22nd Lomonosov Conference on
Elementary Particle Physics

SND@LHC in 2025 and beyond

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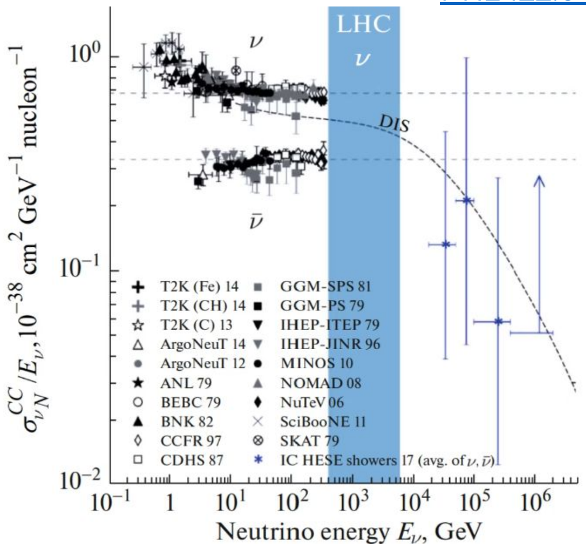
NUST MISIS

on behalf of the SND@LHC collaboration

23.08.2025

Neutrinos at the Large Hadron Collider

PRL 122.041101



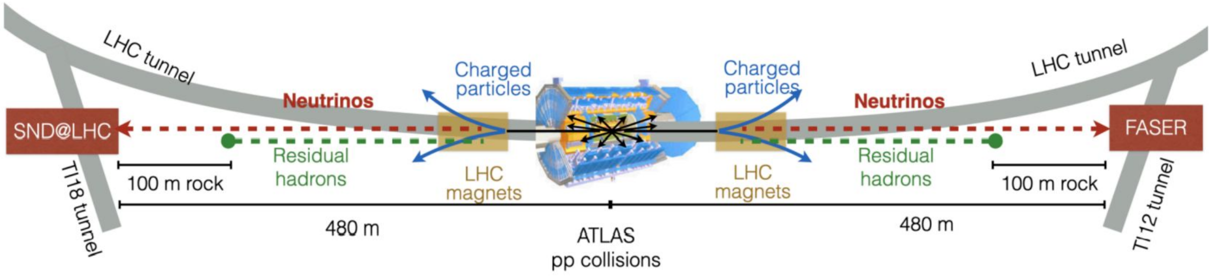
- **Large Hadron Collider**
  Proton interactions produce intense neutrino beams of all three flavors.
- **Neutrinos of three flavors**
  The most powerful particle accelerator with a collision energy of 13.6 TeV.

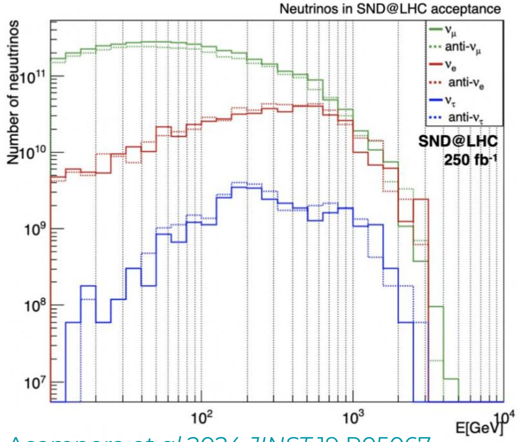
  pseudorapidity range: 7.2 < η < 8.4

  Enhances ν flux from charm parents
- **Start of the SND@LHC experiment**
  The SND@LHC experiment was approved in 2021. The exposure began in April 2022.

Strategy

- Existing site (avoided major engineering work)
- Enough material to shield from background particles
- Use of LHC magnets to deflect charged particles





G. Acampora *et al* 2024 *JINST* 19 P05067

SND@LHC – Physics Goals

Study Neutrino interactions

- Measure neutrino interactions in ~TeV energy range
- Large yield of neutrinos will likely double existing data (about 20 events observed by DONuT and OPERA)

Flavour

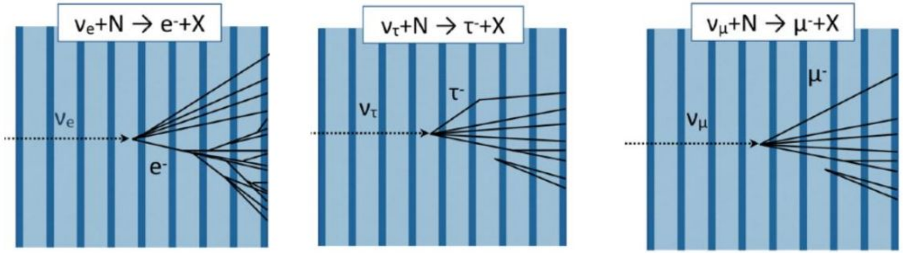
- Detection of all three types of neutrinos allows for tests of lepton flavour universality

QCD

- 90% of **ν_e and $\bar{\nu}_e$ produced at SND@LHC originate from *charm* decays**
  [J. Phys. G: Nucl. Part. Phys. 47 125004]
  -> indirect measurement of charm cross section
- constrain the gluon distribution in the proton at **low x** (x~10^{-6})

