Search for feebly-interacting particles at SHiP

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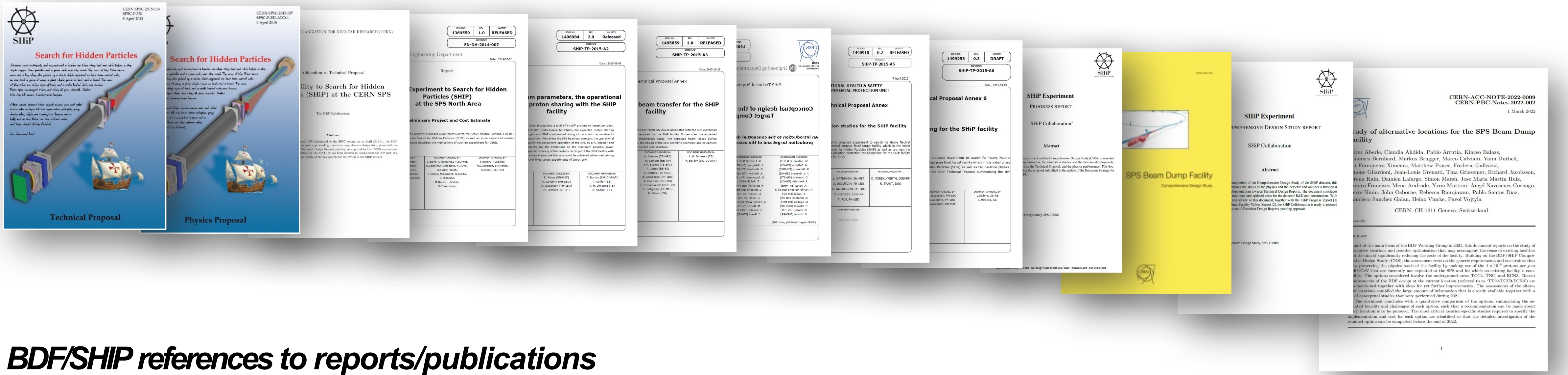
on behalf of the SHiP Collaboration of 38 institutes from 15 countries and CERN

SHiP
Search for Hidden Particles

HISTORY



BDF/SHIP references to reports/publications

- *17 submitted to SPSC and ESPPSU2020*
- *26 on the facility development*
- *37 on the detector development*
- *11 on physics studies*
- *20 on theory developments dedicated to SHiP*
- *20 PhD thesis, a few more in pipeline*

BDF/SHiP approved by the CERN RB in March 2024

Recent documents:

✓ *Proposal, BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-2023-033*

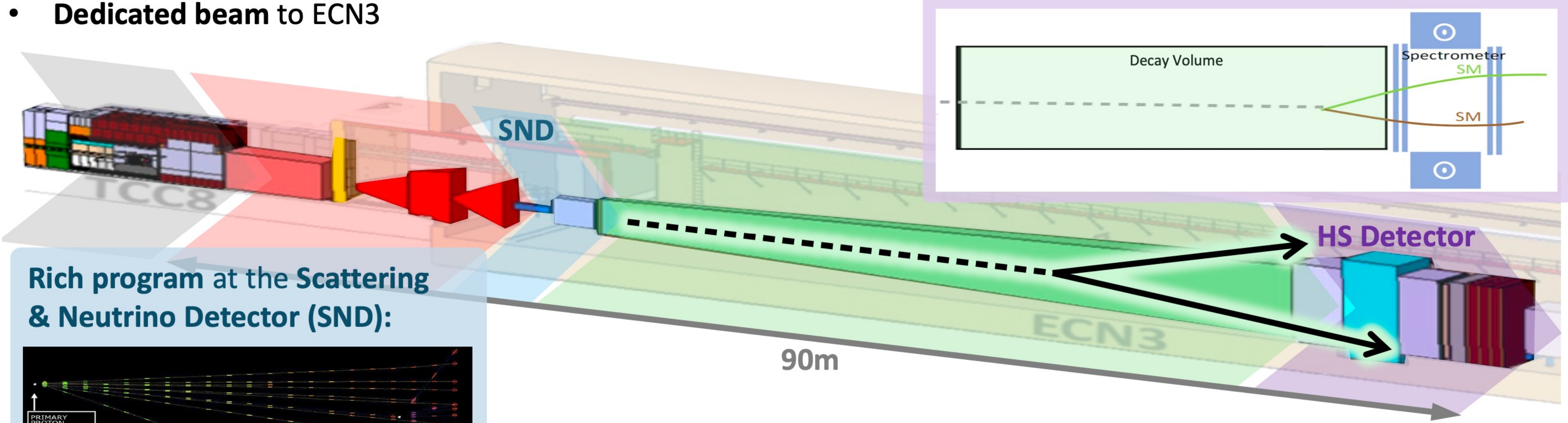
✓ *Letter of Intent, BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-2022-032*

In a nutshell…

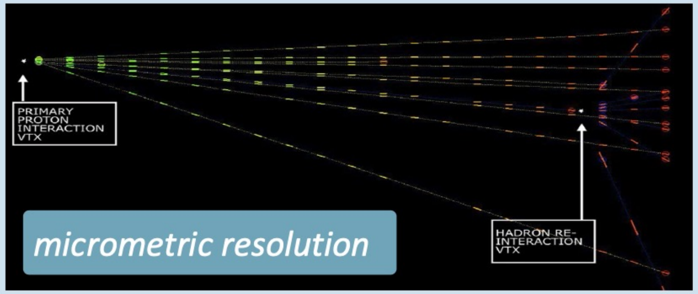
Search for Hidden Particles (SHiP) at a dedicated **Beam Dump Facility (BDF):**

- High-Intensity (HI) upgrade of **CERN SPS 400GeV proton facility**
- General-purpose **beam dump facility**
- **Dedicated beam** to ECN3

Search for **Feebly-Interacting Particles** with the **Hidden Sector Decay Spectrometer (HSDS):**



