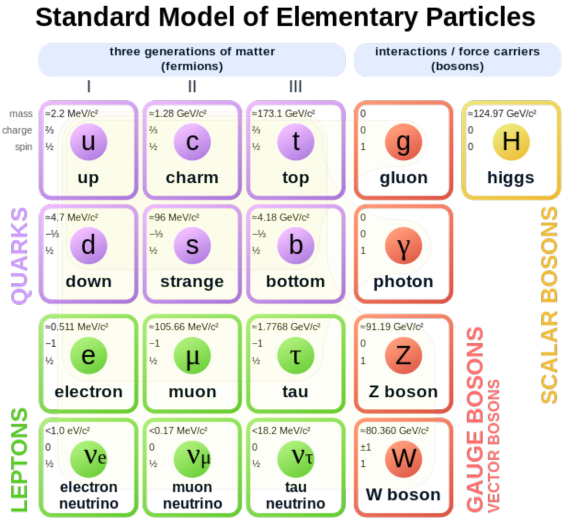
Neutrino activities at CERN

Alexey Boyarsky
NuFact 2024

September 20, 2024

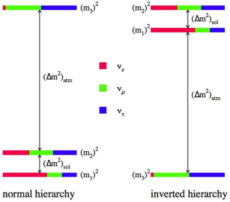
Beyond the Standard Model



Still missing:

Dark matter

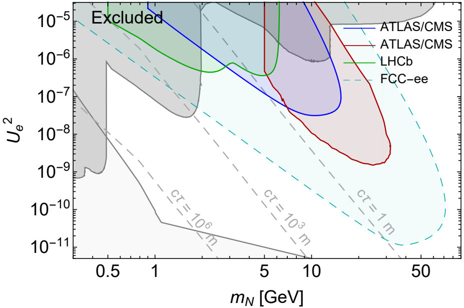
Baryon asymmetry

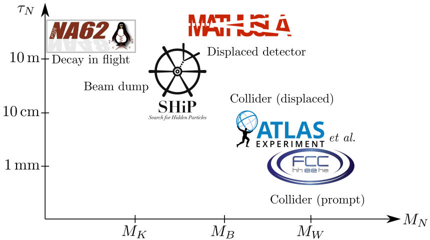


Neutrino masses

New physics

– *Neutrino oscillations — indication of* ***new physics.***

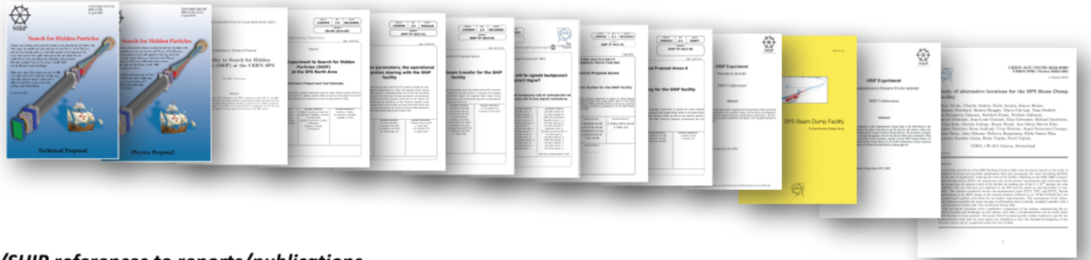




- LHC during high luminosity phase and FCC will collect large integrated luminosity — can probe light new physics below ~ 100 GeV
- LHC/FCC are not suitable for probing NP at the **GeV** scale because of large decay length $\sim 1/m^n \times \langle E_{\rm NP}\rangle/m$ ($n = 1-5$ depending on the model)

SHiP I

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



BDF/SHIP references to reports/publications

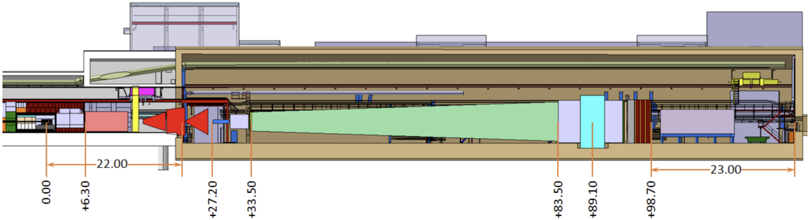
- *17 submitted to SPSC and ESPPSU2020*
- *26 on the facility development*
- *37 on the detector development*
- *11 on physics studies*
- *20 on theory developments dedicated to SHiP*
- *20 PhD thesis, a few more in pipeline*

