Physics with SHiP (NA67) @ a dedicated Beam-Dump Facility (BDF)

Heiko Lacker
HU Berlin

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SHiP Physics Case in a nutshell

Physics with the Scattering-and-Neutrino Detector (SND) @ SHiP

Physics with the Hidden-Sector Spectrometer @ SHiP

Liquid-Scintillator Surrounding Background Tagger (HU Berlin contribution)

Status and timeline of the project

Looking for Physics Beyond the SM: Diversity and Complementarity!

If Higgs boson is SM Higgs boson:
SM complete, w/o explaining
→ (tiny) ν masses
→ BAU
→ dark matter

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Low-energy manifestation
of UV-complete theory

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

New „high"-mass states
→ energy frontier
→ rare decays (e.g. flavour physics)
→ precision measurements
… No smoking gun yet

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Low-energy extensions

$\mathcal{L}_S = c_1 H^\dagger H S + c_2 H^\dagger H S^2,$ Dark scalars

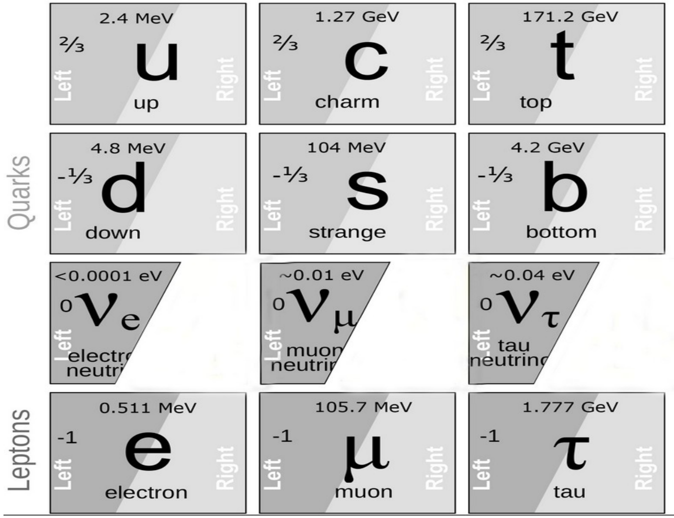
$\mathcal{L}_N = F_{N\alpha} \bar{N}^c \sigma_2 H^* L_\alpha + \text{h.c.},$ Majorana Neutrinos

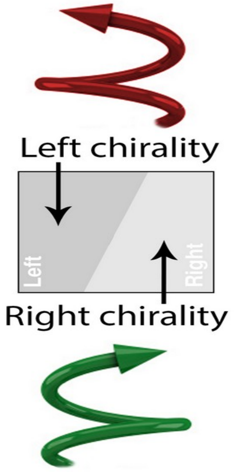
$\mathcal{L}_V = -\frac{\epsilon}{2} V_{\mu\nu} B^{\mu\nu},$ Dark Photons

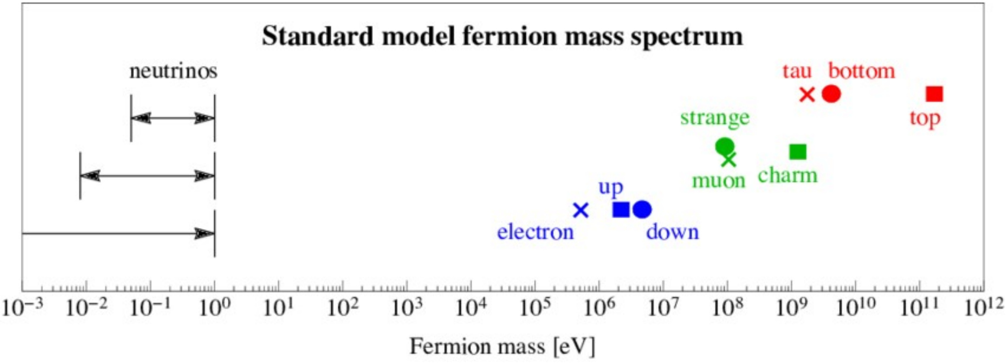
$\mathcal{L}_a = \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$ ALPs (non-renomalizable)

Direct search for
low-mass, feebly interacting particles (FIPs)

Example: Heavy Neutral Leptons

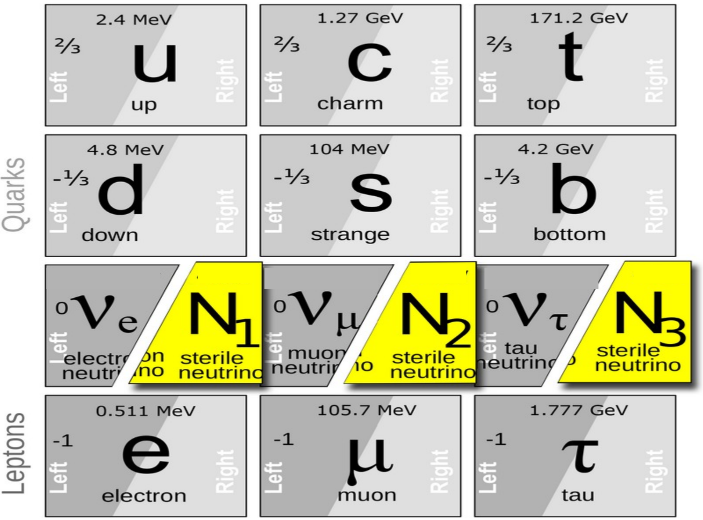


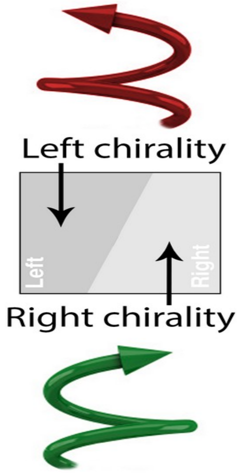




Example: Minimal Neutrino Standard Model νMSM

Add 3 right-handed Majorana neutrinos





Higgs mechanism: m_D

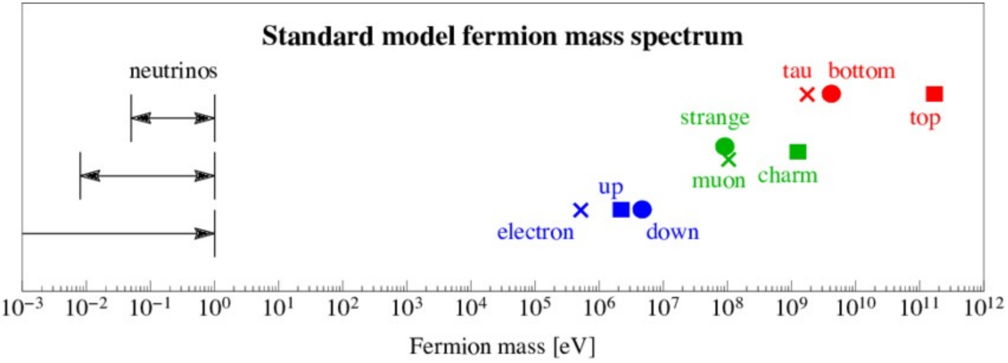
Majorana mass: M

$\rightarrow$**3 Neutrinos** ν **with tiny masses:** $m_\nu \approx m_D \dfrac{m_D}{M}$

