

Searching New Physics with SHiP and Recent Results from SND@LHC

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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Strong Evidence for BSM Physics

- Neutrino masses and oscillations
- The nature of non-baryonic Dark Matter
- Excess of matter over antimatter in the Universe

- No hints for BSM physics neither from direct searches at LHC nor from flavour physics
- New physics is either too heavy or interacts very feebly, i.e. much weaker than neutrino, in order to have escaped detection
- ▷ Look for Feebly Interacting Particles (FIPs) at the intensity frontier

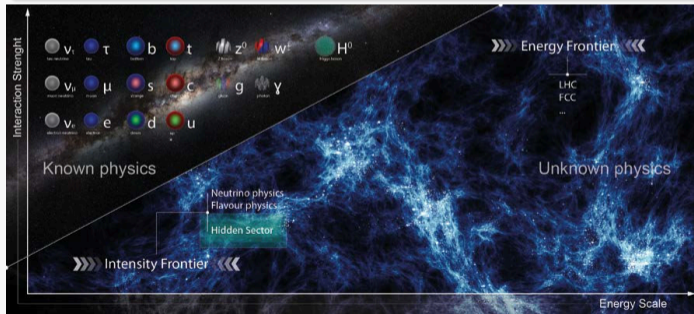


Image: CERN Courier 2/2016

- Phenomenologies of HS models share a number of unique and common physics features
 - ▷ Production through meson decays (π , K , D , B)
 - ▷ Production and decay rates are strongly suppressed relative to SM
 - Production branching ratios $\mathcal{O}(10^{-10})$
 - Long-lived objects $\mathcal{O}(\mu\text{s})$
 - Travel unperturbed through ordinary matter
 - ▷ Decay into two charged particles

Models	Final States
HNL, SUSY neutralino	$l^\pm \pi^\mp, l^\pm K^\mp, l^\pm \rho^\mp$
DP, DS, ALP (fermion coupling), SUSY sgoldstino	$l^+ l^-$
DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^+ \pi^-, K^+ K^-$
HNL, SUSY neutralino, axino	$l^+ l^- \nu$
ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0 \pi^0$

- Production of FIPs in a high intensity proton beam

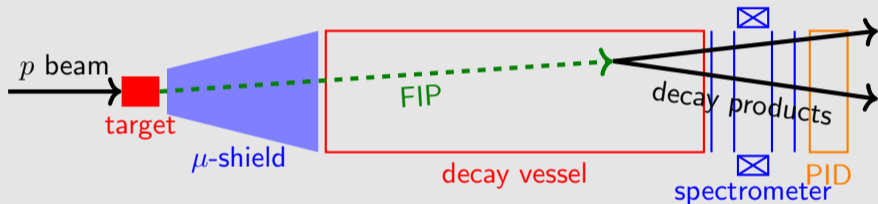
Decay of FIPs



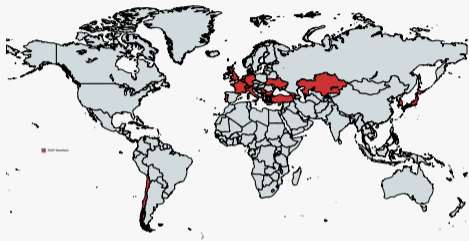
- Model independent search for Feebly Interacting Particles (FIPs)

- Production of FIPs in a high intensity proton beam

Decay of FIPs



- Large decay volume followed by spectrometer and PID
- Shielding from SM particles: hadron absorber, muon-shield and veto detectors
- Model independent search for Feebly Interacting Particles (FIPs)



- 325 scientists
- 48 institutions
- 18 countries
plus CERN and JINR



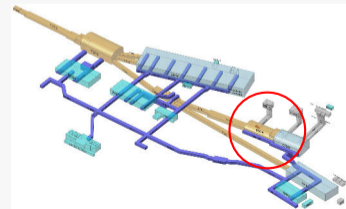
- 2013: Expression of interest for SHiP at SPS
- 2024: CERN approved construction of **High Intensity ECN3** facility
 - 64 MCHF in CERN MTP 2024
- Choice of SHiP as next experiment at ECN3 (NA67)
- TDR phase of the experiment