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 II

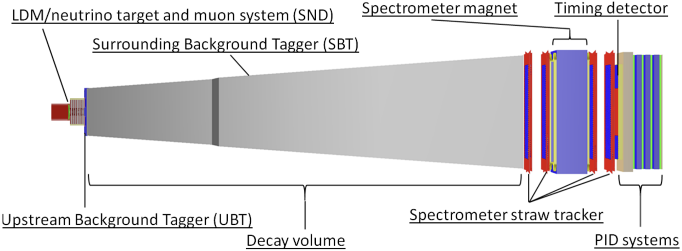


- The SHiP experiment: a beam dump experiment with huge intensity $N_{\mathrm{PoT}} = 6 \cdot 10^{20}$
- Contains Scattering and Neutrino Detector (SND) and Hidden Sector Decay Spectrometer (HSDS)
- Both are important for neutrino physics

New physics at SHiP I

HSDS:

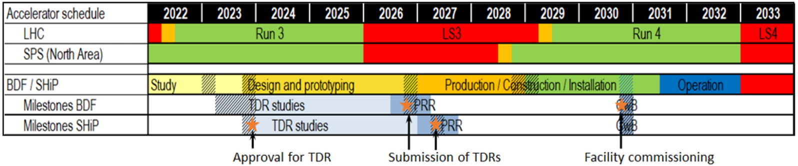
- Large $50 \times 5 \times 10$ m^3 on-axis decay volume: optimal placement to maximize the event yield with new physics



- PID: EM calorimeter, magnetized spectrometer — sensitivity to many new particles
- Background is reduced to a negligible level

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

New physics at SHiP II



Accelerator schedule: 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033

LHC: Run 3 | LS3 | Run 4 | LS4

SPS (North Area)

BDF / SHiP: Study | Design and prototyping | Production / Construction / Installation | Operation

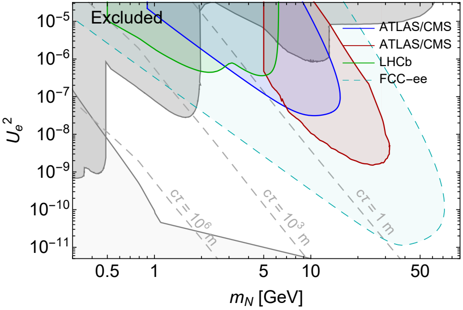
Milestones BDF: TDR studies | PRR | CwB

Milestones SHiP: TDR studies | PRR | CwB

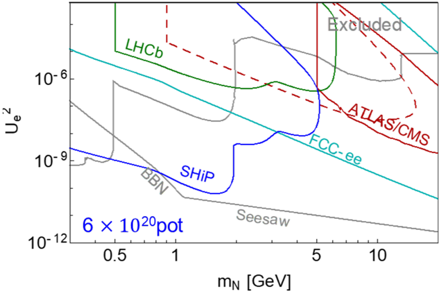
Approval for TDR

Submission of TDRs

Facility commissioning

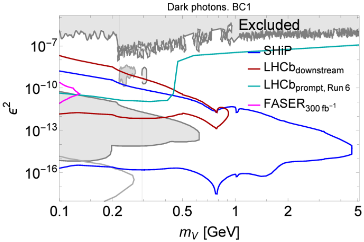


$\Longrightarrow$

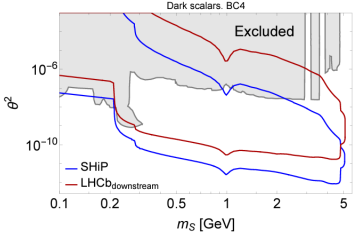


– HDSC will explore the parameter space of **new physics** by orders of magnitude