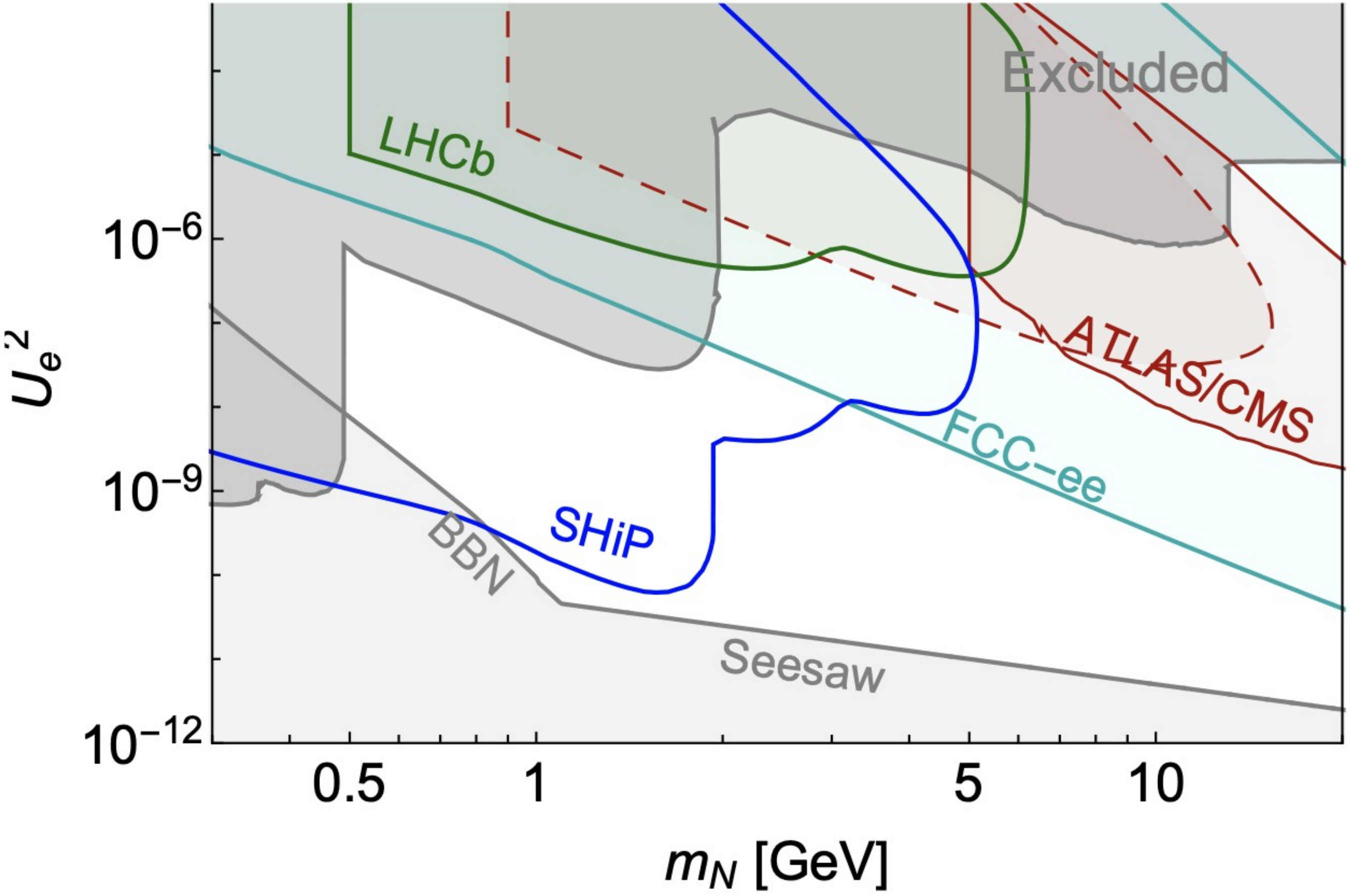
$\rightarrow$**3 Neutrinos N with masses:** $M_N \approx M$

2 N with $M \cong \mathcal{O}(GeV) \rightarrow$ **Leptogenesis** $\rightarrow$ **Baryogenesis**

1 N with $M \cong \mathcal{O}(keV) \rightarrow$ **Dark Matter candidate**



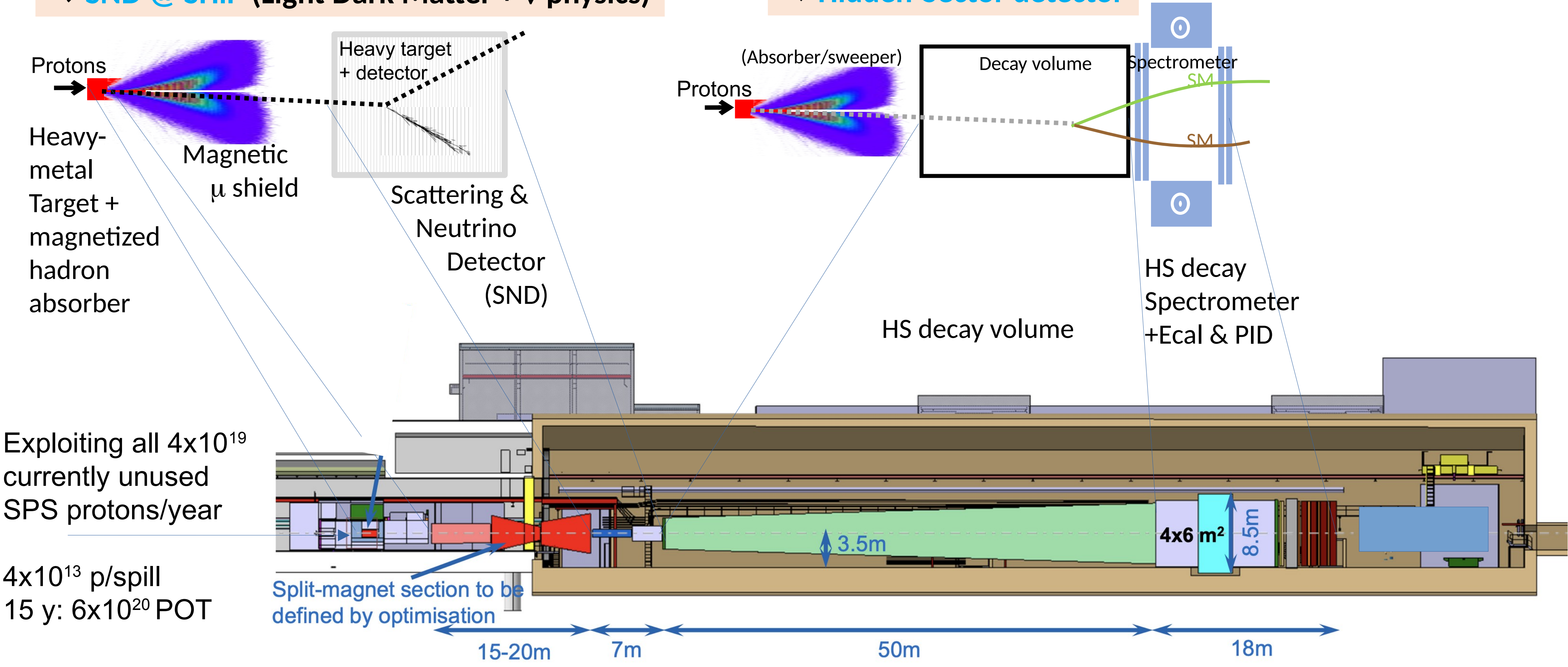
Complementarity of Collider and Beam-dump experiments



