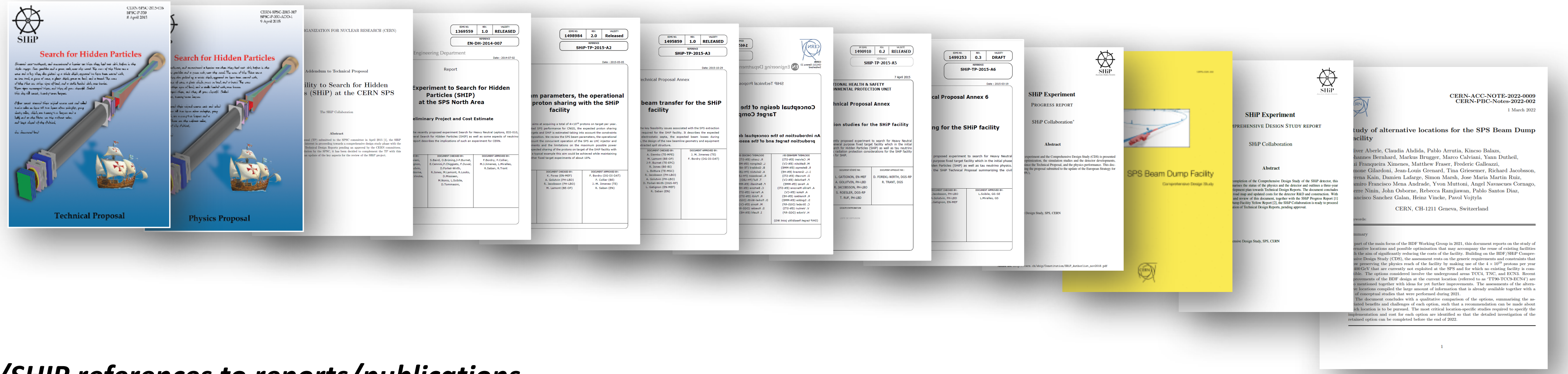
BDF/SHiP facility at CERN

Andrey Golutvin
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

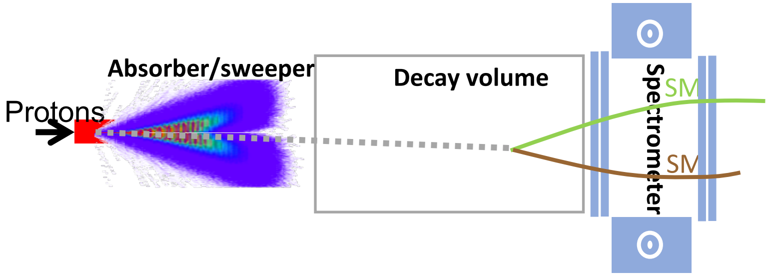
Recent documents:

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

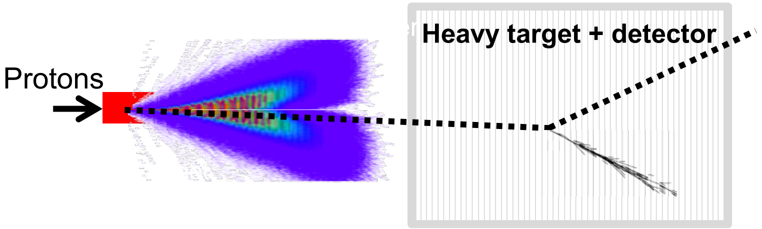
✓ ***Letter of Intent, BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-2022-032***