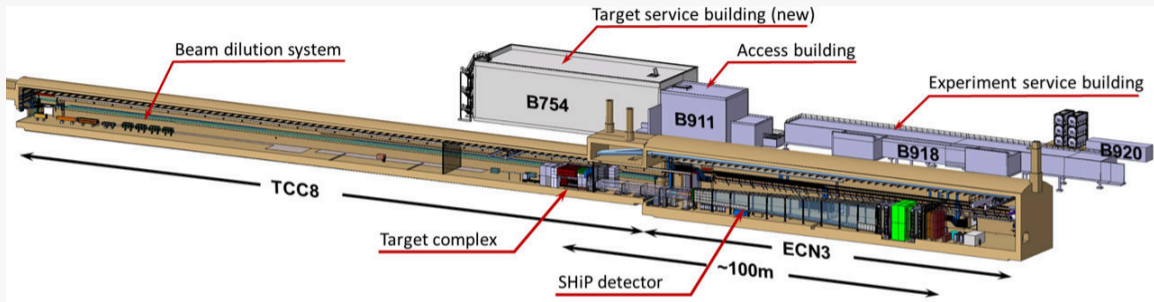
SPS

- Has been delivering $<1.5 \times 10^{19}$ protons/yr recently
- Is capable of delivering $>5 \times 10^{19}$ protons per year
- BDF: return full exploitation of available protons

SHiP at HI-ECN3

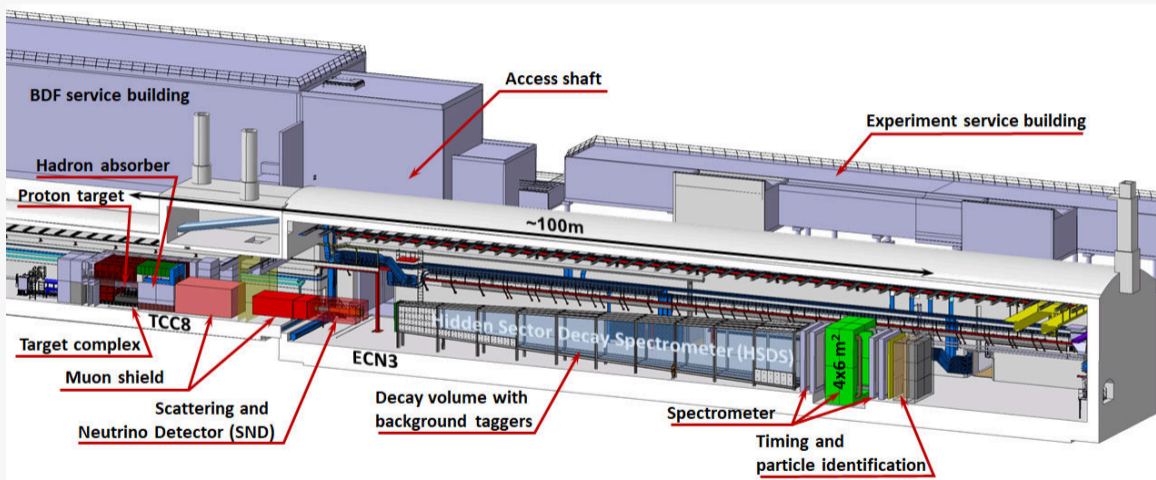
- TCC8 target hall and ECN3 experimental cavern in the north area (currently hosting NA62)
- 10^6 spills of 4×10^{13} protons per year
- 6×10^{20} PoT for SHiP in 15 years
- Slow extraction of proton spills over 1 s
 - to reduce combinatorial bg





- HI-ECN3 project run by CERN
 - Beamline and target complex
- Ground breaking in 2025
- Work side prepared for LS3





