SHiP
Search for Hidden Particles

IDM2026
ZARAGOZA

Search for MeV-GeV Hidden Sectors with the SHiP experiment

Note that many plots and results shown come from work in progress

BDF/SHiP at the ECN3 high-intensity beam facility - Technical Proposal 2023

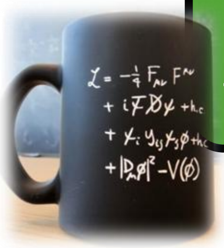
BDF/SHiP Annual Report 2025

R. Jacobsson, CERN

Theory of a Hidden Sectors

- *Standard Model gives us tools to implement Hidden Sector with well-defined phenomenology*

$$\mathcal{L} = \mathcal{L}(\psi_{SM}, A_{SM}, H_{SM})_{dim\leq 4} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda_{NP}^{d-4}} \mathcal{O}^{(d)} + \mathcal{L}_{portal}(m, \epsilon) + \mathcal{L}(\psi_{HS}(m), A_{HS}(m, \alpha), H_{HS})$$



Visible Sector
Standard Model

"Portal interaction"

Hidden Sector
"Dark standard model"

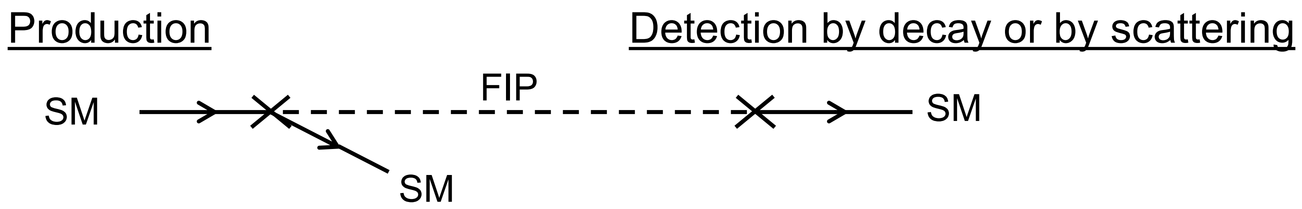
Portal interactions may "drive" dynamics observed in the Visible Sector!

- Dark Matter (trivial)
- Neutrino mass and oscillations
- Baryon asymmetry
- Hierarchy and naturalness
- Structure formation
- Inflation and Dark Energy
- ….

➔ *Plethora of alternative SM extensions!*

➔ *And possibly no need for new energy scale !*

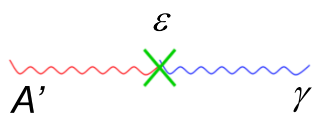
Profiting from "portal" coupling at accelerator!



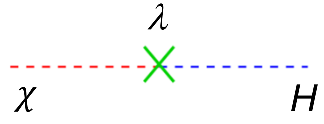
Physics prospects in Hidden Sector

Composite operators as "portals" :

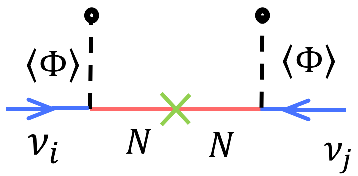
- **D = 2: Vector portal**
  - Kinetic mixing with massive dark/secluded/paraphoton A' : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$
  - ➔ Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter,, …



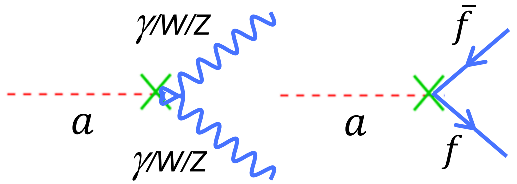
- **D = 2: Scalar portal**
  - Mass mixing with dark singlet scalar χ : $(g\chi + \lambda\chi^2)H^\dagger H$
  - ➔ Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…



- ***D = 5/2: Neutrino portal***
  - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $\mathrm{Y}_{\mathrm{I}\ell}\mathrm{H}^\dagger\overline{\mathrm{N}}_\mathrm{I}\mathrm{L}_\ell$
  - ➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

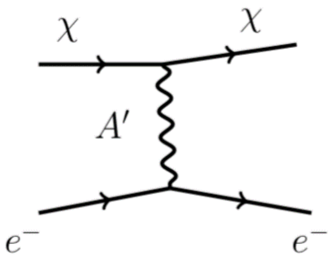


- **D = 4: Axion portal**
  - Mixing with Axion Like Particles, pseudo-scalars pNGB : $\frac{a}{F}G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc
  - ➔ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F
  - ➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…



- **Also light SUSY** (Neutralino, sgoldstino, axino, saxion, hidden photinos…)

- **Light dark matter χ interpretation of scattering signatures**



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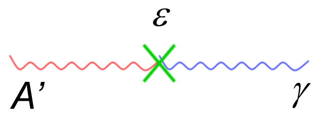

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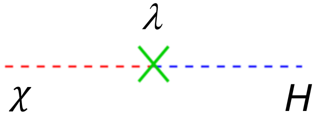

Bottom line: We need large production of $\gamma, q/g, c, b, W, Z, H$!

  - ➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

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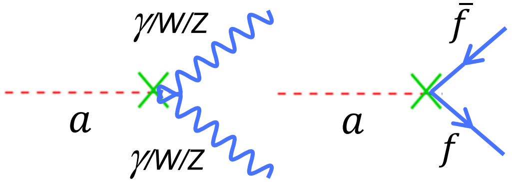

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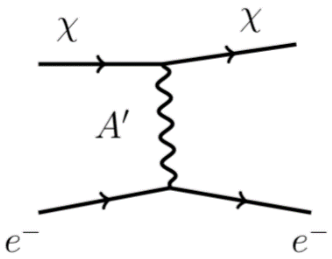
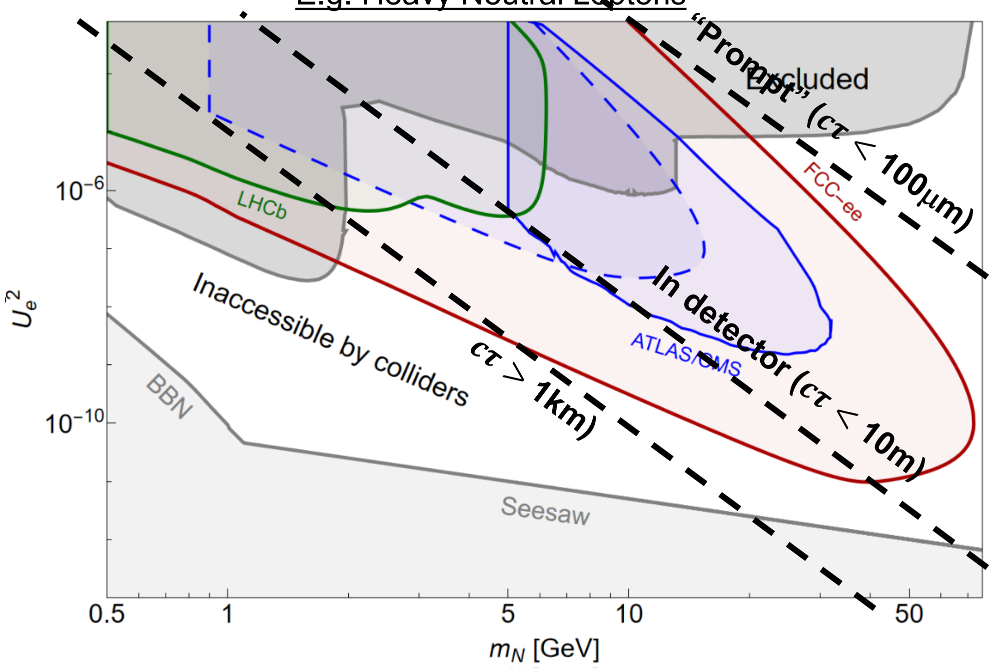


SHiP@SPS raison d'être

- SPS accelerator energy and intensity unique to explore FIPs
  - ➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes
  - ➔ Large lifetime acceptance with beam-dump setup - production modes in limited forward cone

E.g. Heavy Neutral Leptons



Similar behaviour $\tau_{FIP} \propto \frac{1}{\epsilon_{FIP}^2 m_{FIP}^y}$ for all types of FIPs

➔ Return CERN SPS accelerator to full exploitation of unique physics potential

➔ SHiP Physics Proposal compiled and signed by a collaboration of 80 theorists: *Rep. Prog. Phys.* **79** (2016)124201

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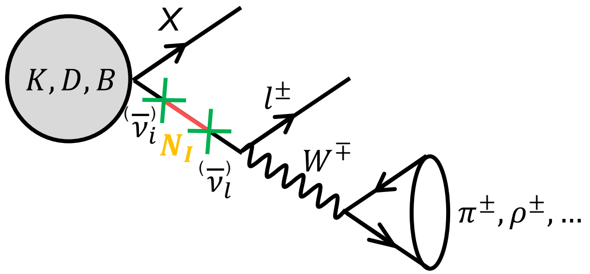

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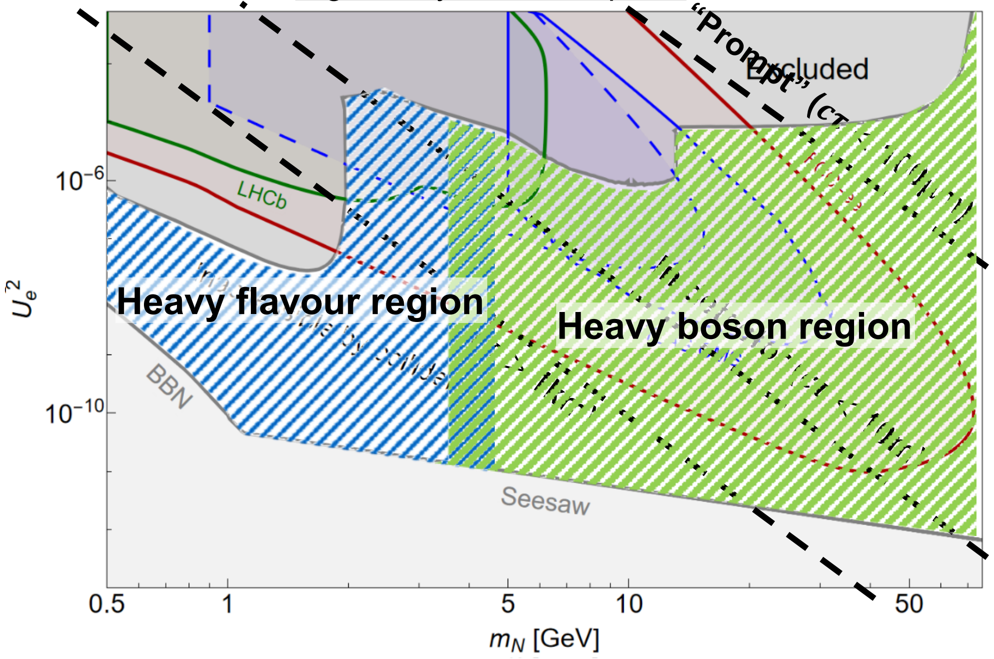