Rich program at the **Scattering & Neutrino Detector (SND):**

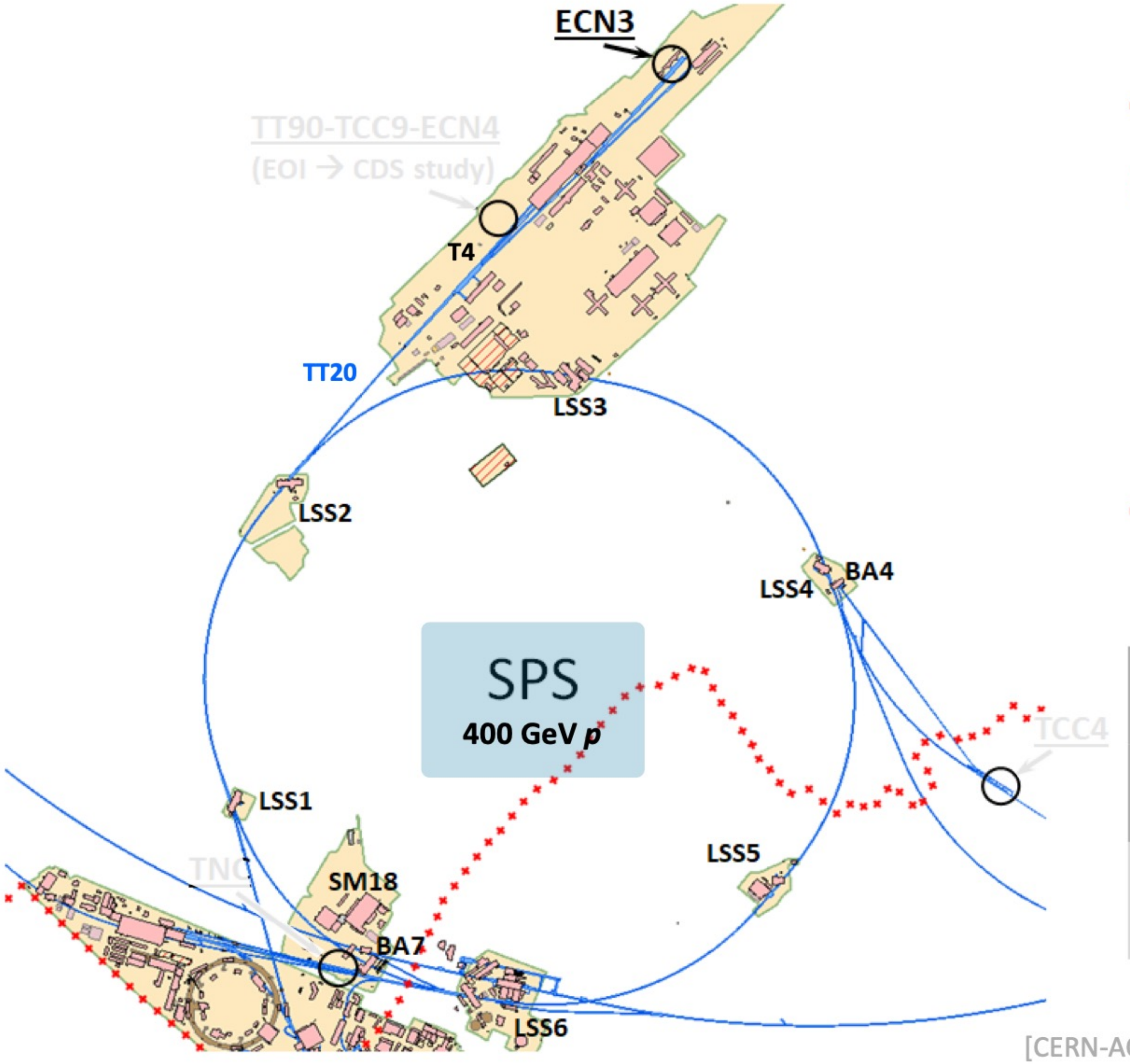


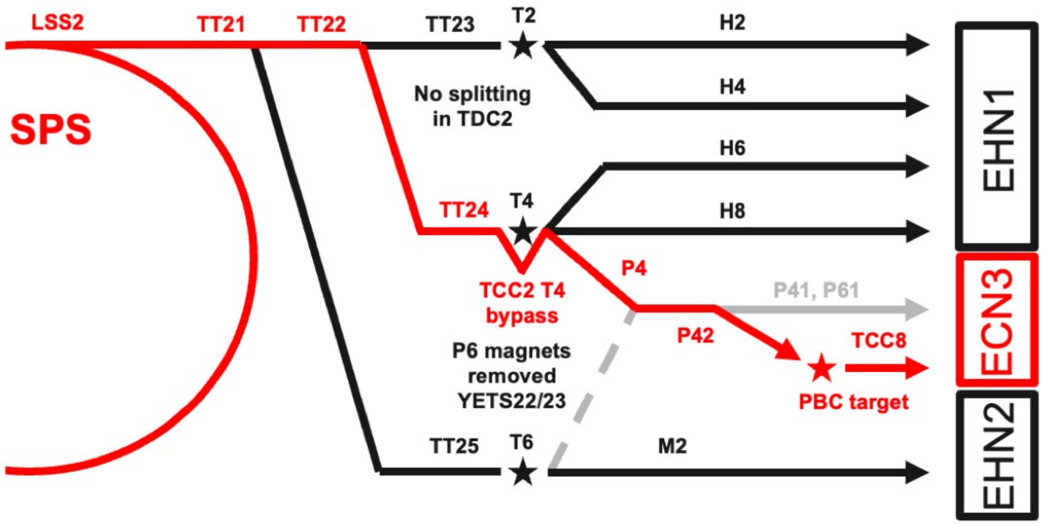
- **Original Proposal (2013):** Developed for new cavern EHN4

► Refined Proposal (2023): **Adaptation to existing ECN3 facility**

New dedicated operational scenario (T4 bypass):

beam transported through TT20 and TCC2 and delivered exclusively onto experimental target





ECN3 scenario	SPS p^+ Intensity	ECN3 p^+ Intensity	Spills	Spill Length	Repetition period
	[p/spill] [pot/yr]	[p/spill] [pot/yr]	[ECN3/day] [NA/day]	[s]	[s]
Dedicated T4 bypass	$\leq 4.2 \times 10^{13}$ $\leq 5 \times 10^{19}$	$\leq 4.0 \times 10^{13}$ $\leq 4.0 \times 10^{19}$	≤ 5000 ≤ 6250	≥ 1.0	≥ 7.2

[CERN-ACC-NOTE-2022-0009, CERN-PBC-REPORT-2023-001, CERN-PBC-REPORT-2023-003]

The physics of portals

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portal} + \mathcal{L}_{\rm HS}$$

There are four possible types of portal:

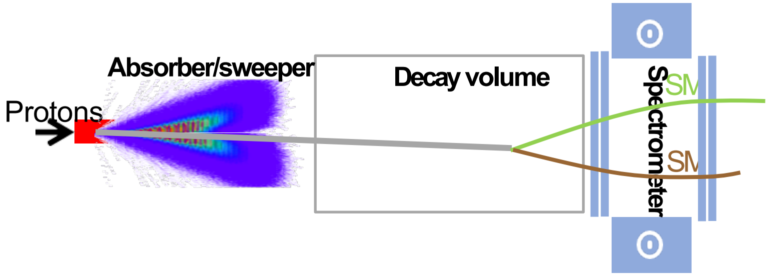
- Scalar (e.g. dark scalar, dark Higgs) $(H^\dagger H)\phi$
- Vector (e.g. dark photon) $\epsilon F_{\mu\nu} F'_{\mu\nu}$
- Fermion (e.g. heavy neutral lepton (HNL)) $H^\dagger \overline{N} L$
- Axion-like particle (ALP) $a F^{\mu\nu} \tilde{F}^{\mu\nu}$

Expected signals

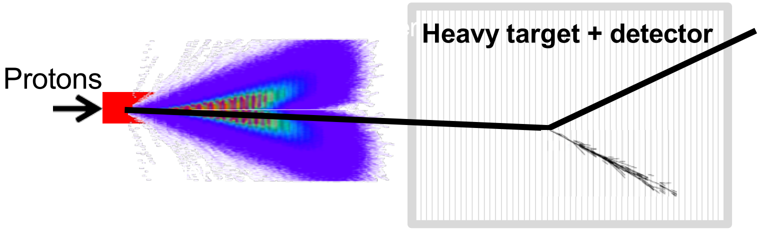
	Physics model	Final state
HSDS	SUSY neutralino	$\ell^\pm\pi^\mp,\ \ell^\pm K^\mp,\ \ell^\pm\rho^\mp, \ell^+\ell^-\nu$
	Dark photons	$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
	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	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
SND	LDM	electron, proton, hadronic shower
	$\nu_\tau,\ \overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production $(\nu_e, \nu_\mu, \nu_\tau)$	$D_s^\pm,\ D^\pm,\ D^0,\ \overline{D^0},\ \Lambda_c^+,\ \overline{\Lambda_c}^-$

SHiP experimental techniques

Visible decay to SM particles



Scattering off atomic electrons and nuclei



Also suitable for neutrino interaction physics with all flavours

EPJC 83 1126 (2023)

✓ ***Sensitivity depends on three factors***

- *Yields (protons on target)*
- *Acceptance (lifetime & angular coverage)*
- *Background level*

✓ ***Exhaustive search should aim at a "model-independent" detector setup***

- *Full reconstruction and identification of both fully and partially reconstructible modes*
  - ➔ *Sensitivity to partially reconstructed modes also proxy for the unknown*
- *In case of discovery ➔ make precise measurements to discriminate between models and test compatibility with hypothetical signal*

➔ ***FIP decay search in background-free environment and LDM scattering***

➔ ***Rich "bread and butter" neutrino interaction physics with unique access to tau neutrino***

Beam dump optimization

✓ *Target design for signal/background optimization:*

- *Very thick ➔ use full beam and secondary interactions (12λ)*
- *High-A&Z ➔ maximize production cross-sections (Mo/W)*
- *Short λ (high density) ➔ stop pions/kaons before decay*