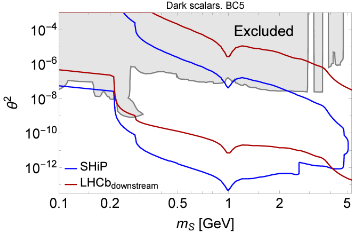
New physics at SHiP III

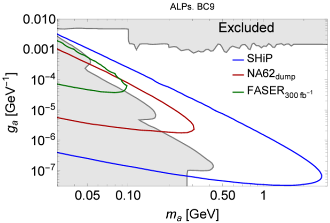

Dark photons. BC1

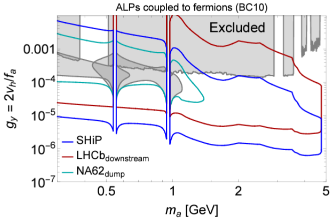
BC 4


Dark scalars. BC4

BC 5


Dark scalars. BC5

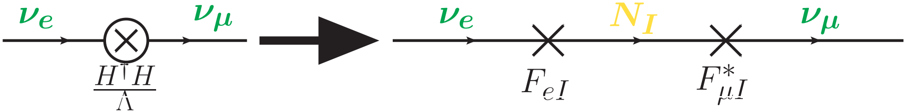

ALPs. BC9


ALPs coupled to fermions (BC10)

– HDSC will explore the parameter space of **new physics** by orders of magnitude

Example: Neutrino Portal and BSM problems. I

- Neutrino oscillation can be described by an effective dimension-5 operator (Weinberg operator). ⇒ new particles (e.g. HNL) are needed:

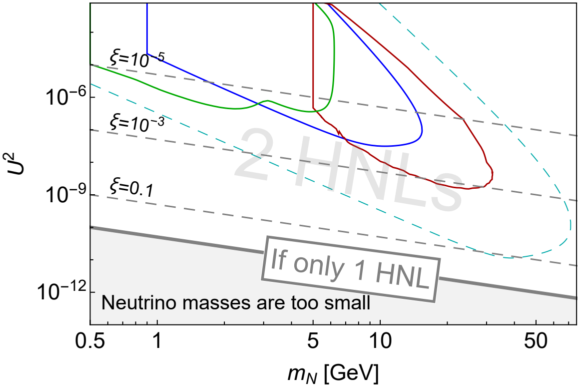


- Naïvely, to explain neutrino oscillations, HNL should interact with SM through **tiny** mixing angles $U_\alpha \sim F_\alpha / M_N$ of order

$$U^2_{\text{seesaw}} \equiv \frac{\sqrt{\Delta m^2_{\text{atm}}}}{M_N} = 5 \cdot 10^{-11} \frac{1\ \text{GeV}}{M_N} \tag{1}$$

- But we need at least **two HNLs**: much larger coupling $U^2 \gg U^2_{\text{seesaw}}$ if HNLs have approximate symmetry

Example: Neutrino Portal and BSM problems. II

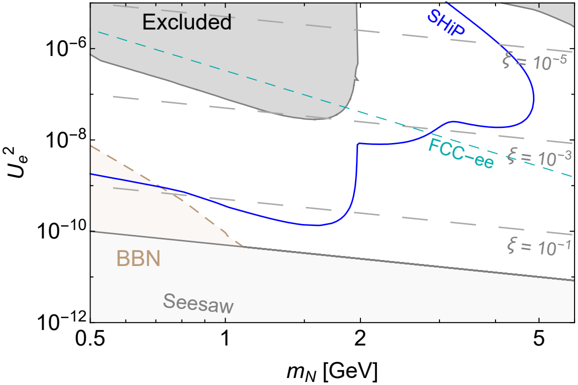


To quantify how fine-tuned such HNLs are, one can define the ξ-parameter

$$\xi = \frac{\sqrt{\Delta m^2_{\text{atm}}}}{M_i U_i^2} = \frac{U^2_{\text{seesaw}}}{U^2} \tag{2}$$

Accelerator experiments do not have enough sensitivity to cover so small mixing angles for light.