BDF/SHiP @ ECN3: dual-platform experiment with two search techniques

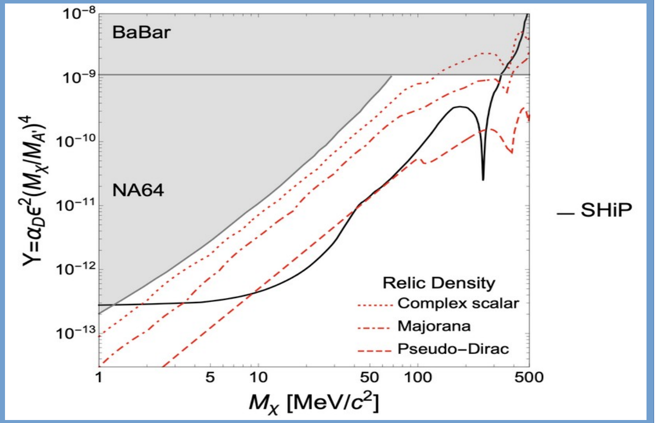
Scattering off atomic electrons (and nuclei)
→ SND @ SHiP (Light Dark Matter + ν physics)

FIP decay to SM particles
→ Hidden-Sector detector

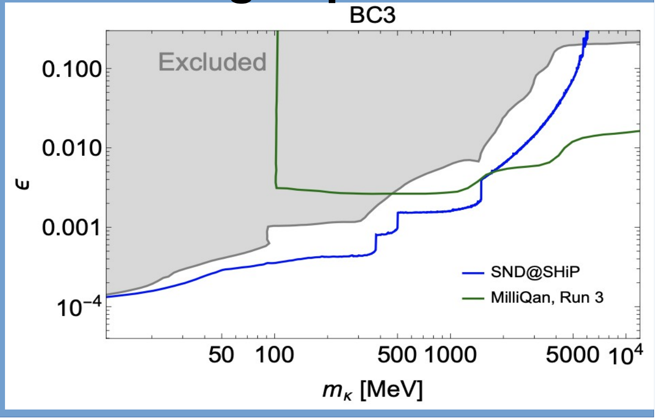


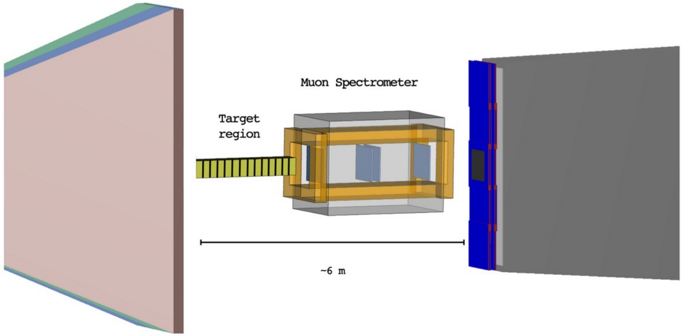
Physics with SND@SHiP

Light dark matter search:



Additional opportunities: Milli-charged particles





First high-stat. ν_τ experiment

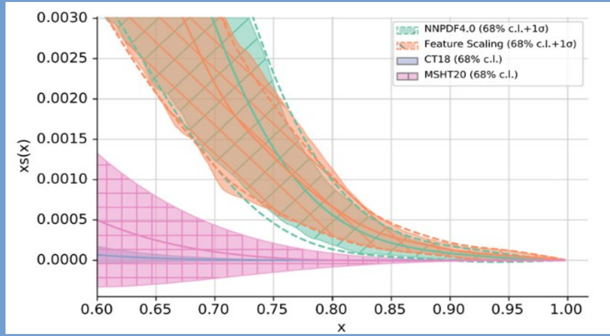
(DONUT, OPERA: 14 evts)

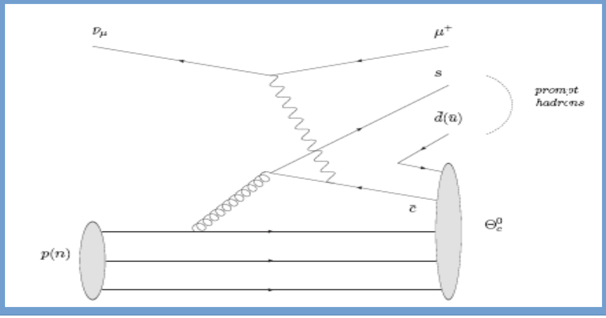
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

* 1st time: - $\nu_\tau/\overline{\nu}_\tau$ separation
  - Structure fcts $F_{4,5}$
* $\mu(\nu_\tau) < 9 \cdot 10^{-8}\ \mu_B$

CC $\nu_{\mu/e}$ interactions with charm (O(100) increase in statistics):

* (double)charm Xsections
* s-quark PDF→M_W determination
* CKM element V_{cd}
* Charmed pentaquarks

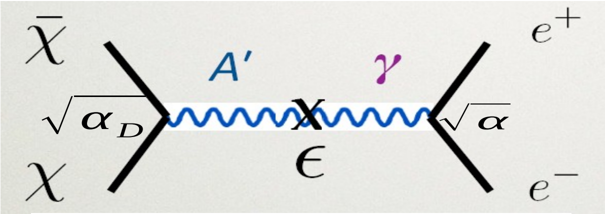




Sub-GeV Dark Matter (χ) search with SND@SHiP

Sub-GeV WIMPs require new light mediators:

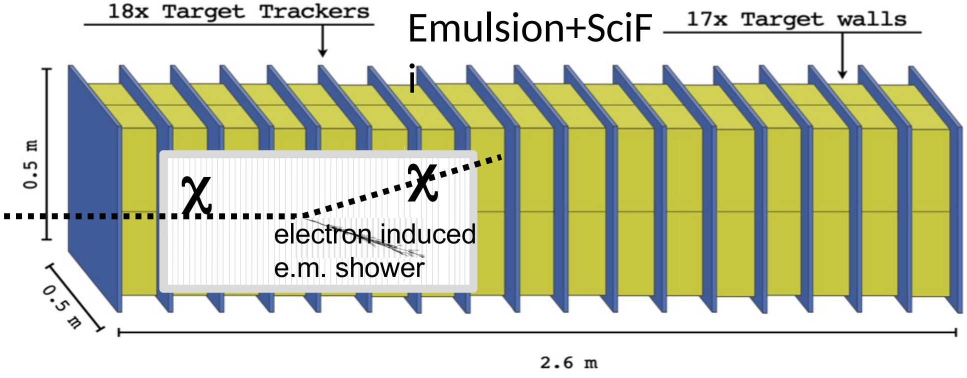
E.g.: χ coupling to SM via “dark photons” A'
from $\pi^0/\eta^{(')}\rightarrow A'\gamma$, $\omega\rightarrow A'\pi^0$ and p bremsstrahlung