SHiP experimental techniques

Visible decay to SM particles



Scattering off atomic electrons and nuclei



Also suitable for neutrino interaction physics with all flavours

✓ ***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***

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*

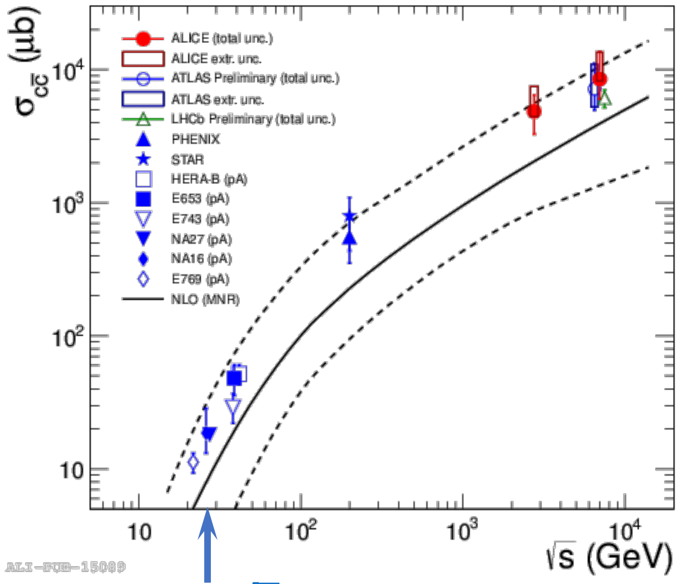
➔ *BDF luminosity for a very thick target (e.g. >1m Mo/W) with*

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*

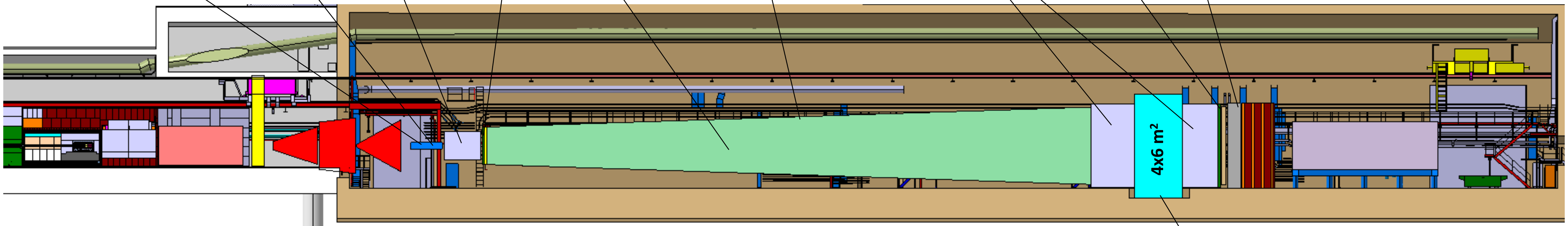


BDF @ $\sqrt{s} = 27\ GeV$

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) ~ 1.6×10^{-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



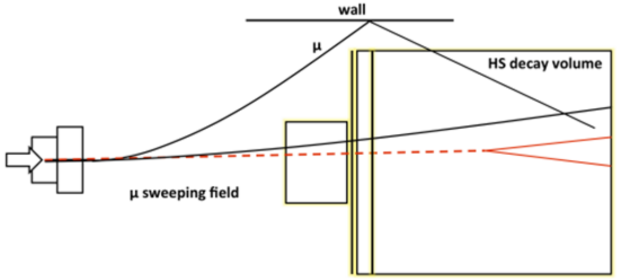
see w38 - CERN Bulletin article),

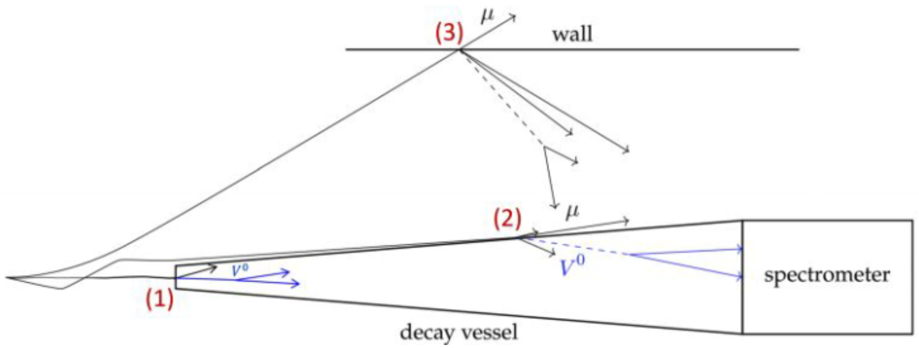
Designed for "zero background" in decay search