Example: Neutrino Portal and BSM problems. III

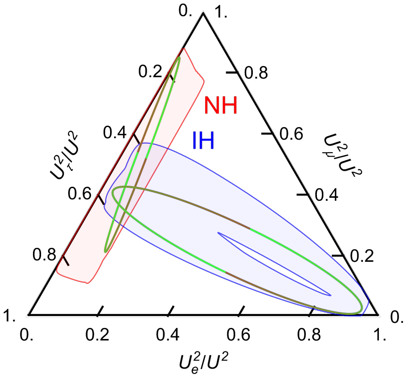


SHiP would allow us to probe many orders of magnitude larger ξ than the past experiments, approaching the most interesting part of the parameter space!

If we found an HNL-like signal with $\xi \ll 1$, *can we reveal neutrino nature?*

Neutrino masses from **two HNLs**

- Neutrino masses can be explained with **only two** HNLs.
- In symmetric regime ($\xi \ll 1$), the seesaw relation limits the possible ratios $U_e^2 : U_\mu^2 : U_\tau^2$
- Model: arbitrary total U^2 and mixing ratios $x_\alpha = U_\alpha^2/U^2$



$\longrightarrow$

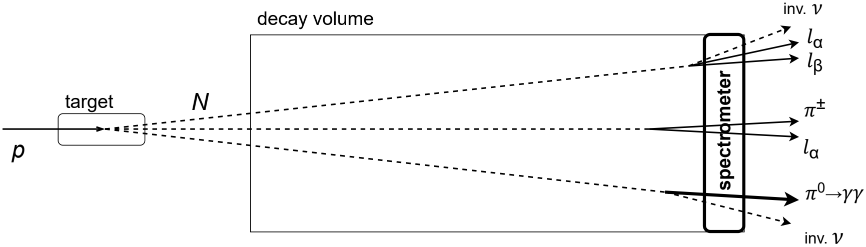
Measure mixing ratios

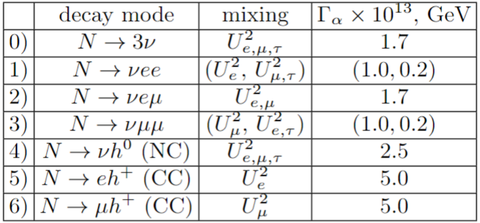
x_α

$\downarrow$

Test two HNLs
hypothesis

Measure relevant branching ratios I



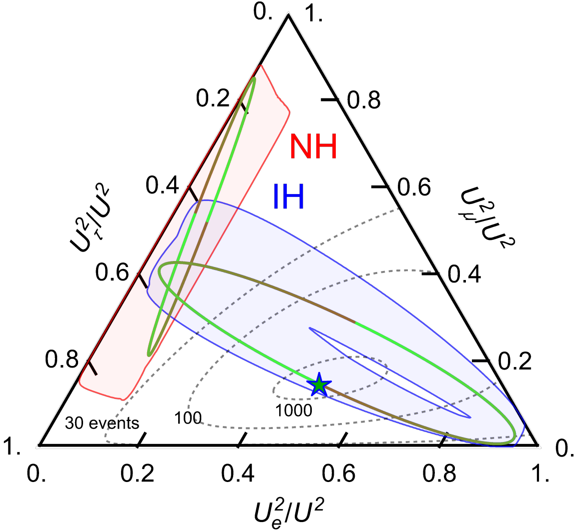


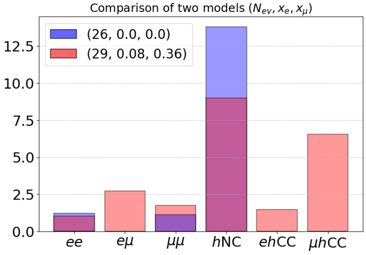
	decay mode	mixing	$\Gamma_\alpha \times 10^{13}$, GeV
0)	$N \to 3\nu$	$U^2_{e,\mu,\tau}$	1.7
1)	$N \to \nu e e$	$(U^2_e,\, U^2_{\mu,\tau})$	$(1.0, 0.2)$
2)	$N \to \nu e \mu$	$U^2_{e,\mu}$	1.7
3)	$N \to \nu \mu \mu$	$(U^2_\mu,\, U^2_{e,\tau})$	$(1.0, 0.2)$
4)	$N \to \nu h^0$ (NC)	$U^2_{e,\mu,\tau}$	2.5
5)	$N \to e h^+$ (CC)	U^2_e	5.0
6)	$N \to \mu h^+$ (CC)	U^2_μ	5.0