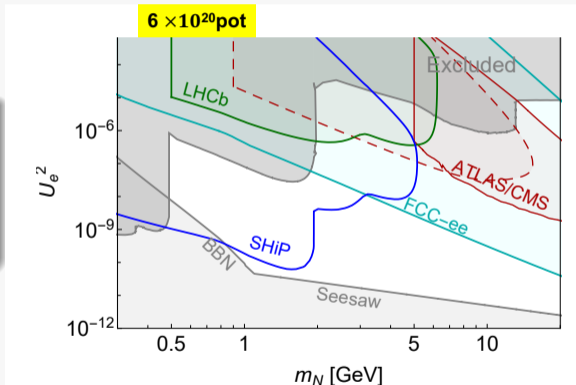
Huge R&D effort ongoing for all sub-detectors, (some) details in backup

- HI-ECN3 will cover a unique region that can only be explored by an optimized Beam Dump experiment

Each year, the target will produce:

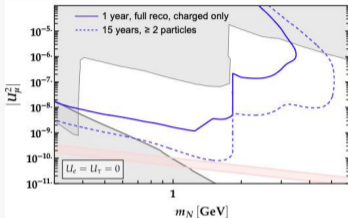
- $\simeq 10^{17}$ charmed hadrons,
 - $\simeq 10^{13}$ beauty hadrons,
 - an unprecedented sample of $\nu_\tau/\bar{\nu}_\tau$
- SPS energy and intensity provide unique **direct discovery potential**

- BDF/SHiP sensitive to a variety of models
E.g. Heavy Neutral Leptons

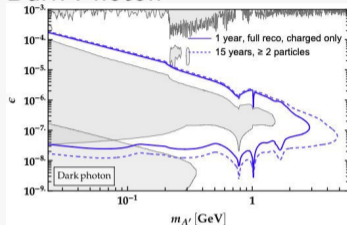


Needs to be designed as a zero-background experiment

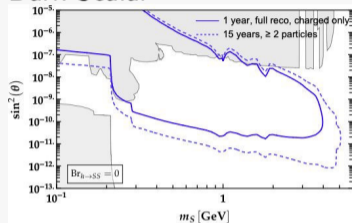
HNL



Dark Photon

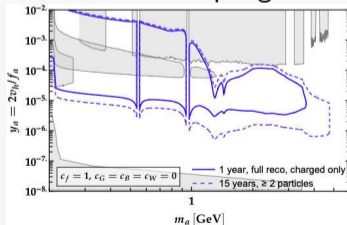


Dark Scalar

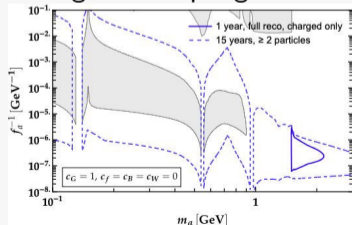


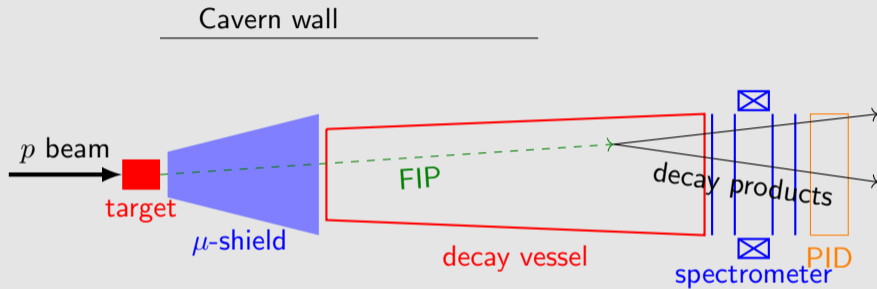
- Assuming zero background
- Only fully reconstructed charged particle final states in 1st year of operation

