Search for Hidden Particles at the SPS ECN3 high-intensity beam facility

Annual Meeting of the Swiss Physical Society

ETH Zürich,
9-13 September 2024 | Switzerland

Martina Ferrillo, Universität Zürich (UZH)
martina.ferrillo@cern.ch

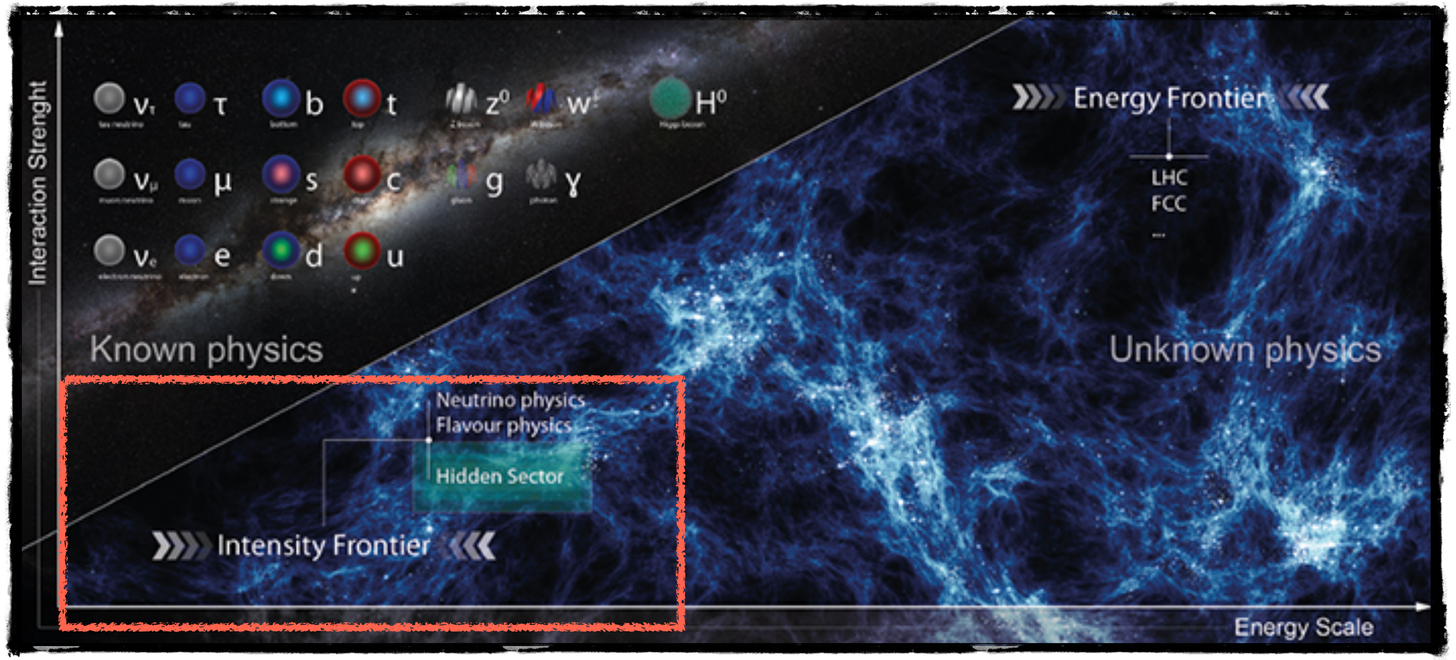
SHiP

Physics Motivation

Many experimental evidences for physics **Beyond** the **Standard Model**

- Neutrino masses
- Baryon/Anti-baryon asymmetry of the Universe
- Dark Matter and Dark Energy

Hidden Sector Portals: **New Physics** might hide in long-lived **Feebly Interacting Particles** (FIPs)



Main research strategies to look for FIPs:

1. **High-Energy** frontier (LHC, FCC)

   heavy particles
   high energy events

2. **High-Intensity** frontier

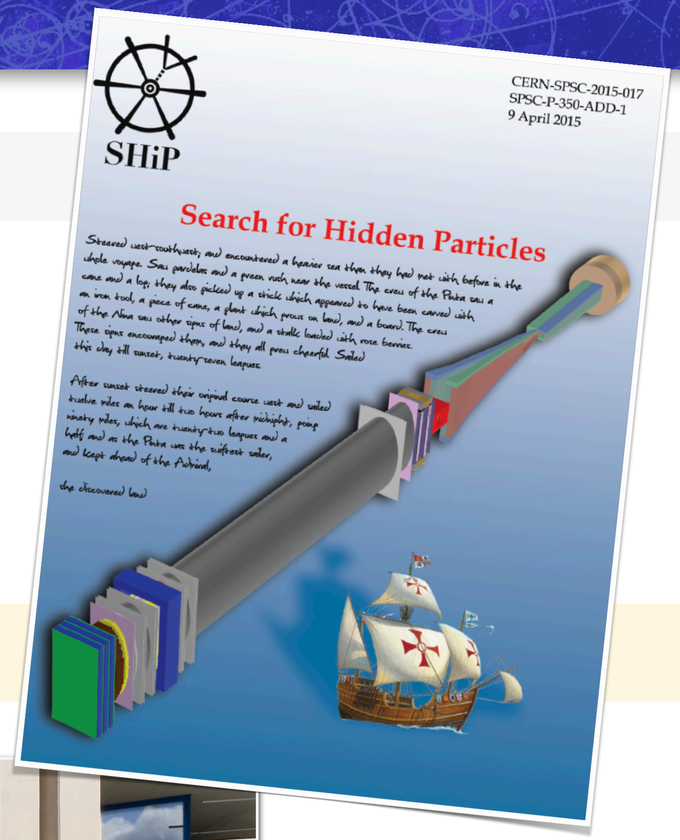
   light(er) particles
   rare events

SHiP
Search for Hidden Particles

The SHiP Experiment

History of BDF/SHiP at CERN:

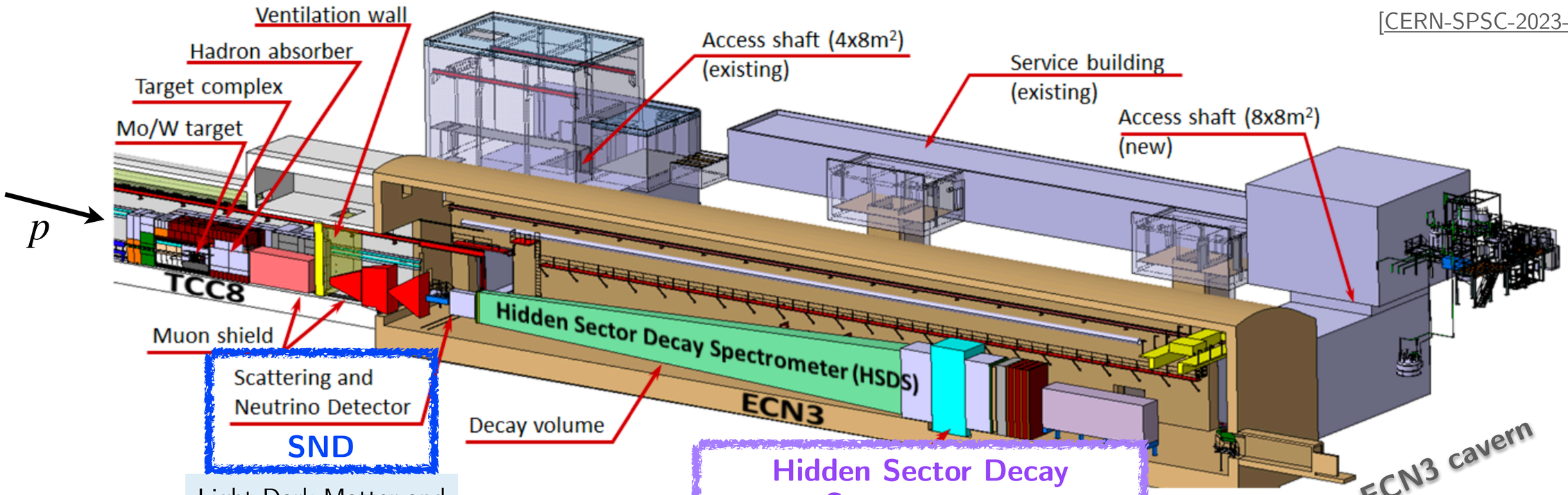
- **2013**: Letter of Intent [arXiv:1310.1762]
- **2015**: Technical Proposal, Physics Proposal [arXiv:1504.04956, arXiv:1504.04855]
- **2019**: Comprehensive Design Study Report [CERN-SPSC-2019-049]
- **2023**: BDF/SHiP at the *ECN3* high-intensity beam facility [CERN-SPSC-2023-033]*
  - ↳ From **ECN4** to **ECN3** cavern, update downstream detector dimension
- **Approval by CERN RB in March 2024** ⇒ moving onto the Technical Design Report phase



SHiP at a dedicated Beam Dump Facility

- **SPS beam**: 400 GeV protons with intensity 4×10^{19} p.o.t./yr
- *General-purpose* beam dump facility (BDF)
- **15 years**-long **physics** program: 6×10^{20} p.o.t.

[CERN-SPSC-2023-033]



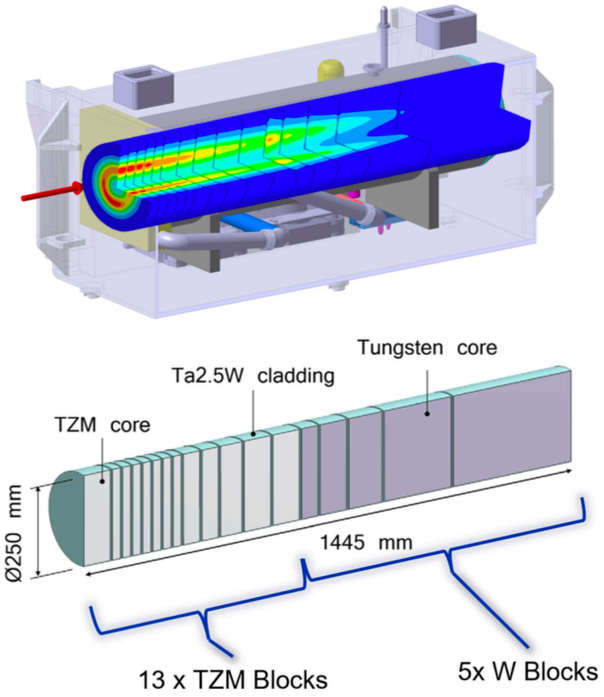
Light Dark Matter and tau neutrino physics

