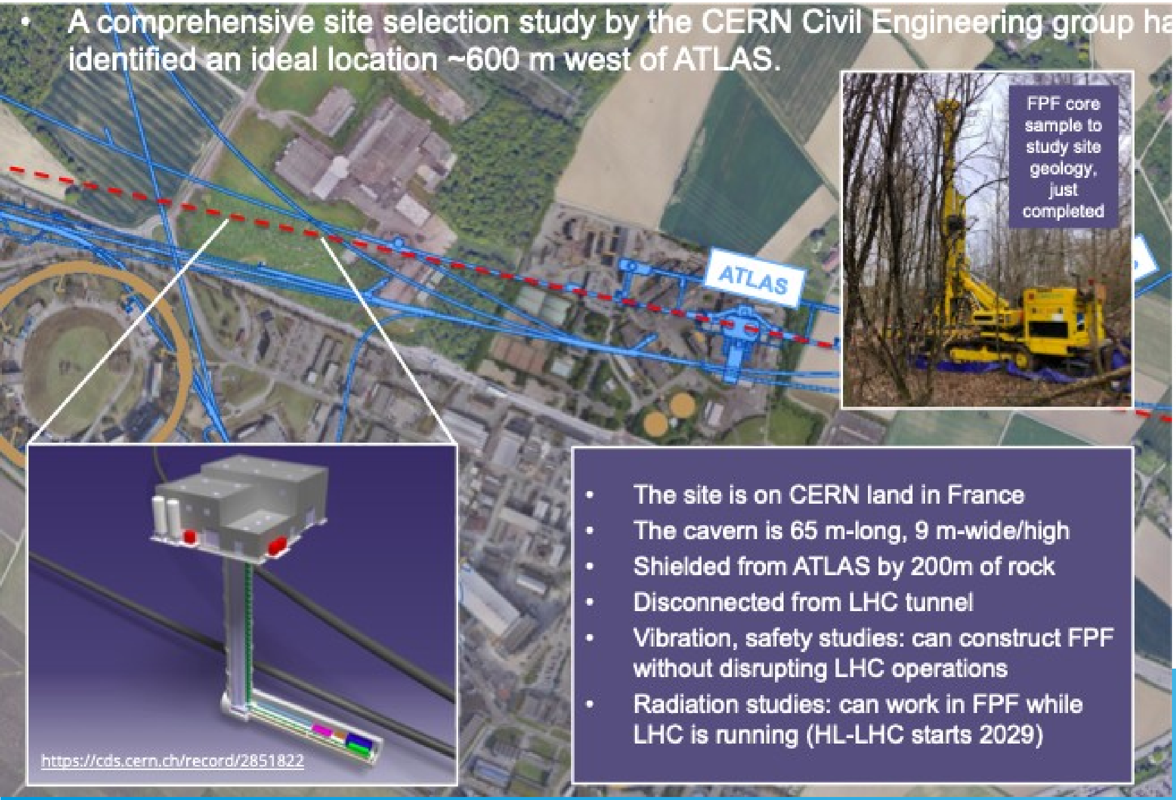
100 x 100 x 30 m3 detector with robust tracking (e.g. RPC) located partly above partly below the surface.

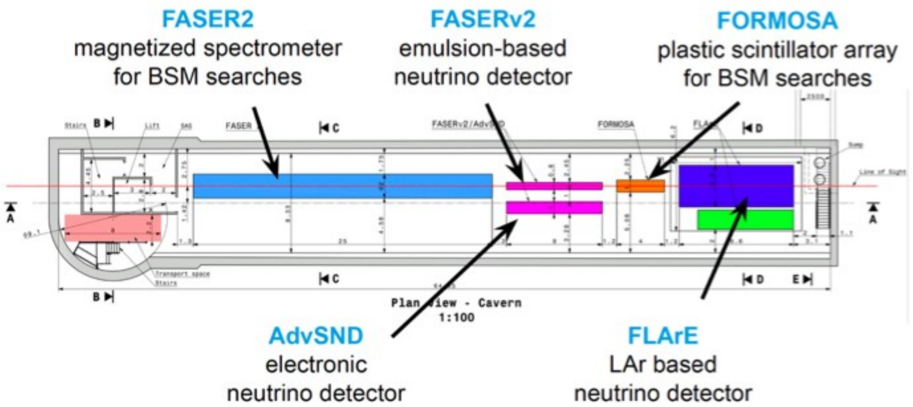


Background from the beam and from cosmics reduced by a combination of tracking and timing