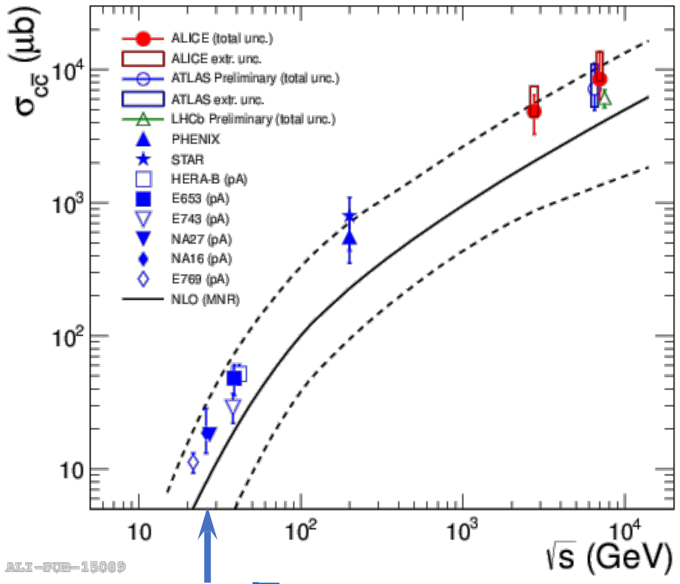
➔ *BDF luminosity for a very thick target (e.g. >1m Mo/W) with*

4×10^{19} protons on target per year currently available in the SPS

➔ *BDF/SHiP **annual** yields in the detector acceptance:*

- *~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)*
- *~ 2×10^{12} beauty hadrons*
- *~ 2×10^{15} tau leptons*
- *O(10^{20}) photons above 100 MeV*
- *Large number of neutrinos detected with 3t-W ν-target:*

$3500\ \nu_\tau + \bar{\nu}_\tau$ *per year, and* $2\times10^5\ \nu_e + \bar{\nu}_e$ / $7\times10^5\ \nu_\mu + \bar{\nu}_\mu$ *regardless of target design*

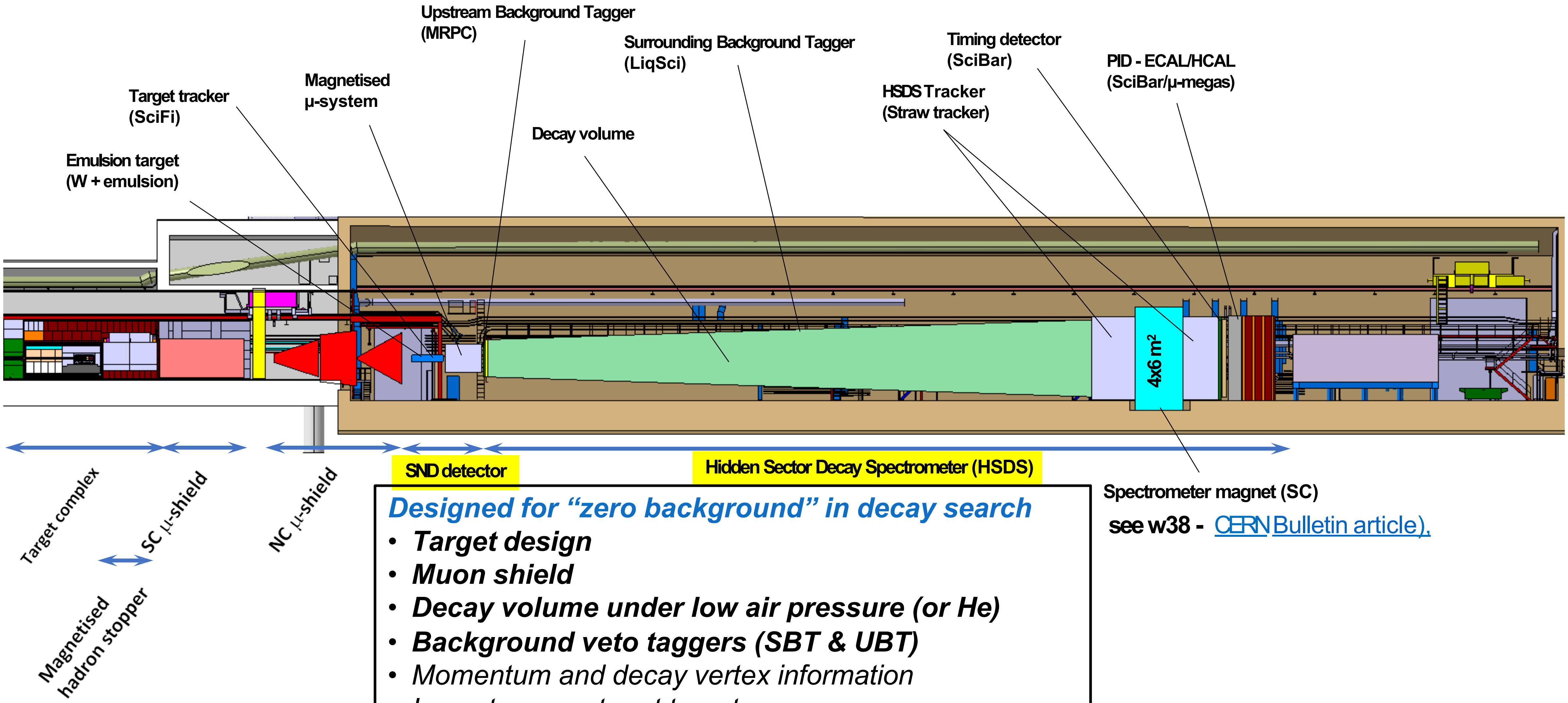


BDF @ $\sqrt{s} = 27\ GeV$

σ(pp→ssbar X)/σ(pp→X) ~ 0.15
σ(pp→ccbar X)/σ(pp→X) ~ 2×10^{-3}
σ(pp→bbbar X)/σ(pp→X) ~ 1.6 $\times10^{-7}$
Cascade effect, e.g. >2 for charm

✓ ***No technical limitations to operate beam and facility with 4×10^{19} protons/year for 15 years***

SHiP detector



see w38 - CERN Bulletin article),

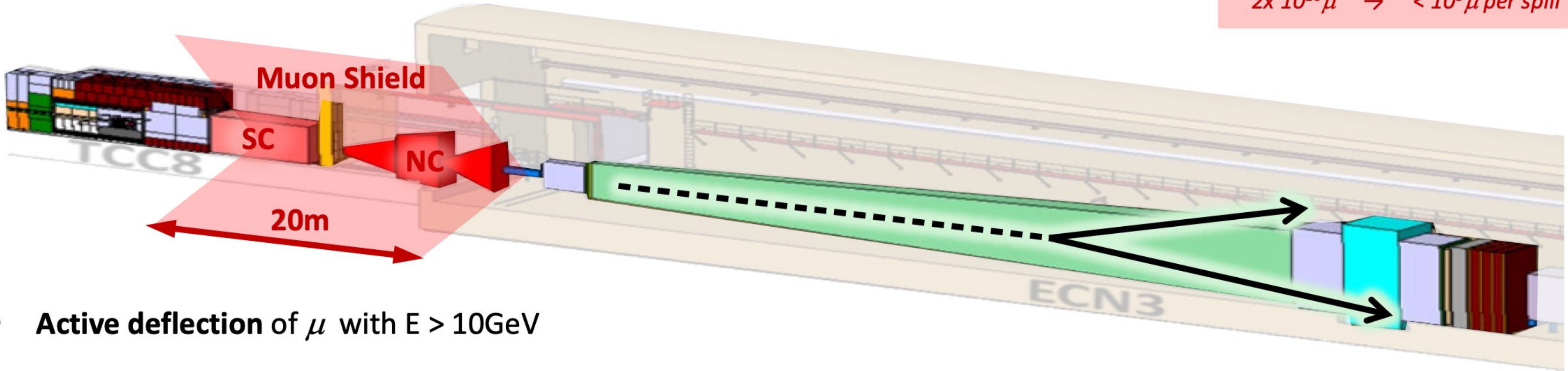
Designed for "zero background" in decay search