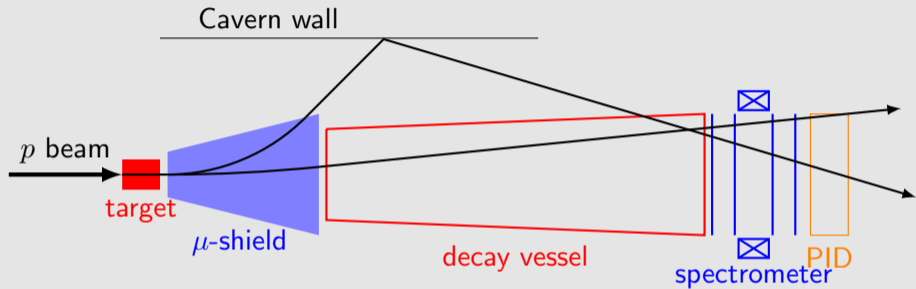
ALP fermion coupling



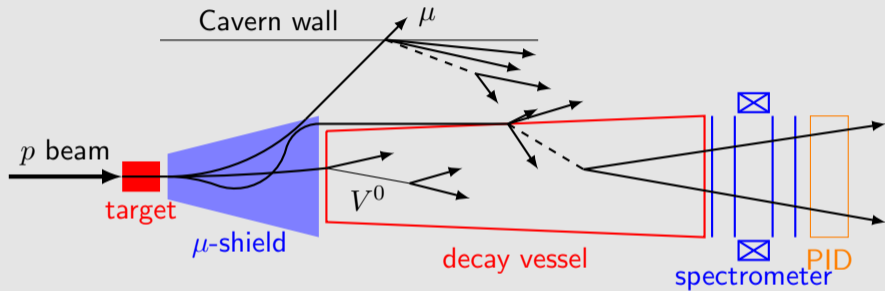
ALP gluon coupling



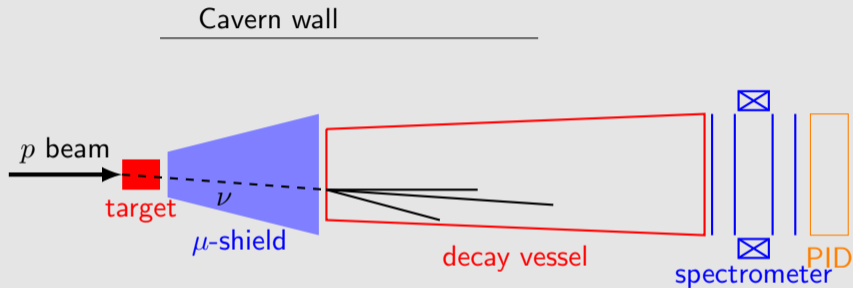




- Muon Combinatorial Background



- Muon Combinatorial Background
- Muon DIS



- Muon Combinatorial Background
- Muon DIS
- Neutrino DIS

Background estimation based on full GEANT-based MC

- Very simple and common selection for both fully and partially reconstructed events
- Model independent

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)	$< 250 \text{ cm}$

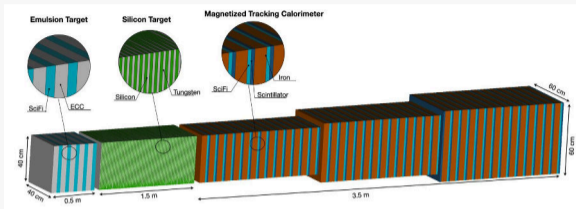
+Time coincidence +BG Tagger

Events

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	$(1.3 \pm 2.1) \times 10^{-4}$

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

- To be re-evaluated for optimized design



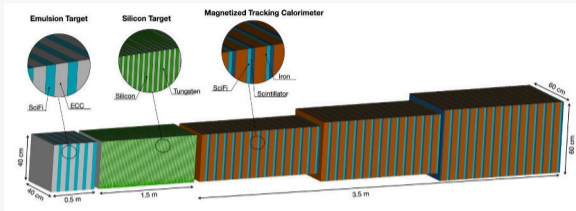
- Exploit the huge flux of neutrinos produced in the target
- Two complementary ν detector concepts
- Integration inside the muon shield

Upstream

- High-granularity calorimeter in a region free from magnetic field
- Si/W calorimeter, $O(10 \mu\text{m})$ accuracy
- Also optimal for LDM detection
- Measurement of the (mostly e.m.) energy in the ν target is essential

Downstream

- Magnetized tracking calorimeter
- Iron, interleaved with scintillating plates and SciFi trackers
 - Energy measurement
 - Tracking and momentum measurement



