Scattering and Neutrino Detector at the LHC

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

NEUTRINO INTERACTION STUDIES WITH SND@LHC DETECTOR

CSN1
24/11/2025

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On behalf of the SND@LHC Collaboration

Neutrinos at the LHC

Interest in high energy neutrino studies at LHC has been investigated since the 90's

More recent feasibility study [1] confirmed:

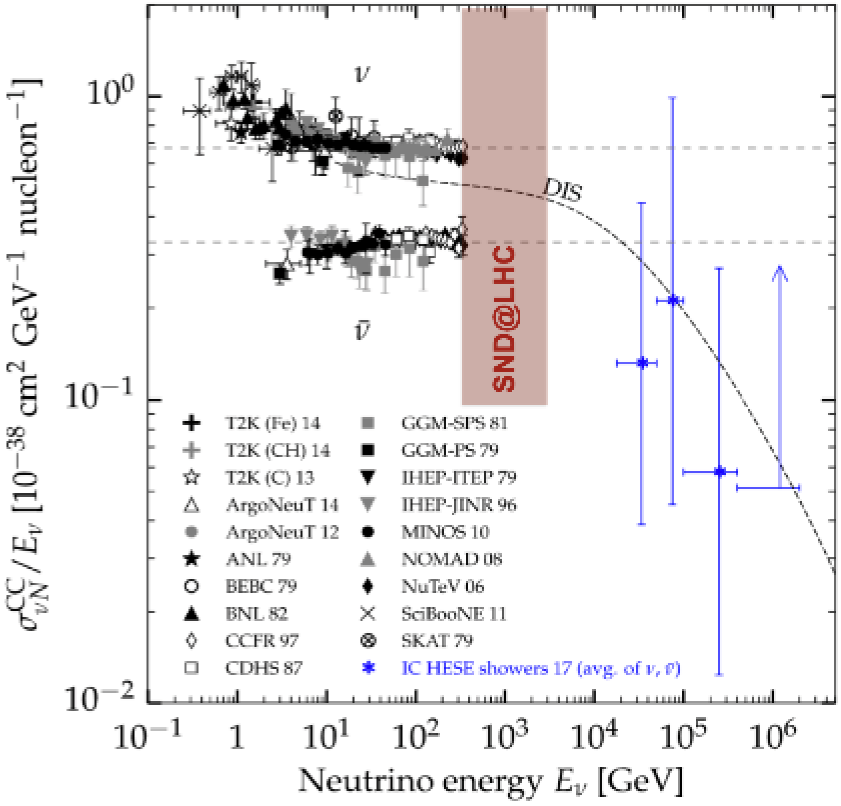
→ Possibility to study pp→νX in an **unexplored range**

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

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

  → **Compact** experiment at ~ton scale

PRL 122 (2019) 041101

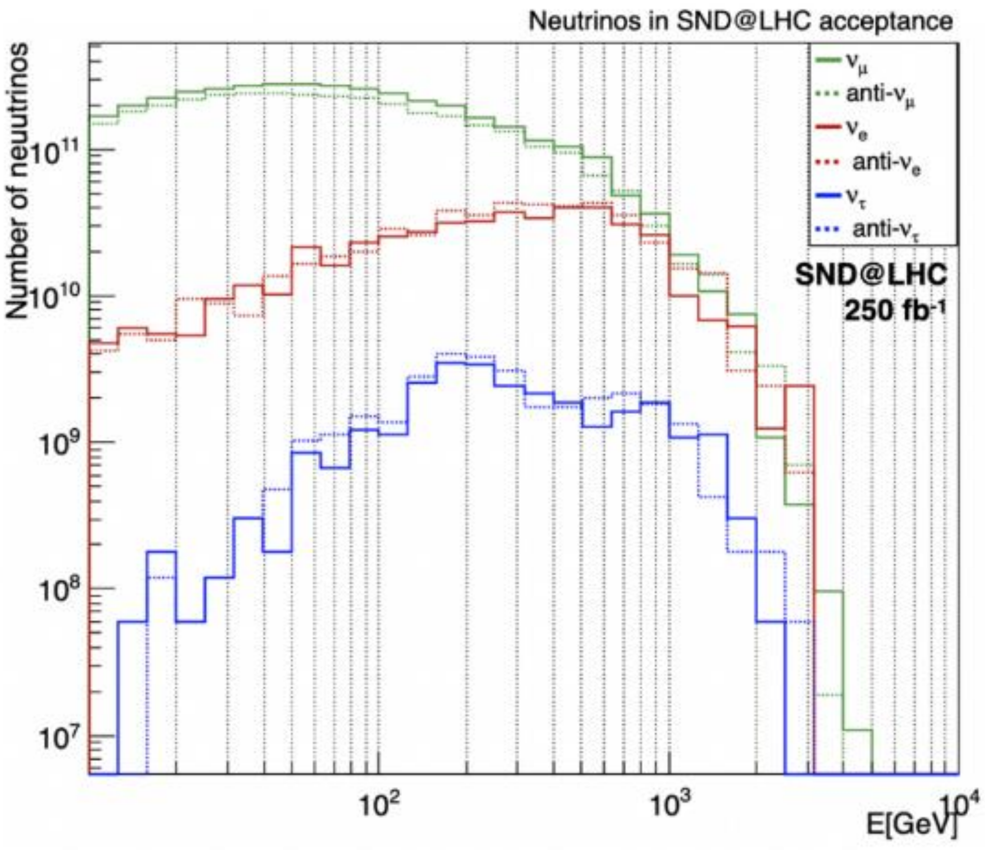


[1] Physics potential of an experiment using LHC neutrinos, J. Phys. G: Nucl. Part. Phys. 46 (2020) 115008