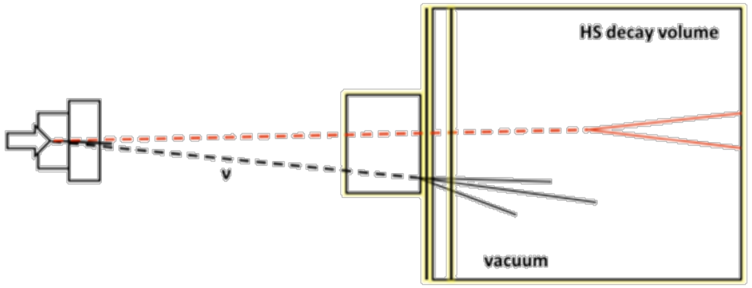
- ***Target design***
- ***Muon shield***
- ***Decay volume under low air pressure (or He)***
- ***Background veto taggers (SBT & UBT)***
- *Momentum and decay vertex information*
- *Impact parameter at target*
- *Time coincidence*
- *Particle identification* — Not currently used in background suppression

HSDS: Background evaluation for FIP decay search

Background estimation based on full GEANT-based MC







➔ *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

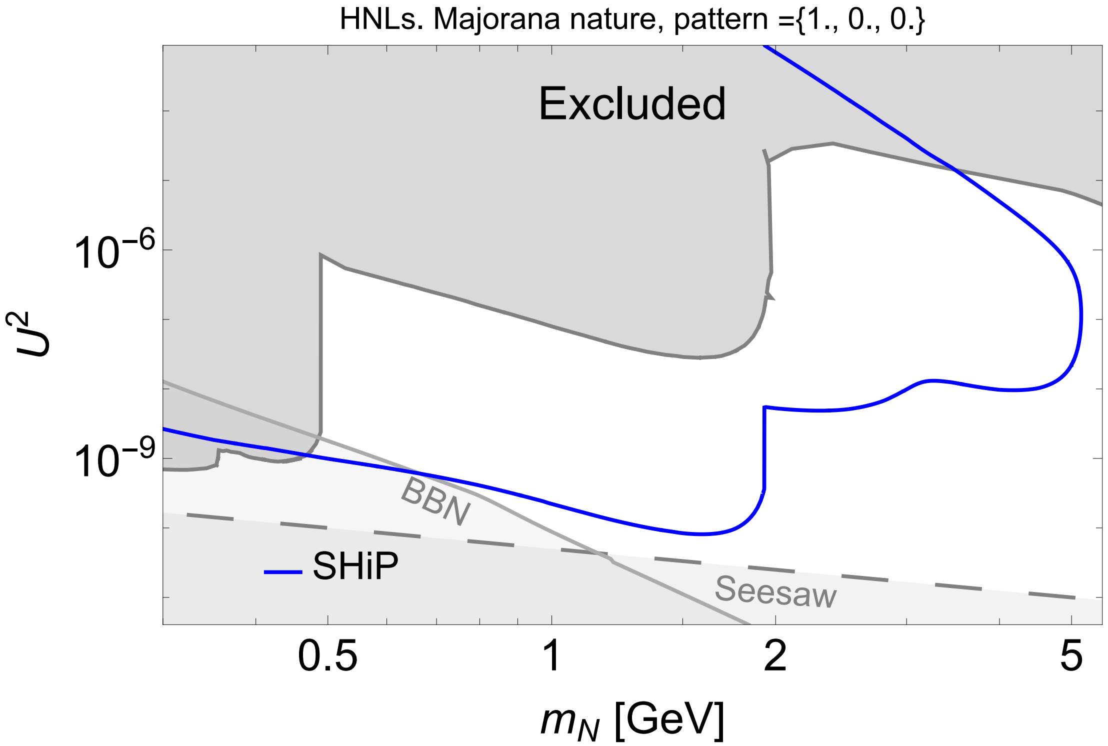
Track momentum	$> 1.0\,\text{GeV}/c$
Track pair distance of closest approach	$< 1\,\text{cm}$
Track pair vertex position in decay volume	$> 5\,\text{cm}$ from inner wall
	$> 100\,\text{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\text{cm}$
Impact parameter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

