Results from SND@LHC (Scattering & Neutrino Detector)

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LHCC poster session, 27th November 2023, CERN

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Introduction

SND@LHC is a compact and stand-alone experiment measuring neutrinos produced at the LHC [1]. It was approved by CERN on March 17th, 2021. Built & commissioned in less than 1 year, it has successfully collected 68.6 fb^{-1} data during LHC Run 3!

Overview:

- Located in **TI18**, 480m downstream of the **ATLAS IP1 (forward direction) –** large flux of **high energy neutrinos (100 GeV – few TeV).**
- Off-axis – unexplored pseudo-rapidity region of $7.2 < \eta < 8.4$ – all three flavour neutrinos (**including tau**) from **charmed hadron decays.**

Figure 1. Location of SND@LHC. (forward direction)

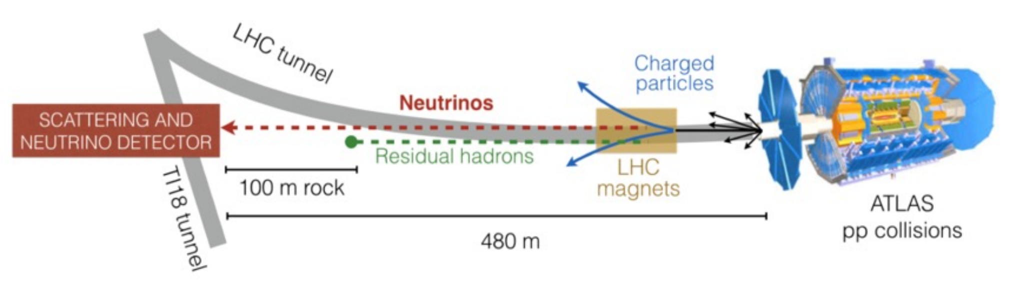
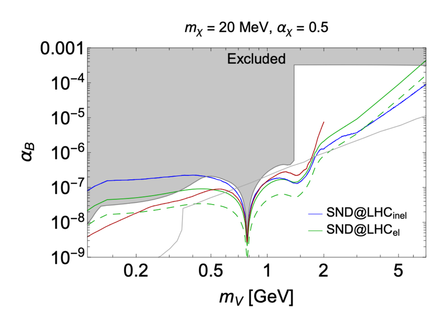


Figure 2. SND@LHC detector in TI18.

Physics Programme

- Measurement of the **pp → ν_X X cross section** (including the least studied tau neutrinos ν_τ).
- **Heavy flavour production** in pp collisions.
- **Lepton flavour universality test** in neutrino interactions.
- Direct search for **feebly interacting particles (FIPs)** through their scattering.

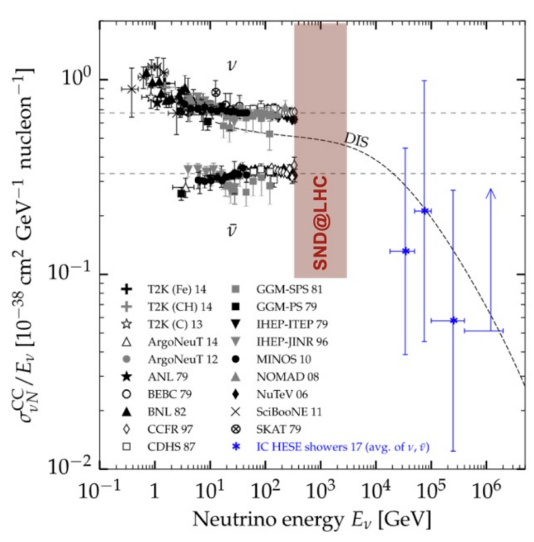
Figure 3. Sensitivity of SND@LHC to the leptophobic portal – FIP search [2].



Run 3: 250 fb^{-1}

Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Yield	CC neutrino interactions ⟨E⟩ [GeV]	Yield
ν_μ	130	3.0×10^{12}	452	910
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360
ν_e	339	3.4×10^{11}	760	250
$\bar{\nu}_e$	363	3.8×10^{11}	680	140
ν_τ	415	2.4×10^{10}	740	20
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10
TOT		4.0×10^{12}		1690

Figure 4. Available cross-section measurements. SND@LHC lies in the unexplored energy range.



Electromagnetic Shower Reconstruction in Sci-Fi detector

Reconstruction of the Electromagnetic (EM) showers – identification of ν_e CC events.

