XXIII INTERNATIONAL SEMINAR ON HIGH-ENERGY PHYSICS

QUARKS-2026 | MAY 18-23

Recent results and prospects of the SND@LHC experiment

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on behalf of the SND@LHC collaboration

18.05.2026

Neutrinos at the Large Hadron Collider

PRL 122.041101

- The observation of collider neutrinos were proposed since the early 90's (J.Phys.G 46 (2019) 11, 115008)

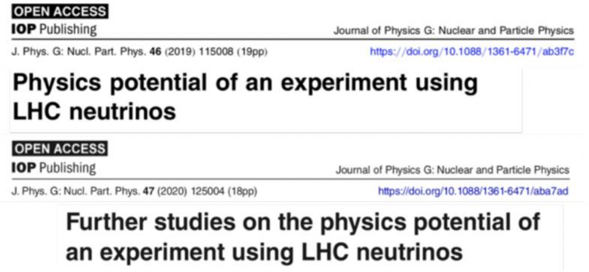
LHC produces neutrinos with the highest energy achieved to date
->Bridges the gap between accelerator neutrinos and high-energy neutrino telescopes

pseudorapidity range: 7.2 < η < 8.4

- Large neutrino fluxes in forward region from pp collisions
- High ν energies → Large ν - N cross-section

Start of the SND@LHC experiment

The SND@LHC experiment was approved in 2021. The exposure began in April 2022.


OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 46 (2019) 115008 (19pp)
https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

OPEN ACCESS
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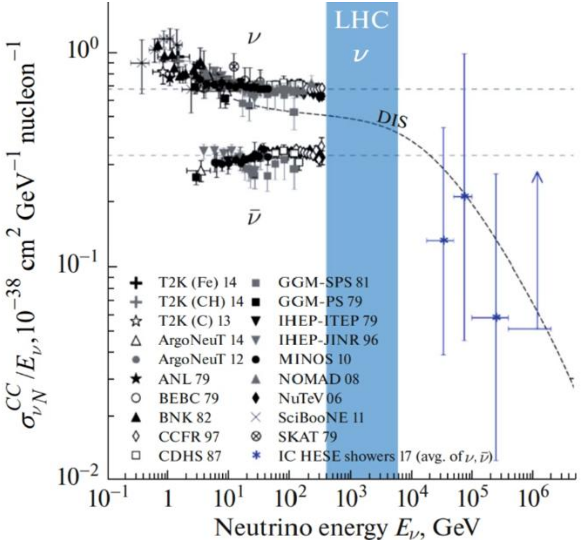
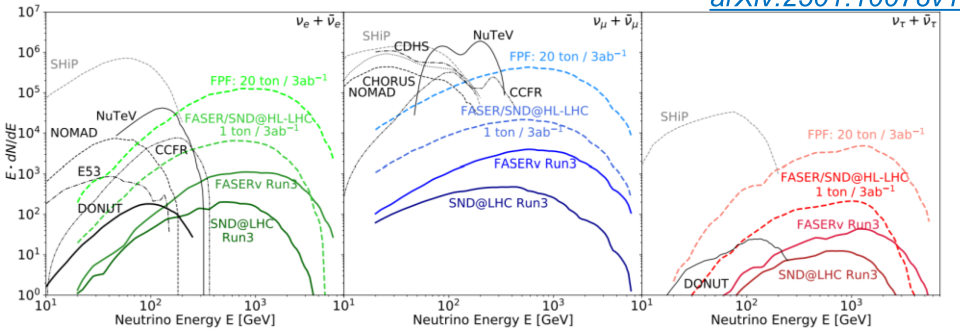
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 47 (2020) 125004 (18pp)
https://doi.org/10.1088/1361-6471/aba7ad

Further studies on the physics potential of an experiment using LHC neutrinos



arXiv:2501.10078v1



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

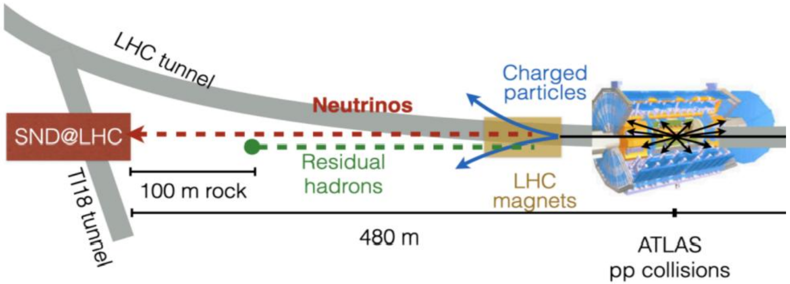
- Detection of all three types of neutrinos allows for tests of lepton flavour universality

QCD

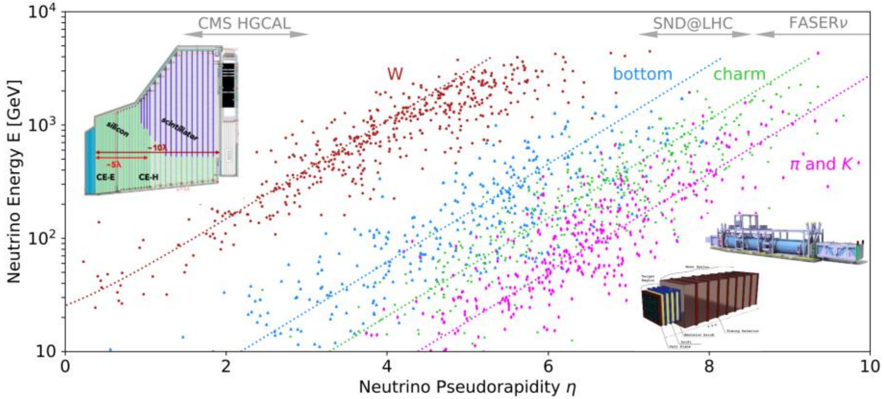
- 90% of ν_e and $\bar{\nu}_e$ **produced at SND@LHC originate from *charm* decays**
  [J. Phys. G: Nucl. Part. Phys. 47 125004]
  -> indirect measurement of charm cross section
- constrain the gluon distribution in the proton at **low x** (x~10^{-6})

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]



480 m downstream of ATLAS IP1 in TI18 tunnel
– shielded by 100 m of rock and LHC magnets



Location of the detector in the TI18 tunnel

View of the machine to the IP (left) and of the detector in TI18 (right)

Location benefits

1 Existing site (avoided major engineering work)

2 **Natural protection**

100 m of rock effectively shields the detector from charged particles and background from the collision point

3 Use of LHC magnets to deflect charged particles

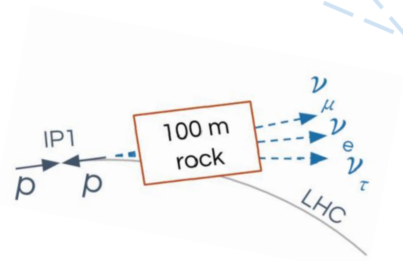
SND@LHC – Hybrid Detector

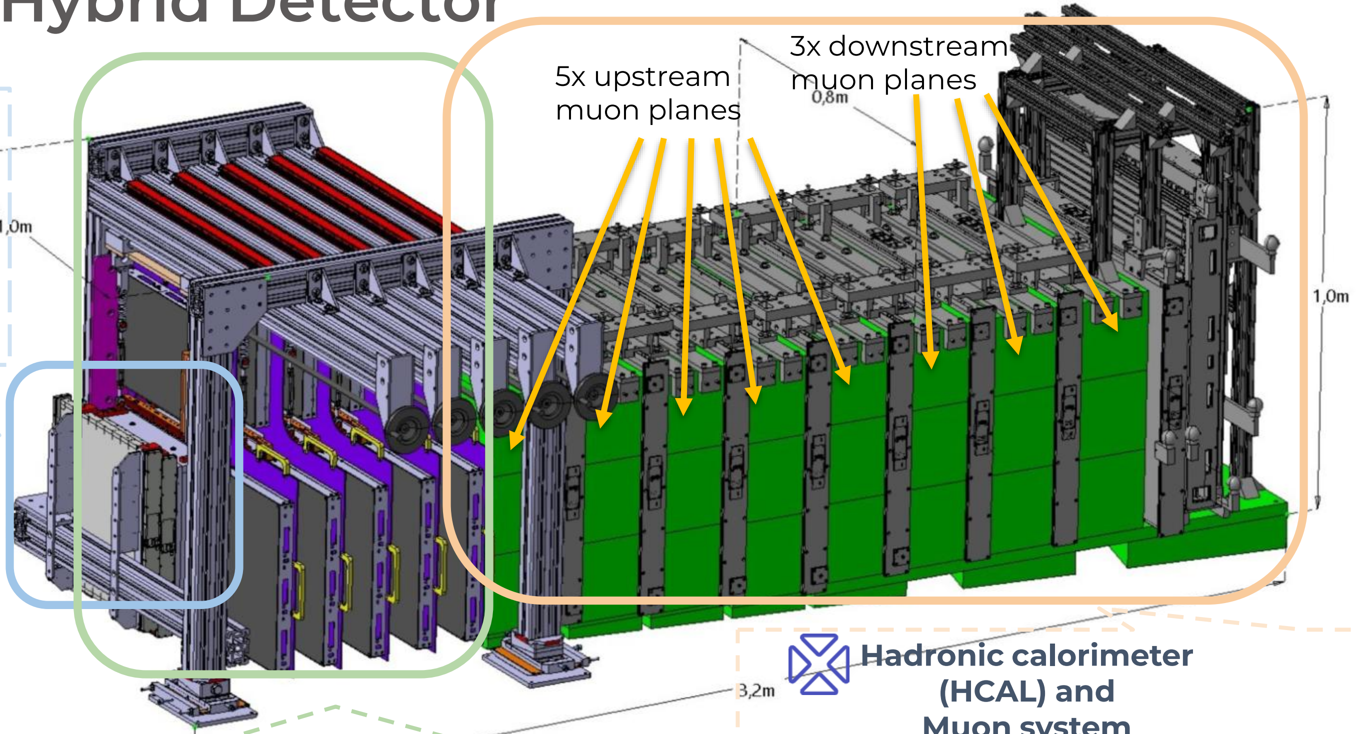
[JINST 19 (2024) 05, P05067]

Veto system

2 (2022 – 2023) / 3 (2024 – now)
1 cm thick scintillator planes
[*JINST* **20** P07011]

- Reject charged particles and suppress muons





Target region

Emulsion Cloud Chamber (ECC)
Tungsten emulsion films 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

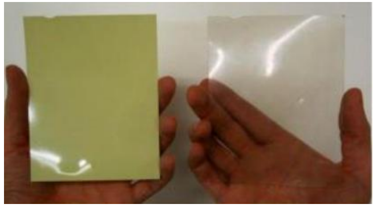
8 Fe absorbers + 8 scintillator planes interleaved with iron:

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

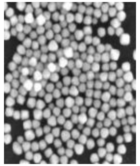
Emulsions - Exposure to Analysis

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

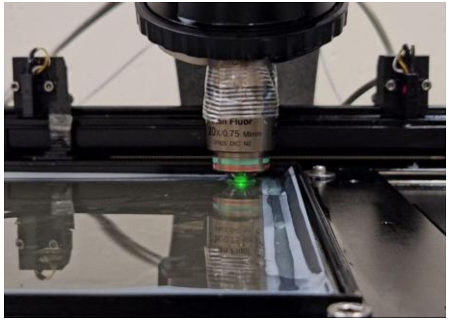
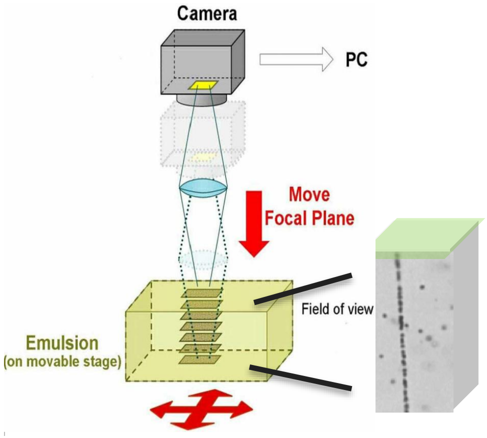