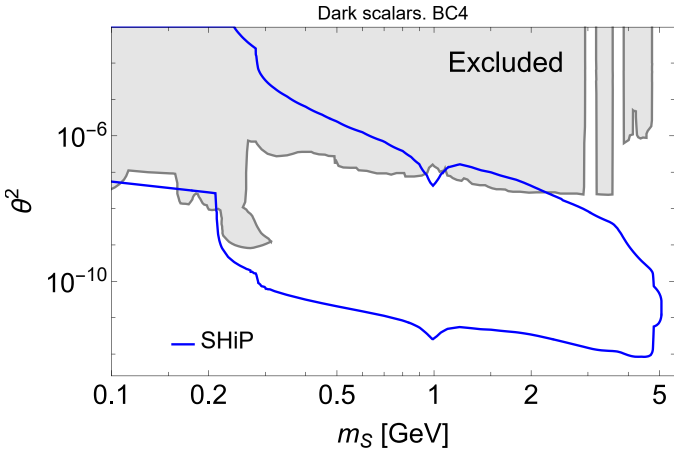
+ **Time coincidence** + **UBT/SBT**

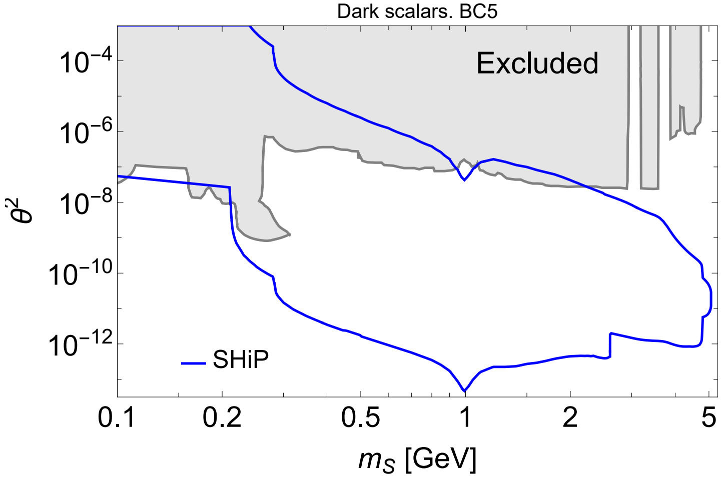
Expected background
for 6×10^{20} pot (15 years of operation)

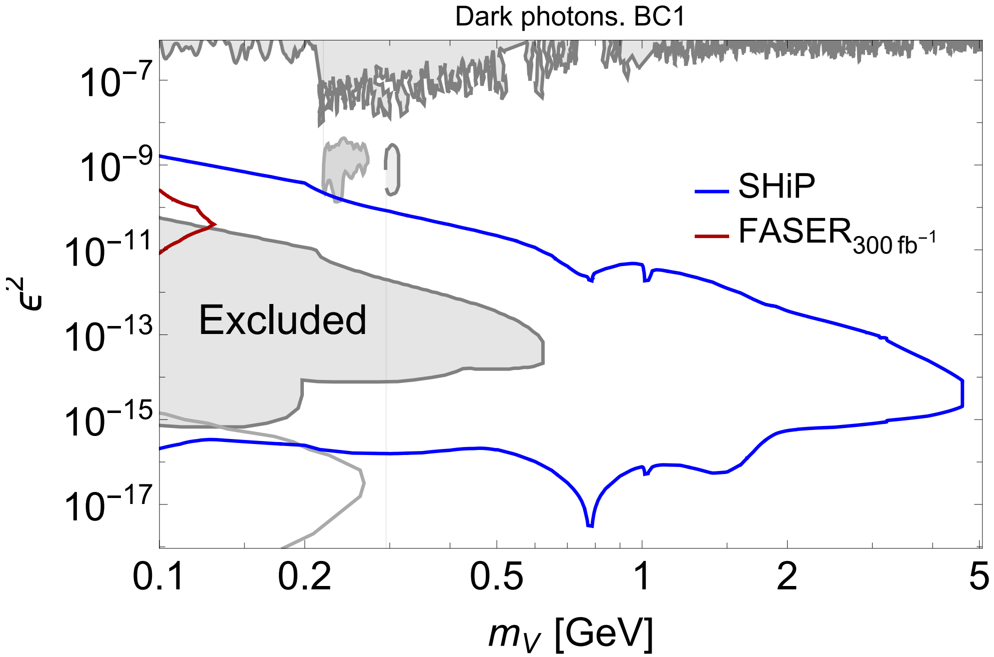
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