Hidden Sector Decay Spectrometer

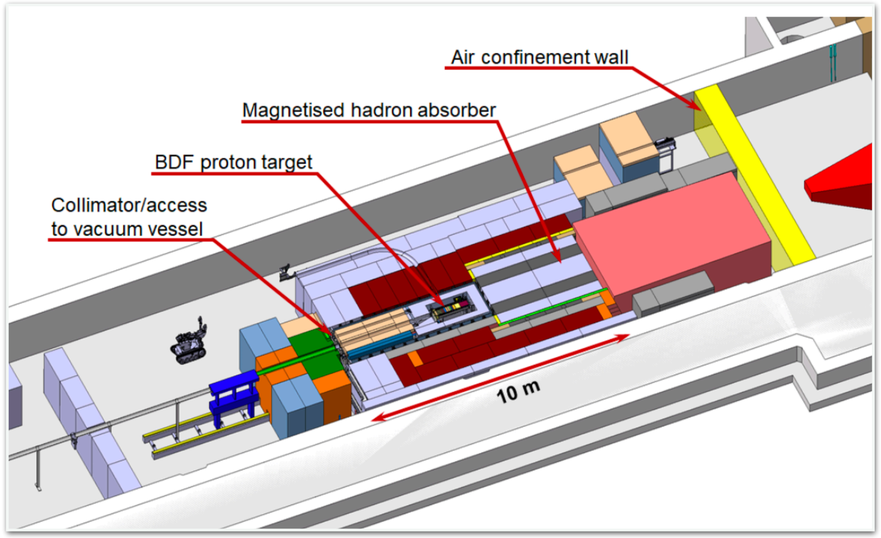
Search for the decay of FIPs

Beam Dump Optimisation

MC simulation, temperature map during pulse



CERN-SPSC-2023-033



Ti-Zr-Mo alloy + W blocks, optimised to enhance production of charm and beauty mesons

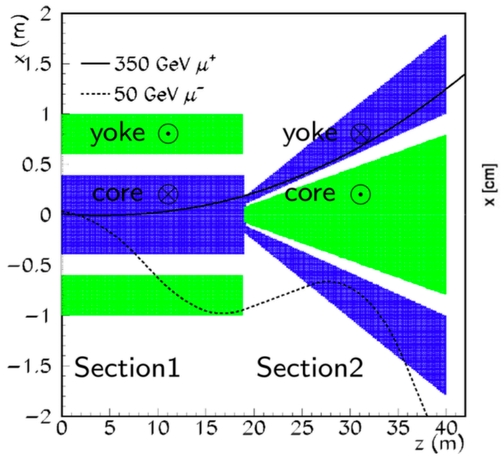
- **Thick target**, $12\,\lambda$: using full beam primary and secondary interactions
- **High A&Z**: maximising production cross-section
- 5m-long magnetised **hadron absorber**: stopping pions/Kaons before decay
- Cast-iron and concrete shielding, water-cooled and vacuum confined

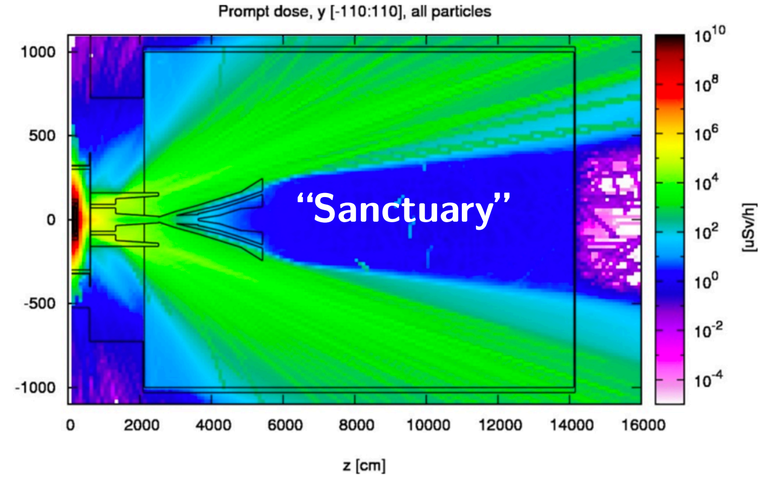
Annual Yields within Acceptance

- $\sim 2 \times 10^{17}$ charmed hadrons (> 10x HL-LHC)
- $\sim 1.4 \times 10^{13}$ beauty hadrons
- $\sim 2 \times 10^{15}\, \nu_\tau/\bar{\nu}_\tau$

