

Recent results from SND@LHC

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EPFL



Scattering and Neutrino Detector
at the LHC



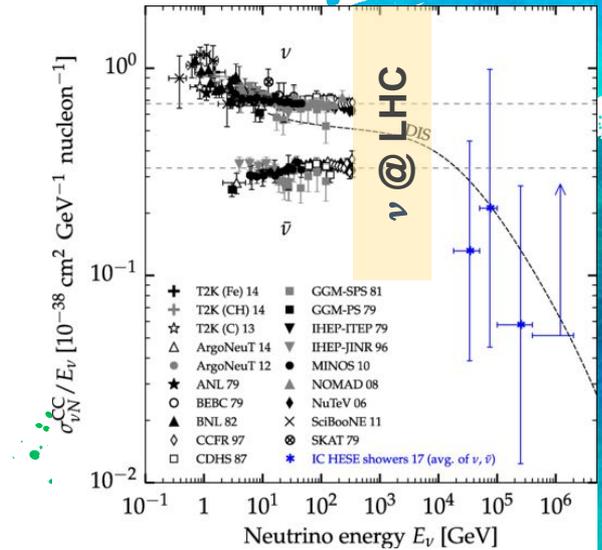
Neutrinos at LHC

Possibility to study $pp \rightarrow \nu X$ in an unexplored range:

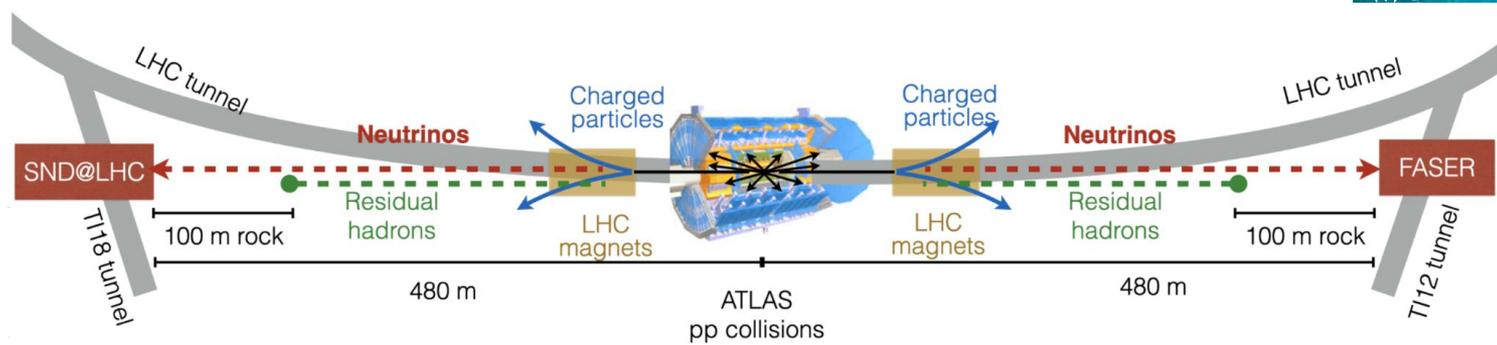
- High ν energies: $E(\nu)$ [$10^2, 10^3$] GeV
- Large ν flux in forward region from pp collisions

Currently, **two experiments** in complementary ranges:

- **FASER ν** on axis: $\eta > 9$
- **Scattering and Neutrino Detector at the LHC (SND@LHC)** slightly off axis: $7.2 < \eta < 8.4$



[PRL 122 041101 \(2019\)](https://arxiv.org/abs/1808.07401)



Physics goals

Neutrino interaction

- Measure ν interaction in unexplored \sim TeV energy range
- Observation of ν_τ with high yield

Flavour

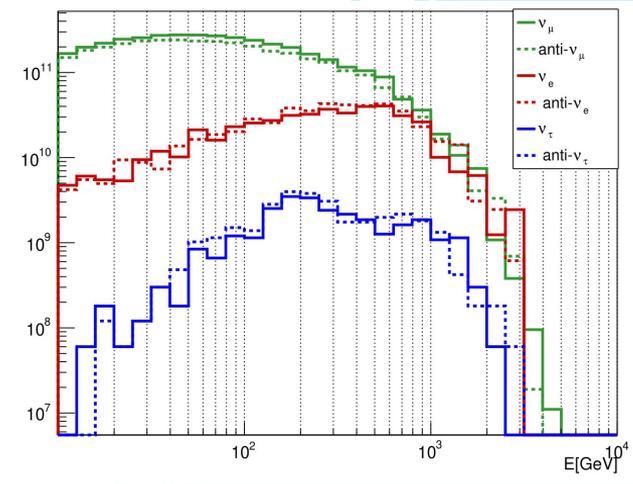
- Observation of all three neutrino flavours \rightarrow test of lepton flavour universality