- **Problem : Hit counting - insufficient** to reconstruct the EM shower energy precisely.
  - **Coarse sampling** of EM shower by the **Sci-Fi** detectors leads to degeneracy between the energy and shower starting position.
- **Methodology:** Adopted the **Maximum Likelihood approach.**
  1. Generate "particle gun" electron Monte Carlo (MC) simulations using Geant4.
  2. Produce **templates of the hit patterns** for each event.
  3. Evaluate the **likelihood for each shower** using the hit pattern templates & Poisson statistics

Figure 7. Hit Templates for various energies.

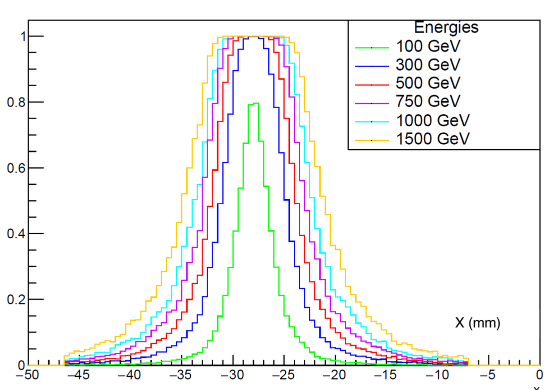
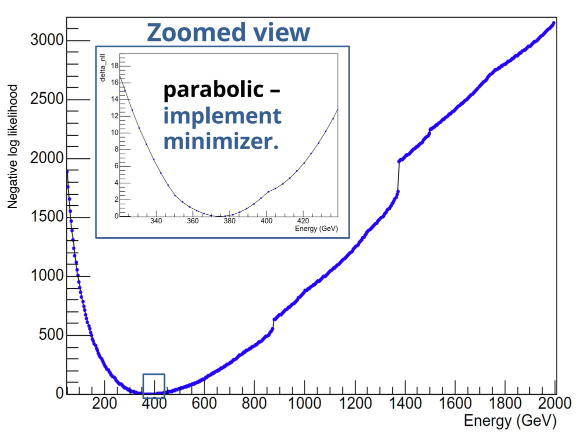


Figure 8. Likelihood Scan for event energy = 300 GeV.



- **Result:**

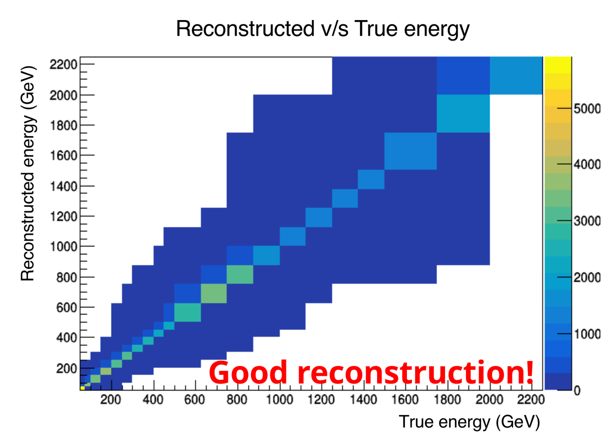


Figure 9. Reconstruction performance.

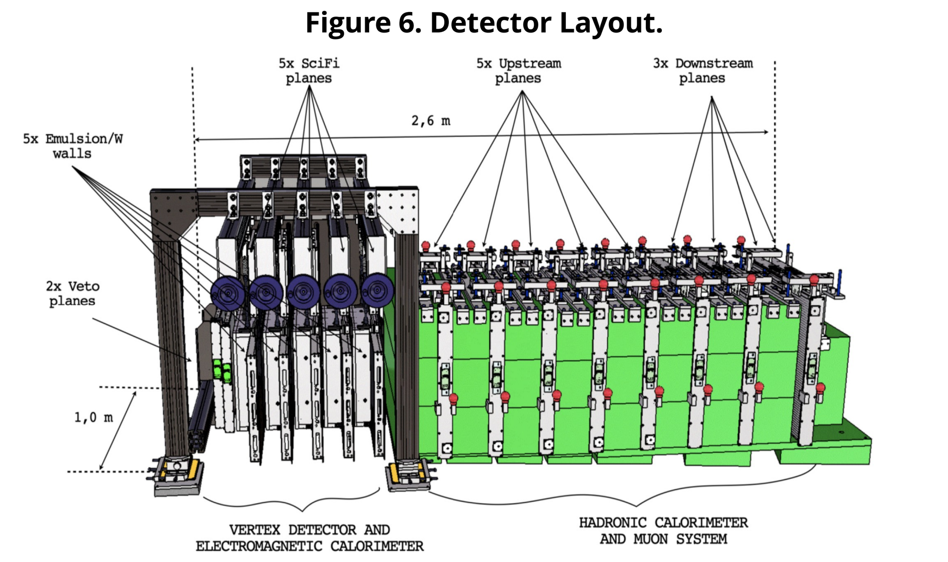
Scanned over discrete energy points and found the maximum likelihood