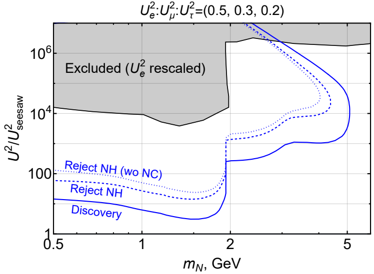
① e/μ-coupling — probed directly by $ee{+}eh/\mu\mu{+}\mu h$

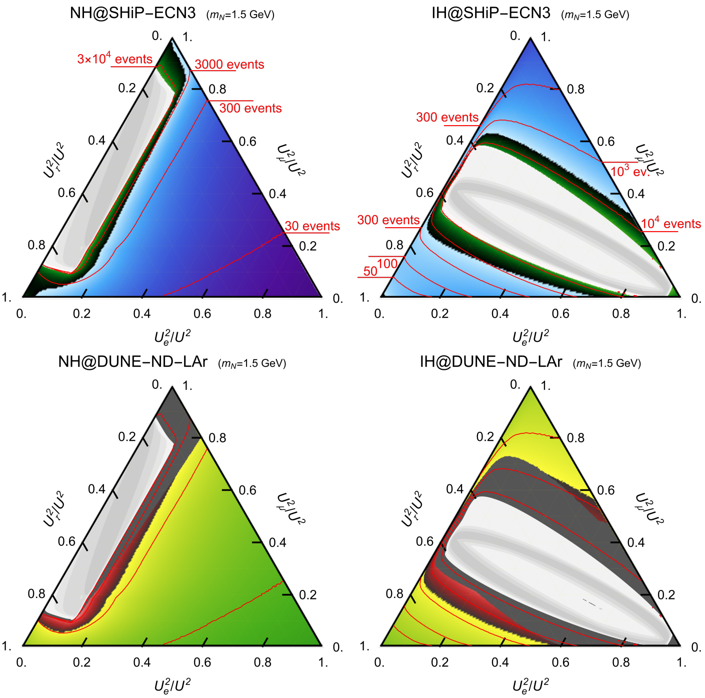
② τ-coupling — is probed *indirectly* via total normalization ($e\mu{+}h$ NC)

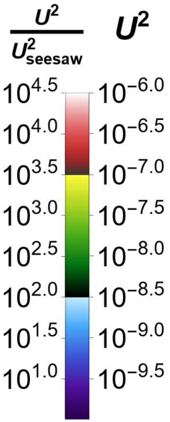
Measure relevant branching ratios II




Comparison of two models (N_{ev}, x_e, x_μ)


U_e^2:U_μ^2:U_τ^2=(0.5, 0.3, 0.2)

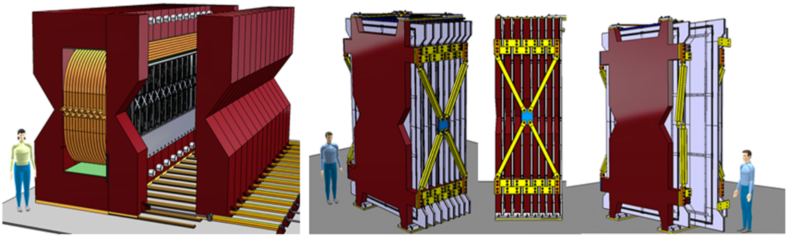


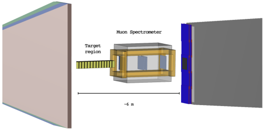


[2312.00659]

[2312.05163]

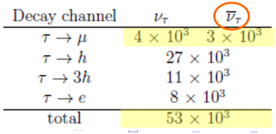
Neutrino physics: SHiP as τ-neutrino factory I