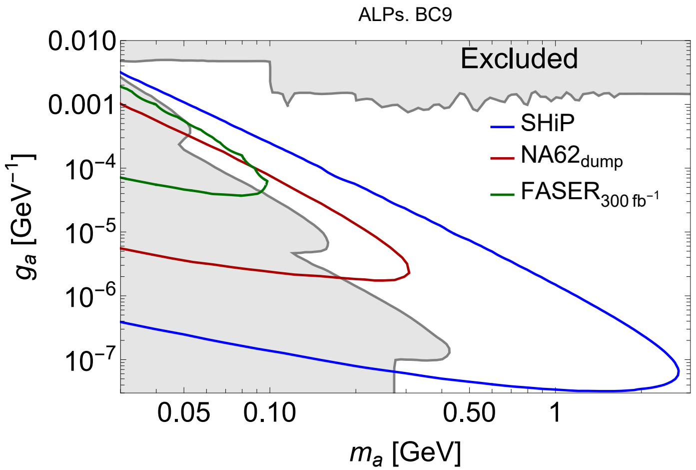
FIP decay search performance

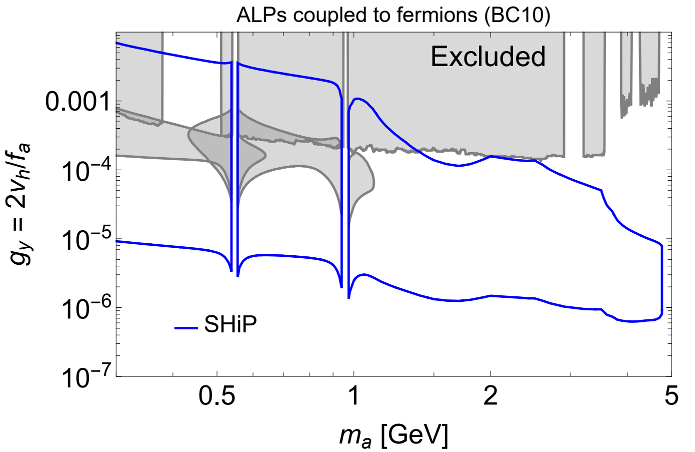












- ✓ *SHiP sensitivities to FIPs are orders of magnitude better than existing limits*
- ✓ *Sensitivity is not limited by backgrounds in 6 x 10^{20} PoT*