- Exploit the huge flux of neutrinos produced in the target
- Two complementary ν detector concepts
- Integration inside the muon shield
- Large synergies with SND@LHC

Upstream

- High-granularity calorimeter in a region free from magnetic field
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SND@SHiP

- $\mathcal{O}(10^3 - 10^5)$ neutrino interactions/year
- ▷ First observation of $\bar{\nu}_\tau$
- ▷ $\nu_\tau, \bar{\nu}_\tau$ physics with high statistics
- ▷ ν_τ magnetic moment
- ▷ F4 and F5 structure functions
- ▷ ν_e cross sections
- ▷ ν -induced charm production
- ▷ strange quark nucleon content
- ▷ LFV
- ▷ LDM via elastic scattering

SND@LHC

Neutrinos in the forward direction from IP1
Neutrino interactions

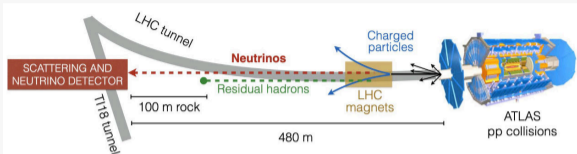
- ν cross sections in the TeV range
- Double existing data of 20 ν_τ events from DONuT and OPERA
- Test lepton flavor universality

QCD

- Probe of charm quark production in forward region

BSM physics

- Search for FIPs decaying within the detector or scattering in the target



- Located in the TI18 tunnel
- ~ 480 m away from ATLAS interaction point (IP1)
- Acceptance: $7.2 < \eta < 8.4$
- Shielded by ~ 100 m rock, LHC magnets deflect charged particles
- Study of $pp \rightarrow \nu X$ in unexplored energy range 300 GeV – few TeV
- Taking data since LHC run 3



- Recorded $\simeq 300 \text{ fb}^{-1}$ of data with 97% detector uptime

Veto

- Two (2022–2023) / three (2024–) planes of scintillating bars

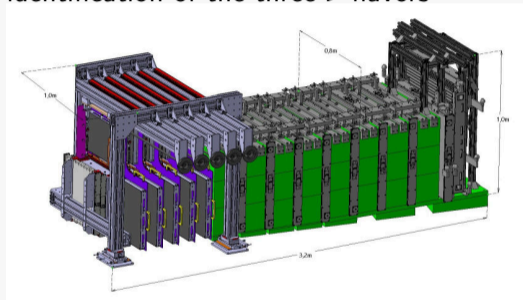
Target, vertex detector and ECAL

- Emulsion Cloud Chambers (ECC) with tungsten for ν identification
- Scintillating Fiber planes providing time and calorimetric information

Muon System and HCAL

- Plastic scintillator planes interleaved with iron walls
- Higher granularity in last 3 DS stations

Modular structure optimized for the identification of the three ν flavors

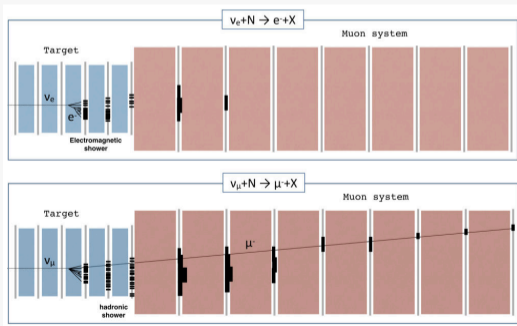


- Target mass: ~ 830 kg
 - $3\lambda_{\text{int}} (84X_0) + 10\lambda_{\text{int}}$
- JINST 19 P05067 (2024)

Two stages of reconstruction

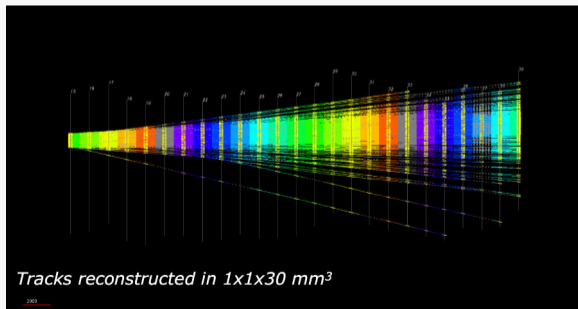
Online with electronics detectors

- Identify signal candidates
- Tag muons (muon system)
- Energy reconstruction (ECAL+HCAL)