- ***Target design***
- ***Muon shield***
- ***Decay volume under low air pressure (or He)***
- ***Background veto taggers (SBT & UBT)***
- *Momentum and decay vertex information*
- *Impact parameter at target*
- *Time coincidence*
- *Particle identification* — Not currently used in background suppression

Muon shield

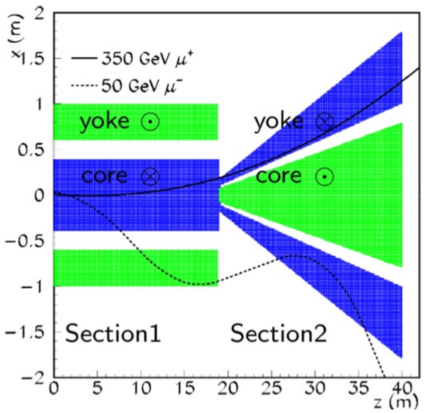
(Superconducting) Magnetic Muon Shield

Reduction of μ rate:
$2x\ 10^{10}\mu$ → $< 10^{5}\mu$ per spill



- **Active deflection** of μ with E > 10GeV

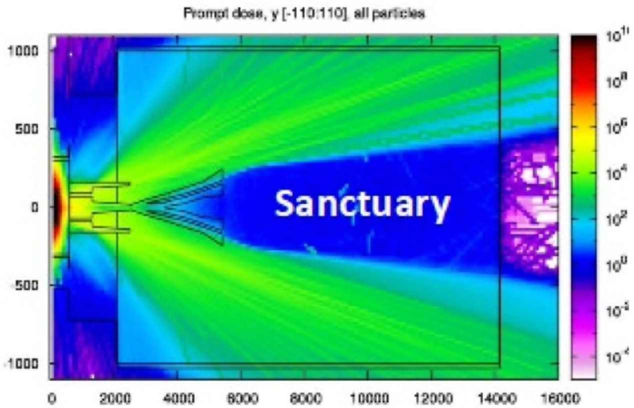
[CERN-SHiP-NOTE-2016-005, 2017 JINST-12-P05011, CERN-SPSC-2019-049 / SPSC-SR-263, **EPJC-80(2020)3-284**, **CERN-SPSC-2023-033** / **SPSC-P-369**]



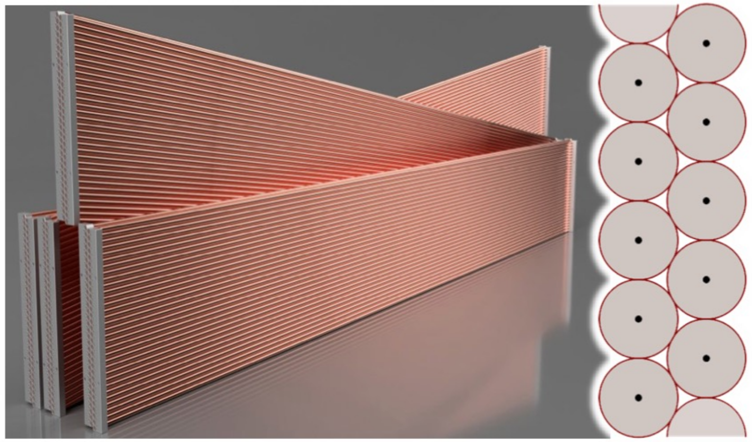
- **Alternate-polarity scheme:**
  Split of **positive & negative μ** to **left & right** of decay volume

- **ECN3 optimisation (hybrid SC / NC):** 5.1T
  Shortened, preserving experiment sensitivity
- Initial (& fallback) design (NC): 1.7T

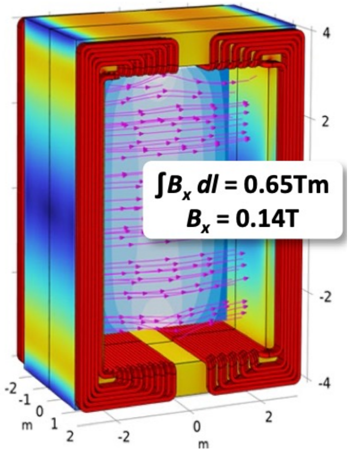
► Ongoing **ML-assisted optimisation campaign**

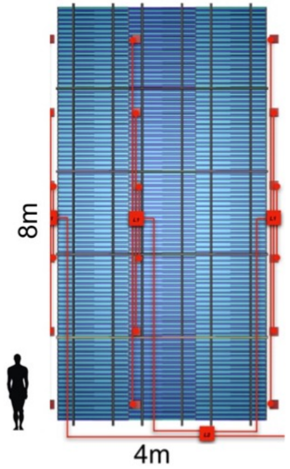


Some crucial detector parts

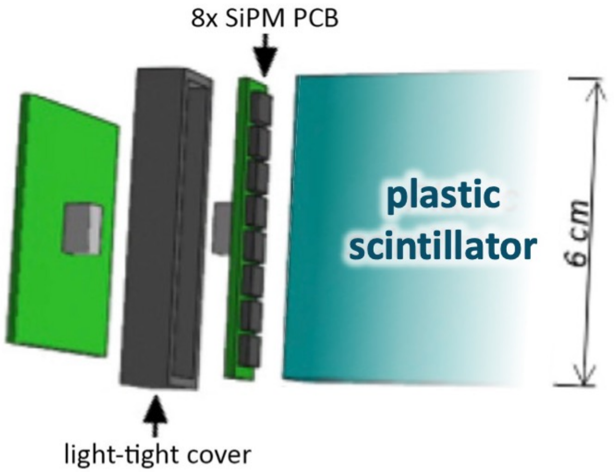


- **Cu/Au-coated Mylar drift tubes (NA62 design):** 4m length, 2cm diameter, 36µm wall thickness, Ar:CO_2 mixture (70:30)
- ▶ **Low material budget**
- 2x 2 stations of 4 double layers at 10° stereo angle, **10 000 channels altogether**
- **Magnet (NC baseline):** 0.65Tm / 0.15T
  SC options being studied (MgB_2)





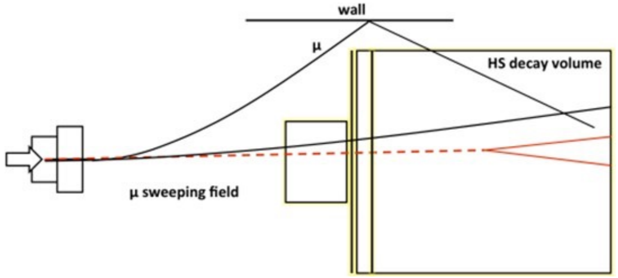
- **EJ200 plastic scintillator bars:** 135cm x 6cm x 1cm
- **Readout** at both ends by **SiPM arrays**
- 3 columns of 111 vertically staggered bars (5mm overlap), **666 channels altogether**
- ▶ **Timestamp** for SST
- ▶ **ToF identification** of particle decay products



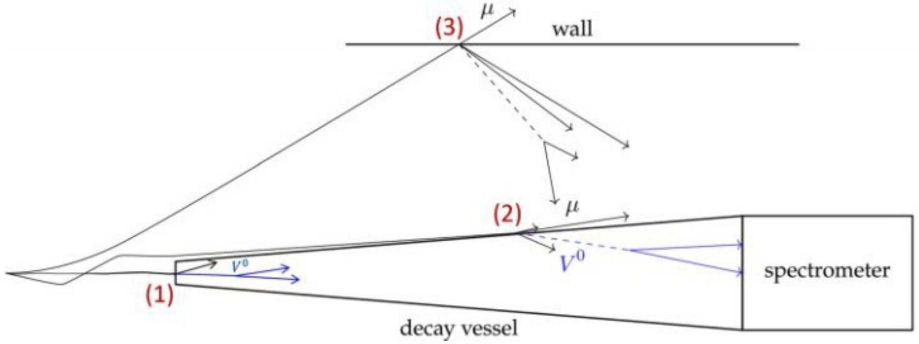
HSDS: Background evaluation for FIP decay search

