BDF/SHiP facility at CERN

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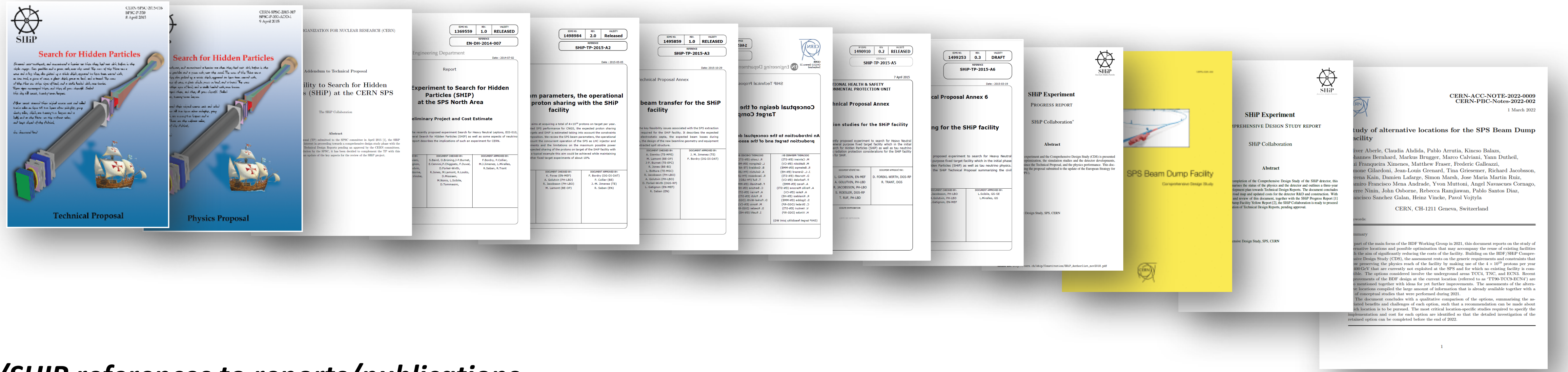
Imperial College London
& CERN

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



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*

Brief reminder on **Dark Sector**

Many theoretical models (portal models) predict new massive feebly interacting particles (FIP) which can be tested experimentally

SHiP Physics Paper – Rep.Progr.Phys.79(2016) 124201 (137pp),
SLAC Dark Sector Workshop 2016: Community Report – arXiv: 1608.08632,
Maryland Dark Sector Workshop 2017: Cosmic Visions – arXiv:1707.04591
Report by Physics Beyond Collider (PBC) study group - https://arxiv.org/abs/1901.09966v2
Most recent one is dedicated to ECN3 proposals - https://arxiv.org/abs/2310.17726

Family of Hidden Particles:

- ✓ ***Light Dark Matter (LDM)***
- ✓ ***Portals (mediators) to Hidden Sector (HS):***
  - *Heavy Neutral Leptons (spin ½, coupling coefficient* $\boldsymbol{U^2}$*)*
  - *Dark photons (spin 1, coupling coefficient* $\boldsymbol{\varepsilon}$*)*
  - *Dark scalars (spin 0, coupling coefficient* θ^2*)*
  - *Special case (non-renormalizable) Axion Like Particles (ALP) (spin 0, coupling coefficient* ***g****)*

Properties of Hidden Particles

$$L = L_{SM} + L_{mediator} + L_{HS}$$

Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

Naturally accommodates Dark Matter (may have rich structure)

✓ *HS production and decay rates are strongly suppressed relative to SM*

- *Production branching ratios O(10^{-10})*
- *Long-lived objects*
- *Interact very weakly with matter*
- *May decay to various final states, e.g.*

Portal models	***Final states***
HNL	$l^+\pi^-$, l^+K^-, $l^+\rho^-$
Vector, scalar, axion portals	l^+l^-
HNL	$l^+l^-\nu$
Axion portal	$\gamma\gamma$

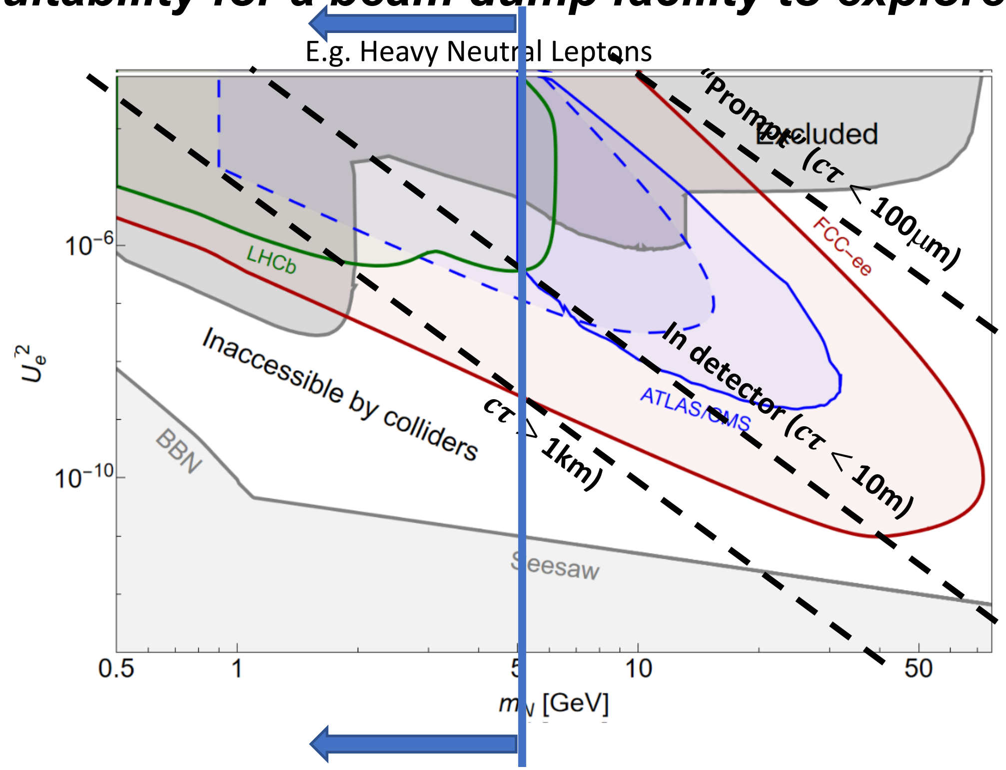
Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression

Search for Feebly Interacting Particles (FIP) in heavy flavour decays at BDF/SHiP @ SPS

✓ *Unique physics potential of SPS available since CNGS* (*Rep. Prog. Phys.* **79** *(2016)124201*)

✓ *Rich and relevant physics programme with the injectors at CERN going beyond LHC, bridging gap to next collider* ➔ ***SPS suitability for a beam dump facility to explore FIPs – opens new programme at CERN***



Similar behavior $\tau_{FIP} \propto \frac{1}{U^x_{FIP} m^y_{FIP}}$

for all types of FIPs

➔ ***Region that can only be explored by optimized beam-dump experiment***

➔*Optimise for maximum production of charm and beauty, and electromagnetic processes*

➔*SPS energy and intensity provide unique direct discovery potential in the world*

➔*Capable of reaching "physical floor" or "technical/background floor"*

Beam dump optimization

✓ *Target design for signal/background optimization:*

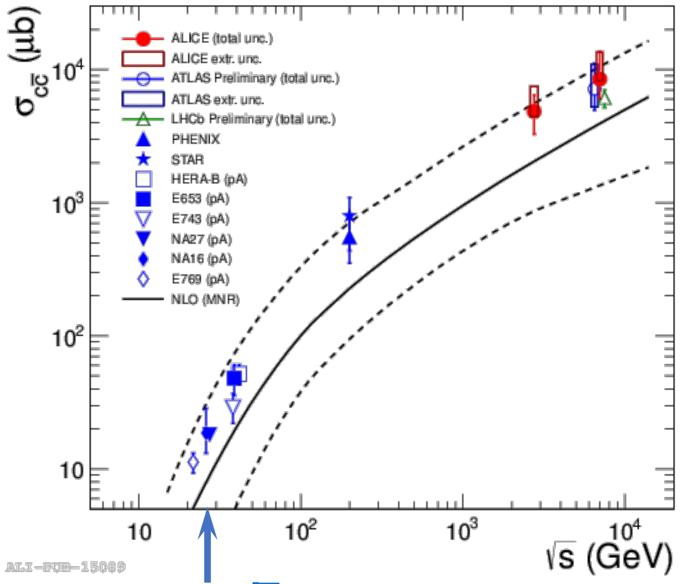
- *Very thick → use full beam and secondary interactions (12λ)*
- *High-A&Z → maximize production cross-sections (Mo/W)*
- *Short λ (high density) → stop pions/kaons before decay*

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

4x10^{19} protons on target per year currently available in the SPS

➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = >4 x 10^{45} cm^{-2} (cascade not incl.)

➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = 10^{42} cm^{-2}



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

➔ *BDF/SHiP* ***annually*** *access to yields towards 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*:

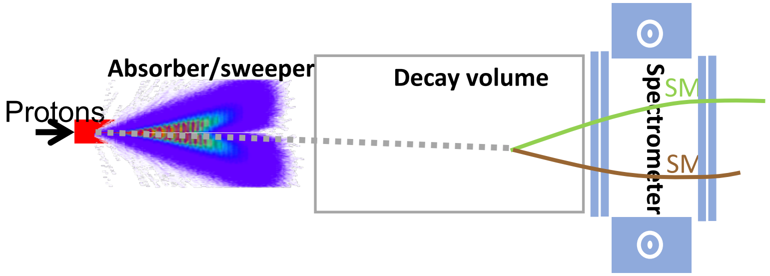
  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year, and* 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu + \bar{\nu}_\mu$ *despite target design*

σ(pp→ssbar X)/σ(pp→X) ~ 0.15
σ(pp→ccbar X)/σ(pp→X) ~ 2x10^{-3}
σ(pp→bbbar X)/σ(pp→X) ~ 1.6 x10^{-7}
Cascade effect, e.g. >2 for charm

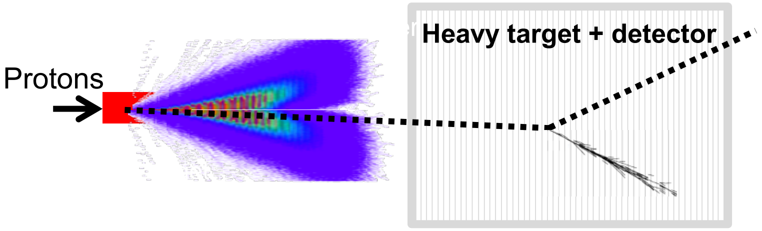
✓ ***No technical limitations to operate beam and facility with 4x10^{19} protons/year for 15 years***