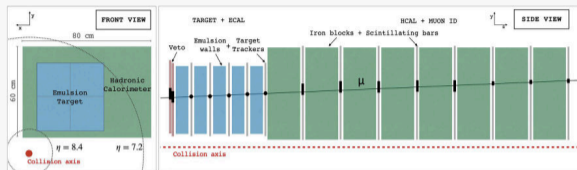


Offline with Emulsion Cloud Chambers

- Reconstruct vertices with sub-micron resolution.
- Match vertices with electronic data, get timestamp, reconstructed energy

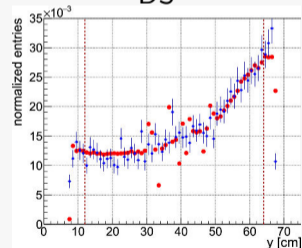
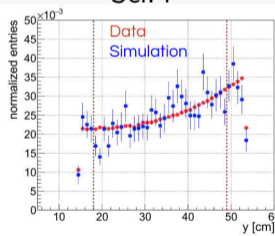


- Crucial for detector operations and physics analyses
 - Main backgrounds are muon induced
- Muon flux measured during the 2022 LHC proton run
 - Excellent agreement between subdetectors, including emulsions
 - Agreement with MC predictions within 20%



SciFi

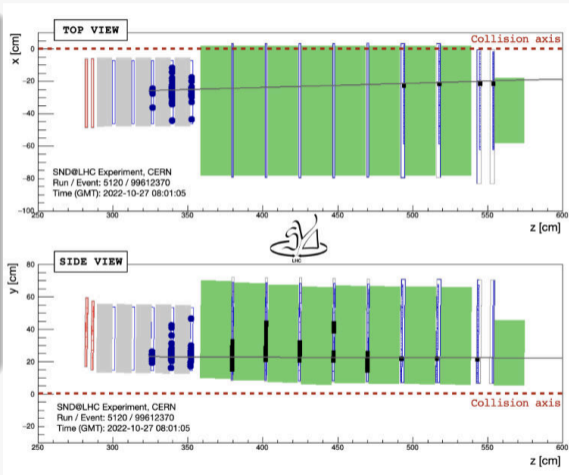
DS



Eur. Phys. J. C 84, 90 (2024)

High purity sample of ν_μ CC events

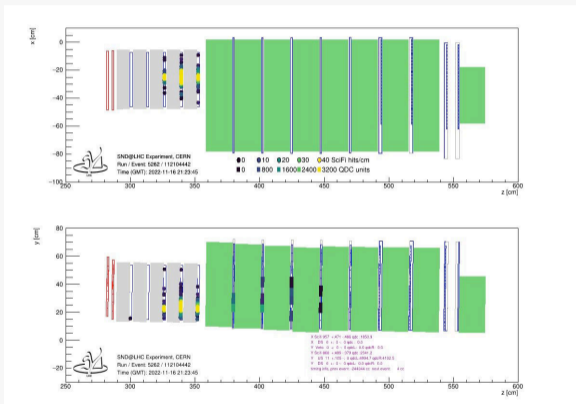
- 2022 data
 - Neutral vertex event (start in target walls 3 or 4)
 - Large hadronic activity in the SciFi and HCAL
 - Isolated outgoing muon track DS
 - Hit time consistent with event originating from IP1
-
- 8 candidate events, background 0.086, significance 6.8σ
 - Updated results with with more data and improved analysis in preparation!



Phys. Rev. Lett. 131, 031802 (2023)

- Measurement using electronic detectors, sensitive to ν_e or ν_τ CC, and NC interactions.
- First observation of non- ν_μ CC neutrino interaction using electronic detectors at the LHC.
- First step towards flavor classification with SND@LHC.
- 9 candidate events, background of 0.32 , observation with significance 6.4σ

Phys. Rev. Lett. 134, 231802 (2025)



SND@LHC is a ν experiment at CERN, operating since the start of LHC Run 3.