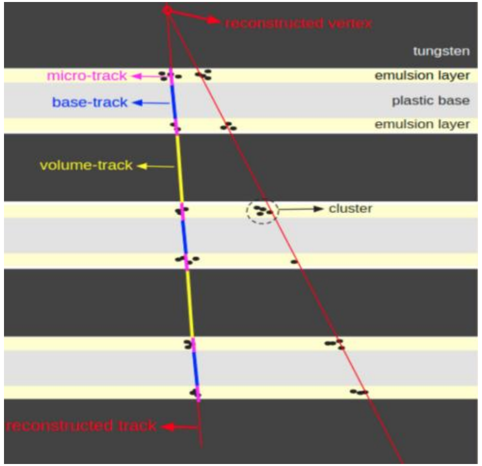



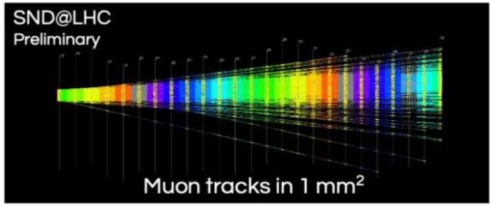
before + after



6 Laboratories

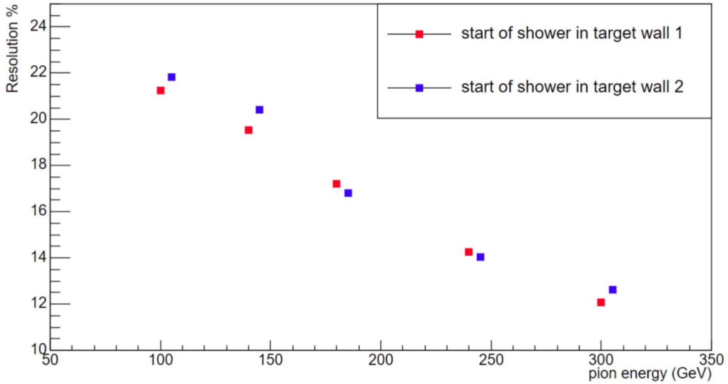



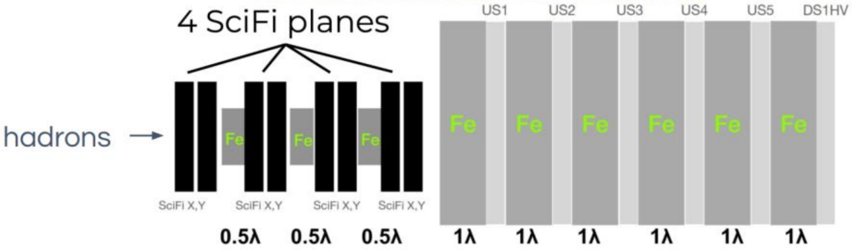


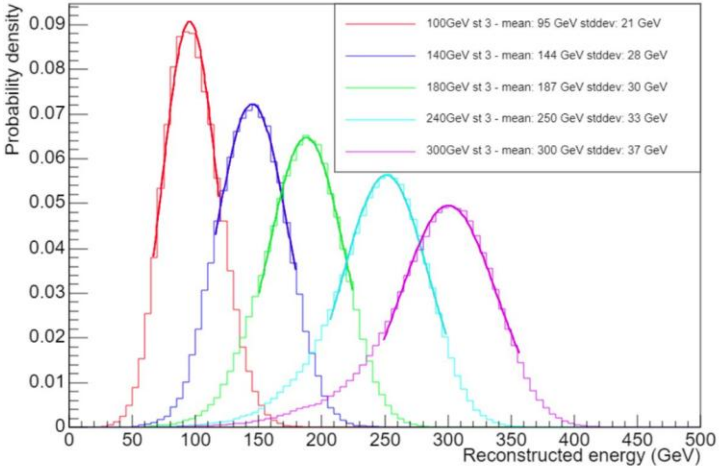


Energy calibration with testbeam data

- Very successful hadron test beam data taking campaign in August 2023
- Exact replica of the hadron calorimeter
- Downsized mockup of the target
- Energy deposited in target contributes significantly
- Calibrated calorimeter response JINST 20 P10039







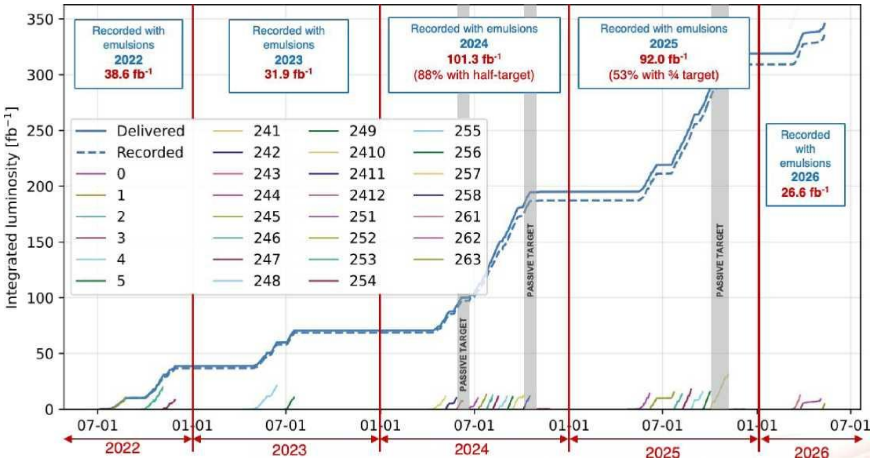
SND@LHC during Run 3 of LHC

Electronic Detectors

~340 fb^{-1} Recorded (2022-2026)	**97%** Uptime

2022:	36.8 fb^{-1}
2023:	31.8 fb^{-1}
2024:	118.6 fb^{-1}
2025:	122.1 fb^{-1}
2026 (ongoing):	**31.3 fb^{-1}**

Integrated Luminosity per Year



Emulsion Detectors

23 Targets Exposed and developed in 2022-2026	**810 m^2** Emulsion Area

Track density: < 4 × 10^5 tracks/cm^2 (OPERA × 10^3)

Percent of total luminosity recorded with emulsions: 83%

Event Reconstruction

- **Online:** With electronic detectors for real-time selection
- **Offline:** With emulsion detectors for precision vertexing

Emulsion scanning is carried out in 6 laboratories : CERN, Napoli, Bologna, Nagoya, LNGS, Santiago

Muon Flux Measurement

Muons are the primary background for neutrino interaction searches
• The muon flux is dependent on LHC configuration (e.g. crossing angle)
• Published 2022 muon rates: Eur. Phys. J. C (2024) 84: 90
• 2023-2025 muon rates for pp and heavy-ion runs: arXiv:2602.23412, submitted to EPJC

Proton Collisions

2023 Data: $\Phi_\mu = (1.90 \pm 0.04) \times 10^{-2}\ \mathrm{nb/cm^2}$

2024 Data: $\Phi_\mu = (3.74 \pm 0.06) \times 10^{-2}\ \mathrm{nb/cm^2}$

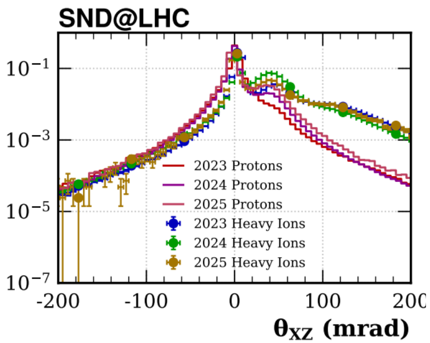
2025 Data: $\Phi_\mu = (2.48 \pm 0.04) \times 10^{-2}\ \mathrm{nb/cm^2}$

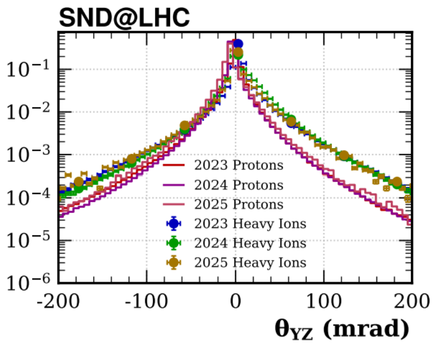
Heavy-Ion Collisions

2023 Data: $\Phi_\mu = (3.13 \pm 0.11) \times 10^{4}\ \mathrm{nb/cm^2}$

2024 Data: $\Phi_\mu = (5.54 \pm 0.17) \times 10^{4}\ \mathrm{nb/cm^2}$

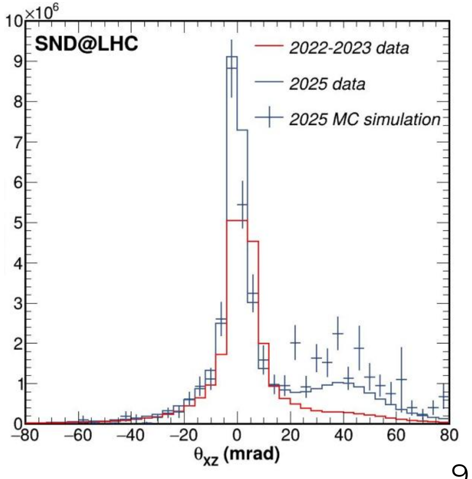
2025 Data: $\Phi_\mu = (3.60 \pm 0.13) \times 10^{4}\ \mathrm{nb/cm^2}$



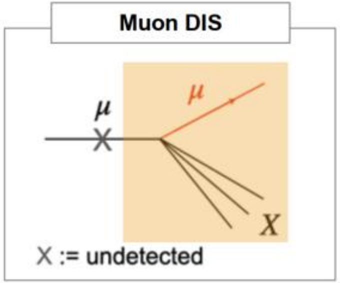


The measured muon fluxes are in good agreement with Monte Carlo: at the level of ~10% for 2023–2024, ~20% for 2025, and ~5% for 2023.

Muon origins and data/LHC FLUKA simulation comparisons for the Run-3 proton runs in close collaboration with the CERN SY-STI team arXiv:2603.21878

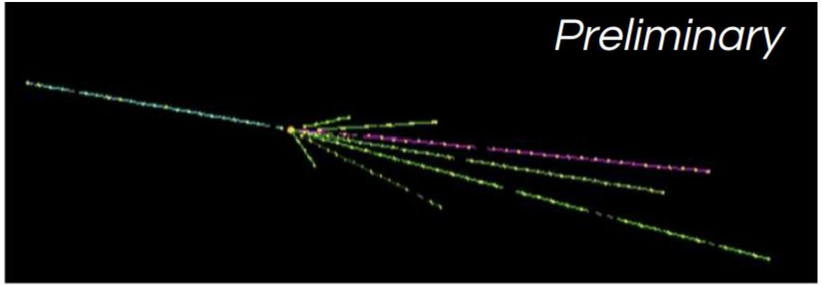


Muon DIS search with emulsion



- Selection based on topological and kinematic variables

Muon DIS event candidate



Preliminary

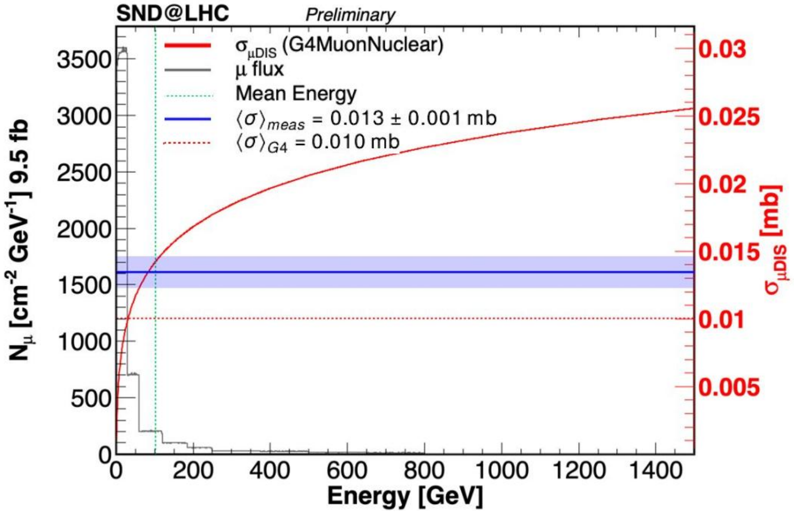
Number of events expected in 1 brick x 9.5 fb^{-1}: 225 ± 14