QCD

- Majority of ν s in the acceptance is from charm decays \rightarrow measurement of forward charm production with ν_e

Feebly interacting particles

- Search for BSM particles decaying within the detector volume or scattering in the target

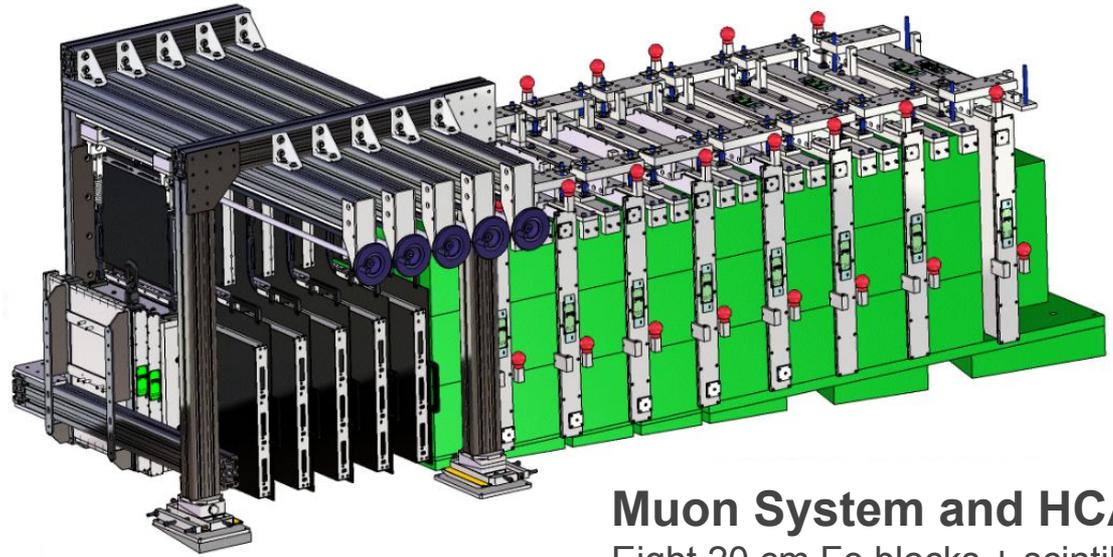
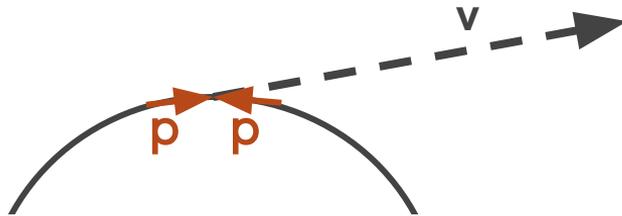


Flavour	CC neutrino interactions		NC neutrino interactions	
	$\langle E \rangle$ [GeV]	Yield	$\langle E \rangle$ [GeV]	Yield
ν_μ	452	910	480	270
$\bar{\nu}_\mu$	485	360	480	140
ν_e	760	250	720	80
$\bar{\nu}_e$	680	140	720	50
ν_τ	740	20	740	10
$\bar{\nu}_\tau$	740	10	740	5
TOT		1690		555

SND@LHC detector

Veto System

2 (2022-2023) → 3 (2024-)
scintillating bars planes to tag
charged particles



Vertex Detector and ECAL

830 kg tungsten target
Five walls x 59 emulsion layers
+ five scintillating fibre stations
 $84 X_0$, $3 \lambda_{\text{int}}$

Muon System and HCAL

Eight 20 cm Fe blocks + scintillator
planes
Last 3 planes have finer granularity
to track muons
 $9.5 \lambda_{\text{int}}$
NEW in 2025: drift-tube plane

Addition to the detector up to 2025

3rd Veto plane added

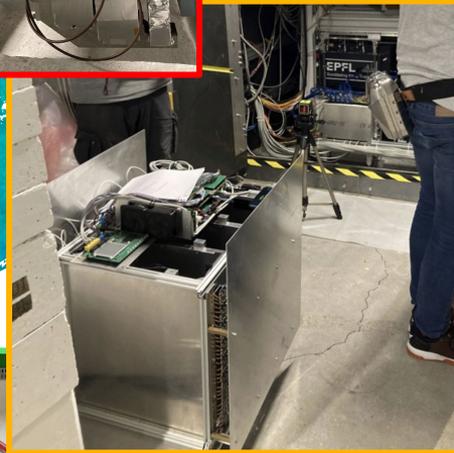
- Inefficiency lowered from $(7.8 \pm 2.8) \times 10^{-8}$ in a fiducial area to $(4.9 \pm 1.9) \times 10^{-9}$ on the full target area → expected increase of 56% of observable neutrinos