- Designed to measure high-energy neutrinos at the LHC, it can study lepton universality in the neutrino sector, probe heavy-flavor physics, and search for BSM signatures.
- Has recorded $\simeq 300 \text{ fb}^{-1}$ of data, with 97% detector uptime

Published results

- ν_μ , μ -flux, first observation of 0μ LHC neutrino interactions using electronic detectors

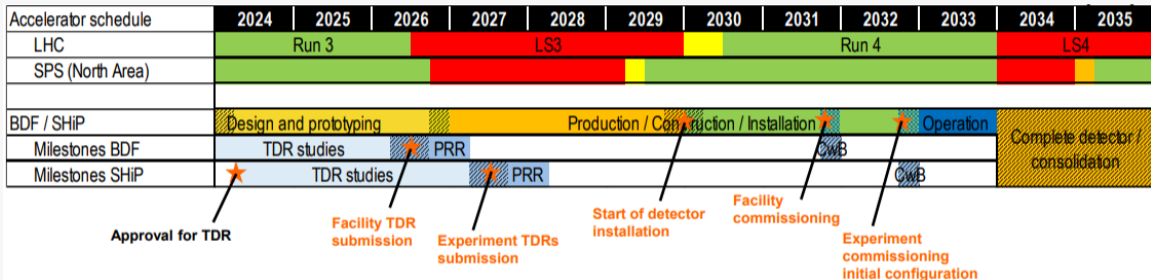
Upcoming results

- Updated ν_μ measurement, μ -trident cross-section, colorimetric measurements with emulsions using multiple Coulomb scattering and shower track density

Detector upgrade

- Approved for Run 4. Silicon strip modules in place of nuclear emulsion to cope with the high-intensity of the HL-LHC, and magnetized volume for $\nu/\bar{\nu}$ discrimination
- Similar concept for SND@SHiP

- BDF/SHiP provides a clear opportunity to discover FIPs in the decays of heavy mesons.
- Complementary to the FIP searches at HL-LHC and future e^+e^- -colliders.



- Intense R&D going on for all sub detectors
- TDRs by end of next year
- Plan to start data taking more than one year before LS4 – Operation in 2033

① Hidden Sector

② Subsystems

- So we know there must be physics beyond the standard model, but where can we find it?

Mediators (portals) to the Hidden Sector

Visible Sector

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Mediator}} + \mathcal{L}_{\text{HS}}$$

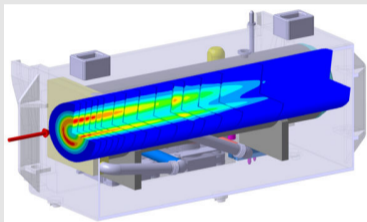


Hidden Sector

Mediator/portals to the HS:
vector, scalar, axial, neutrino

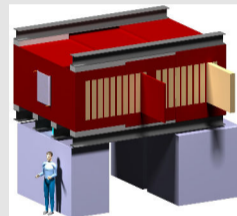
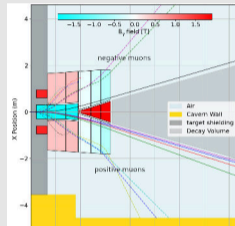
- Ability to couple to SM gives constraints from theory
- Different options
 - ▷ c.f. [arXiv:1504.04855v1](https://arxiv.org/abs/1504.04855v1)
 - ▷ Dark photons
 - ▷ Scalar and pseudoscalar mediators
 - ▷ ALPs
 - ▷ Heavy Neutral Leptons