Beyond the Standard Model

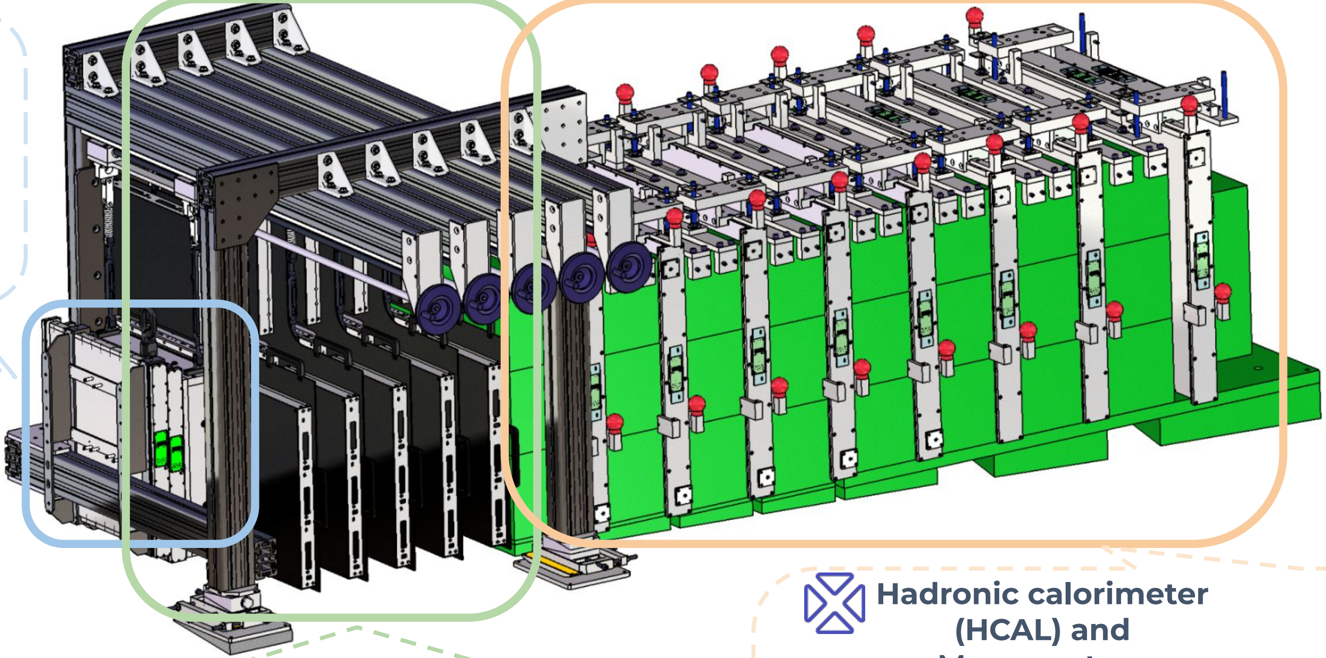
- Search for new, feebly interacting, particles decaying within the detector or scattering off the target
- probe into large variety of **Beyond SM scenarios**
  JHEP03(2022)006

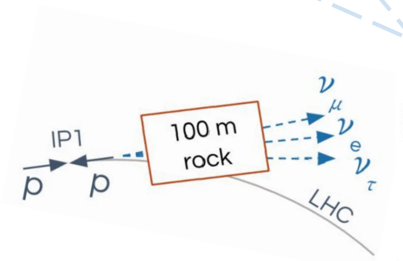


Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield
ν_μ	130	3.0×10^{12}	452	910
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360
ν_e	339	3.4×10^{11}	760	250
$\bar{\nu}_e$	363	3.8×10^{11}	680	140
ν_τ	415	2.4×10^{10}	740	20
$\bar{\nu}_\tau$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

Expected neutrino interaction in Run 3: 250 fb^{-1}

SND@LHC – Hybrid Detector





Veto system

3 plastic scintillator planes

- Reject charged particles and suppress muons

Target region

Emulsion Cloud Chamber (ECC)

Tungsten plates interleaved with emulsions

- Sub-μm tracking and vertex ID

Electronic trackers (SciFi)

Scintillating fibers with SiPM readout

- Fast timing (~320 ps layer)
- electromagnetic calorimeter

Hadronic calorimeter (HCAL) and Muon system

8 Fe absorbers + 8 scintillator planes interleaved with iron:

- 5 US: horizontal bars, focus on calorimeter
- 3 DS: horizontal and vertical bars, focus on muon tracking

SND@LHC during Run 3 of LHC

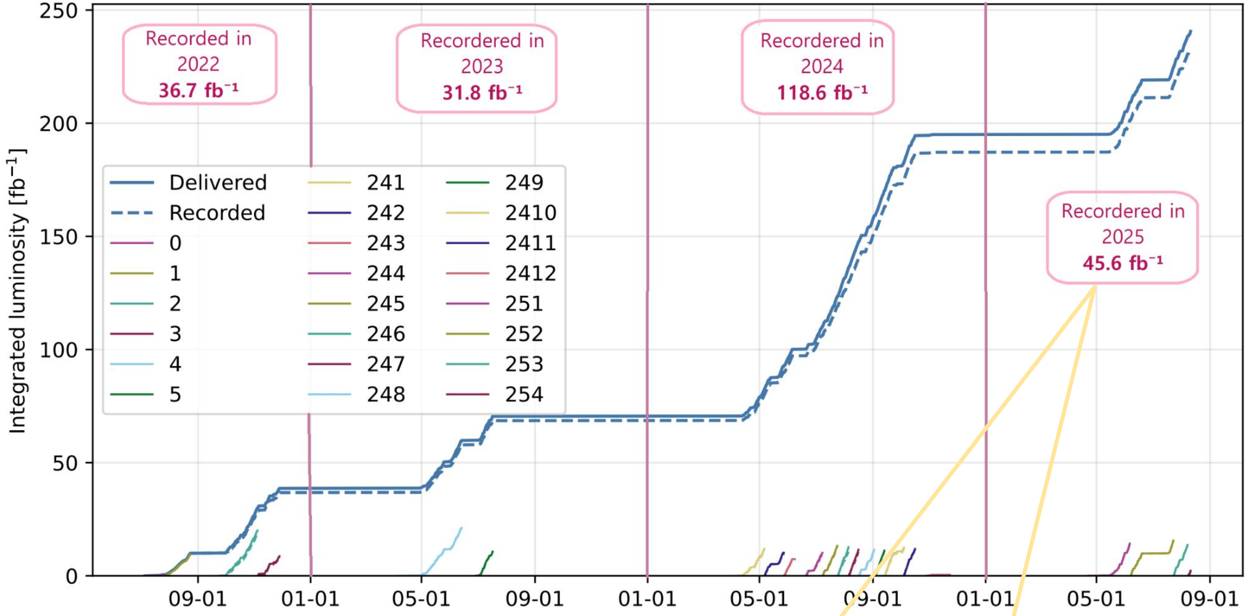
luminosity summary

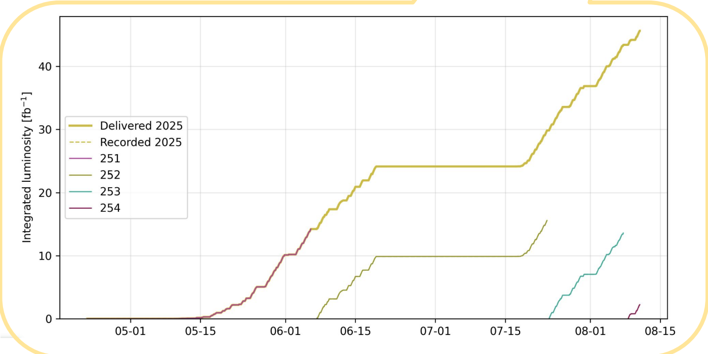
Period	Delivered [fb^{-1}]	Recorded [fb^{-1}]
All time	240.6	**232.8**
2025	45.63	**45.63**
2024	124.5	**118.6**
2023	31.86	**31.78**
2022	38.65	**36.77**