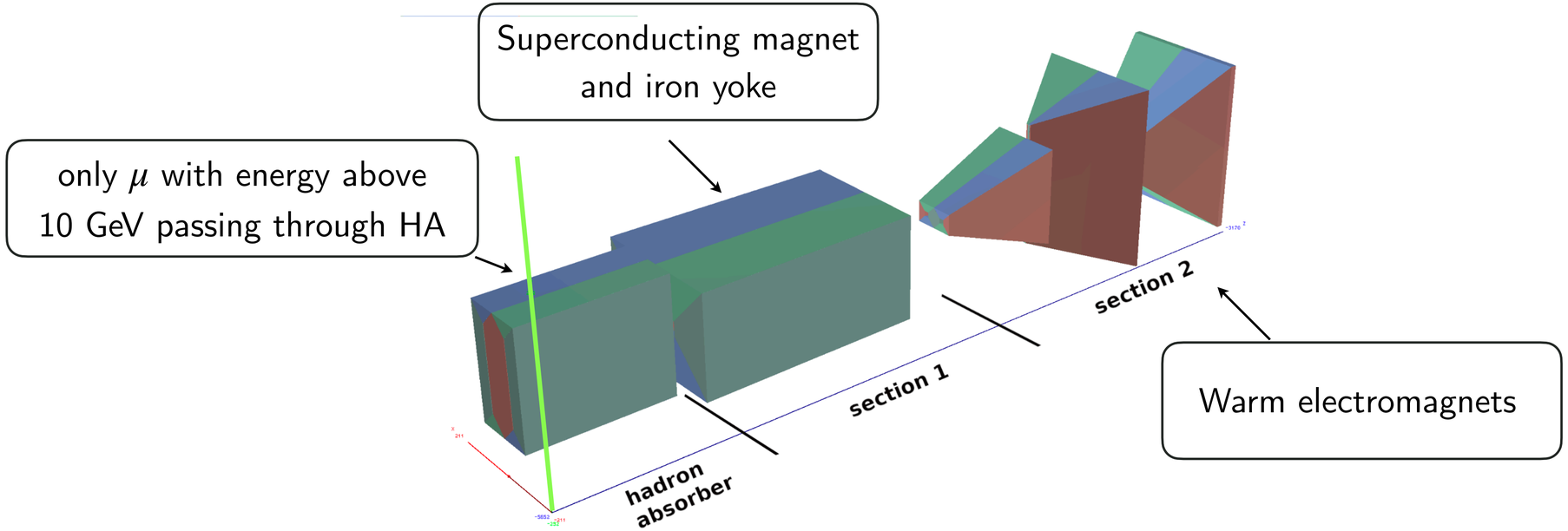
Muon Shield Optimisation

- Concept: **alternate-polarity** design to deflect μ^+/μ^- away from the decay volume
- **Hybrid magnet (SC/NC)** to accommodate ECN3 constraints, while preserving performance
- **Machine Learning**-based **optimisation** efforts for the TDR