Target

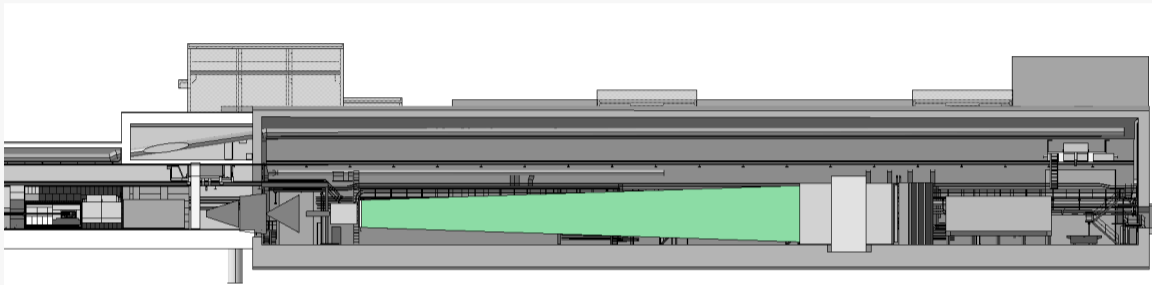


- Helium cooled W-Target
- $12\lambda_{\text{int}}$
- 2.3 m magnetized hadron stopper
- 2.6 MJ per 1 s spill, every 7 s

Magnetic Shield



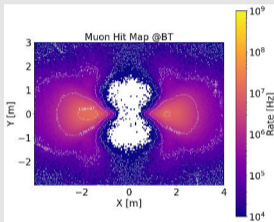
- Recently decided for warm option
- StellaTRYon: Tuned Return Yoke
- Foresee sufficient space in last part for Scattering Detector



Helium filled decay vessel

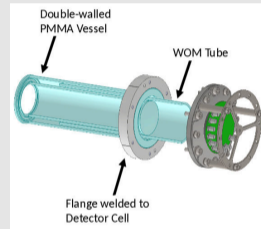
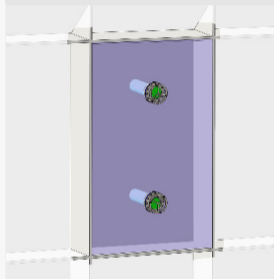
- Changed from 1 mbar vacuum to 1 bar Helium balloon
- ν interactions inside fiducial volume increased, but bkg seems still ok
- Surrounding material drastically reduced (less inelastic)
- Surroundings instrumented with efficient background taggers.

Upstream Background Tagger



- Tag combinatorial bkg and inelastics before Decay Volume
- Require a good time and spatial resolution
- Combination of Scintillating tiles and Straw tubes

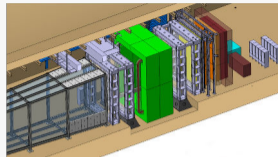
Surround Background Tagger



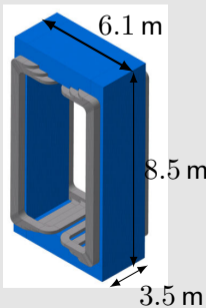
- Cells filled with liquid scintillator
 - LAB + PPO
- Read out by WOMs equipped with SiPMs
- Cells of 80 cm width, up to 150 cm high

Straw Tracker

- Reconstruct tracks with high precision (better 120 μm)
 - Measure charge and momentum
 - Vertex reconstruction
- Low material budget
- Large aperture 4 m \times 6 m
- Moderate rate $\mathcal{O}(10 \text{ kHz})$
- 4 m horizontal **straws**, 2 cm diameter
- Au/Co plated mylar tubes, 36 μm wall thickness



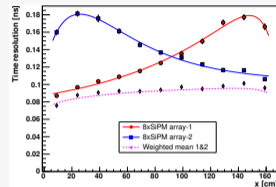
Spectrometer Magnet



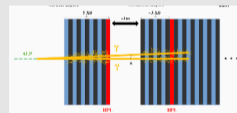
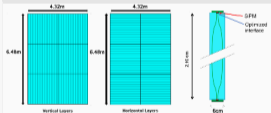
- Bending field 0.65 Tm
- Coil: intermediate temperature superconductor MgB_2
 - Prototyping ongoing

Dedicated Timing Detector

- Reduction of muon combinatorial bkg
- Provide t_0 for straw tubes
- Identification of particle decay products (ToF)
- ▷ Three columns of vertically staggered scintillator bars
- ▷ Time resolution ≤ 100 ps



PID



- PID Detector composed of sampling ECAL and HCAL based on scintillators readout by SiPMs