RPC telescope

- Technology demonstrator: sealed resistive-plate chambers
- Independent measurement of the muon flux → analysis ongoing
- Further validation of the background model

Muon system downstream detectors

- Two Drift Tube chambers installed downstream
- Improve muon tracking → extrapolation of tracks to the vertex



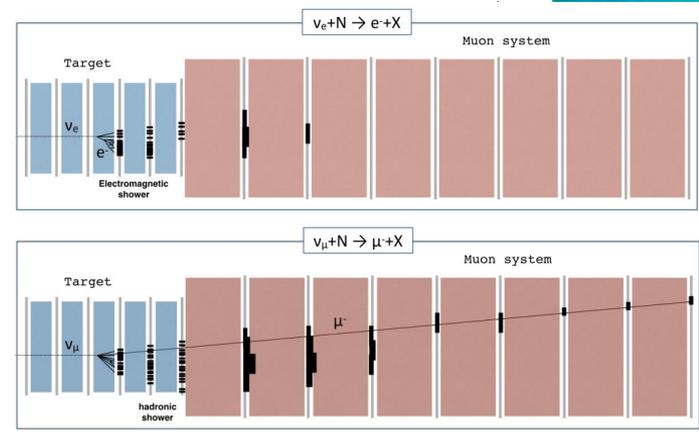
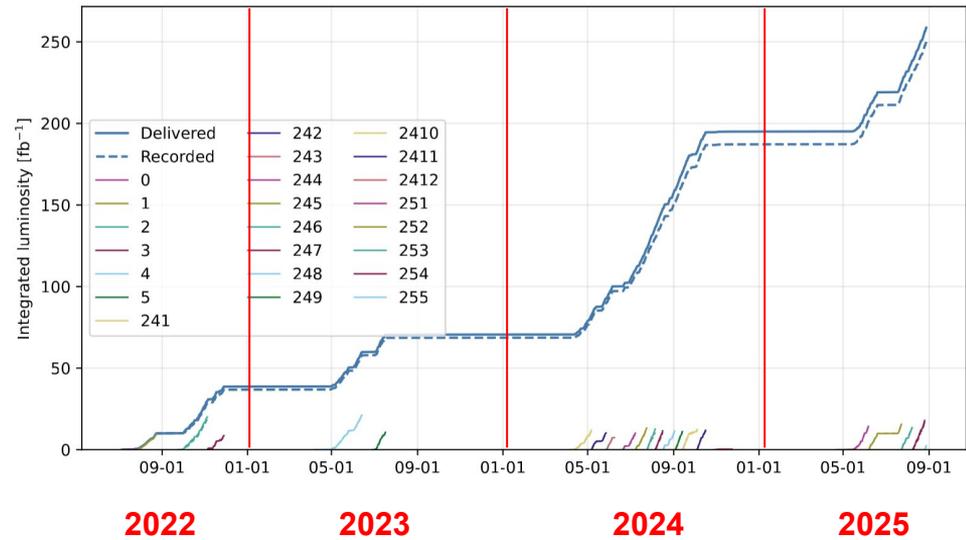
Data collection

Electronic detectors:

- 96% efficiency
- delivered: 195 fb^{-1}
- recorded: 187.1 fb^{-1}

Emulsions:

- 16 target replacements (210 m² of emulsions exposed between 2022 and 2024)
- increase in muon flux in 2024 → instrumented only lower half of the target and 9 replacements,
 - exposure limited to 12 fb^{-1} (nominal 20 fb^{-1}) → kept 65% of events in the emulsions

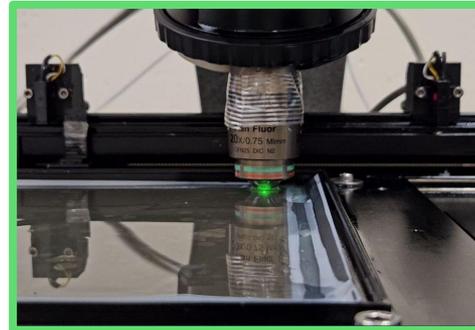
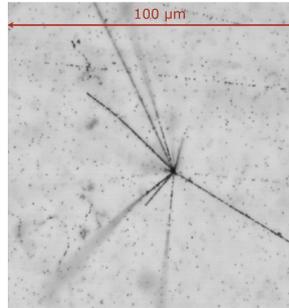


Emulsion scanning

Emulsions are **extracted** from the detector, **developed** and then **scanned**:

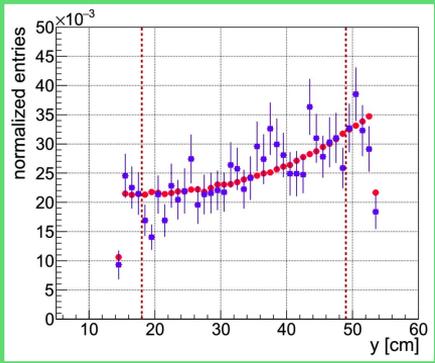
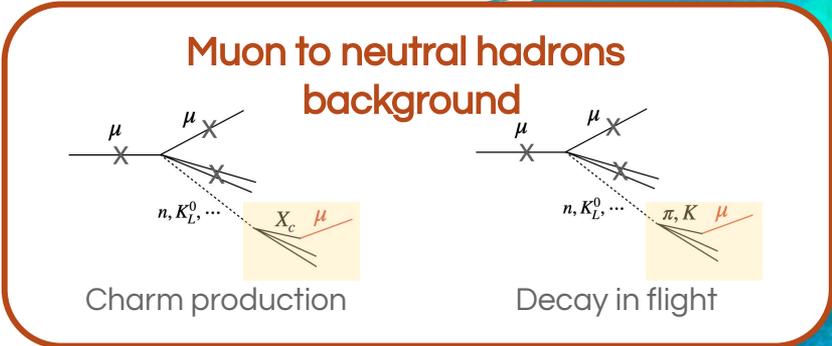
- Emulsion scanning is performed with fully automated microscopes in six laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Santiago
- Track density up to 4×10^5 tracks/cm²

Status of emulsion scanning:
 $800 \text{ kg} \times 42 \text{ fb}^{-1}$

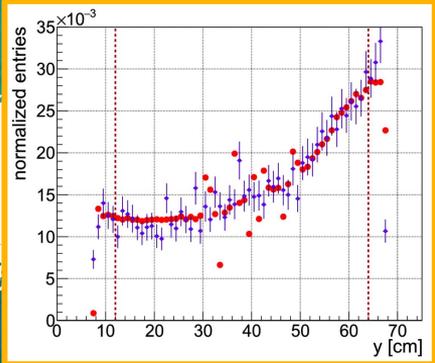


Muon flux measurement

- **Backgrounds** to neutrino signals in SND@LHC are mainly due to **muon interactions** in the tunnel walls
- Precise measurements of the **muon flux** allow for validating and constraining our background model using 2022 data
- measurement with 2023 and 2024 data will be published in the future
- Independent measurement with **SciFi tracker**, **muon system (DS)** and emulsions are in agreement



SciFi



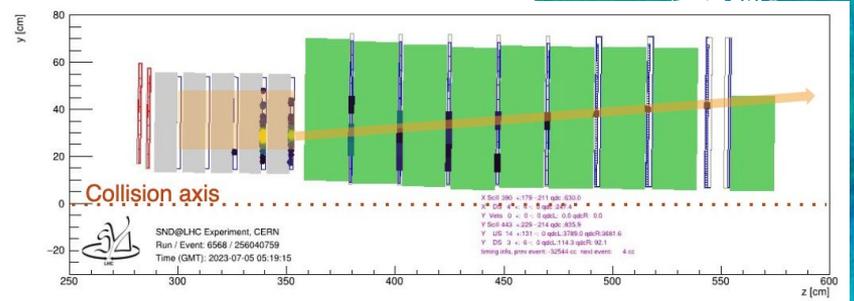
DS

System	Muon flux [10^4 fb/cm ²] same fiducial area
SciFi	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$
DS	$2.02 \pm 0.01(\text{stat.}) \pm 0.08(\text{sys.})$

Muon ν observation

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

- observation of collider muon neutrinos achieved with one year (2022) of data
 - 8 ν_μ candidates, 0.09 background $\sim 7\sigma$
- updated results with more data (2022+2033), extended fiducial, improved analysis
 - Expected 19.1 ν_μ candidates \rightarrow Observed 32 candidates (PRELIMINARY) publication in preparation

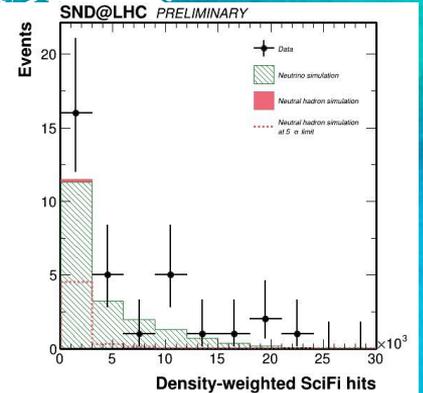
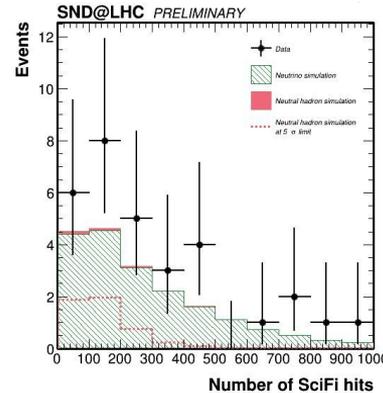