- **SND@SHiP**: emulsion-based technology (in current setup, electronic readout studies in progress)
- **Huge sample of tau neutrinos available at BDF/SHIP via $D_s \to \tau\nu_\tau$**

proposal



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	

Neutrino physics: SHiP as τ-neutrino factory II

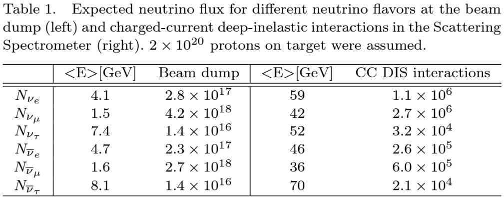
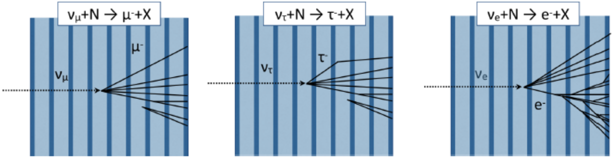


Table 1. Expected neutrino flux for different neutrino flavors at the beam dump (left) and charged-current deep-inelastic interactions in the Scattering Spectrometer (right). 2×10^{20} protons on target were assumed.

	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	4.1	2.8×10^{17}	59	1.1×10^{6}
N_{ν_μ}	1.5	4.2×10^{18}	42	2.7×10^{6}
N_{ν_τ}	7.4	1.4×10^{16}	52	3.2×10^{4}
$N_{\overline{\nu}_e}$	4.7	2.3×10^{17}	46	2.6×10^{5}
$N_{\overline{\nu}_\mu}$	1.6	2.7×10^{18}	36	6.0×10^{5}
$N_{\overline{\nu}_\tau}$	8.1	1.4×10^{16}	70	2.1×10^{4}



Rich neutrino physics

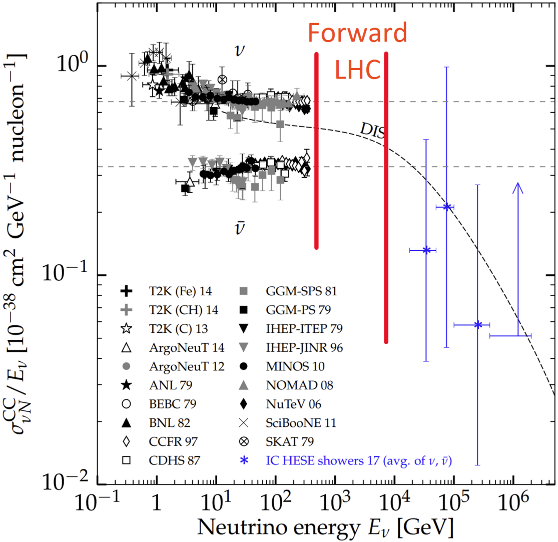
1. *LFU in neutrino interactions*: $\sigma_{\text{stat+sys}} \sim 3\%$ accuracy in ratios: ν_e/ν_μ, ν_e/ν_τ, ν_μ/ν_τ
2. *DIS cross-section* from $E_\nu \lesssim 10\,\text{GeV}$ (input to DUNE) to $\sim 100\,\text{GeV}$
3. *Measuring structure functions* F_4, F_5 (only accessible with tau neutrinos)

[C.Albright and C.Jarlskog, NP B84 (1975)]

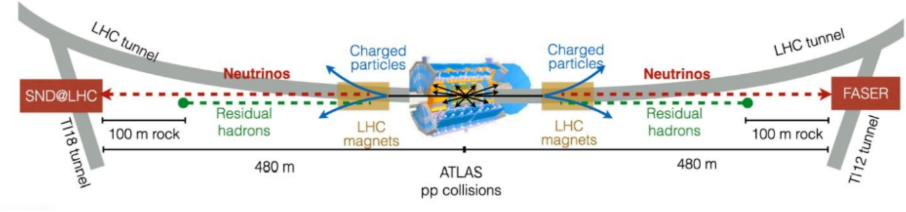
– *SND@SHiP technology is currently tested at LHC*

Forward LHC experiments I

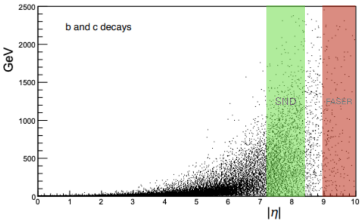
- Forward LHC experiments: fill the gap in the unprobed neutrino energy range $E_\nu = 400$ GeV – 10 TeV
- Two experiments:
  - SND@LHC
  - FASERν
- Both use the emulsion detector technology