Next steps:

- Implement this likelihood method into a **minimizer.**
- Account for shower parameters – **x, y position and angle θ.**

SND@LHC Detector Concept

Figure 6. Detector Layout.

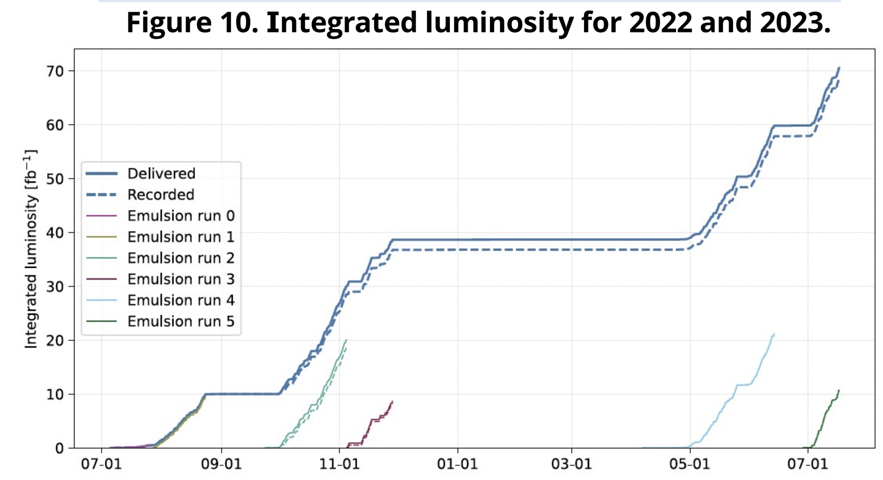


Identify **all neutrino flavours** & detect **FIPs** - **Hybrid Detector**

- Veto System
- Vertex detector & Electromagnetic Calorimeter — Emulsion Cloud Chamber (interleaved **tungsten** neutrino target + emulsion) + electronic trackers (**Sci-Fi**)
- Hadronic calorimeter (**HCAL**) & Muon system

Recorded Luminosity

Figure 10. Integrated luminosity for 2022 and 2023.



Integrated luminosity: 70.5 fb^{-1}

Recorded efficiency: 97.3% (2022 95%, 2023 99.7%)

Test Beam Analysis

Test beam was conducted in August 2023 at SPS. Pion runs with 100, 140, 180, 240, 300 GeV beam energies + 160 GeV muon run. Average event-recording rate - 15x10^6 events/hour.

Goal – to calibrate SND@LHC **HCAL and Sci-Fi response** as function of **hadron shower energy** and of **shower origin** in the target.

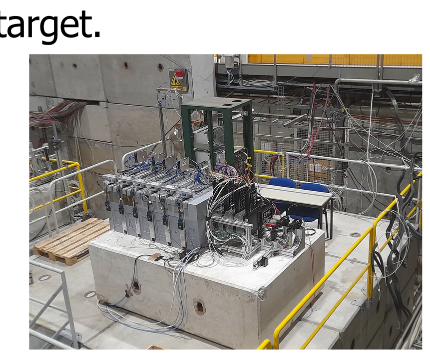


Figure 11. Test beam detector at SPS.

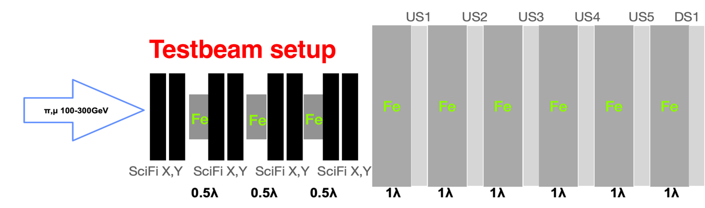


Figure 12. Detector layout.