BDF/SHiP experimental techniques

Visible decay to SM particles



Scattering off atomic electrons and nuclei



Also suitable for neutrino interaction physics with all favours

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

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

arXiv:2304.02511, submitted to EPJC

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

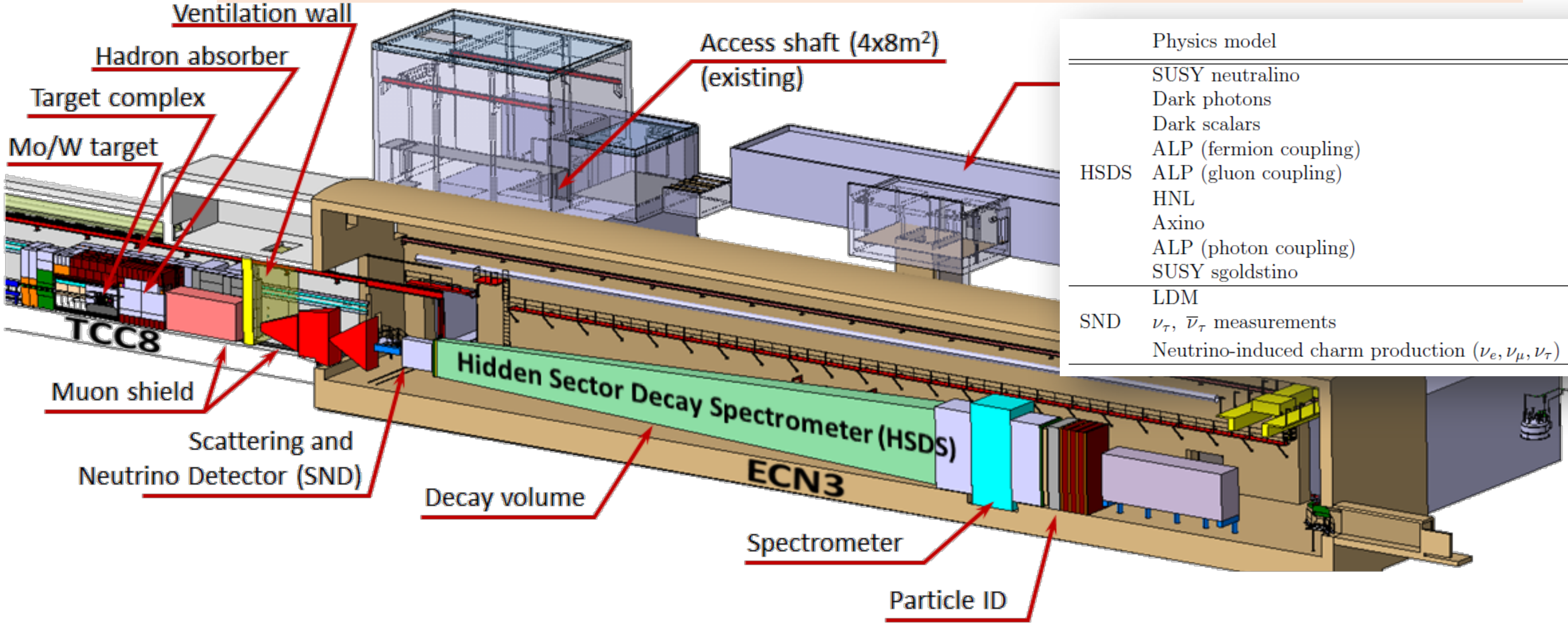
- *Full reconstruction and identification of both fully and partially reconstructible modes*
  - ➔*Sensitivity to partially reconstructed modes also proxy for the unknown*
- *In case of discovery ➔ make precise measurements to discriminate between models and test compatibility with hypothetical signal*

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

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

BDF/SHiP at ECN3

Two separate detector systems:* *S*cattering *N*eutrino *D*etector *(SND)* and *H*idden *S*ector *D*ecay *S*pectrometer *(HSDS)



	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
	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^+, $\overline{\Lambda_c}^-$

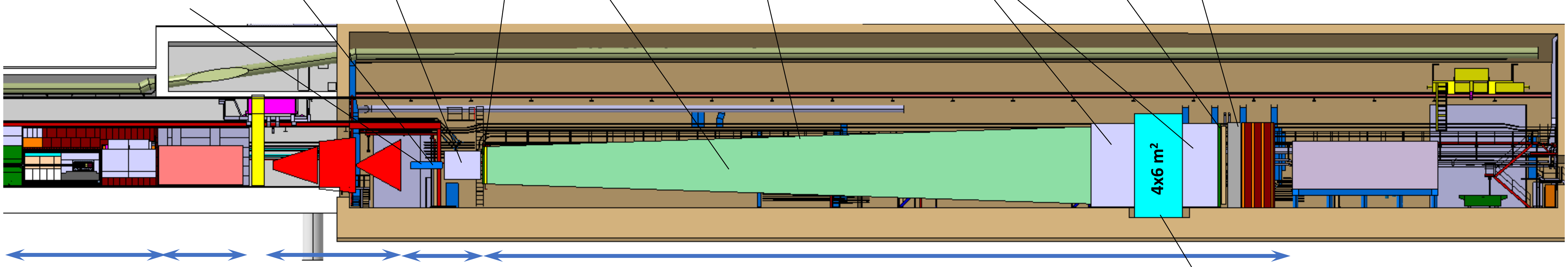
2020-2023: Facility/experiment adaptation to the available ECN3 line at SPS

- ✓ *Reduction in transversal size of detector w.r.t. the original design*
- ✓ *Shortening of the muon shield*

➔ *Background suppression is combined effect of upstream shielding ⊗ detector*

➔ *Further improvement by use of superconducting technology for muon shield*

SHiP detector in more detail



see w38 - [CERN Bulletin article),](#)

Designed for "zero background" in decay search

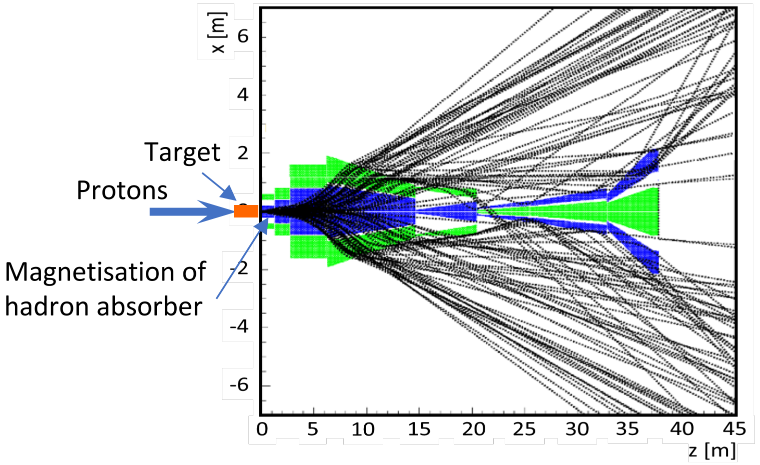
- ***Target design***
- ***Muon shield***
- ***Decay volume under low air pressure (or He)***
- ***Background veto taggers (SBT & UBT)***
- *Momentum and decay vertex information*
- *Impact parameter at target*
- *Time coincidence*
- *Invariant mass*
- *Particle identification*

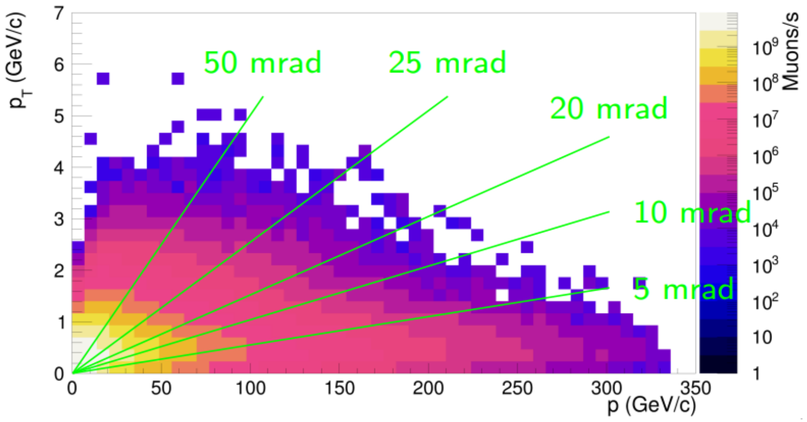
} Not currently used in background suppression

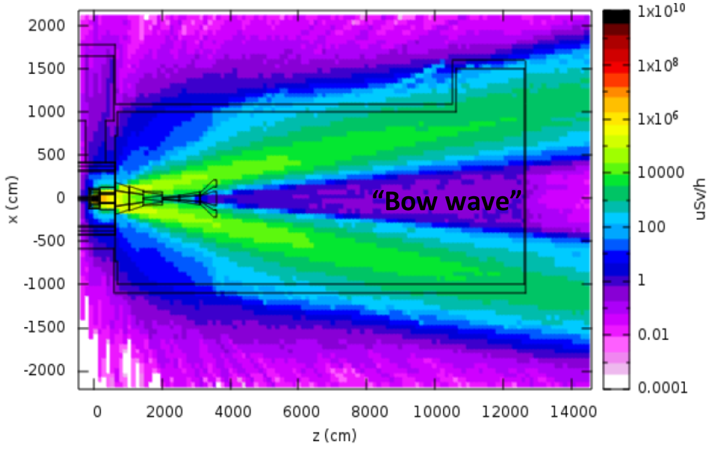
Muon shield principle

JINST 12 (2017) P05011 [1703.03612]

Suppress muon flux by ~6 orders of magnitude by magnetic sweeper system (illustrations from earlier studies)



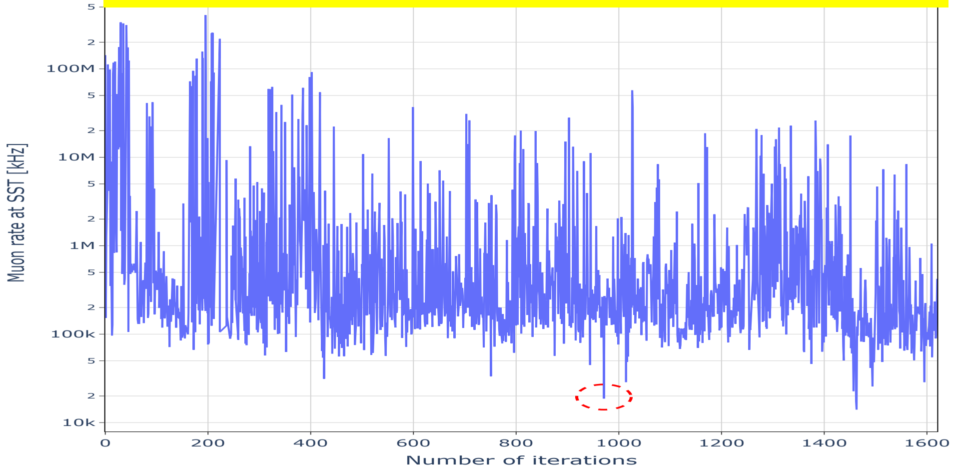




SHiP "bow wave"

Field configuration optimised by machine learning
with the large sample of muons simulated with PYTHIA/GEANT

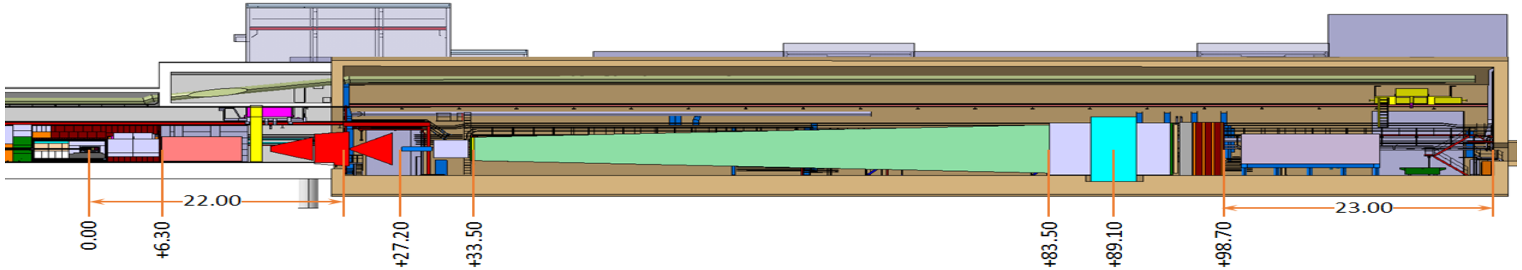
Optimisation finds many local minima in rates

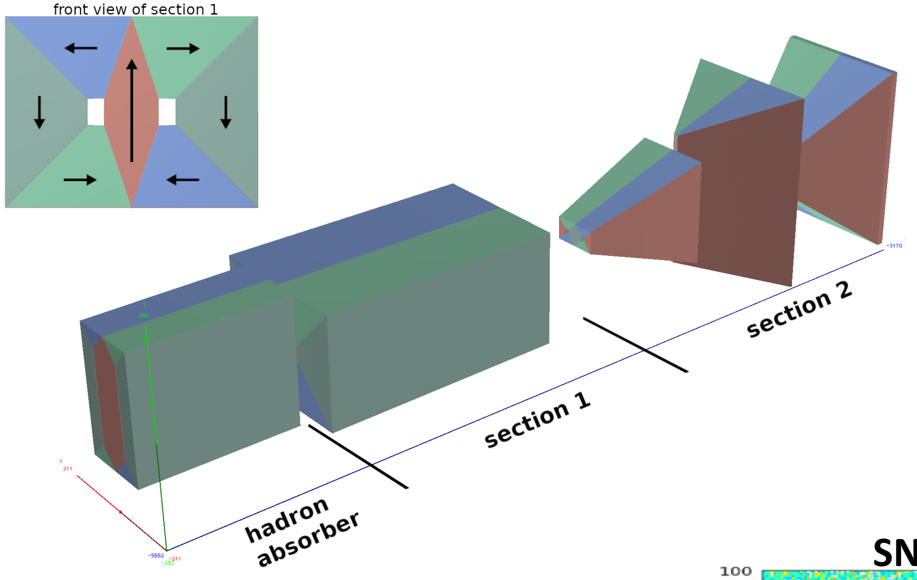


Different configurations with similar performance

- *Demonstrates robustness against systematics and engineering*
- *Engineering studies will be used to further constrain optimization and select final configuration*