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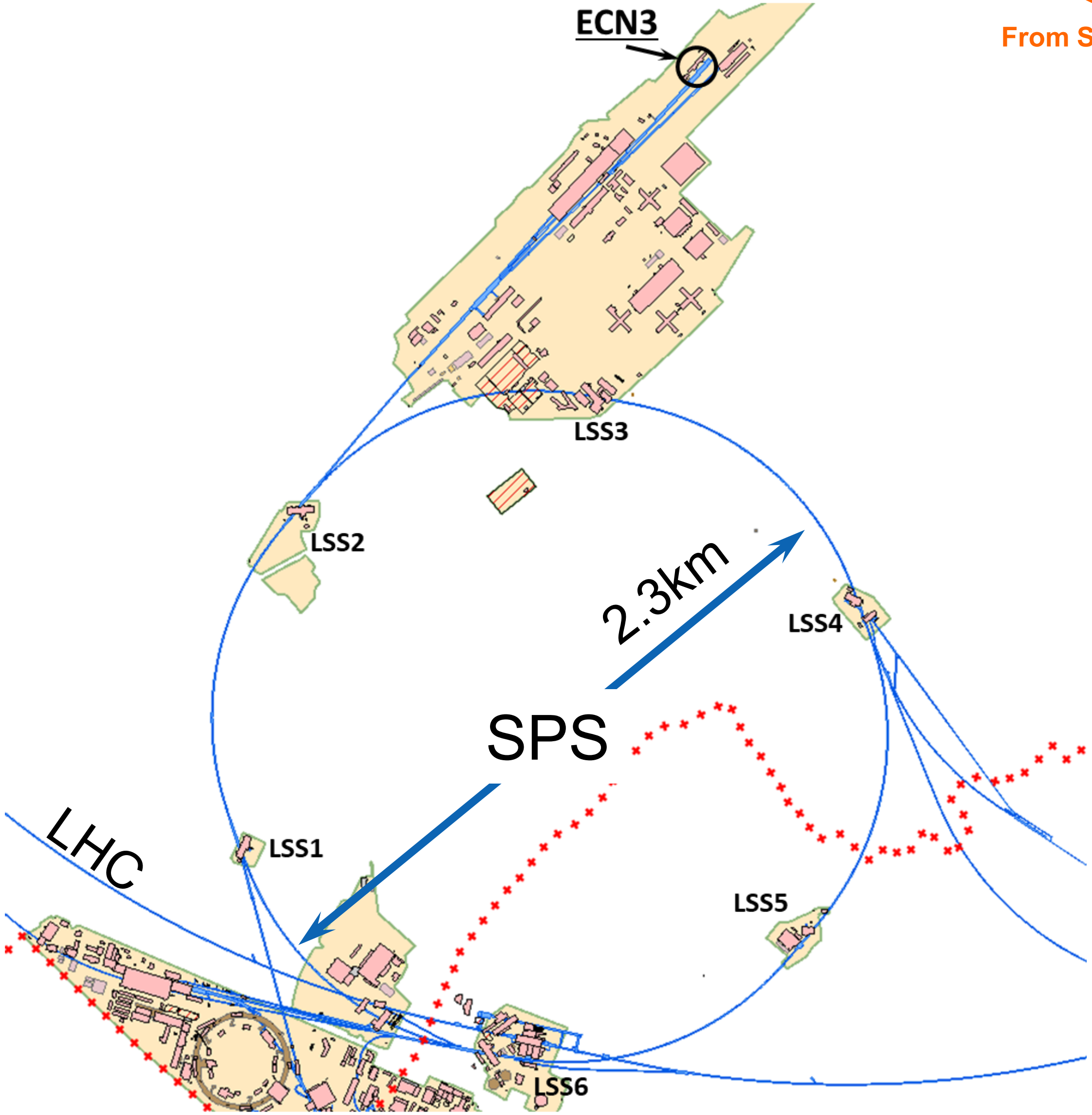
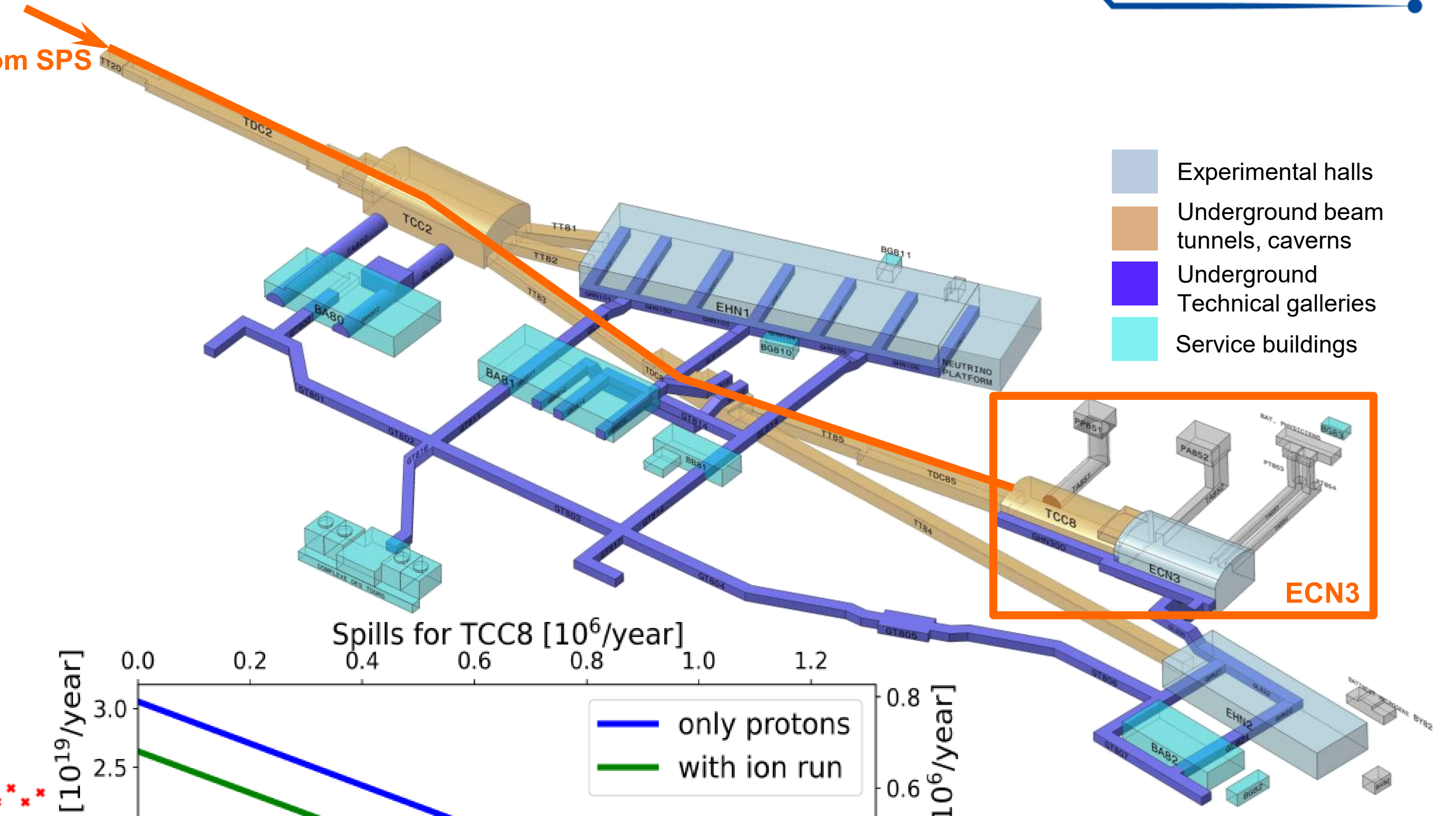
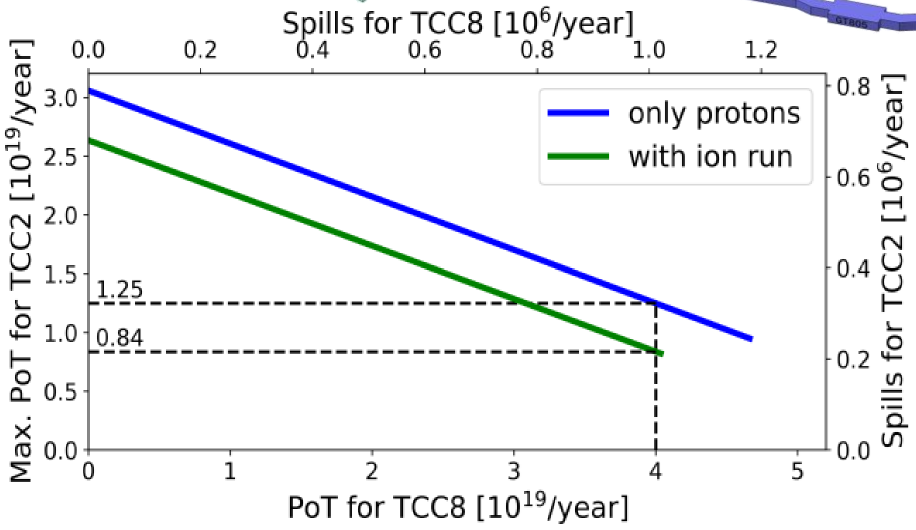
SHiP capable of addressing all classes of FIP models

SHiP @ SPS HI-ECN3 beam facility

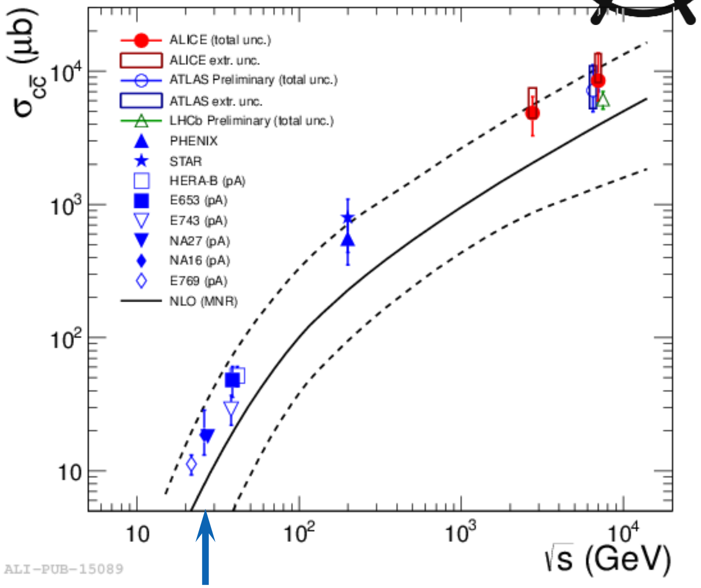






$4x10^{19}$ protons per year at 400 GeV approved for SHiP

SHiP's physics foundation



SHiP @ $\sqrt{s} = 27\ GeV$

➔ BDF "luminosity" with the **long high-A/Z target** and 4x10^{19} protons on target per year *currently available* in SPS

- ➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = **>4 x 10^{45} cm^{-2}**
- ➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = **10^{42} cm^{-2}**

➔ BDF/SHiP ***annually*** access to yields inside detector acceptance:

- ~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)
- ~ 2 × 10^{12} beauty hadrons
- ~ 2×10^{15} tau leptons
- $\mathcal{O}$(10^{20}) photons above 100 MeV

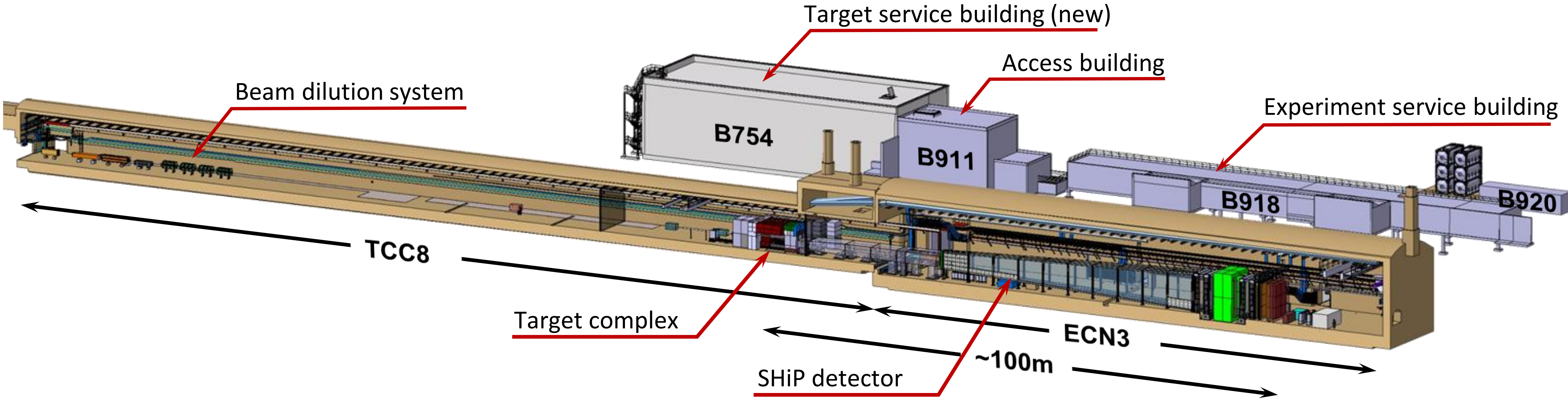
***Direct* New Physics searches For Hidden Sector and LDM**

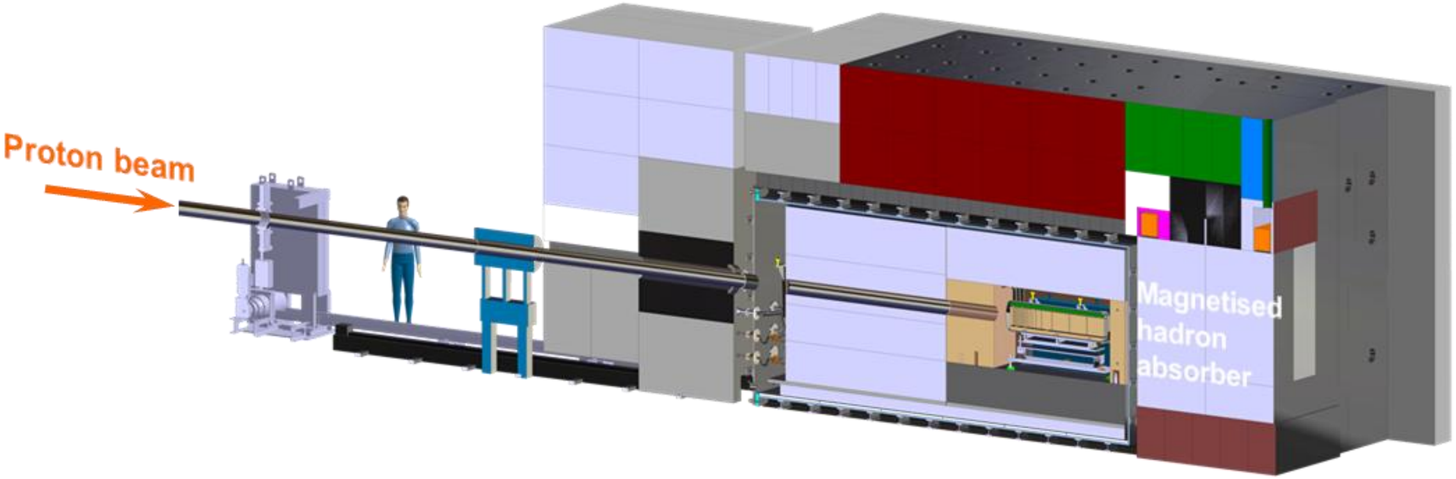
- Large number of neutrinos *detected per-tonne* W ν-target:

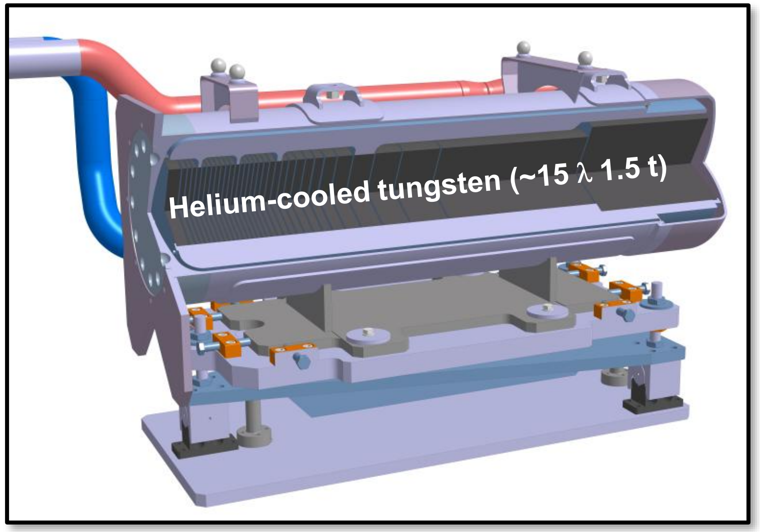
  $\sim 1000\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and ~10^5 $\nu_e + \bar{\nu}_e$ / ~2×10^5 $\nu_\mu + \bar{\nu}_\mu$

Standard Model measurements and BSM with neutrinos

SHiP @ SPS Beam Dump Facility (BDF)







Start of facility construction

<u>May - July 2025: Ground-breaking at ECN3 for BDF/SHiP:</u>
Rerouting of service trench to make space for the construction of the new BDF target complex service building 754 and installation of new access door to 911

<u>June – Sep 2025: Ground-breaking at TT7:</u>
Recovery of 600t of iron shielding blocks from the PS neutrino facility, operated in the early 80's, to be reused for shielding at BDF/SHiP

<u>Helium-cooled W target in beam Q2-2026</u>

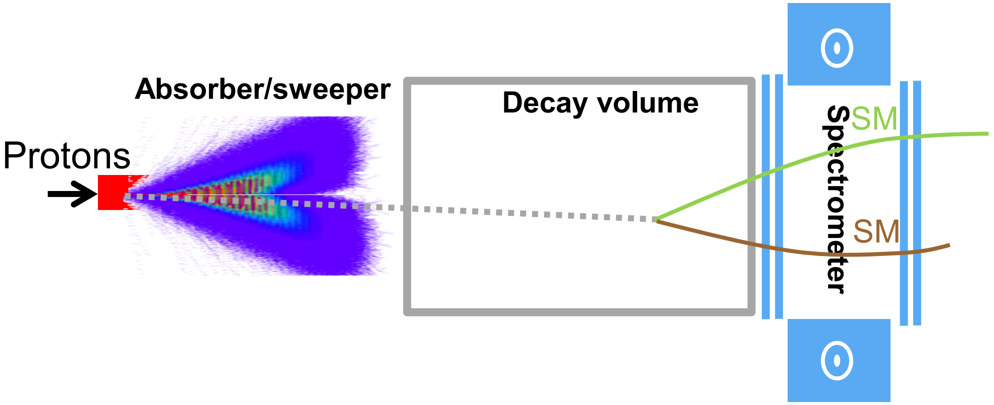
World first !!

<u>Civil engineering consultancy contract launched Q3-2026</u>

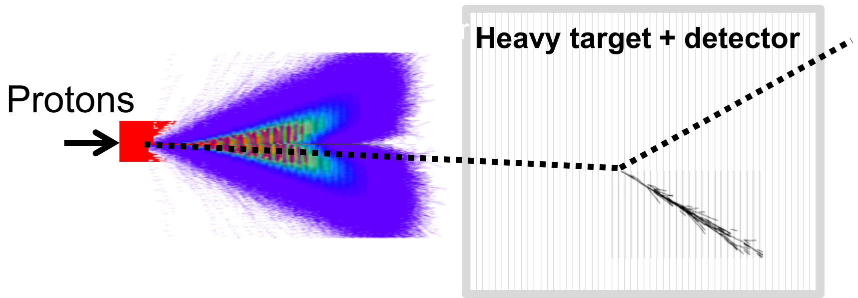
SHiP experimental techniques

Two-in-one detector concept:

Decay signatures (Decay Detector - DD)



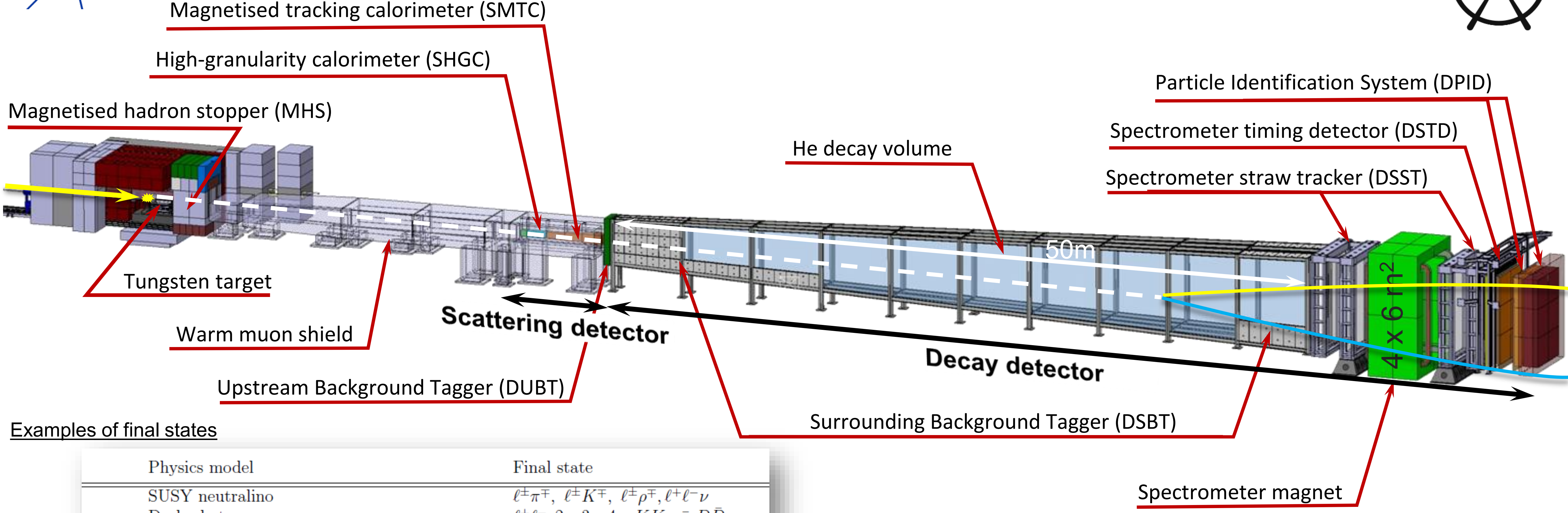
Scattering signatures (Scattering Detector - SD)



Also suitable for neutrino interaction physics with all flavours

- Design for exhaustive search by aiming at model-independent detector setup
  - Full reconstruction and identification of as many final states as possible of both fully and partially reconstructible modes
    ➔Sensitivity to partially reconstructed modes also proxy for the unknown
  - **In case of discovery ➔ precise measurements to discriminate between models / test compatibility with hypothetical signal**

Overview of SHiP detector



Examples of final states

	Physics model	Final state
DD	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	$\gamma\gamma, \ell^{+}\ell^{-}, 2\pi, 2K$
SD	LDM	electron, proton, hadronic shower
	ν_{τ}, $\overline{\nu}_{\tau}$ measurements	$\tau^{\pm}$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^{\pm}$, $D^{\pm}$, D^{0}, $\overline{D^{0}}$, Λ_c^{+}, $\overline{\Lambda_c}^{-}$

Challenge is background suppression

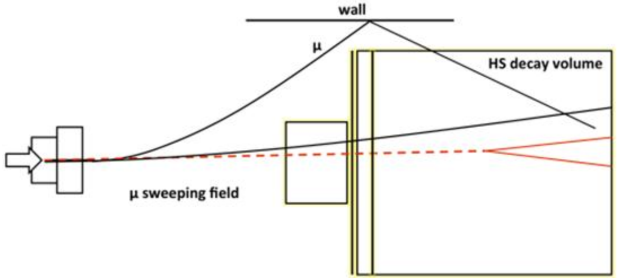
Background challenge for decay search

➔ Per spill of 4x10^{13} protons

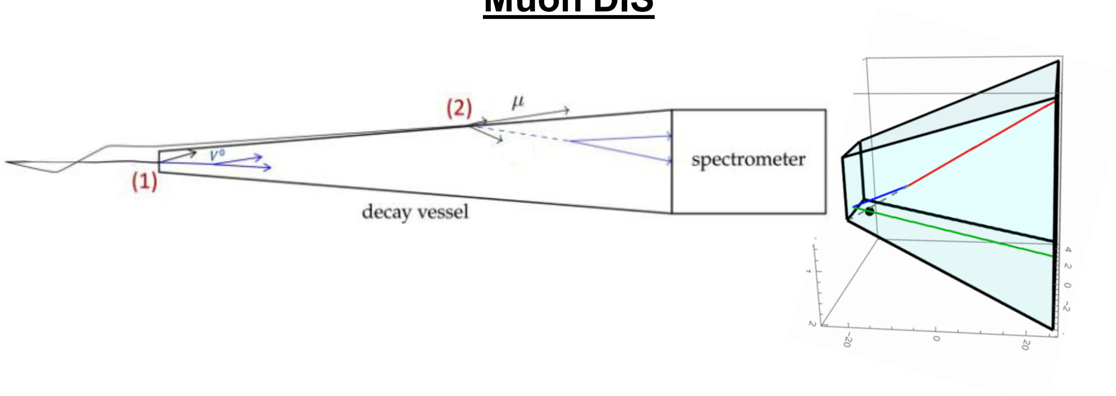
- 1.5 ×10^{12} neutrinos and anti-neutrinos through SHiP's fiducial volume
- $\mathcal{O}(10^{11})$ muons above 1 GeV/c (spectrum validated in measurement at SPS with prototype target - agreement within 30%) (Eur. Phys. J. C 80 (2020) 284)

➔ Residual flux of muons and neutrinos lead to three categories of physics background:

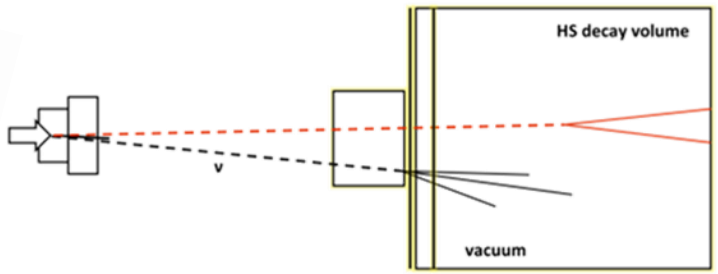
Muon combinatorial



Muon DIS



Neutrino DIS

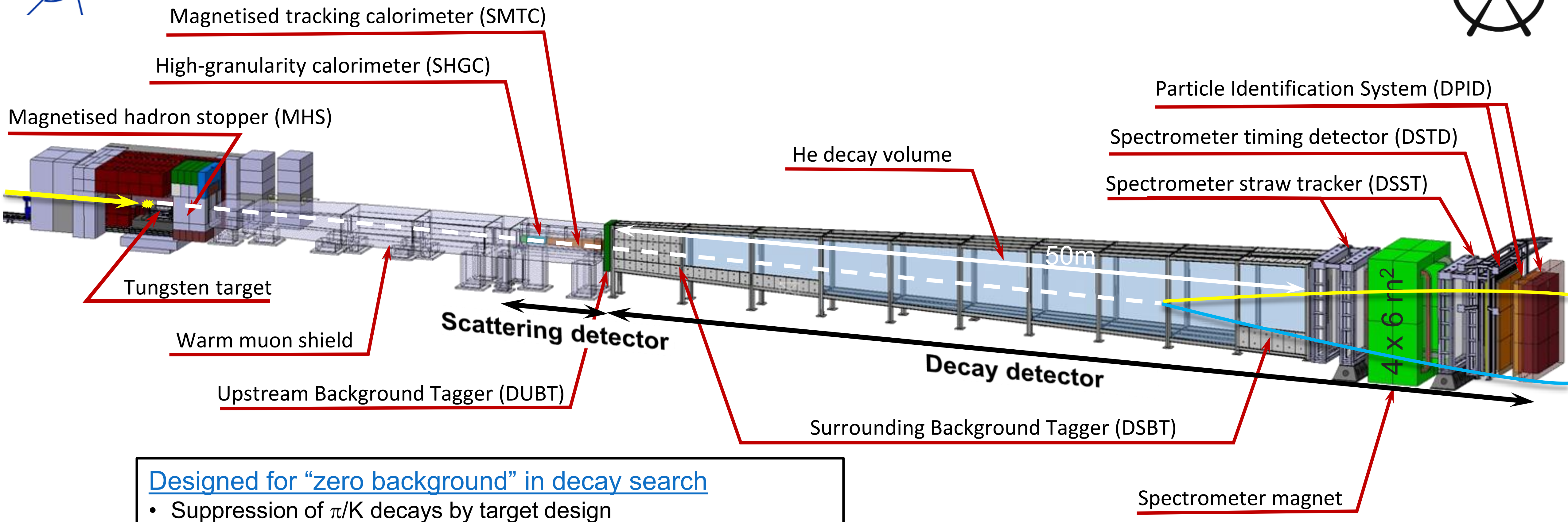


⊙ Very simple and common selection for both fully and partially reconstructed modes – model independence