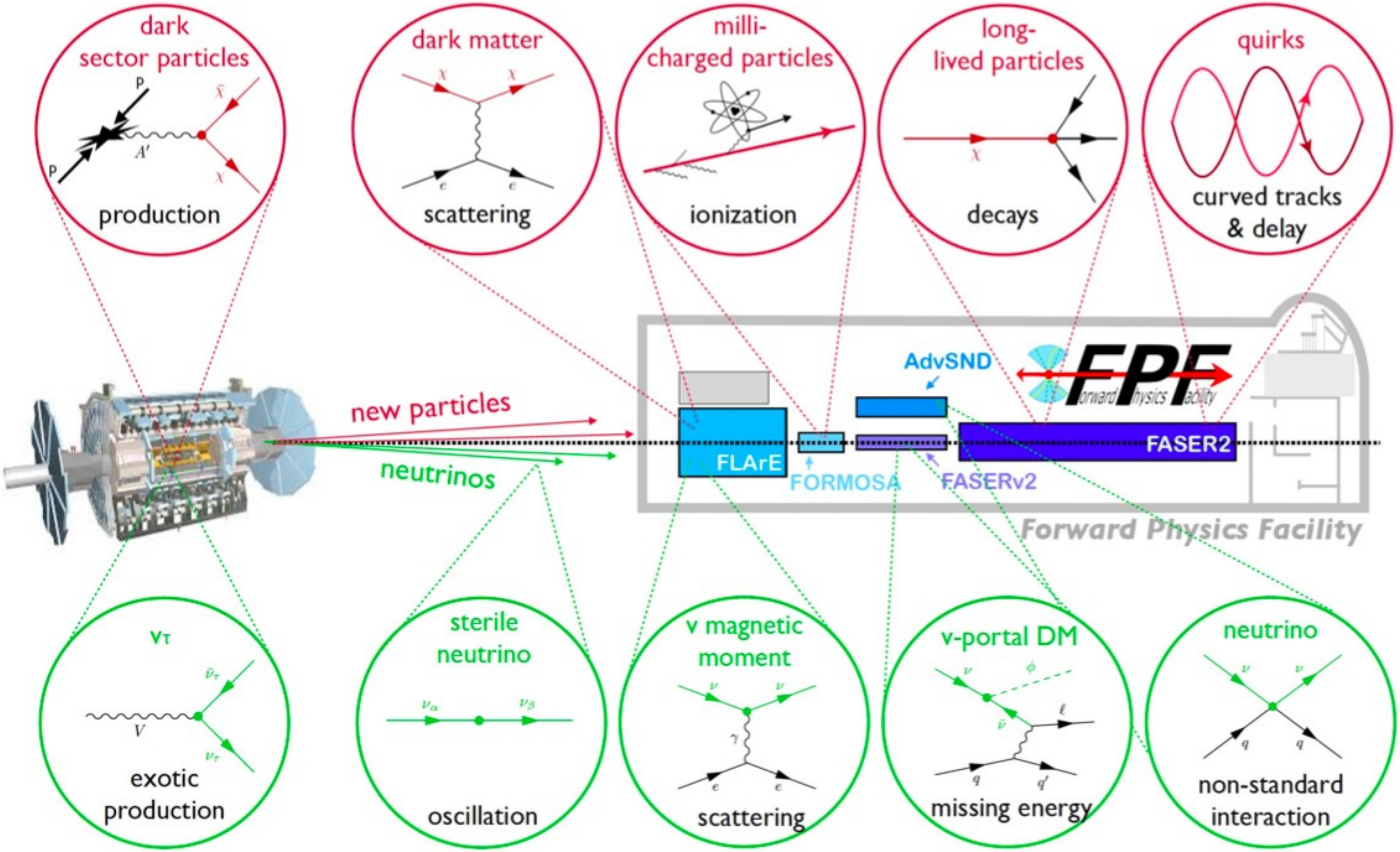
The Forward Physics Facility

- Currently, two small experiments are located in service tunnels symmetrically on the line of collision 480m from ATLAS: FASER and SND@LHC
- Next-generation forward LHC experiments will need more space



