The Scattering and Neutrino Detector at the LHC

XXI Workshop on Neutrino Telescopes

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On behalf of the SND@LHC Collaboration

01/10/2025

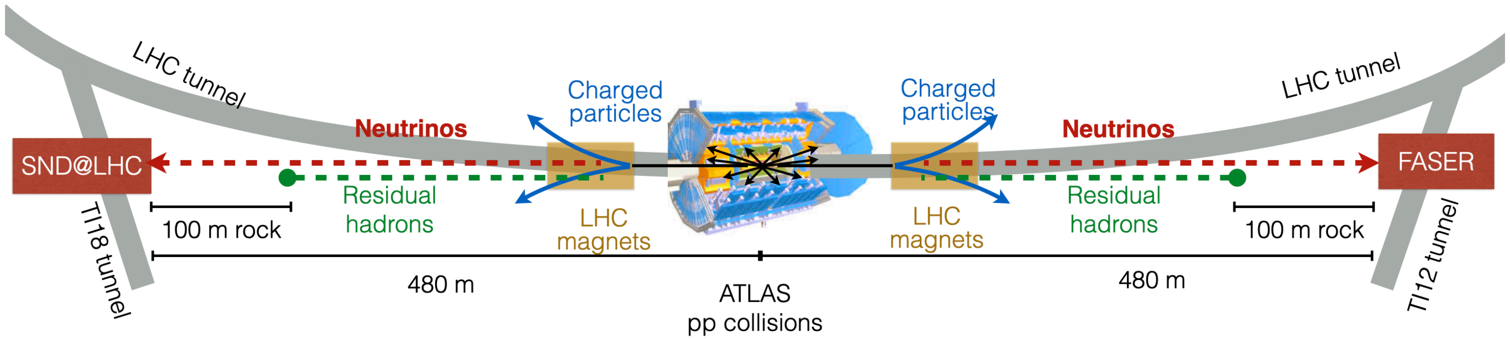
Neutrinos at LHC

Potential of high energy neutrino studies at LHC recognised in early 80s

- Highest energy man-made neutrino beam
- Possibility to study pp→vX in an unexplored range [300 GeV - few TeV]
- Large ν flux in forward region from pp collisions

Currently, two experiments in complementary ranges:

- **SND@LHC off axis:** $7.2 < \eta < 8.4$
- **FASERν on axis:** $\eta > 9$



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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

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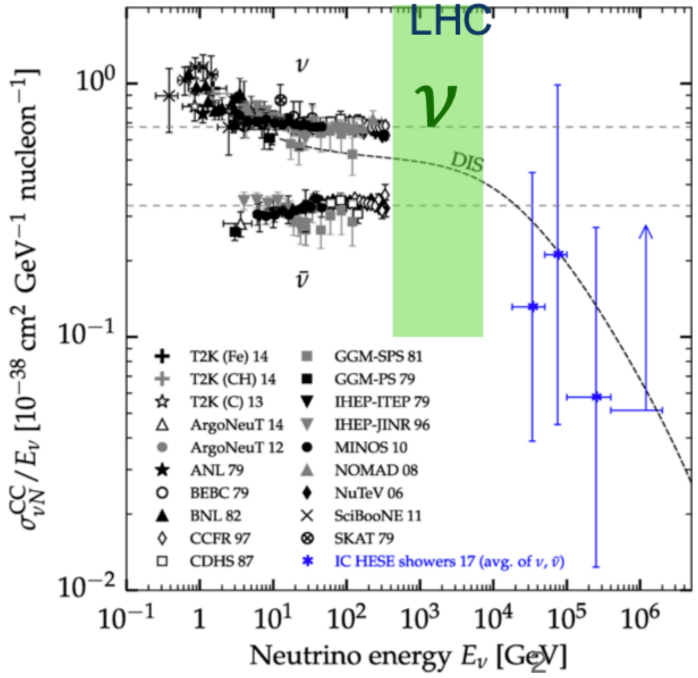
J. Phys. G: Nucl. Part. Phys. 47 (2020) 125004 (18pp) https://doi.org/10.1088/1361-6471/aba7ad

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

PRL 122.041101



18 Jul 2025

SND@LHC physics goals

Neutrino interactions

- Measure ν **interactions** in the ~TeV energy range.
- Large yield of ν_τ will likely double existing data.

QCD

- Decays of **charm** hadrons contribute significantly to the neutrino flux in SND@LHC.
- Measure forward charm production with ν_es.
- Constrain **gluon PDF** at very **small x**.

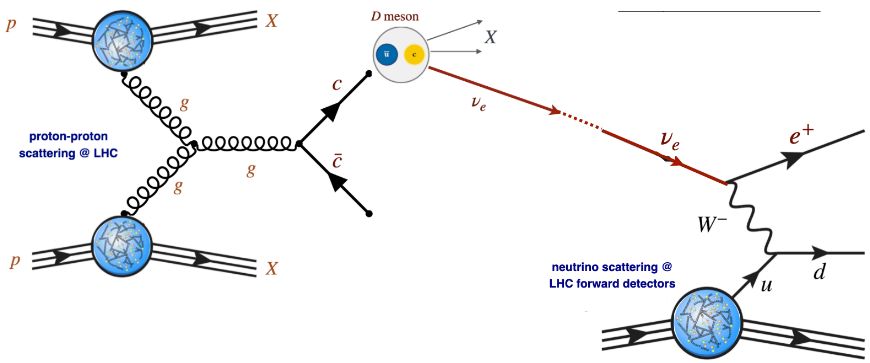
Flavour

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

Beyond the Standard Model

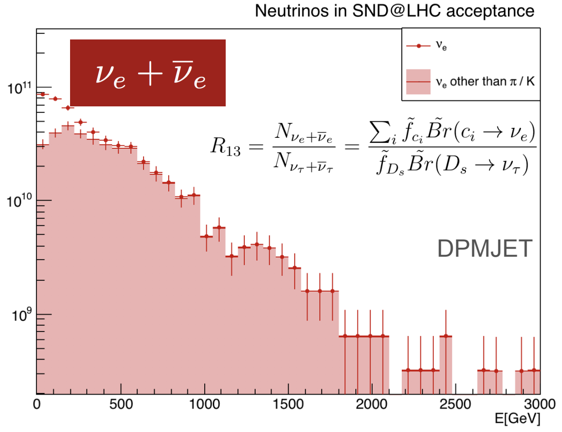
- Search for **new**, feebly interacting, **particles decaying** within the detector or **scattering** off the target.
- ν_τ magnetic moment and Dark Higgs to $\mu^+\mu^-$.

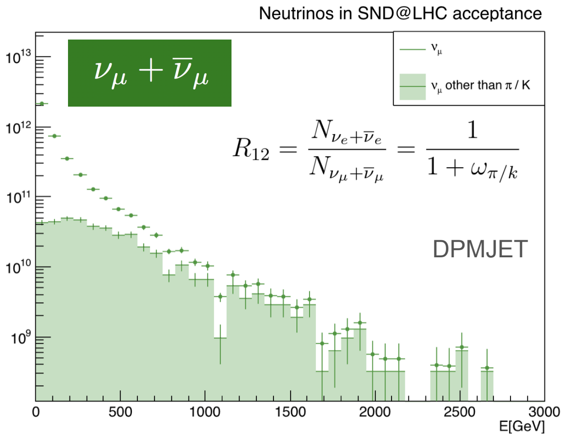
Adapted from Juan Rojo's CERN TH seminar



Flavour	DIS-CC	DIS-NC
$\nu_\mu+\bar{\nu}_\mu$	1270	410
$\nu_e+\bar{\nu}_e$	390	130
$\nu_\tau+\bar{\nu}_\tau$	30	15
Tot	1690	555