➔ **< 1 events expected in decay search in 6x10^{20} pots (15 years) in fully / partially reconstructed modes**

➔ Redundant selection - Possibility to measure background with data by relaxing suppression techniques

Overview of SHiP detector

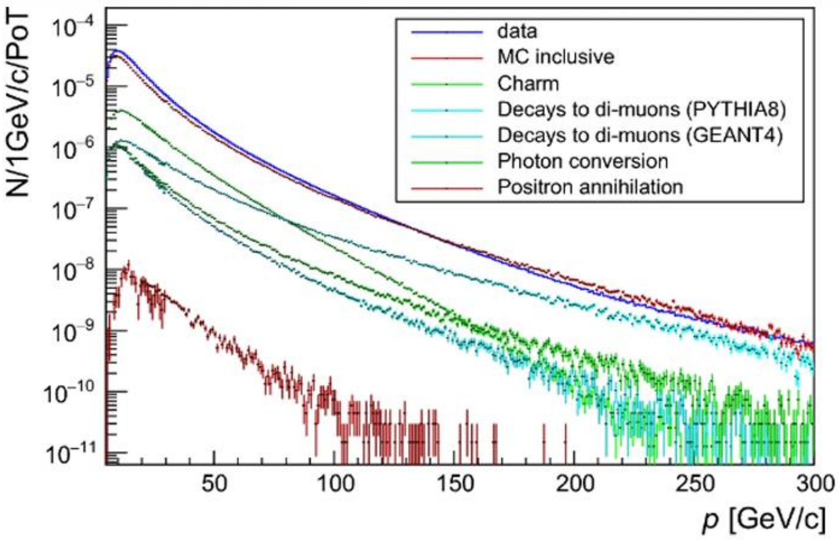


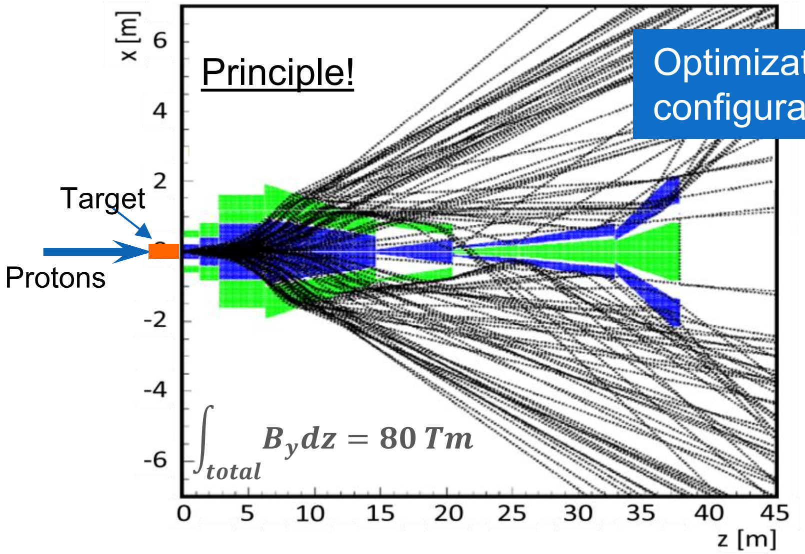
Designed for "zero background" in decay search

- Suppression of π/K decays by target design
- Suppression of muons by magnetic shield
- Suppression of neutrino by decay volume by evacuating air
- Background taggers – upstream and surrounding
- Momentum and decay vertex information } by main tracker
- Impact parameter at target } by main tracker
- Coincidence timing

- Invariant mass } Not currently used in background suppression
- Particle identification } Not currently used in background suppression

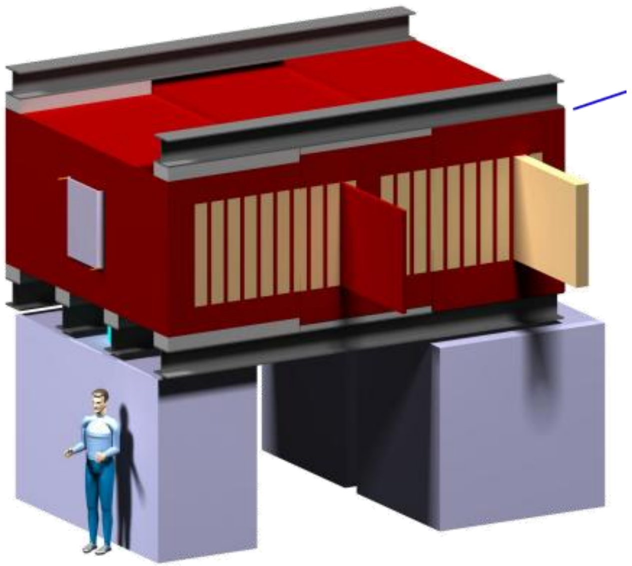
Muon shield – magnetic sweeper system

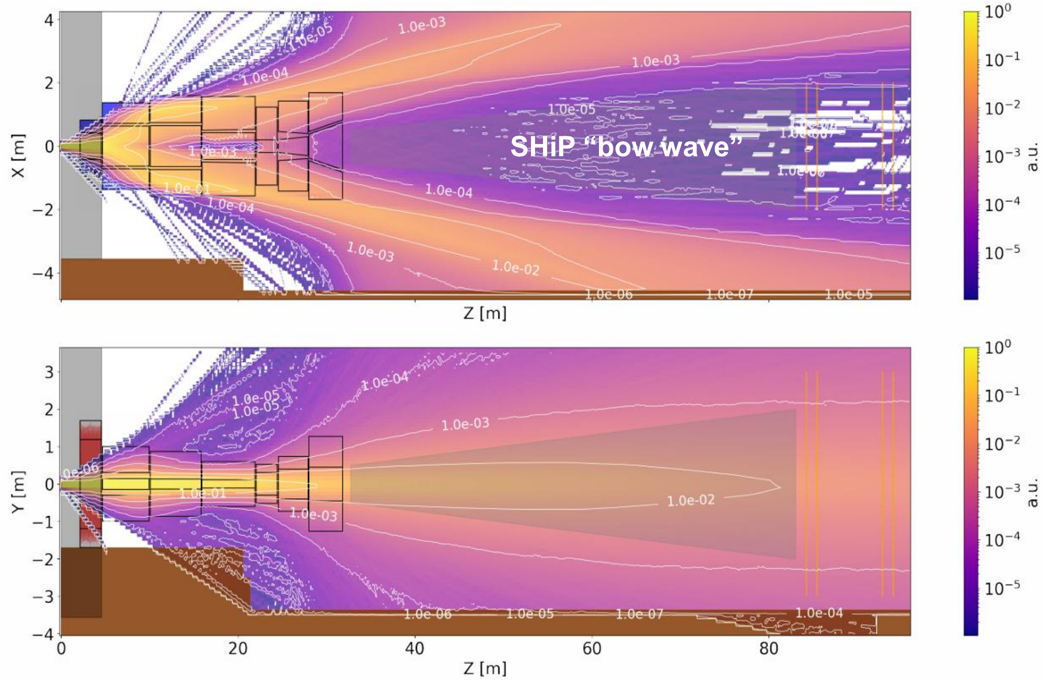




Optimization of field configuration by ML

Warm magnet model

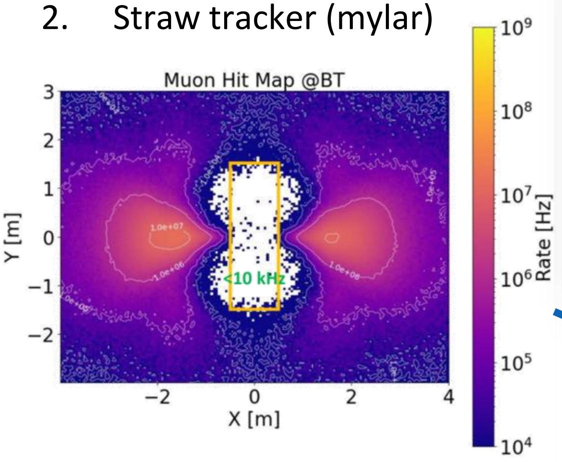


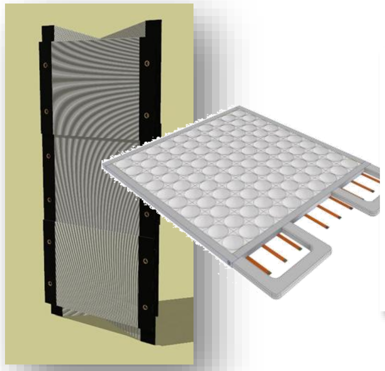


Decay Detector technologies

Upstream Background Tagger (eff >99%)

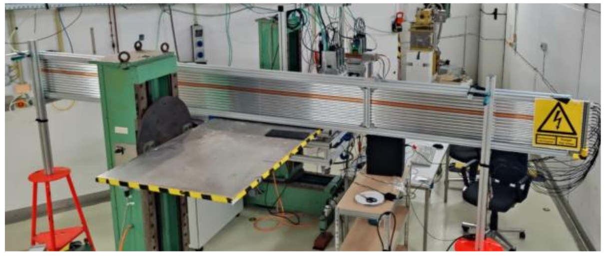
- σ_{space} ~100 μm, σ_{time} ~200 ps
1. Scintillating tiles + SiPM
2. Straw tracker (mylar)





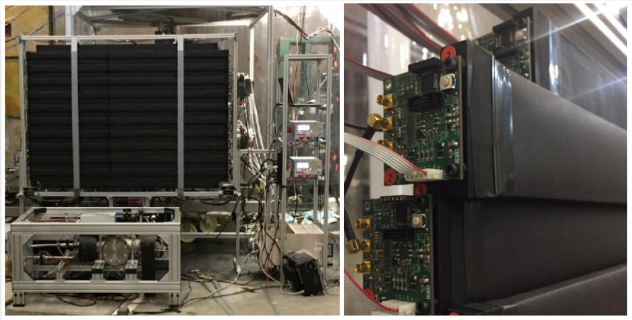
Spectrometer Straw Tracker

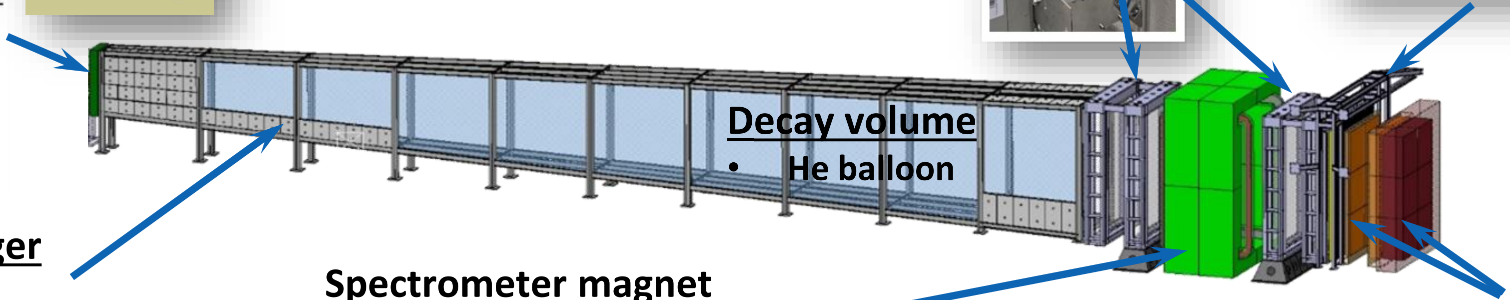
- σ_{space} ~120 μm
- Mylar straws



Spectrometer Timing Detector

- <100 ps
- Scintillating bars + SiPM



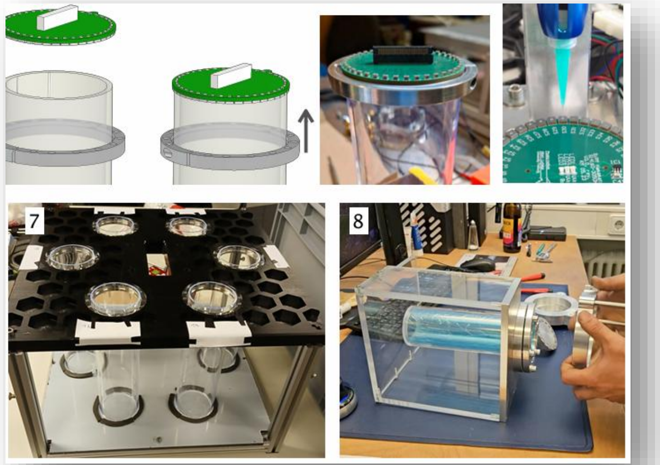


Decay volume

- He balloon

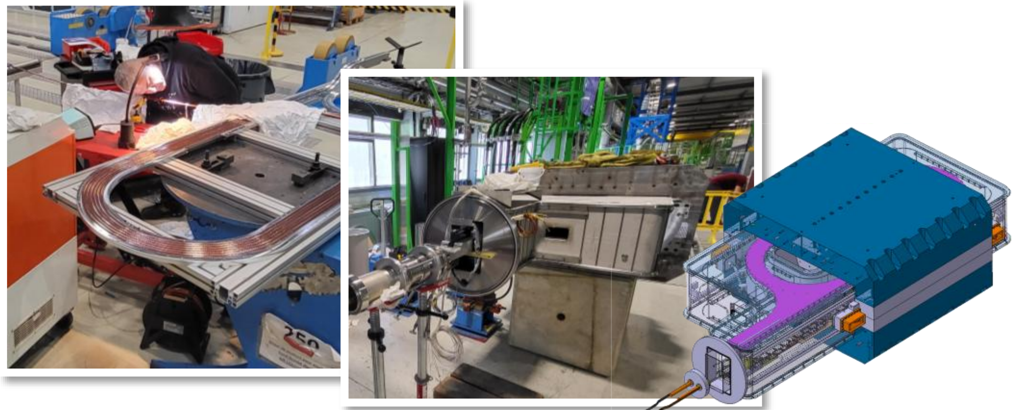
Surrounding Background Tagger

- σ_{space} ~$\mathcal{O}$(cm), σ_{time} < ns ps
- Liquid scintillator + WLS optical modules