Fiducial volume

- reject events in first wall
- previously used only walls 3 and 4
- reject side-entering backgrounds
- signal acceptance: 18% (up from 7.5%)

Muon neutrino event identification

- large scintillating fibre detector activity
- large HCAL activity
- one muon track associated to the vertex
- signal selection efficiency: 35%



0μ neutrino observation

[Phys. Rev. Lett. 134, 231802](#)

The **first observation of non- ν_μ CC neutrino interaction** using electronic detectors at the LHC

Total expected background: 0.32 ± 0.06 events

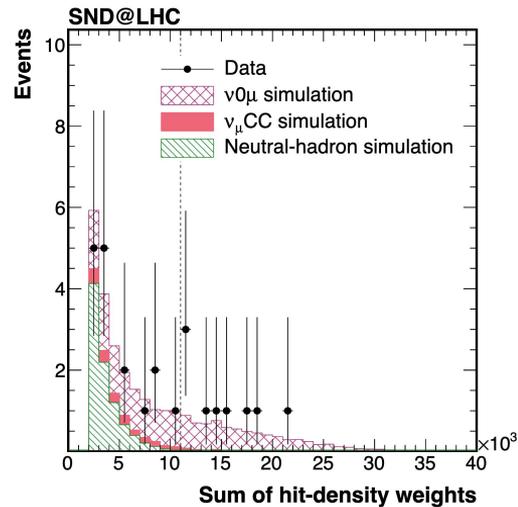
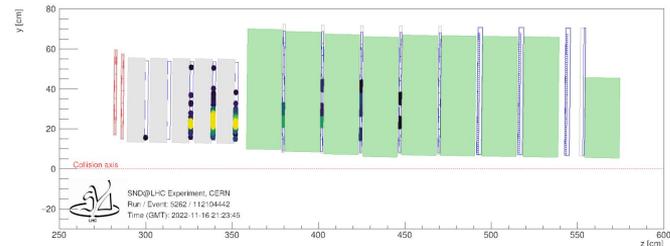
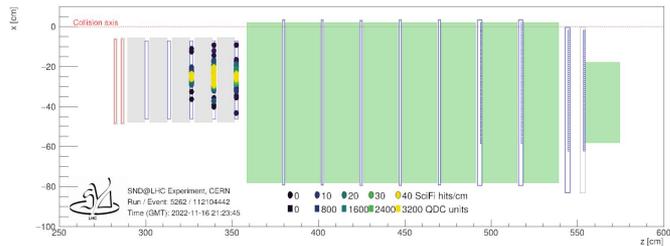
- Neutral hadrons: 0.015 events \rightarrow constrained by control region data
- Neutrino background: 0.30 events \rightarrow due to ν_μ CC interactions

Signal: ν_e CC and NC interactions

- Expected signal: 7.2 events \rightarrow 4.9 ν_e CC, 2.2 NC, 0.1 ν_τ CC
- Expected significance: 5.5σ