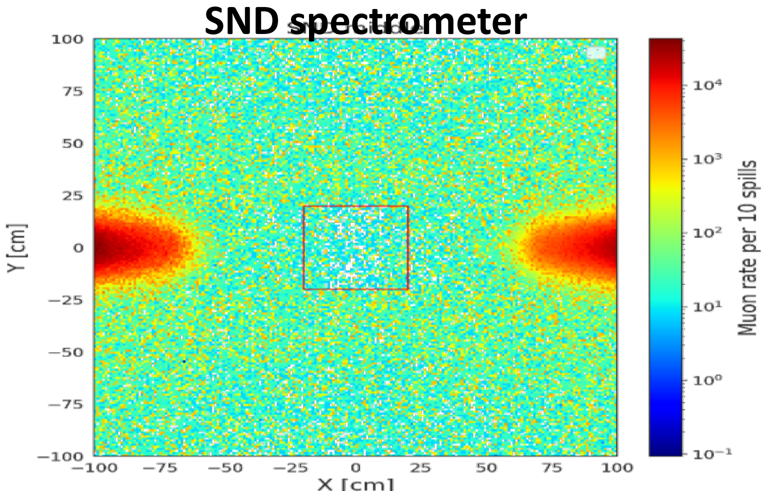
Expected muon rates with SC/NC hybrid muon shield (baseline option)

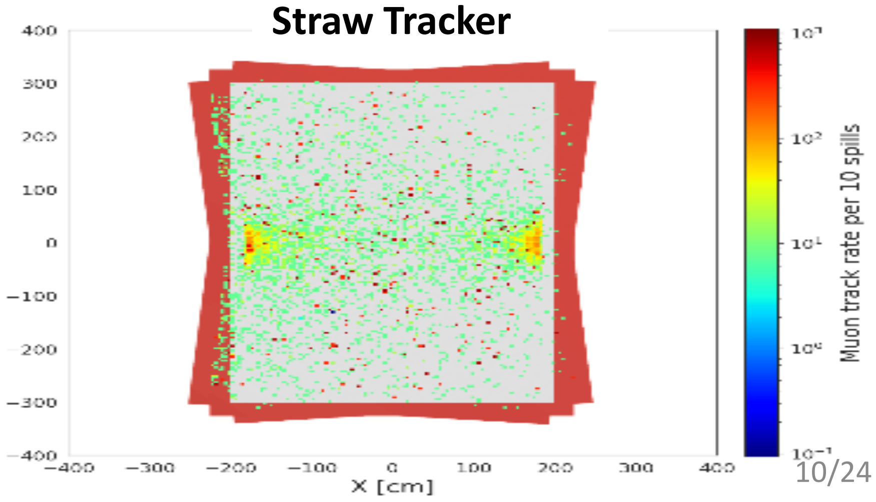




Hadron absorber: Warm
Section 1: Superconducting
Section 2: Warm

Low rates of residual muons:
~12 kHz in the Straw Tracker
~1 Hz/cm² in SND





Background simulations

Optimization and background challenges studied with complete experimental setup implemented in GEANT *(FairShip)*

➔ *Simulation tuned with detector performance parameters measured in test beam on prototypes*

✓ ***Large rejection power needed***

- *$\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4x10^{13}$ protons*
- *1.3×10^{19} neutrinos and $9x10^{18}$ anti-neutrinos in acceptance in 6×10^{20} proton on target* (Eur. Phys. J. C 80 (2020) 284)

➔ *Requires large sample of simulated events*

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

➔ *Rates of neutrinos and muons efficiently suppressed by high-A&Z target and muon shield*

✓ *Most "dangerous" signal-type muons are produced in charm and beauty decays, and in QED resonance decays (e.g. $\rho \rightarrow \mu\mu$).*

- *Dedicated samples of charm and beauty decays with Pythia6, and resonance decays enhanced by two orders of magnitude*

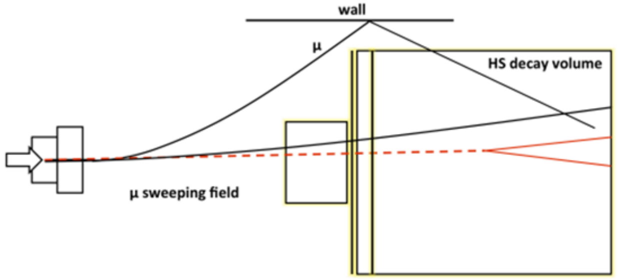
✓ *Muon and neutrino DIS processes*

- *Use Pythia6 to generate muon DIS events and GENIE generator for neutrino DIS events in material*
- *Boost statistics by forcing each muon and neutrino to interact according to the material distribution*

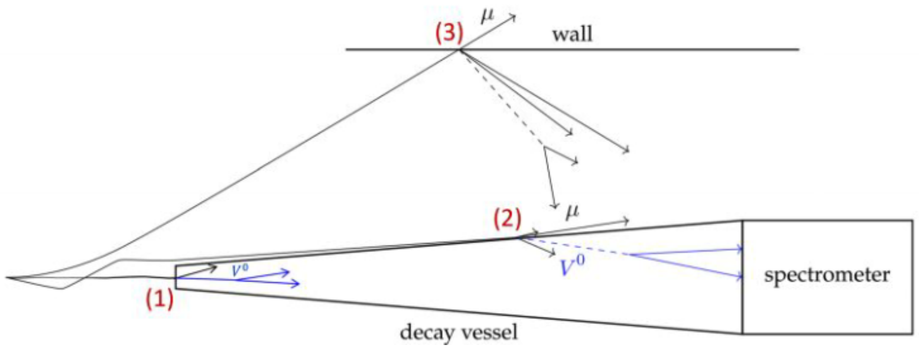
HSDS: Background evaluation for FIP decay search

Background estimation based on full GEANT-based MC

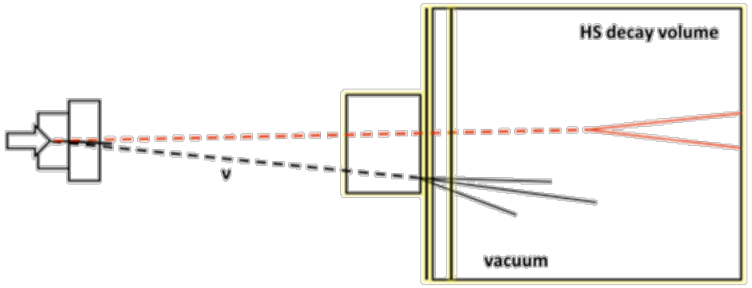
Muon combinatorial



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*

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)

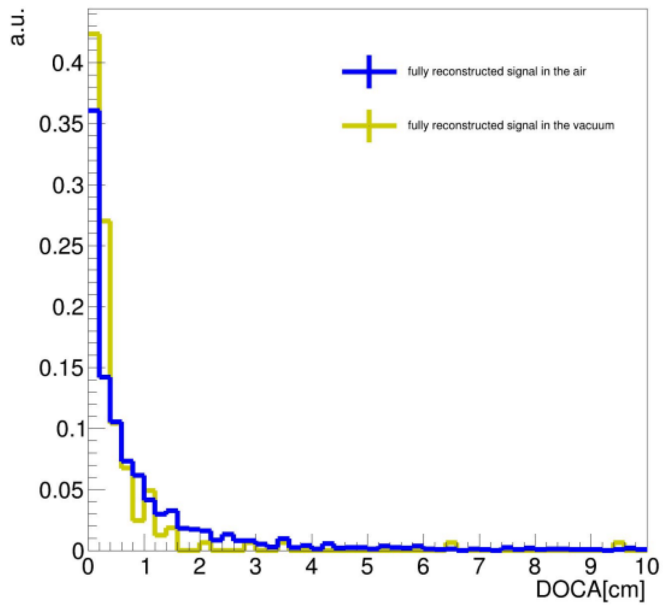
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

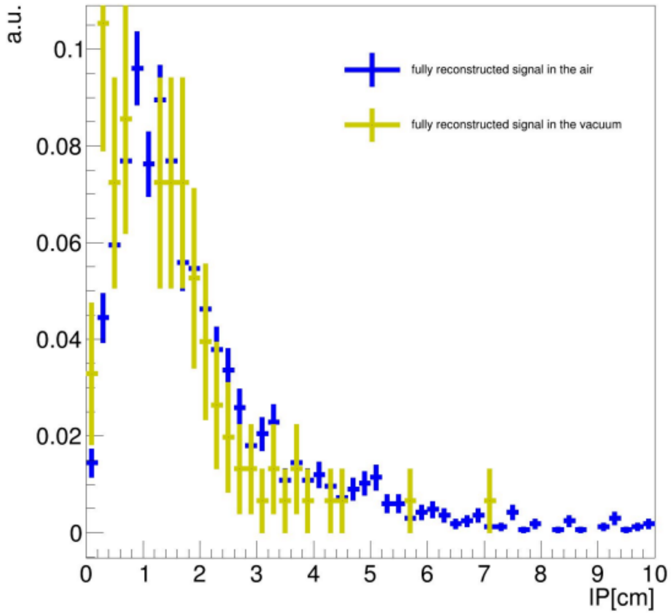
Backgrounds in FIP decay search

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

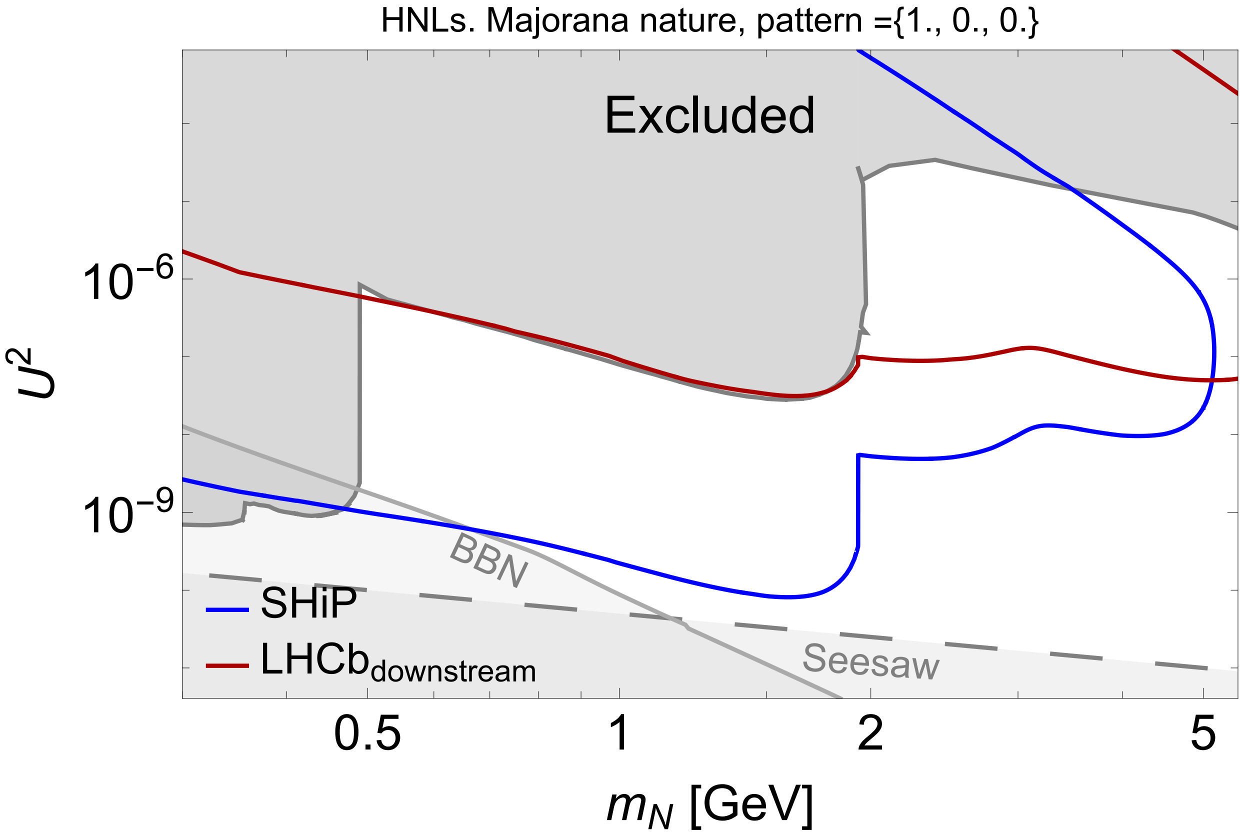
- *Significant simplification in the Main spectrometer section*
- *Needs further study → **looks very promising***