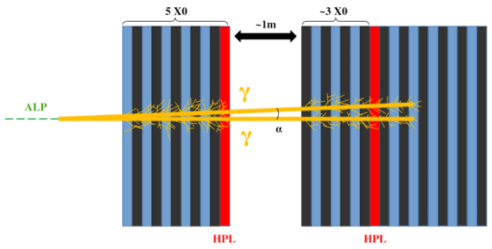
Spectrometer magnet

- 4m x 6m, 0.7 Tm
- Super-ferric technology (MgB_2@20-30K)



PID system

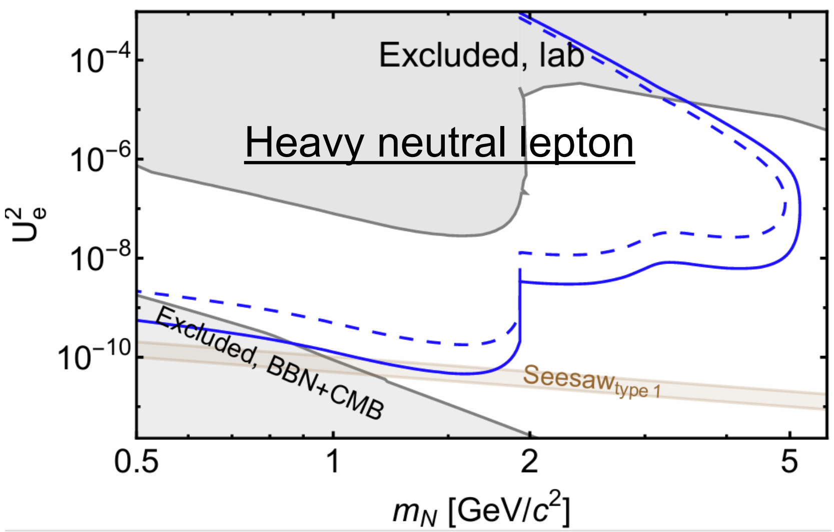
- LHCb PS/SPD, HCAL
- PID + shower axis <5mrad
- High-precision layer with GEMs, RPCs, or SciFi

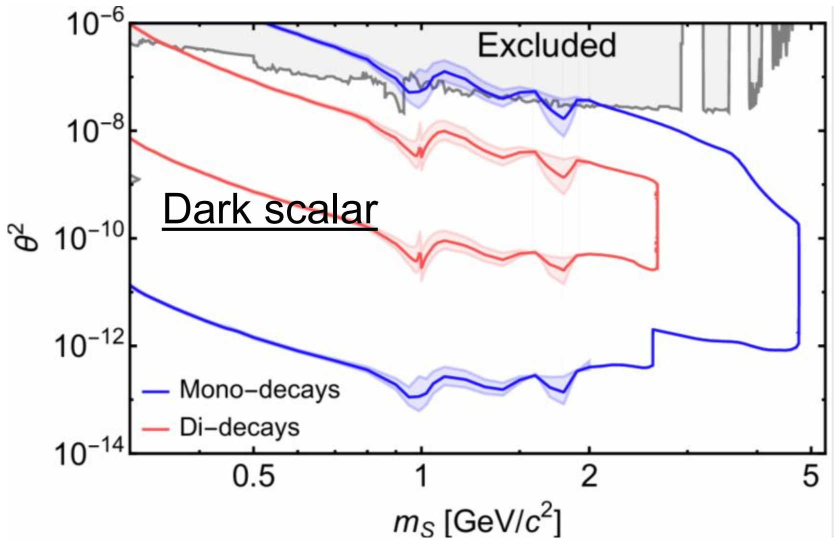


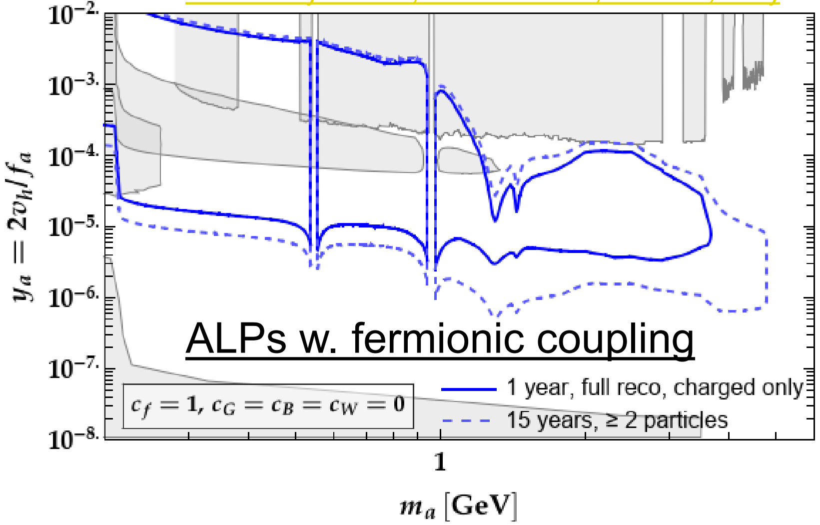
SHiP physics reach with Decay Detector

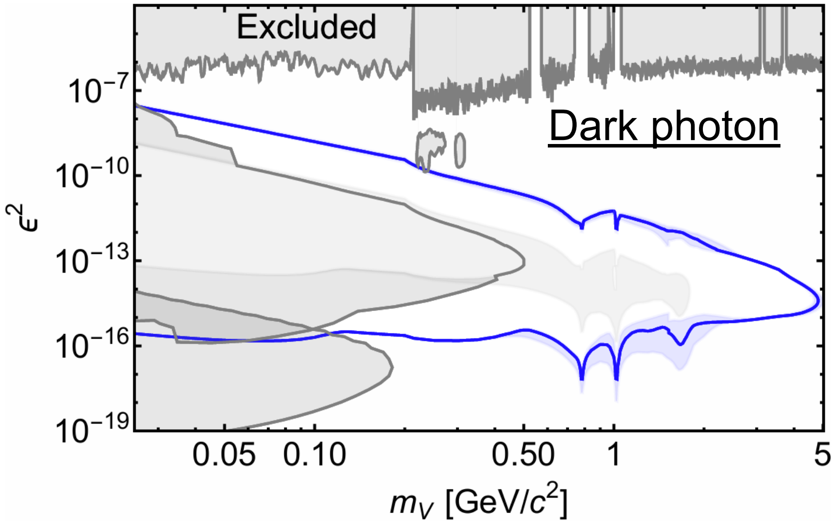
SHiP experiment direct sensitivity to all classes of FIPs in virtually zero background environment

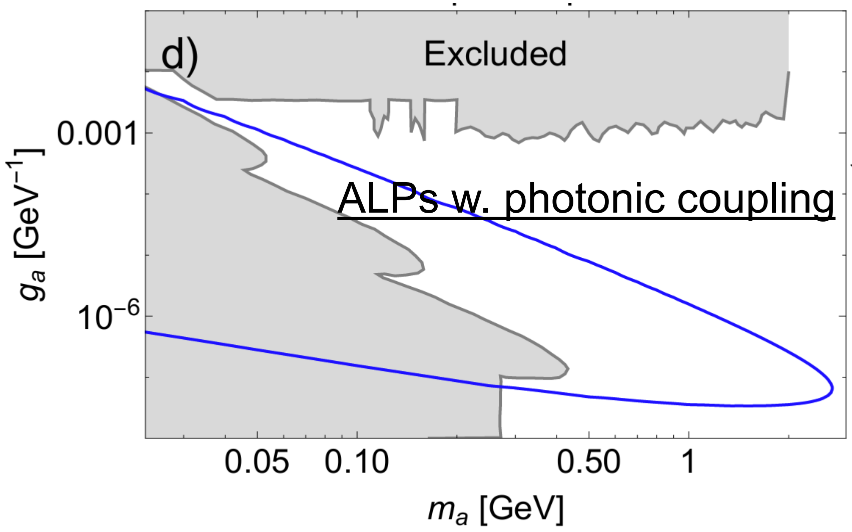
M. Ovchynnikov, ESPP 2025, Venice, Italy

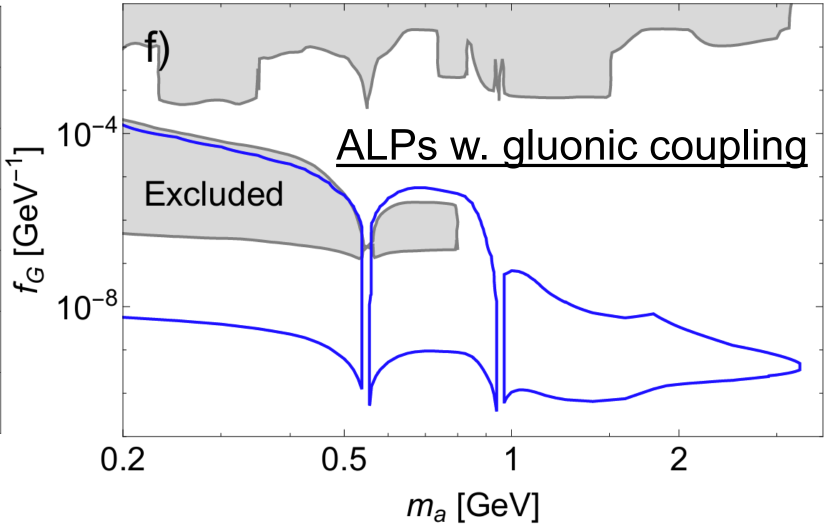






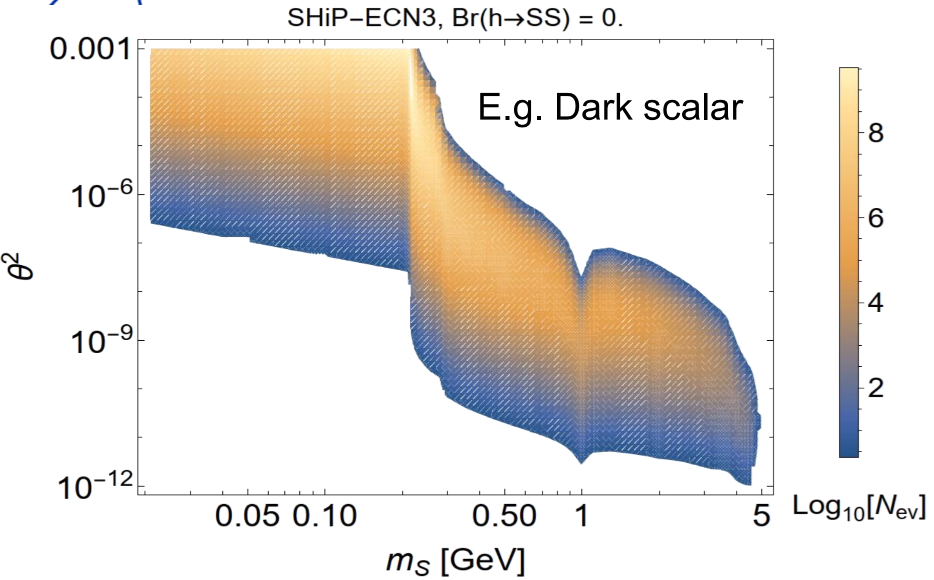






➔ Exploration of (2-5 ⊗ 1-2) orders of magnitude (coupling^2 ⊗ mass) beyond current experiments