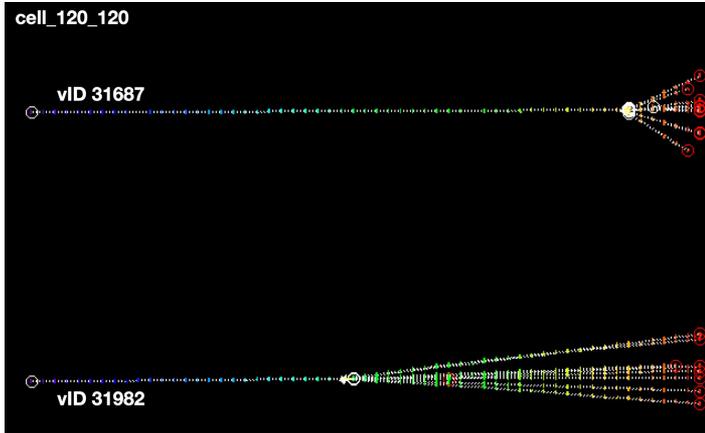
Number of events observed: 9

Observation significance: 6.4σ

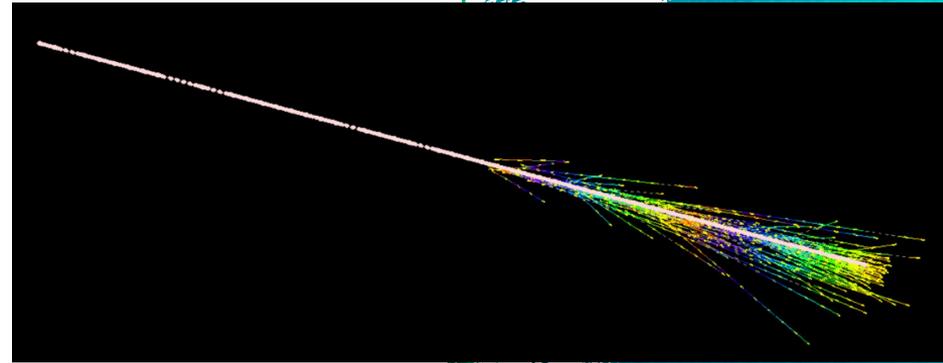
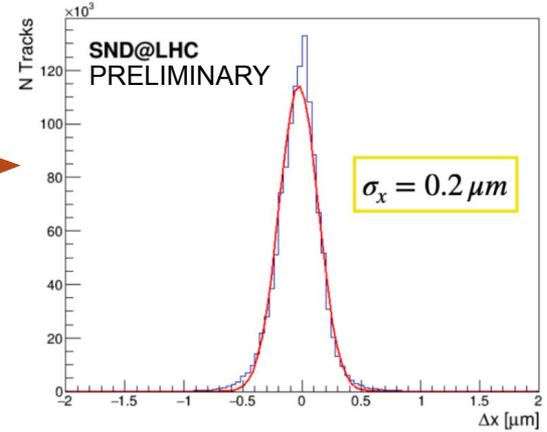


Emulsion data analysis

- Achieved **position resolution of $\sim 0.2 \mu\text{m}$** \longrightarrow
- Ongoing vertex reconstruction and **EM shower searches**



Muon DIS in emulsions



Muon trident production

Signal: three-muon production in the rock



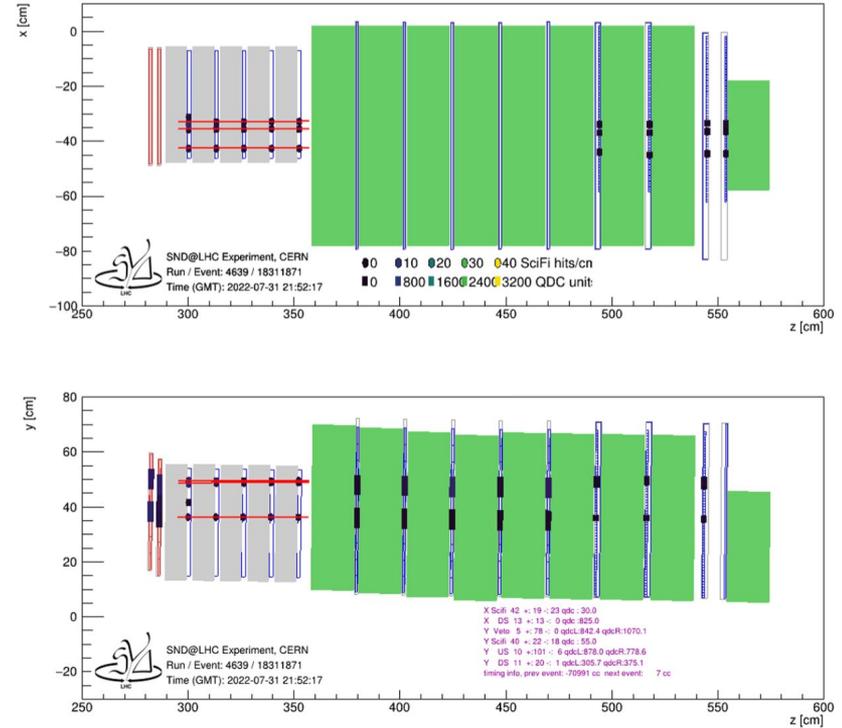
Event selection

- three parallel tracks traversing the detector
- 2 close tracks, 1 separated
- Main background: muon bremsstrahlung followed by gamma conversion \rightarrow resolved in SciFi background



Cross section

- Aim to validate GEANT4 simulation \rightarrow analysis ongoing



SND@LHC Upgrade

The goal is to **extend to the High-Lumi LHC** physics scope

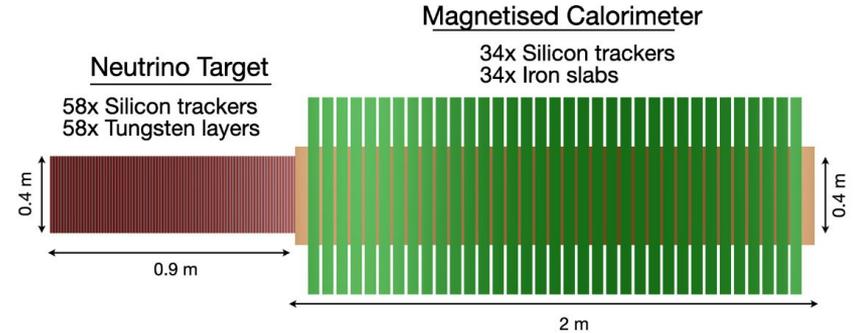
- perform neutrino physics measurements at TeV scale with unprecedented statistics
- off-axis, for enhanced charm production

