Scattering and Neutrino Detector at the LHC

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare Sezione di Bologna

MUON NEUTRINO INTERACTION STUDIES WITH SND@LHC DETECTOR

EPS-HEP
08/07/2025

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On behalf of the SND@LHC Collaboration

Neutrinos at the LHC

Feasibility of high energy neutrino studies at LHC has been investigated since the 90's

→ Possibility to study pp→νX in an **unexplored range**

→ **High ν energies**: E_ν [10^2,10^3] GeV

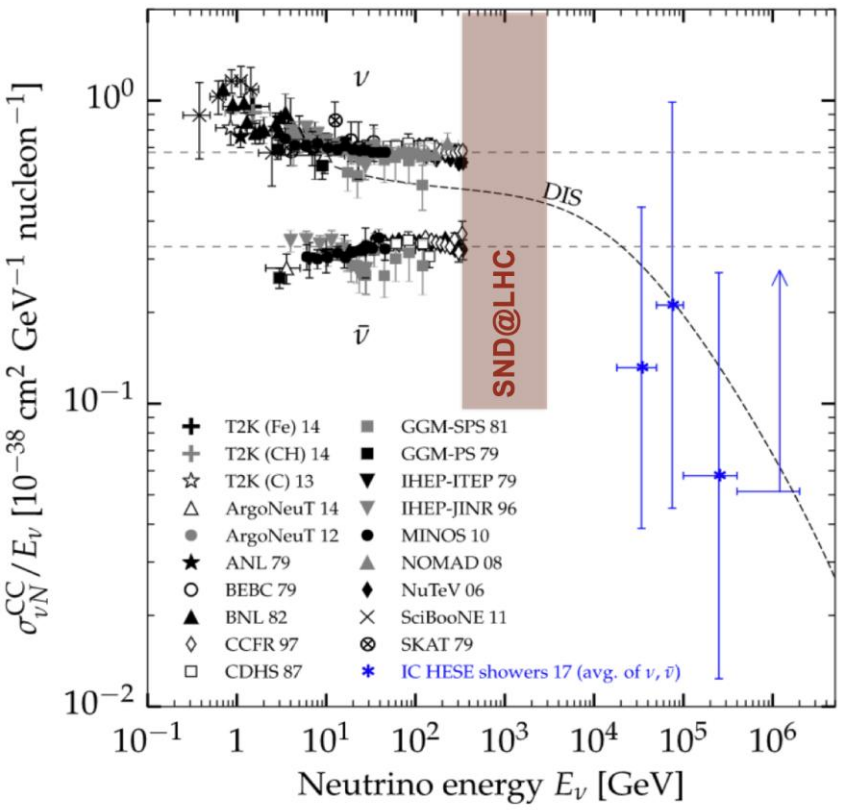
→ **Large ν flux** in forward region from pp collisions

Currently, two experiment in complementary ranges:

→ **FASERν** on axis: $\eta > 9$

→ **S**cattering and **N**eutrino **D**etector **at the LHC** slightly off axis: $7.2 < \eta < 8.4$

PRL 122 (2019) 041101



SND@LHC physics goal

SND@LHC studies **all neutrino flavours** at **TeV** energies

→ Measure **charm production** at high η ($gg \rightarrow cc$)

  → Given the η region, the majority of vs is from charmed hadrons decay

→ High-energy neutrino cross section measurements

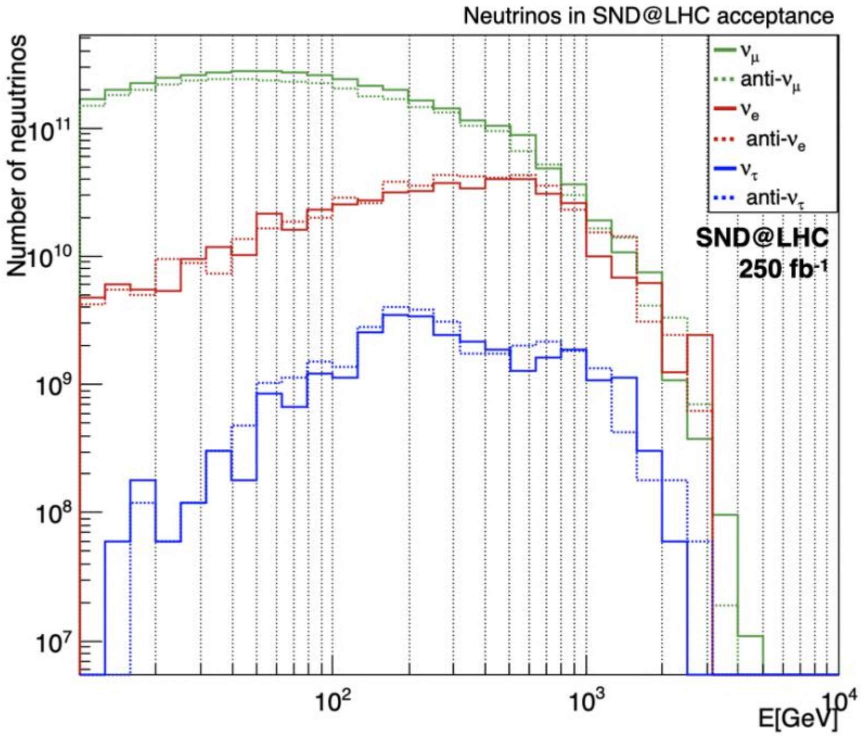
→ ν_τ observations

→ Test lepton **flavour universality** measuring ${}^{\nu_e}/_{\nu_\mu}$ and ${}^{\nu_e}/_{\nu_\tau}$

→ Direct search of **feebly-interacting particles** (FIPs)

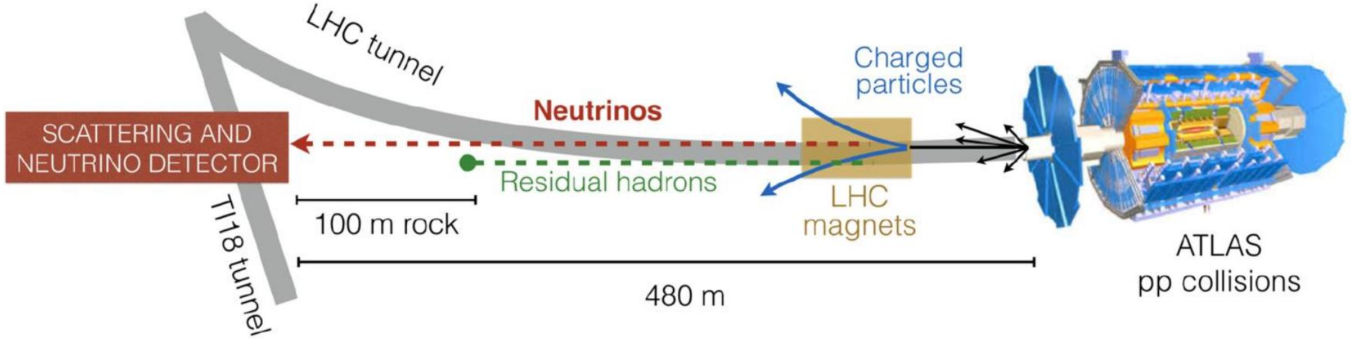
Flavour	Neutrinos in acceptance $\langle E\rangle$ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions $\langle E\rangle$ [GeV]	CC neutrino interactions Yield
ν_μ	130	3.0×10^{12}	452	910
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360
ν_e	339	3.4×10^{11}	760	250
$\bar{\nu}_e$	363	3.8×10^{11}	680	140
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}



The detector: location

480 m away from the ATLAS interaction point (IP1) in the TI18 tunnel



→ Shielded by **100 m rock**

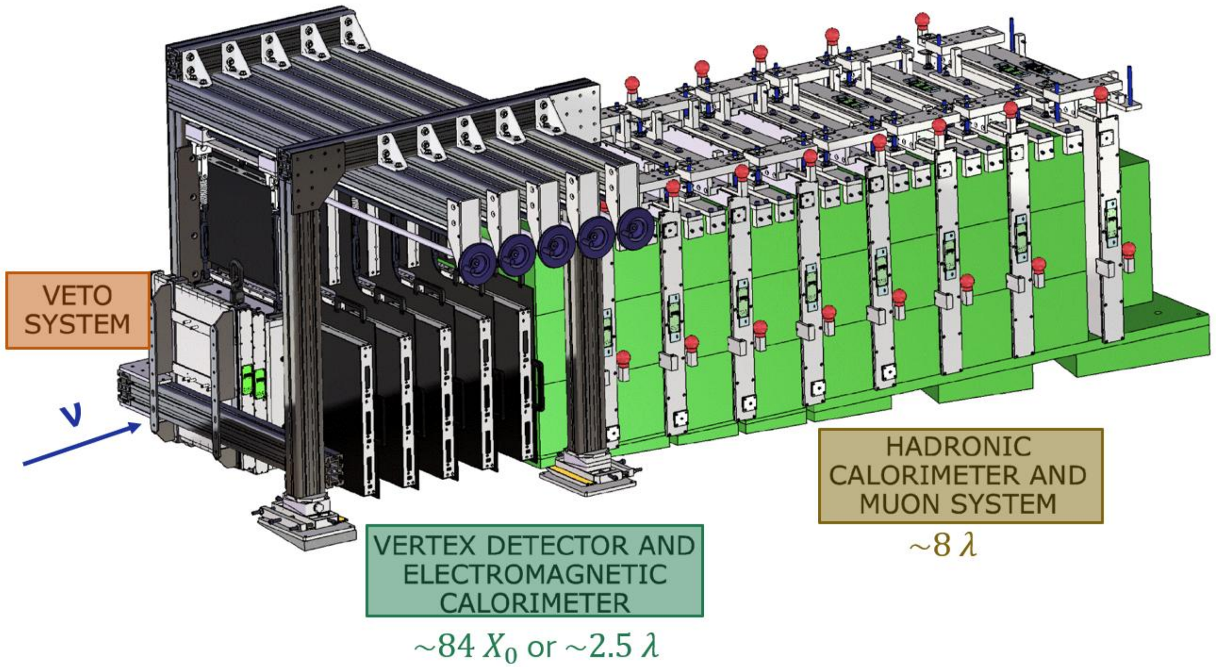
→ **LHC magnet** deflects charged particles

↓

Neutrinos and FIPs reach the detector

The detector

Hybrid detector composed of:

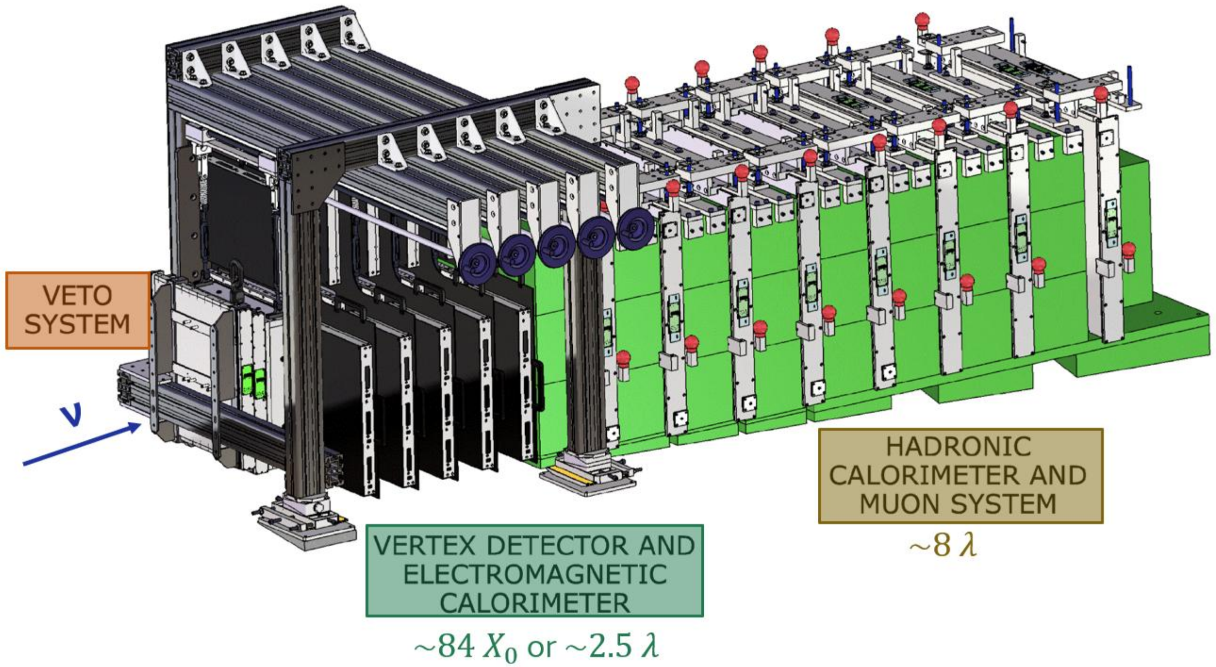


The detector

Hybrid detector composed of:

→ Veto system

→ Since 2024: **3** planes of scintillating bars **to tag incoming charged** particles

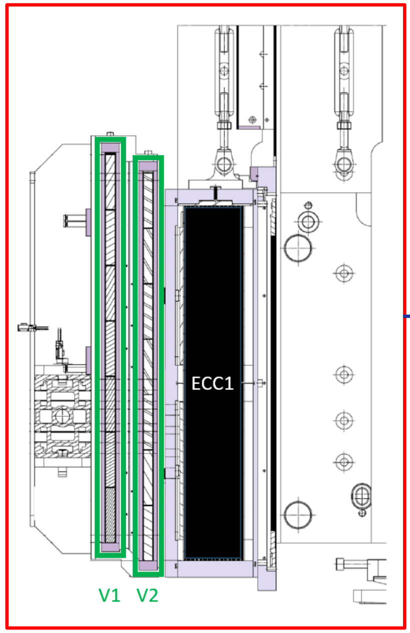


Veto System Upgrade

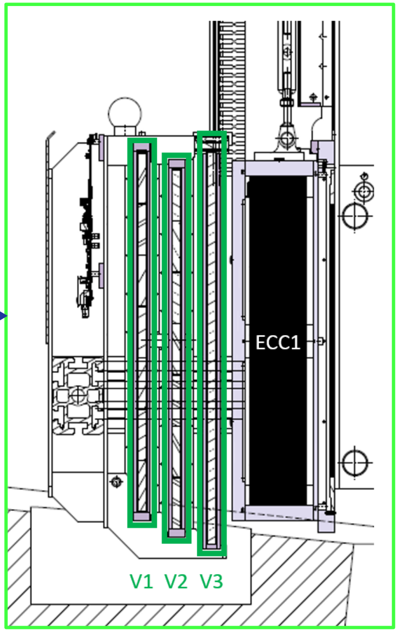
Inefficiency **optimal value** in the 2022-23 period was $(7.8 \pm 2.8) \times 10^{-8}$ achieved on a fiducial area of 35×35 cm^2→ target coverage of ~ 64%.