Iron blocks instead of tungsten $7.5\lambda_{int}$ covers 95% of the 300 GeV pion shower profile.

Test beam data

- **Sci-Fi** can be used for shower origin reconstruction. (criterion: >30 hits within 1.6 cm^2)
- Correlation between the **Sci-Fi** & the **HCAL** signal sum:

$$E_{sh} = \alpha\Sigma^{HCAL}_{signal} + \beta\Sigma^{SciFi}_{signal}$$

- Preliminary results of calibration:

$\Delta E/E \sim$ 25-30% for 100 GeV pions

$\Delta E/E \sim$ 15-20% for 300 GeV pions

Simulation

- Simulations of pion run - same correlation between **Sci-Fi** and **HCAL** signals.
- With equal slopes for different pion energies - the pion energy reconstructed by the offset.
- Result for the MC truth:

$\Delta E/E \sim$ 30% for 100-300 GeV pions.

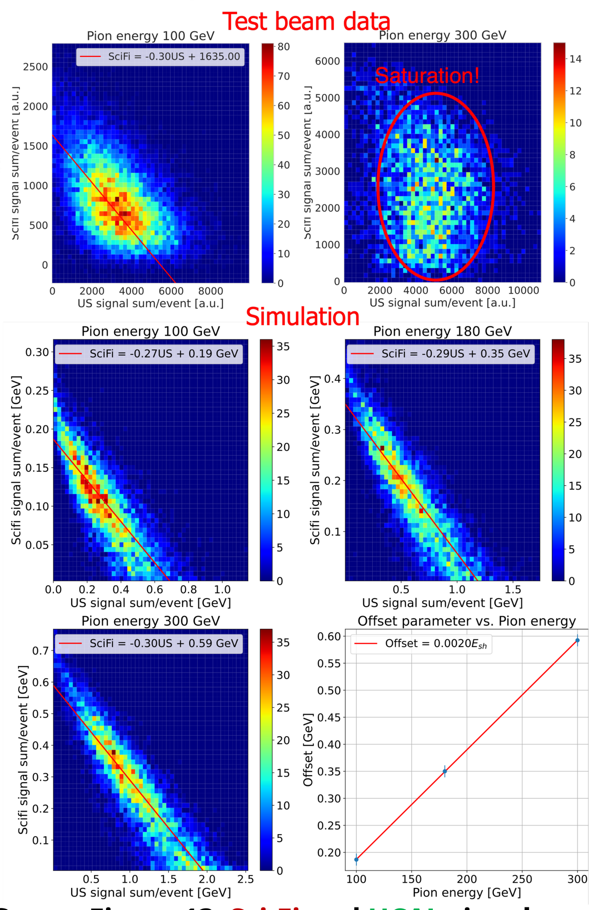


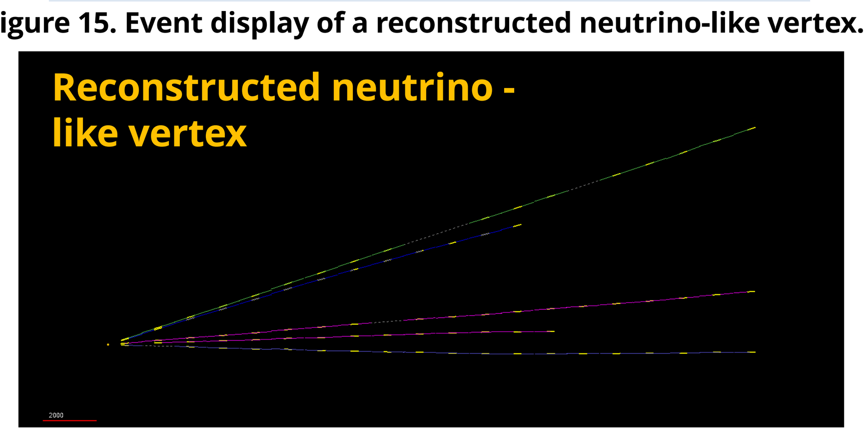
Figure 13. Sci-Fi and HCAL signal correlation.

Next steps:

- **Calibrate MC** with test beam data.
- Use small SiPM signal to **improve** the energy resolution.

Vertex Reconstruction in Emulsion

Figure 15. Event display of a reconstructed neutrino-like vertex.