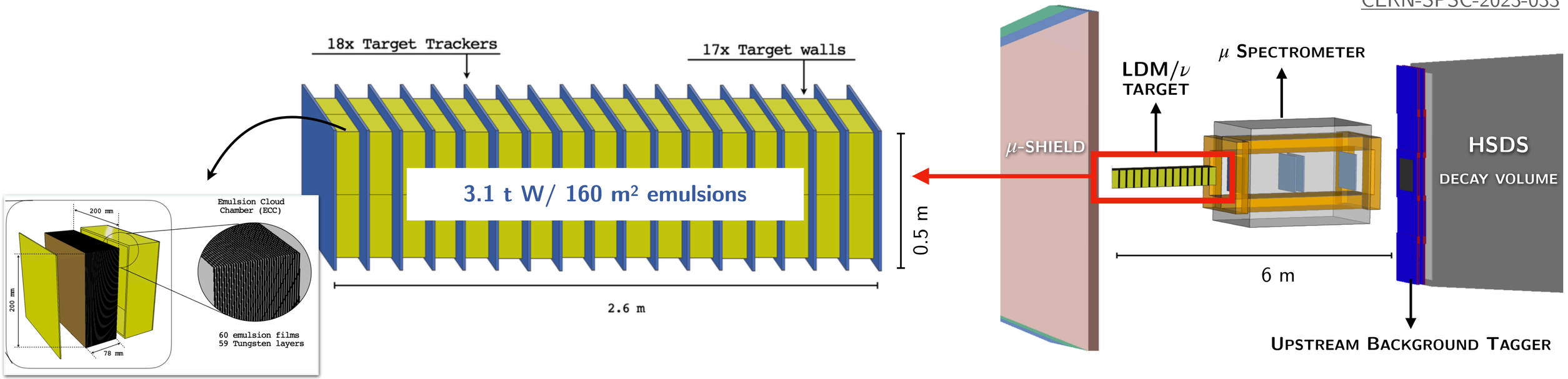


CERN-SPSC-2023-033



Scattering and Neutrino Detector

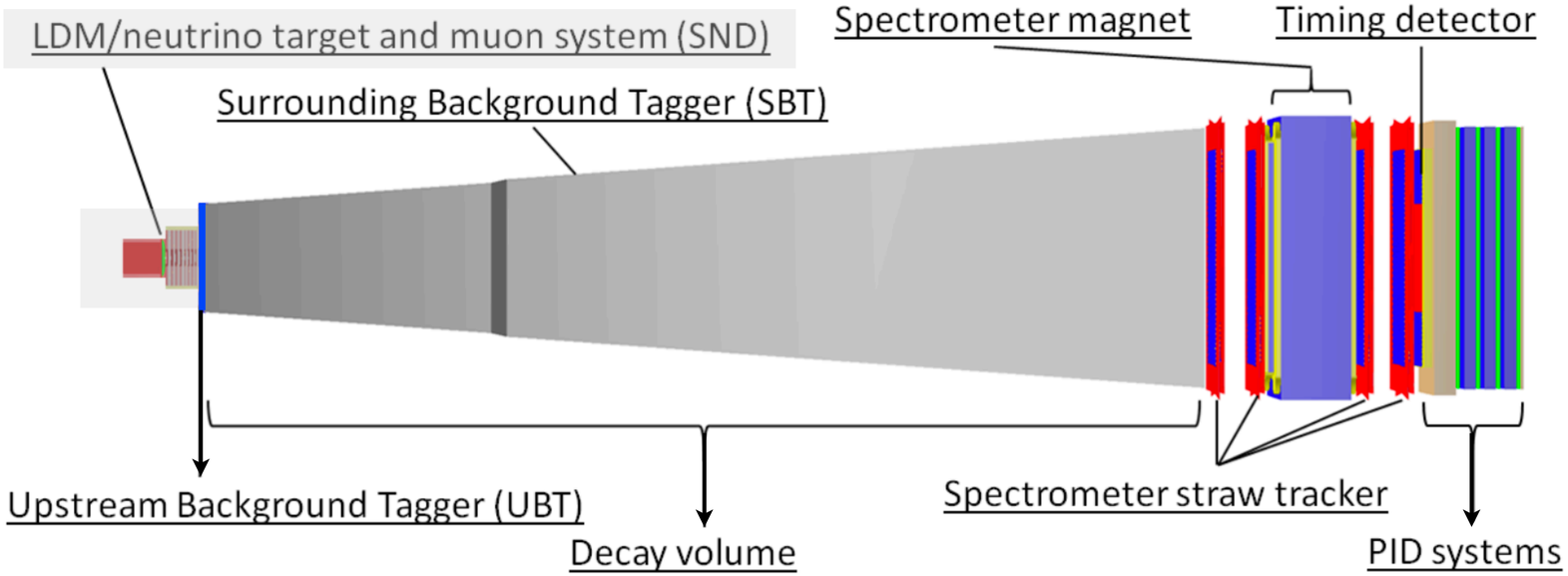
CERN-SPSC-2023-033



Light Dark Matter and Neutrino detector **hybrid design** similar to **SND@LHC**: *target, vertex detector, calorimeter*

- Target (ECC): **nuclear emulsion films** interleaved with **W plates**
- Target Trackers: **electronic detectors** (SciFi)
- **Muon spectrometer** downstream for muon charge/momentum measurement

Hidden Sector Decay Spectrometer



CERN-SPSC-2023-033

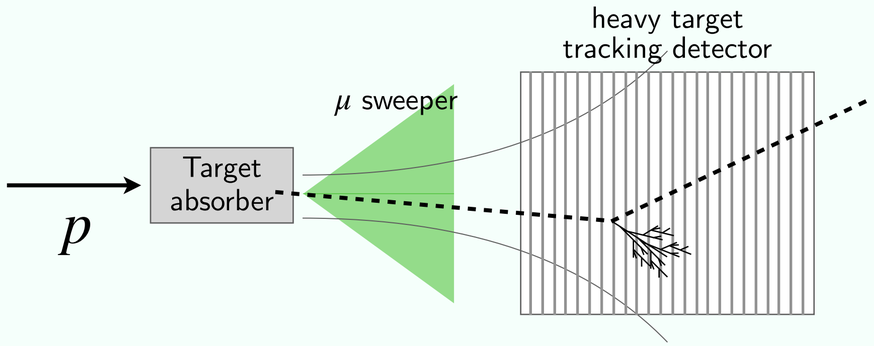
Designed to achieve **zero background** **in FIPs decay search**, *further optimisation ongoing*

- Low pressure Air (or Helium) based **decay volume** to minimise μ, ν interactions
- Background taggers: **SBT** (decay volume) and **UBT** (upstream of HSDS)
- **Spectrometer magnet** + straw-**tracker** to reconstruct *decay vertices* and the *impact parameter* at the proton target
- SiPM + Scintillators **timing detector** to reject *combinational* background
- **PID system** for e/γ shower reconstruction and μ/hadron separation (Calorimeters + Muon ID system)

SHiP Experimental Techniques

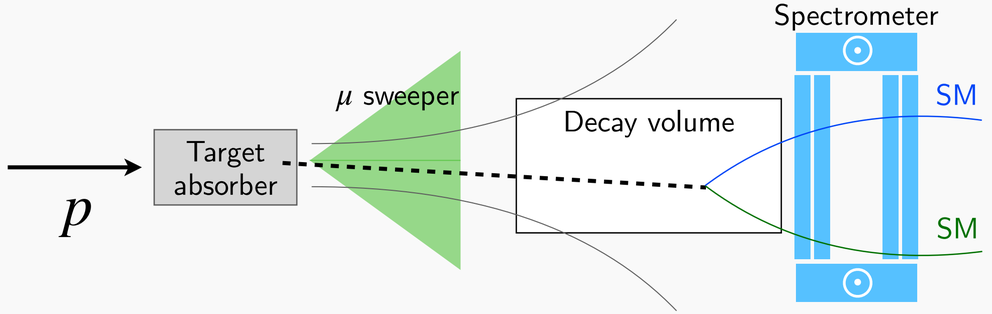
Model-independent setup for a broad FIPs search