In Year End Technical Stop of 2023-24
a 3rd **veto plane** was added

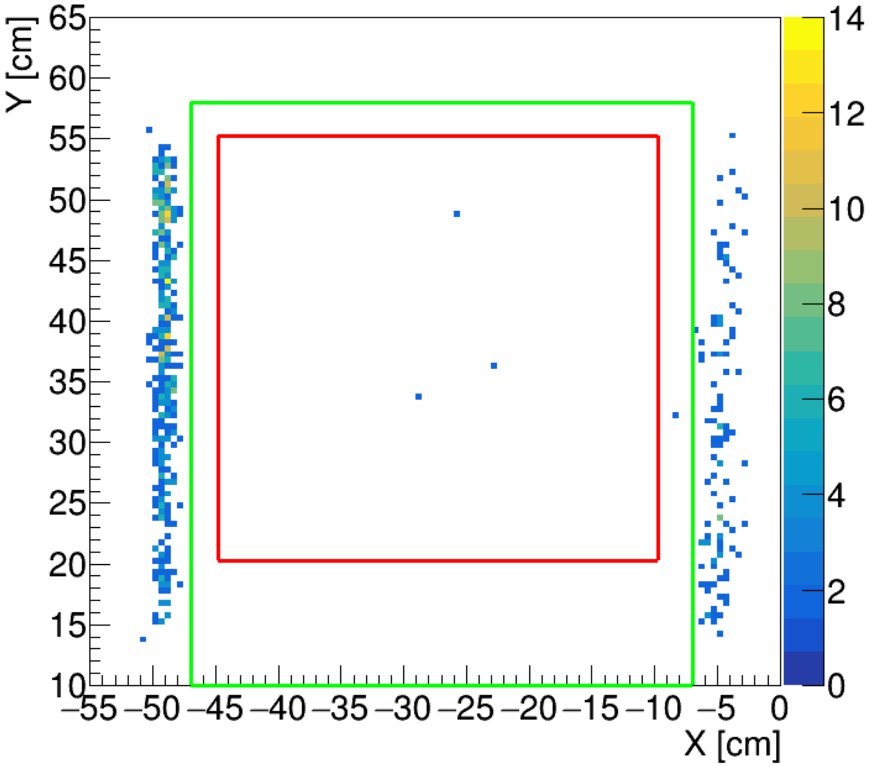
The 3rd plane has **vertical** bars to reduce overlapping area → minimizes signal loss due to spatial and temporal coincidences



2022/23 veto system



Updated veto system



In the new configuration the inefficiency is $\mathbf{(4.9 \pm 1.9) \times 10^{-9}}$ on the **full target area**

↓

increase of 56% of observable neutrinos

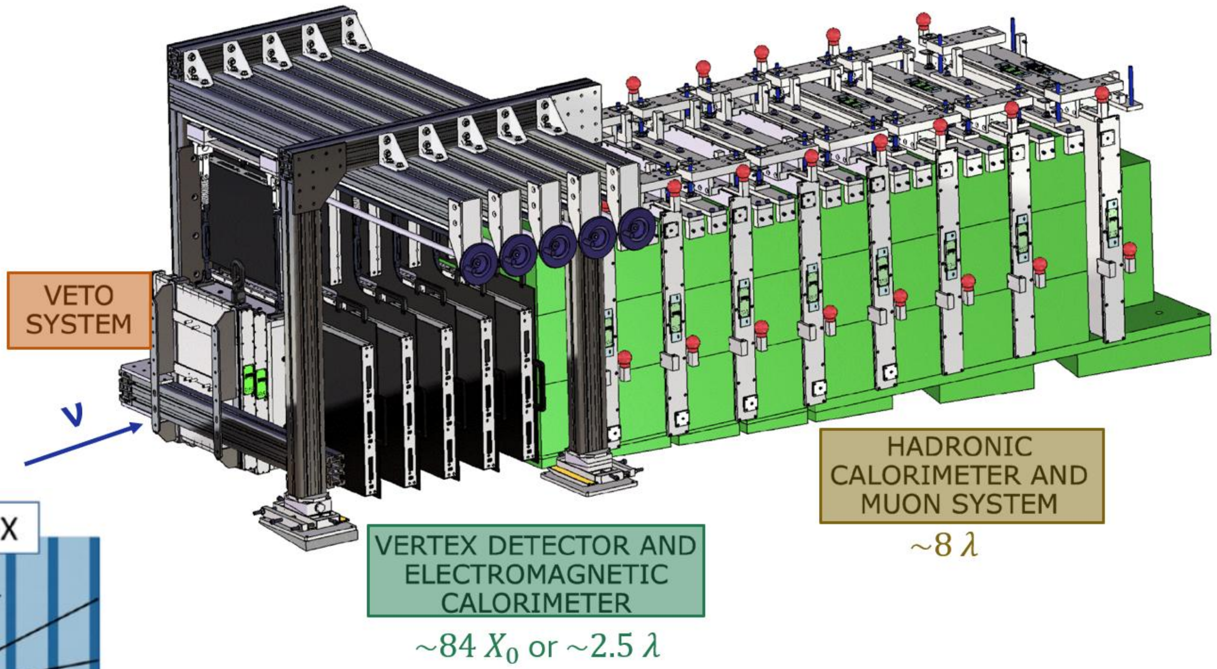
On arXiv, submitted to JINST!

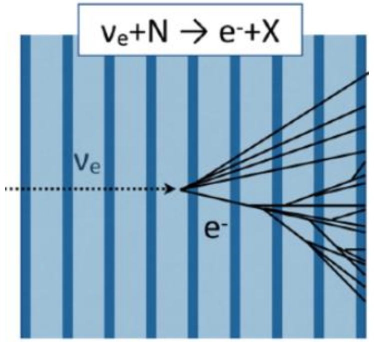
The detector

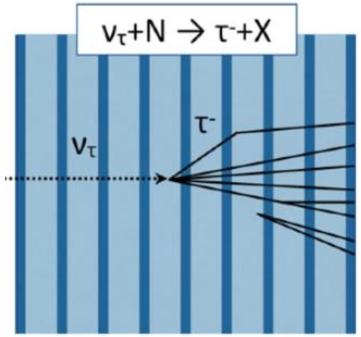
Hybrid detector composed of:

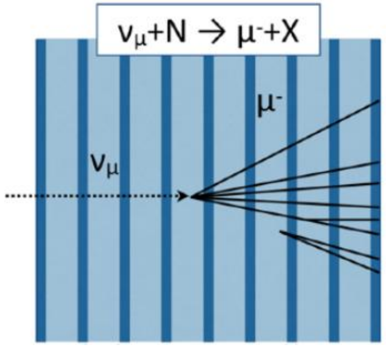
→ Veto system
  → 3 planes of scintillating bars **to tag incoming charged** particles

→ Target with vertex detector and electromagnetic calorimeter
  → Emulsion plates interleaved with tungsten (Emulsion cloud chamber) for **tracking and vertex identification**
  → Scintillating fibers (SciFi) for **time and calorimetric information**









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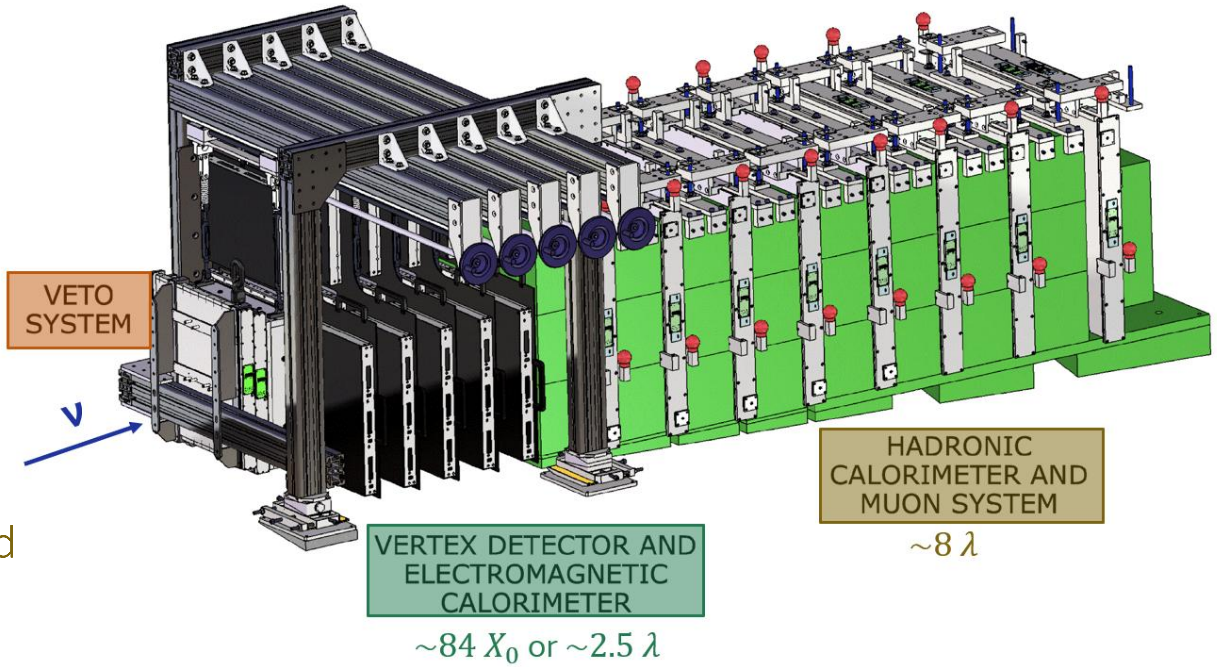
→ Hadronic calorimeter and muon system
  → 5+3 scintillator planes read by SiPMs interleaved with iron
    → 5 US: horizontal bars, focus on **calorimeter**
    → 3 DS: horizontal and vertical bars, focus on **muon tracking**



Upgrade of Muon system

Ongoing analyses confirm a need for better muon tracking → in 2024 two drift chambers with CMS DT technology were installed

Aim of **reducing resolution** from ~3 cm **to ~1.5 cm**

Before

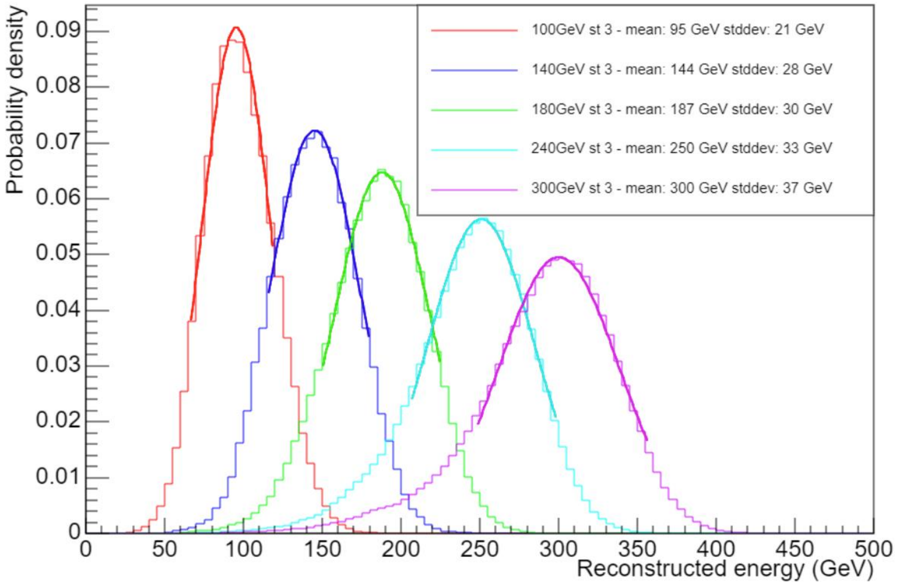
After

- Offline event matching validated
- Track reconstruction development ongoing

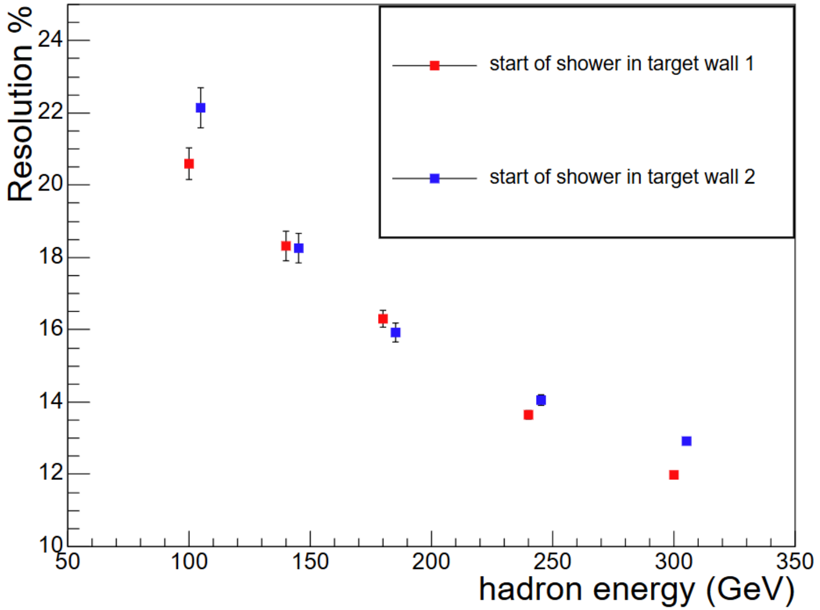
Hadron calorimeter calibration

νN collisions produce hadronic showers → **estimate the energy** deposited in both the target and the calorimeter

Test beam in 2023 to calibrate with hadrons beam at various energies reaching a resolution of **12-22%**



All infos in
Filippo Mei's poster



On arXiv, submitted to JINST!