Background estimation based on full GEANT-based MC

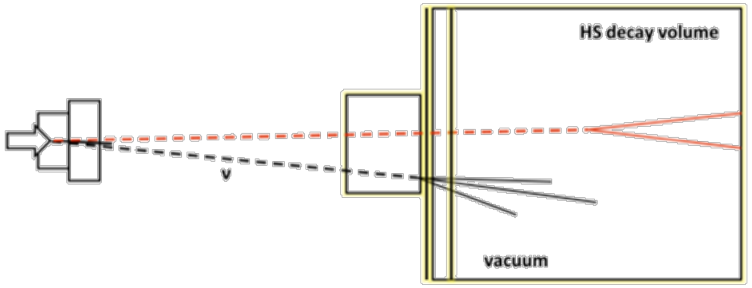
Muon combinatorial



Muon DIS



Neutrino DIS



➔ *Very simple and common selection for both fully and partially reconstructed events – model independence*

➔ *Possibility to measure background with data, relaxing veto and selection cuts, muon shield, decay volume*

Muon spectrum validated at SPS with BDF/SHiP prototype target - agreement within 30%

Selection

Track momentum	> 1.0 GeV/c
Track pair distance of closest approach	< 1 cm
Track pair vertex position in decay volume	> 5 cm from inner wall
	> 100 cm from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	< 10 cm
Impact parameter w.r.t. target (partially reconstructed)	< 250 cm

+ Time coincidence + UBT/SBT

Expected background is << 1 event for 6×10^{20} pot (15 years of operation)

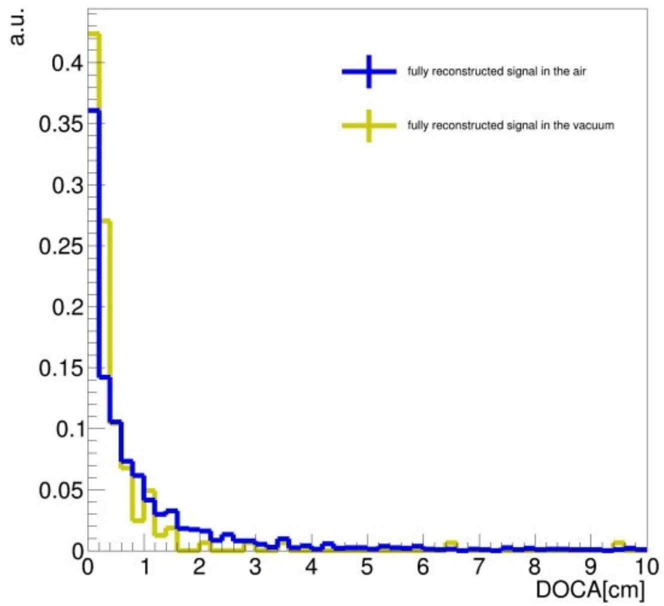
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/< 0.3(partially)
Muon DIS (factorisation)	< 5 x10^{-3} (fully) / < 0.2(partially)
Muon combinatorial	(1.3 ± 2.1)x 10^{-4}

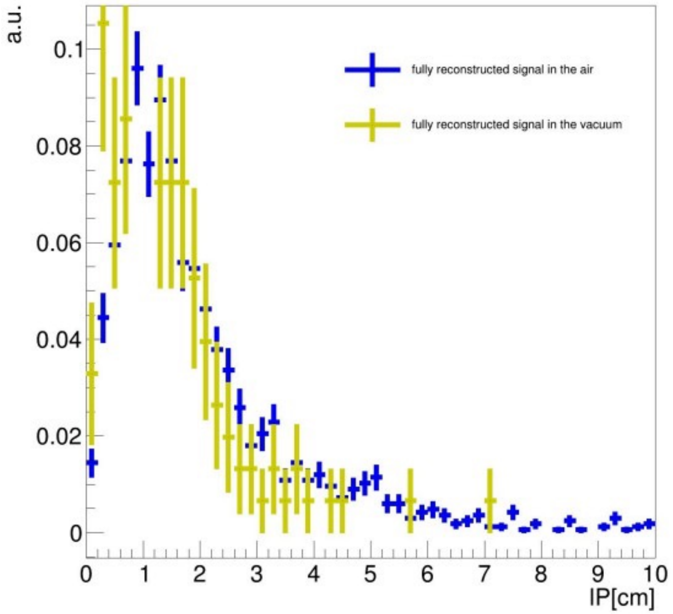
Backgrounds in FIP decay search

Background sufficiently low that He @ 1atm being considered in decay volume

- *Significant simplification in the Main spectrometer section*
- *Needs further study ➔ **looks very promising***

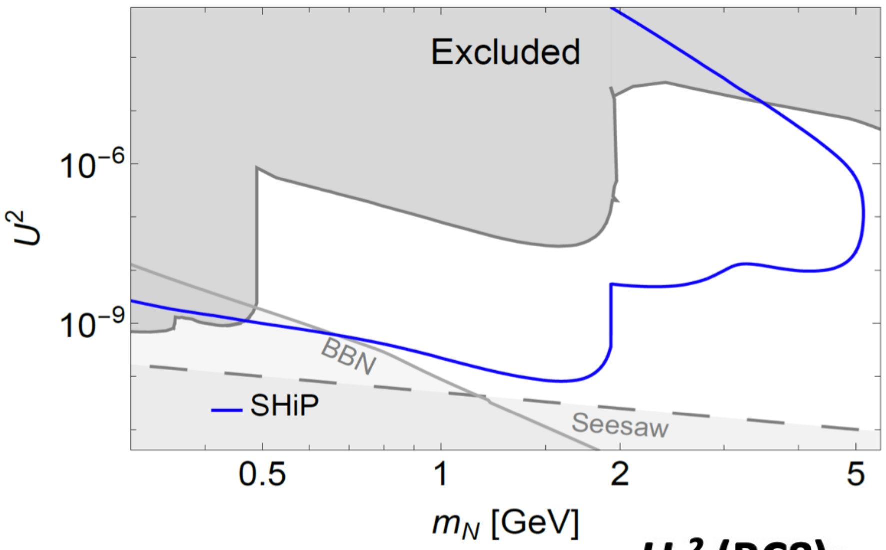
Check of signal resolution air vs vacuum



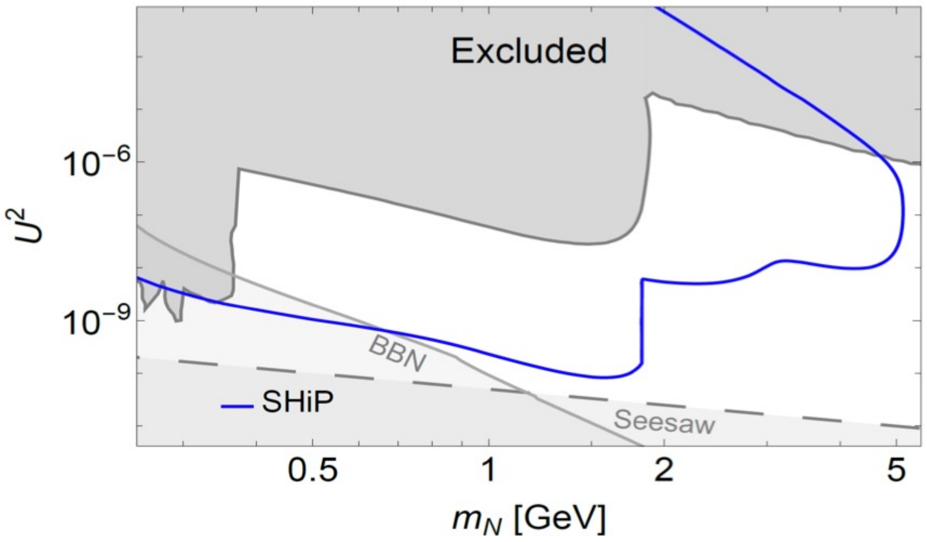


FIP decay search performance

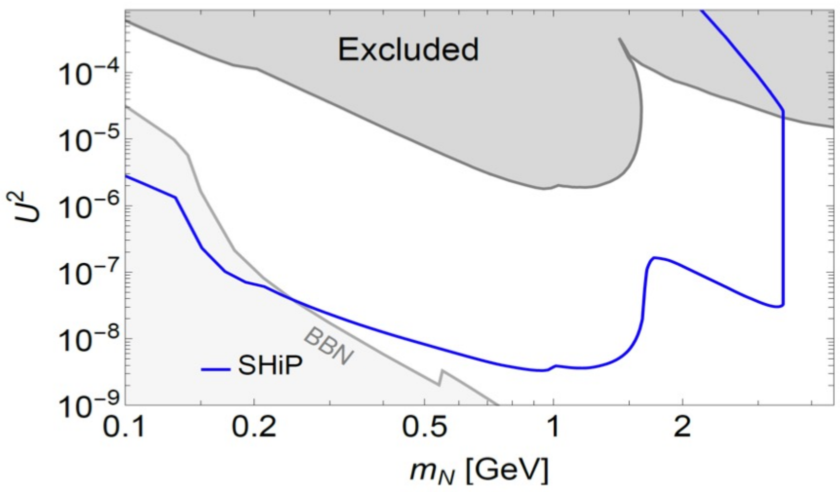
U_e^2 (BC6):