Emulsion detectors:

18 targets exposed in 2022-2025

5100 emulsion films (210 m^2) exposed and developed





Muon Flux Measurement

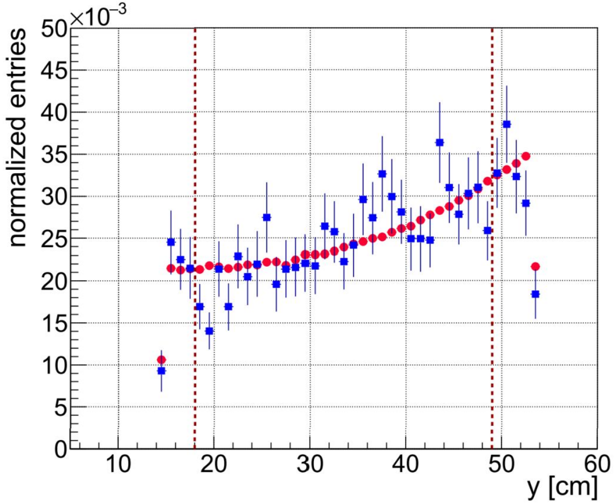
Backgrounds to neutrino signals in SND@LHC are mainly due to muon interactions in the tunnel walls.

Easily penetrate the ~100 m rock shielding, can be rejected by veto
Albanese, R., Alexandrov, A., Alicante, F. *et al.* Measurement of the muon flux at the SND@LHC experiment. *Eur. Phys. J. C* **84**, 90 (2024).

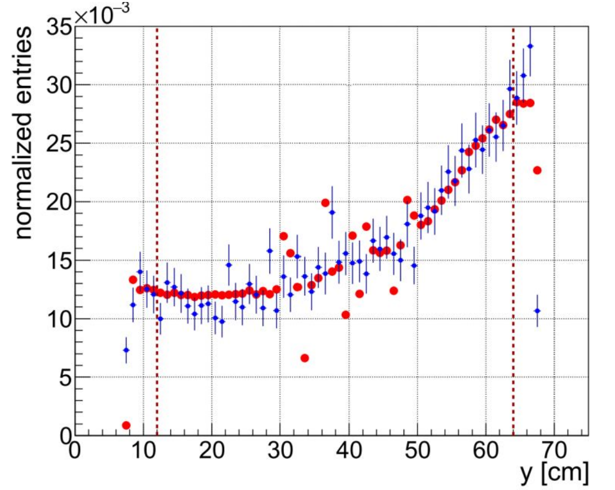
Measurements with independent systems:

System	Sample	**Muon flux** [10^4 fb/cm^2] (same fiducial area)
SciFi	**Data** **Sim**	2.06 ± 0.01 (stat.) ± 0.12 (sys.) 1.6± 0.05 (stat.) ± 0.19 (sys.)
Muon system	**Data** **Sim**	2.02 ± 0.01 (stat.) ± 0.08 (sys.) 1.79 ± 0.03 (stat.) ± 0.15 (sys.)

Updated geometry and scoring regions in simulations
NOW in agreement with data within ~5%
(preliminary result)



SciFi tracks: Simulation vs Data



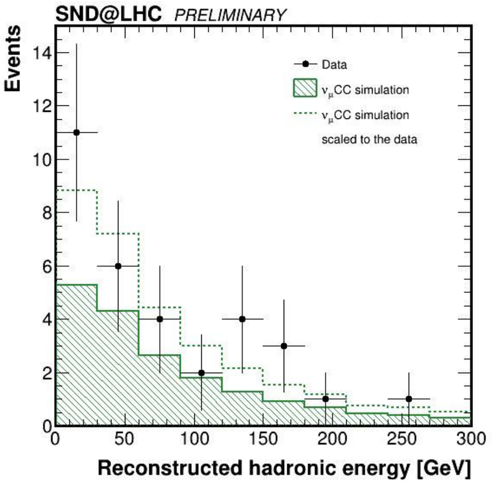
Muon system tracks: Simulation vs Data

Muon Neutrino Observation

[Phys. Rev. Lett. 131, 031802](#)

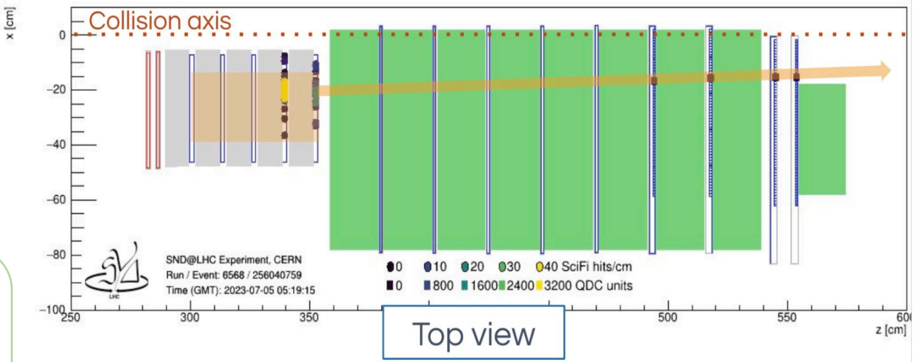
The signs of these interactions are:

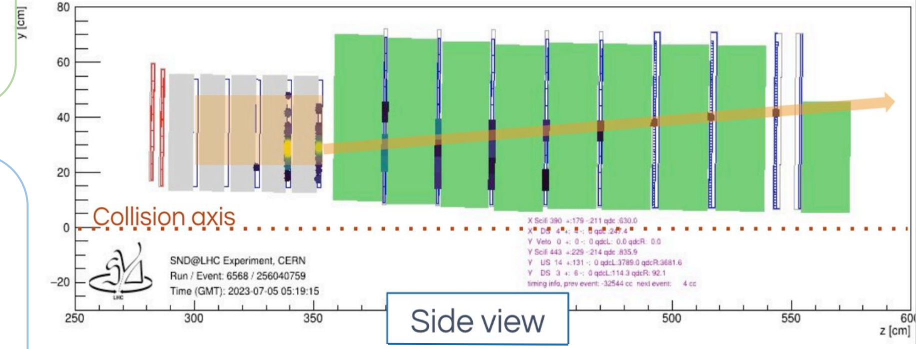
- the presence of an isolated muon track in the muon system;
- a hadron shower in the SciFi scintillating fiber system and in the hadron calorimeter.