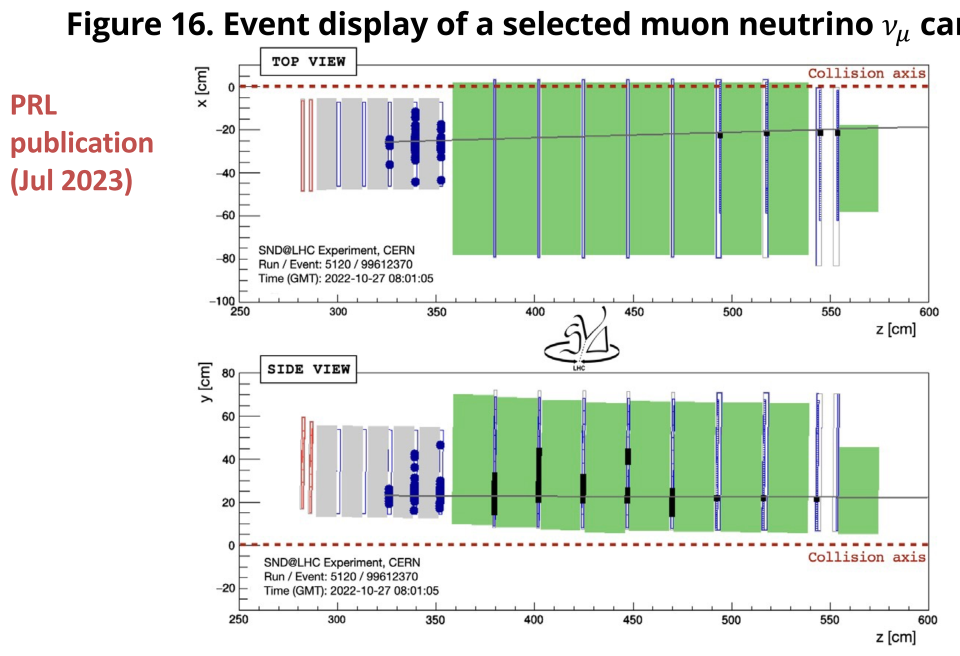
- To cope with unprecedented track density: 5×10^5 tracks/cm^2 - developed tracing and vertexing algorithms.
- BDT analysis is applied for background rejection.

Next step: matching reconstructed vertices to electronic signals.

Observation of collider ν_μ events

Figure 16. Event display of a selected muon neutrino ν_μ candidate.

PRL publication (Jul 2023)



8 candidate events consistent with ν_μ charged-current interactions with **a significance of 6.8σ** were observed [3].

Muon flux measurement

- **First measurement** of muon flux at high pseudo-rapidity range and long distance from the IP.
- Agreement between three tracking detectors: **Sci-Fi**, **Muon Tracker**, **Emulsions**.
- Agreement with a FLUKA simulation (within 20%).

system	sample	muon flux [10^4 fb/cm^2]	$1-\frac{\text{sim}}{\text{data}}$ [%]
SciFi	data	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$	22 ± 9
	sim	$1.60 \pm 0.05(\text{stat.}) \pm 0.19(\text{sys.})$	
DS	data	$2.35 \pm 0.01(\text{stat.}) \pm 0.10(\text{sys.})$	24 ± 9
	sim	$1.79 \pm 0.03(\text{stat.}) \pm 0.15(\text{sys.})$	

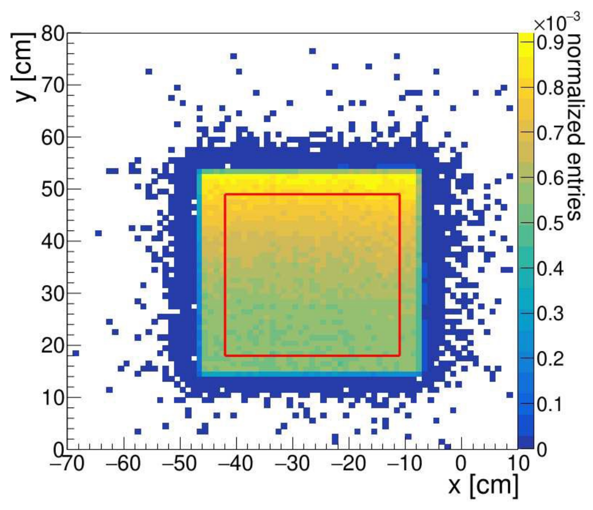


Figure 17. Reconstructed Sci-Fi tracks x–y profile at the upstream detector face. (Hough Transform) [4].