U_μ^2 (BC7):



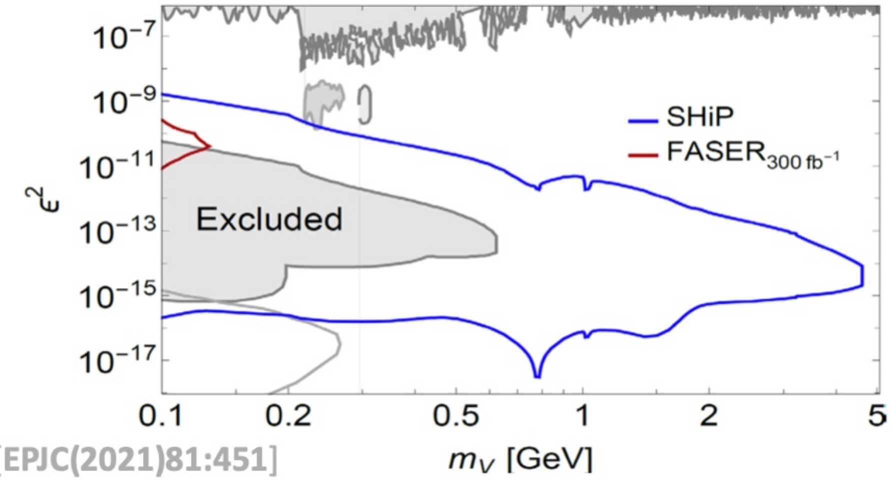
U_τ^2 (BC8):



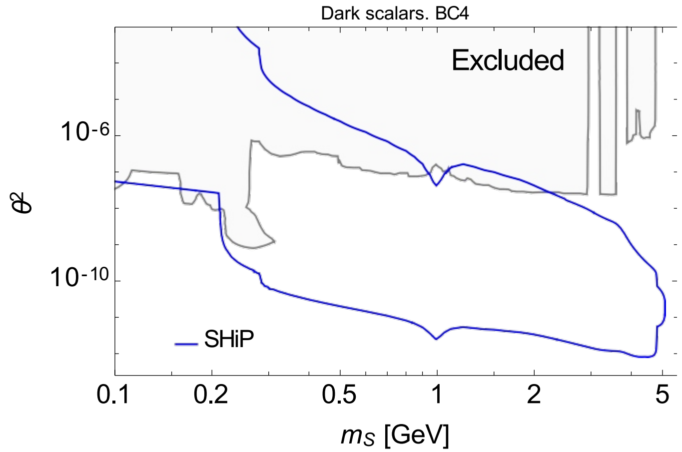
FIP decay search performance

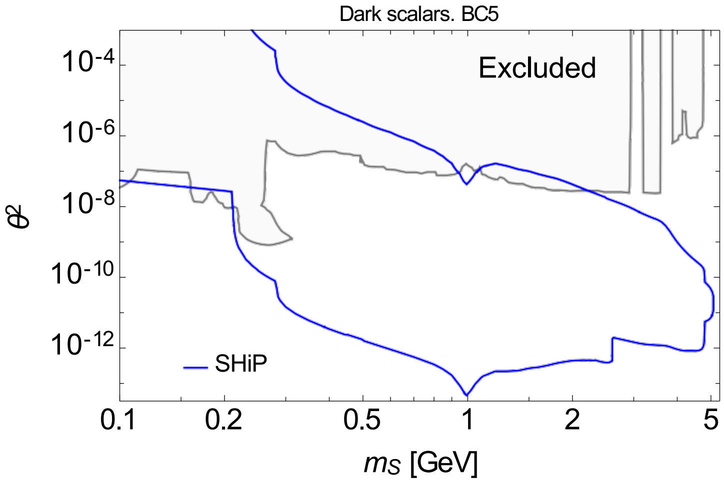
Sensitivity to dark photons: ε^2 (BC1)

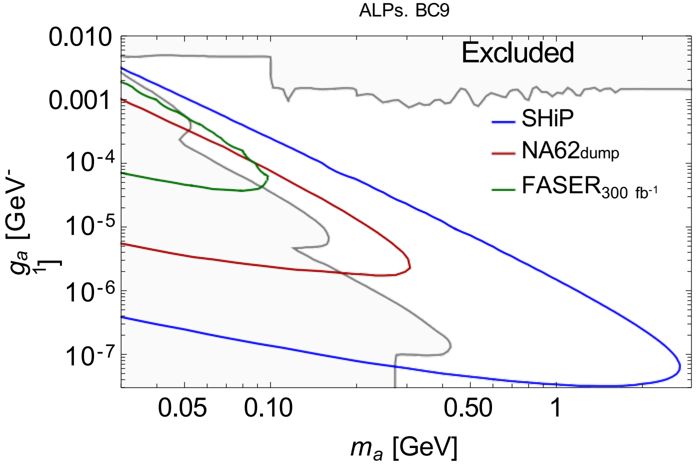
90% CL, assuming 6x 10^{20} p.o.t., vector portal

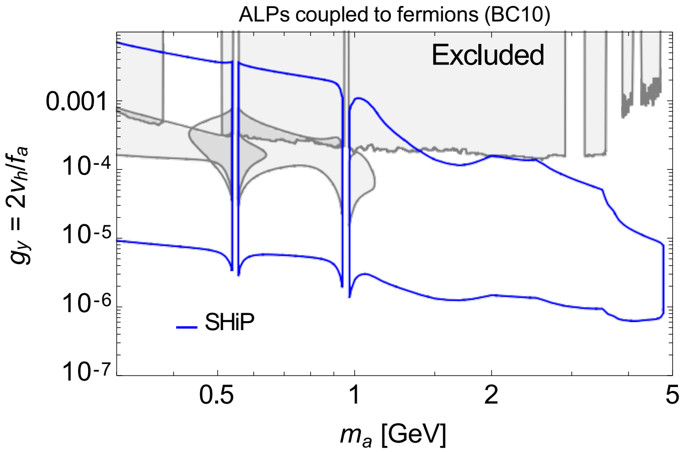


[EPJC(2021)81:451]