SND@LHC Data

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  - 2025 (so far): Recorded 10 fb^{-1}
  - 2022 – 2024: Recorded **187** fb^{-1}
    - **96%** uptime
- Emulsion detector:
  - **14** targets exposed in 2022 – 2024
  - **~170** fb^{-1} integrated
  - 5700 emulsion films (**210** m^2) exposed and developed
- Unexpected increase in the muon flux in **2024.**
  - Doubled the target replacement rate.
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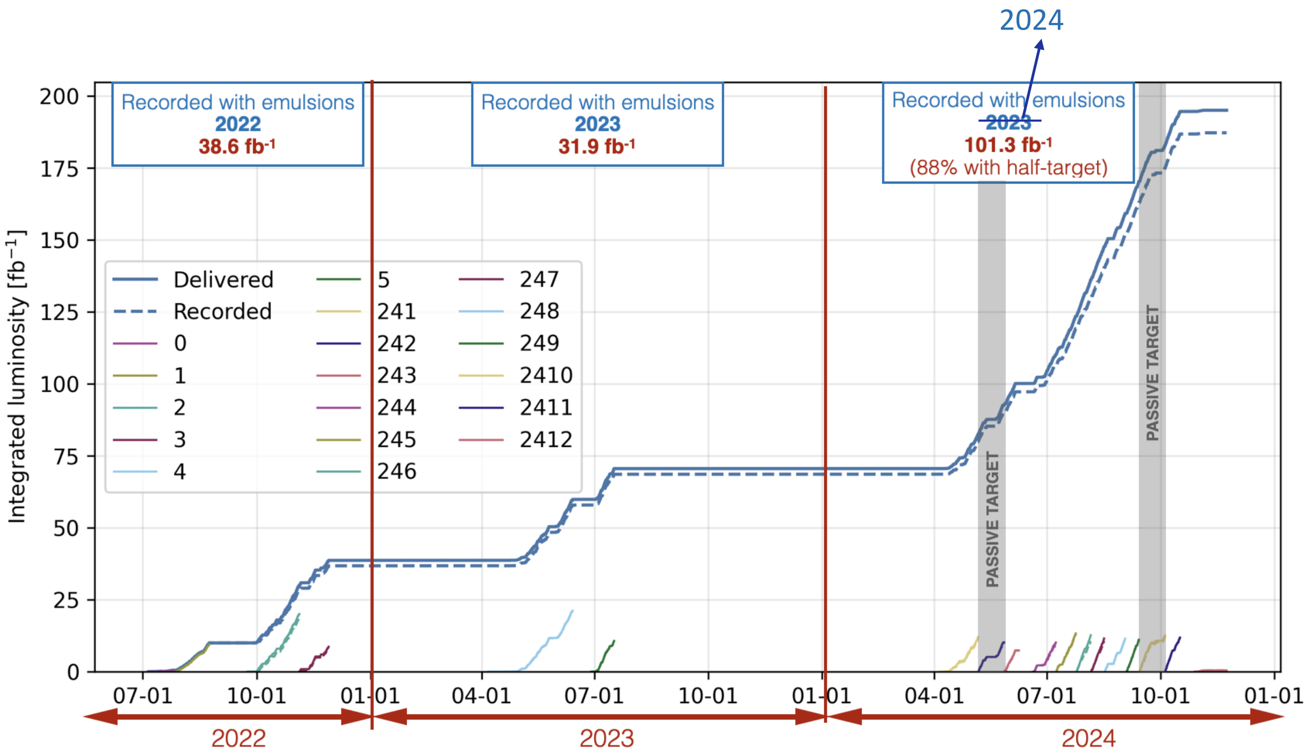
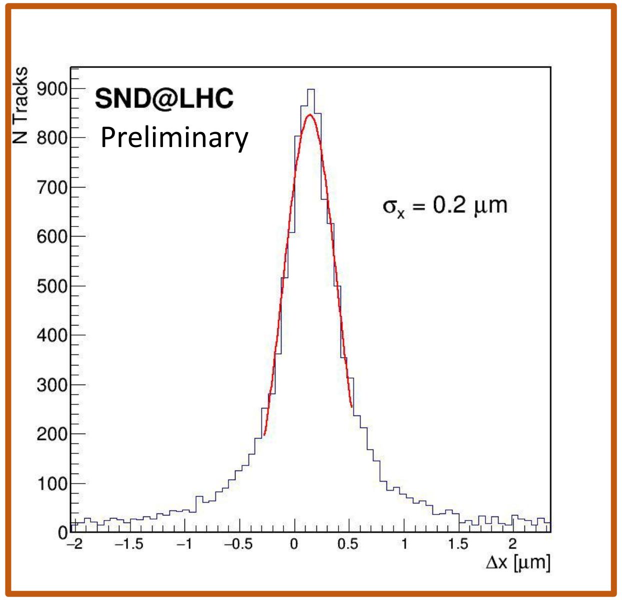
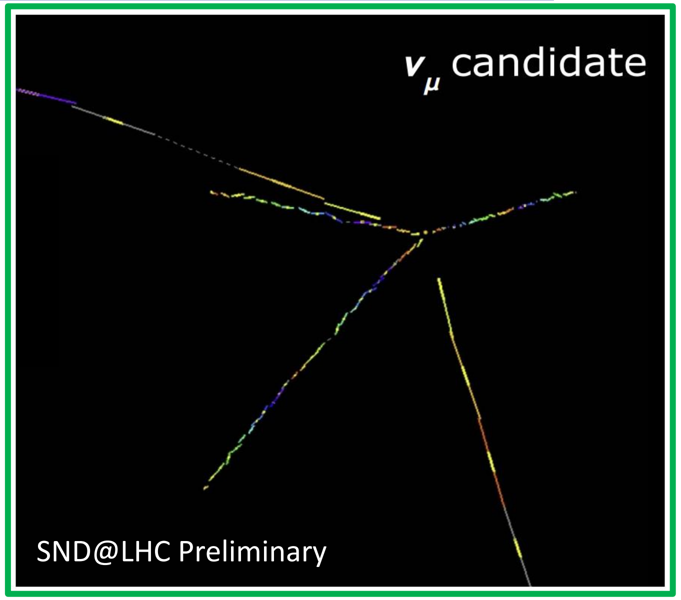


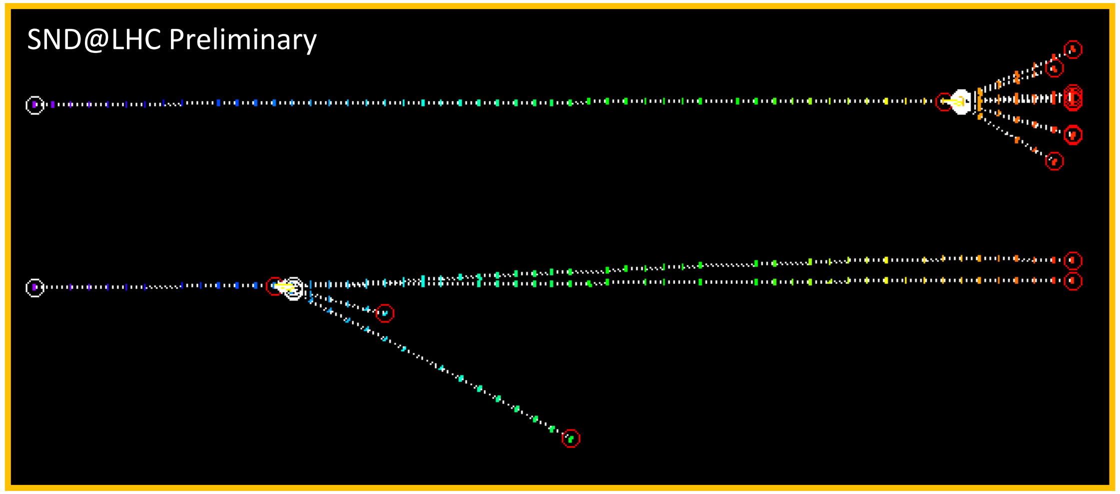
Emulsion data analysis

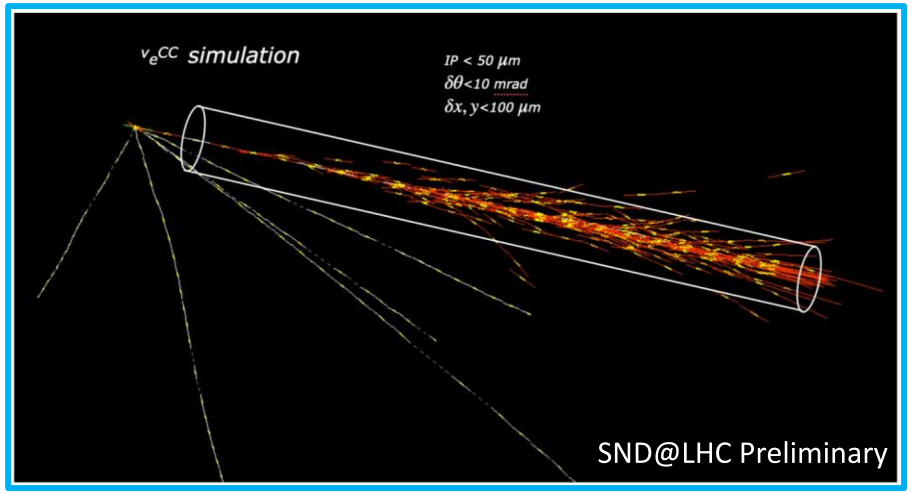
Neutrino search in emulsion:

- Achieved position resolution 0.2 μm
- Vertices search ongoing on reconstructed data
  - Muon neutrinos
  - Electron neutrino
  - Muon DIS → crucial for background studies









μ analysis with electronic detector

Muon analysis

- **Passing muons:** Muon flux is important for detector operations and physics analyses
  - 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 emulsion
- **Passing muons in heavy ions runs:** Softer energy spectrum due to different LHC optics
  - Cross-check of detector performance
  - Further validation of the background model
- **Muon trident cross-section measurement**: look for Onur Durhan's poster
- **Muon DIS in emulsion:** discussed before

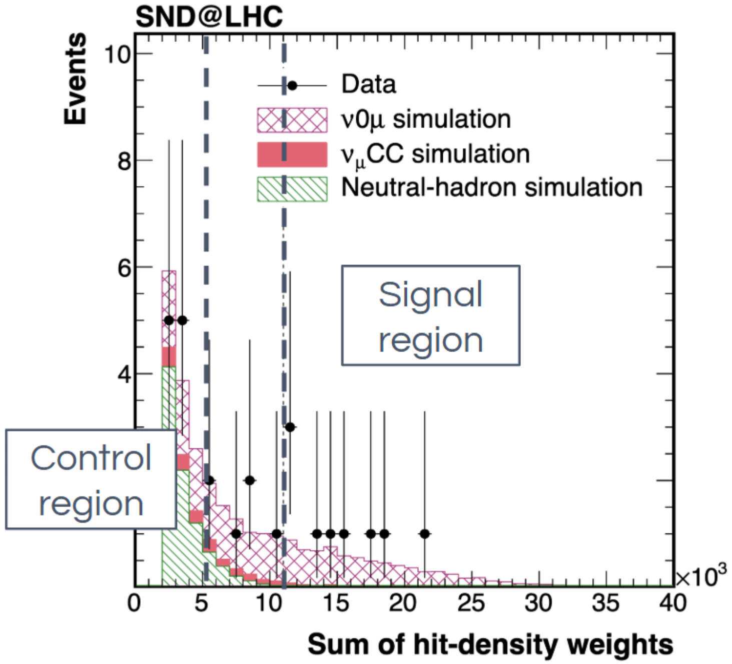
ν analysis with electronic detector

Recently published:

- ***0 μ final states***: the *first* observation of non-ν_μ CC neutrino interaction using electronic detectors at the LHC PRL 134 231802 (2025)

- Signal: νeCC and NC interactions
  - Expected signal: 7.2 events → 4.9 ν_e CC, 2.2 NC, 0.1 ν_τCC
  - Expected significance: 5.5 $\boldsymbol{\sigma}$
- Total expected background: 0.32 ± 0.06 events
  - Neutral hadrons: 0.015 events → constrained by control region data
  - Neutrino background: 0.30 events → due to ν_μ CC interactions