- Signal: 210 ± 13
- Background: 15 ± 4
  - Passing muons: 10 ± 3
  - Hadronic re-interactions: 5 ± 2

Number of events observed: 288

Muon DIS cross-section:

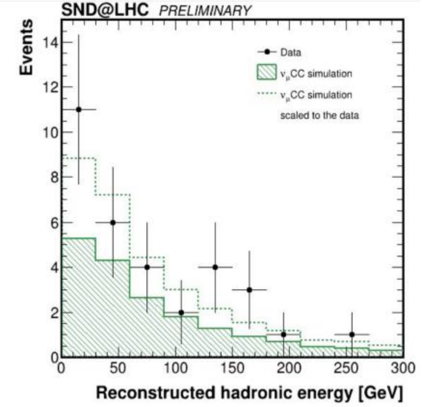
- Expected: 0.010 mb
- **Measured: 0.013 ± 0.001 mb**

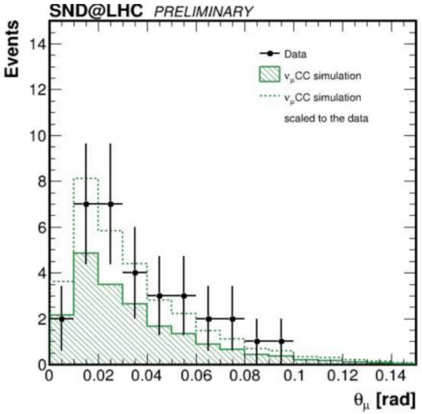


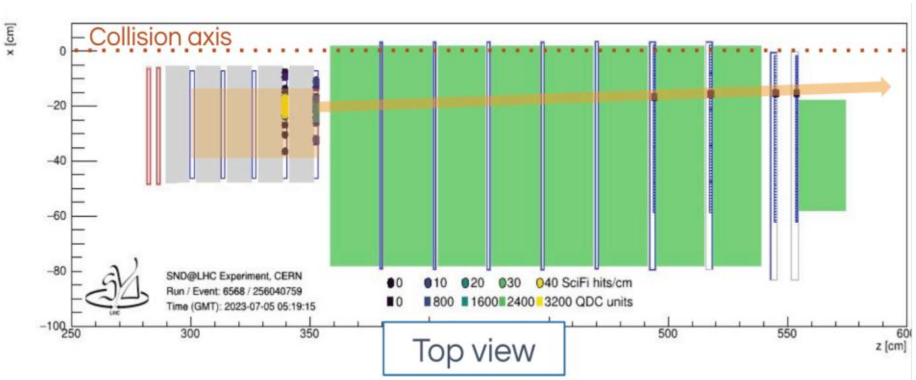
Muon Neutrino Observation

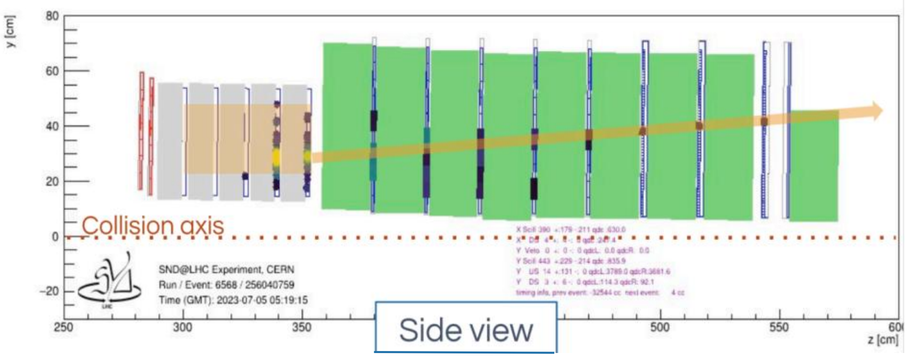
Publication with 2022 data in [Phys. Rev. Lett. 131, 031802](#) [(8 neutrino event candidates with 0.09 background)](#)

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









The signs of these interactions are:

- **Isolated muon track** in muon system
- **Hadron shower** in SciFi and HCAL
- **No veto hits** for incoming charged particles

Muon Neutrino Observation

Updated Results (2022+2023 Data)

- Selection update: extended acceptance from 7.5 to 18%, time-filtering of signals, MC Event Building
- Background expectation updated with side-entering background estimation
- Signal expectation updated with EPOSLHC+POWHEG as baseline

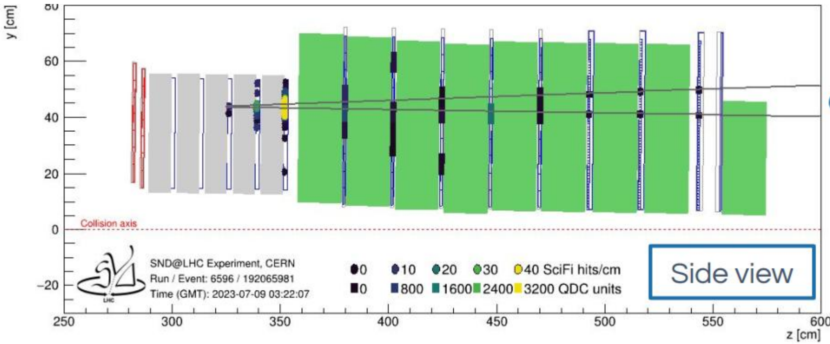
Preliminary:

Data 2022+2023:
Integrated Luminosity 68.6 fb^{-1}
Expected Signal Events 24^{+10}_{-9}
Number of events observed: 31
background 0.5 ± 1.1
○ Entering muons: 4.7 ± 1.1
○ Neutral hadrons: 0.3 ± 0.1

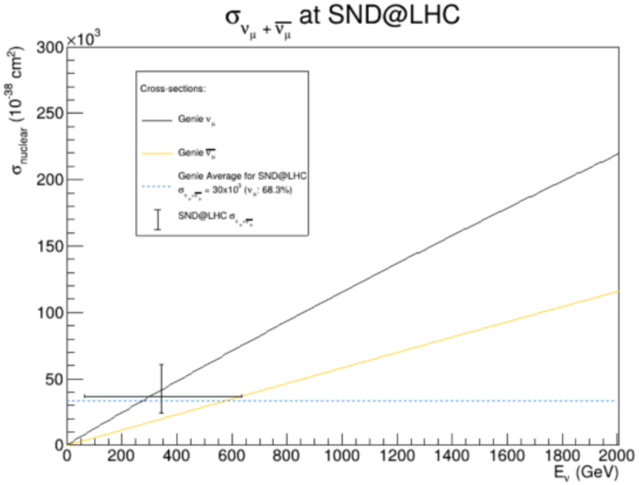
Preliminary:

The nuclear cross section averaging the (anti)neutrino energies:
○ Expected: 34 x 10^{-35} cm^2
○ Measured: 37^{+24}_{-12} x 10^{-35} cm^2

selected ν interaction with 2 muons in final state



charm?

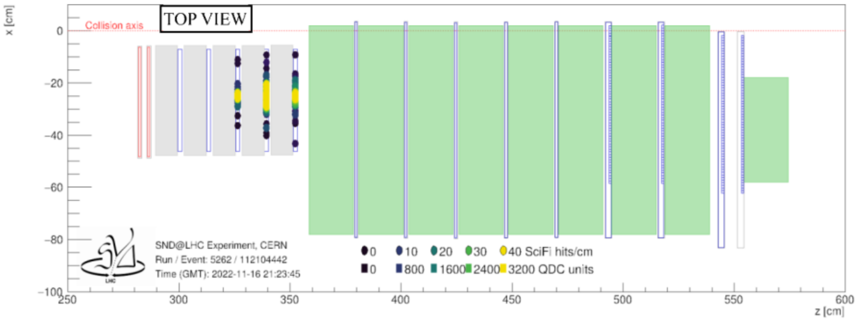


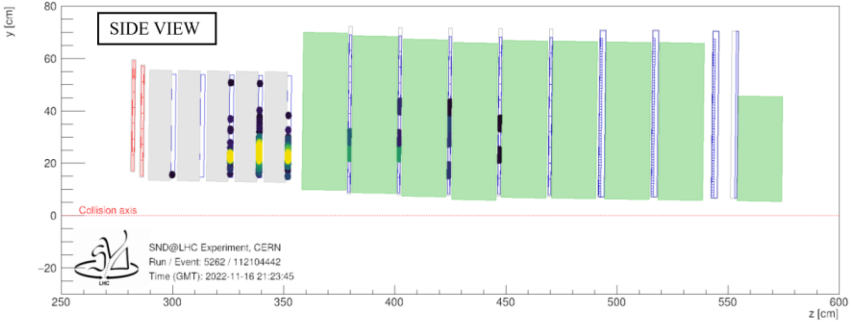
0μ Neutrino Observation With 2022-2023 data

[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:

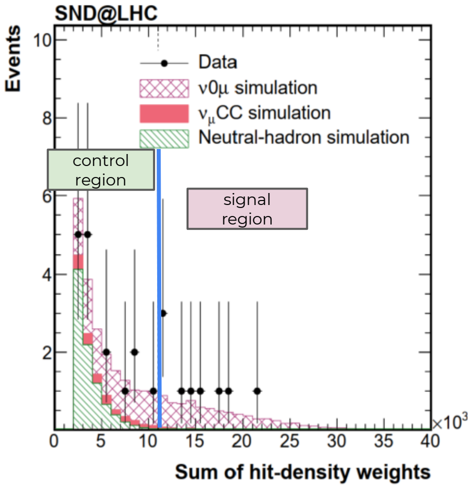
- CC interactions of $\nu\mu$ in which the muon was not detected or identified, **0.30** events

- 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

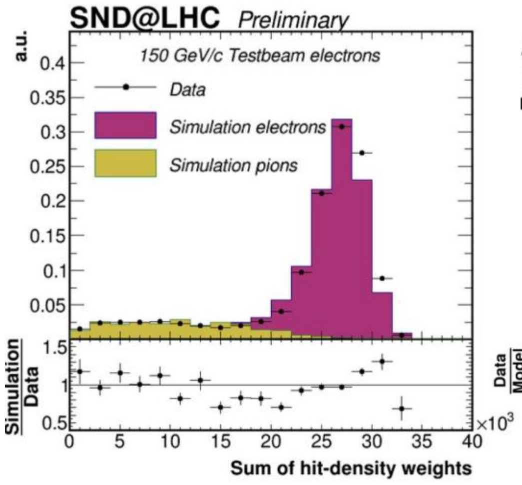
Expected significance: 5.5σ

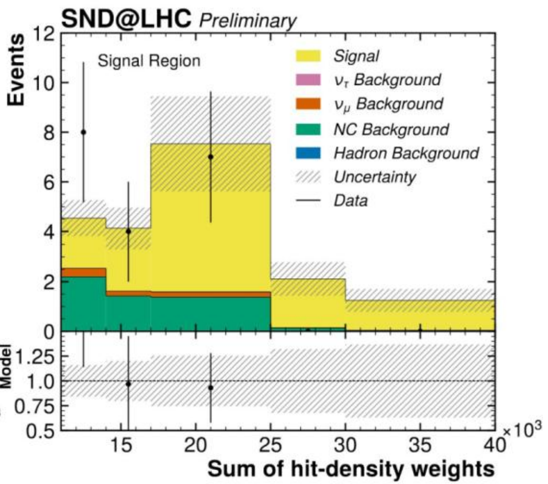


Number of events observed: 9
Observation significance: 6.4σ

ν_eCC with electronic detectors with 22-24 data

Binned likelihood analysis on the summed hit density weights in target, and a count based check





Preliminary:

Expected events in 2022 - 2024, 68.6 + 102.0 fb^{-1}: 19 ± 5

*excluding 12fb^{-1} of 2024 due to SciFi connection issue

Signal: 13 ± 5

Background: 6 ± 1

Observed events: 19

= 9(2022-2023) + 10(2024)