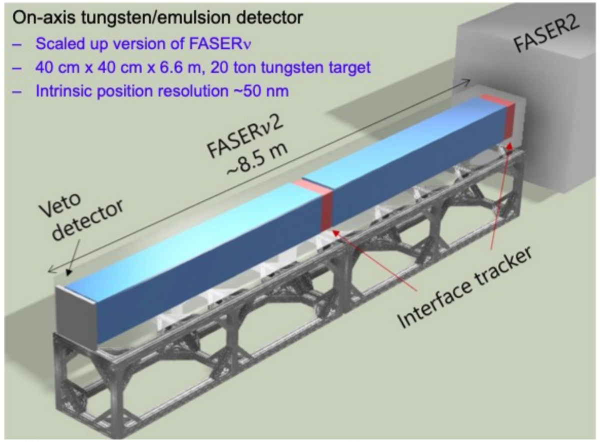


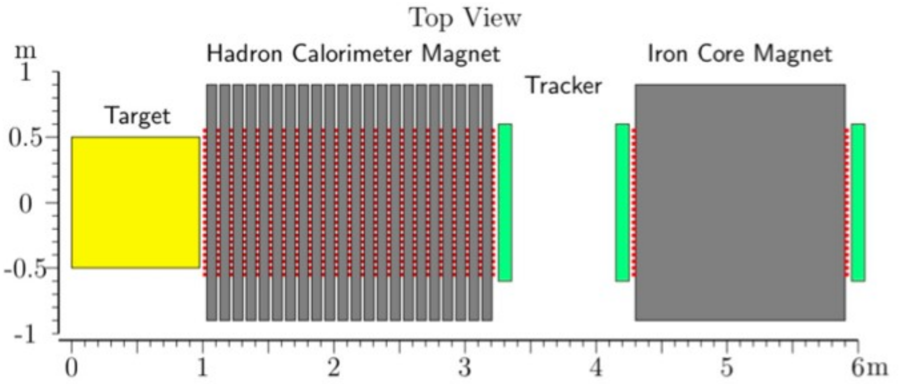
FPF experimental program



Neutrino program: AdvSND, FASER v2, FLArE

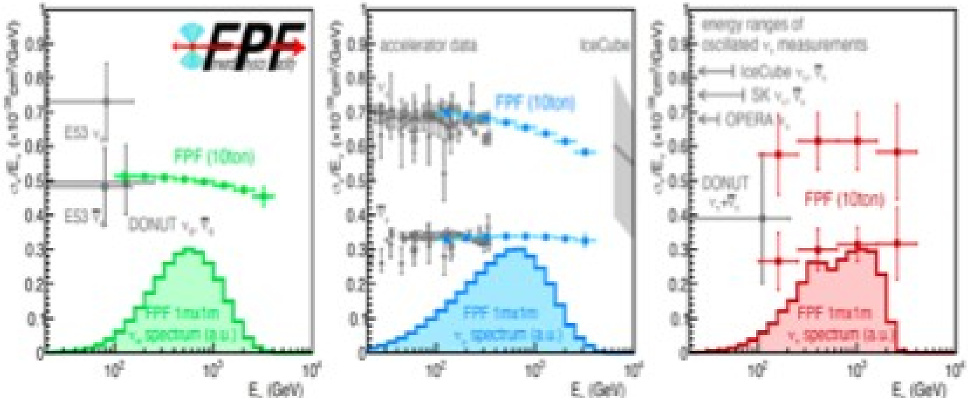
- AdvSND will use silicon trackers instead of emulsions to work at high lumi. Could also be placed in different locations