Expected neutrino interactions in RUN3: 250 fb^{-1}





SND@LHC hybrid detector

JINST 19 (2024) P05067

Veto system

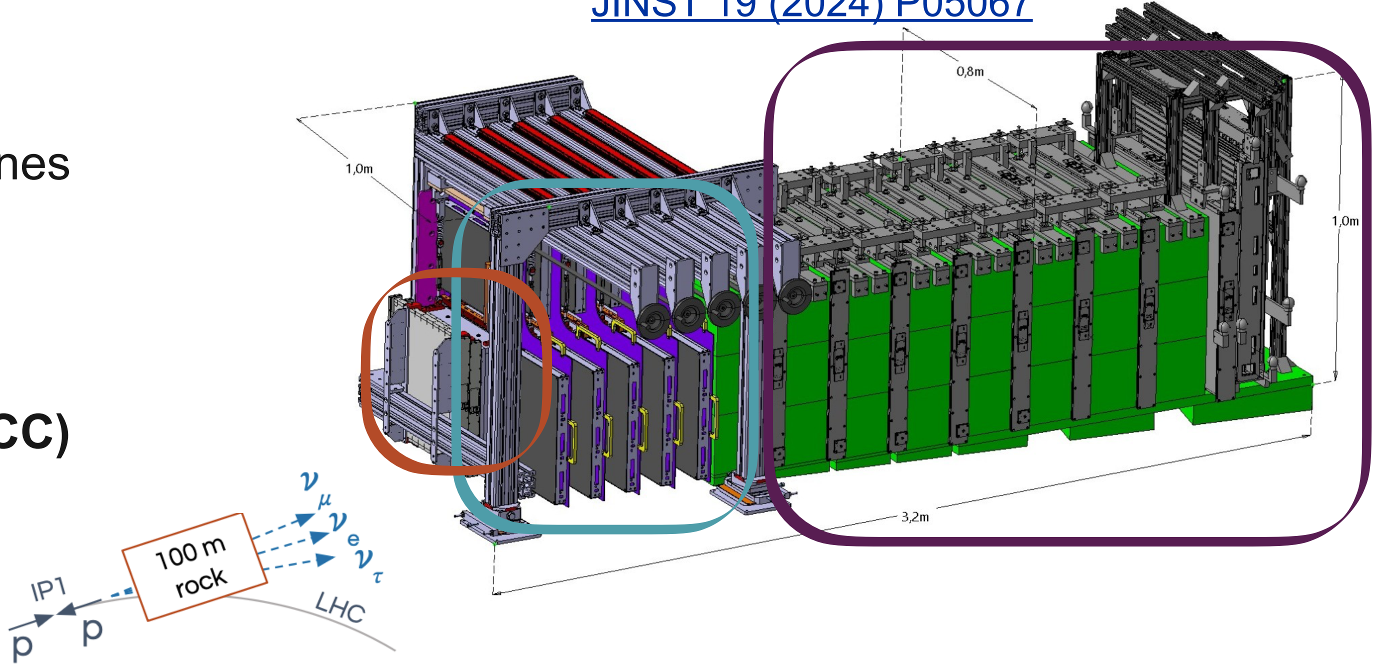
- 2 (2022 - 2023) / 3 (2024 -) scintillator planes
- Tag incoming charged particles

Target, vertex detector and ECal

- ~800 kg tungsten target
- Five walls of Emulsion Cloud Chamber **(ECC)** + five scintillating fibre stations **(SciFi)**
- 84 X_0, $3\lambda_{int}$

HCal and muon system

- Eight Fe blocks + scintillator planes
- Last 3 planes have finer granularity to track muons
- (2025) Drift-tube plane
- 9.5 λ_{int}



Off-axis: $7.2 < \eta < 8.4$
Enhanced flux with charm origin.

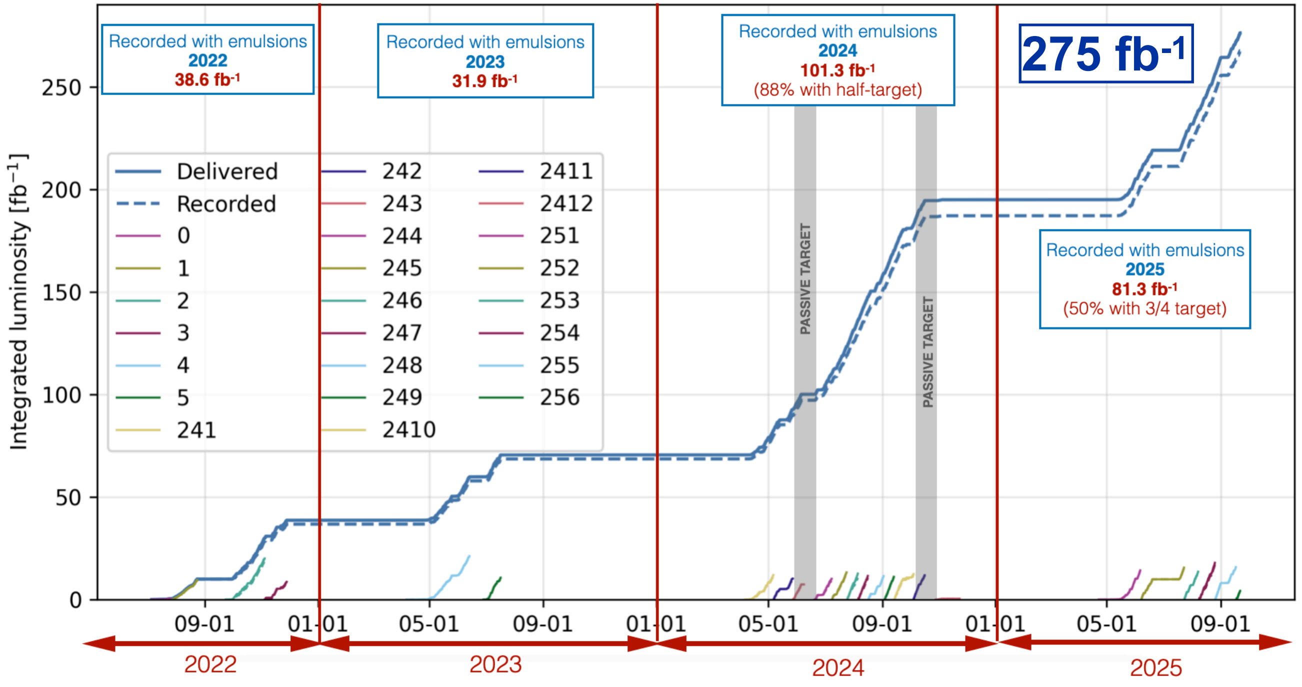
Detector operation

Electronic detectors

- 2025 (- ongoing): Recorded **88 fb^{-1}**
- 2022 - 2024: Recorded **187 fb^{-1}**
- **97% detector uptime**

Emulsion detector

- **20 emulsion target** (~215m^2) exposed and developed in 2022-2025
- **252 fb^{-1}** integrated
- Instrumentation strategy adapted to the optics changes in the years to keep the highest fraction of neutrino interactions



Emulsion scanning and analysis

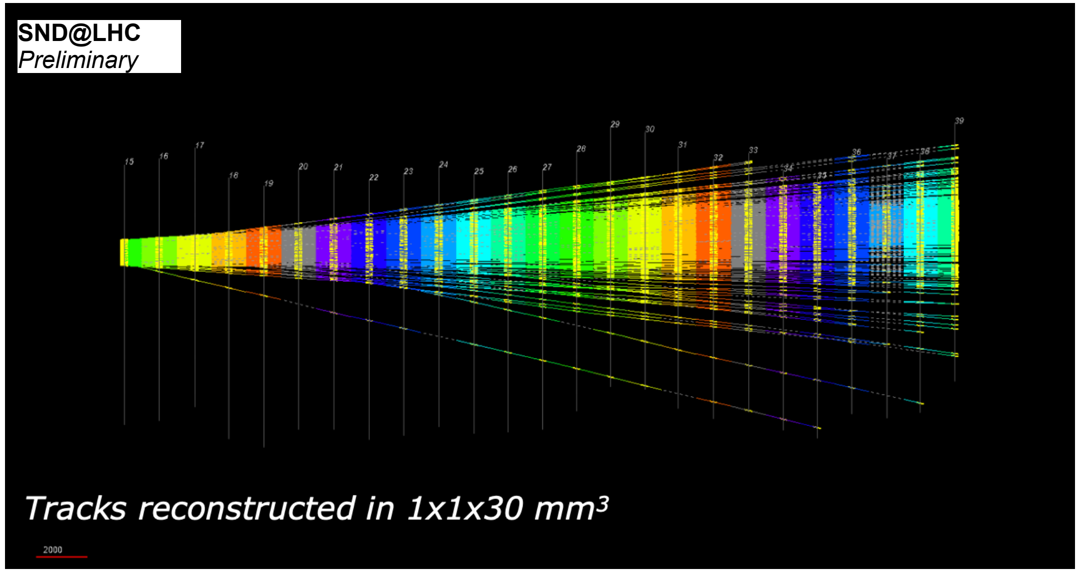
Emulsion scanning is performed with fully automated microscopes in six laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Santiago