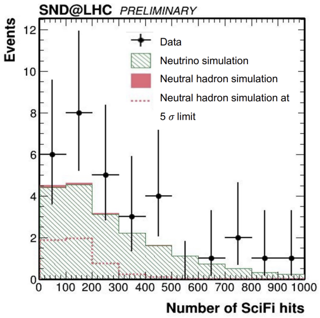
Forward LHC experiments II

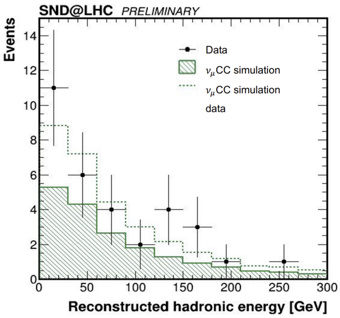


- SND@LHC and FASERν: located in the opposite directions relative to ATLAS IP
- Complementary η coverage: SND@LHC covers $7.2 < \eta < 8.4$, FASERν $\eta > 8.8$



Forward LHC experiments III



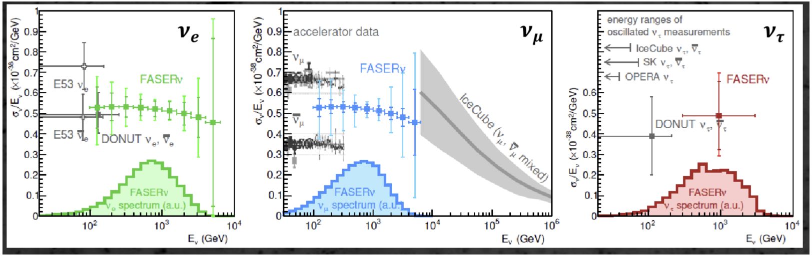


Credits: R. Biswas, ICHEP

Collected data at SND@LHC:

- 32 observed ν_μ events for the signal estimate from simulation $19 \pm 4(\text{syst}) \pm 4(\text{stat})$
- 6 observed ν_e events (0μ) with the signal simulation estimate of 4.9 events
- 3 observed 3μ events (muon trident interactions)

Forward LHC experiments IV



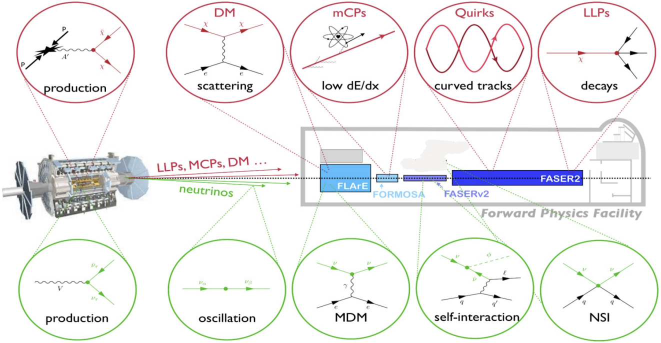
Credits: *S. Dmitrievsky, ICHEP*

Collected data at FASERν:

- First ever observation of ν_e at the LHC Phys.Rev.Lett.133.021802 (2024)
- 4 ν_e and 8 ν_μ CC events observed
- 153^{+12}_{-13} neutrino scattering observed using the main FASER detector

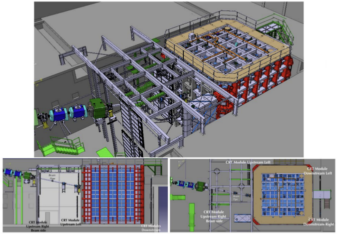
Forward Physics Facility

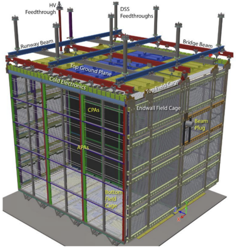
- **Forward Physics Facility**: a set of experiments that would explore various scenarios with new physics at HL-LHC
- Includes upgraded **FASERν2** and **AdvSND**.
- Problems with emulsion due to high muon flux $\Rightarrow$ rely on electronic detectors