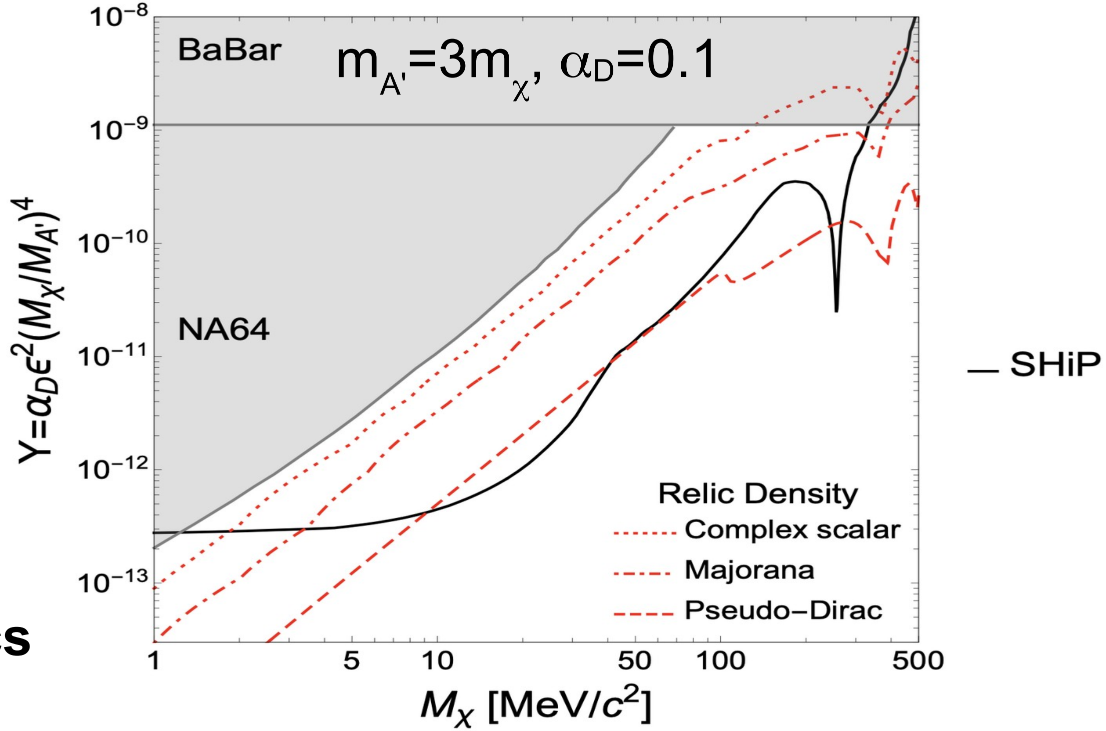


$$\sigma(\chi e^- \rightarrow \chi e^-) \simeq \frac{4\pi\alpha\alpha_D\epsilon^2}{m_{A'}^2}$$

$m_{A'}>2m_\chi$: $A' \rightarrow \chi\bar{\chi}$; detection via: $\chi+e^-\rightarrow\chi+e^-$

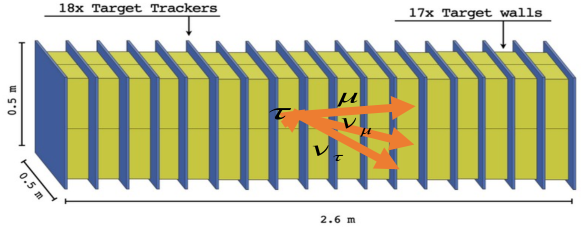
Concept as in SHiP proposal:

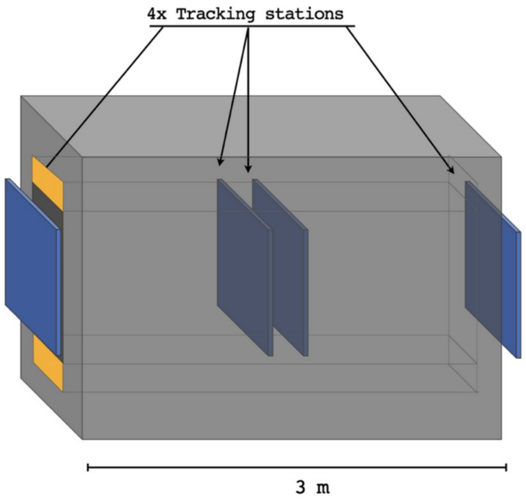


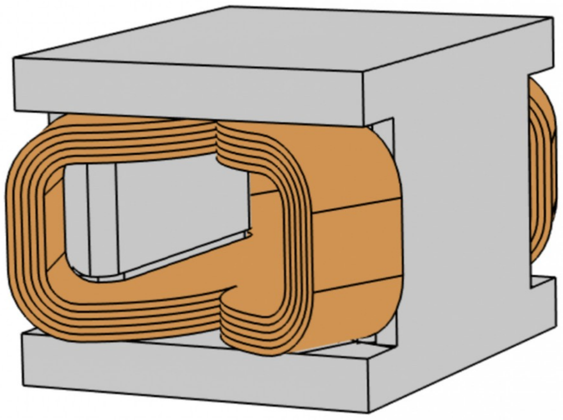


Main BG: ν elastic scattering
Suppression via scattering kinematics

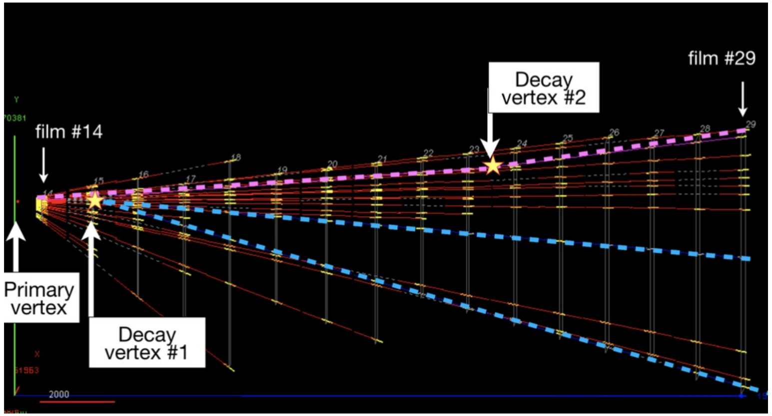
Neutrino Physics with emulsion spectrometer: original design







Testbeam measurement:
Double-charm production candidate from SPS-protons impinging on an emulsion-instrumented SHiP-like target (high-density track environment)



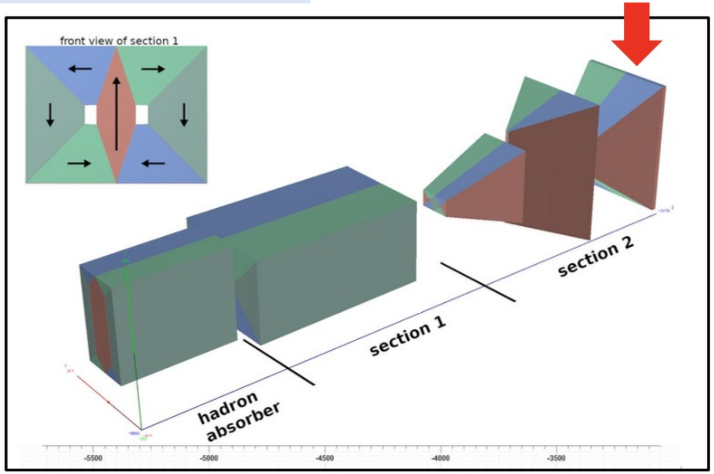
Technology in use in SND @LHC

Emulsion→τ reco from kink topology → sub-μm precision
→Track momenta from multiple scattering
SciFi→Track and, in particular, muon tagging