Data 2022:
Integrated Luminosity 36.8 fb^{-1}
Expected Signal Events 4.2
Number of events observed: 8
background 0.09
Observation significance: 6.8σ

Data 2022+2023:
Integrated Luminosity 68.6 fb^{-1}
Expected Signal Events 19.1 ± 4.1
The search for νμ interactions is updated with extended fiducial volume and inclusion of 2023 data, **results to be published**



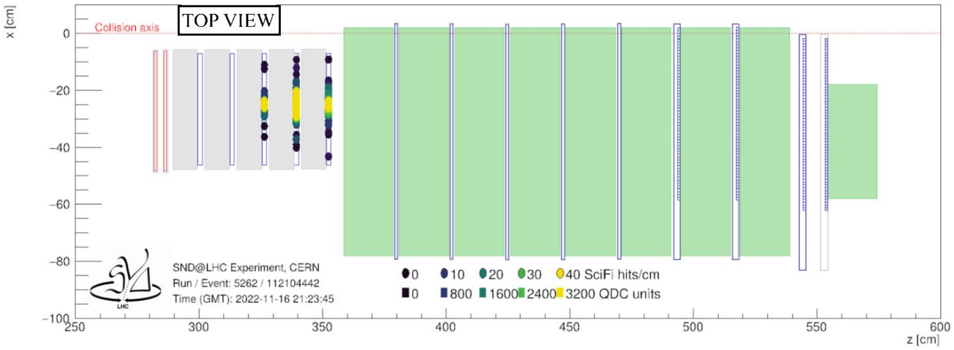


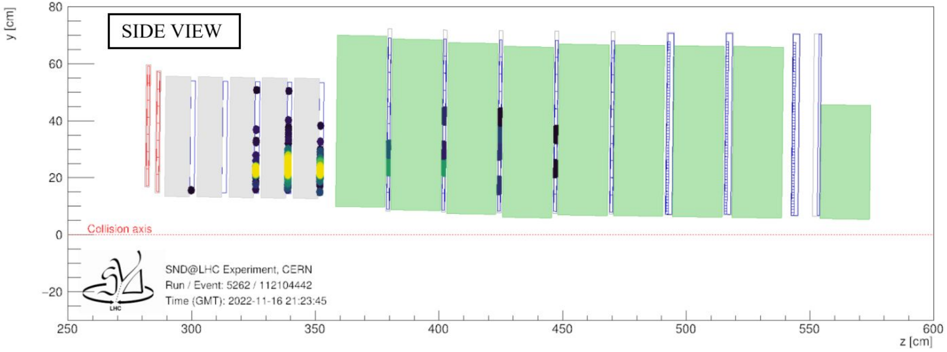
0μ Neutrino Observation

[PRL 134 231802 (2025)](#)

The signs of these interactions are:

- **Vertex Identification**
  In a neutrino target without connection with the incident charged particle.
- **Absence of muons**
  There are no muon tracks at the selected vertex.
- **Shower registration**
  Electromagnetic or hadron shower in SciFi detectors.





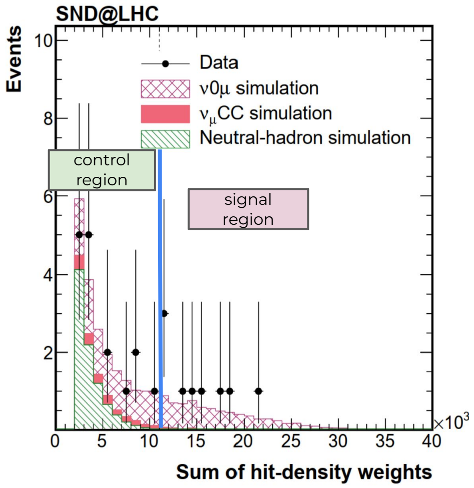
Background events are:

- CC interactions of ν_μ in which the muon was not detected or identified, **0.30** events
- interactions of background neutral hadrons in a neutrino target. **0.01** events

Total expected background: 0.32 ± 0.06 events

Expected signal: **7.2 events:** 4.9 ν_eCC, 2.2 NC, 0.1 ν_τCC

Expected significance: 5.5σ

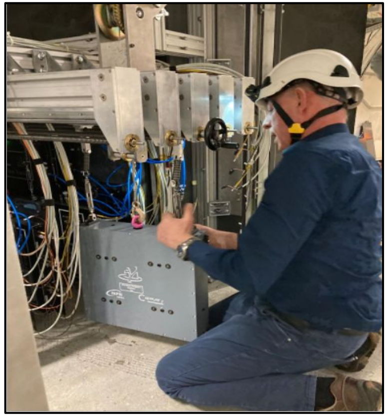


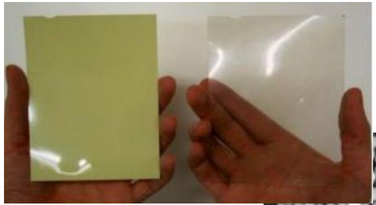
Number of events observed: 9
Observation significance: 6.4 σ

Emulsions - Exposure to Analysis

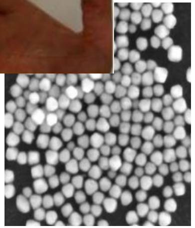
Manufacture

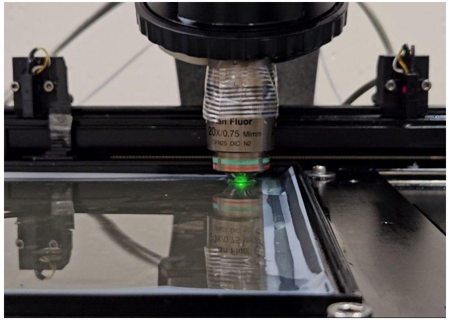
Exposure → Chemical Development → Micro-track Scanning → Track Reco / Vertex ID