HL-LHC Upgrade: AdvSND@LHC

Extended Physics Goals

AdvSND-Near: $4 < \eta < 5$

- LHCb pseudo-rapidity coverage.
- Neutrino cross-section measurements.

AdvSND-Far: $7.2 < \eta < 8.4$

- Acceptance similar to SND@LHC.
- Charm production measurements.
- Lepton flavour universality.

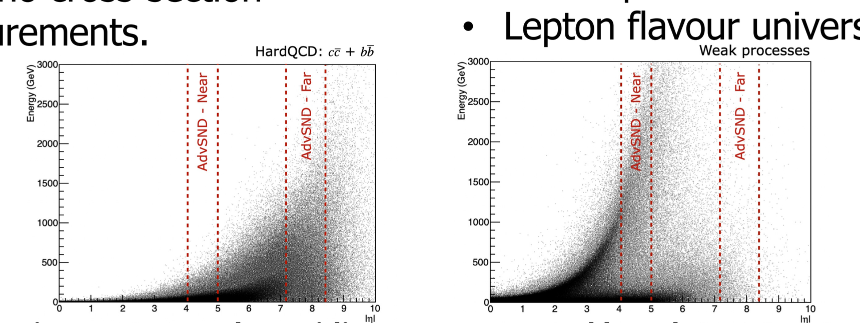


Figure 18. Pseudo-rapidity ranges covered by AdvSND@LHC.

Upgrade: Two detectors (near & far)

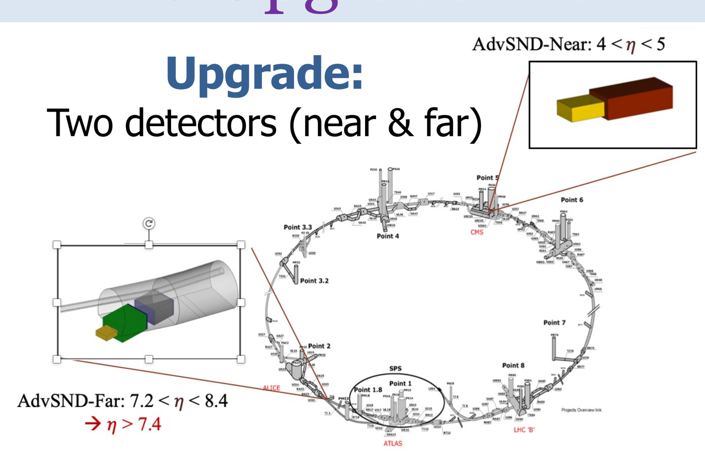


Figure 19. Proposed locations of the detectors.

Major upgrades in the detector:

- ❖ Replace emulsions with compact electronic trackers for high intensity muon rates.
- ❖ Magnet ($B = 1$ T over 2 metres) with two high-resolution tracking stations.

Unique installation to register **large flux of $\nu_\tau/\bar{\nu}_\tau$**.

Detector layout

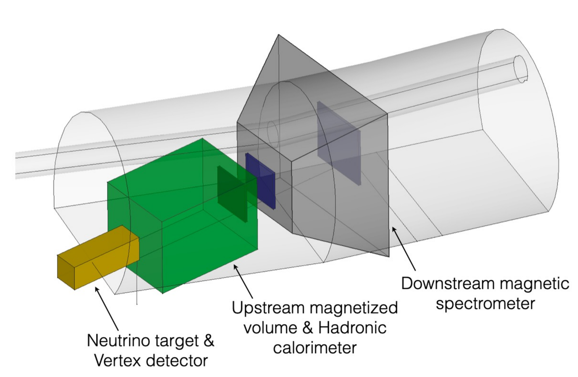


Figure 20. Schematic of Detector layout.

References

[1] SND@LHC Collaboration. (2021). SND@LHC-Scattering and Neutrino Detector at the LHC (No. CERN-LHCC-2021-003)..

[2] Boyarsky, A., Mikulenko, O., Ovchynnikov, M., & Shchutska, L. (2022). Searches for new physics at SND@ LHC. Journal of High Energy Physics, 2022(3), 1-30.

[3] SND@LHC Collaboration. (2023). Observation of collider muon neutrinos with the SND@LHC experiment. Physical Review Letters, 131(3), 031802.

[4] SND@LHC Collaboration. (2023). Measurement of the muon flux at the SND@ LHC experiment. arXiv preprint arXiv:2310.05536