Track density up to 4×10^5 tracks/cm^2

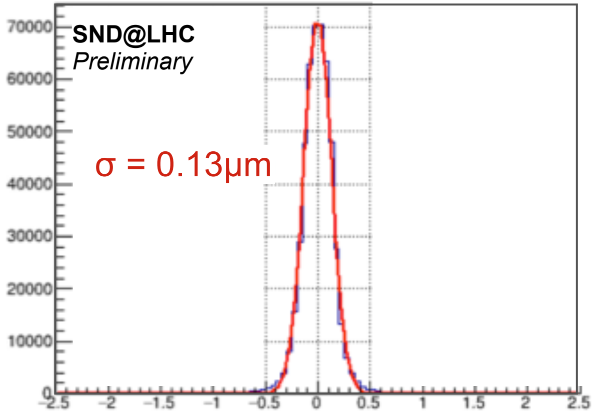
Achieved emulsion track position **resolution < 150 nm**

Status of emulsion scanning: **800 Kg x 53 fb^{-1}**

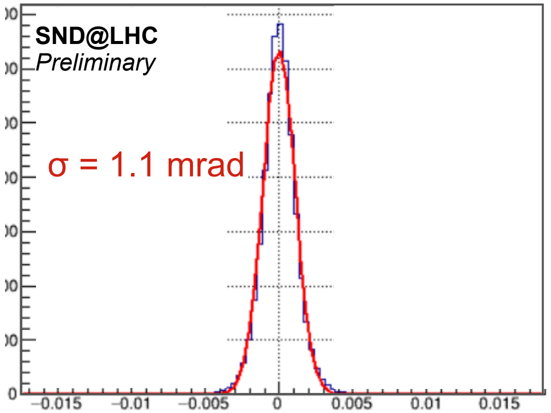
Status of emulsion reconstruction: **40 Kg x 70 fb^{-1}**

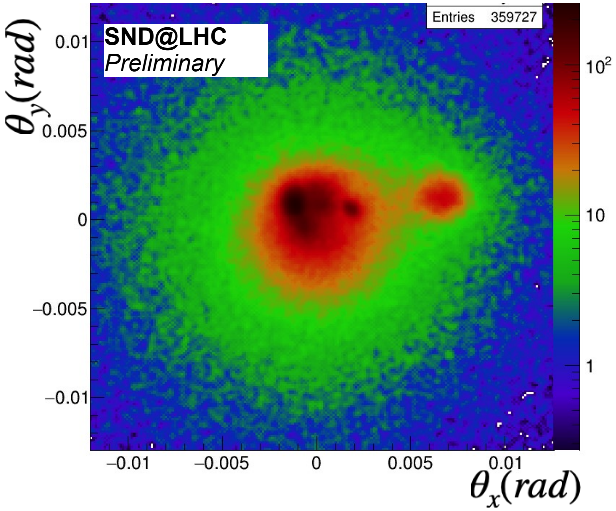


Position resolution



Angular resolution

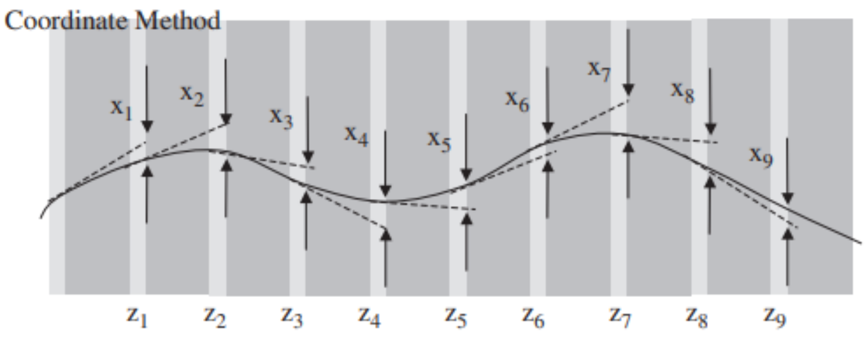




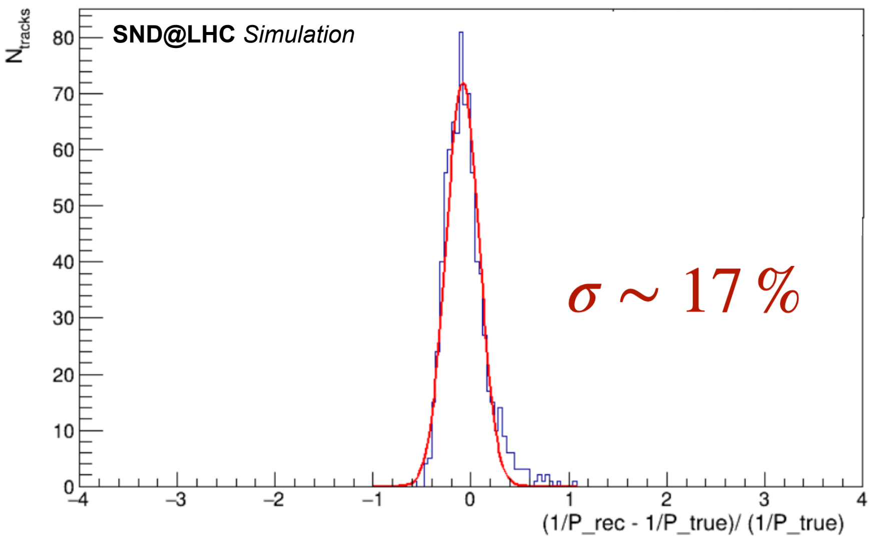
Momentum measurement in emulsion

- Momentum measurement of charged particles in ECC
- Deflection induced by MCS used to infer particle's momentum
- Estimated resolution on simulated charged pions: 15÷25%
- Neutrino energy resolution for simulated vertices: ~20%