Number of events observed: 9
Observation significance: 6.4 $\boldsymbol{\sigma}$



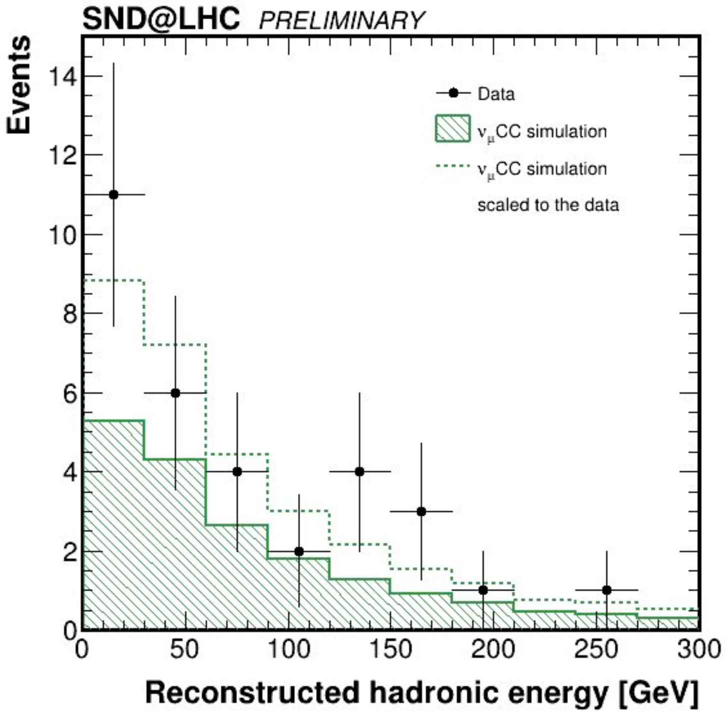
ν analysis with electronic detector

Muon neutrino analysis

- **Published:** Observation of collider muon neutrinos with the SND@LHC experiment, PRL 131 031802 (2023)
  - On 2022 data, 36.8 fb^{-1}
  - Observed 8 ν_μ interaction candidates
- **Ongoing:** Update on 2022+2023 dataset
  - Larger statistic: 68.8 fb^{-1}
  - Optimized fiducial volume cuts → acceptance 18% up from 7.5%

- 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



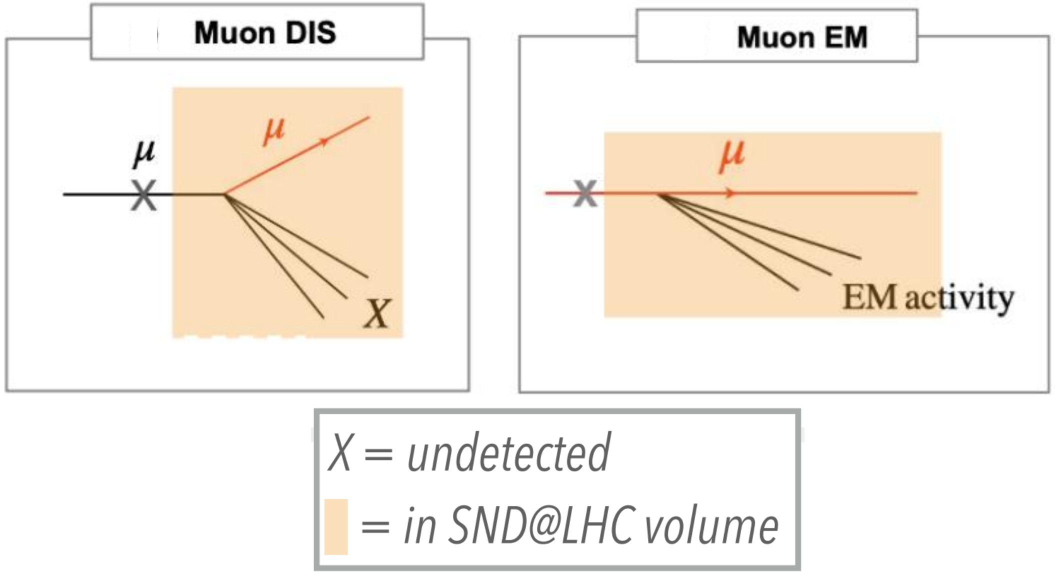
2024 ν_μ update

Goal: update the CC ν_μ study with the 2024 SND@LHC data and exploiting the upgraded veto system and new algorithms developed on 2023 test beam data

2024 dataset: SND@LHC recorded 119 fb^{-1} → **1.75x dataset** 2022+2023

Given the large sample → selection method and background rejection* are developed on a subsample of ~20 fb^{-1} keeping the rest of the data blinded

*Use data also for **undetected** muon background estimation → reversing veto requirements



2024 ν_μ update: event selection

Aim:

- ν_μ sample: find the cleanest set of events to characterize the main features of a neutrino interaction

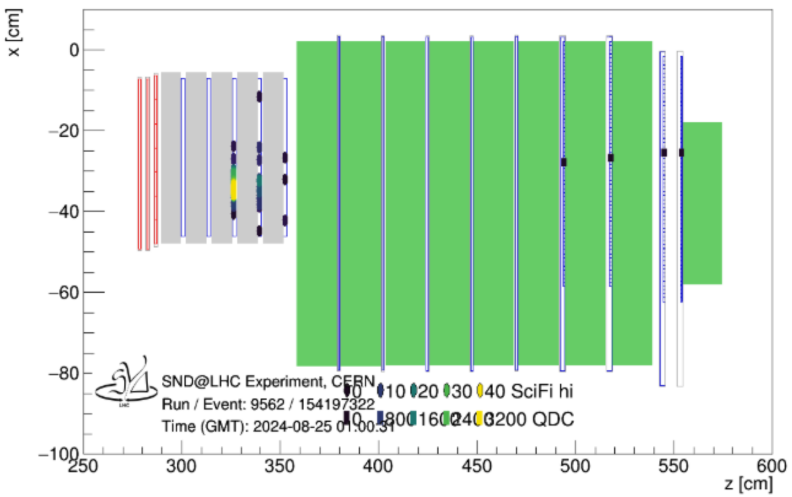
For now we require:

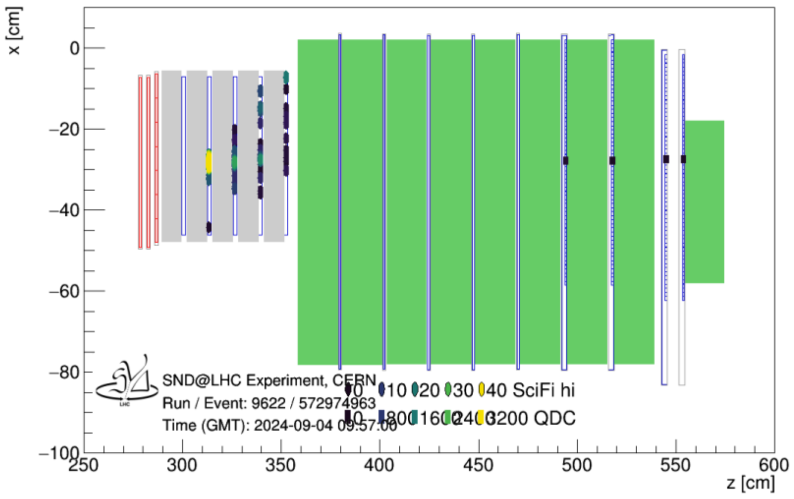
- **No hit** in the veto system in ν_μ sample
- Activity in all us planes → ensure **muon is crossing the whole detector**
- **Two consecutive planes** to match the shower tag criteria → minimum number of hits close to each other
- At least a reconstructed track that:
    - Extrapolated (x,y) to the scifi wall in which the shower start is tagged inside the target region
    - Extrapolated (x,y) is **close to computed *centroid*** ≡ average of hits position, weighted by signal
    - Extrapolated (x,y) with centroid correction to the veto is in the active area

Given **new veto inefficiency** → using a larger fiducial area of 34×35 cm^2 instead of 25×26 cm^2 of 2022-23 analysis

Work in progress!

ν_μ candidates





SND@LHC Preliminary

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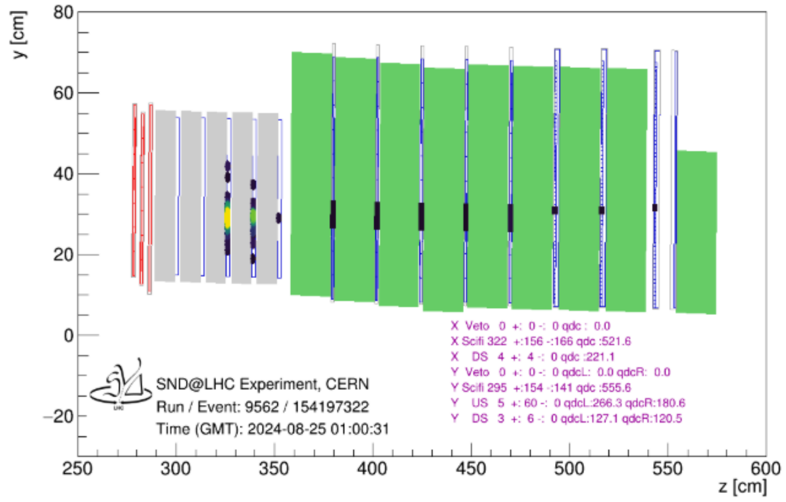
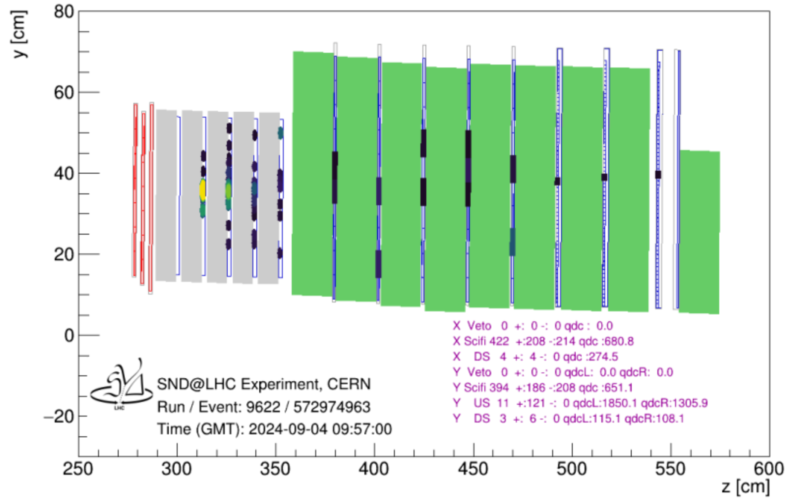
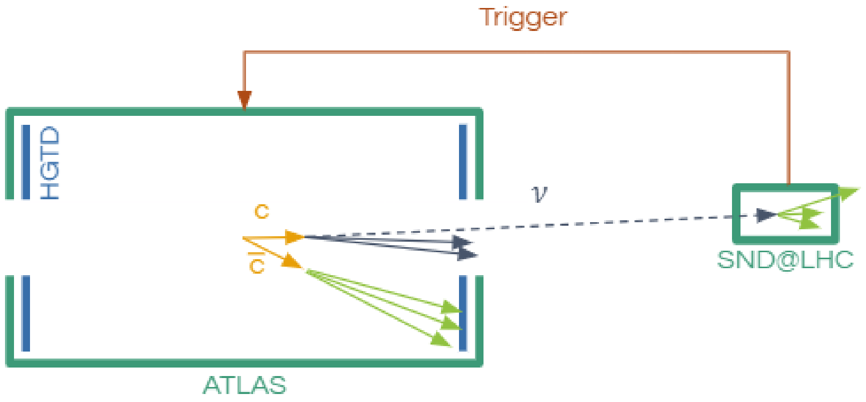




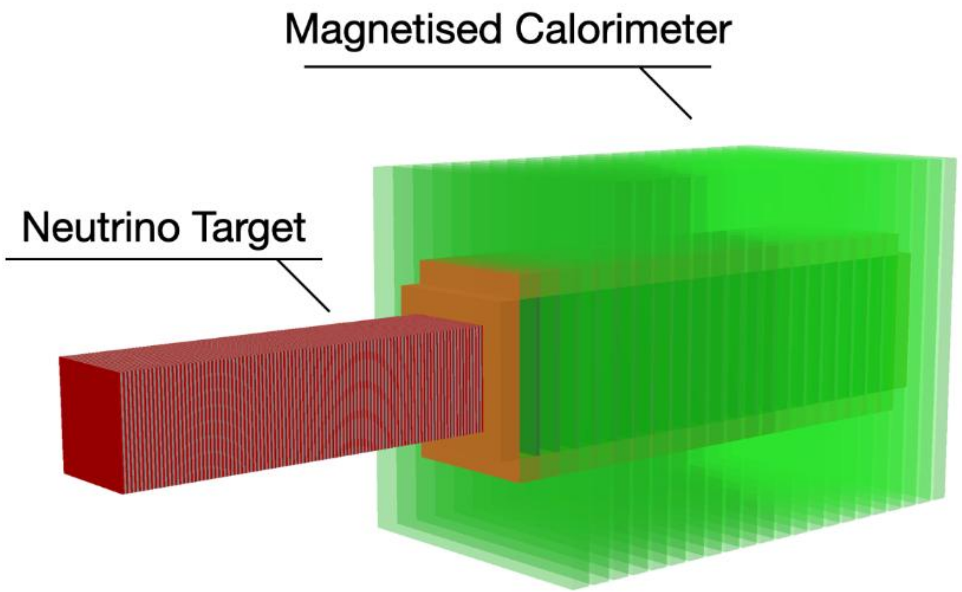
HL-LHC prospect

Recently approved (CERN-LHCC-2025-004) upgrade to run during HL-LHC

- Need to replace emulsions → reuse CMS Outer Barrel strips making it the first Si-based neutrino vertex detector
- Add **magnetized** calorimeter for charge and momentum measurement → distinguish ν and $\bar{\nu}$
- Include fast-timing detector → resolve the pile-up and sending a trigger signal to ATLAS, **feasibility study ongoing**



Measurement	Run 3 Uncertainty Stat.	Run 3 Uncertainty Sys.	HL-LHC Uncertainty Stat.	HL-LHC 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 $\bar{\nu}_\mu$ cross-section	-	-	1%	5%



Summary and outlook

Summary:

- Lot of ongoing analyses both on electronic detector and emulsion data
- Detector upgrade:
  - **3rd veto plane** allows for strong incoming particle rejection over **all target area**
  - **Muon system** upgrade
- Thanks to test beam campaign:
  - **Calibrated** the detector response to **hadronic showers**
  - Developed and validated simple but effective **shower tagging algorithm**

Into the future:

- Stay tuned for SND@HL-LHC: recently approved

THANKS FOR THE ATTENTION

Remember to check out
Onur Durhan's poster
Filippo Mei's poster

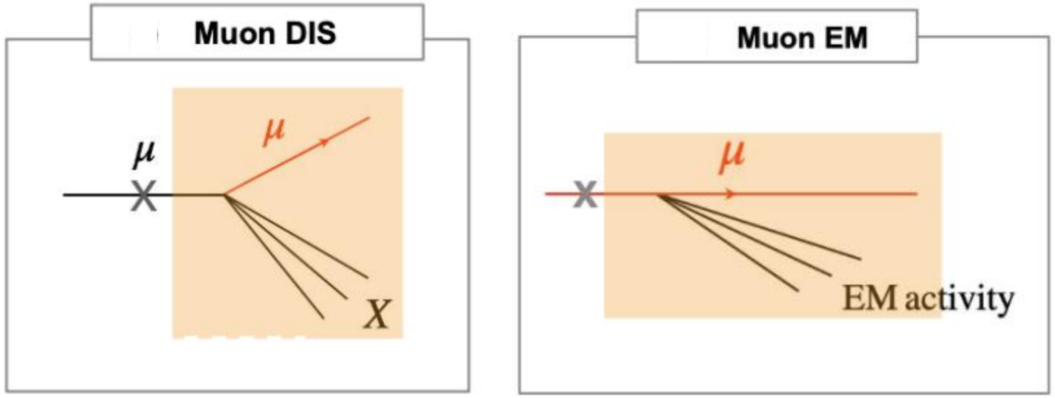
Observation of ν_μ: background

Select a μ subsample reversing the veto cut

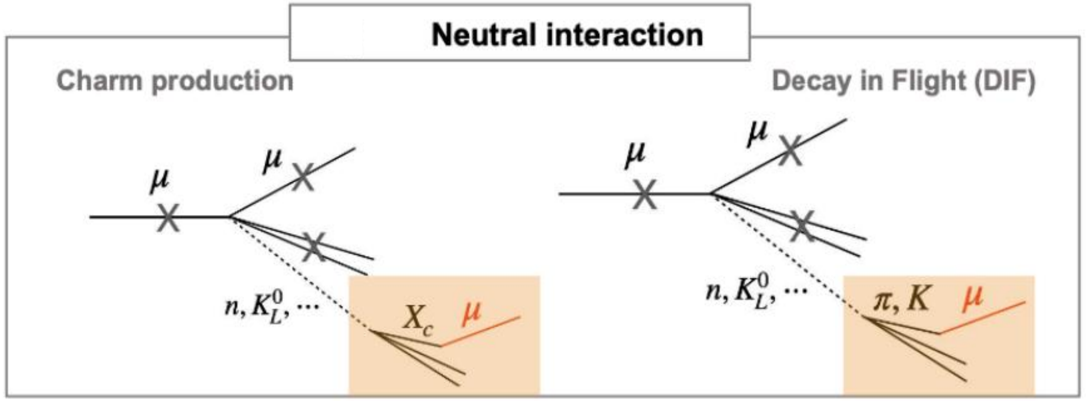
- >= 2 veto hits;
- A shower tagged in SciFi

To be estimated from **simulations**

Undetected muon background



Muon-induced **neutral particles**



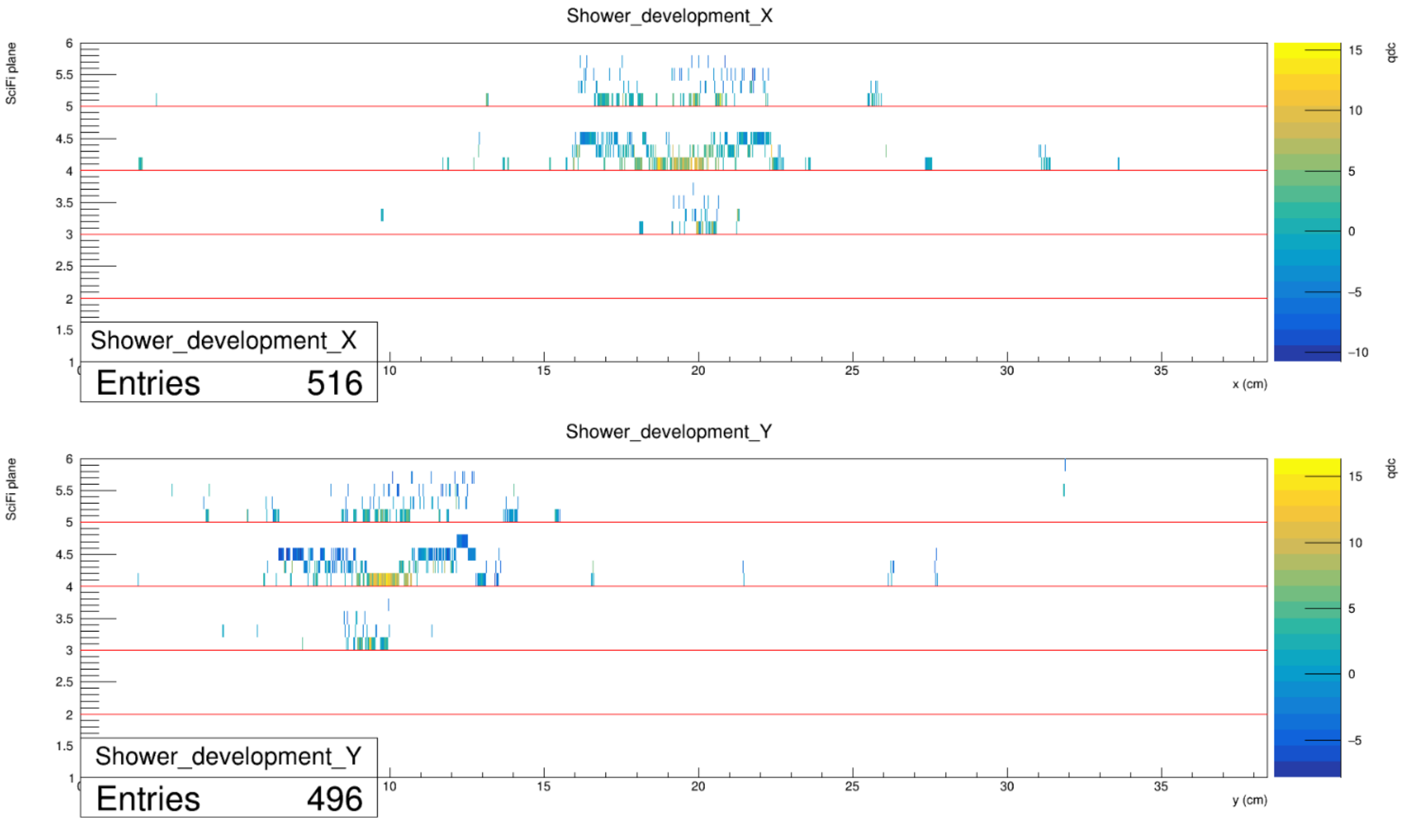
X = undetected

= in SND@LHC volume

Shower tagging

Aim: tag the first wall in which an hadronic shower is visible

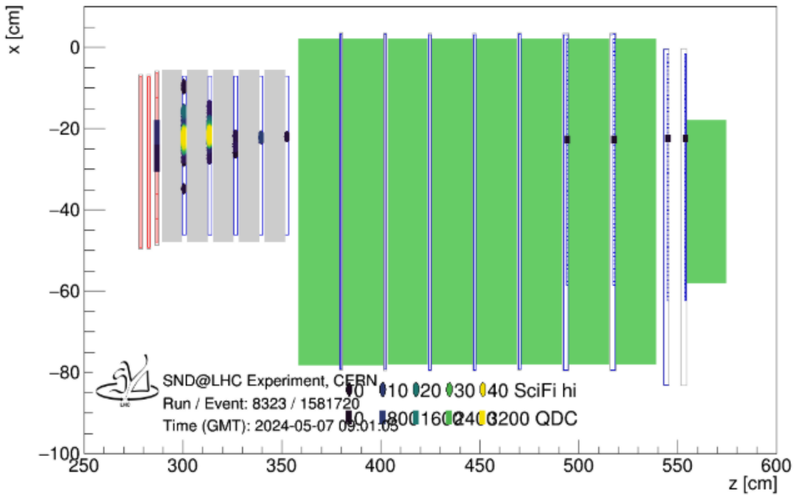
Achieved by: requiring a minimum number of hits close to each other



Event from first observation of collider muon neutrinos [1] with 2022 data

[1] The SND@LHC Collaboration, Observation of collider muon neutrinos with the SND@LHC experiment, Phys. Rev.Lett. 131

μ candidates



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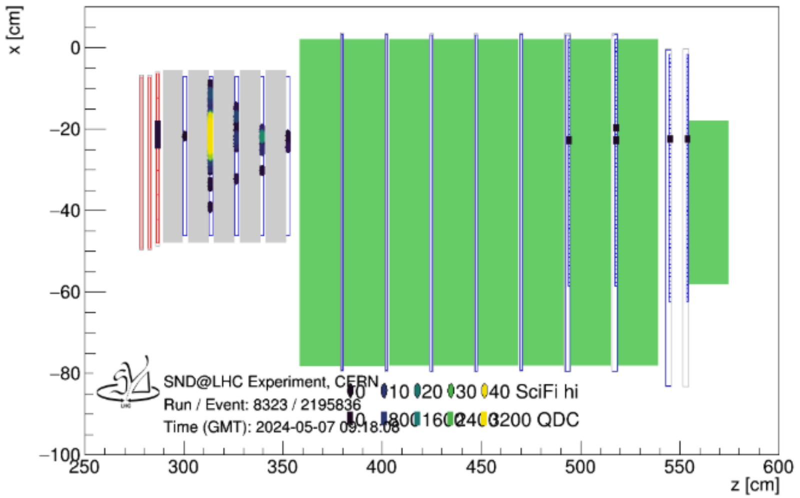

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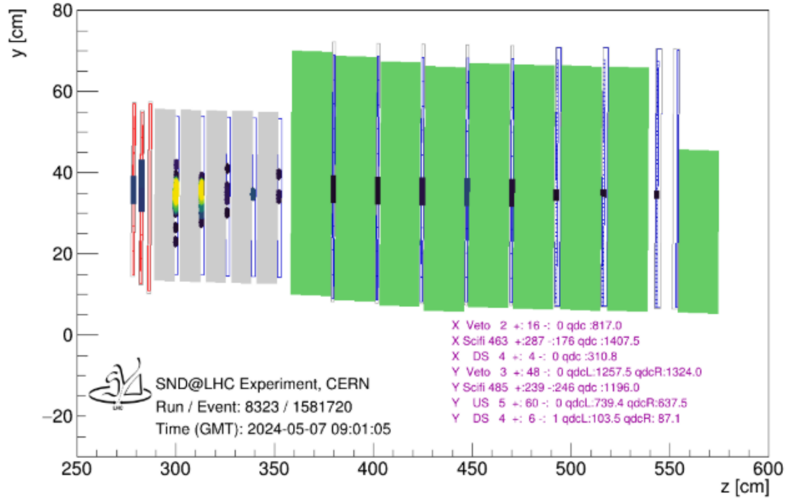
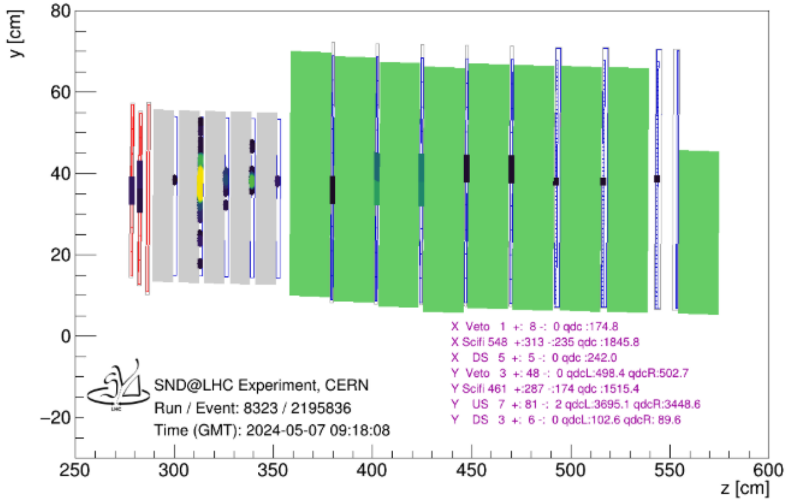
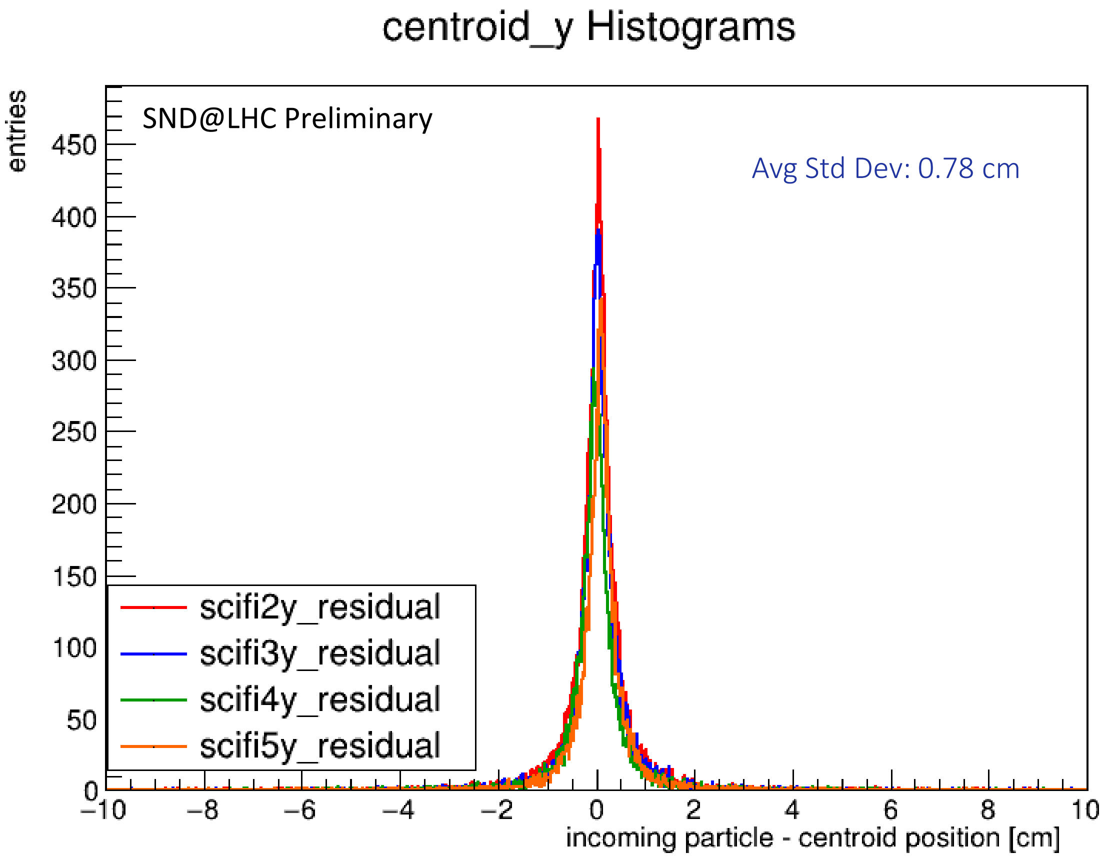