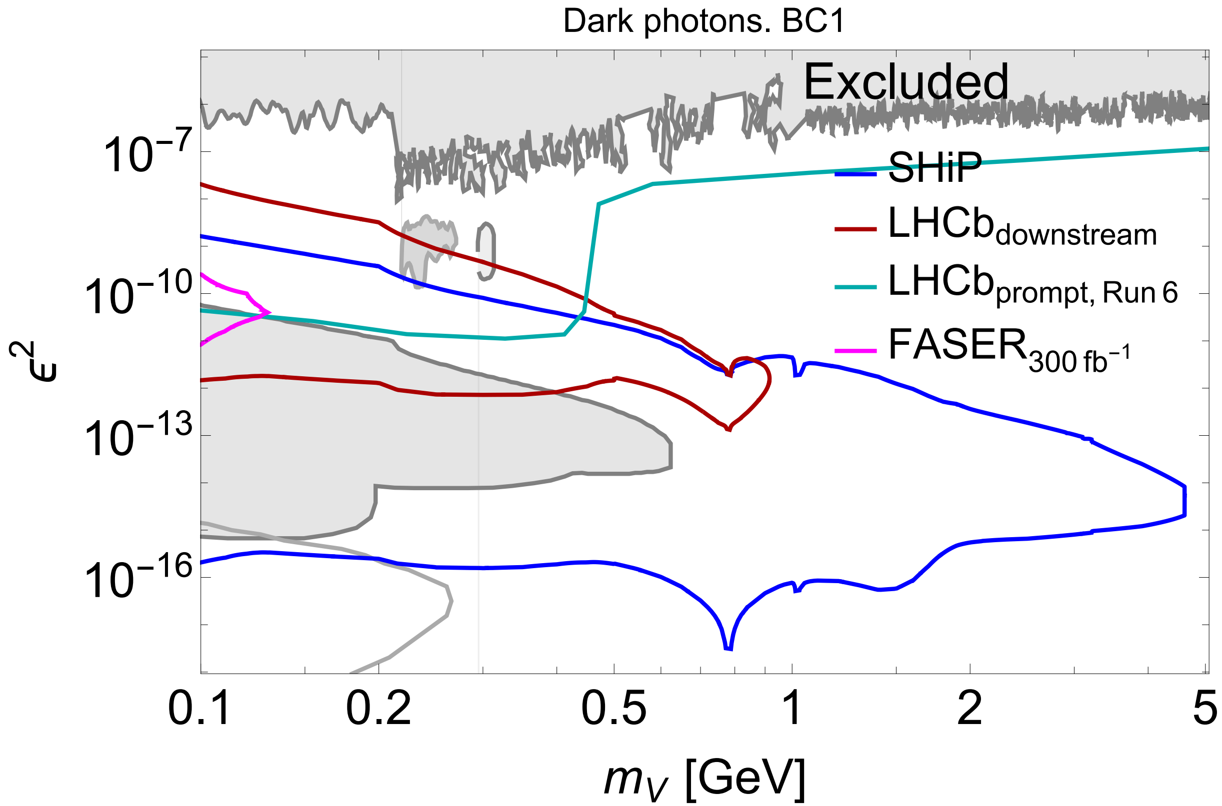
Check of signal resolution
air vs vacuum





FIP decay search performance: HNLs & Dark photons

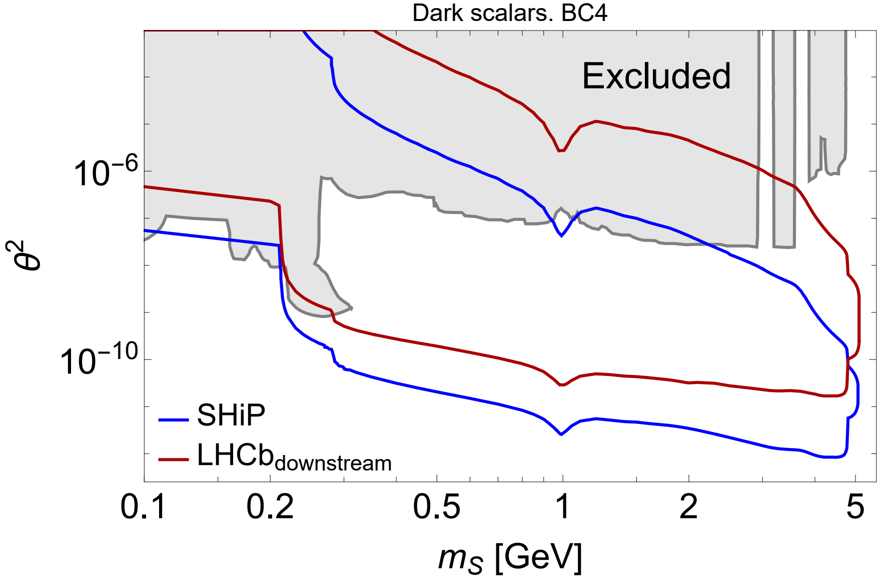




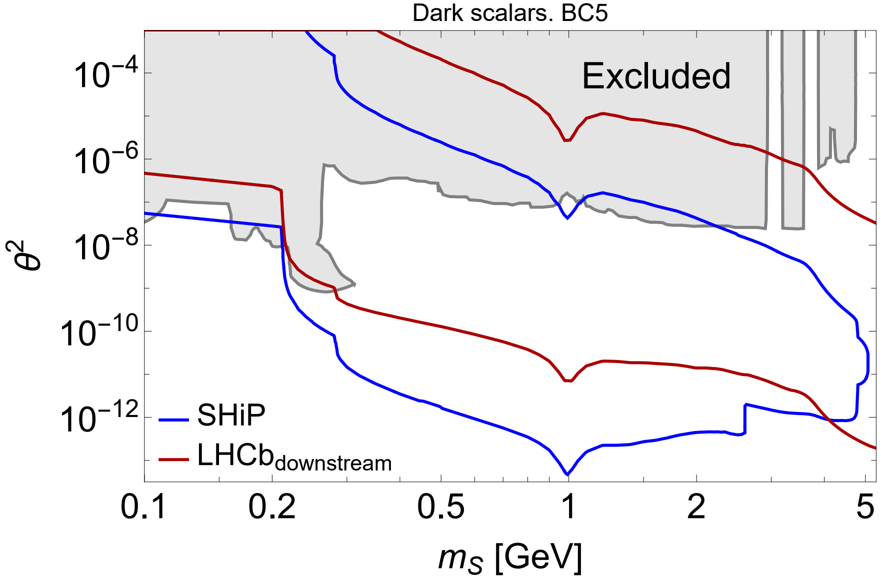
- ✓ *SHiP sensitivities to FIPs are orders of magnitude better than competing projects*
- ✓ *Sensitivity is not limited by backgrounds in 6 x 10^{20} PoT*

FIP decay search performance: Dark scalars & ALPs

BC 4



BC 5



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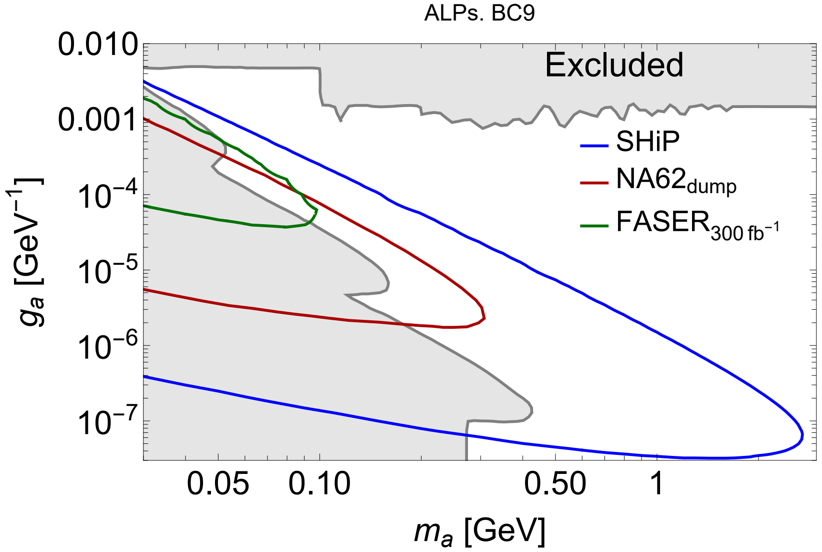
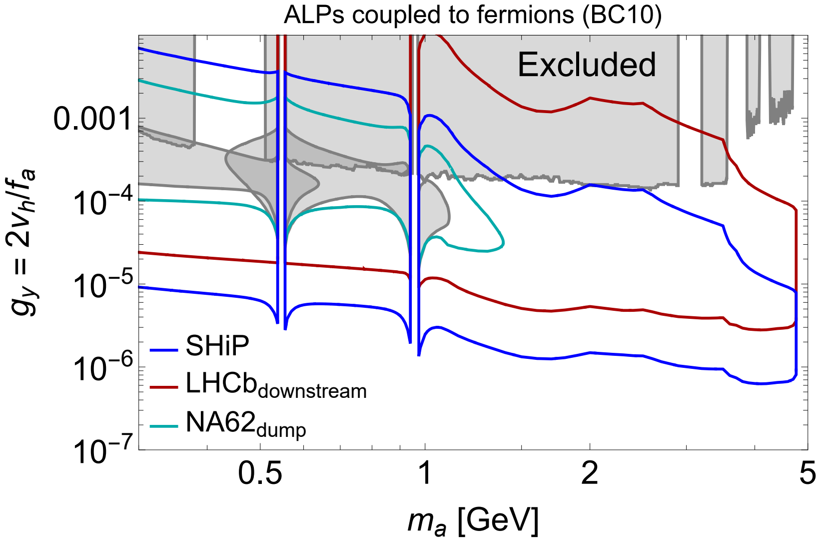
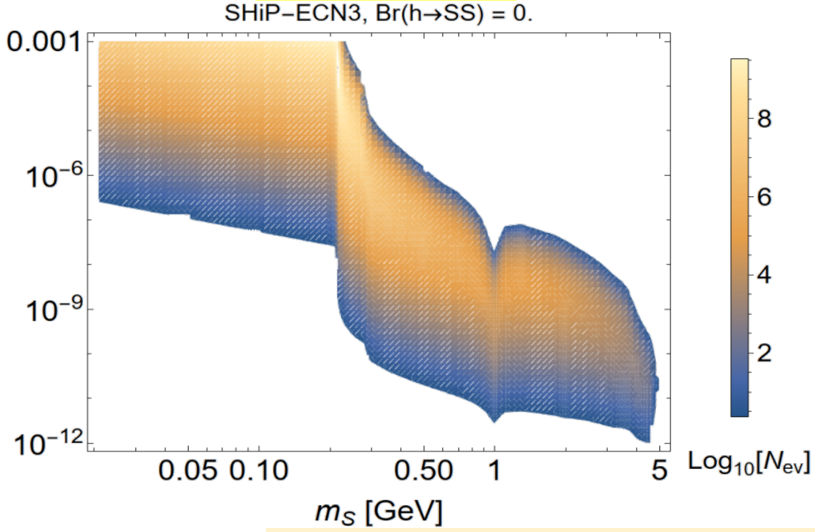




Physics sensitivities: FIPs cont'd

Experiment aimed at discovery and measurements
➔ Number of events ($6x10^{20}$ pot)

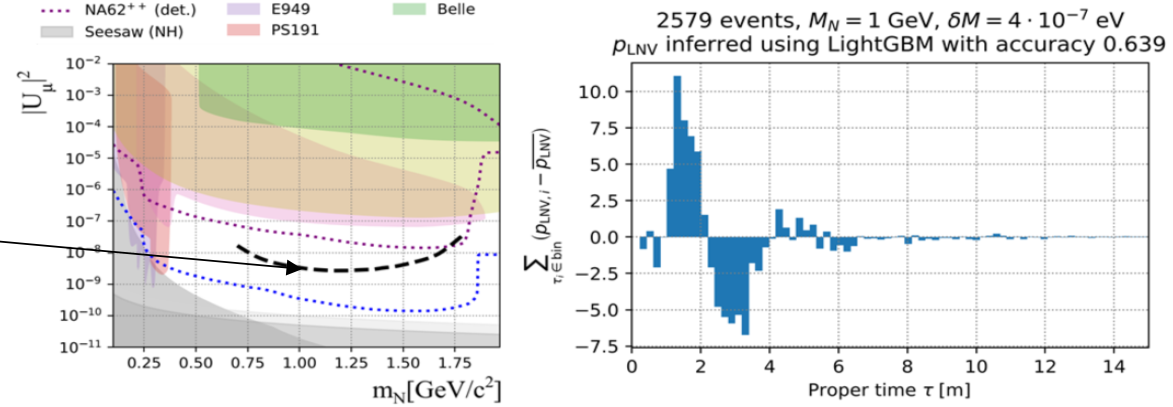
Dark scalar



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

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



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 4×10^{-7} eV.