Muon Spectrometer → p_{μ}

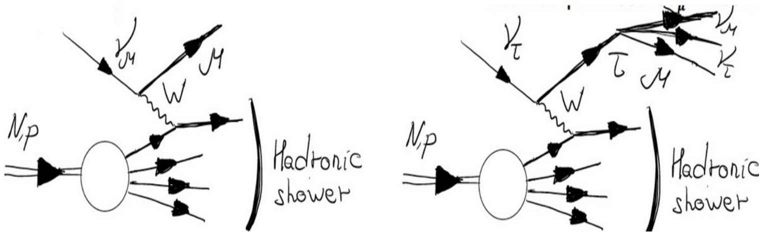
Challenges → high exchange rate of emulsions
→ high-density track environment
→ geometrical constraints (μ shield length)

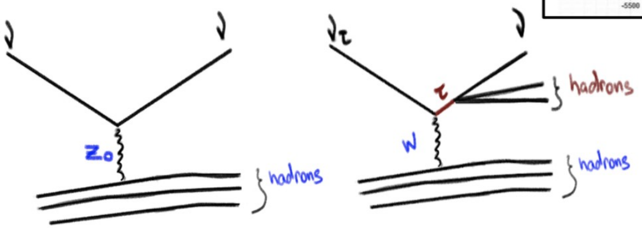
ν_τ physics with SND @SHiP: new concept



Geometrical constraints → Embed SND into μ shield
Risk to pass μ flux of 1 Hz/cm^2→ No emulsion-only detector

Electronic detectors: reconstruction of τ-kink very difficult





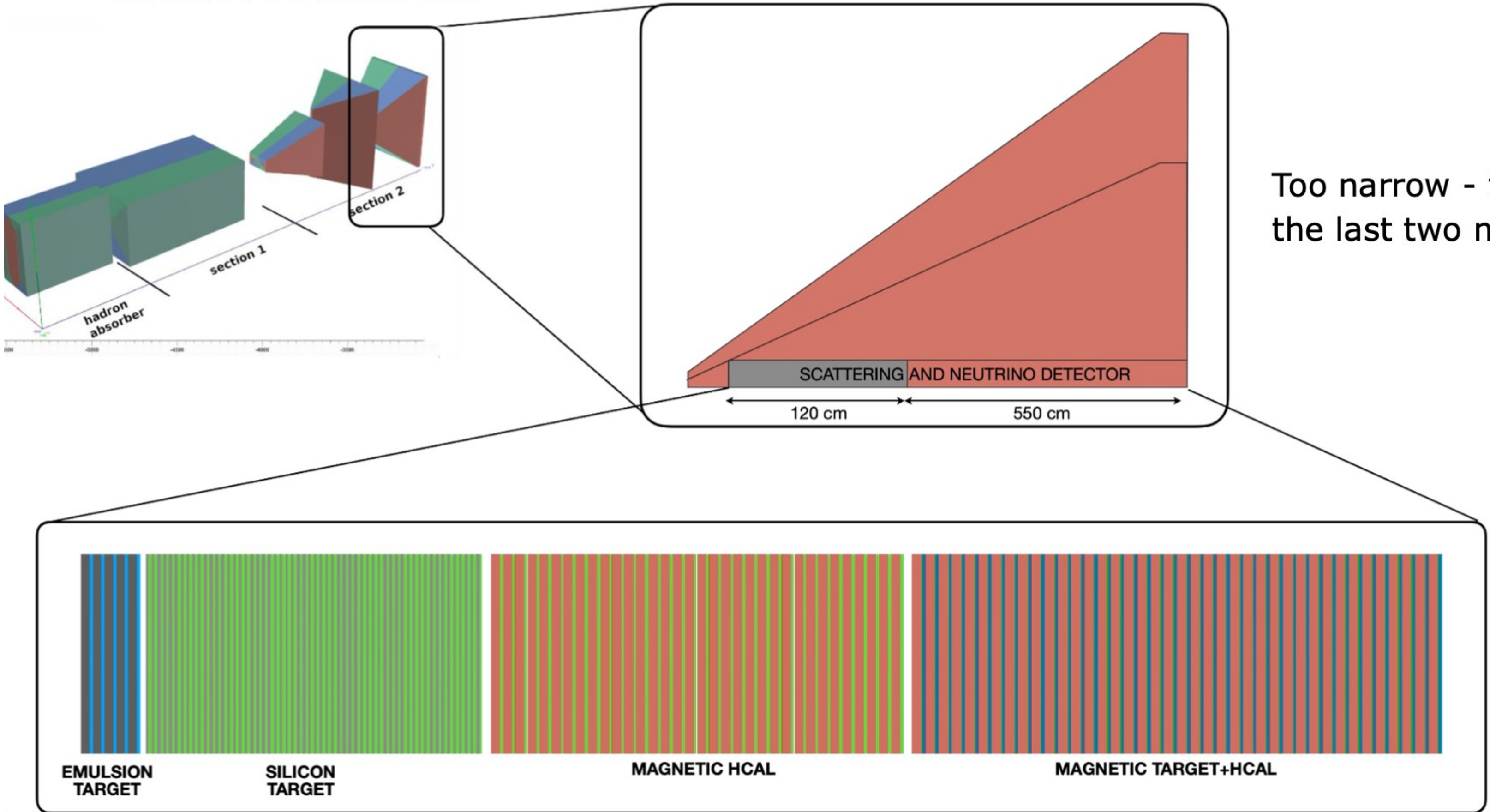
Instead: ν_τ-$\nu_{(\mu)}$ separation not event-wise but on a statistical basis using kinematics
(most promising for hadronic final state)

Detector opportunities:
→ Silicon and SciFi
→ CALICE technology for hadron calorimetry

SND LAYOUT

Current baseline for SND:

- system made of a sequence of four sub-detectors, embedded into last section(s) of the Muon Shield
- magnetized Iron of the Muon Shield used as passive material in last two sub-detectors
- centered on beam axis



Too narrow - to be shared among the last two magnet sections

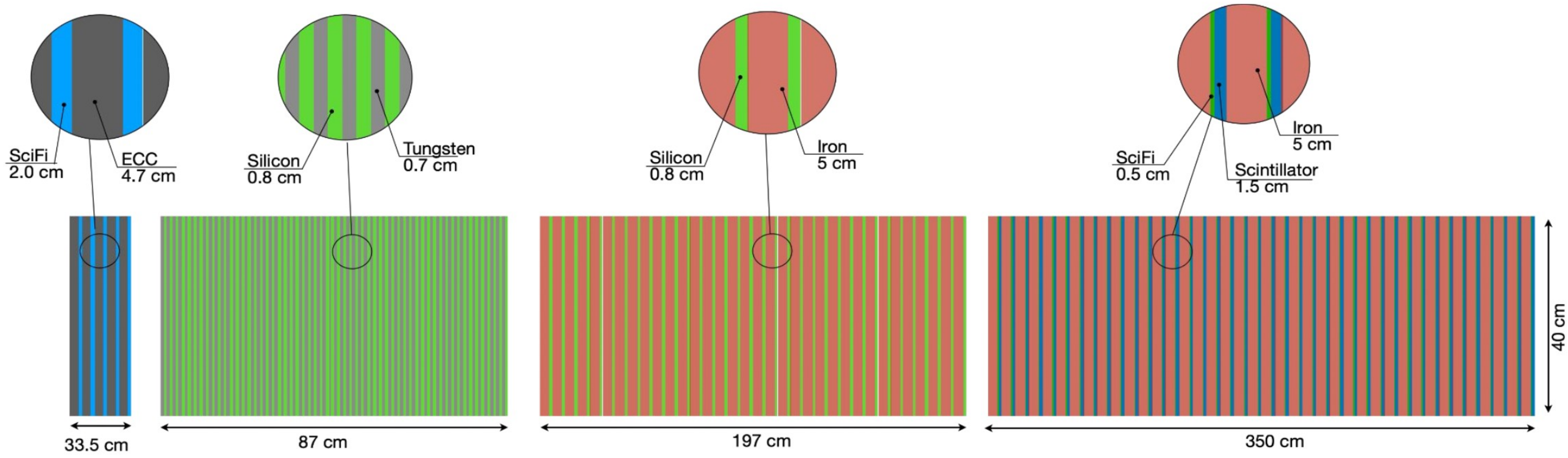
Overall detector concept

χ/ν elastic scat. off e-

μ reconstruction (from ν DIS, ν_τ vs ν_μ CC separation)