Credits: *A. Barr, ICHEP*

ProtoDUNE





Credits: J. Shi, ICHEP

- ProtoDUNE: full-scale prototype of DUNE. LAr TPC technology allows low detection thresholds
- Two detectors were constructed and installed in the CERN Neutrino Platform at the end of EHN1: NP02 (**ProtoDUNE-VD**) and NP04 (**ProtoDUNE-SP/ProtoDUNE-HD**)

Current and future neutrino experiments at CERN

- **ProtoDUNE** (2018-)
  Test of the prototype detector for the DUNE experiment
- **FASERν** & **SND@LHC** (2022-)

Study neutrino interactions at TeV energies and meson production in far-forward direction. Different technology and focus on bottom/charm hadrons

Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7	134	790	7.6
DPMJET	DPMJET	3457	7088	97	395	1034	18.6
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2	267	1123	11.5
QGSJET	Pythia8 (Soft)	970	5351	16.1	185	1015	7.2
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$	245^{+149}_{-111}	991^{+132}_{-200}	$11.3^{+7.3}_{-4.0}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$	195^{+71}_{-61}	976^{+146}_{-185}	$8.8^{+2.7}_{-1.5}$

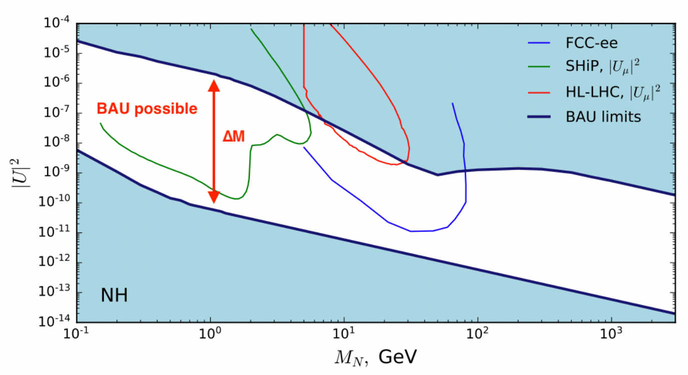
[2105.08270]

- **SHiP** (2030+)
  Study τ (anti)neutrinos + search for new physics
- **FASERν2** & **AdvSND** (proposal, HL-LHC) Successors to the current detectors, with ×100 more statistics

Backup

Probing baryon asymmetry of the Universe

- Same HNLs that are responsible for neutrino oscillations can generate *baryon asymmetry of the Universe*
- Baryon asymmetry also demands *at least* 2 HNLs with *almost degenerate masses*: $\Delta M = |M_1 - M_2| \ll M_1, M_2$ and have the same mixing angles



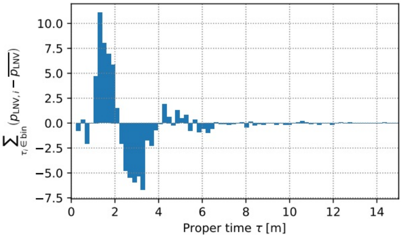
Can we understand that we observed such HNLs?

Distinguishing two HNLs?

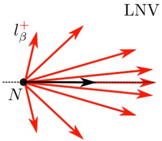
- Two HNLs with similar masses $\Rightarrow$ *HNL oscillations*
- Ratio of probability of lepton number violating (LNV) and conserving (LNC) processes:

$$\frac{P_{\text{LNV}}}{P_{\text{LNC}}} \sim \frac{1-\cos\Delta M\tau}{1+\cos\Delta M\tau} \qquad \tau \text{ – HNL proper time} \tag{3}$$

- Kinematics of LNV and LNC decays are statistically different



✓ SHiP can resolve HNL oscillations [1912.05520]
✓ Needs $\mathcal{O}(10^3)$ events – middle of the exploration region
✓ Oscillation period: $2\pi/\Delta M$



$\langle E^{(H)}_{l_\beta,\text{LNV}}\rangle \gtrsim \langle E^{(H)}_{l_\beta,\text{LNC}}\rangle$