Physics sensitivities – FIP decays cont'd

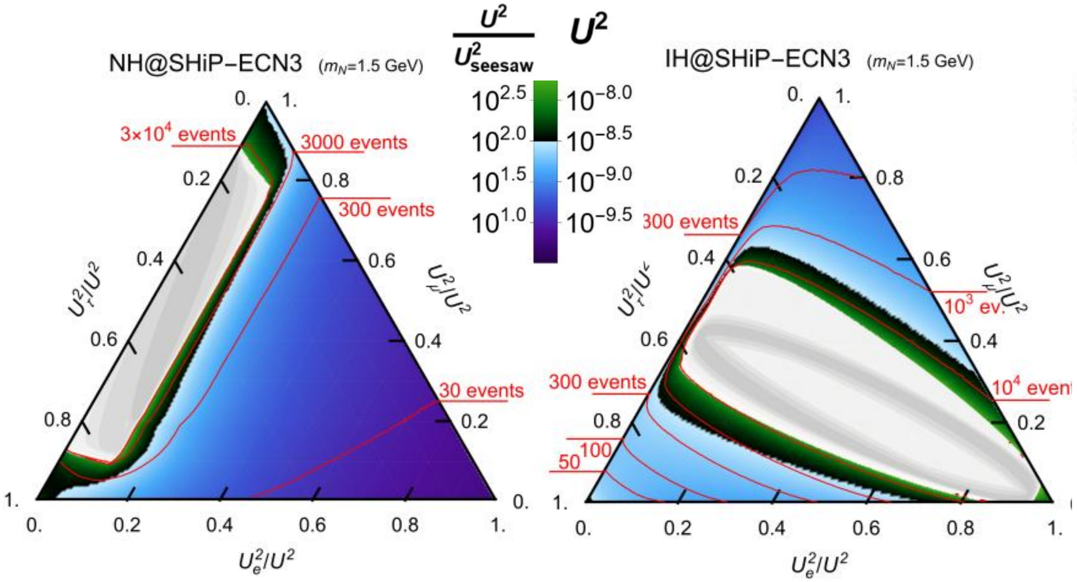


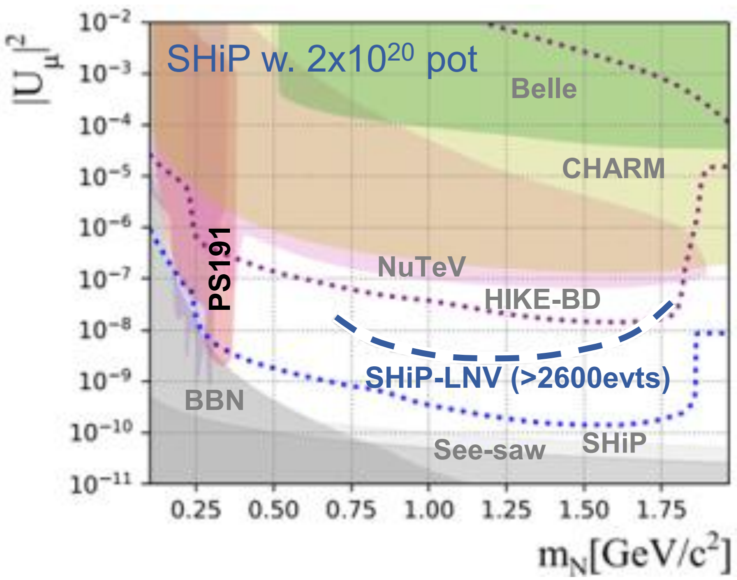
- Step 1: Characterise new object - precise mass, branching ratios, spin: $\mathcal{O}(10)$ evts

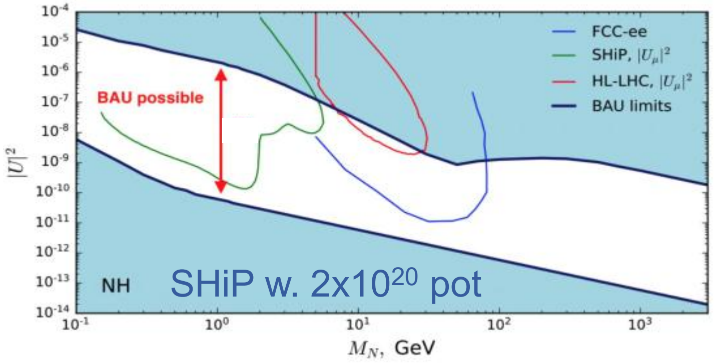
- Step 2: Test compatibility with hypothesis addressing SM issues: $\mathcal{O}(100-1000)$ evts

https://arxiv.org/abs/2312.00659
https://arxiv.org/abs/2312.05163

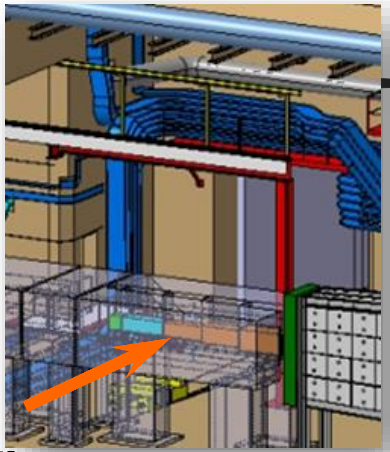
➔ *E.g. check if HNL mixing pattern fits neutrino flavour oscillations, and lepton number violation and BAU*







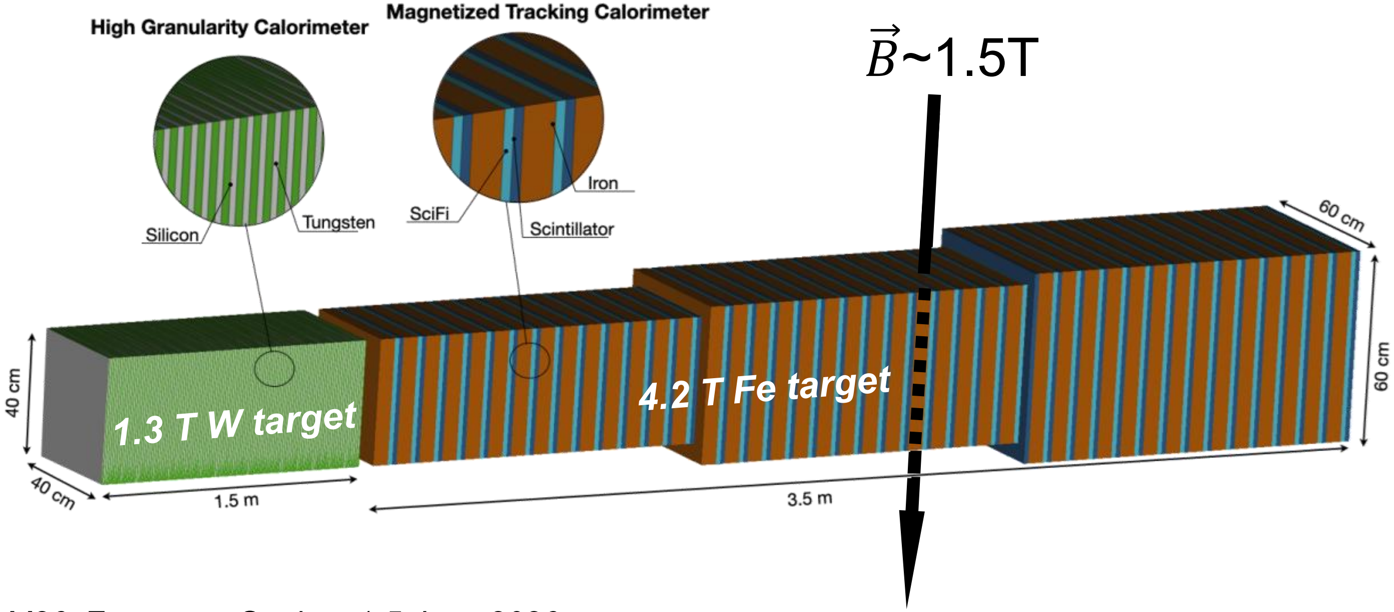
Scattering Detector



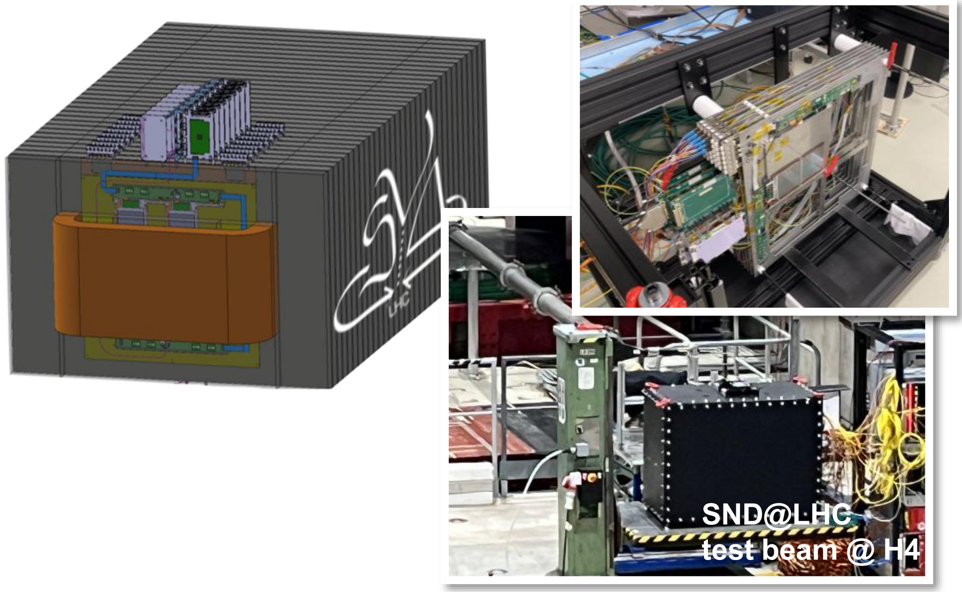
➔ *Reconstruction of all ν flavours, e.m./had shower, μ momentum, charge determination*

- High-granularity calorimeter with silicon detector interleaved with tungsten
  - ν_e, ν_τ ,ν-induced charm, LDM
- Magnetised tracking calorimeter with silicon, scintillating fibres & tiles interleaved with iron
  - ν_{μ}, ν_τ, ν-induced charm, $\nu/\bar{\nu}$ distinction

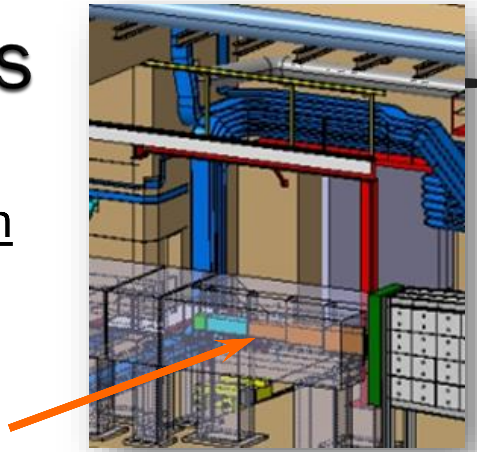
➔ ν_τ identification by kinematics (high-statistics analysis) and potentially by topology (event-by-event analysis)



Detector prototyping in the context of the SND@LHC experiment upgrade



Scattering Detector – Neutrino physics



Reconstruction of all ν flavours, e.m./had shower, μ momentum, charge determination

→ **Measurement of neutrino DIS cross-sections for all flavours up to 100 GeV**

- $\boldsymbol{\sigma_{stat+syst}}$**~5%**

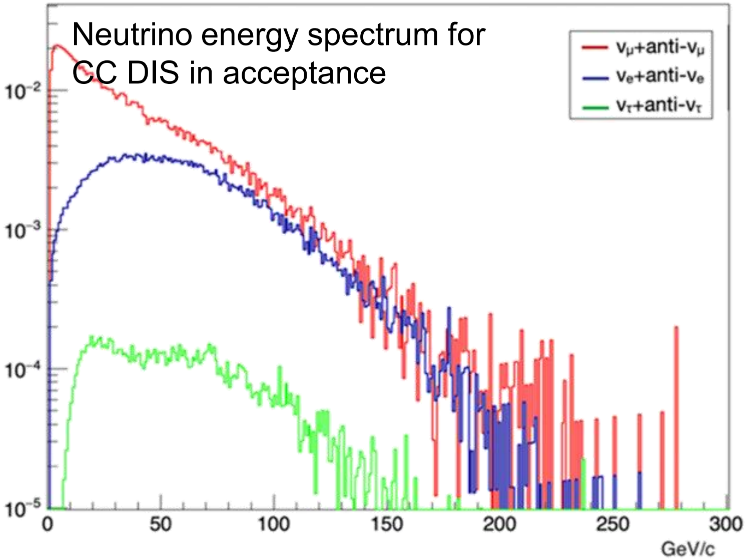
→ LFU in neutrino interactions

- $\sigma_{stat+syst}$~5% accuracy in ratios: ν_e/ν_μ , ν_e/ν_τ and ν_μ/ν_τ

→ Test of F_4 and F_5 ($F_4 \approx 0,\ F_5 = F_2/2x$ with $m_q \to 0$) structure functions in $\sigma_{\nu-CC\ DIS}$ (<10%)

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right),$$

	CC DIS (W)	Charm CC DIS (W)	CC DIS (Fe)	Charm CC DIS (Fe)
N_{ν_e}	6.8×10^4	4.1×10^3	1.6×10^5	9.8×10^3
N_{ν_μ}	2.0×10^5	8.7×10^3	4.6×10^5	2.0×10^4
N_{ν_τ}	2.1×10^3	1.2×10^2	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1	3.8×10^3	2.1×10^2



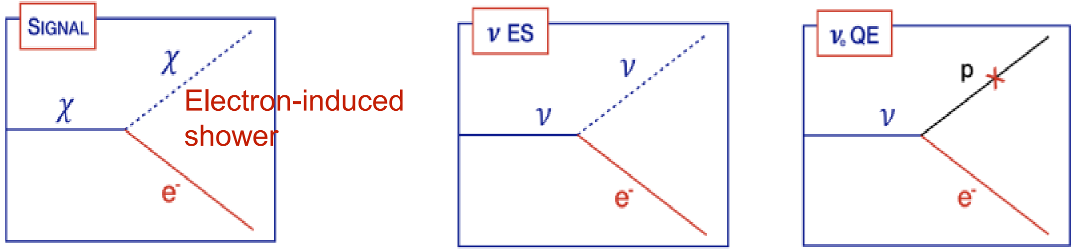
→ Neutrino-induced charm production: nucleon strangeness, $|V_{cd}|$ (<2%),…

→ Neutrino-induced hyperon production

→ BSM physics with neutrinos

Scattering Detector - “Direct” light dark matter search

- *Direct LDM search through e-scattering*, sensitivity to ϵ^4 instead of indirect searches ϵ^2 with E_{miss} technique
  - ➔ Clean vertex and accurate e.m. shower reconstruction