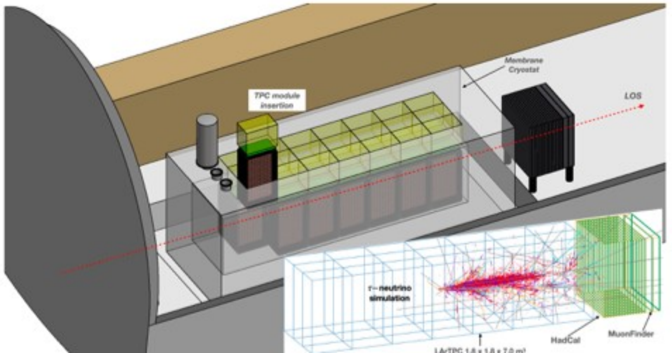


FASER v2, scaled up version of FASERν, on axis heavy emulsion detector

FLArE: 10 ton LAr TPC for neutrino and dark matter detection



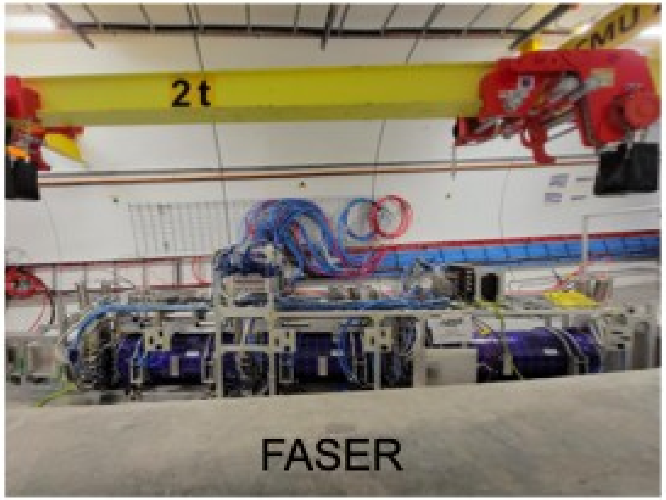
Crease by order of magnitude precision on high-energy neutrino statistics