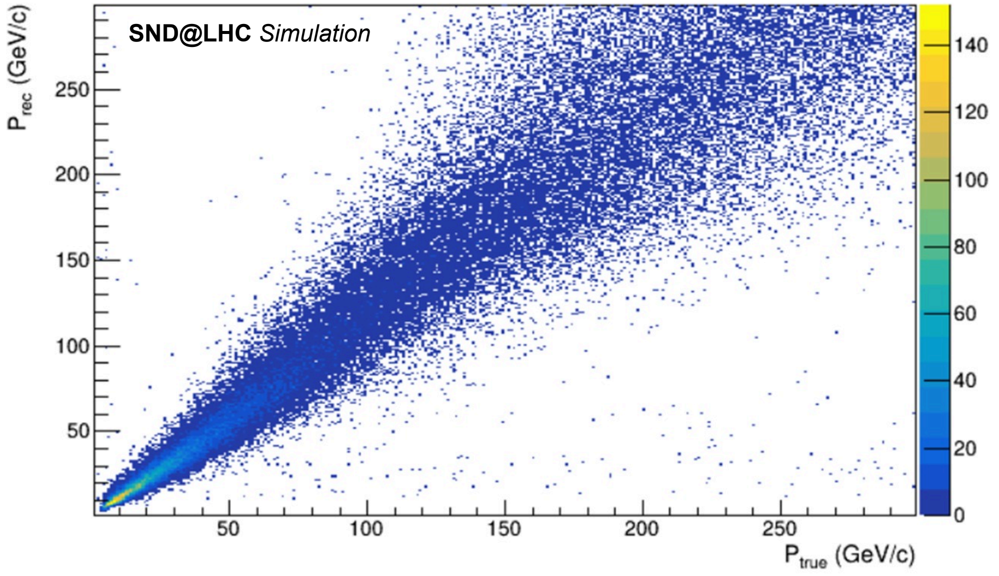
NIM A 574 (2007) 192



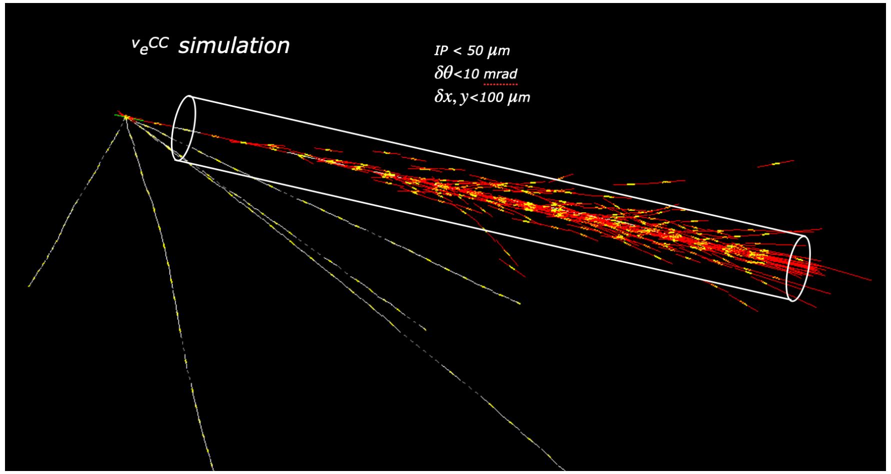
Simulation: 40 GeV charged pions



Reconstructed vs true muon momentum



Em shower measurements in emulsion

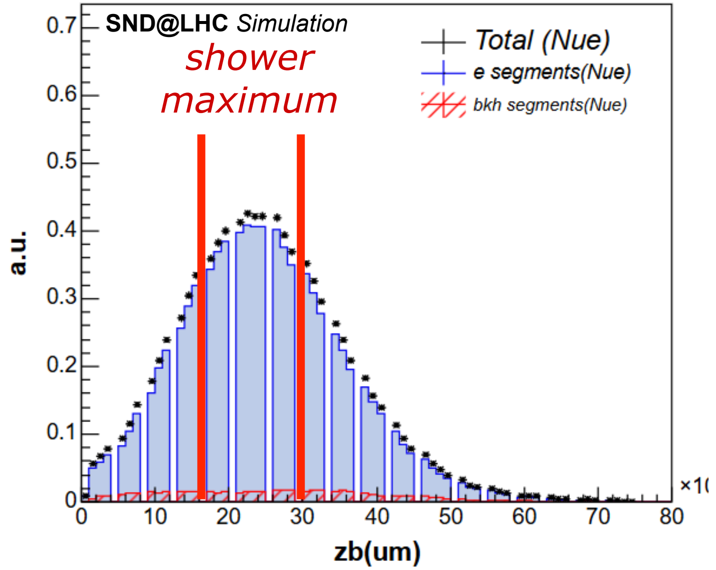


Electron neutrino ID based on em shower identification

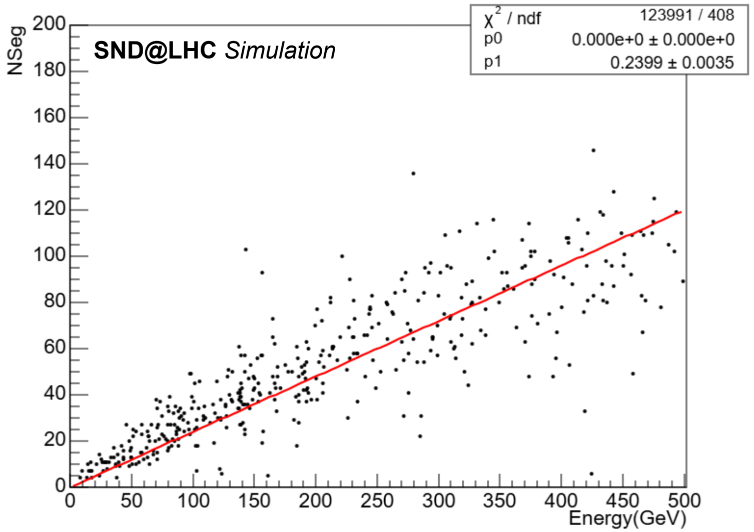
Electron energy estimate based on calorimetric measurements

- Reconstruct tracks inside a cylinder
- Using vertex tracks as injectors
- Based on number of tracks at the shower maximum

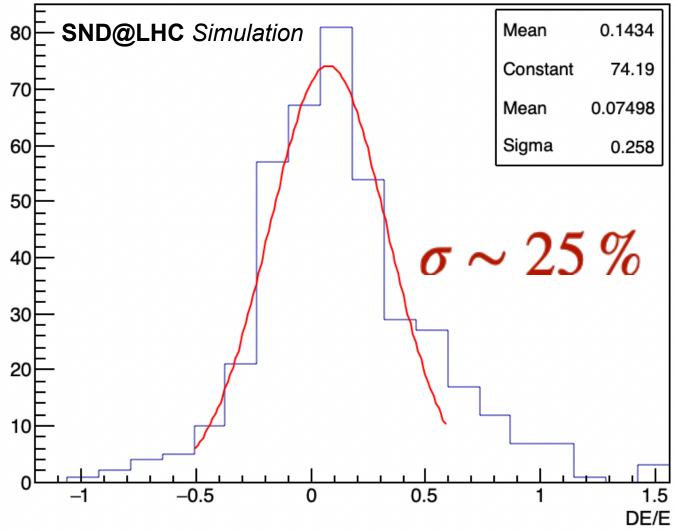
Longitutinal profile



Energy calibration



Energy resolution



Passing muons

Muon flux is important for detector operations and physics analyses.

- Defines the **emulsion exposure limit**.
- **Main experimental backgrounds** are due to muon interactions.

Measurement of flux with 2022 data.

- Eur. Phys. J. C (2024) **84**: 90
- Excellent **agreement between all sub-detectors**, including emulsions.
- Agreement with MC predictions within 20%.

Measurement of the muon flux in heavy ion collisions.

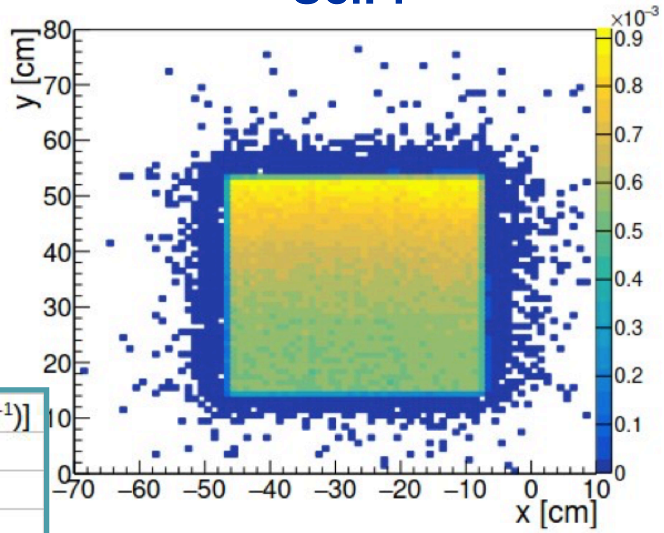
- Different physics and LHC optics compared to pp.
- Allows for further validation of the background.
- Cross-check of detector performance.