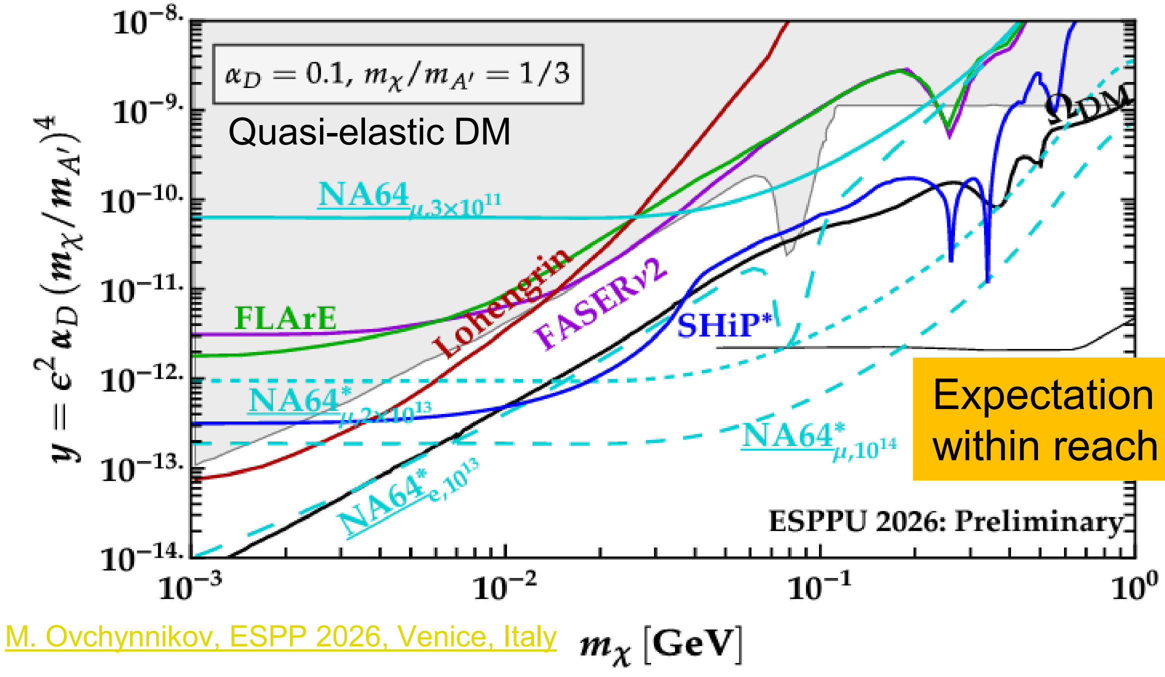


➔ Background is dominated by neutrino elastic and quasi-elastic scattering, for 6×10^{20} PoT

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	260	135	320	210	925
Quasi - elastic scattering	-	45			45
Resonant scattering		-			-
Deep inelastic scattering	-	-			-
Total	260	180	320	210	970

Need update with latest detector configuration

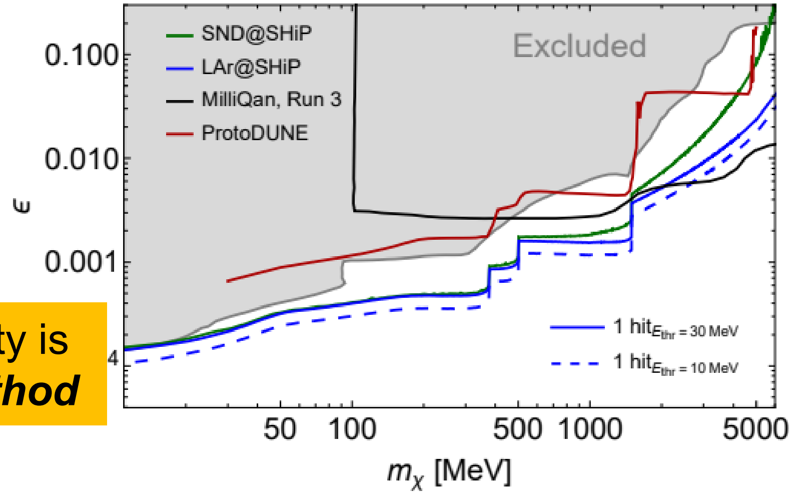
2312.14868v2



M. Ovchynnikov, ESPP 2026, Venice, Italy

Expectation from relic density is within reach with ***direct method***

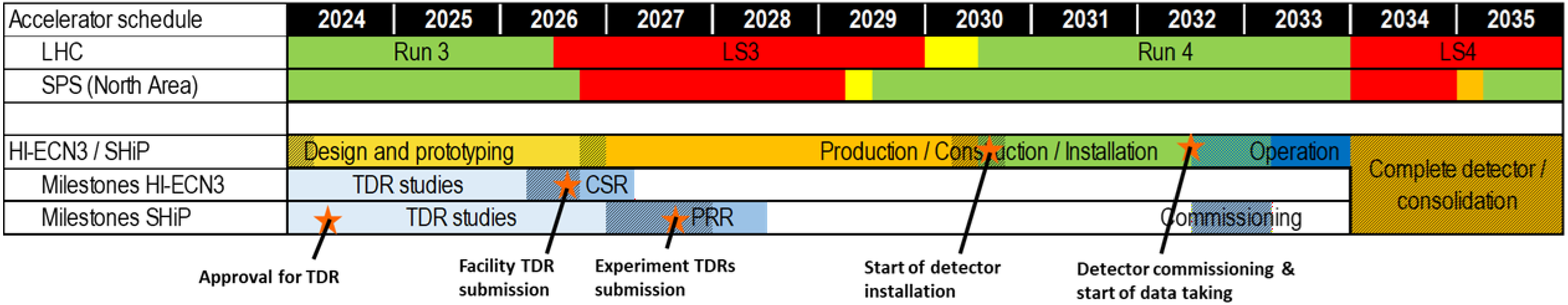
Milli-charged particle – electron scattering



2312.14868v2

Focusing on scattering against atomic electrons, investigate nuclear scattering in future

SHiP schedule and Run 4 objectives



SHiP objectives for Run 4

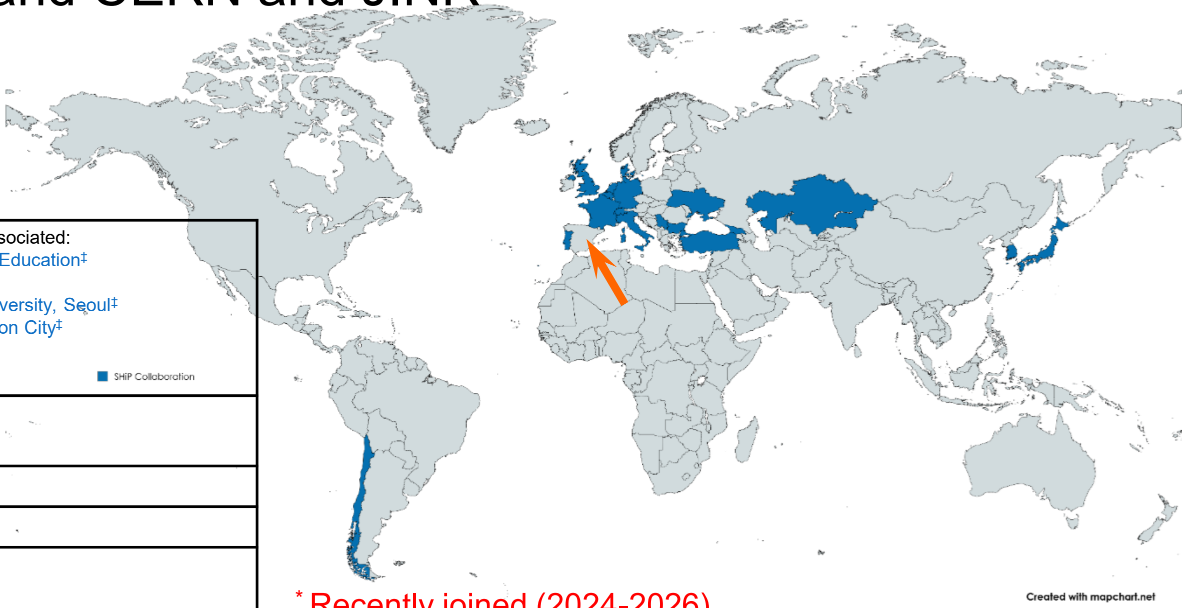
1. **Facility and detector commissioning, background measurements and reconstruction – 2032 Q3-Q4**
2. **Physics run in nominal conditions, aiming for 4 x 10^{19} p/target – 2033**

➔ *Run 4 provide key input to preparation of run for full programme post-LS4 – risk mitigation*

➔ Post-LS4: up to 15 years physics exploration

SHiP Collaboration

33 institutes + 5 associate institutes from 18 countries, and CERN and JINR



Country	Institute
Belgium	University of Ghent*
Bulgaria	University of Sofia‡
Chile	Saphir/UNAB‡
Denmark	Niels Bohr Institute‡
France	IJCLab†
Georgia	Georgia Technical University, Tbilisi†
Germany	Humboldt University of Berlin‡ Constructor University Bremen University of Freiburg University of Hamburg Forschungszentrum Jülich Karlsruhe Institute of Technology* University of Mainz‡ University of Siegen University of Wuppertal RWTH Aachen
Italy	University & INFN Bari‡ University & INFN Bologna‡ University & INFN Cagliari‡ University Fed. II & INFN Napoli‡
Kazakhstan	Institte of Experimental Physics, Almaty*
Korea	Gyeongsang National University, Jinju‡. Associated: Gwangju National University of Education‡ Jeju National University‡ Physics Department, Korea University, Seoul‡ Sungkyunkwan University, Suwon City‡
The Netherlands	Leiden University‡
Portugal	LIP, Lisbon & Coimbra‡
Serbia	University of Belgrade
Switzerland	EPFL‡ University of Zurich‡
Turkey	Middle East Technical University‡ Department of Physics and Engineering, Ankara University‡
United Kingdom	H.G. Wills Physics Laboratory, University of Bristol Imperial College London‡ University of Liverpool* University College London
Ukraine	Taras Shevchenko National University of Kiev
	CERN
	JINR, Dubna

* Recently joined (2024-2026)
† Strengthened by addition of new group(s)
‡ Also in SND@LHC. New groups are regularly joining SND@LHC; they will eventually join SHiP (Genova, Catania, Salerno)

Applications received from:

- USTC (China)
- HNSC (China)

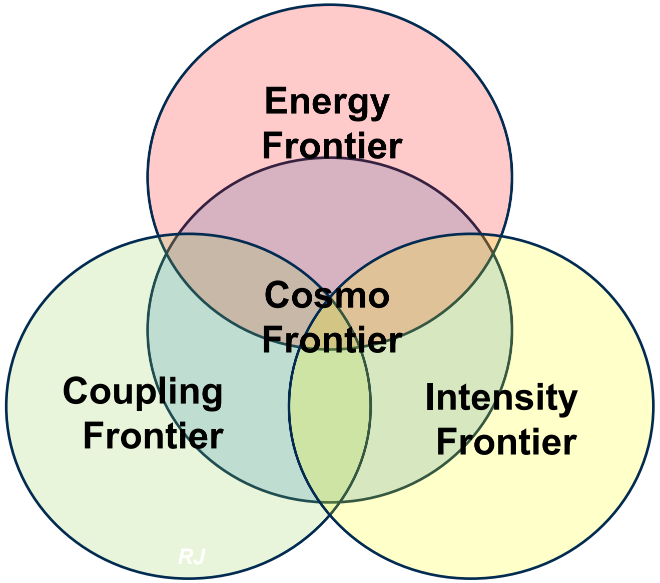
CERN Grey book Experiment's detail

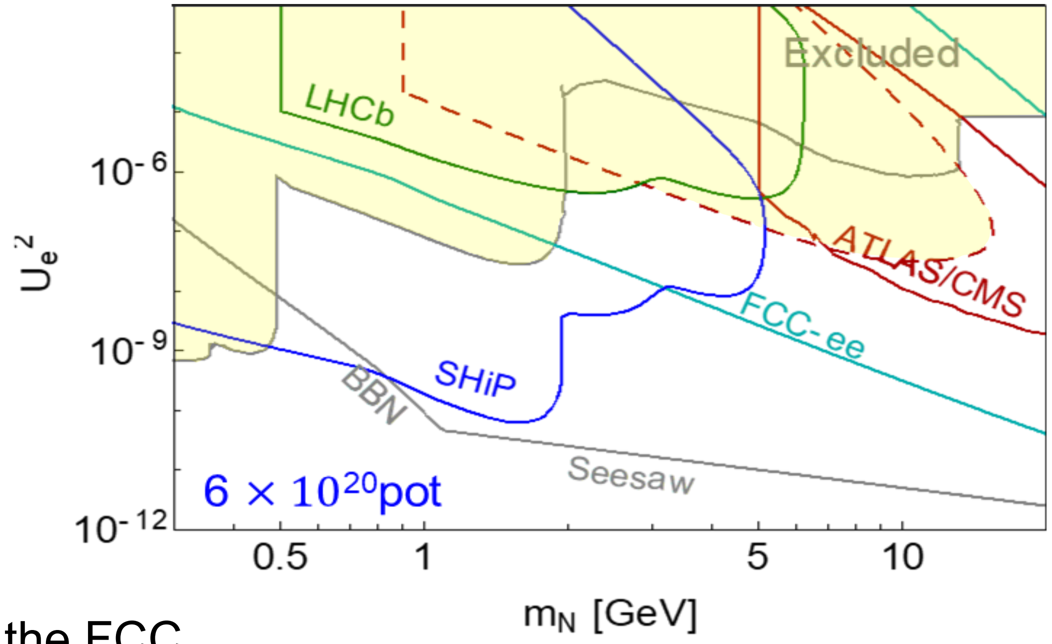
Invitation to join the adventure !