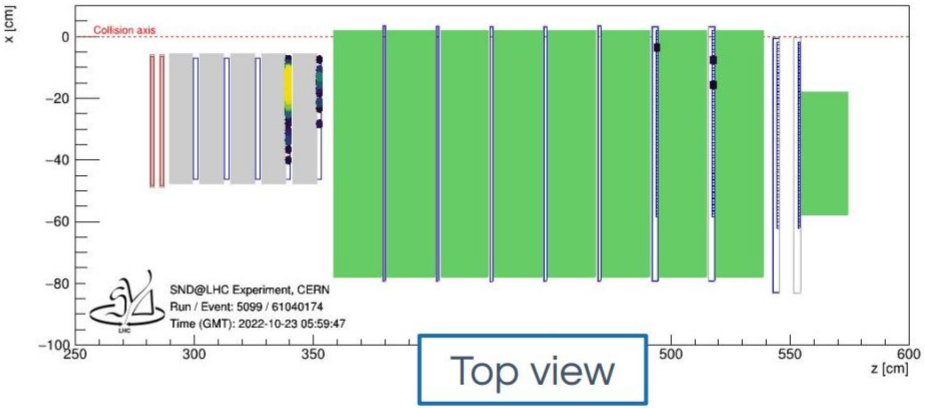
Significance for the binned(unbinned) data, using DPMJET as baseline:

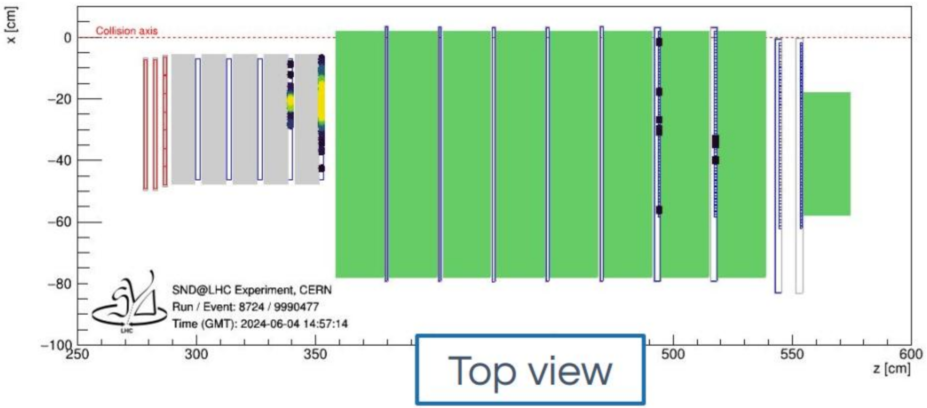
Expected: 4.5 σ

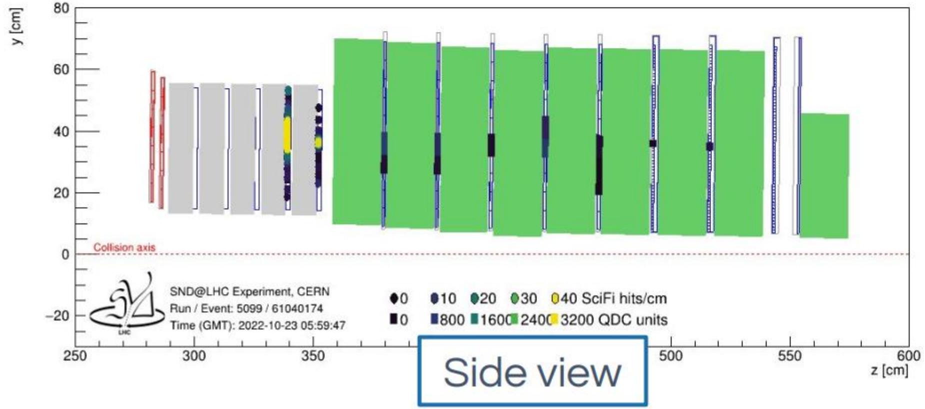
Observed: 2.7 σ

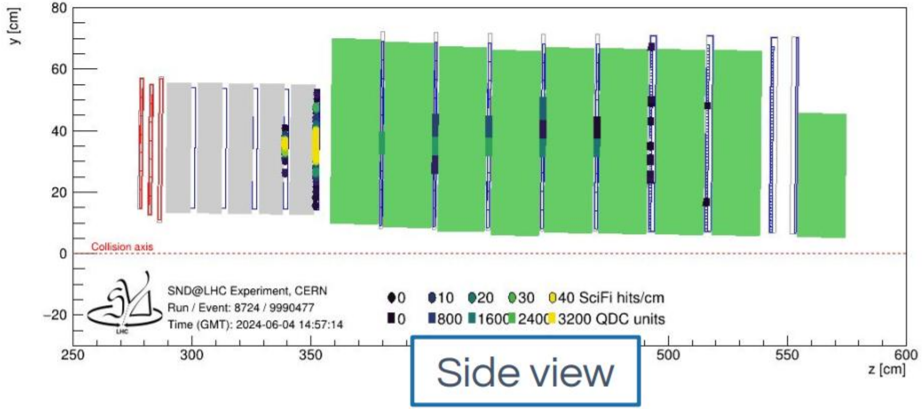
- Clear evidence of ν_e component in the electronic detector data
- Investigating the reason simulation does not predict the shape of the hit density distribution well enough
- On the physics model side: EPOSLHC(light)+POWHEG(heavy hadrons) were also tested

ν_eCC events candidates





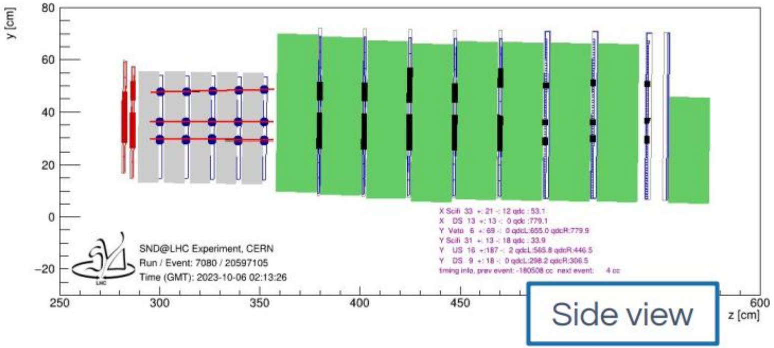




Muon trident process

SND@LHC is sensitive to muon trident interaction in the upstream rock

$$\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$$



- Choice of generator has a potentially large impact on the efficiency correction.
- Considering both Geant4 and MESMER
- Currently evaluating our efficiency with MESMER.

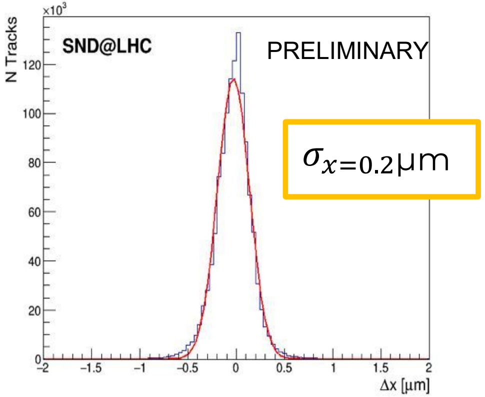
ν_τ magnetic moment

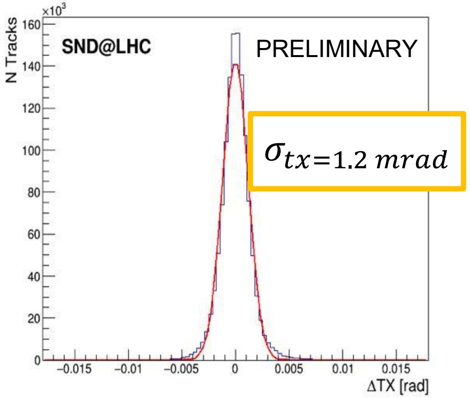
- Signal: ν_τ- electron scattering
- Signature: single EM shower, no hadronic activity
- Preliminary neutrino background prediction: 0.22 events
- Assuming no events are observed in 309.3 fb^{-1}, the expected preliminary sensitivity is 3.68 x $10^{-6}\,\mu_B$
- Extrapolating to HL-LHC and assuming same efficiency as DONuT, expect 2.9 x $10^{-7}\mu_B$

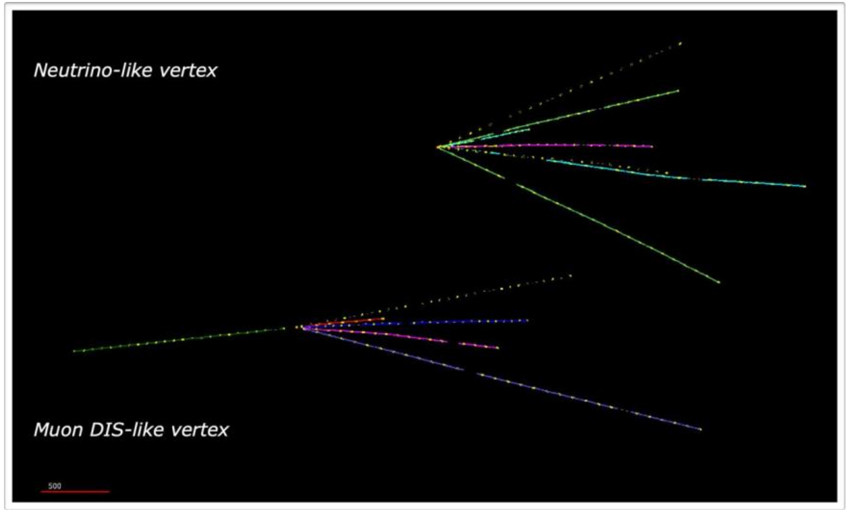
Upgrades in emulsion data processing

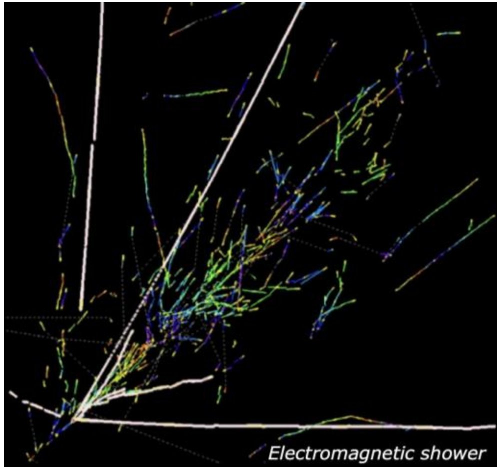
FEDRA software *Tioukov et al. (2006), NIM A559:103–105.*
upgraded
Track density up to 4×10^5 tracks/cm^2 (factor 10^3 larger w.r.t. OPERA)

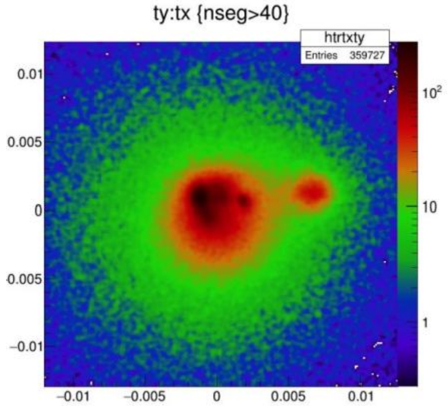
Excellent tracking resolution achieved!