ν_τ (kink)

Hadronic shower reco. (from ν DIS, ν_τ vs ν_μ CC separation)



EMULSION TARGET			
ECC	5	Tungsten	180
		Emulsion	180
SciFi	5		

SILICON TARGET	
Tungsten	58
Silicon	58

MAGNETIC HCAL	
Iron	34
Silicon	34

MAGNETIC TARGET+HCAL	
Iron	50
Scintillator	50
SciFi	50

Common features of Hidden Sector (HS)

- tiny production branching ratios → Huge number of POT
- long-lived particles → Long decay volume
- model discrimination by final states

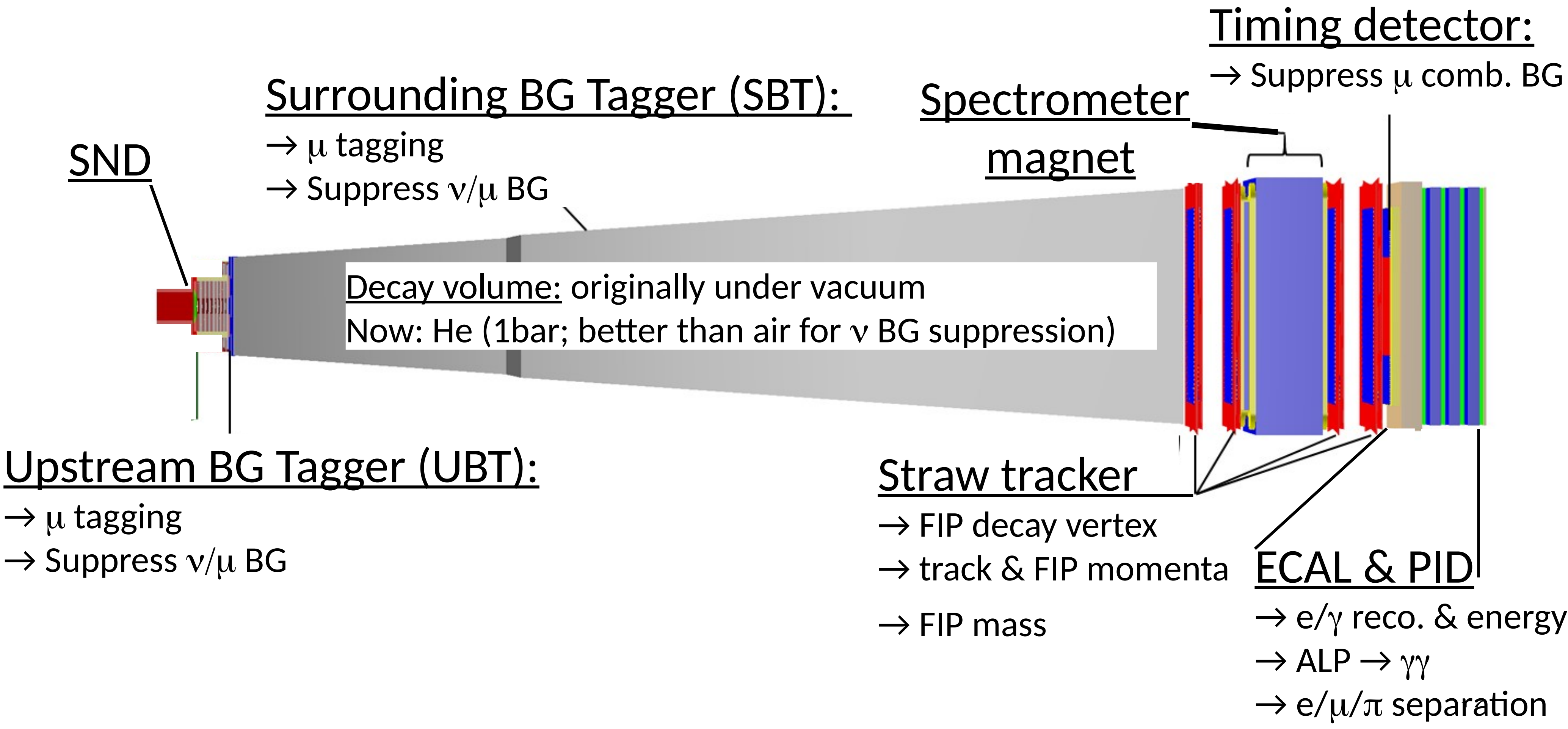
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

- in case of discovery: measurement of FIP properties
  (Ex.: mass splitting, Dirac vs Majorana nature of Heavy Neutral Leptons)

→ PID (e, γ, π, μ) of decay products + full reco. (vertex; momentum)

→ Efficient and redundant background suppression (< O(0.1 evts))

Hidden Sector detector: main components

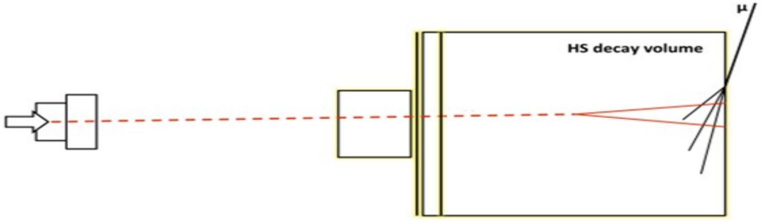


BG for decay volume under vacuum (15 y/6×10^{20} POT)

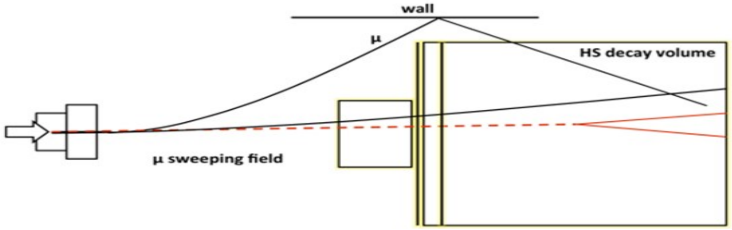
Pythia/Geant4 simulation with complete description of detector and infrastructure

- ✓ *O(10^{11}) muons (>1 GeV/c) per spill of 4x10^{13} POT → O(12 kHz) in straw tracker*
- ✓ *1.35×10^{19} (9x10^{18}) (anti-)neutrinos in acceptance*