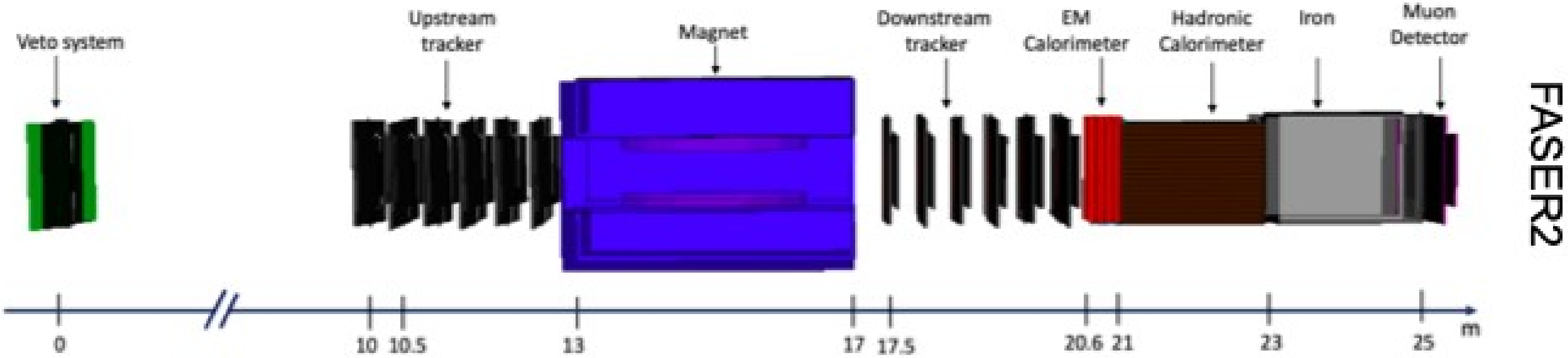


FLArE with simulated 500 GeV tau neutrino

FASER2

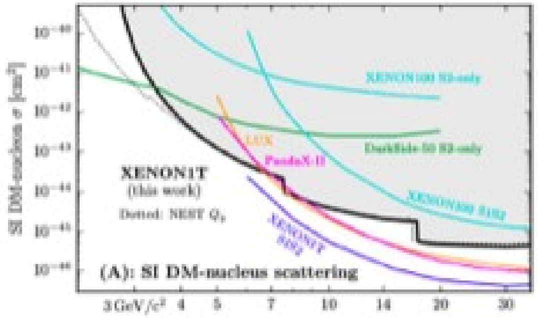
- On-axis magnetic spectrometer
  - Superconducting magnet with 4 Tm bending power
  - Trackers based on LHCb's SciFi detector
- FASER → FASER2
  - R = 10 cm, L = 1.5 m (V = 0.05 m^3) → 3 m x 1 m x 10 m (V = 30 m^3)
  - Luminosity ~ 30 fb^{-1} → 3 ab^{-1}
  - Sensitivity increases over current bounds by ~60,000 for many models



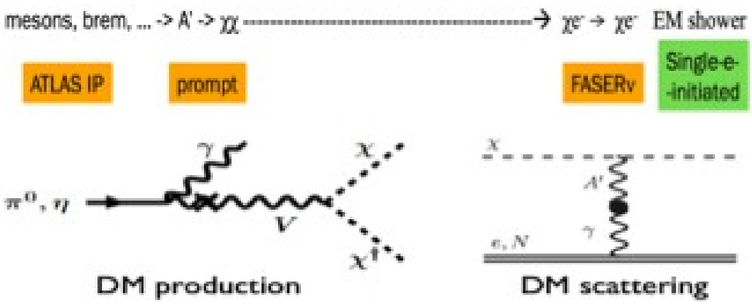


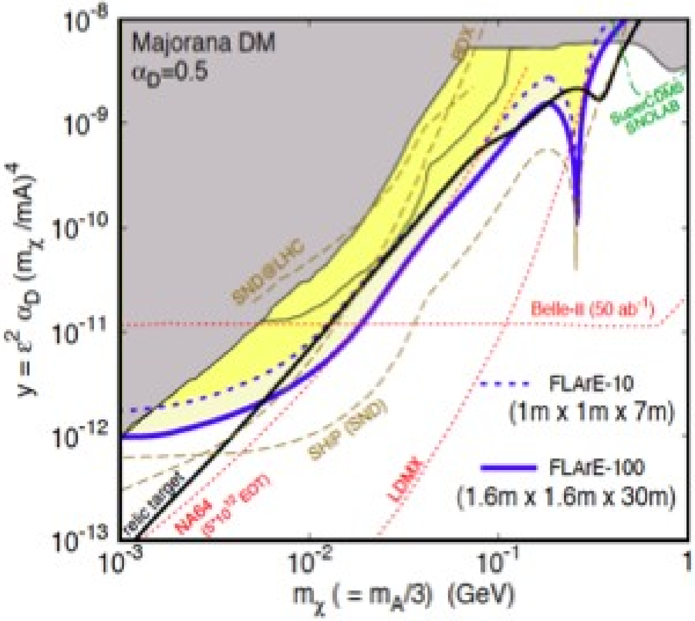
Direct DM detection

- Light DM with masses at the GeV scale and below is famously hard to detect.
  - Galactic halo velocity ~ 10^{-3} c, so kinetic energy ~ keV or below.



- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.





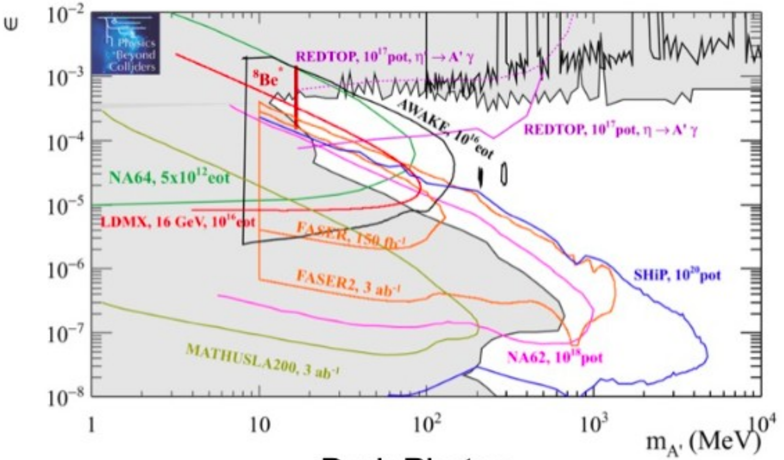
Batell, Feng, Trojanowski (2021)

- FLArE is powerful in the region favored/allowed by thermal freezeout.