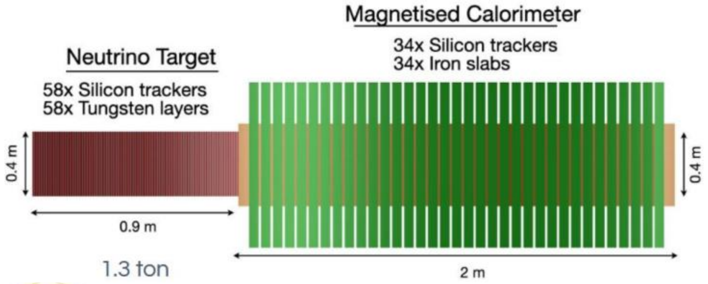


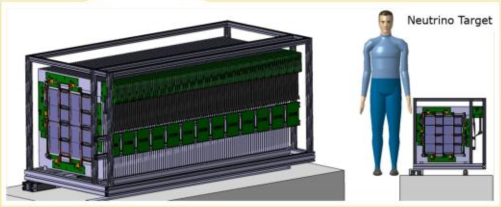


Beam core clearly visible with passing-through tracks

Work plans for the HI-LUMI period

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





The SND@HL-LHC detector schematic, realized in 3D modeling, side view

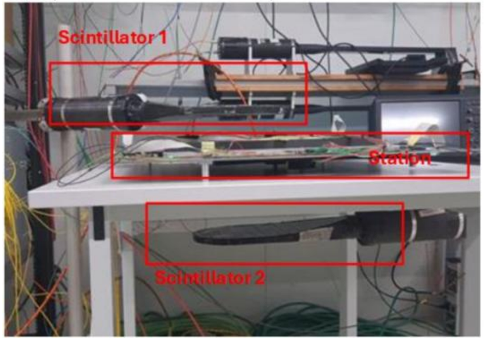
A fivefold increase in luminosity is expected (up to 680 fb^{-1}) -> the use of emulsions is impossible

- **Replace emulsions with silicon strips**

Reuse from the CMS tracker (Outer Barrel)
Will be the first neutrino vertex detector based on Silicon
- 30 μm resolution expected
- First cosmic rays with prototype

- **New magnetized calorimeter**

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

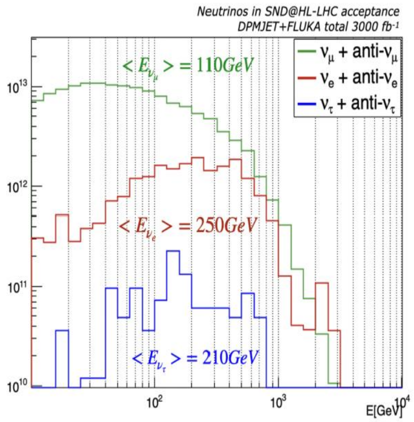


16 x 16cm^2 scintillators for testing cosmic rays placed above Si strip modules 4 and 5

Expected neutrino interactions in the Target in Run4, 3000 fb^{-1}

Flavour	DIS-CC	DIS-NC
$\nu_\mu + \bar{\nu}_\mu$	1.5×10^4	4.8×10^3
$\nu_e + \bar{\nu}_e$	2.9×10^3	9.0×10^2
$\nu_\tau + \bar{\nu}_\tau$	1.4×10^2	5×10^1
Tot	1.8×10^4	5.7×10^3

13 times more statistics than Run3!

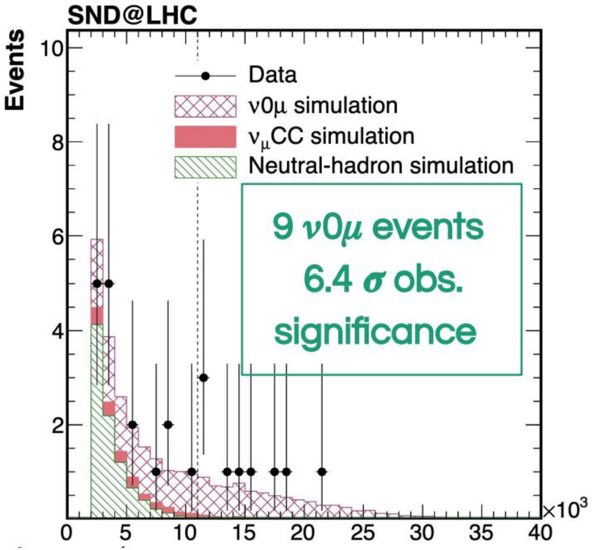


Summary and Outlook

- SND@LHC measures neutrinos in the forward region of pp collisions.
- Recorded 310 fb-1 of 2022-2025 data, 97 % detector uptime
- Run3 muon flux measurement in agreement with LHC FLUKA prediction

Progress in emulsion data reconstruction with excellent tracking resolution and semi-automatic processing chain

Preliminary ν_μ nuclear xsec:
$37^{+24}_{-12} \times 10^{-35}\ \mathrm{cm}^2$



- Reported evidence of ν_eCC in electronic detectors
- Muon trident and sensitivity to BSM underway; including 2024-2025 data in analyses
- First Run4 prototype station currently taking cosmic ray data!

Thank you for your attention!

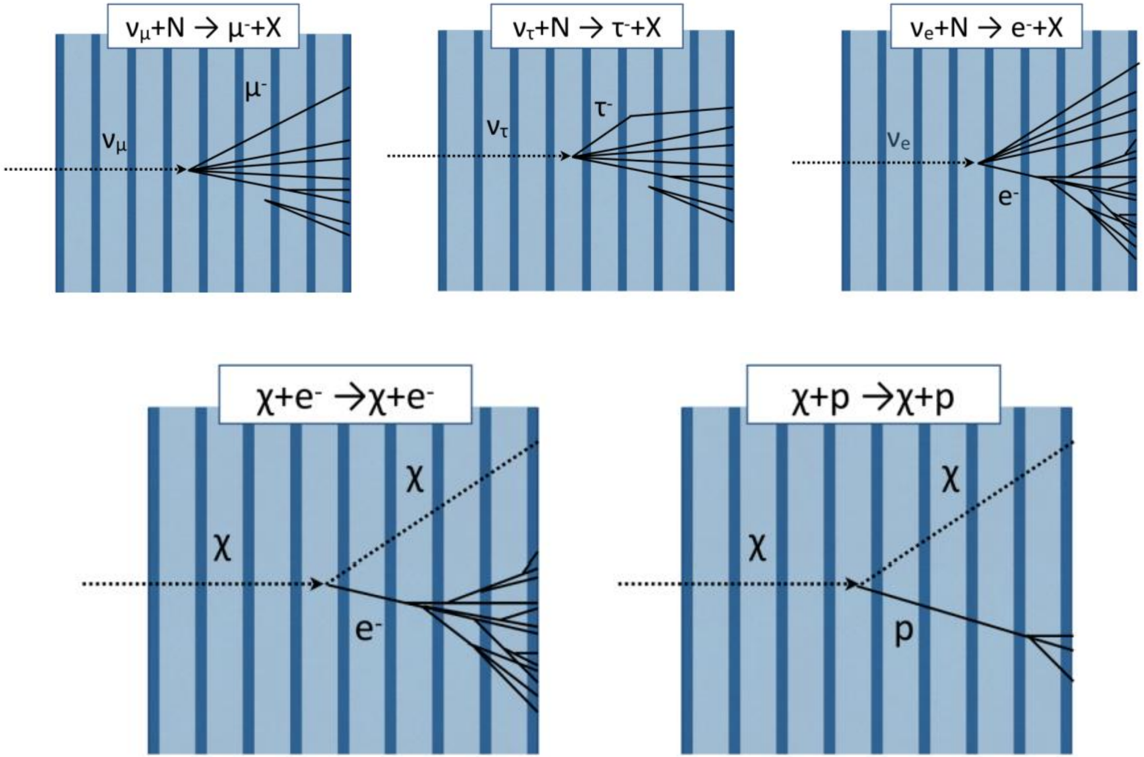
Neutrino Signature

Vertex Detector and ECAL

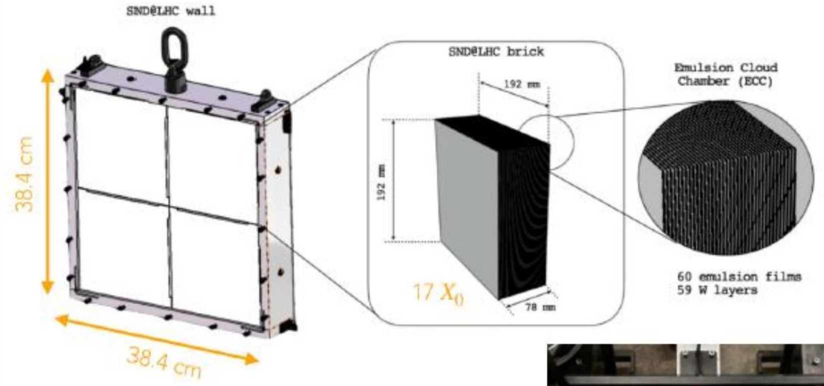
- EM shower
- Second vetex of τ

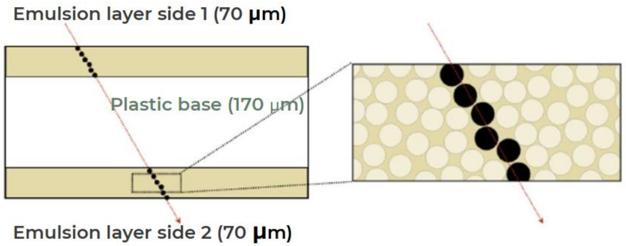
Muon system and HCAL

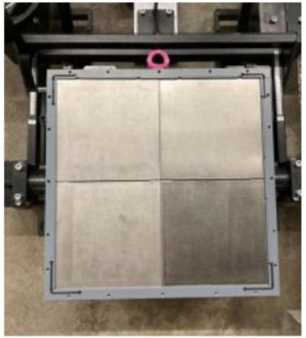
- Muon Track
- Hadronic shower



Emulsion target

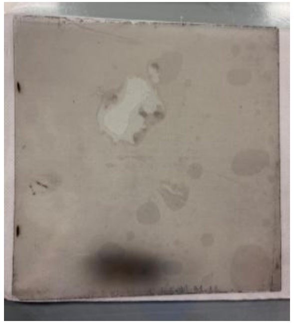






single SND wall composed of 4 bricks

- Full target system equipped with 5 Tungsten/emulsion walls
- Total mass: ~800 kg
- Number of emulsion films: 1200
- Limit to the integrated track density: 4×10^5 tracks corresponding to 20 (10) fb^{-1} in 2022-2023 (2024)
- Emulsion development in the CERN emulsion facility
- Emulsion scanning with automated optical microscopes in several scanning stations (CERN, Bologna, Gran Sasso, Nagoya, Napoli, Santiago)

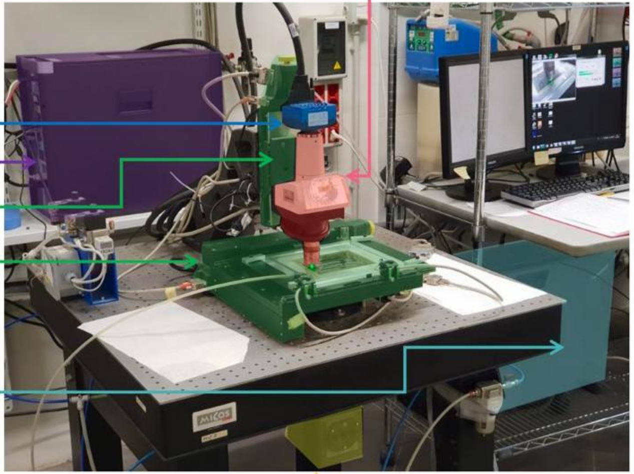


Emulsion scanning

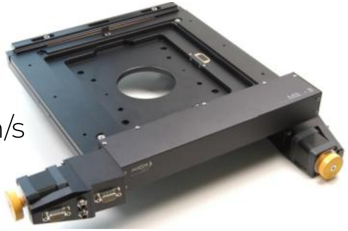
Nucl. Instrum. Meth. A **568** (2006) 578

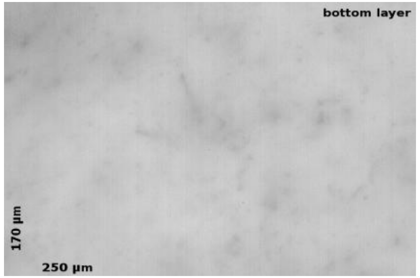
LHC
Scattering and Neutrino Detector at the LHC

Optical microscope
Illumination system
Image acquisition system
Motorized stages
Control computer + SW
Processing computer(s) + SW



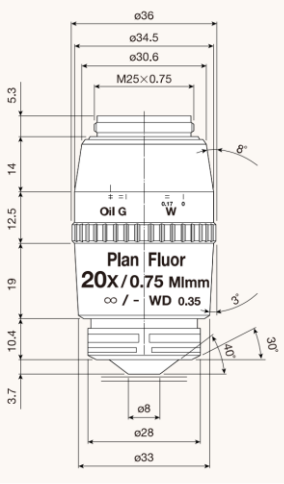
Z stage (Micos)
0.05 μm nominal precision
Max speed 30 mm/s