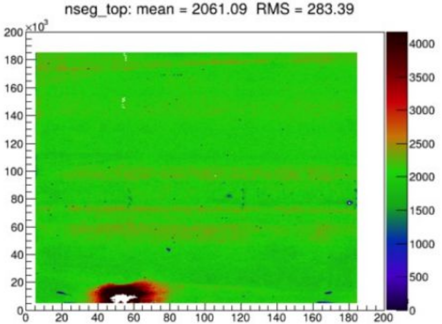


before + after

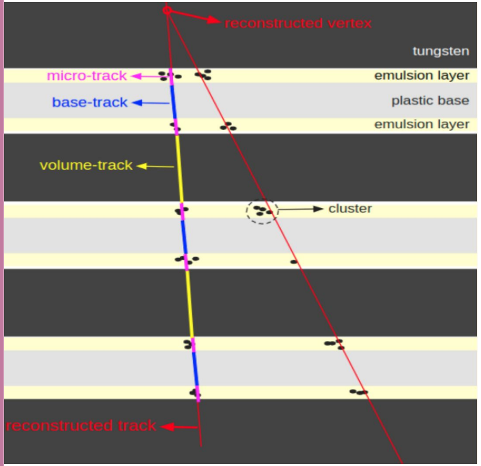


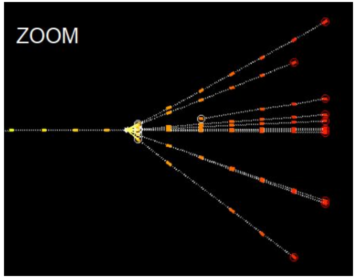


14 Systems - 7 Laboratories



Raw Data (micro-tracks)





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Upgrades in emulsion data processing

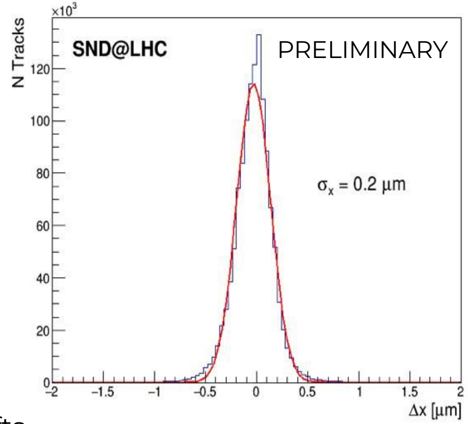
FEDRA software *Tioukov et al. (2006), NIM A559:103–105.*
upgraded

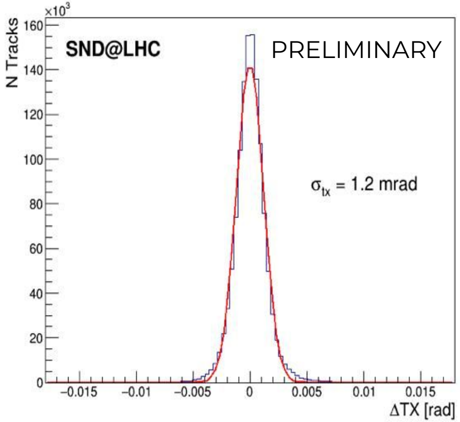
Track density up to 4 × 10^5 tracks/cm^2 (factor 10^3 larger w.r.t. OPERA)

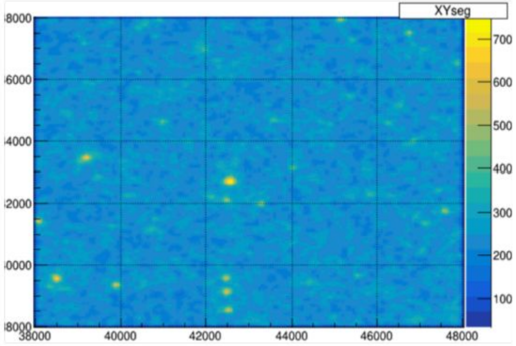
Excellent tracking resolution achieved!

Several processing steps:

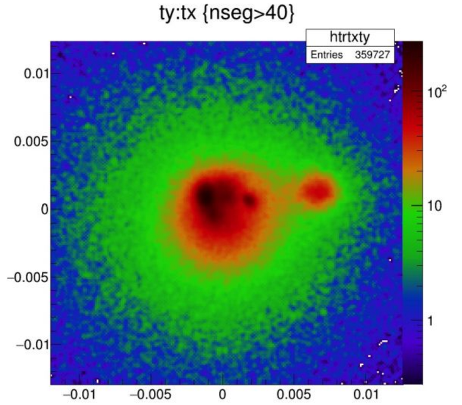
- **Alignment**
  - Mosaic: Stitch overlapping mic views correct tiny position shifts
- **Tracking**
  - Stable across volumes position resolution 0.2 μm (10 times better than OPERA)
  - Combine tracks of each plate into volume tracks
- **Volume Unbending**
  - Aligns tracks in 3D using beam muons
  - Improves track straightness across large volumes
- **New method for Global Shower Tagging**
  - 3D density-peak method
  - Used for automatic brick alignment







Electromagnetic shower search based on the observation of high density spots



Beam core clearly visible with passing-through tracks

Work plans for the HI-LUMI period

SND@LHC for HL-LHC is approved!!!
[CERN-LHCC-2025-004]

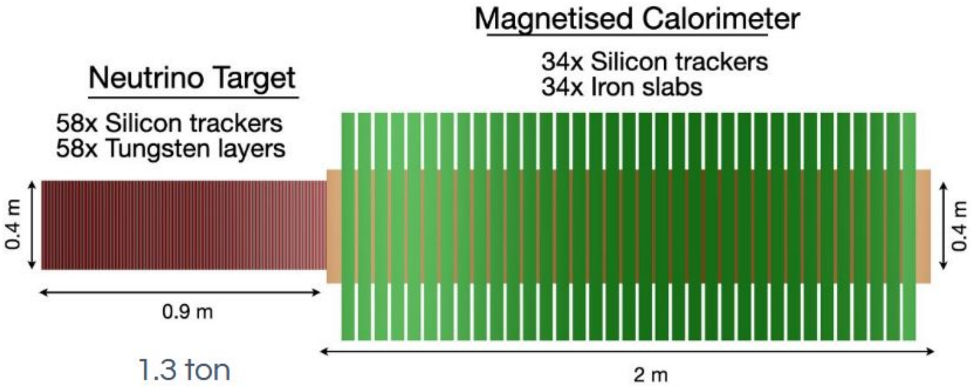
A fivefold increase in luminosity is expected (up to 680 fb-1) -> the use of emulsions is impossible