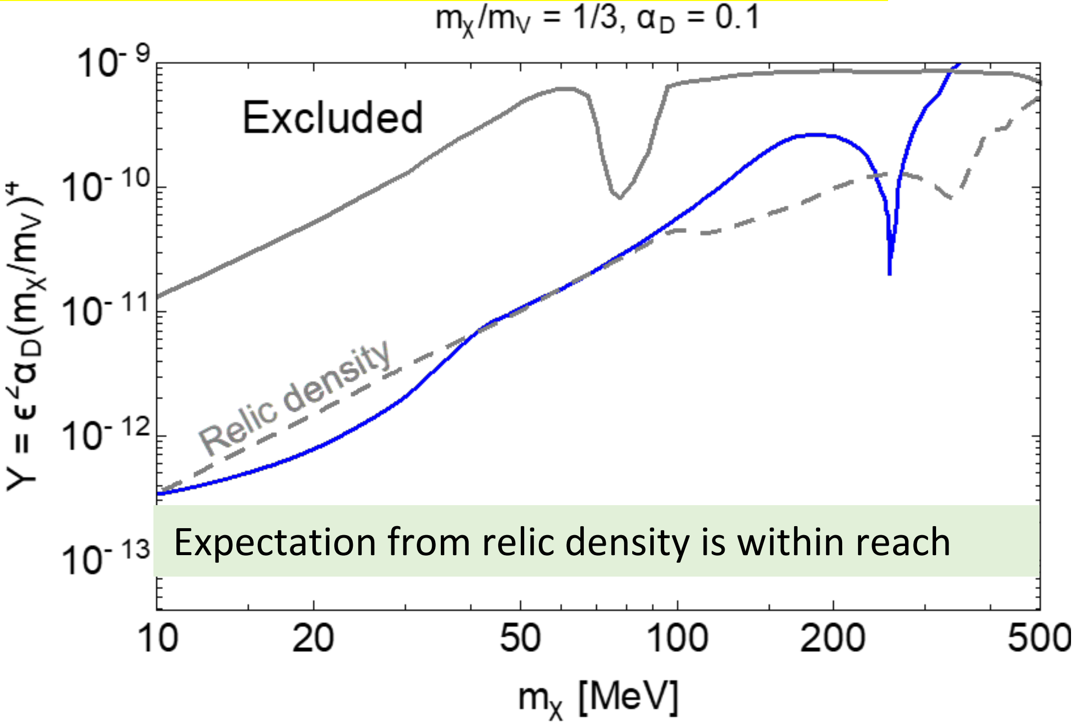
Main goals of SND

✓ ***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***, **sensitivity to ϵ^4 instead of indirect searches ϵ^2 (E technique)**

✓ *Background is dominated by neutrino elastic and quasi-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

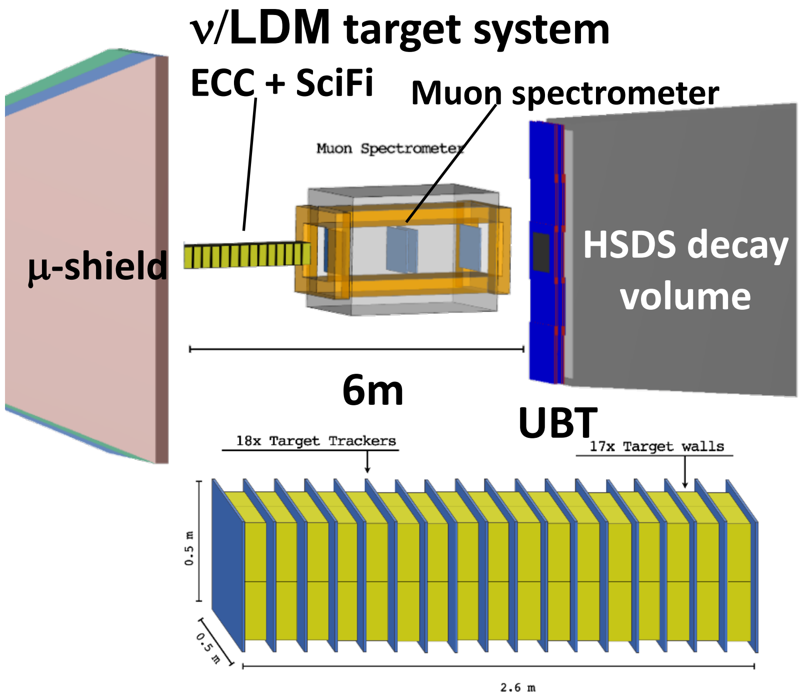
✓ ***Tau neutrino physics***

- Experimental signature of tau neutrino:

*(i) **"double-kink" topology** (resulted from ν_τ–interaction and τ–decay)*

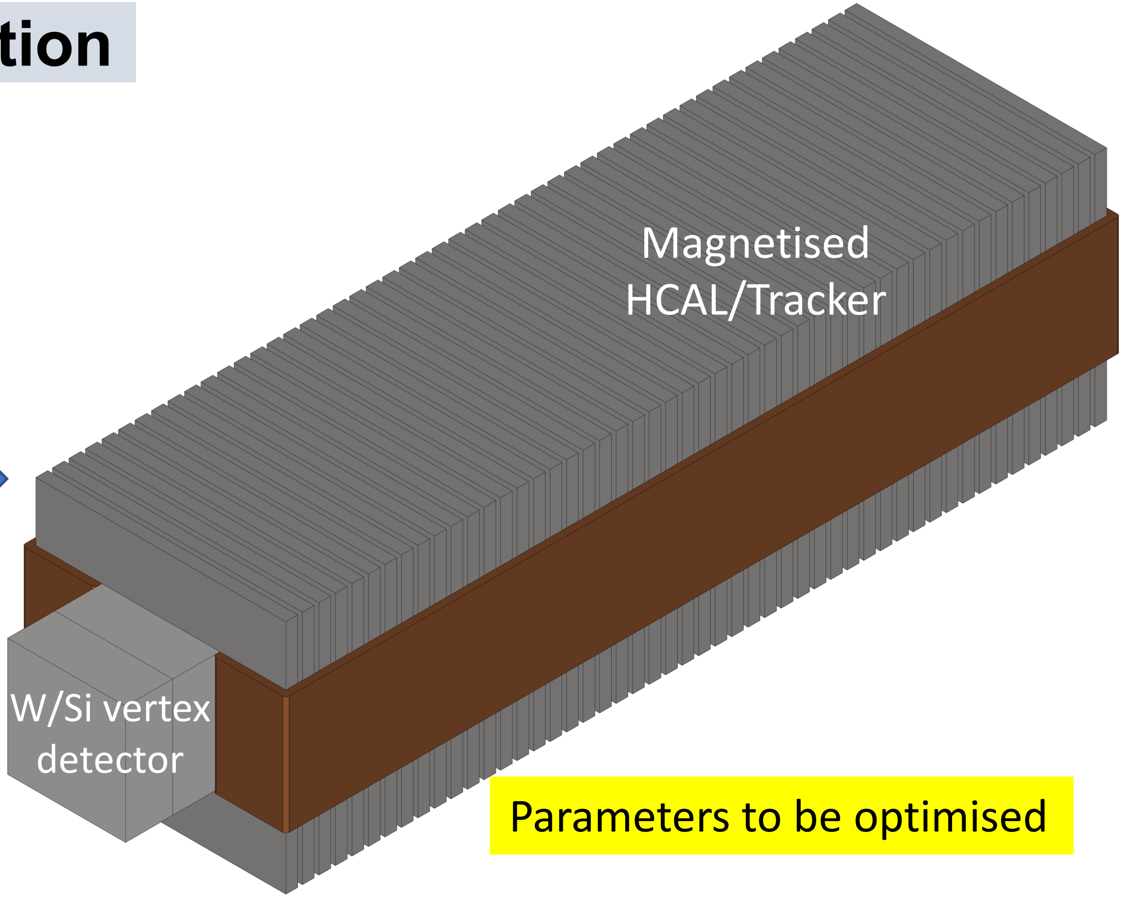
*(ii) **Missing P_t** carried away by 2 neutrinos from τ–decay*

SND detector optimization



3.1 t W / 145 m² emulsion

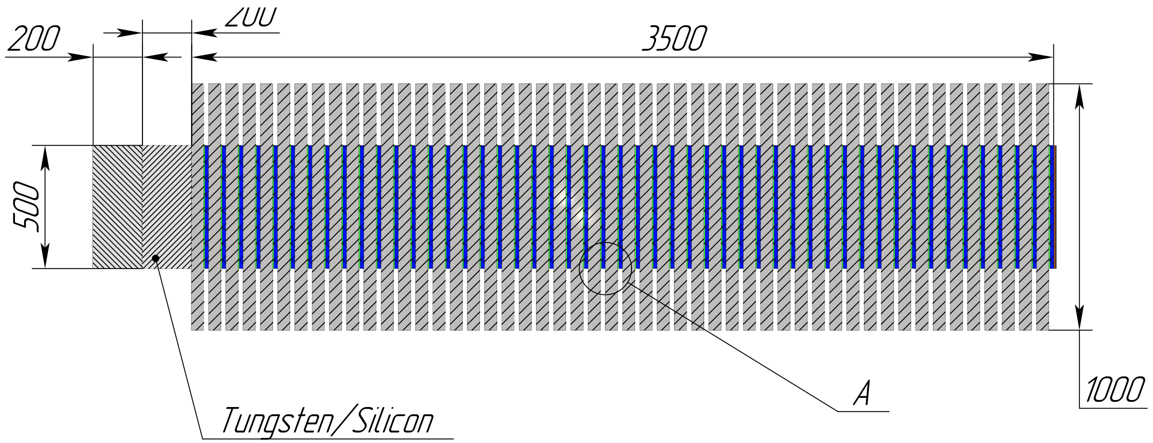
Replace emulsion films with electronic detectors

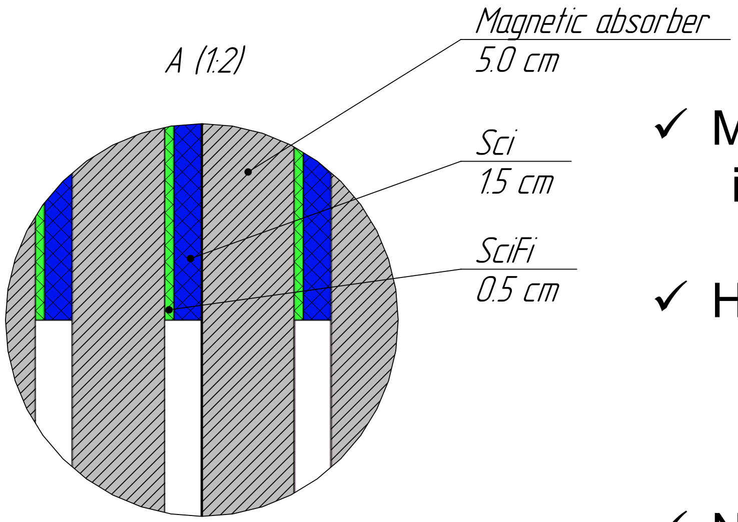


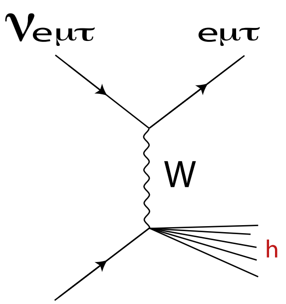
- ✓ LDM/neutrino W-target instrumented with layers of emulsion films (topological analysis only)
- ✓ SND muon spectrometer measures muon charge and momentum (10% accuracy in 1T field)