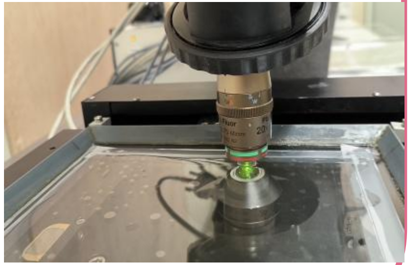




Lens

Feature	CFI Plan Fluor 20XC MI (MRH07241)
Magnification	20X
Numerical Aperture (NA)	0.75
Working Distance	0.3 mm
Immersion Medium	Glycerin, Water, Oil, Silicone
Cover Glass Thickness	0.17 mm





Emulsion scanning

Data acquisition

2015 *JINST* **10** P11006

The vertical stage starts moving until it reaches the required velocity

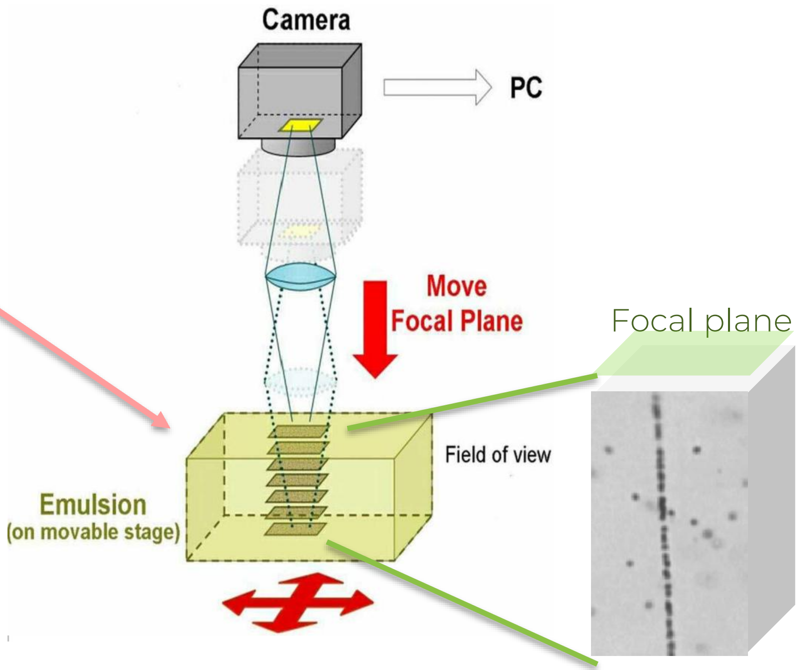
Tomographic images taken through the emulsion layer at equal steps

Images are immediately sent to the control PC for processing

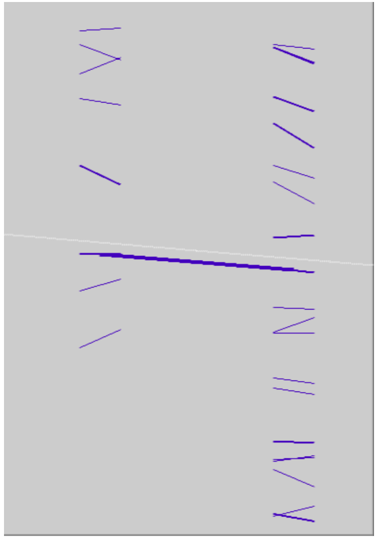
The vertical stage decelerates until a complete stop

The objective lens is moved to the beginning of the next FoV

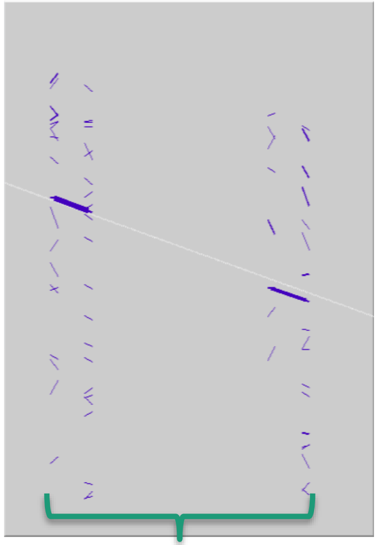
Microscope type	Standard mic (FoV = 800 × 600 μm²)		
Data rate	2336 × 1728 @ 563 fps = 2.1 GB/sec		
Scanning technique	SG	CM	IM
Time limit [ms/image]	4.2	2.5	1.7



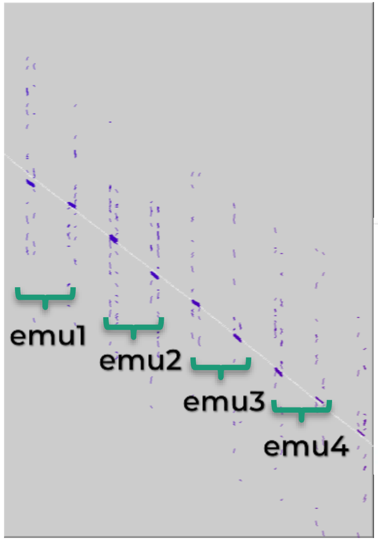
Algorithm for recognizing particle tracks in an emulsion detector



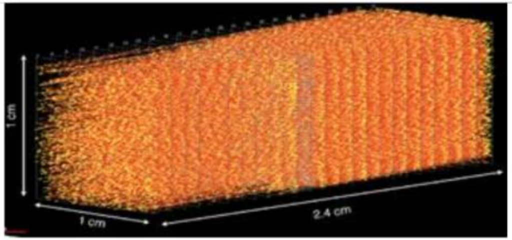
Reconstruction of **microtrack** in one emulsion layer



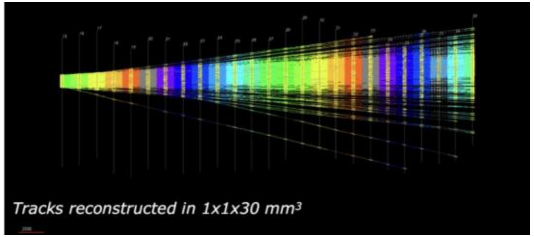
Reconstruction of the **base track** in two layers of emulsion



Reconstruction of a **volume track** in several emulsion plates



Emulsion reconstruction
Muon tracks in 1x1 cm_2 integrated in EMULSION RUN0 (7/4/22 - 26/7/22)

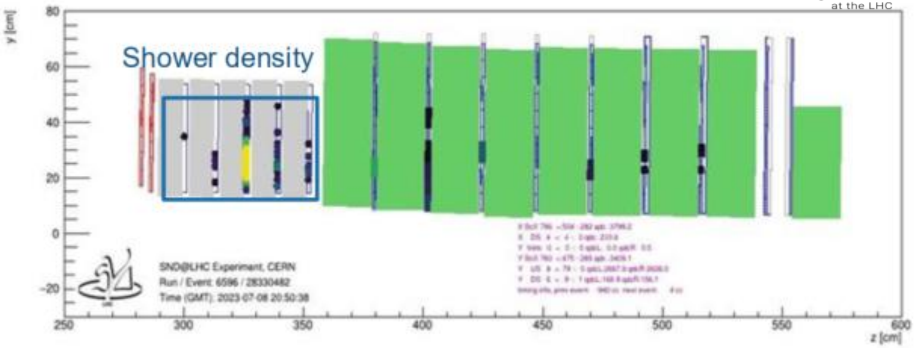


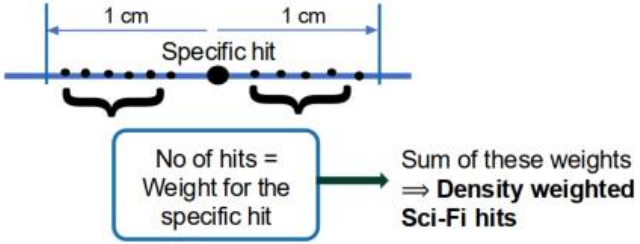
Shower density

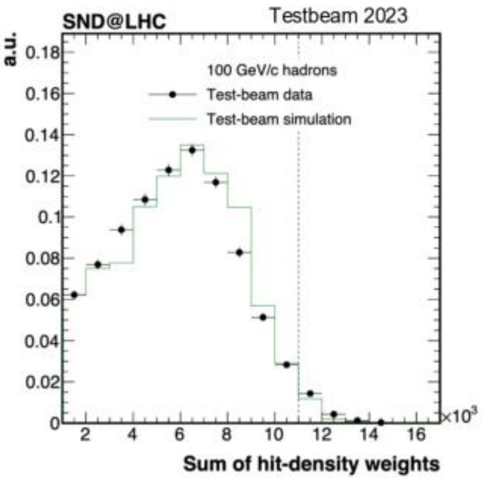
- Topological Signal Discriminator: characterizing the **shower density**.
  - **More effective than simpler metrics** like the number of Sci-Fi hits.

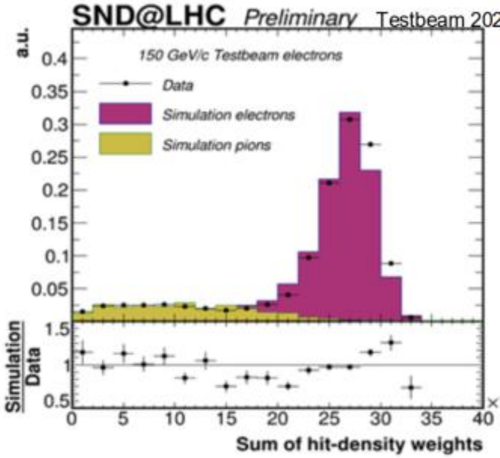
- Validated by Testbeam 2023 data - 100 GeV/c hadrons have a low sum of hit-density weights.
  (Signal selection for **0μ observation**)

- 2024 Test Beam validation – 150 GeV/c electrons have a high sum of hit-density weights, separating well from hadrons of the same energy
  (Binned Likelihood fit - **ν_e observation**)









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

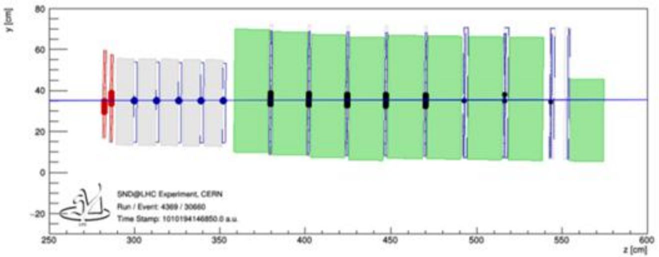
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