- **Replace emulsions with silicon strips**

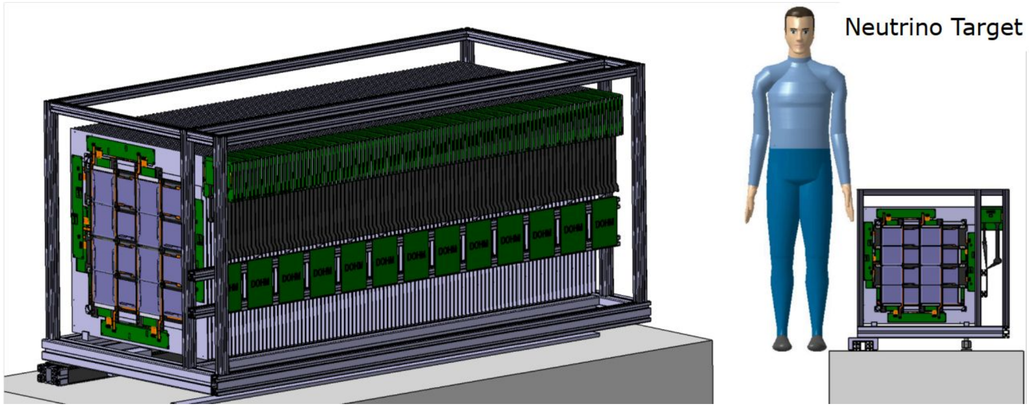
Reuse from the CMS tracker (Outer Barrel)
Will be the first neutrino vertex detector based on Silicon
(40 µm spatial resolution, 0.1 mrad angular resolution)

- **New magnetized calorimeter**

Muon charge and momentum measurements, distinguish ν and anti-ν



1.3 ton

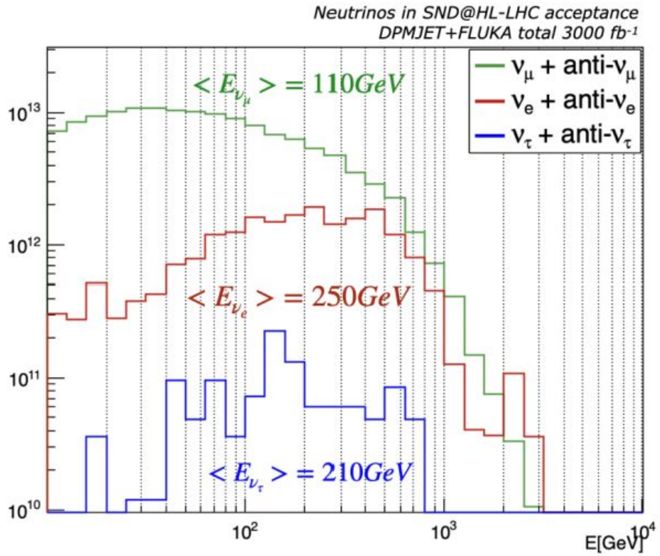


Physics Goals of HL-LHC Upgrade

Number of neutrinos CC DIS interactions

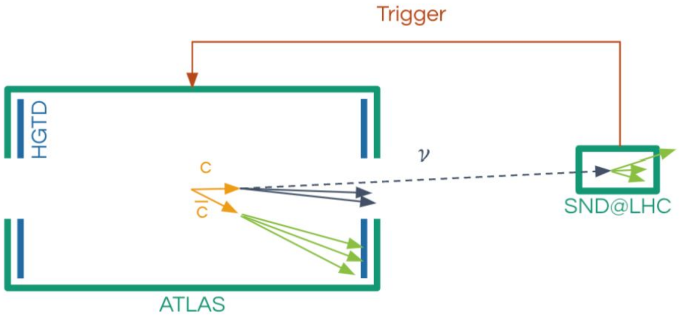
Flavour	Target	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	1.5×10^4	2.4×10^4
$\nu_e+\bar{\nu}_e$	3.4×10^3	5.5×10^3
$\nu_\tau+\bar{\nu}_\tau$	2.8×10^2	4.5×10^2
Tot	1.9×10^4	3.0×10^4

13 times more statistics than Run3!



Prospects for charm-tagged neutrinos

- sizeable fraction of the interacting neutrinos originate from open charm decays
- In around 10% of these events, the associated charm quark is emitted within the acceptance of ATLAS
- A charm-tagged neutrino sample would allow for clean flavour ratio measurements.



Measurement	LHC Run3 Uncertainty Stat.	LHC Run3 Uncertainty Sys.	HL-LHC Uncertainty Stat.	HL-LHC Uncertainty Sys.
Gluon PDF	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	$< 5\%$
ν_μ and $\bar{\nu}_\mu$ cross-section	-	-	1%	5%

Summary

- SND@LHC is successfully taking data since start of RUN3 of LHC
- The experiment has recorded **232.8 fb^{-1}** of data
  - ✓ Observation of collider muon neutrinos (2023)
  - ✓ Observation of neutrinos without final state muons (2024)
- Progress in emulsion data reconstruction with excellent tracking resolution and semi-automatic processing chain

- SND@LHC for RUN 4 is approved, expanding the neutrino and FIPs search
- The detector will be instrumented with **silicon strip modules** and a **magnetised calorimeter** to run in the HL-LHC

Thank you for your attention!