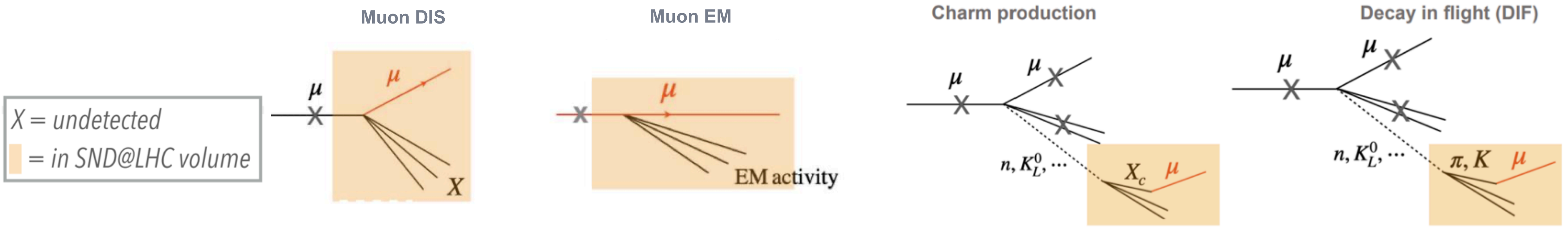
SND@LHC *Preliminary*

year	rate* [Hz]	flux [trk/(cm^{-2}fb^{-1})]
2022 – 2023	557	1.8E+04
2024	1154	3.8E+04
2025	**782**	**2.7E+04**
MC 2025	818	2.7E+04

*normalized to L_0=2x10^{34} cm^{-2}s^{-1}

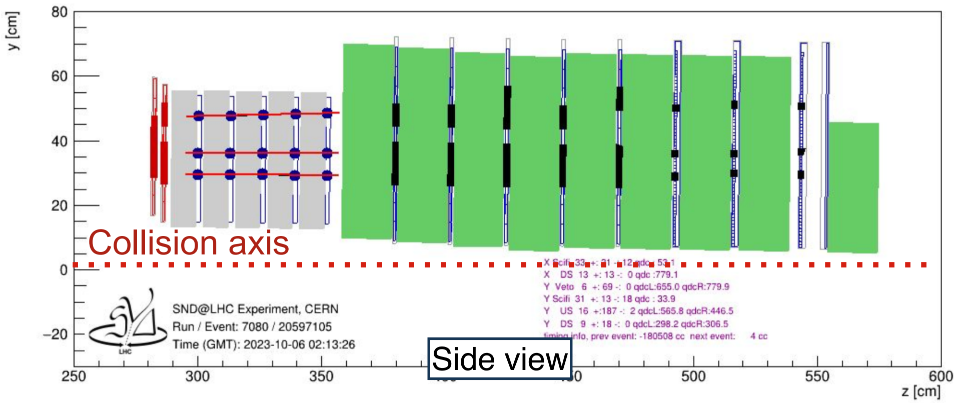
SciFi





Muon trident cross-section measurement

- SND@LHC is sensitive to **muon trident interactions** in the rock upstream of the detector.
- Signature: three parallel muon tracks.
- **Trident signal**: $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$
- Background: $\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \gamma$, $\gamma + N \rightarrow N + \mu^{+}\mu^{-}$
  - Muons from γ conversion are too soft to reach the detector.
- **Cross-section measurement is being performed with interactions inside the rock**
- Disagreement with GEANT4 prediction



PhysRev.167.1308
M. Tannenbaum

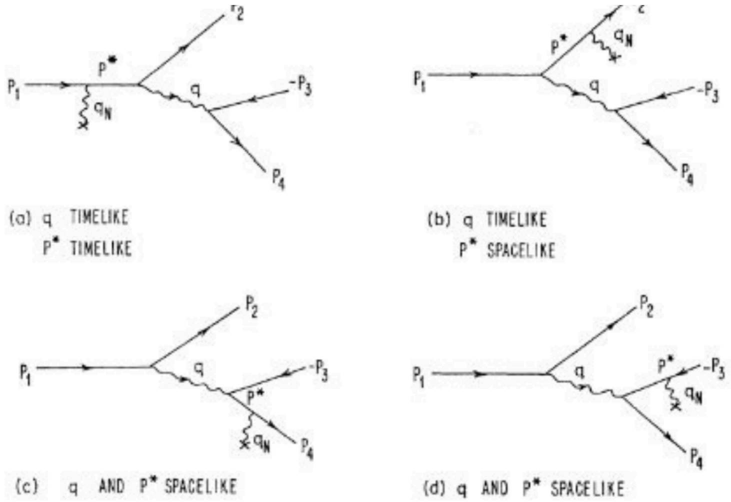


FIG. 1. The four Feynman diagrams for muon tridents (a) and (b) have timelike virtual photons while in (c) and (d) the virtual photon is spacelike. p^* is the four-momentum of the virtual muon; q is the four-momentum of the virtual photon and q_N is the nuclear recoil four-momentum.

Muon neutrino analysis

Observation of collider muon neutrinos achieved with one year of data.

- Phys. Rev. Lett. 131, 031802

Updated result in 2024 with more data and improved analysis.

12-20 % energy resolution was achieved with the test beam campaign in 2023.

Event selection:

Fiducial volume

- Reject events in first wall.
- Reject side-entering backgrounds.
- Signal acceptance: 18%

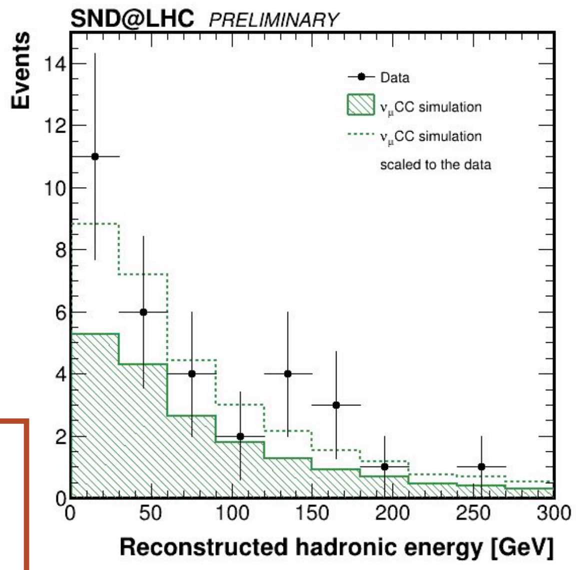
Muon neutrino identification

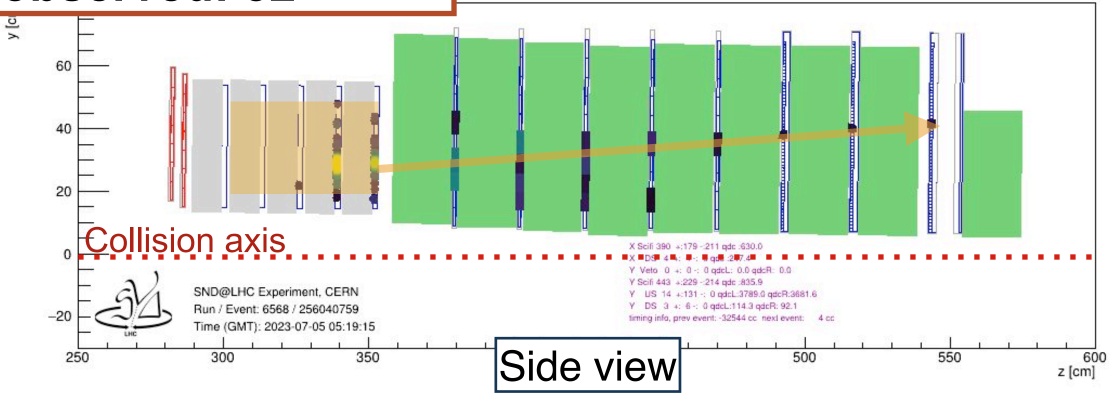
- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 35%

Number of events expected in 68.6 fb^{-1}:

- Signal: 19.1± 4.1 (syst) ± 4.4 (stat)
- Neutral hadrons: 0.25 ± 0.06
- Passing muon background: 1.53