An **upgrade is required**

- for coping with high background rates → no emulsions
- to improve energy measurement and charge separation → magnetic field

But maintaining a compact geometry

- emulsions replaced with electronic tracker → **silicon strip detectors** from CMS Outer Barrel
- **magnetic field** added, for muon pT/q measurement (neutrino/anti-neutrino)



Flavour	CC DIS Interactions (3k fb ⁻¹ , 1.3 ton)	
	total (DPMJET)	cc-bar (DPMJET)
$\nu_\mu + \bar{\nu}_\mu$	1.5x10 ⁴	2.4x10 ³
$\nu_e + \bar{\nu}_e$	3.4x10 ³	2.7x10 ³
$\nu_\tau + \bar{\nu}_\tau$	2.8x10 ²	2.8x10 ²
Total	1.9x10⁴	5.4x10³

The upgrade has been recently approved!

[CERN-LHCC-2025-004](#)

Conclusions

SND@LHC measures neutrinos in the forward region of pp collisions, and it has a potential to search for new feebly interacting particles

The **experiment has recorded 197 fb of data** so far

- **Observation of collider muon neutrinos** with electronic data (2023)
- **Observation of neutrinos without final state muons** with electronic data (2024)

Progress in emulsion data reconstruction with excellent tracking resolution

The detector will be upgraded with silicon strip modules and a magnetised calorimeter to run in the HL-LHC



Thanks for the
attention



Backup slides

Muon ν observation: update

Updated results with more data (2022+2023), extended fiducial, improved analysis

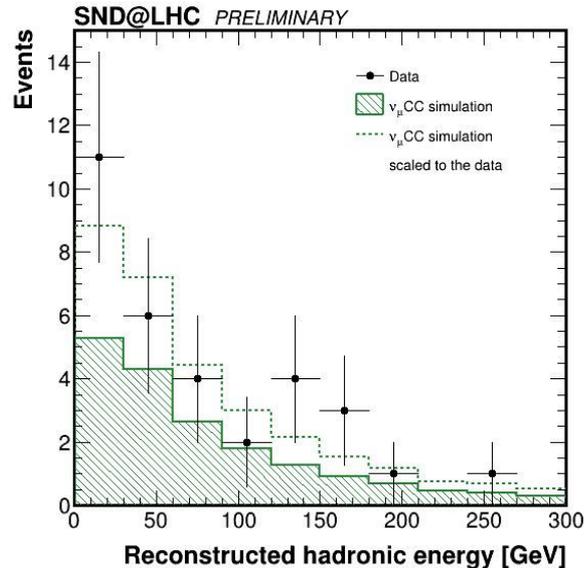
- Background
 - Neutral hadrons: 0.25 ± 0.06
 - Passing muons: 1.53
- Signal
 - Expected 19.1 $\nu\mu$ candidates
 ± 4.1 (production)
 $+ 1.6 - 3.9$ (selection)

→ Observed 32 candidates

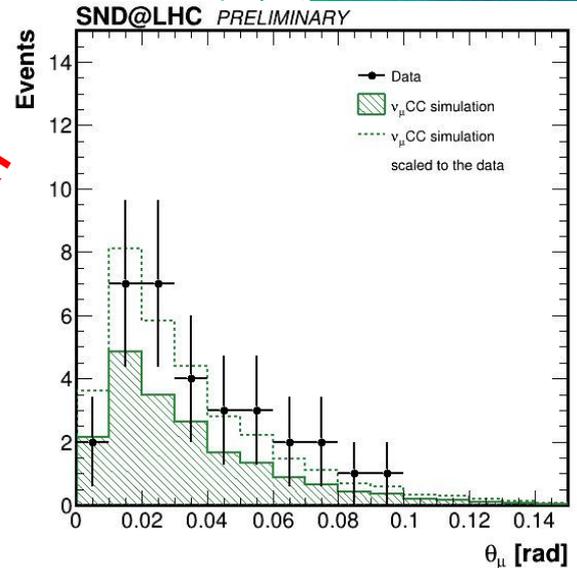
- It's preliminary
- Discrepancy is low: 1.6σ
- FASER observes the same discrepancy in muon neutrino analysis

Muon ν observation: kinematic

- Kinematics of muon neutrino candidates agree with signal prediction
- 10-20% energy resolution of the calorimeter was achieved with a dedicated testbeam campaign in 2023 → paper submitted to JINST



PRELIMINARY



0mu selection

Fiducial volume

- no hits in the veto detector
- reject side-entering backgrounds
- signal acceptance: 12%