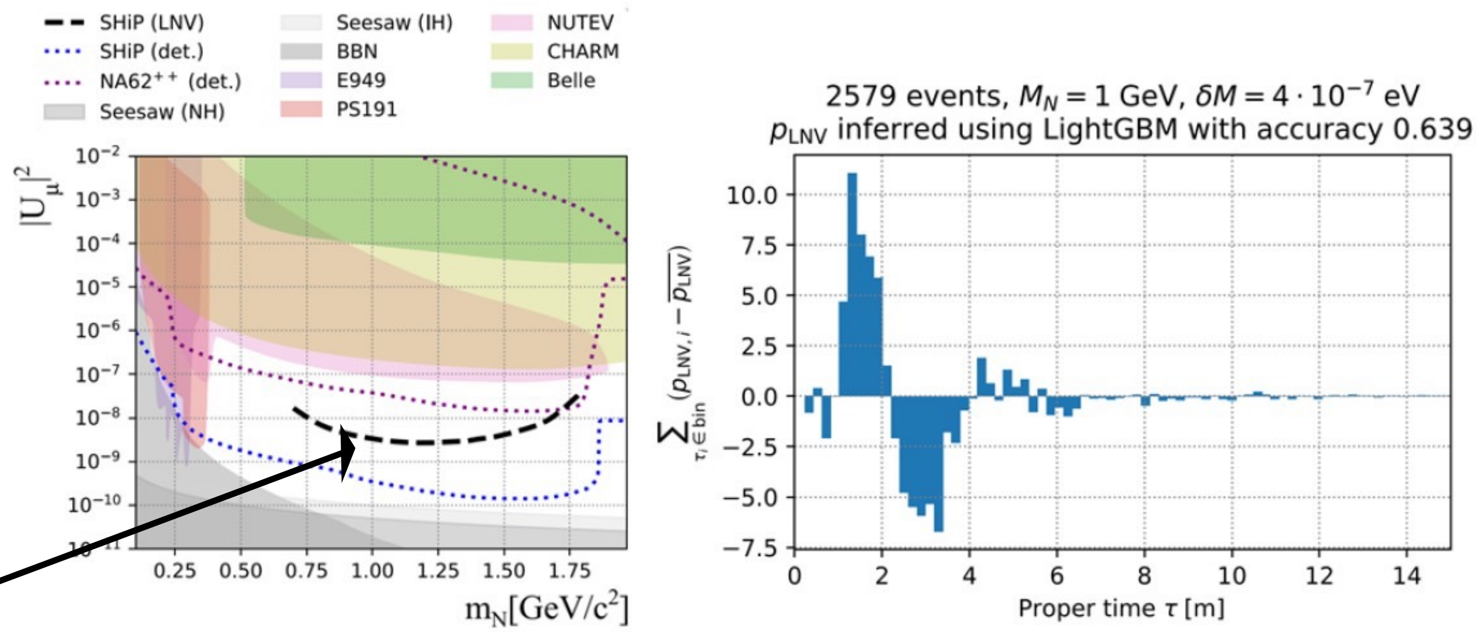


- ✓ *SHiP sensitivities to FIPs are orders of magnitude better than existing limits*
- ✓ *Sensitivity is not limited by backgrounds in 6 x 10^{20} PoT*

Physics sensitivities: FIPs cont'd

HNL

SHiP would register 2600 HNLs in the middle of its sensitivity range can observe oscillations between Lepton Number Violating and Conserving event rates
➔ *Measure mass splitting ΔM = ~10[-7]eV*



ure 4: Left: lower bound on the SHiP sensitivity to HNL lepton number violation (black dashed line). Reconstructed oscillations between the lepton number conserving and violating event rates as a function of the proper time for a HNL with the parameters $M_N = 1\,\text{GeV}/c^2$, $|U|^2_\mu = 2 \times 10^{-8}$ and mass splitting of $4 \times 10^{-}$ 20].

Tastet, JL., Timiryasov, I. Dirac vs. Majorana HNLs (and their oscillations) at SHiP. *J. High Energ. Phys.* **2020**, 5 (2020) https://doi.org/10.1007/JHEP04(2020)005

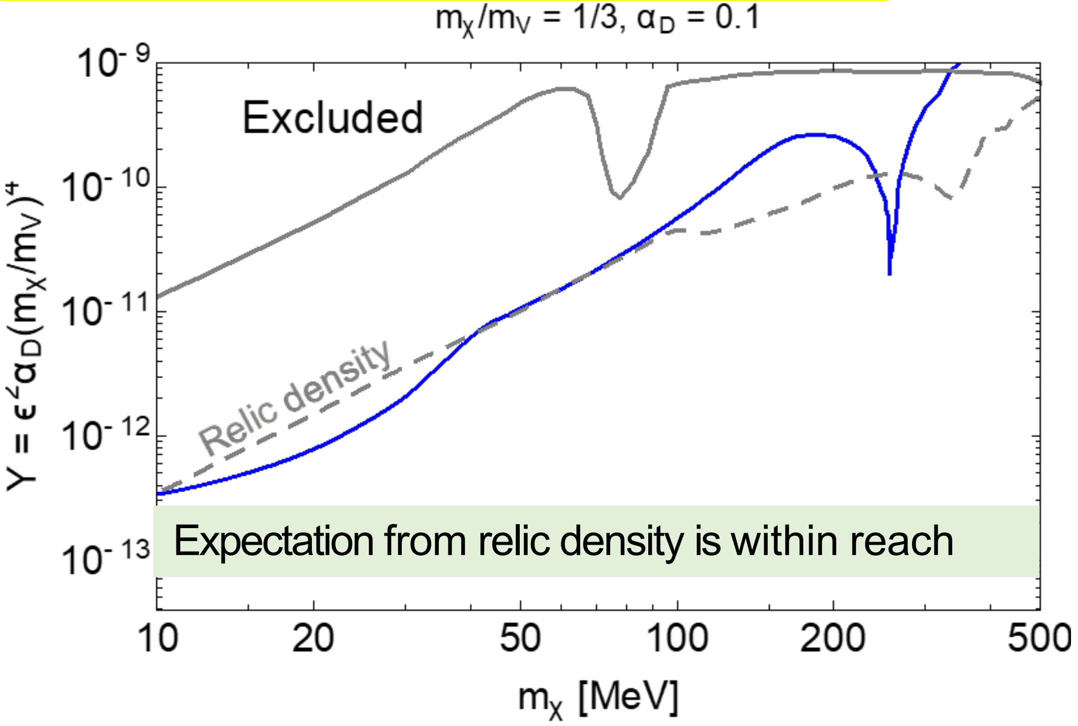
Main goals of SND

✓ ***Search for LDM***

- *Experimental signature of LDM scattering:*

  A shower produced by the electron scattered by LDM and "nothing else"

LDM scattering off atomic electrons (and nuclei)



✓ ***Direct search through scattering***

✓ *Background is dominated by neutrino elastic scattering, for 6×10^{20} PoT:*

6×10^{20}	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	156	81	192	126	555
Quasi - elastic scattering	-	27			27
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	156	108	192	126	582

✓ ***Tau neutrino physics***

- *Experimental signature of tau neutrino:*

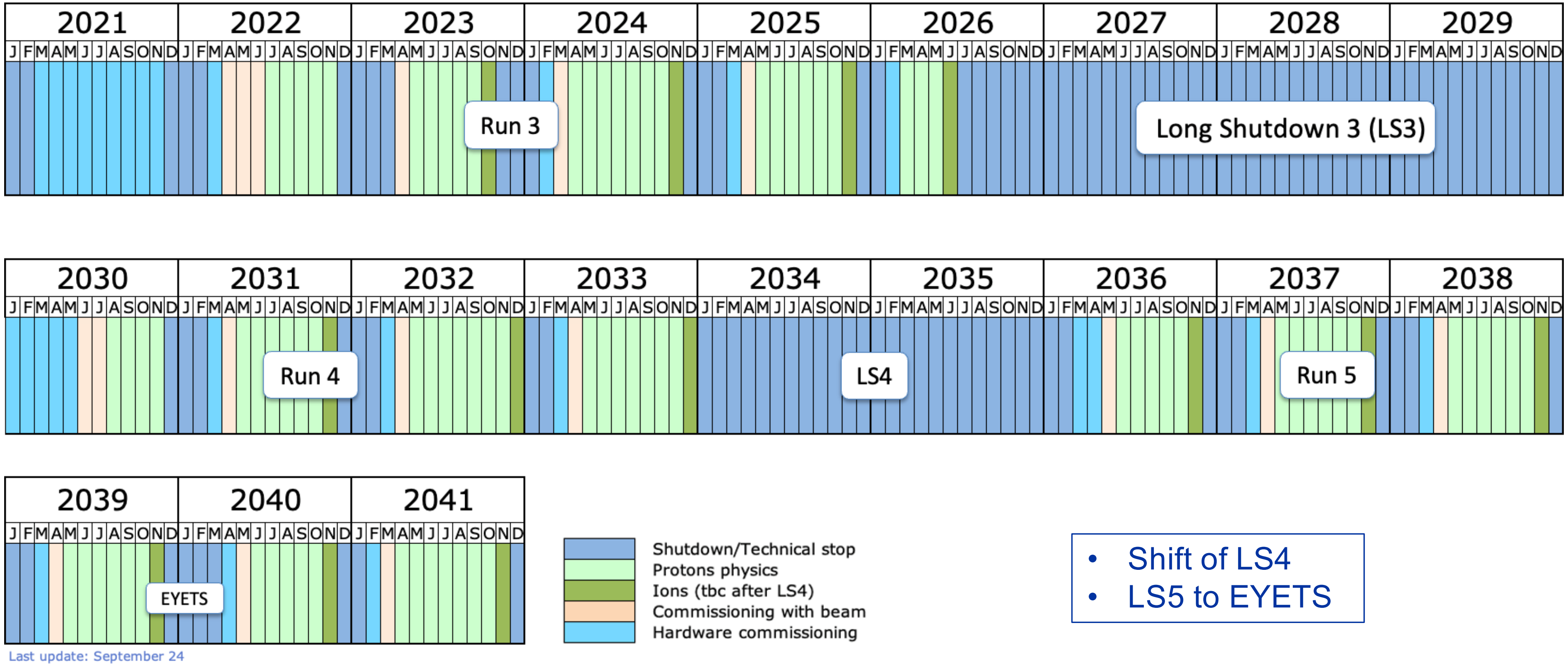
  (i) "double-kink" topology *(resulted from ν_1-interaction and 1-decay)*