Number of events observed: 32

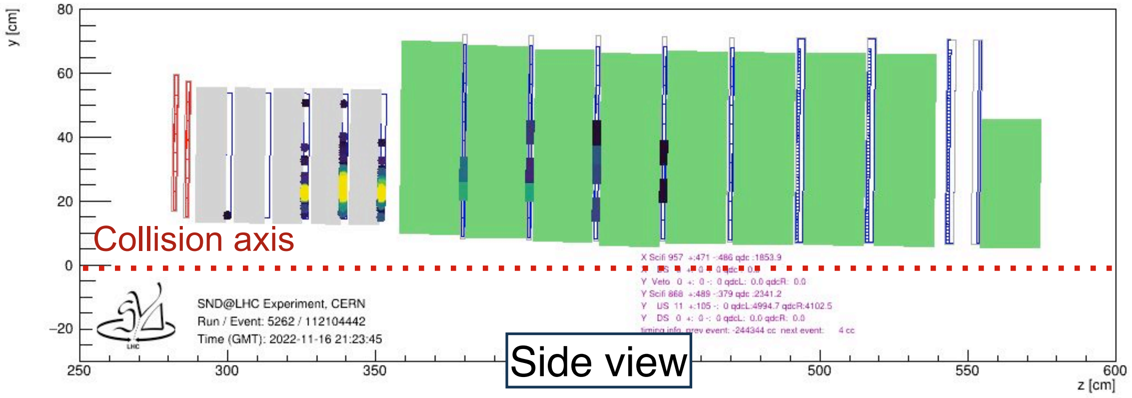




Side view

Observation of 0μ events in SND@LHC

PRL 134 231802 (2025)



Signal: ν_eCC and NC interactions

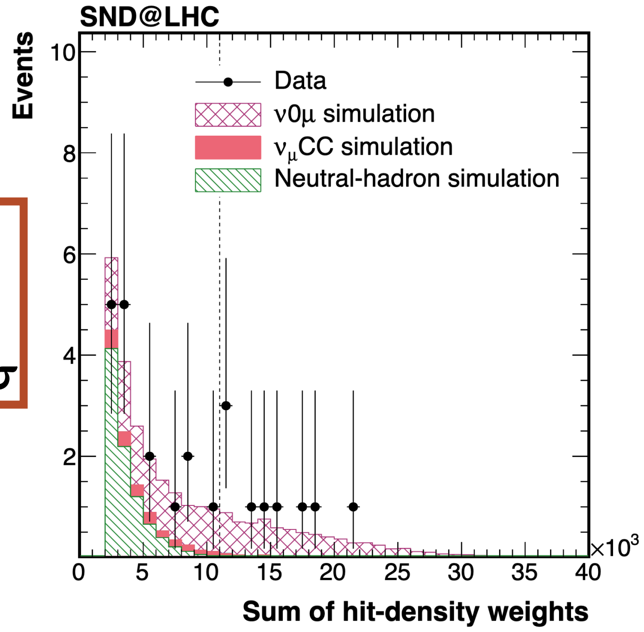
Backgrounds:

- Neutral hadrons: **0.01 events**
  - Constrained by control region data.
- Neutrino background: **0.30 events**
  - Dominated by muon neutrino CC interactions

0μ observation significance:

- **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: 5.5 σ**
- First observation of non-ν_μCC neutrino interaction using electronic detectors at the LHC.
- Milestone towards neutrino observation at the HL-LHC.

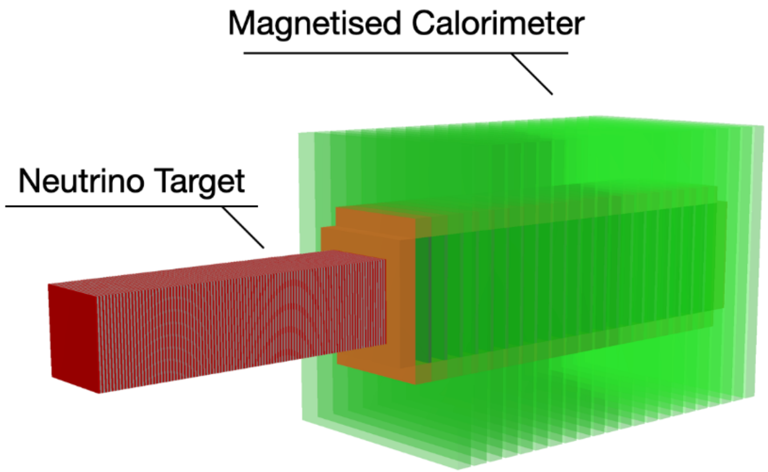
Number of events observed: 9
Observation significance: 6.4 σ
ν_eCC observation significance: 3.7 σ

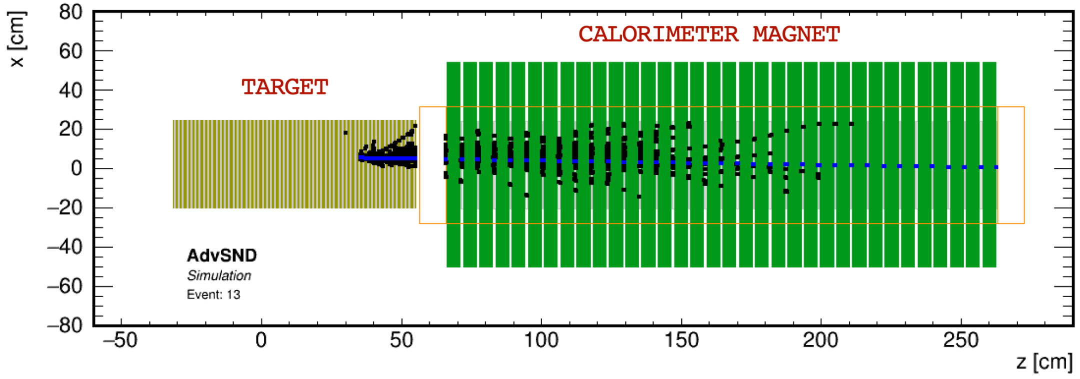


SND@LHC upgrade for HL-LHC

- **Extending** neutrino physics measurements at TeV scale with increased **statistics** during Run 4.
  - Total mass of the tungsten target of about 1.3 tons.
  - Improvement in neutrino interactions yield (18x higher).
- Will be located in the same TI18 of SND@LHC.
- Replace emulsions with **silicon strip detector** (30 µm resolution).
- The calorimeter will be **magnetised** for muon momentum and charge measurement.

Technical Proposal for Run 4





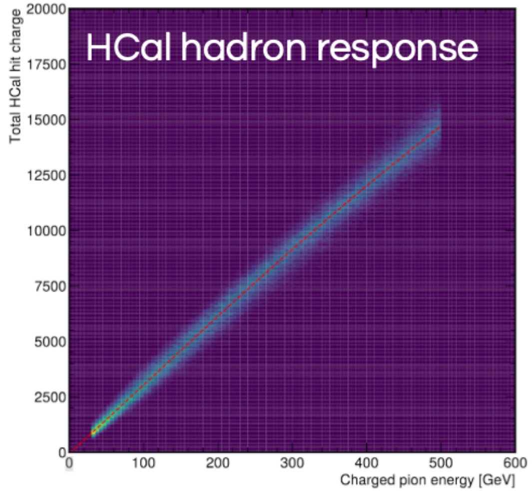
Measurement	Run 3 Uncertainty Stat.	Run 3 Uncertainty Sys.	Run 4 Uncertainty Stat.	Run 4 Uncertainty Sys.
Gluon PDF ($x < 10^{-5}$)	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	$< 5\%$
ν_μ and $\overline{\nu}_\mu$ cross-section	-	-	1%	5%