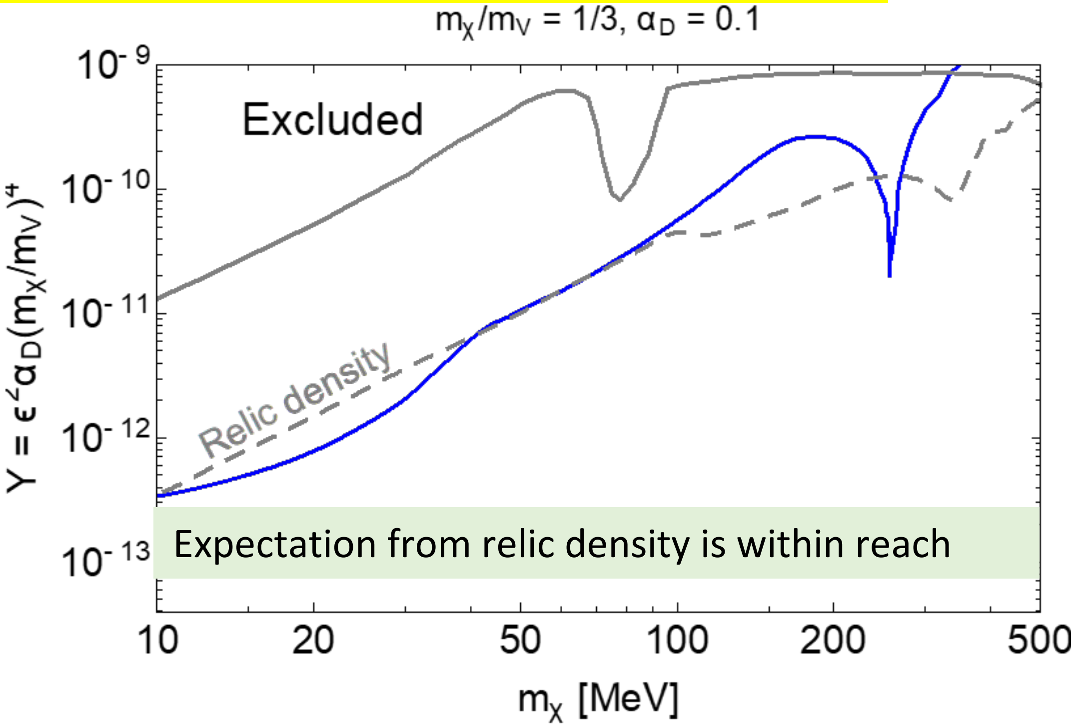
Main goals of SND

✓ ***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_τ–interaction and τ–decay)*

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

Neutrino interaction physics

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	

✓ ***Very large sample of tau neutrinos available at BDF/SHIP via $D_s \rightarrow \tau\nu_\tau$*** *$\rightarrow \sigma_{stat}$ < 1% for all neutrino flavours*

✓ *Accuracy determined by systematic uncertainties ~5% in all neutrino fluxes*

✓ **LFU in neutrino interactions**

- $\sigma_{stat+syst}$~3% accuracy in ratios: ν_e / ν_μ , ν_e / ν_τ and ν_μ / ν_τ

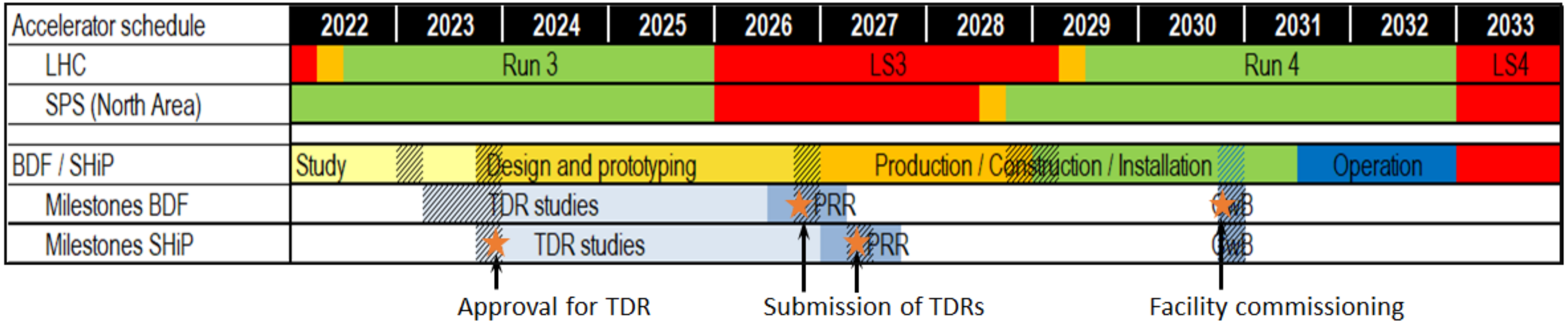
✓ **Measurement of neutrino DIS cross-sections up to 100 GeV**

- E_ν< 10 GeV as input to neutrino oscillation programme (DUNE in particular)
- ν_τ cross-section at higher energies input to cosmic neutrino studies
- $\sigma_{stat+syst}$< 5%