Scattering



Micro-metric resolution for a rich **Light Dark Matter** and **neutrino** physics program

Decay



FIPs decay search: identification of both fully and partially reconstructible modes

Hidden Sector Physics

FIPs Signal Modes

- **Hidden Sector**: possible interaction with the SM sector via ***portals***
- Beyond portals: SUSY

	Physics model	Final state
HSDS	SUSY neutralino	$\ell^{\pm}\pi^{\mp},\ \ell^{\pm}K^{\mp},\ \ell^{\pm}\rho^{\mp}, \ell^{+}\ell^{-}\nu$
	Dark photons	$\ell^{+}\ell^{-}, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^{+}\ell^{-}, 3\pi, \eta\pi\pi, q\bar{q}$
	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^{+}\ell'^{-}\nu, \pi l, \rho l, \pi^{0}\nu, q\bar{q}'l$
	Axino	$\ell^{+}\ell^{-}\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^{+}\ell^{-}, 2\pi, 2K$

CERN-SPSC-2023-033 arXiv:1504.04855

Capability not only to **probe** the **existence**, but also the **properties** of the observed decays in case of discovery
⇒ **Model distinction**

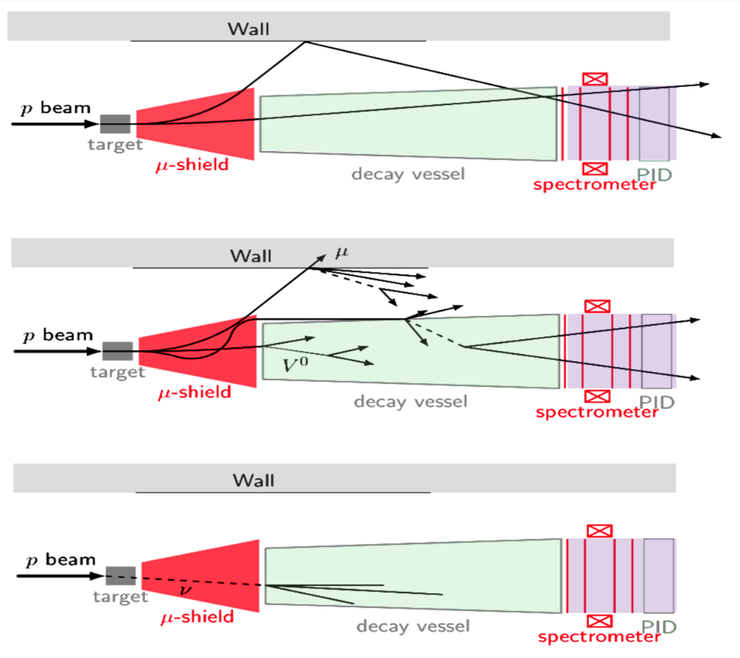
Background Rejection

Simple criteria to suppress bkg while keeping **high signal efficiency**: selection + timing + veto system (UBT&SBT)

μ-combinatorial

μ-DIS

ν-DIS



Expected background $\ll 1$ event for 6×10^{20} p.o.t.

Neutrinos

- **Unprecedented** yield of $\nu_\tau / \bar{\nu}_\tau$ at SHiP from $D_s \to \tau \nu_\tau$

  - First measurement of structure functions F_4 and F_5 in $\sigma_{\nu-\mathrm{CC\,DIS}}$ accessible only with ν_τ [NP B 84 (1975)]; ν_τ anomalous magnetic moment, ...

- SND can **identify** the **flavour of all neutrinos**

  - LFU in neutrino interaction; neutrino xsec measurement up to 100 GeV

Nr of Neutrino Events for 6×10^{20} p.o.t., Including ϵ Reco

Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to \mu$	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	

Neutrino and Light Dark Matter Physics

Neutrinos

- **Unprecedented** yield of $\nu_\tau / \bar{\nu}_\tau$ at SHiP from $D_s \to \tau \nu_\tau$

  - First measurement of structure functions F_4 and F_5 in $\sigma_{\nu-\mathrm{CC\,DIS}}$ accessible only with ν_τ [NP B 84 (1975)]; ν_τ anomalous magnetic moment, ...

- SND can **identify** the **flavour of all neutrinos**

  - LFU in neutrino interaction; neutrino xsec measurement up to 100 GeV

Nr of Neutrino Events for 6×10^{20} p.o.t., Including ϵ Reco

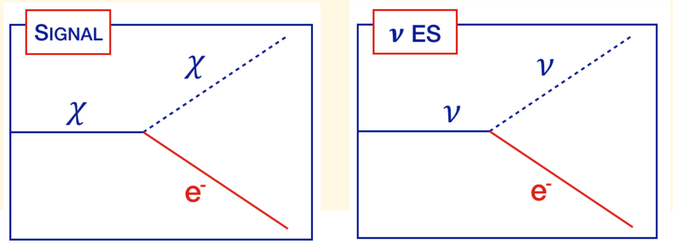
Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