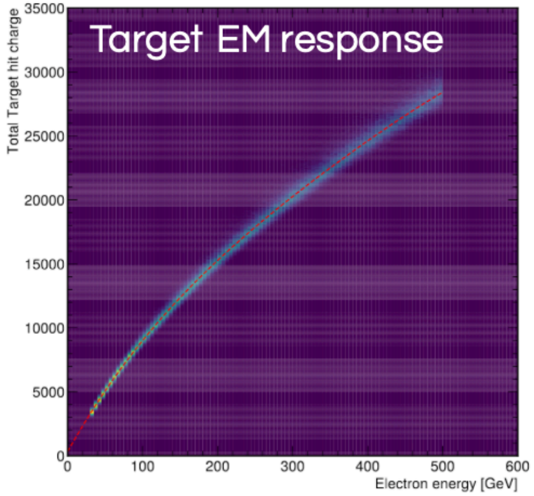
Summary

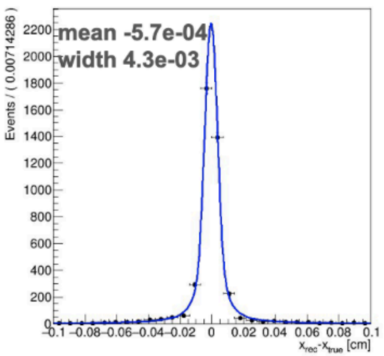
- SND@LHC is designed to investigate leptonic universality in the neutrino sector and probe heavy flavour physics, with measurements of high-energy neutrinos produced at the LHC.
- The experiment has recorded **275 fb^{-1} of data** and counting, with **97% detector uptime**.
- Updated result on the observation of **collider muon neutrinos**.
- First observation of LHC **neutrino interactions without final state muons** using electronic detectors.
- Mature analysis on **muon trident cross-section** measurement with interactions inside the rock.
- Multiple Coloumb Scattering and calorimetric **energy measurements** with the emulsion detector.
- **Approved detector for Run 4** using silicon strip modules to replace the emulsions.

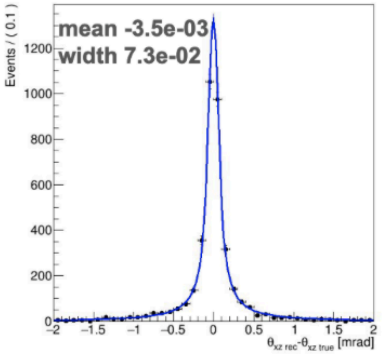
Backup slides

Expected detector performance







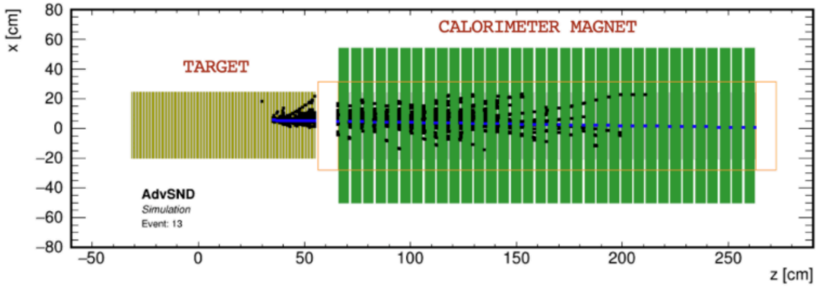


Tracking
- 40 micron and 0.1 mrad resolutions

Muon
- μ momentum resolution 1TeV: 20%
- μ hits isolated in 24 planes

Calorimetry
- Good EM and hadron calorimetry
- Hadron energy resolution: 5 - 10% (> 100 GeV)
- 25% ν_e interactions in HCAL contained

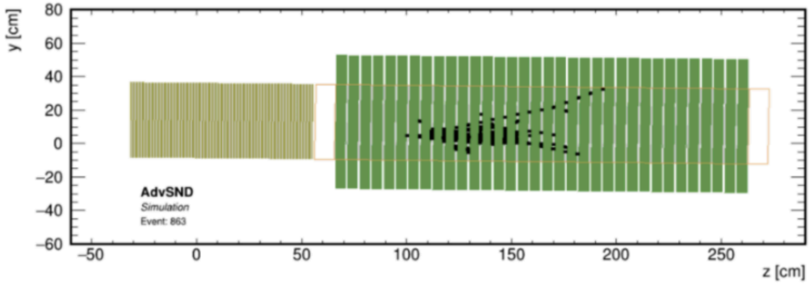
3-flavour identification
- High resolution detector
- Good charge response up to 7 MIPs/strip
- Excellent kinematic reconstruction



CC DIS Interactions (3k fb^{-1}, 1.3 ton)

Flavour	Target	HCAL	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	1.5×10^4	8.8×10^3	2.4×10^4
$\nu_e+\bar{\nu}_e$	3.4×10^3	2.1×10^3	5.5×10^3
$\nu_\tau+\bar{\nu}_\tau$	2.8×10^2	1.7×10^2	4.5×10^2
Tot	1.9×10^4	1.1×10^4	3.0×10^4

An additional 30% interactions can be reconstructed in the HCal.



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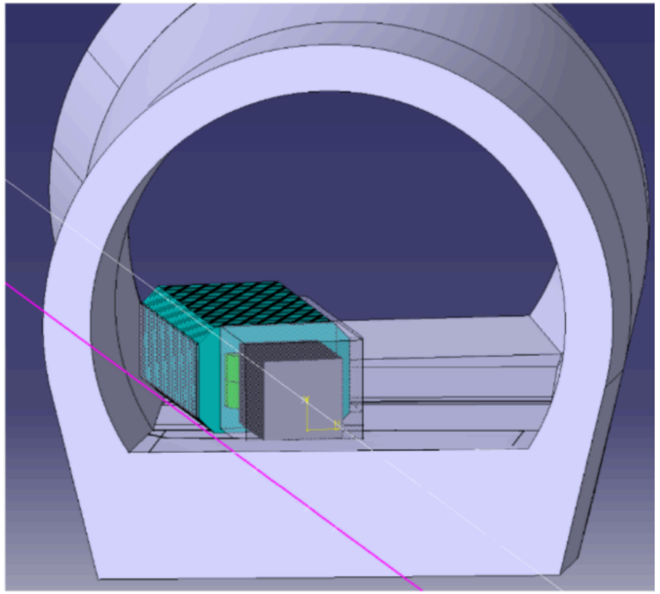
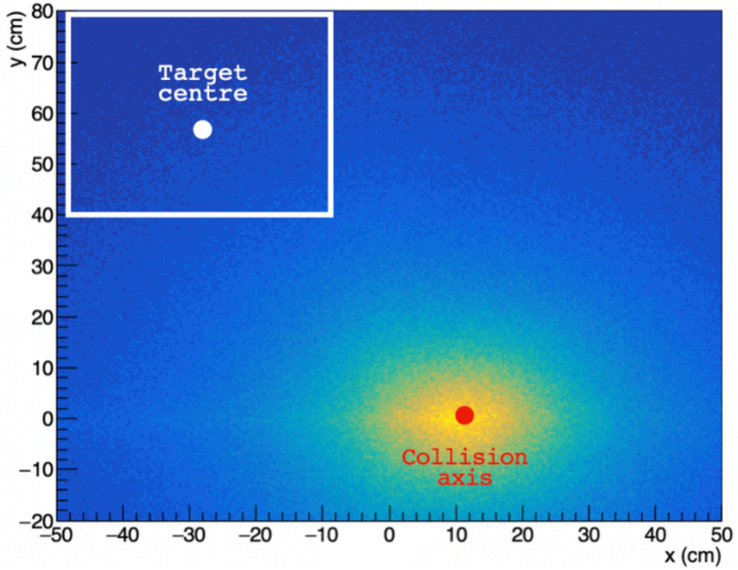
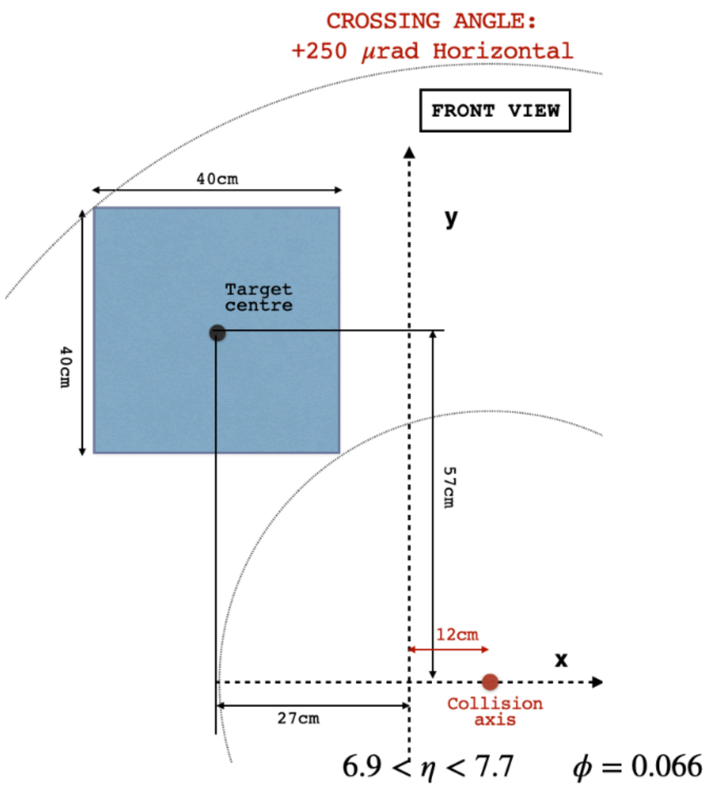
Detector location