Conclusion

- Unique physics potential of SHiP @ SPS to explore *"Coupling Frontier"* in MeV-GeV region out of reach at collider experiments
  - Unique complementarity to FIP searches at HL-LHC and future e^+e^--collider, where FIPs can be searched in boson decays
  - Capability not only to establish existence but to measure properties and test compatibility with solutions to SM problems
  - Rich neutrino physics programme, including physics of tau neutrino interactions

- Synergies with astrophysics and cosmology – welcome more collaboration!





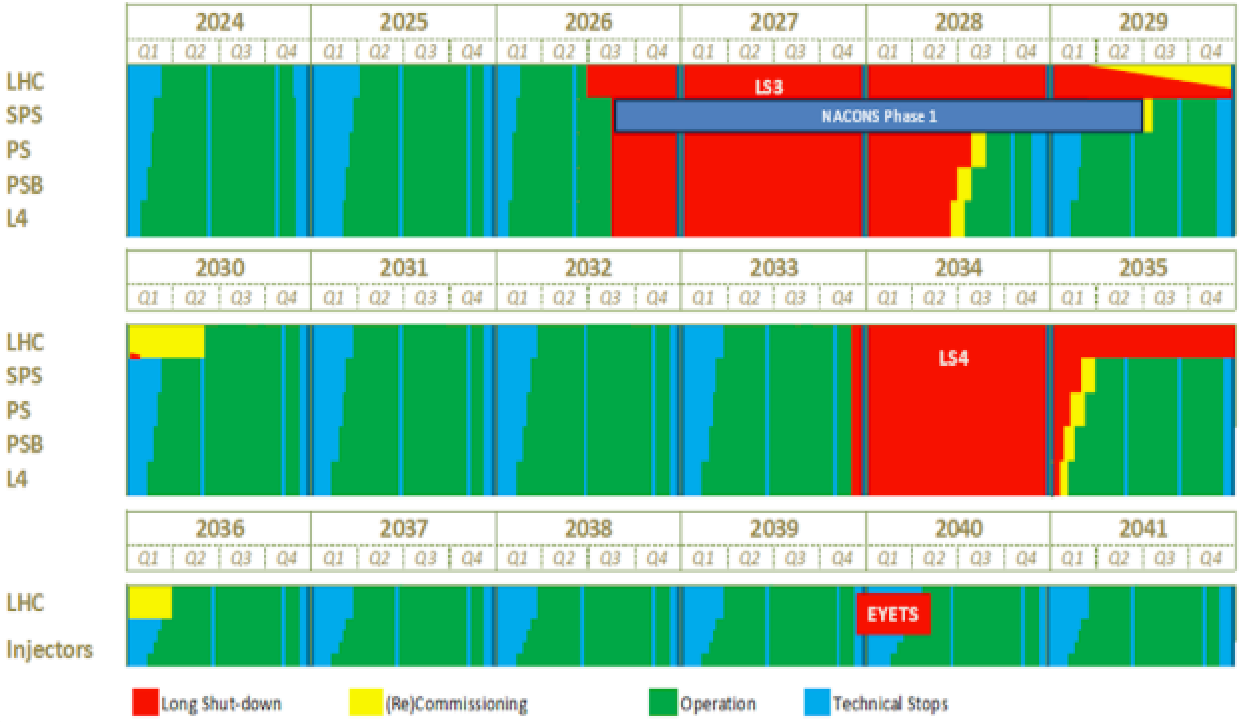
➔ Steppingstone in technology, operation, physics to the FCC

Spare

Overview of extensions of BDF

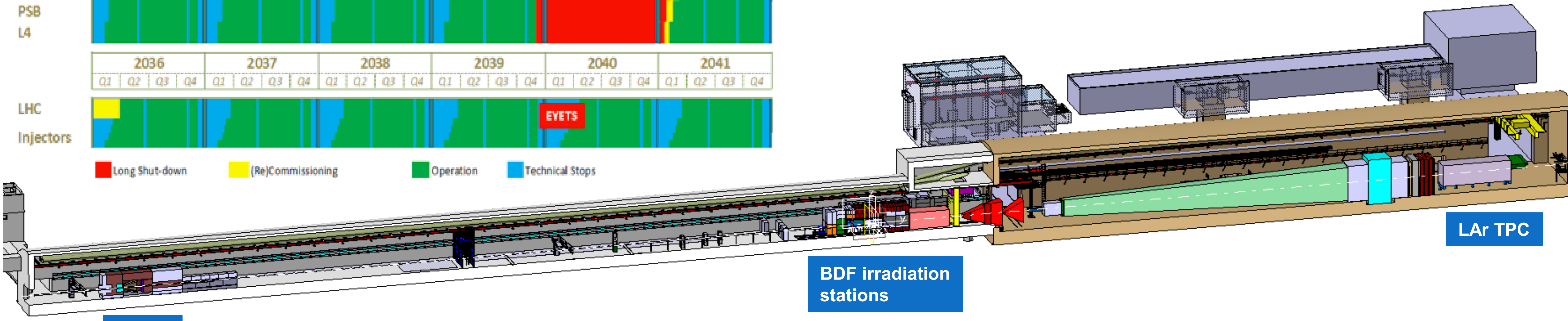
➔ SHiP physics exploration stretches over 15 years

Long Term Schedule for CERN Accelerator complex



Preliminary studies of opportunities to extend physics programme *synergetically with SHiP*:

1. Irradiation stations (nuclear astrophysics and accelerator / material science applications)
   n_ACT@BDF: A Neutron Activation Station at the SPS Beam Dump Facility (BDF)
2. LArTPC to extend search for FIPs using different technology
3. TauFV to search for lepton flavour violation and rare decays of tau leptons and D-mesons

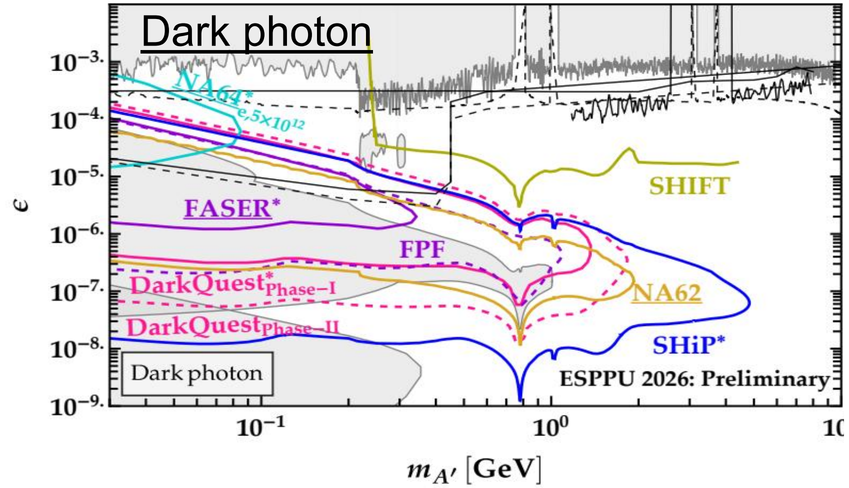


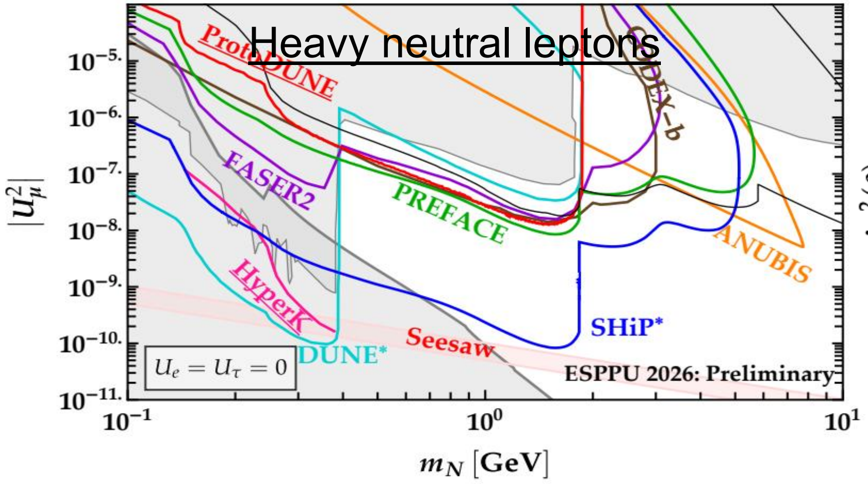
SHiP physics reach with Decay Detector

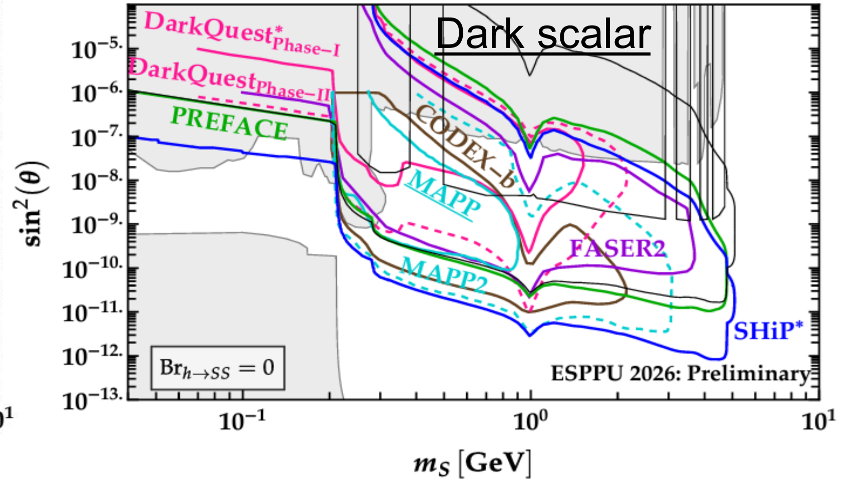
SHiP experiment direct sensitivity to all classes of FIPs in virtually zero background environment

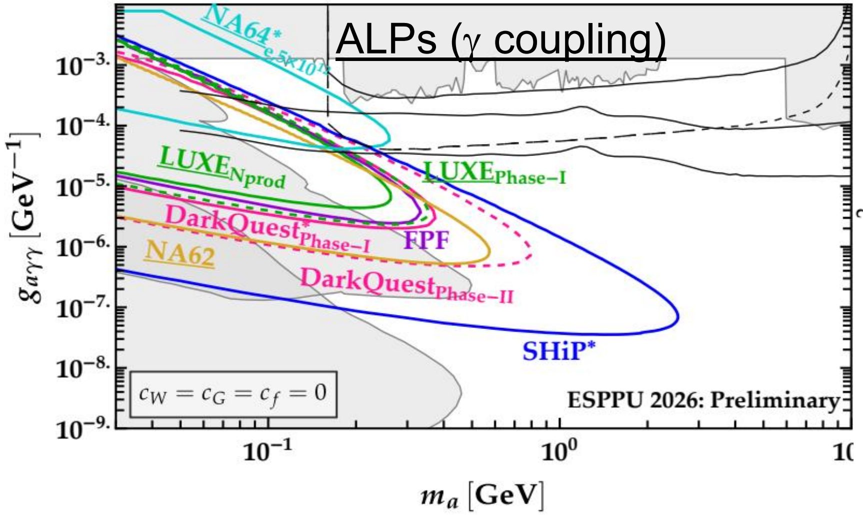
- Benchmark examples:

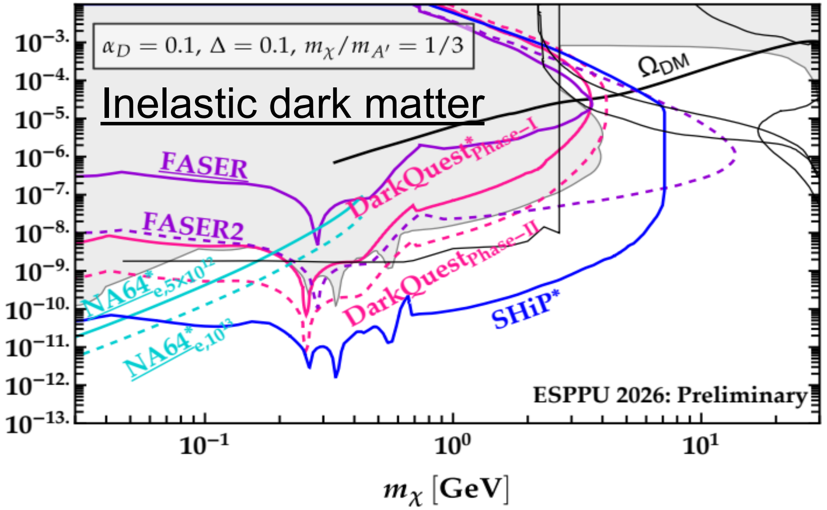
M. Ovchynnikov, ESPP 2026, Venice, Italy











+ also SUSY-related benchmarks

➔ Exploration of (2-5 ⊗ 1-2) orders of magnitude (coupling^2 ⊗ mass) beyond current experiments