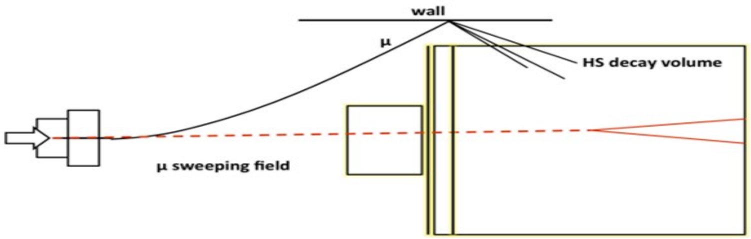
Backgrounds in decay search (fully reconstructable/partially with neutrinos) thanks to highly efficient and redundant suppression strategy:



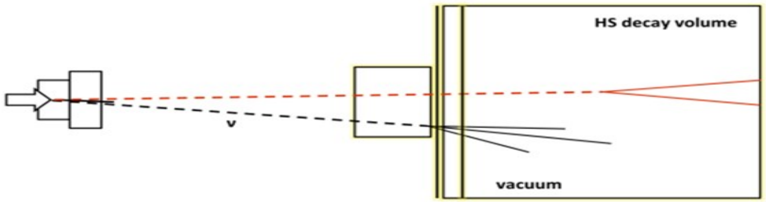
Cosmics: negligible



Muon combinatorial: (1.3 ± 2.1) x 10^{-3}



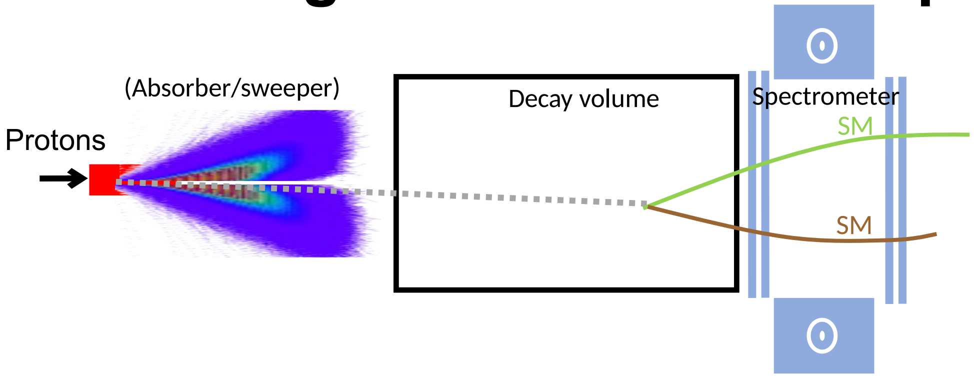
Muon DIS: < 5 10^{-3} (fully) / <0.2 (partially)

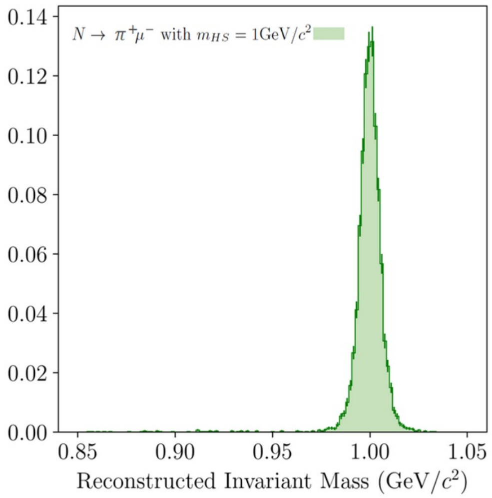


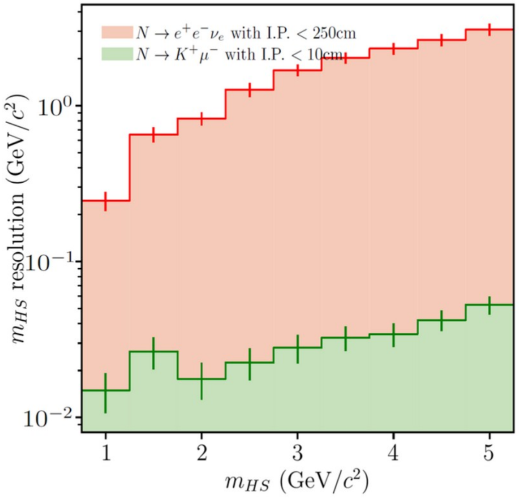
Neutrino DIS: <0.1 (fully) / <0.3 (partially)

→ Background for He-filled decay volume under study

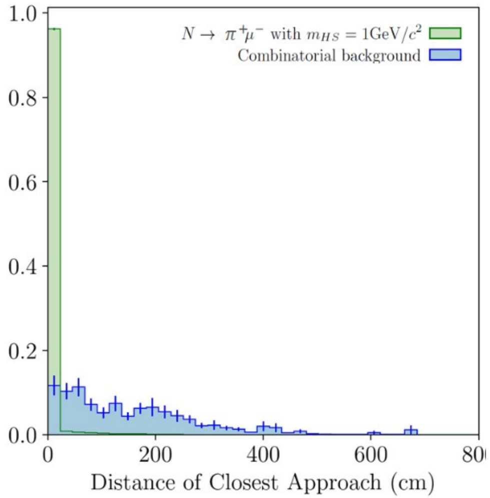
FIP signal reconstruction performance with the straw tracker

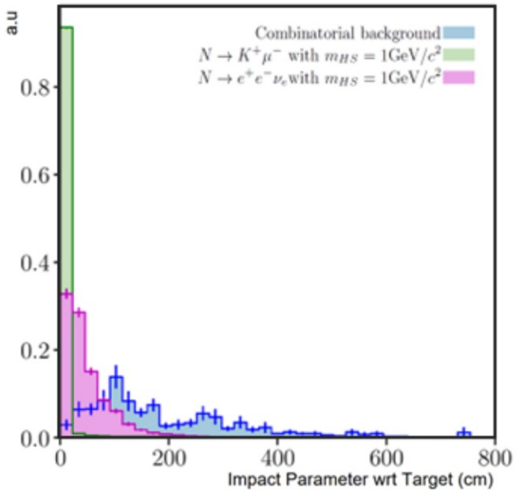


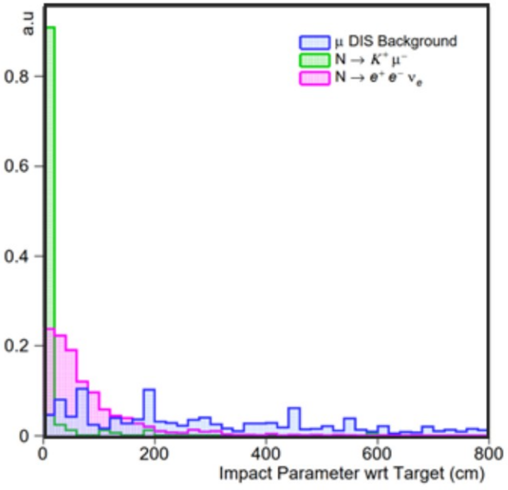


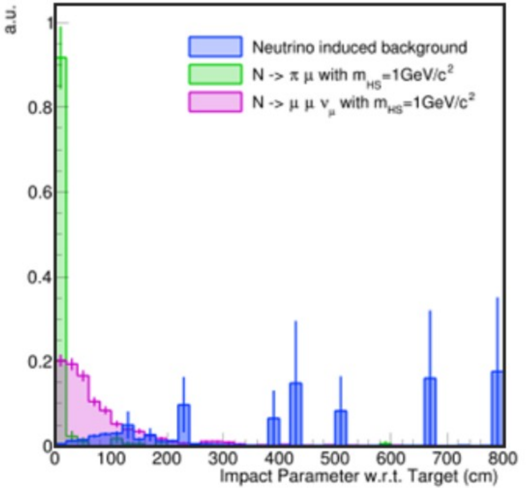


Criterion	Requirement
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	< 1 cm
Track pair vertex position in decay volume	> 5 cm from inner wall
	> 100 cm from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	< 10 cm
Impact parameter w.r.t. target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