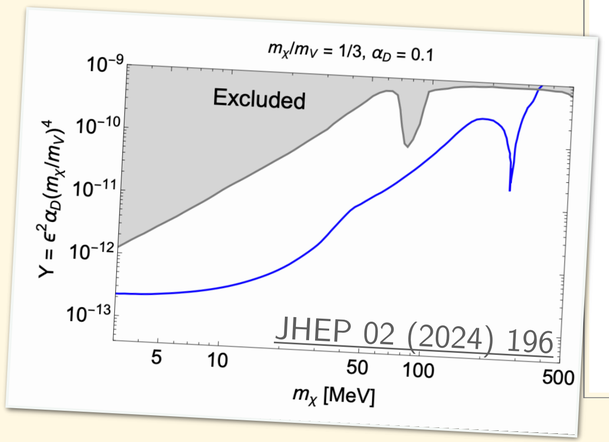
Light Dark Matter (sub-GeV)

- Direct search for **elastic LDM scattering**

  - Experimental signature given by a **shower** from the scattered electron

  - **Background** dominated by elastic **neutrino**-electron elastic scattering





Neutrino Background in LDM-Electron Scattering Search for 2×10^{20} p.o.t.

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	52	27	64	42	185
Quasi - elastic scattering	-	9			9
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	52	36	64	42	194