- ✓ W/Si neutrino vertex detector (topological analysis)
- ✓ Finely segmented HCAL/Tracker with magnetised absorber integrated to the muon shield (missing P_t analysis)

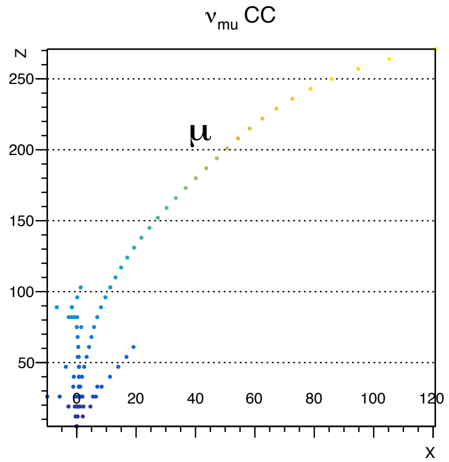
Magnetised HCAL/Tracker

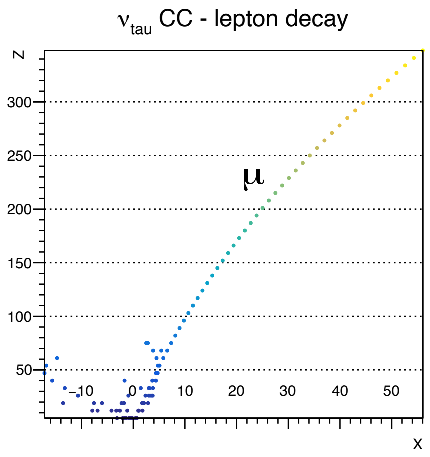


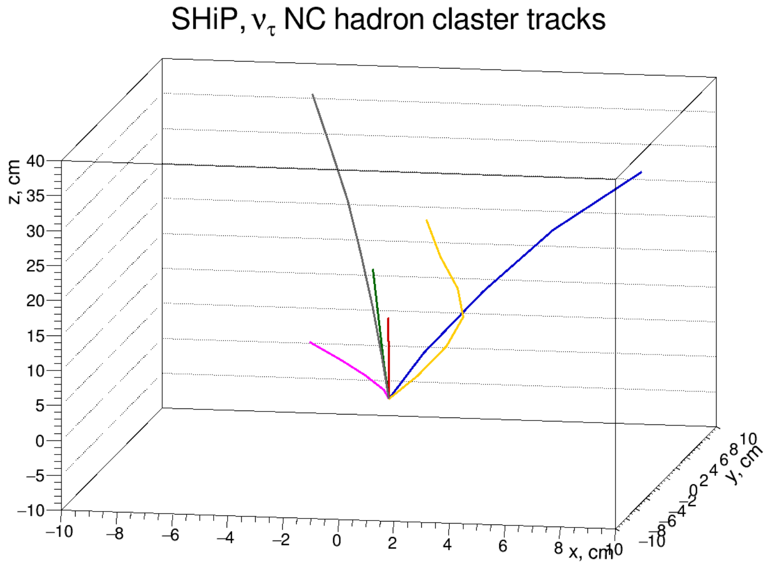




Events are very clean:







- ✓ Muon momentum measurement in 1.7T field (~15% accuracy)
- ✓ Hadronic energy measurement

$$\frac{\sigma(E)}{E} \sim \frac{50\%}{\sqrt{E}}$$

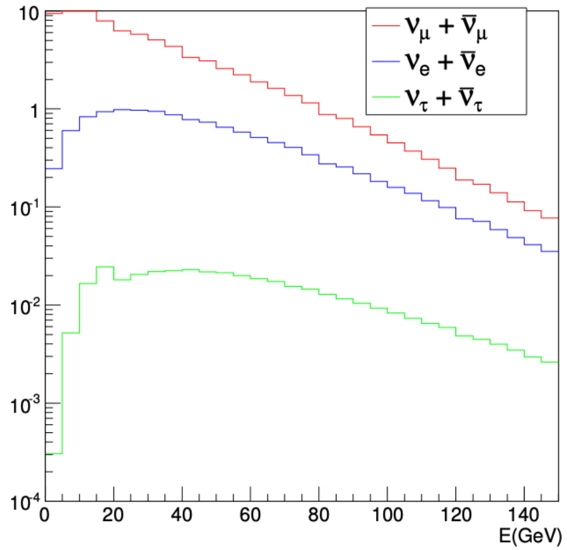
- ✓ Neutrino interaction vertex: $\sigma \sim 1.5$ cm in xy-plane
- ✓ Tau neutrino direction ~1%

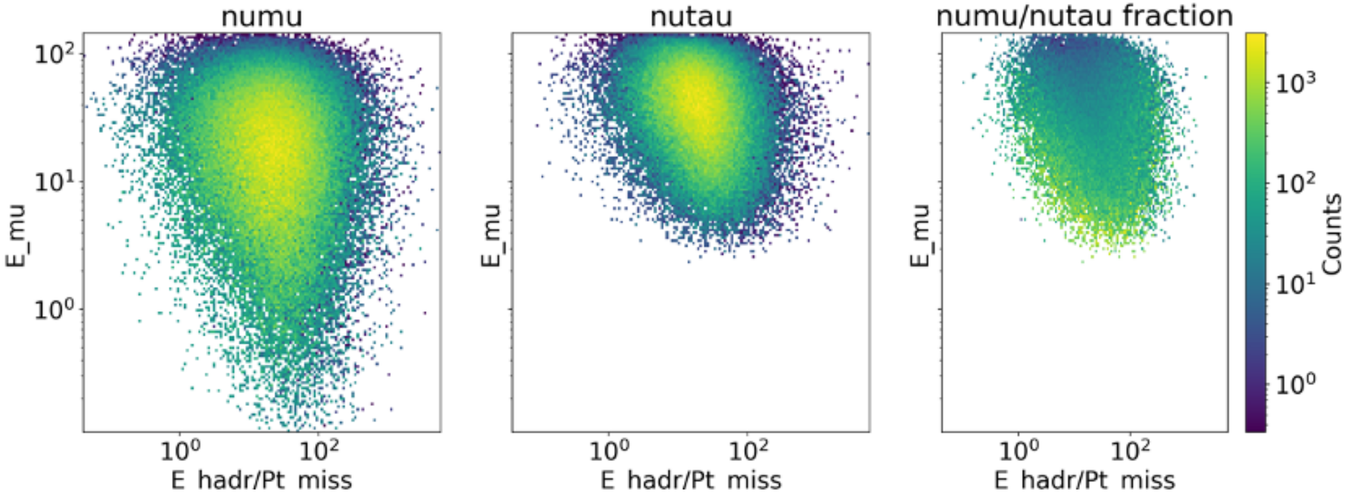
ν_τ – discrimination in leptonic tau decays with magnetised HCAL/Tracker

✓ ***Main background:*** *muon neutrino interactions in charged currents*

✓ ***Kinematical variables used in ML-algorithm***

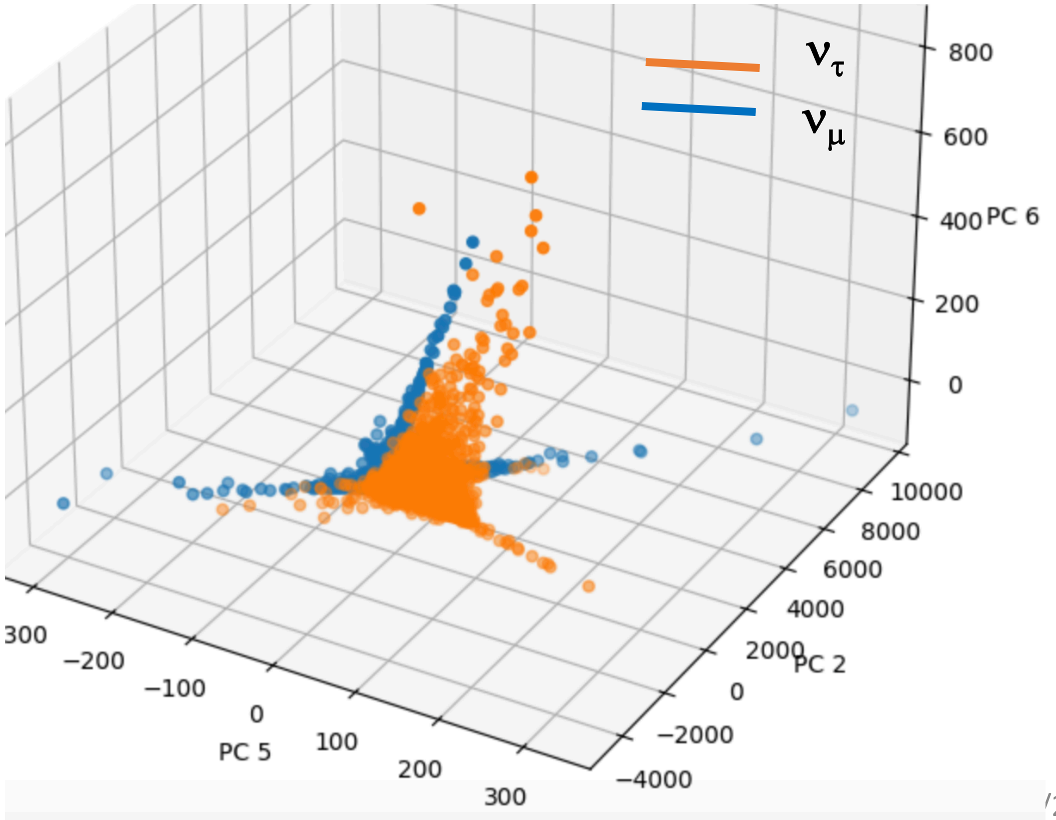
- *Missing momentum wrt ν_τ direction-of-flight*
- *Muon momentum*
- *Energy of hadrons*





✓ **ν_τ / ν_μ are well separated in 3D**

✓ ML-based analysis is being optimised
→ expect very good discrimination



Neutrino interaction physics

- ✓ ***Huge sample of tau neutrinos available at BDF/SHIP via $D_s \rightarrow \tau\nu_\tau$***
- ✓ *σ_{stat} < 1% for all neutrino flavours*
- ✓ *Accuracy determined by systematic uncertainties*

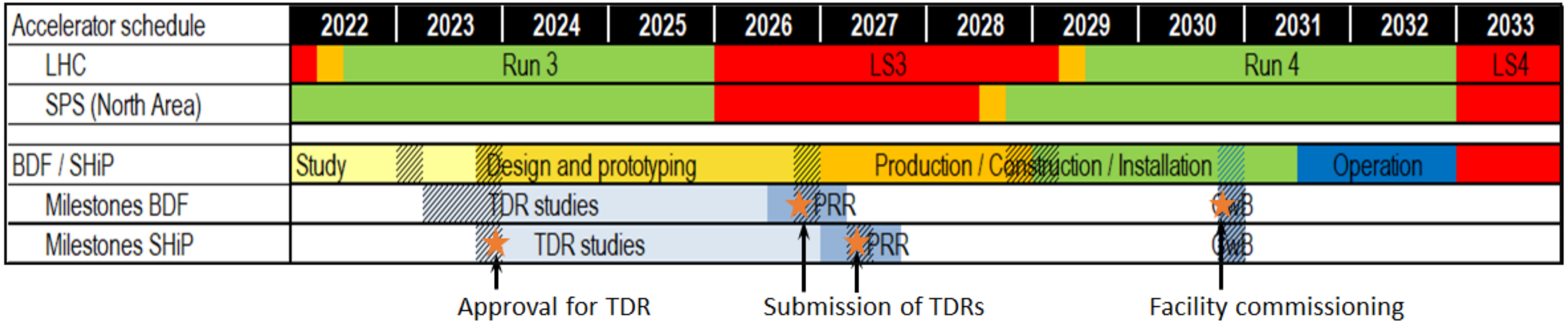
  ~5% in all neutrino fluxes

Incl. reconstruction efficiencies

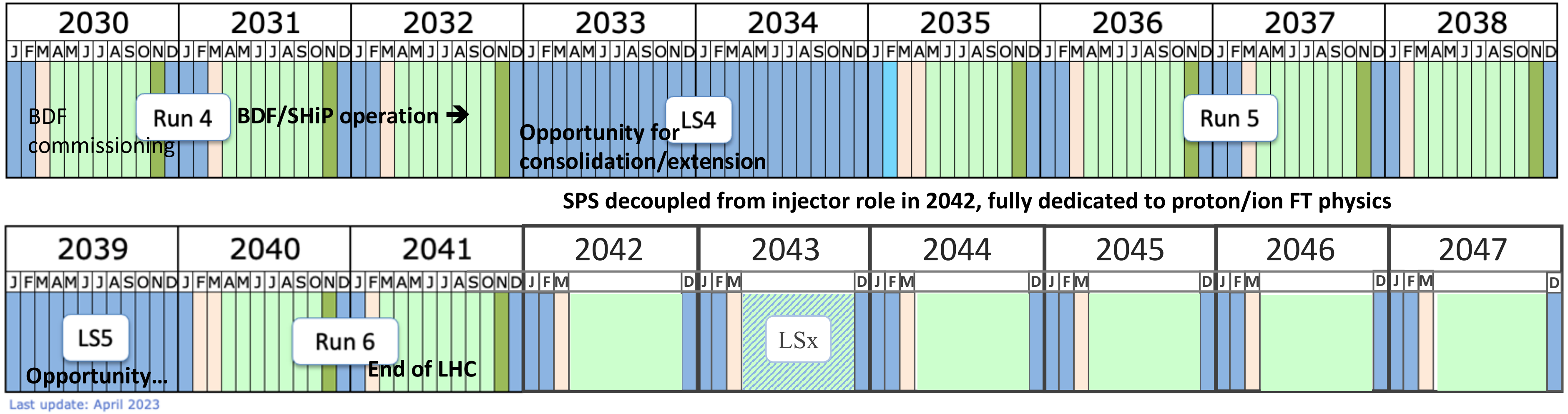
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