0 μ neutrino event identification

- large scintillating fibre detector activity
 - large HCAL activity
 - no hits in last two muon system planes \rightarrow no reconstructable muons
 - sum of hit-density weights $> 11 \times 10^3$
- selects events with high hit density in SciFi
 - optimized for maximum expected significance
 - validated with test-beam data
 - signal selection efficiency: 19%

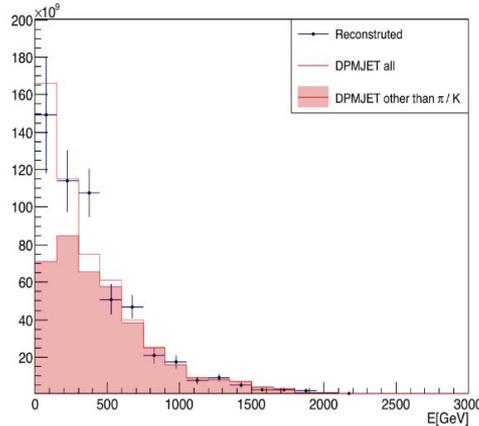
Neutrinos from charm production

90 % of ν_e and $\bar{\nu}_e$ produced SND@LHC come from charmed hadron decays. This provides opportunities to:

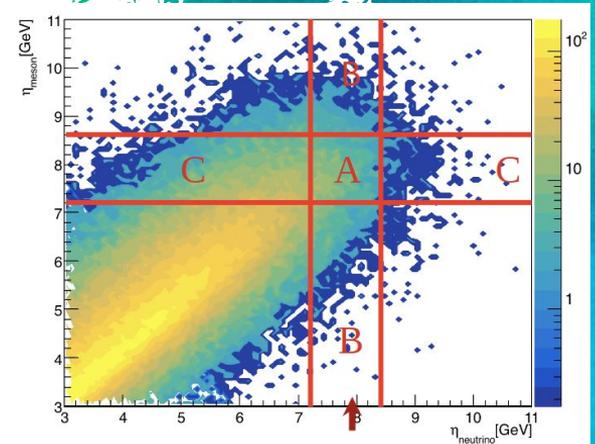
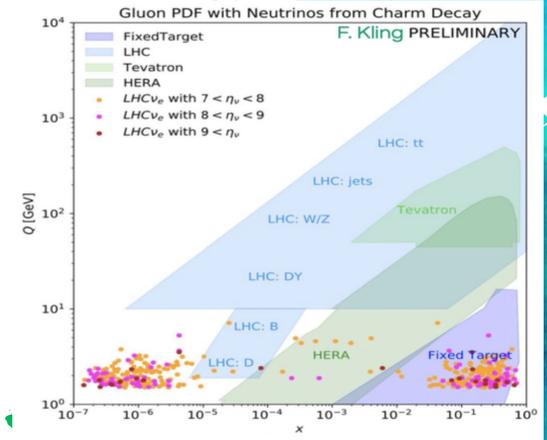
- Measure $pp \rightarrow \nu_e X$ cross section
- Measure forward charm production through neutrinos
- Constrain gluon PDF at very small x

Expected uncertainties:

- $pp \rightarrow \nu_e X$ cross section
 - Statistical: 5%
 - Systematic: 15%
- Charm hadron yield
 - Statistical: 5%
 - Systematic: 35%



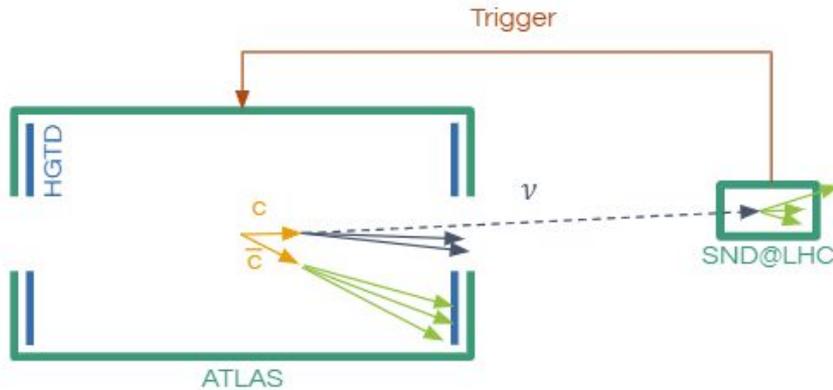
Reconstructed $\nu_e + \bar{\nu}_e$ spectrum at SND@LHC.



Correlation between η_{ν} and η_c 20

SND@LHC Upgrade

- Tag charm hadrons in ATLAS



SND@LHC SND@LHC (HL)

Measurement	SND@LHC		SND@LHC (HL)	
	Stat.	Sys.	Stat.	Sys.
Gluon PDF ($x < 10^{-5}$)	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%