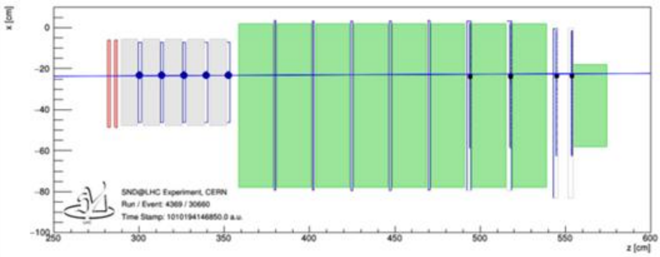
September 2021

December 2021

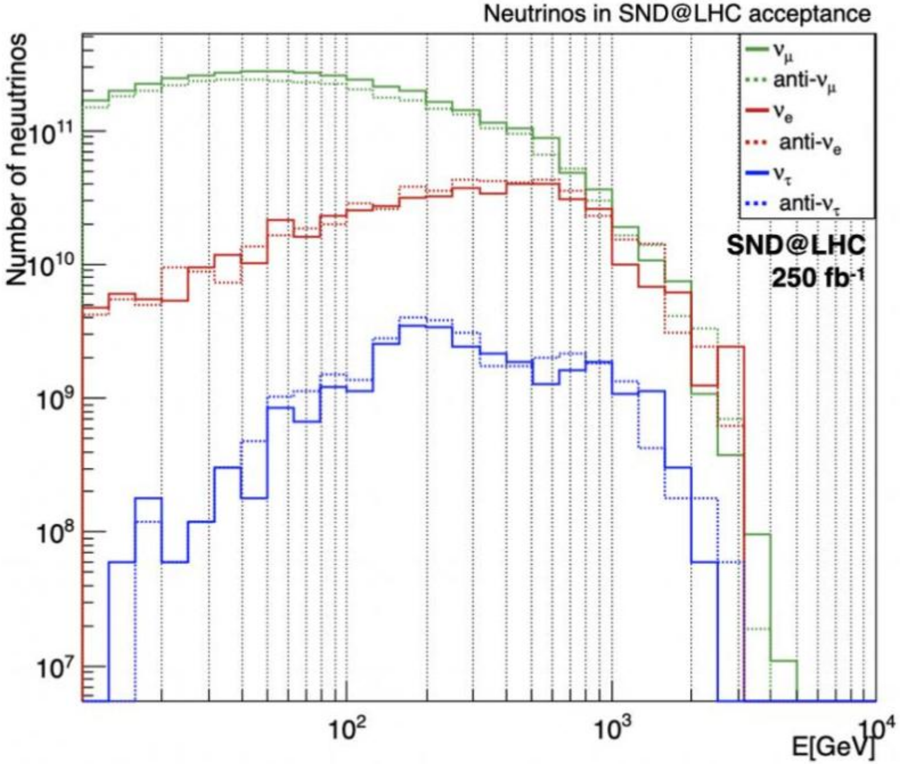
March 2022

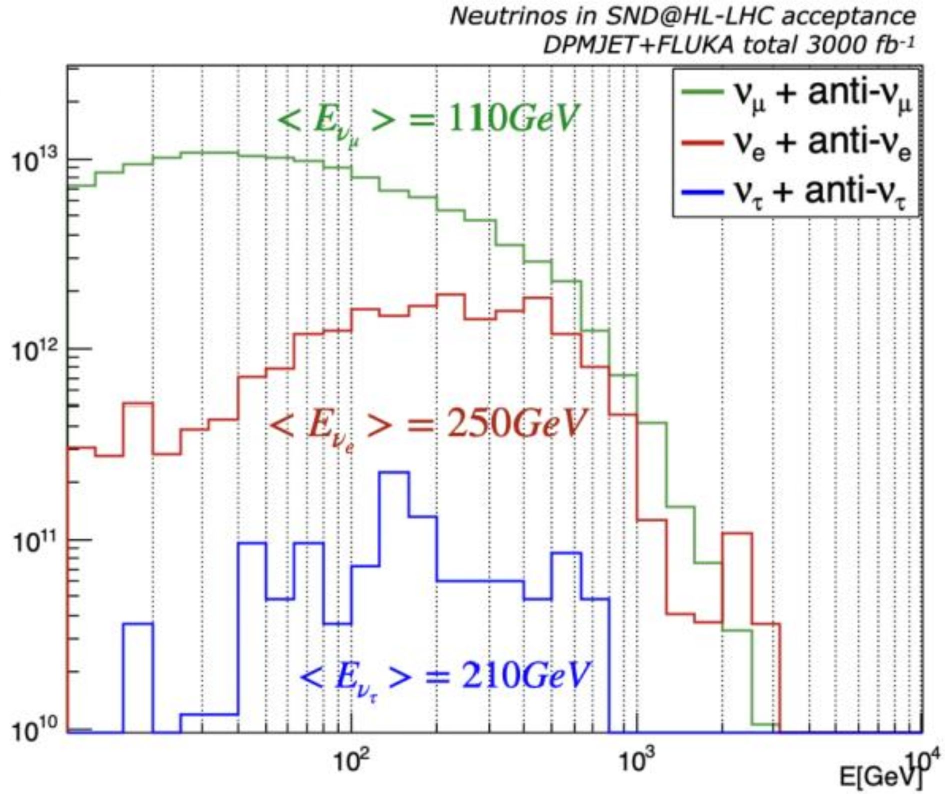
July 2022, Muons from pp collisions at 13.6 TeV recorded





Comparison of the energy spectra of three types of neutrinos in the target reception zone

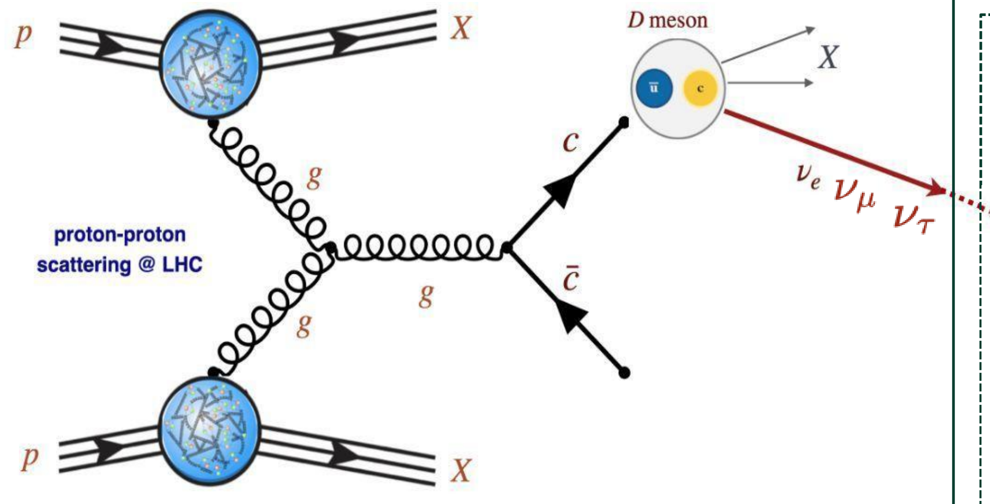




Neutrino detection at SND@LHC

LHC
Scattering and Neutrino Detector at the LHC

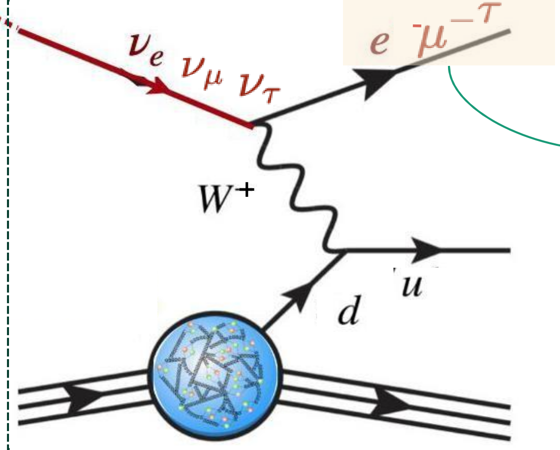
Large neutrino flux - in the **forward region**



Production - Neutrinos from weak decay of hadrons

LHC *pp* collisions ($\mathbf{pp} \rightarrow \boldsymbol{\nu_X}$ **X**)

SND@LHC in TI18

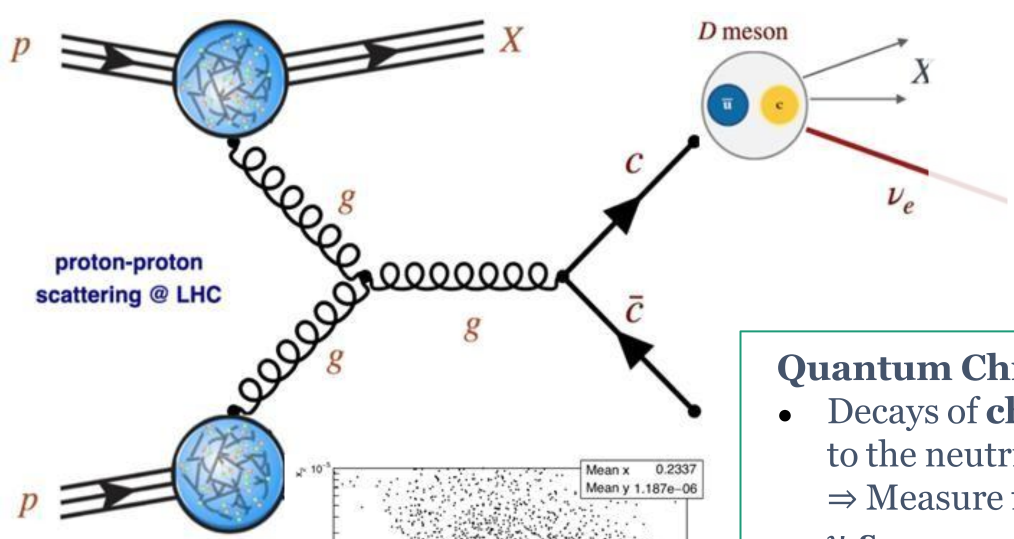


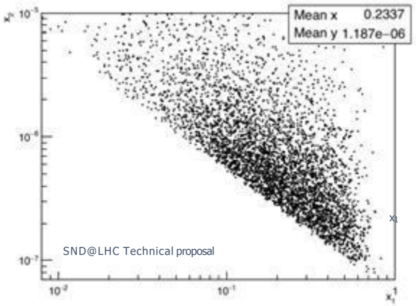
Detection signatures

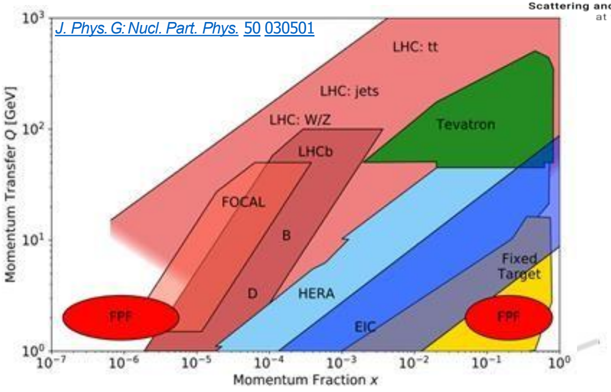
Detection – Measuring ν_X DIS interaction

Research Significance : Quantum Chromodynamics

Production - Neutrinos from weak decay of hadrons





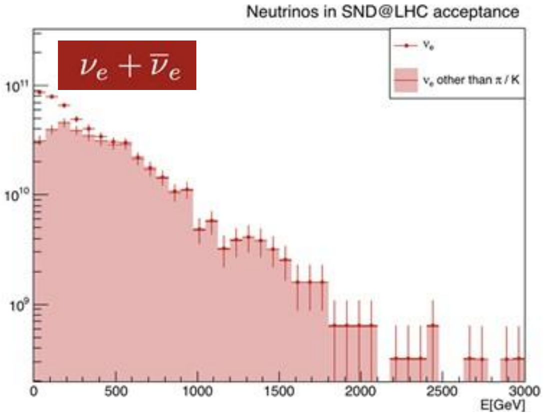


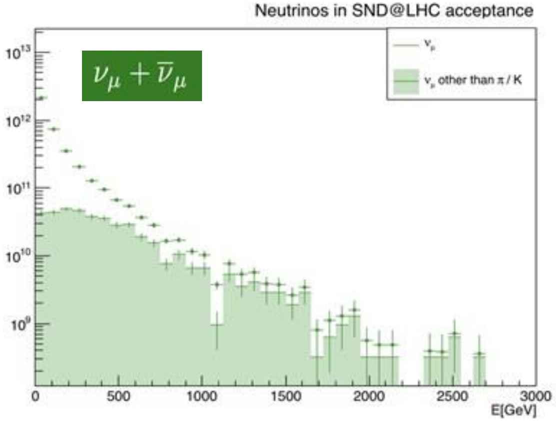
Quantum Chromodynamics

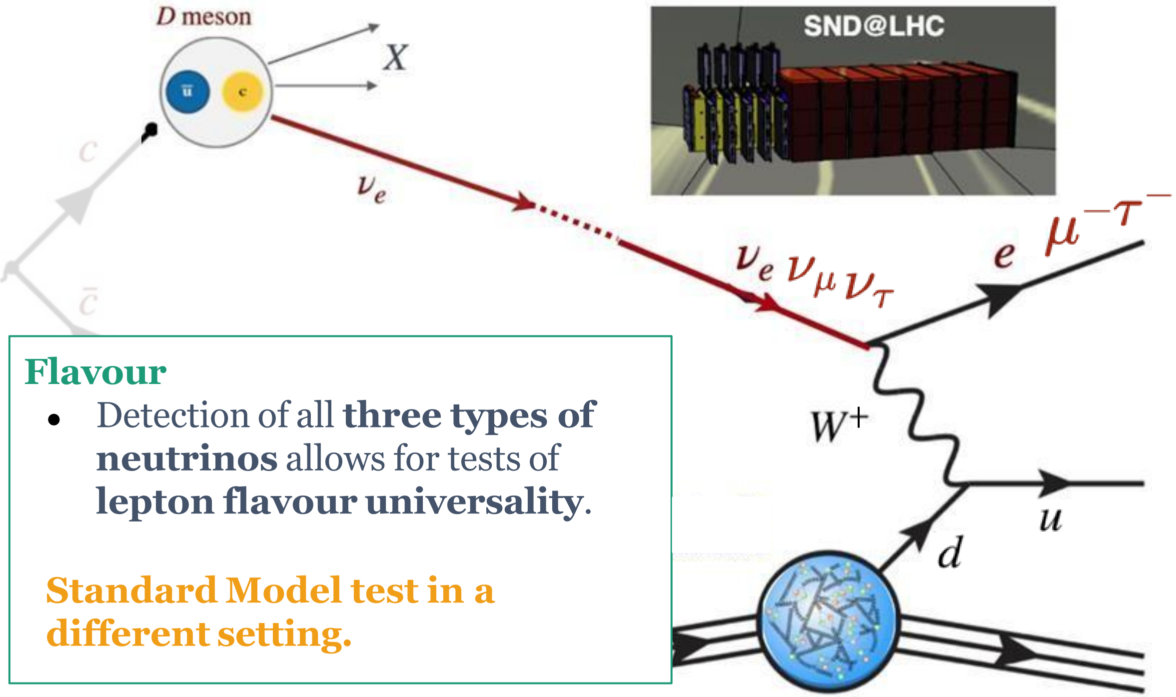
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with ν_e**s.**
  ⇒ Constrain **gluon PDF** at very **small x**