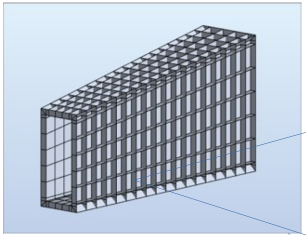


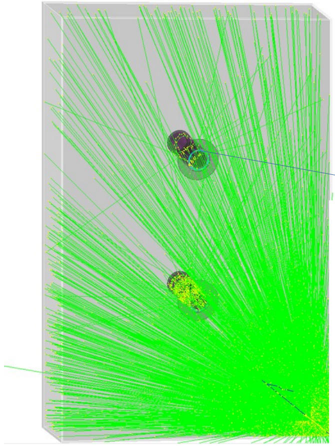


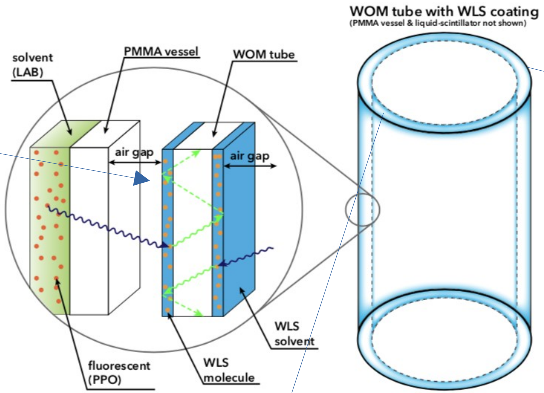


Surrounding Background Tagger (SBT)

✓ High hermiticity → Reduction of μ combinatorial + μ/ν DIS BG down to negligible level



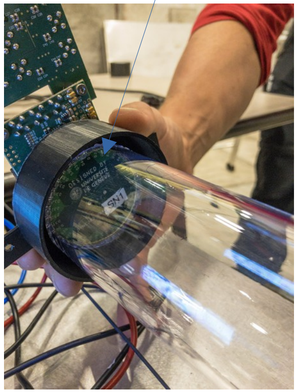




Double-wall PMMA vessel housing the WOM tube

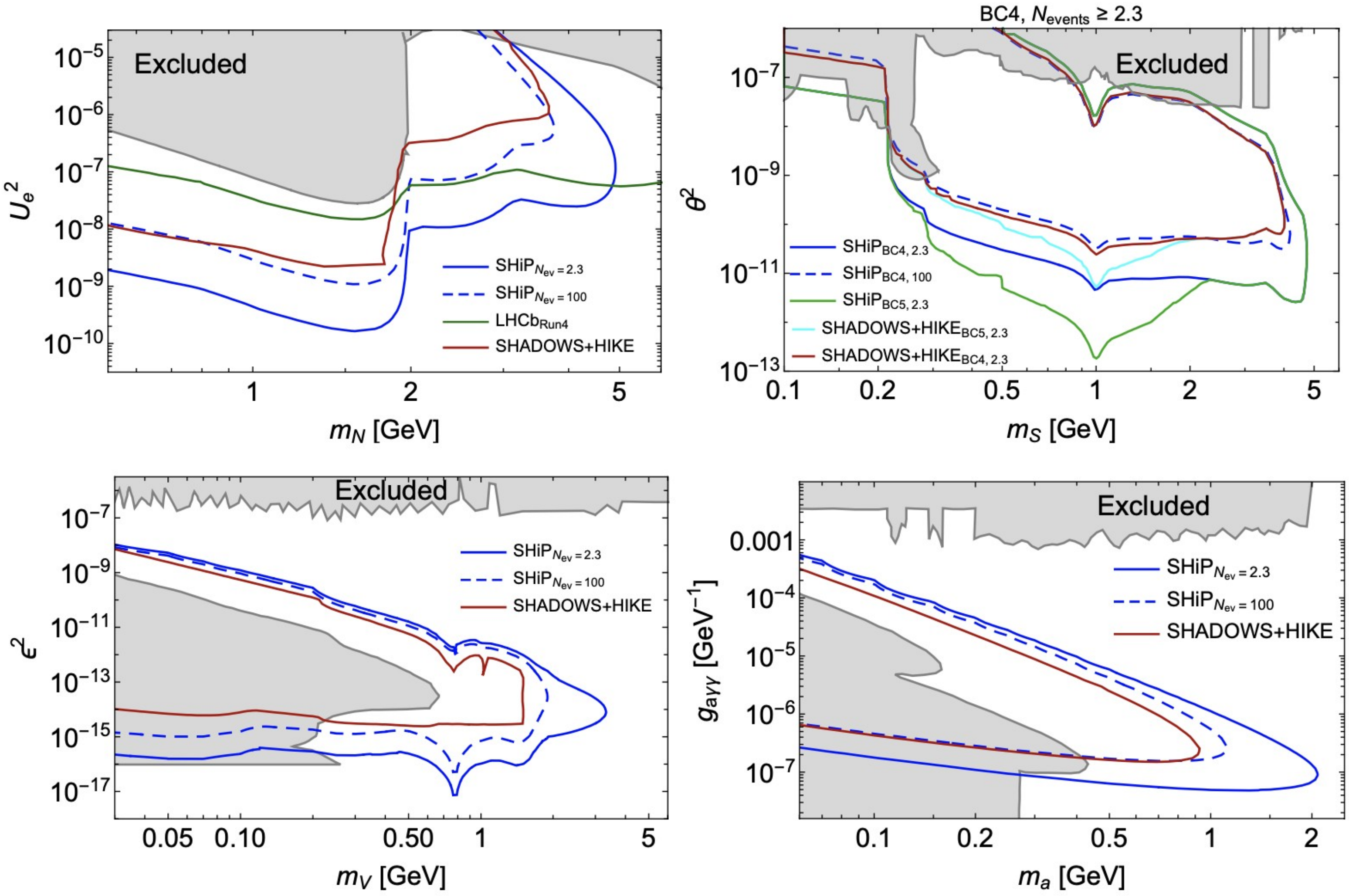
Wavelength-Shifting Optical Module (WOM):
WLS-coated PMMA tube
→ collecting UV photons
→ light-guide to photodetectors via total reflection

(Technology first proposed for IceCube Upgrade)



40 SiPMs
in 8 groups
a 5 SiPMs

Summary: FIP Search Sensitivity



Status of the project and Timeline

10/2013: Expression of interest

12/2014: Foundation of SHiP collaboration

Many Ups and Downs

11/2022: SHiP @ ECN3 proposal

03/2024: CERN RB decides in favour of SHiP to go for TDR

06/2024: CERN Medium Term Plan (MTP) 2025 →O(64) MCHF for BDF @ECN3

09/2024: “Experiment under Study”
→ “Experiment in the SPS research programme“: SHiP = NA67

2027: TDRs

2032/33: First Data Taking

→ Interested groups are highly welcome to board our SHiP!