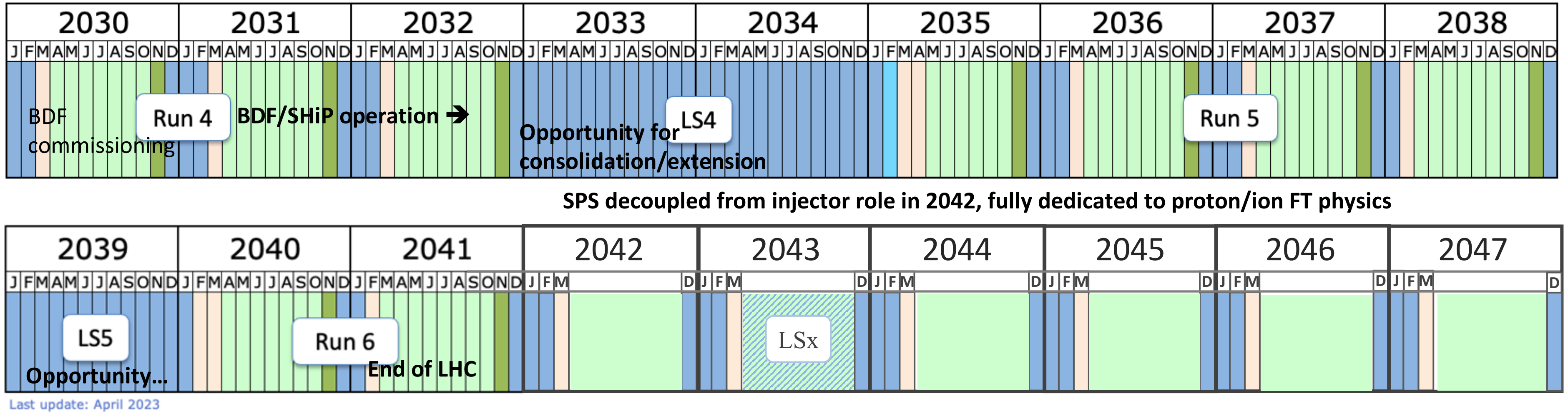
✓ **Test of F_4 and F_5 ($F_4 \approx 0$, $F_5 = F_2/2x$ with $m_q \rightarrow 0$) structure functions in $\sigma_{\nu-CC\ DIS}$**

- 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

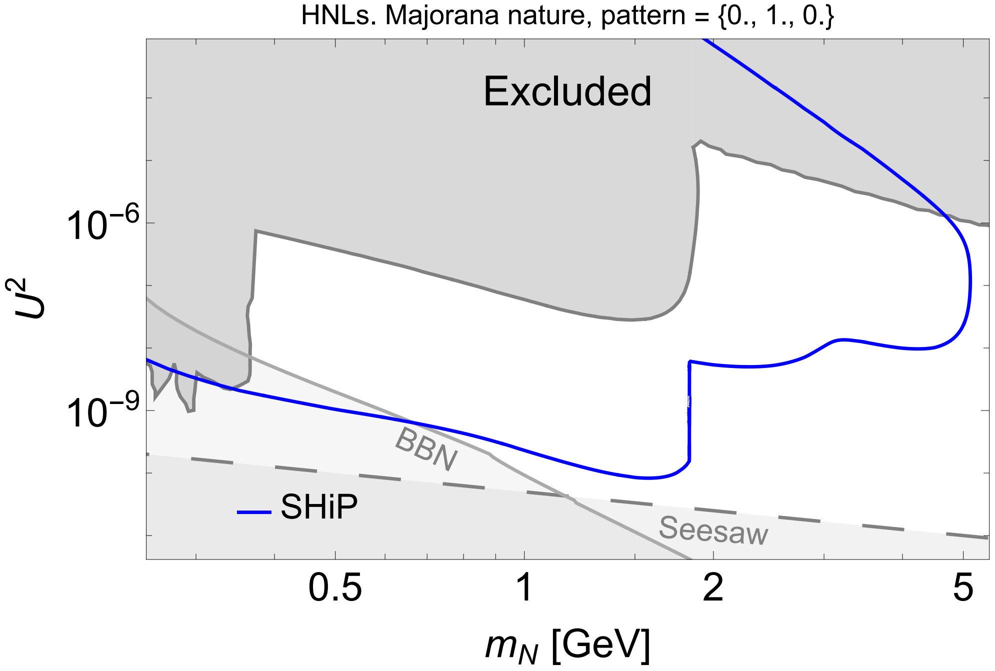


Summary

✓ *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*



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.*