Impact on future higher energy hadron colliders and neutrino astrophysics.

Physics Goals: Lepton Flavour Universality







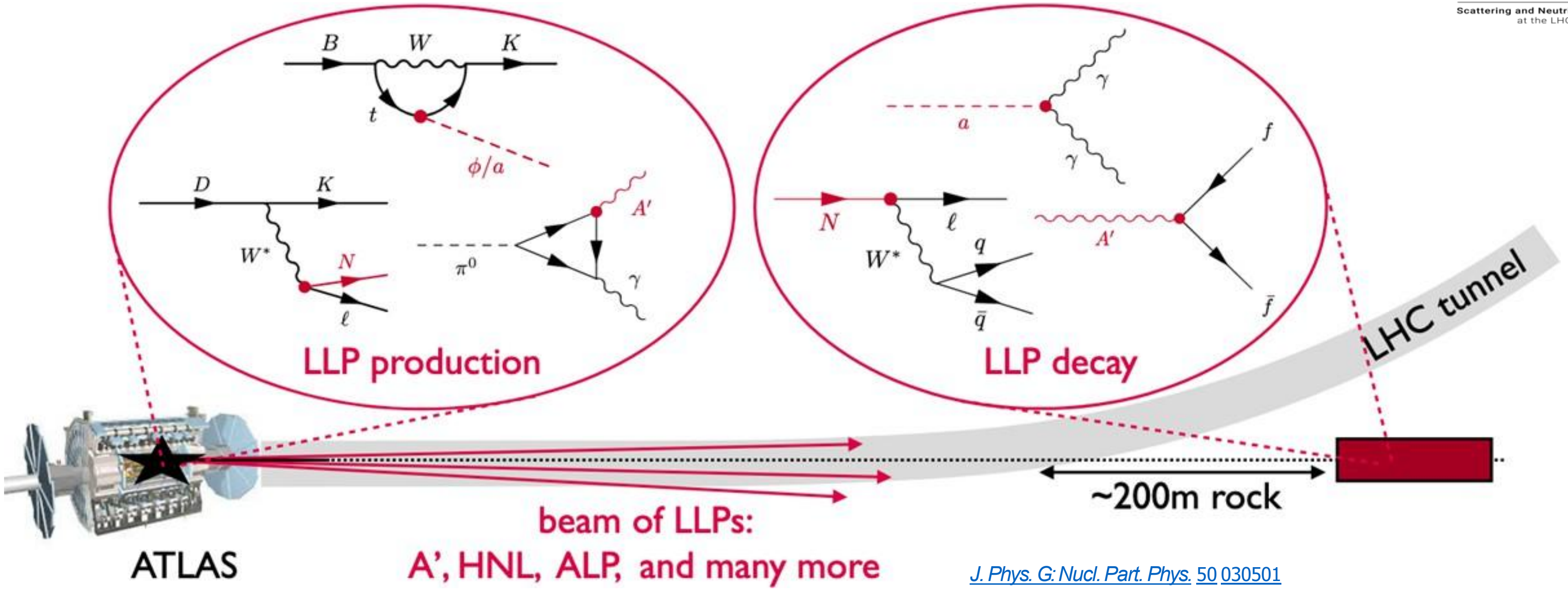
Flavour

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

Standard Model test in a different setting.

Detection – Measuring ν_X DIS interaction

Physics Goals : Beyond the Standard Model



[J. Phys. G: Nucl. Part. Phys. 50 030501]

+scattering signatures

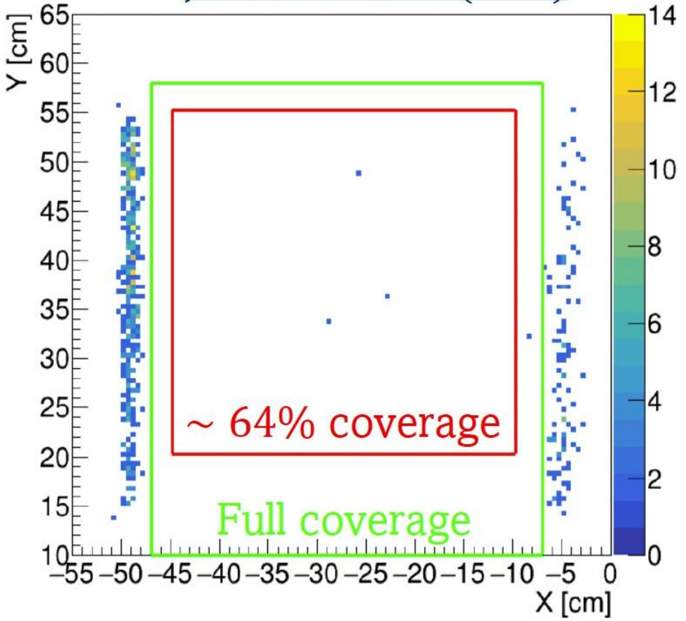
Beyond the Standard Model

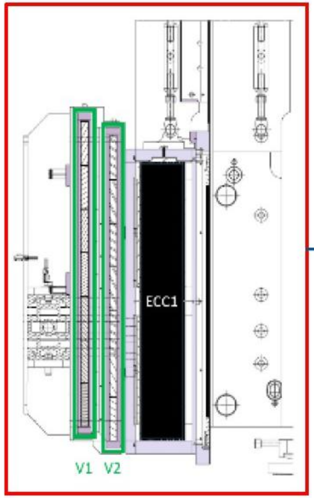
- Search for new, feebly interacting, Long-lived particles (LLP) **decaying** within the detector or **scattering** off the target.

Upgrades: 3rd Veto Plane

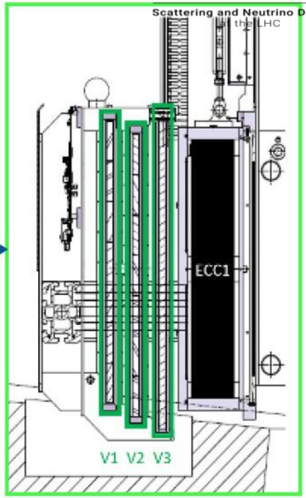
- Lowered the whole system and added a 3rd veto plane with **vertical bars** to minimize inefficiency due to spatial and temporal coincidences.

[JINST 20 P07011 (2025)]





2022/23 veto

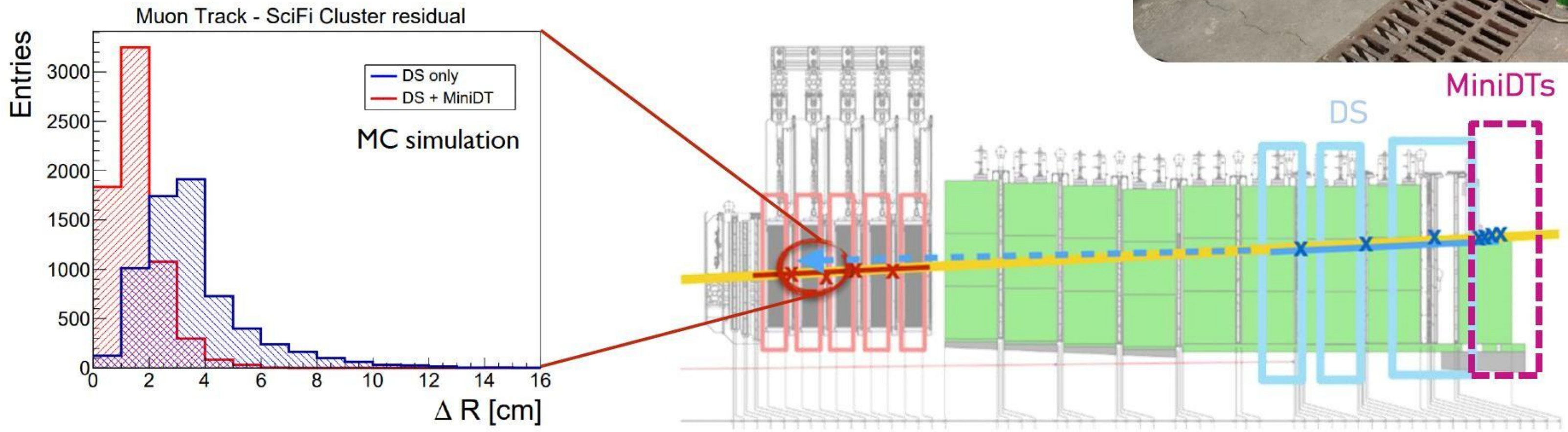


Upgraded veto

- **Before**: $(\mathbf{7.8 \pm 2.8}) \times \mathbf{10^{-8}}$ inefficiency with ~ **64% target** area coverage.
- **After**: $(\mathbf{4.9 \pm 1.9}) \times \mathbf{10^{-9}}$ inefficiency with **full target** area coverage.

MiniDTs

- Small replica of CMS drift tubes.
- **μ tracking** is fundamental for operation and ν_μ analysis.
- DS (1 cm wide bars) + MiniDT (250 μm resolution) **improves resolution** on μ impact parameter by a factor of 2 (**3 cm** $\rightarrow$ **1.5 cm**).

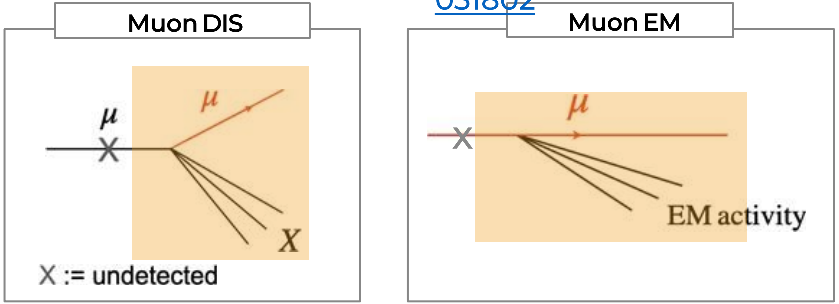


SND@LHC backgrounds

Entering muons

- Incoming muon track may be missed due to detector inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5×10^{8} SNDLHC-NOTE-2023-001
- Detector inefficiency: 5×10^{-12}
    - Two veto and two scintillating fibre planes.
- Negligible background with tight fiducial volume.

Phys. Rev. Lett. 131, 031802



Neutral hadrons

- Neutral hadrons are produced in muon DIS in materials upstream of the detector.
- Muon from pion decay-in-flight or charm production.
- Expect a total of $(8.6\pm3.8) \times 10^{-2}$ background events due to neutral hadrons.