  (ii) Missing P_t *carried away by 2 neutrinos from 1-decay*

BDF/SHiP preliminary schedule

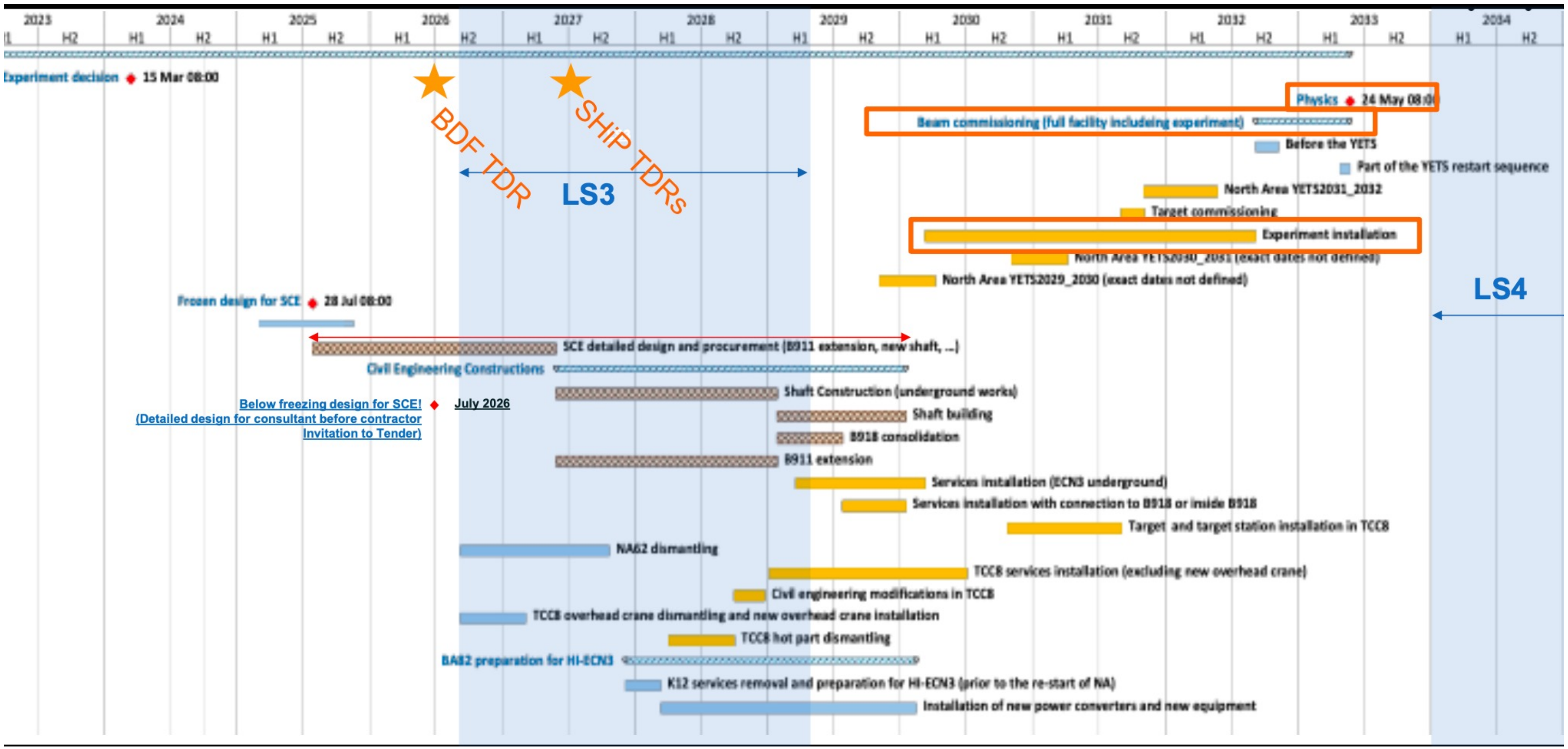
- ✓ *~3 years for detector TDRs*
- ✓ *Construction / installation of facility and detector is decoupled from NA operation*
- ✓ *Important to start data taking >1 year before LS4*
- ✓ *Several upgrades/extensions of the BDF/SHiP is under consideration over the operational life*

Proposed Long Term LHC Schedule



- Shift of LS4
- LS5 to EYETS

BDF/SHiP preliminary schedule



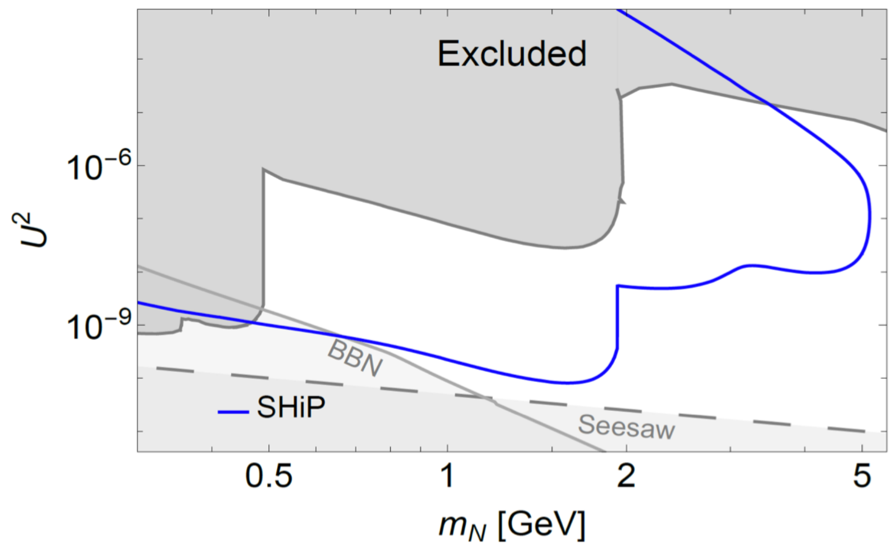
Summary

✓ *New programme at "Coupling frontier" at CERN with synergy between accelerator-based searches and searches in astrophysics/cosmology*

✓ *BDF/SHiP capable of covering the heavy flavour region of parameter space, out of reach for collider experiments*

- *Capability not only to establish existence but to measure properties such as precise mass, branching ratios, spin, etc*
- *Complementary to FIP searches at HL-LHC and future e+e[-] - collider, where FIPs can be searched in boson decays*

U_e^2 (BC6):



See-saw limit is almost in reach below charm mass