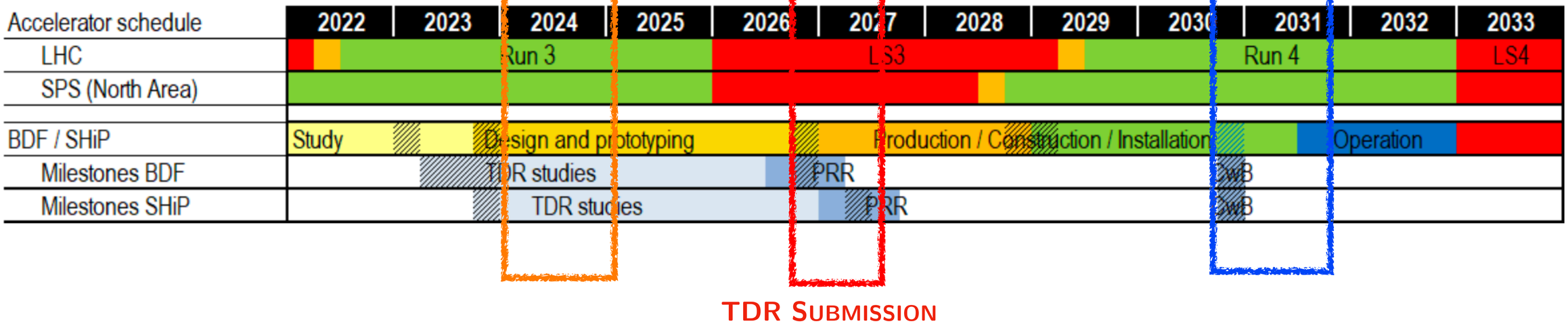
JHEP 02 (2024) 196

Experiment Roadmap

CERN-SPSC-2023-033

Now: TDR preparation

Commissioning, Data taking

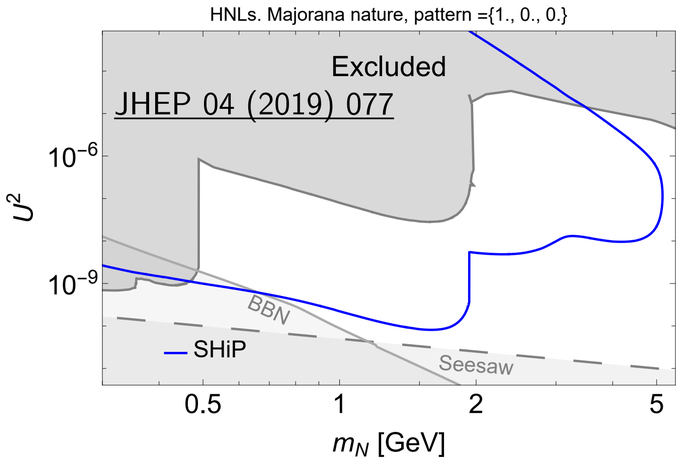


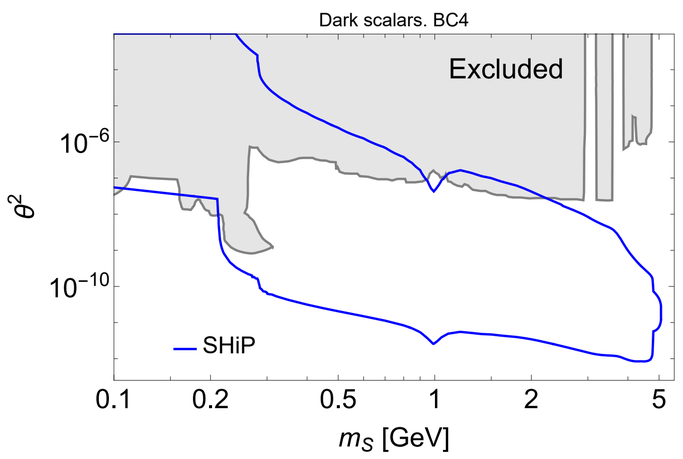
TDR Submission

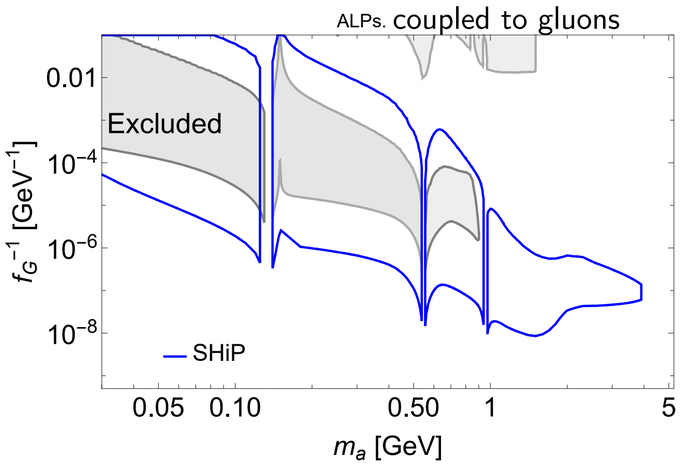
- **Early 2024**: SPSC recommendation and CERN RB decision for the BDF/SHiP proposal at ECN3
- **Technical Design Report (TDR) phase:**
  - Defining the strategy for the muon shield and consequent detectors configuration
- **During LS3:**
  - Decommissioning and detector production/installation; dedicated test-beams
- **2030-2031:** detector **commissioning** and **first data**

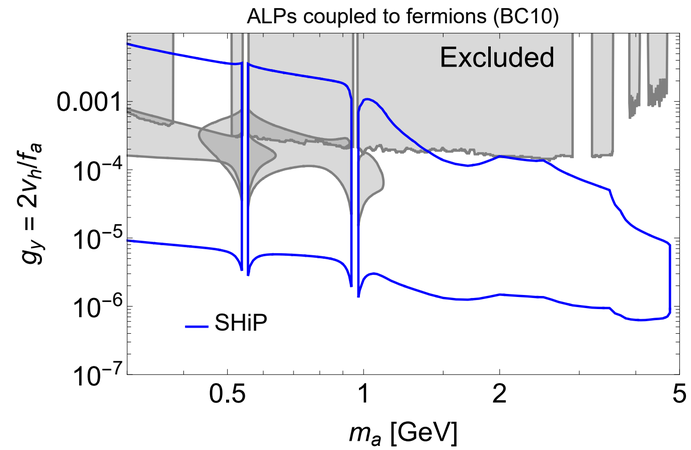
SHiP Physics Performance

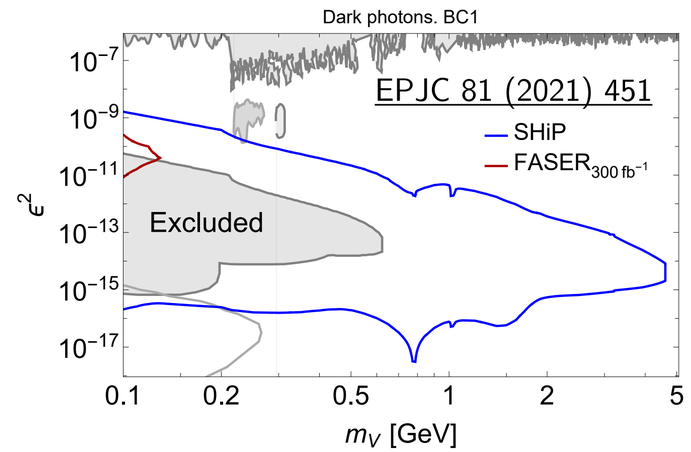
- **SHiP sensitivity** to **FIPs** in *decay* and *scattering* mode is **order of magnitudes better** than existing limits
- 90% CL assuming 6×10^{20} p.o.t., Fairship + SensCalc [PRD 108 (2023) 7, 075028]
- **Strength:** model discrimination in the event of a discovery

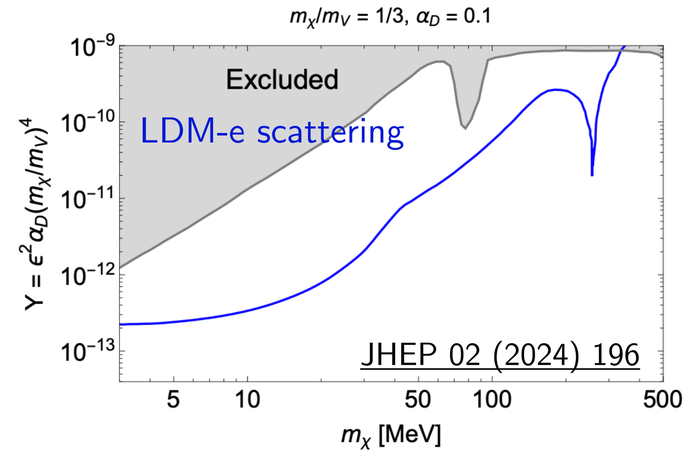












Conclusions

- **SHiP/BDF**: the next SPS-based facility at the CERN intensity frontier
- **Rich physics programme**, covering **FIPs** searches in decay and scattering, and **neutrino** physics
- Substantial **swiss** involvement:
  - CERN EP
  - University of Zurich (UZH)
  - EPFL

Plenty of opportunities to contribute!