- ✓ **LFU in neutrino interactions**
  - $\sigma_{stat+syst}$~3% accuracy in ratios: ν_e / ν_μ , ν_e / ν_τ and ν_μ / ν_τ
- ✓ **Measurement of neutrino DIS cross-sections up to 100 GeV**
  - E_ν< 10 GeV as input to neutrino oscillation programme (DUNE in particular)
  - ν_τ cross-section at higher energies input to atmospheric oscillations and cosmic neutrino studies
  - $\sigma_{stat+syst}$ < 5%
- ✓ **Test of F_4 and F_5 ($F_4 \approx 0,\ F_5 = F_2/2x$ with $m_q \rightarrow 0$) structure functions in $\sigma_{\nu-CC\ DIS}$**
  - Never measured, only accessible with tau neutrinos [C.Albright and C.Jarlskog, NP B84 (1975)]

BDF/SHiP preliminary schedule



- *~2.5 years for detector TDRs*
- *Construction / installation of facility and detector is decoupled from NA operation*
- *Availability of test beams challenging*
- *Important to start data taking >1 year before LS4*
- *Several upgrades/extensions of the BDF/SHiP in consideration over the operational life*



SHiP TDR highest priorities

All subsystems have undergone first level prototyping/beam test, and critical components have been through large-scale prototyping

Main priorities in the early part of the TDR phase

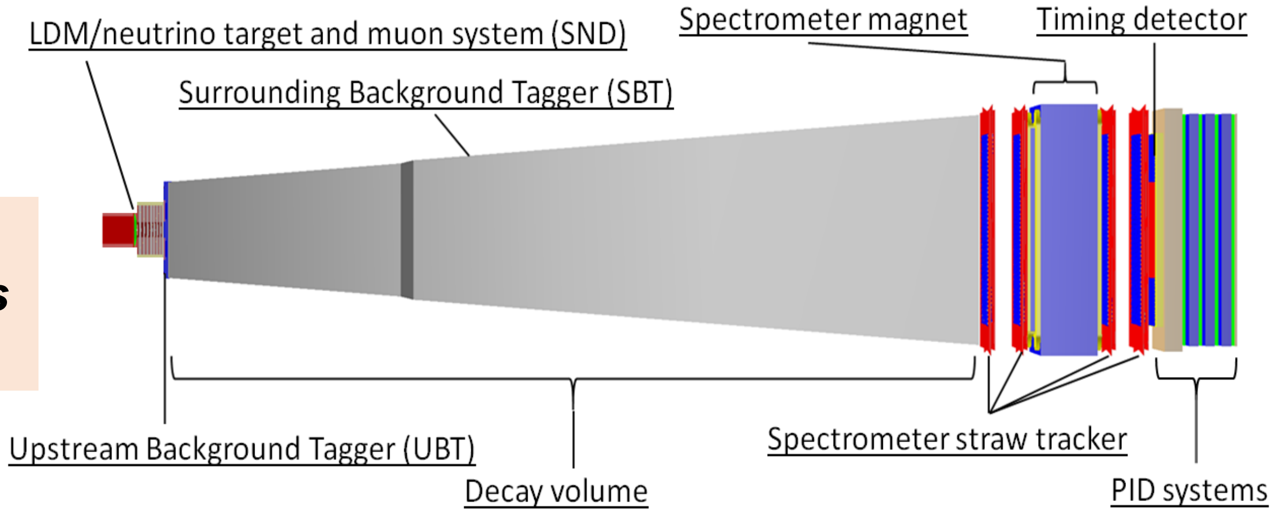
✓ *Muon shield SC technology*
- *Development of NC magnets will continue in parallel*

✓ *Decay volume under 1atm helium + SBT*
- *Removal of vacuum brings significant simplification of spectrometer section and decay volume itself*

✓ *SC option for spectrometer magnet*
- *Promising progress recently with design/operational parameters of spectrometer magnet, cooling scheme and mechanics needed (CERN Bulletin article)*

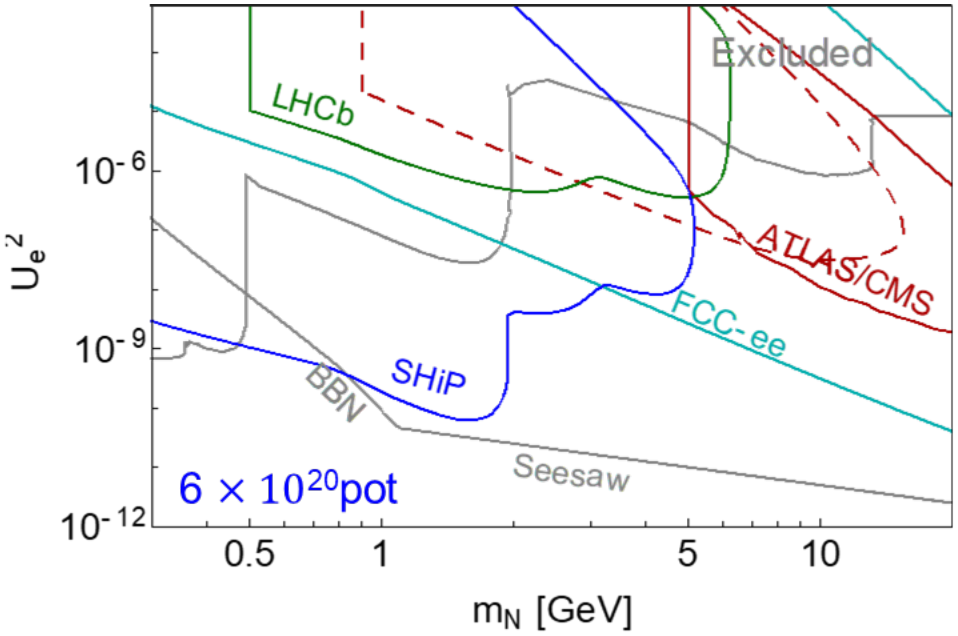
✓ *Development of the electronic SND detector*

Main focus on engineering design in 2024
→ Need for design and magnetic engineers



Summary

- ✓ *New programme at "Coupling frontier" at CERN with synergy between accelerator-based searches and searches in astrophysics/cosmology*
  - *First hints might come with breadth of modern earth/space-based telescopes*
- ✓ *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*



See-saw limit is almost in reach below charm mass

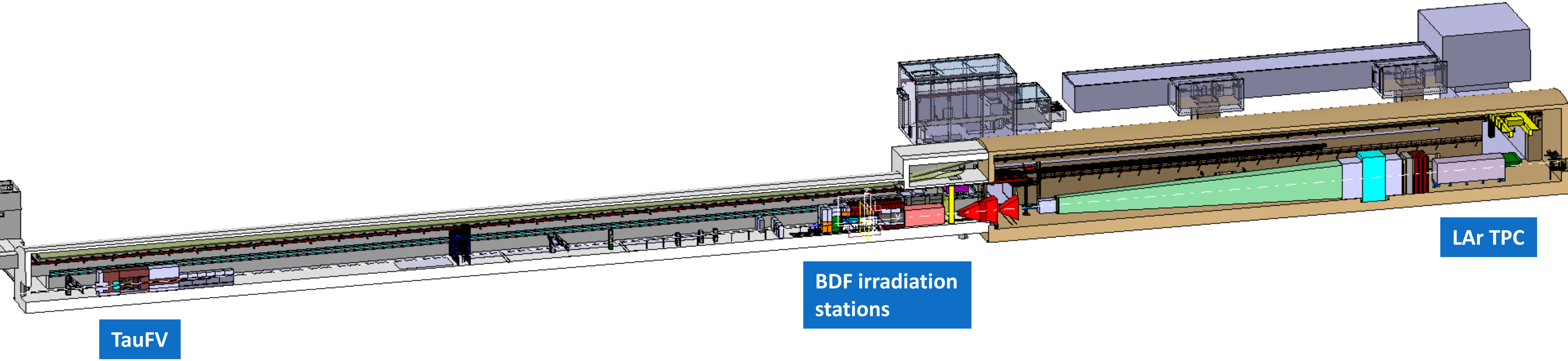
- ✓ *Rich "biscuit'n'rhum" neutrino physics programme, including fundamental tests of SM in tau neutrino interactions.*

SPARE SLIDES

Overview of BDF extensions

Preliminary studies of opportunities to extend BDF's physics programme synergetically with SHiP:

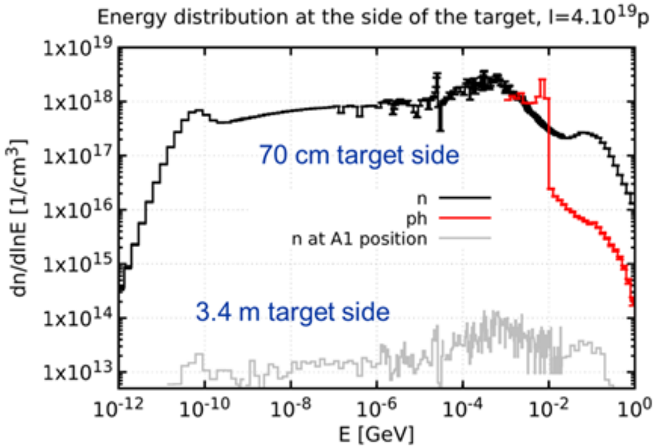
- ✓ *Irradiation stations (nuclear astrophysics and accelerator / material science applications)*
- ✓ *LArTPC to extend search for FIPs using different technology*
- ✓ *TauFV to search for lepton flavour violation and rare decays of tau leptons and D-mesons*