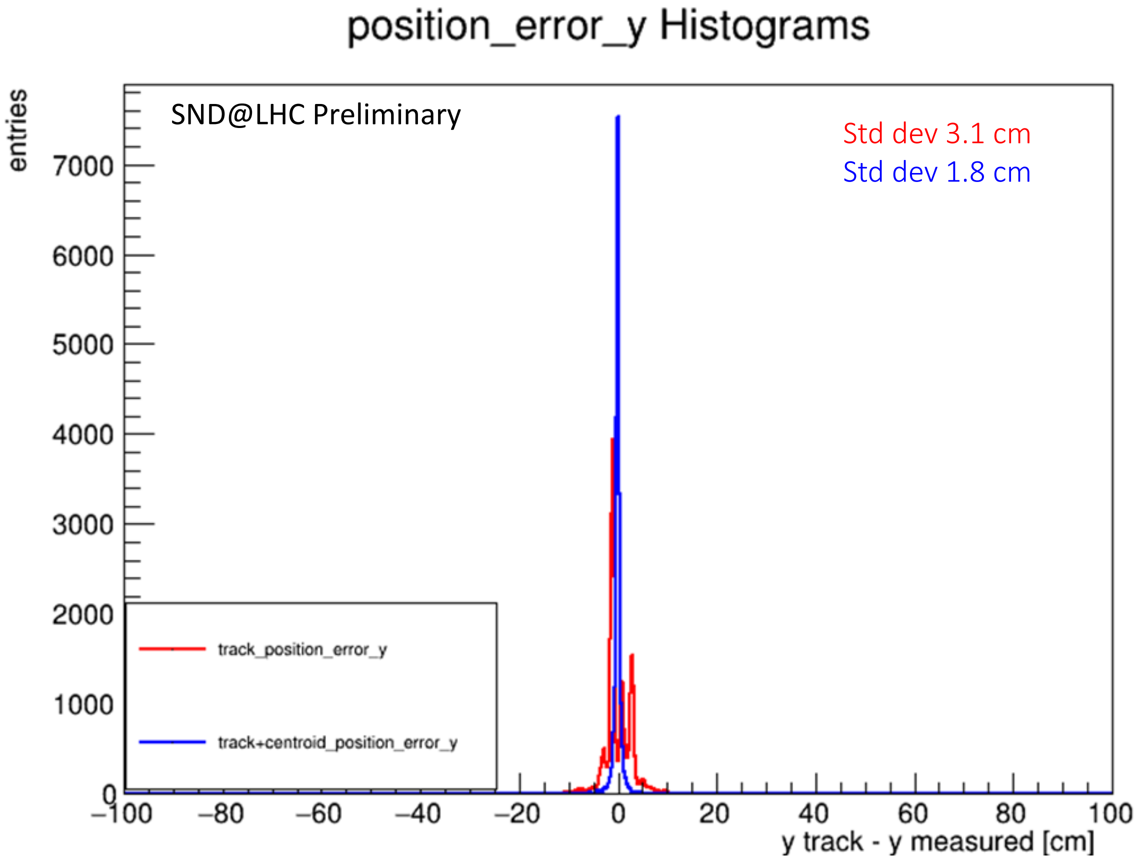


Validation of shower centroid

Centroid: Mean position averaged with qdc value. A minimum number of hits is needed

Aim: Validate centroid distribution using muon producing DIS showers





Backup

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- Electronic detectors:
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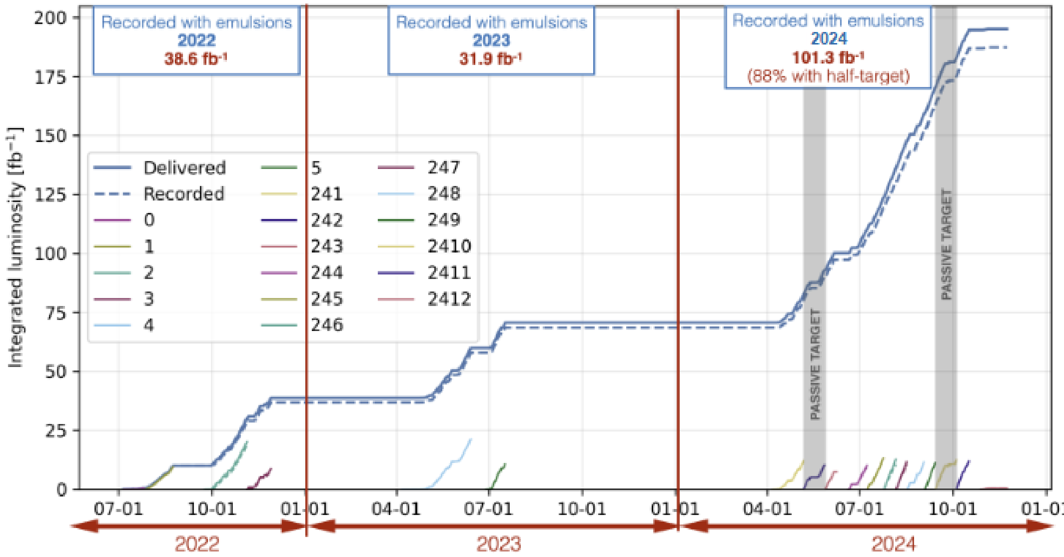
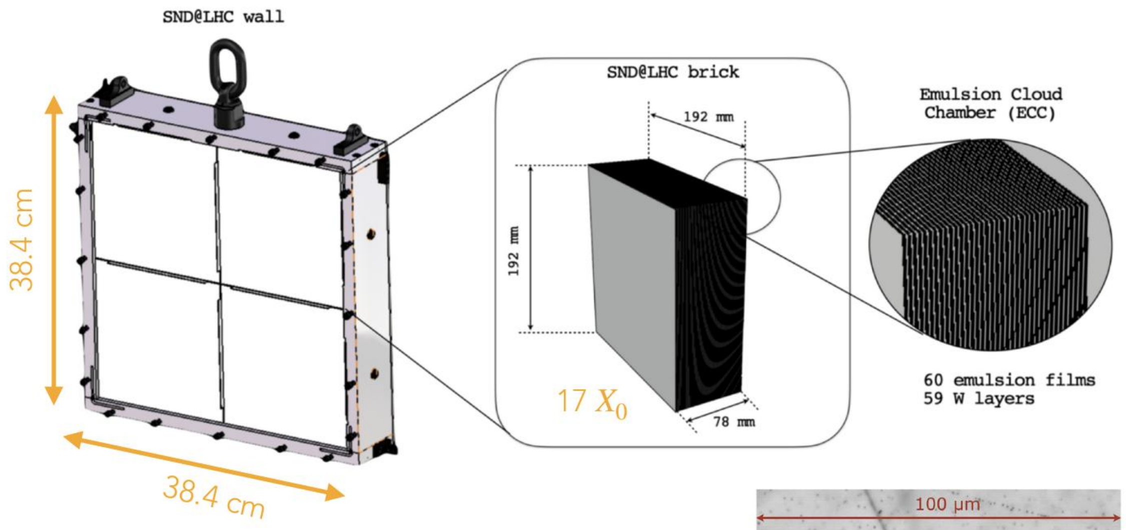
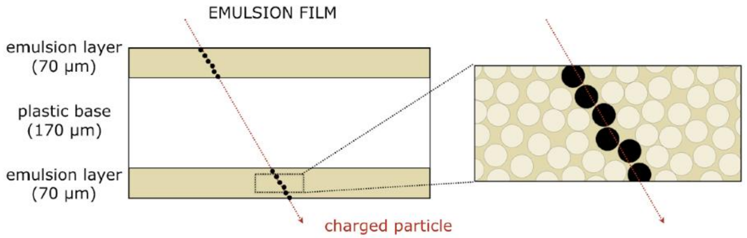


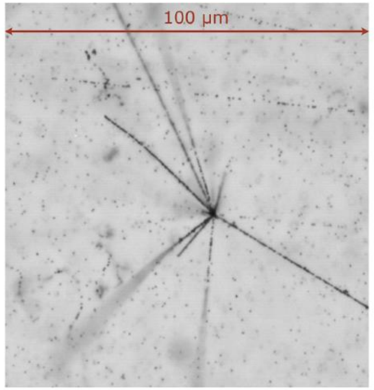
- Emulsion scanning is performed with fully automated microscopes in six laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Santiago
- Track density up to 4×10^5 tracks/cm^2

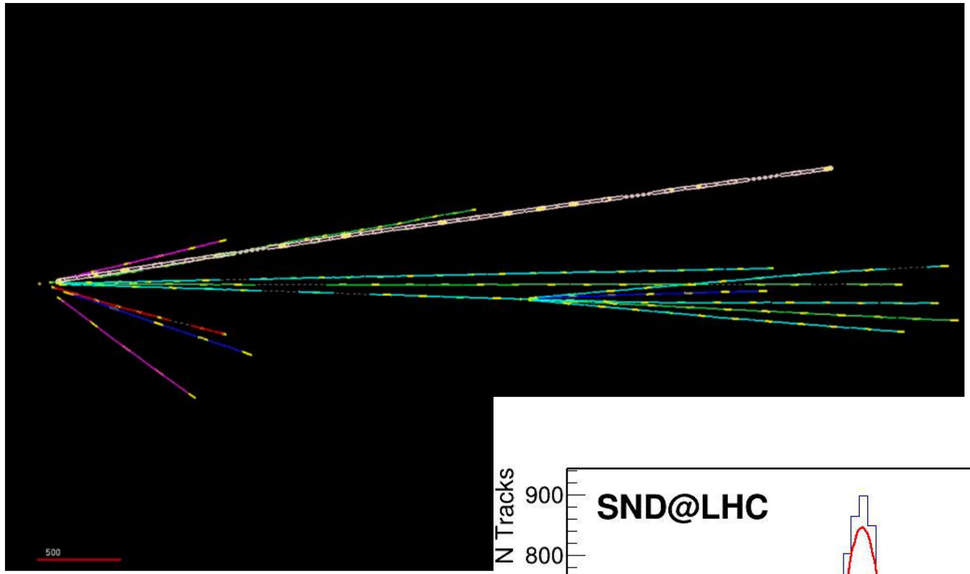
Status of emulsion scanning:
800 kg x 42 fb^{-1}

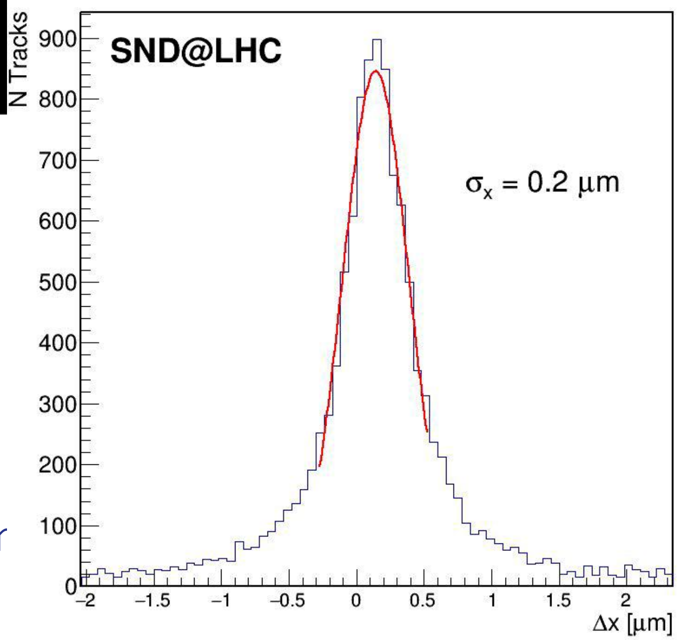
Backup











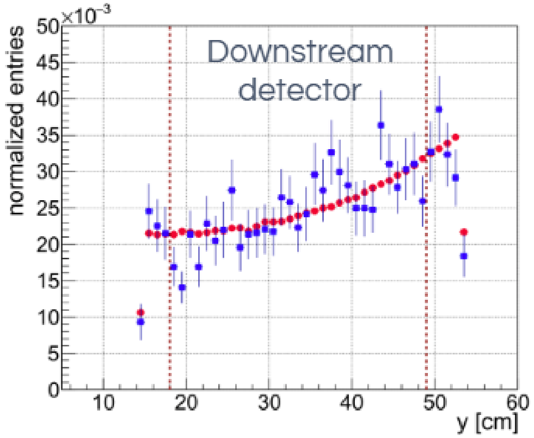
Position resolution 0.2 µm

Backup

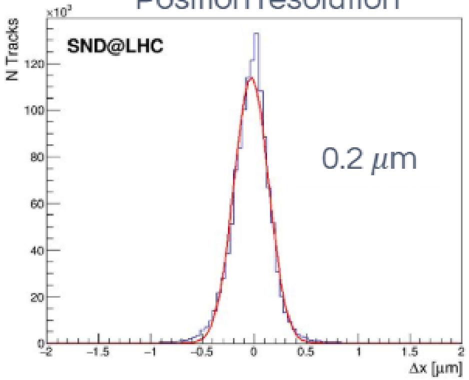
Passing muons

- 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 emulsion.
  - Agreement with MC predictions within 20%.
- Recent improvements in emulsion reconstruction allow for the measurement of muon momentum via multiple Coulomb scattering.