Backup

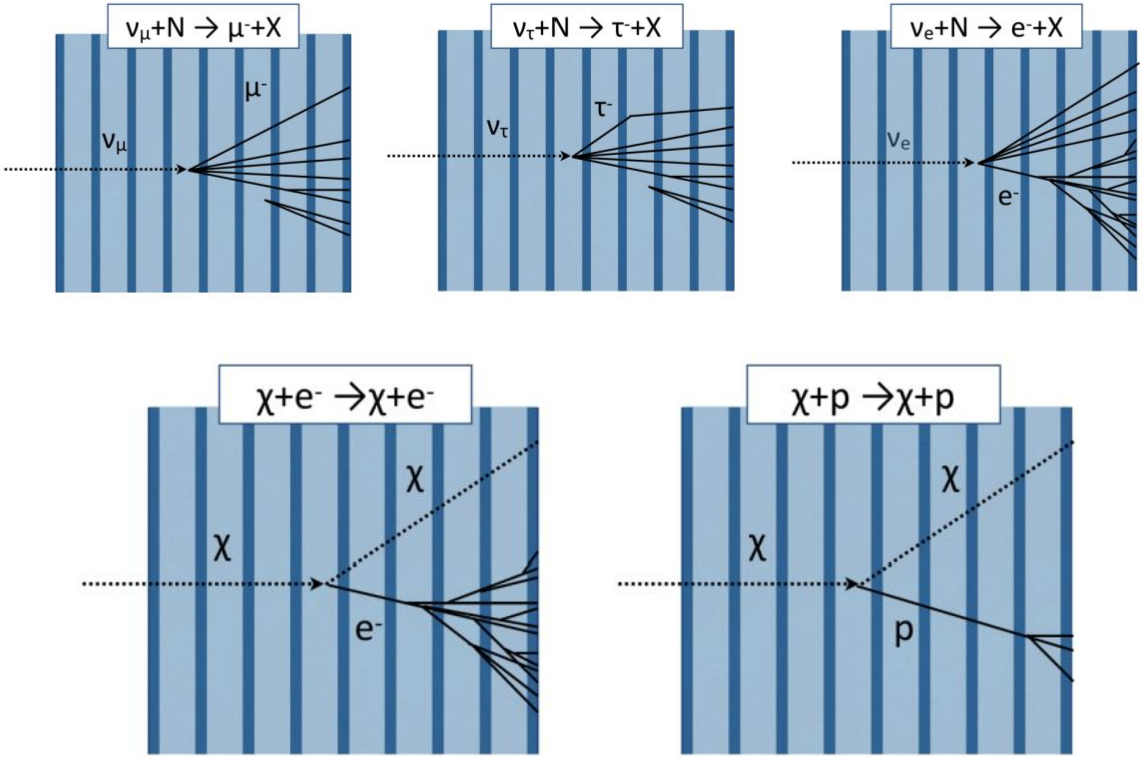
Neutrino Signature

Vertex Detector and ECAL

- EM shower
- Second vetex of τ

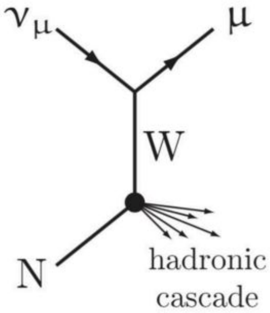
Muon system and HCAL

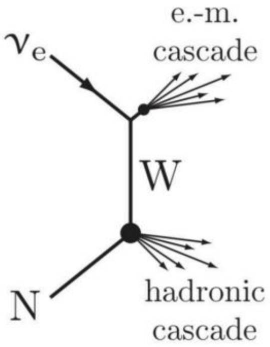
- Muon Track
- Hadronic shower

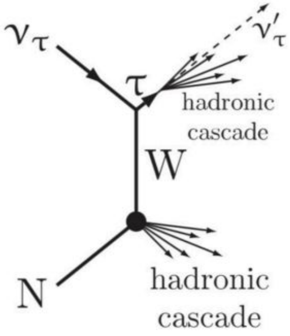


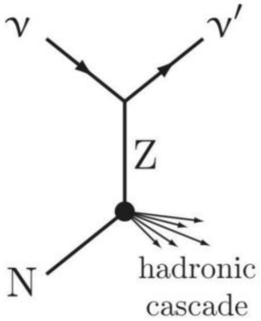
Neutrino Interactions

- ν_μ CC
  - μ
  - Hadronic shower
- ν_e CC
  - EM shower
  - Hadronic shower
- ν_τ CC
  - τ
  - Hadronic shower
- NC
  - ν'
  - Hadronic shower









Experiment Timeline of SND@LHC

August 2020

Scattering and Neutrino Detector at the LHC

Letter of Intent

January 2021

TECHNICAL PROPOSAL

SND@LHC

March 2021

CERN approves new LHC experiment

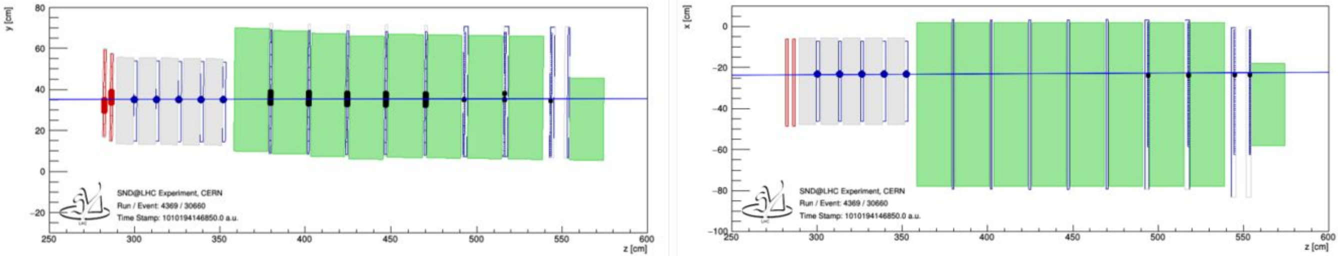
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