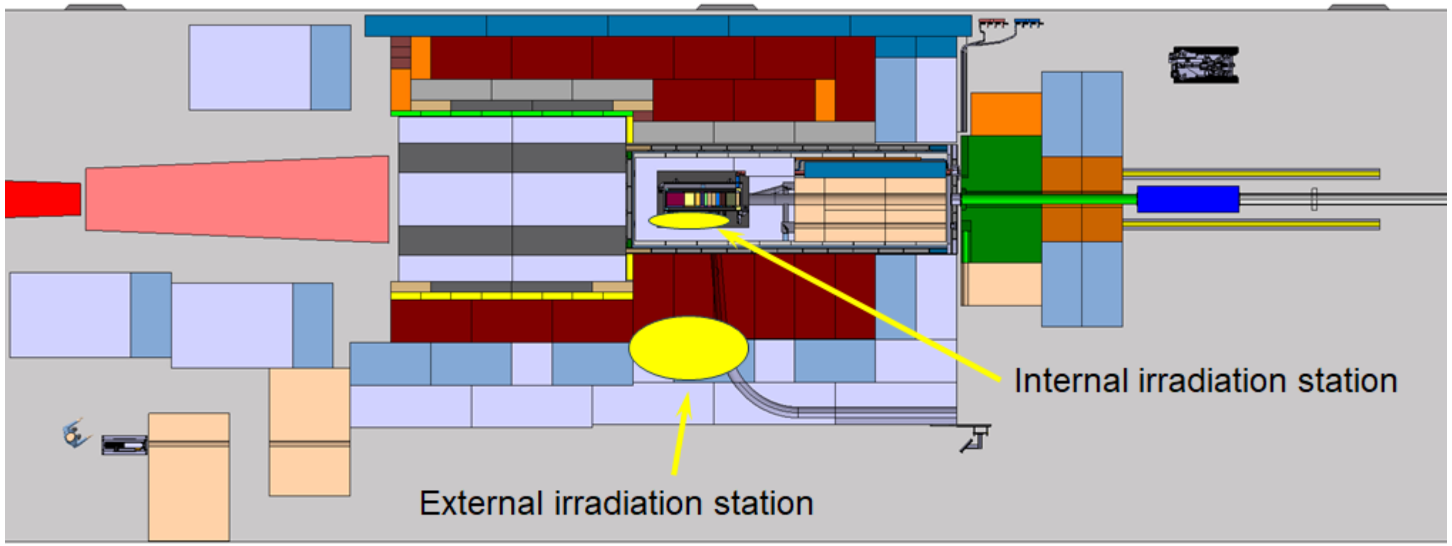


Extensions: Irradiation stations

✓ ***Can be exploited synergetically with SHiP as complementary radiation facility***

- *Similar profile of radiation as at spallation neutron sources*
- *A flux of ~10^{13} - 10^{14} neutrons/cm^2/pulse in the proximity of the BDF target ranging from thermal neutrons up to 100 MeV*
- *Unparalleled mixed field radiation near target ~400 MGy and 10^{18} 1MeV neq/cm^2 per year*





Two zones:

- Internal: 100-400 MGy / year adapted for irradiation of small volumes
- External: Larger zone of O(m^2) with lower radiation level

✓ *Cross-sections important for nuclear astrophysics*

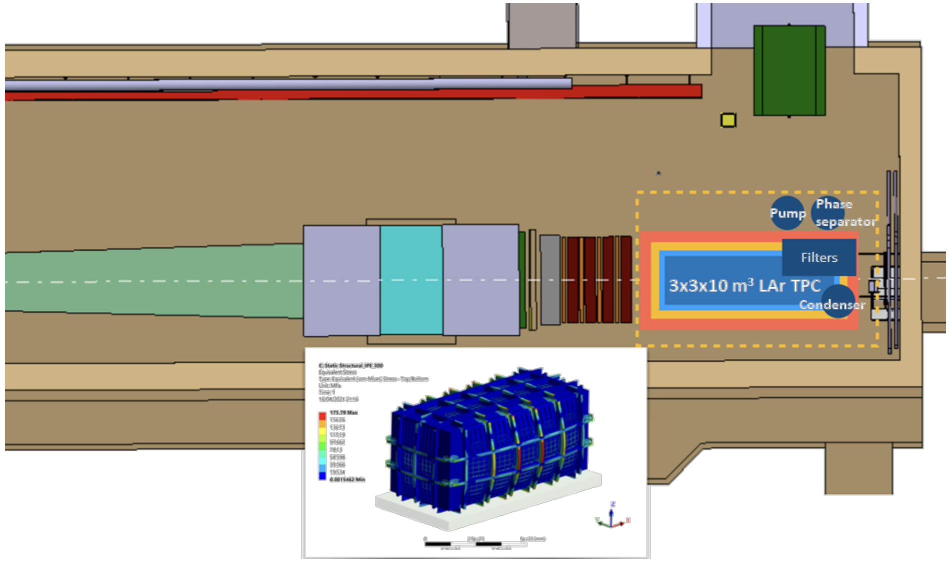
✓ *Radiation tolerance test of materials and electronic components at extreme conditions expected at FCC*

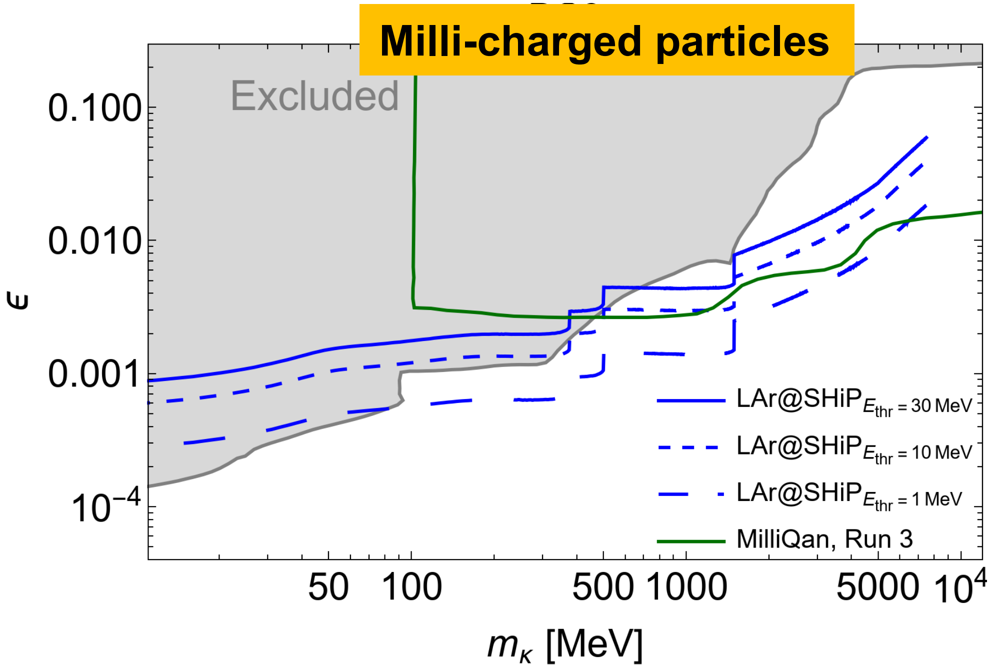
Extensions: FIP searches with LAr TPC detector

LArTPC technology is currently used in neutrino and cosmic Dark Matter search experiments

- *Large experience at CERN with building 700 t detectors for DUNE*
- *Space available behind SHiP allows installation of LArTPC with an active volume ~3×3×10 m³ (~130 t) and associated infrastructure*

➔ *Extends SHiP's physics reach using different technology*

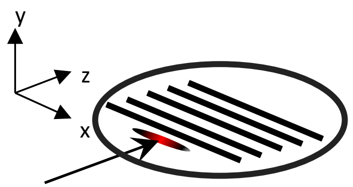


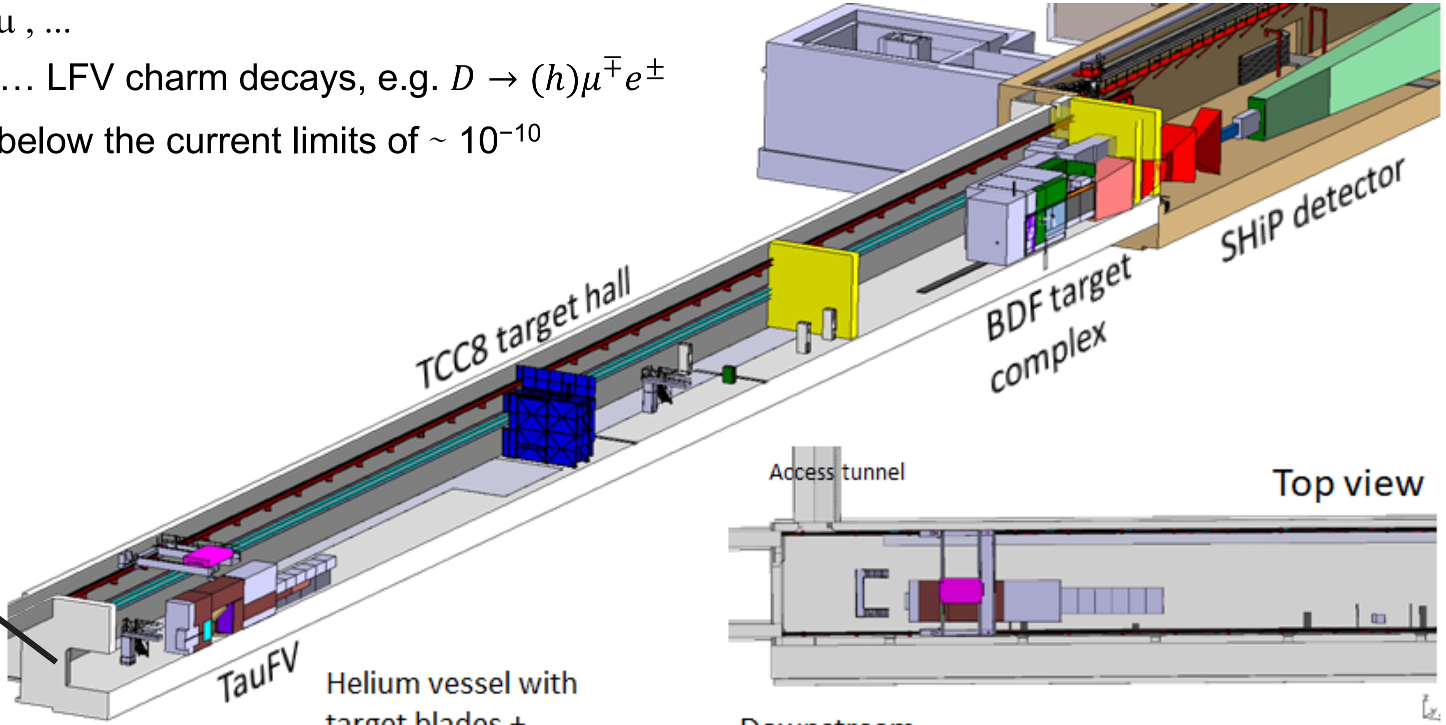


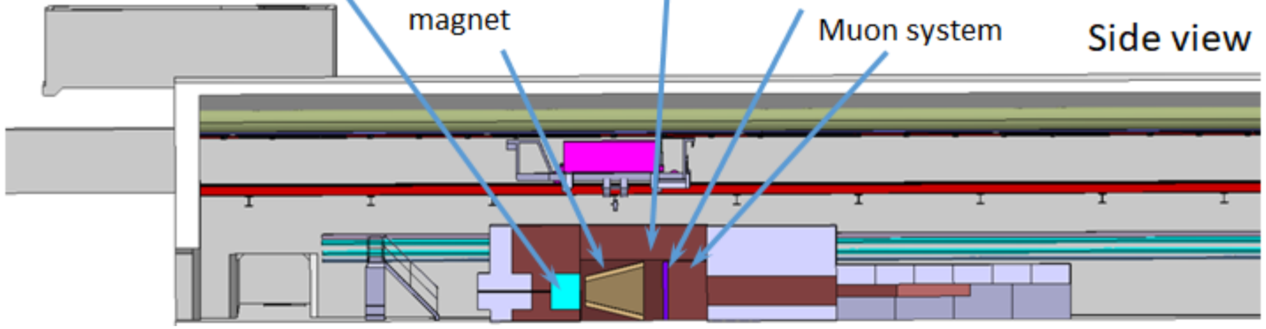
Extensions: Tau flavour violation experiment

Intercepting 1-2% of protons in BDF line with wire target and mini-LHCb-like detector

- n_τ [year^{-1}] ~ O(10^{13}) : $\tau \rightarrow 3\mu$, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow ee\mu$, $\tau \rightarrow e\mu\mu$, ...
- $n_{D\ mesons}$ [year^{-1}] ~ O(10^{15}) : Also opportunity for $D \rightarrow \mu\mu, \ldots$ LFV charm decays, e.g. $D \rightarrow (h)\mu^{\mp}e^{\pm}$
- $n_{K\ mesons}$ [year^{-1}] ~ O(10^{18}) : $K_L^0, K^+ \rightarrow \pi\mu^{\mp}e^{\pm}$ probed far below the current limits of ~ 10^{-10}







➔ $\tau \rightarrow \mu\mu\mu$ yields with *5 years* of operation and assuming branching ratio 10^{-10}
(TauFV acceptance & preselection efficiency = 5%)

Experiment	PoT / $\int \mathcal{L}dt$	Yield
TauFV	4×10^{18}	800
Belle II	50 ab^{-1}	1
LHCb Upgrade I	50 fb^{-1}	14
LHCb Upgrade II	300 fb^{-1}	84