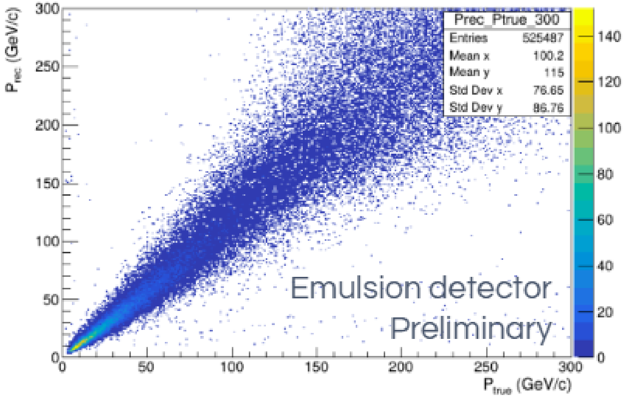
year	flux [trk/(cm^{-2}fb^{-1})]
2022	557
2024	1154
2025	**832**
MC	460



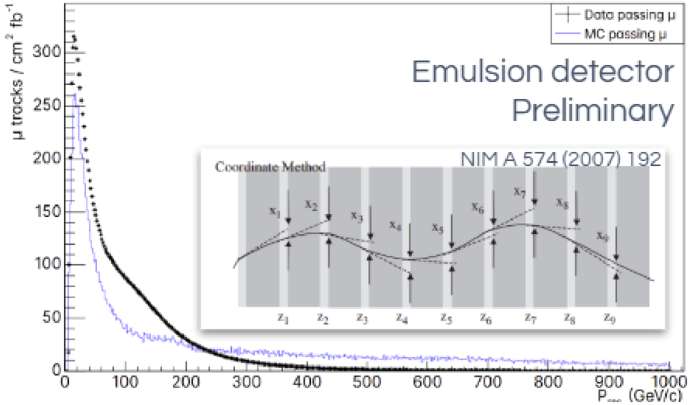
Position resolution



Reconstructed *vs* true muon momentum



Momentum measurement for muons reconstructed in the RUN1 brick21 (2022)



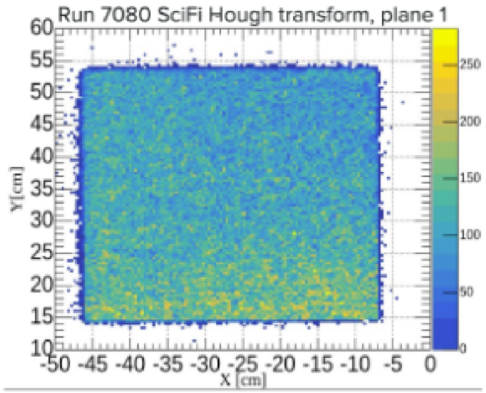
Passing muons in heavy ion runs

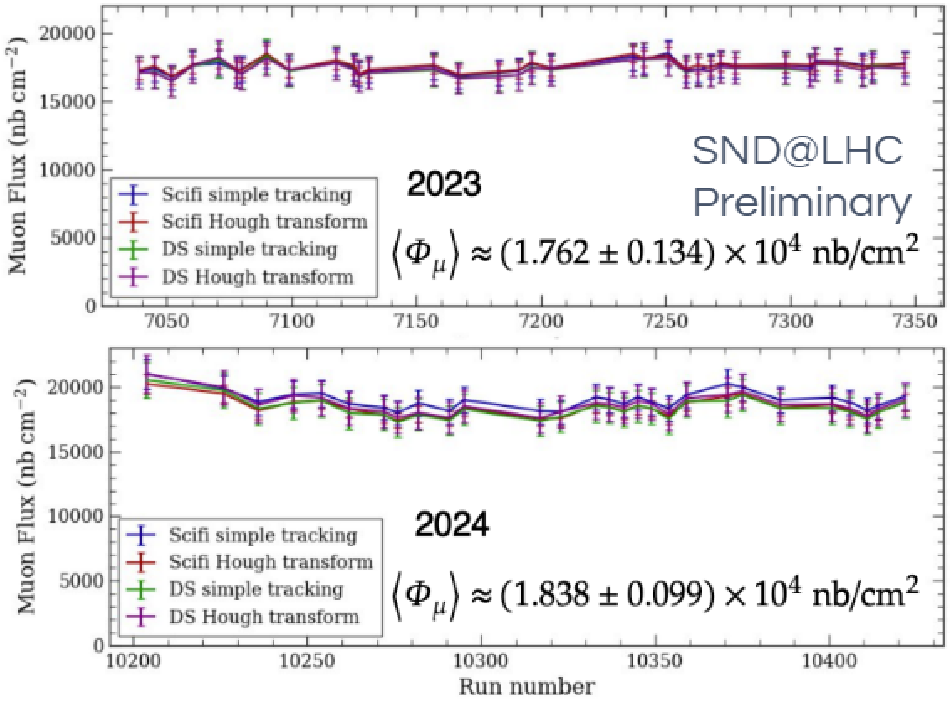
- Measurement of the muon flux in heavy ion collisions.
  - Different physics compared to pp.
    - Softer energy spectrum.
  - Different LHC optics compared to pp.

- Allows for further validation of the background model.
- Cross-check of detector performance.

- Measurement in good agreement with MC expectation:
  - $1.56 \pm 0.19 \times 10^4$ nb/cm^2

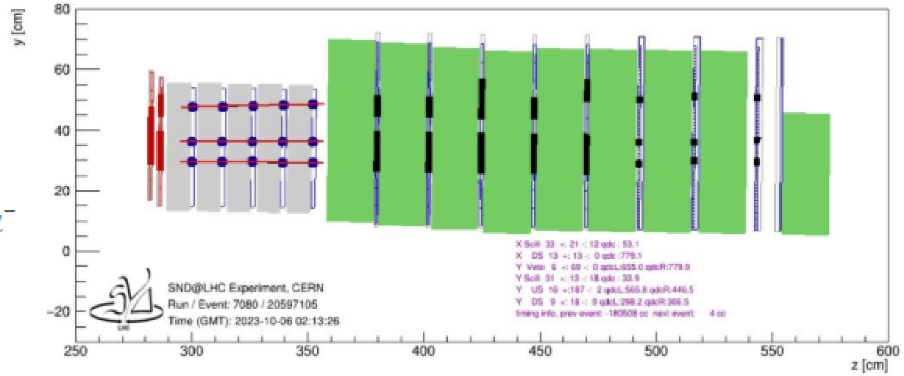
- PbPb/pp flux ratio: ~10^6
  - With different LHC optics





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.
        - Background is negligible.



PhysRev.167.1308
M. Tannenbaum

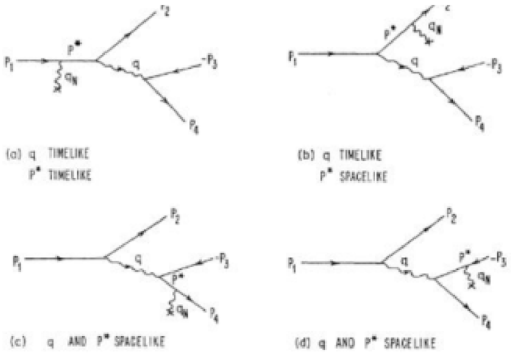
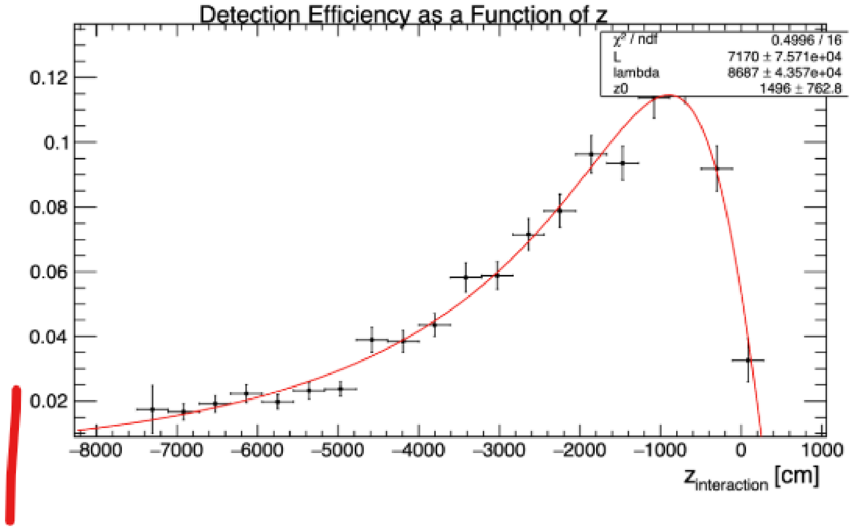


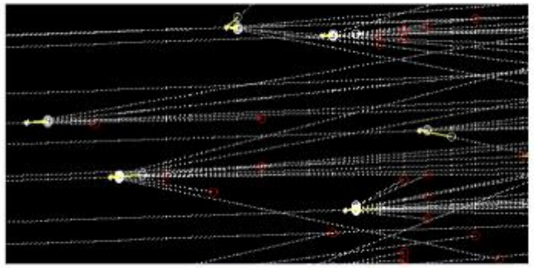
FIG. 1. The four Feynman diagrams for muon tridents (a) and (b) have timelike virtual photons while in (c) and (d) the virtual photon is spacelike. p^* is the four-momentum of the virtual muon; q is the four-momentum of the virtual photon and q_N is the nuclear recoil four-momentum.



Backup

Muon DIS in the emulsion

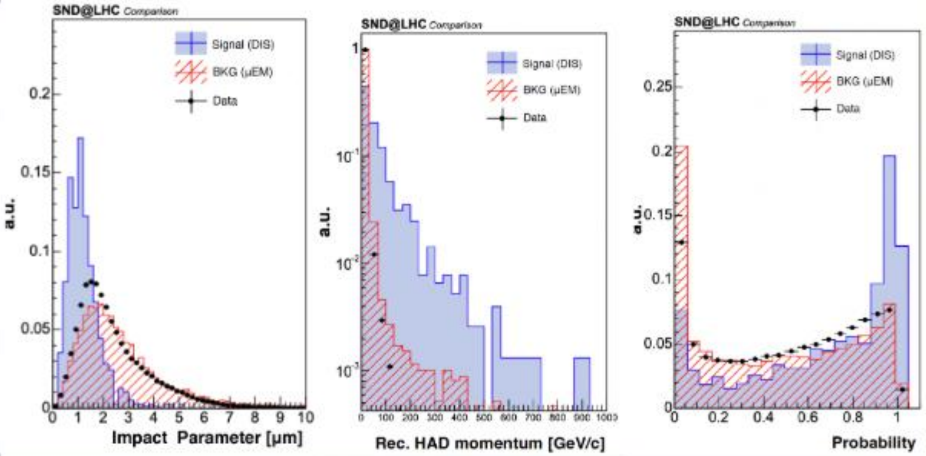
- Identification of **muon DIS** in the emulsion target with cut-based approach on topological and kinematical variables
- Data sample: vertices reconstructed in RUN1 brick 21: 32kg x 9.5fb^{-1}



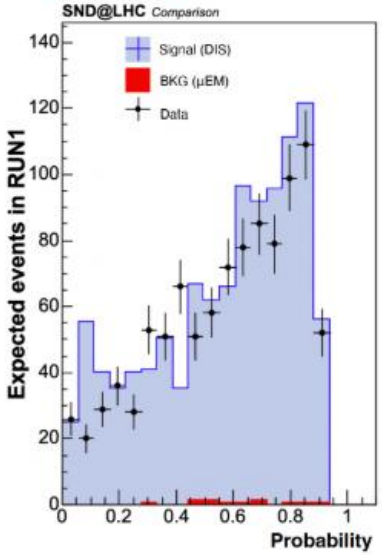
Simulated muon DIS in brick

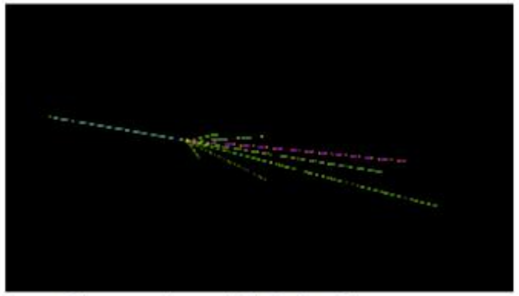
Event selection criteria

- charged vertex
- mean angular aperture > 13 mrad
- impact parameter<2.5μm
- fraction of rec. segments>0.87
- rec. hadron momentum > 16 GeV



Signal region





Observed candidate in data

Observed: **992 ± 32**

Expected: **1092 ± 73**
(Signal 1083 ± 74)
(Background 9 ± 3)