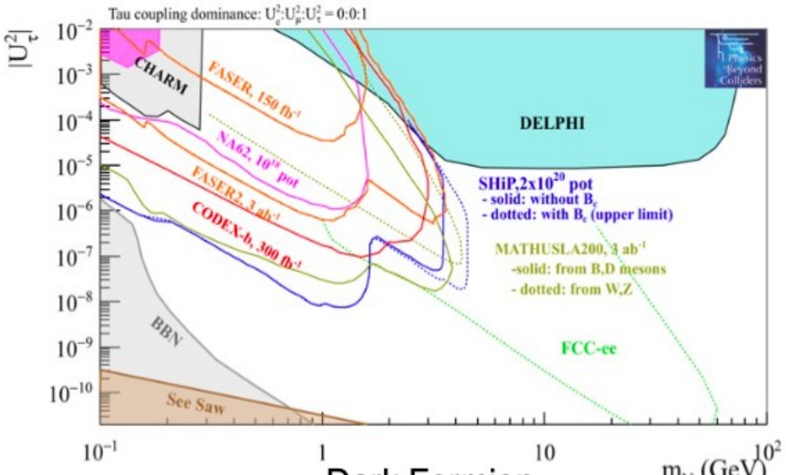
FPF Hidden Sector searches

- FPF detectors have significant discovery potential for a wide variety of BSM/LLP models: dark photons; B-L and related gauge bosons; dark Higgs bosons; HNLs with couplings to e, mu, tau; ALPs with photon, gluon, fermion couplings; light neutralinos, inflatons, relaxions, and many others.

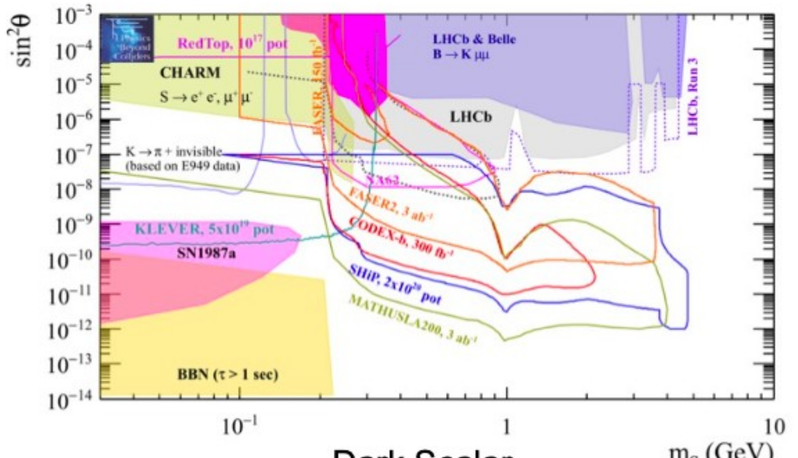
FPF White Paper (2022)



Dark Photon



Dark Fermion



Dark Scalar

However for some benchmarks, very high intensities (SHiP) or masses (MATHUSLA) still dominate parts of the landscape

Conclusions

- The popularity of Hidden Sector models has lead to a large variety of experimental proposals to explore the available phase space
- Two main approaches are: high intensities
  - SPS ECN3 area, soon free due to the end of the NA62 program, and with intensity upgrade (decision in a few weeks between HIKE/SHADOWS and SHiP))
- High energy
  - Neutrinos and HS candidates from the LHC:
    - Currently, FASER and SND@LHC experiments located in small service tunnels
    - Possible 2nd generation experiments close to the surface (MATHUSLA) or in a dedicated underground Forward Physics Facility