September 2021

December 2021

March 2022

July 2022, Muons from pp collisions at 13.6 TeV recorded



Neutral Particle Background

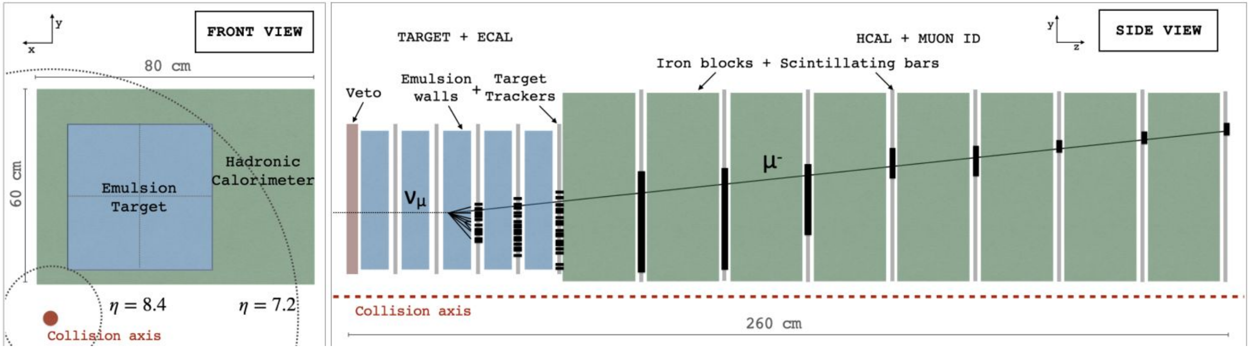
Muon-induced neutral particles

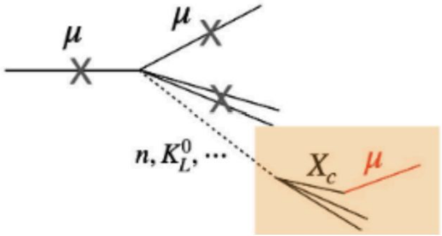
- Neutron
- Kaon

Mimic a neutrino interaction

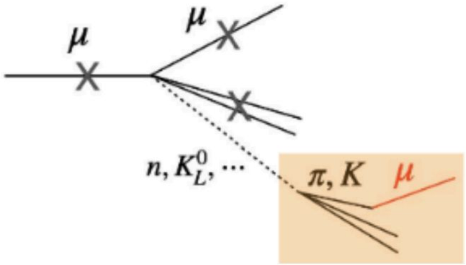
- Charm production
- Decay in flight

How to distinguish between neutrino and neutral background is one of the most important tasks

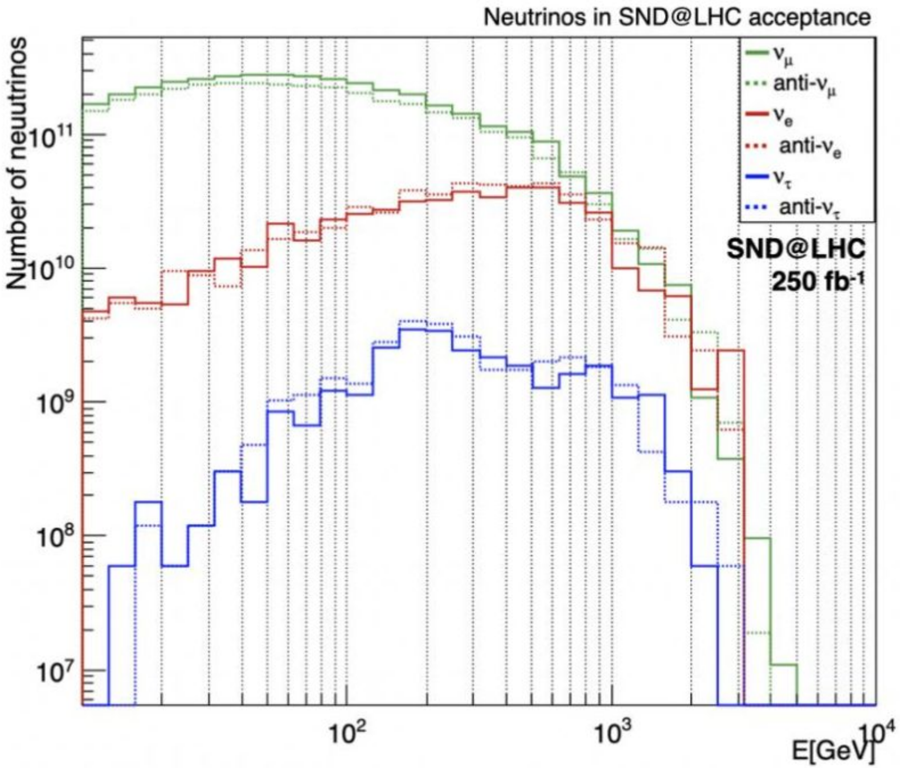


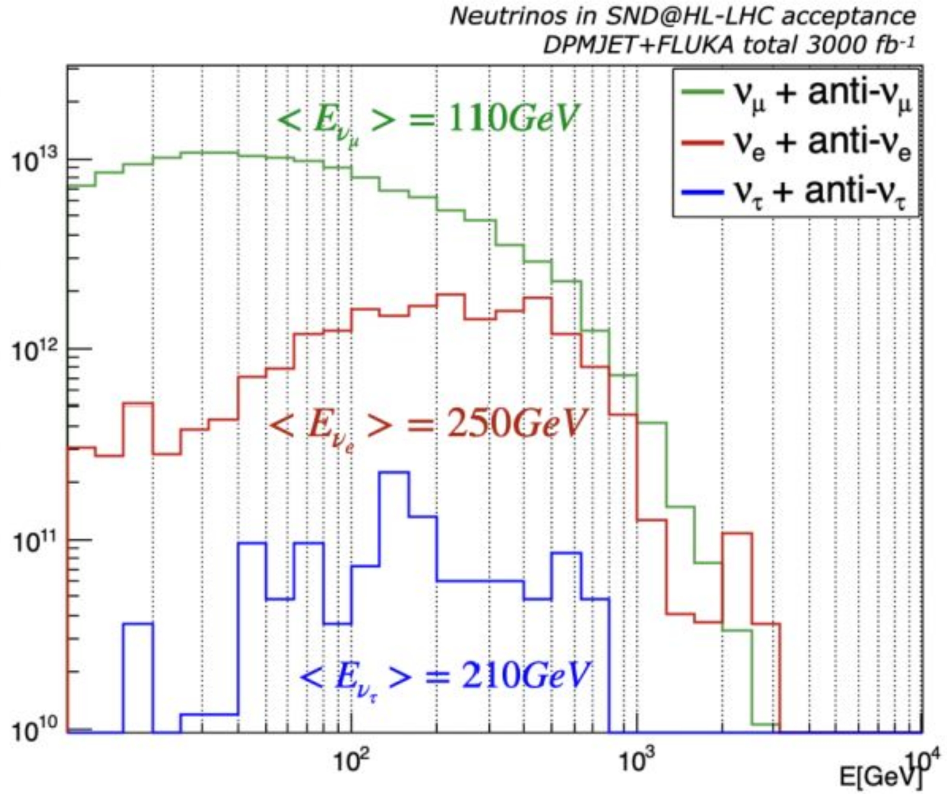


Charm production



Decay in Flight


Neutrinos in SND@LHC acceptance
Number of neuutrinos
ν_μ
anti-ν_μ
ν_e
anti-ν_e
ν_τ
anti-ν_τ
SND@LHC
250 fb^{-1}
E[GeV]


Neutrinos in SND@HL-LHC acceptance
DPMJET+FLUKA total 3000 fb^{-1}
ν_μ + anti-ν_μ
ν_e + anti-ν_e
ν_τ + anti-ν_τ
$< E_{\nu_\mu} > = 110 GeV$
$< E_{\nu_e} > = 250 GeV$
$< E_{\nu_\tau} > = 210 GeV$
E[GeV]