- The detector will be moved upstream and upward to fit in the existing space.
- If there is an opportunity to excavate a trench on the tunnel floor, an increase in the event yield by a factor of 7 is possible. CERN-LHCC-2024-014

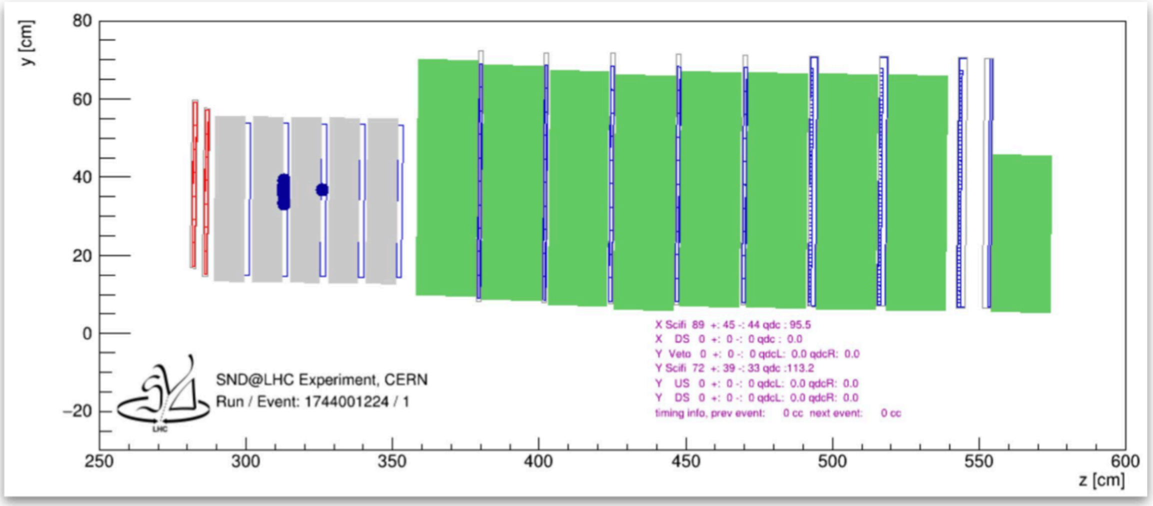


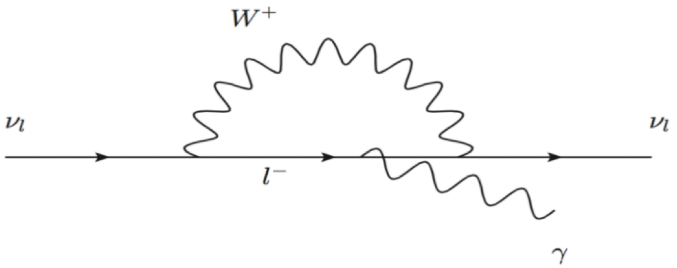




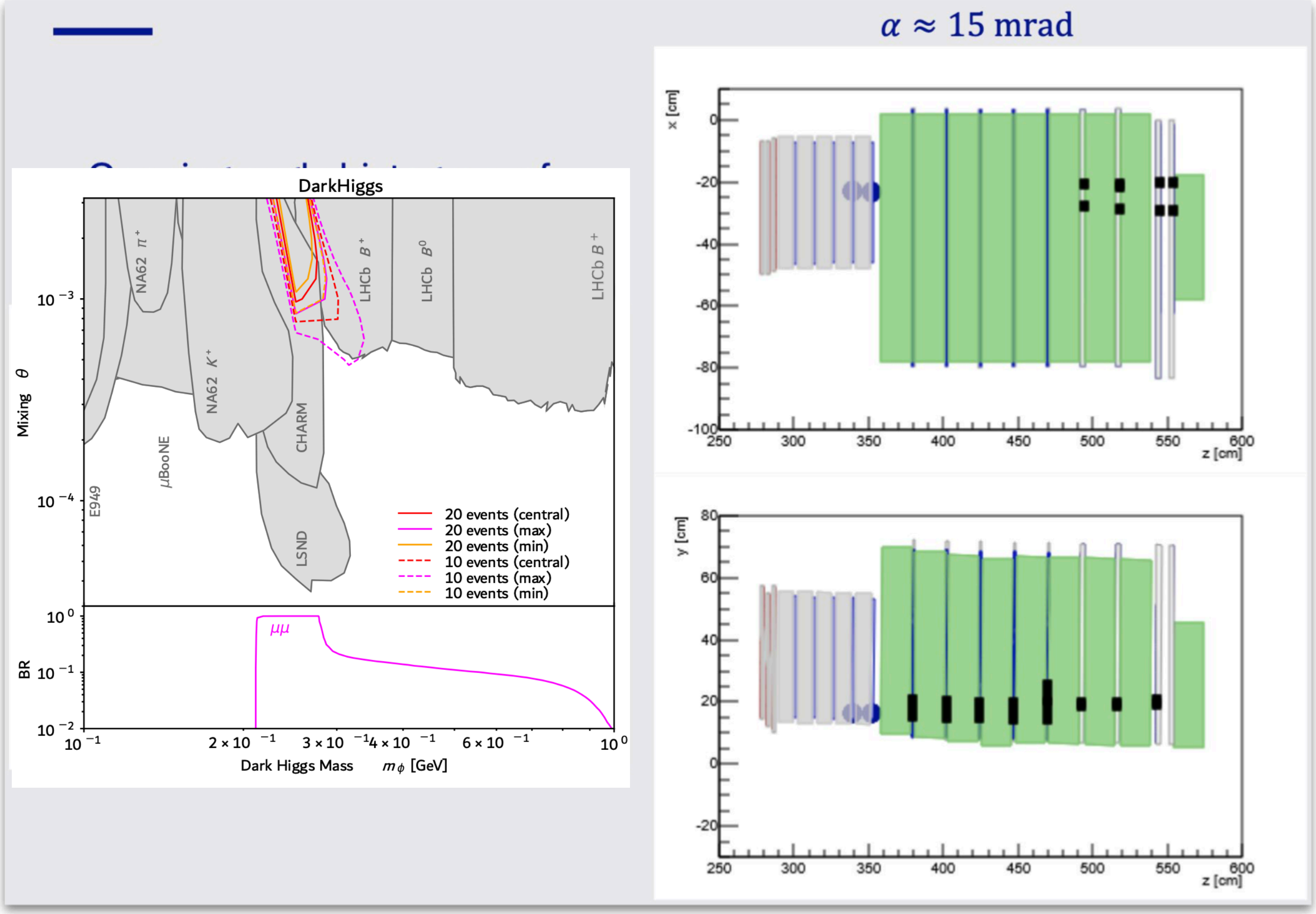
Flavour	CC DIS Interactions (3k fb^{-1}, 1.3 ton) total (DPMJET)	cc-bar (DPMJET)
$\nu_\mu + \bar{\nu}_\mu$	1.5x10^4	2.4x10^3
$\nu_e + \bar{\nu}_e$	3.4x10^3	2.7x10^3
$\nu_\tau + \bar{\nu}_\tau$	2.8x10^2	2.8x10^2
Total	**1.9x10^4**	**5.4x10^3**

BSM





ν_τ magnetic moment



Dark Higgs