Preliminary

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

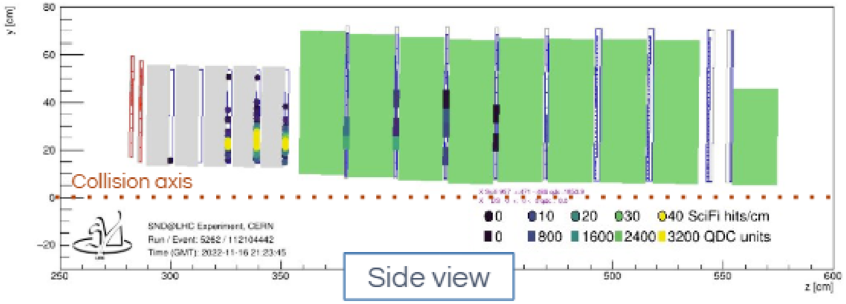
0μ observation significance

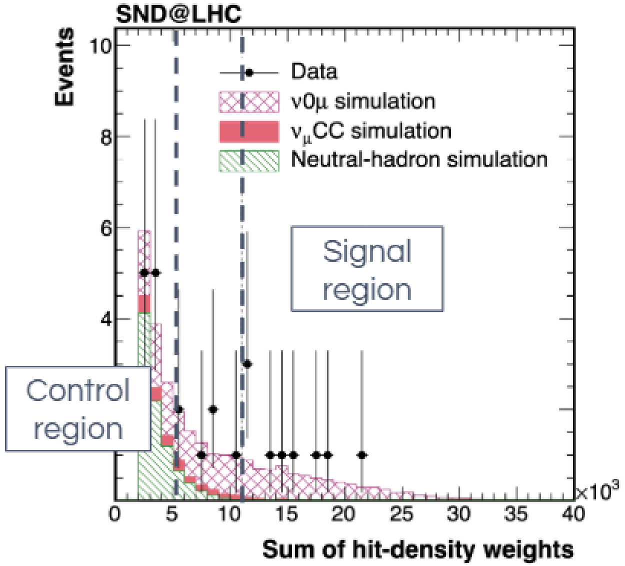
- **Total expected background: 0.32 ± 0.06 events**
- **Expected signal: 7.2 events**
  - 4.9 ν_eCC, 2.2 NC, 0.1 ν_τCC
- **Expected significance: 5.5 σ**

Number of events observed: 9
Observation significance: 6.4 σ

ν_eCC observation significance: 3.7 σ

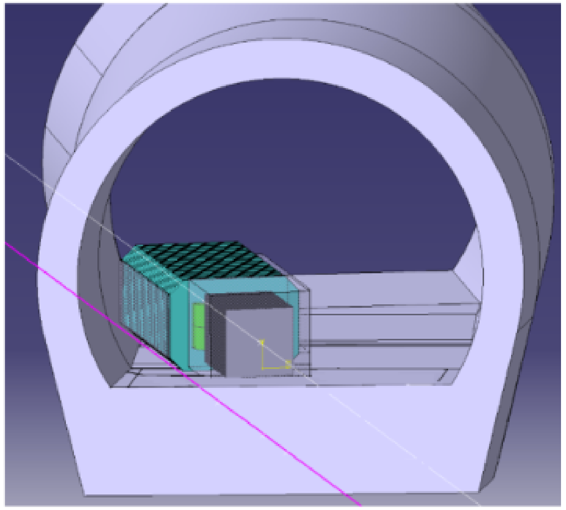
- First observation of non-ν_μCC neutrino interaction using electronic detectors at the LHC.
- Milestone towards neutrino observation at the HL-LHC.

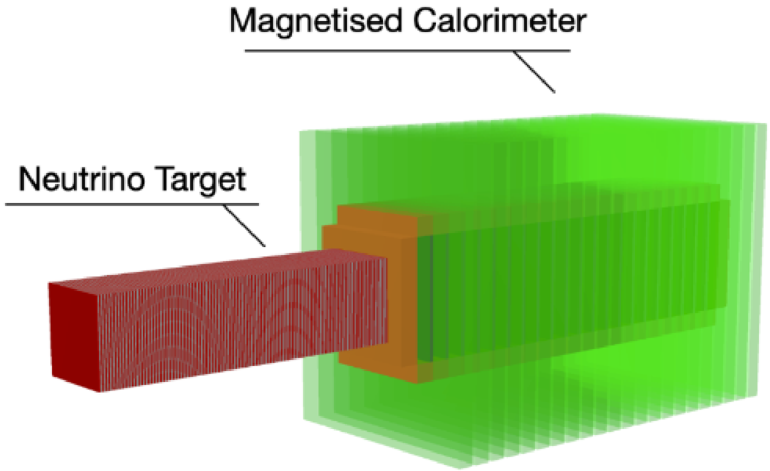


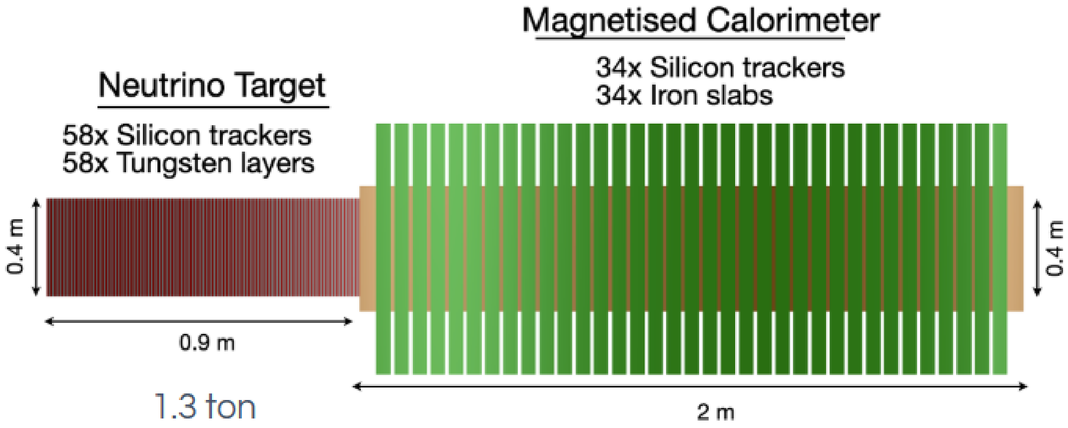


SND@HL-LHC

- Running the emulsion detector during the HL-LHC is unfeasible.
- HL-LHC phase of the experiment will use silicon-strip instrumentation.
  - First Si-based neutrino vertex detector!
- The calorimeter will be magnetised for muon momentum and charge measurement.

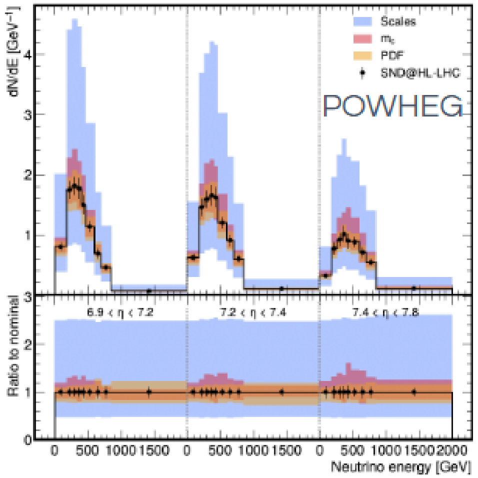


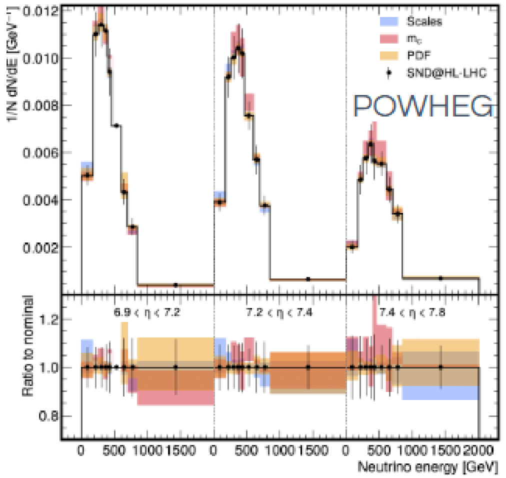


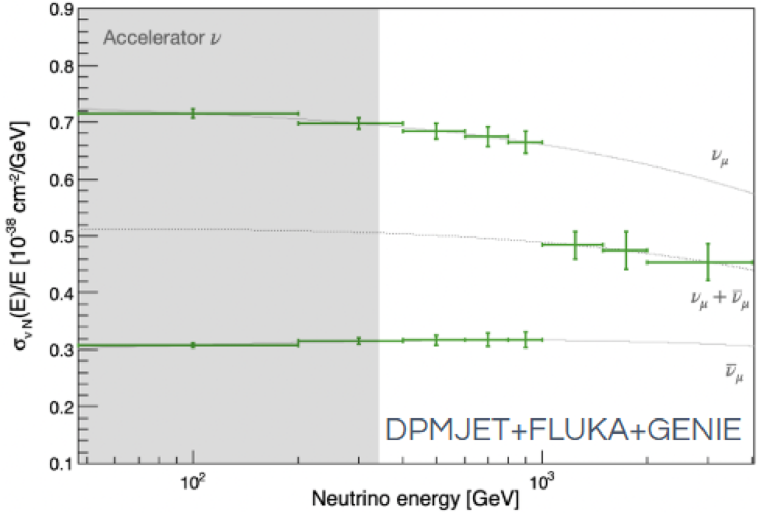


CERN-LHCC-2024-014

SND@HL-LHC Physics case







- Energy and η distribution of (charm-induced) ν_e CC interactions
- Left: event yield. Right: normalized to an arbitrarily chosen reference bin

Extending ν cross-section measurements to a few TeV

Technical Proposal for Run 4
https://cds.cern.ch/record/2926288

ESPPU Input

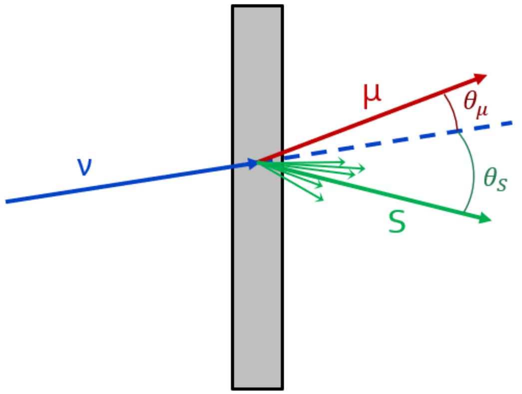
Measurement	Run 3 Uncertainty Stat.	Run 3 Uncertainty Sys.	HL-LHC Uncertainty Stat.	HL-LHC Uncertainty Sys.
Gluon PDF ($x < 10^{-5}$)	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	< 5%
ν_μ and $\bar{\nu}_\mu$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

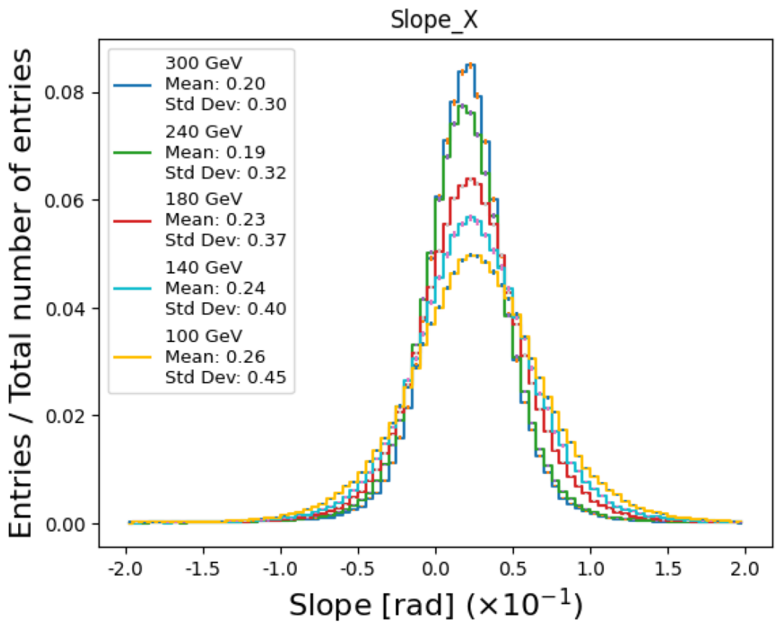
Backup: Shower direction reconstruction

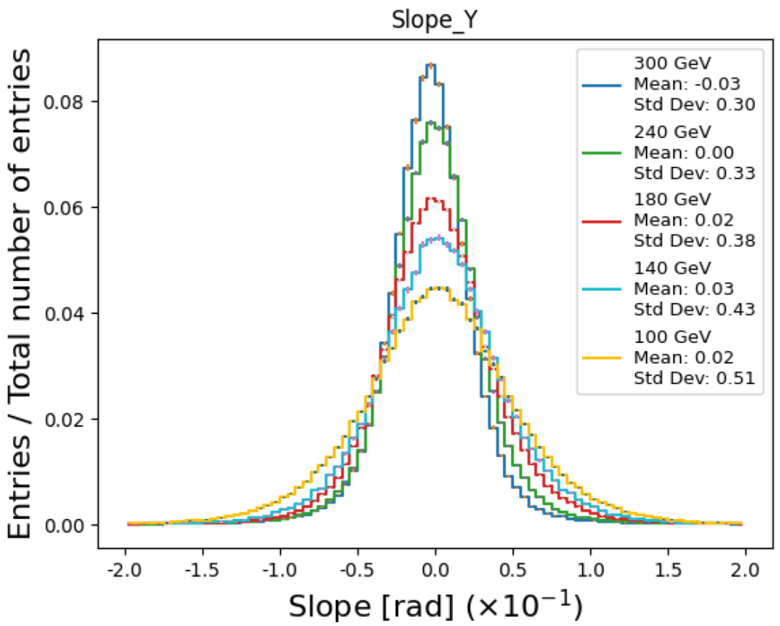
Aim: reconstruct shower direction → crucial for the ν_μ energy reconstruction as $E_\nu \sim E_S\left(1+\frac{\sin(\theta_S)}{\sin(\theta_\mu)}\right)$

Idea:

1. In all SciFi planes with a shower → compute **centroid**: average hit position weighted with signal amplitude
2. Fit centroids position to compute direction







This was validated to be a good method but

- Resolution depends on the dimension of the shower
- Not applicable if the shower starts in the last wall