SND@LHC physics goal

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

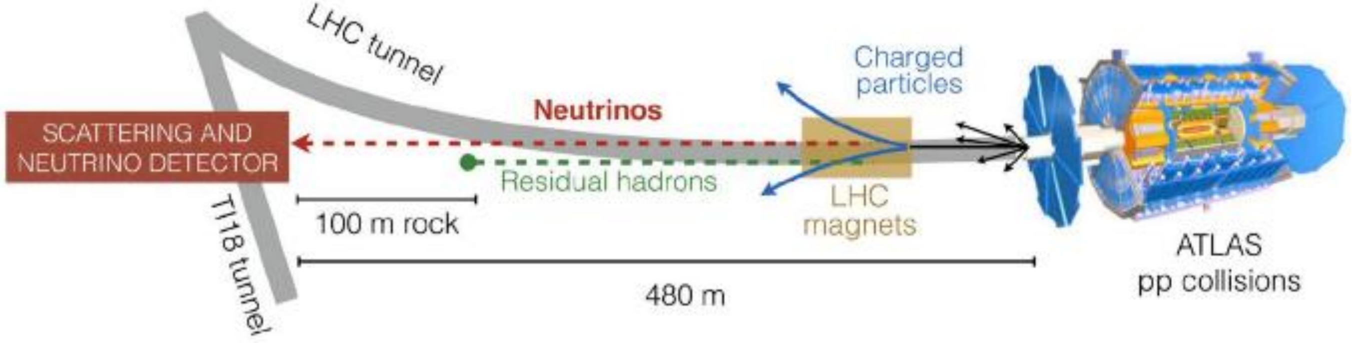
- → Measure **charm production** at high η ($gg \to cc$)
  - → Given the η region, the majority of vs is from charmed hadrons decay
- → High-energy neutrino cross section measurements
- → ν_τ observations at LHC energy
- → Test lepton **flavour universality** measuring ${}^{\nu_e}/_{\nu_\mu}$ and ${}^{\nu_e}/_{\nu_\tau}$
- → Direct search of **feebly-interacting particles** (FIPs)



THE DETECTOR

The detector: location

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



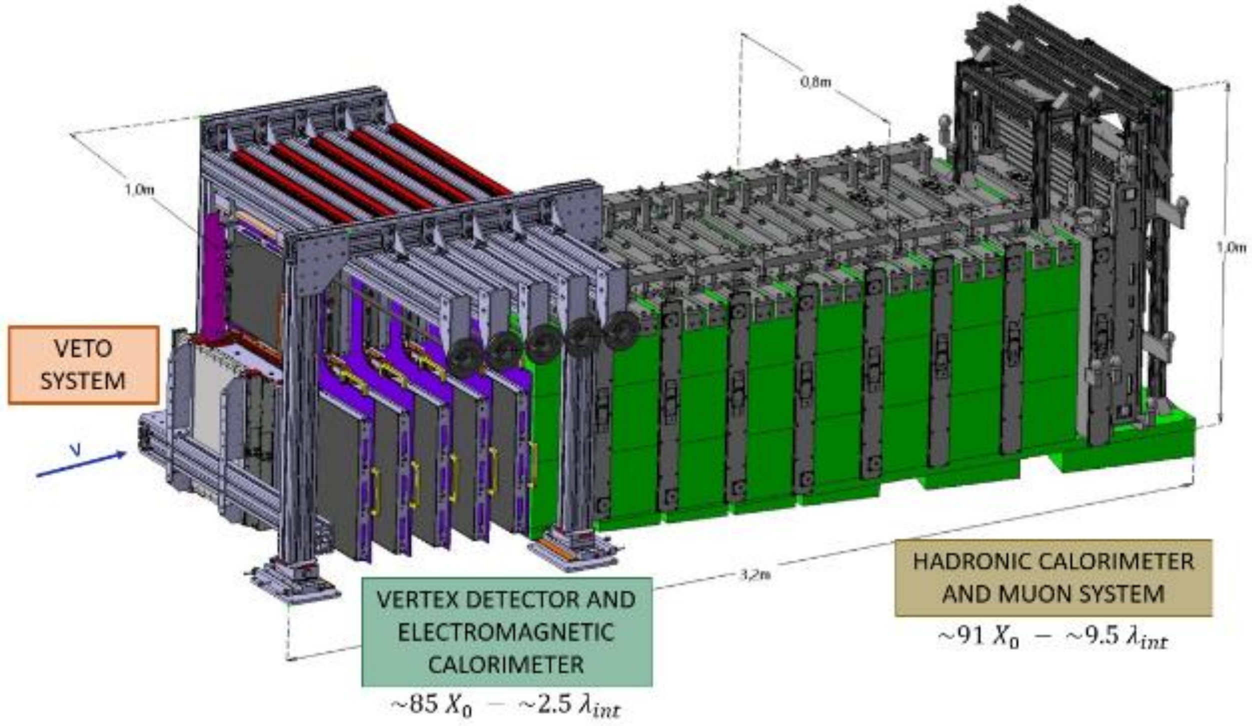
→ Shielded by **100 m rock**
→ **LHC magnet** deflects charged particles

↓

Neutrinos and FIPs reach the detector
Residual muon background

The detector

Hybrid detector composed of:

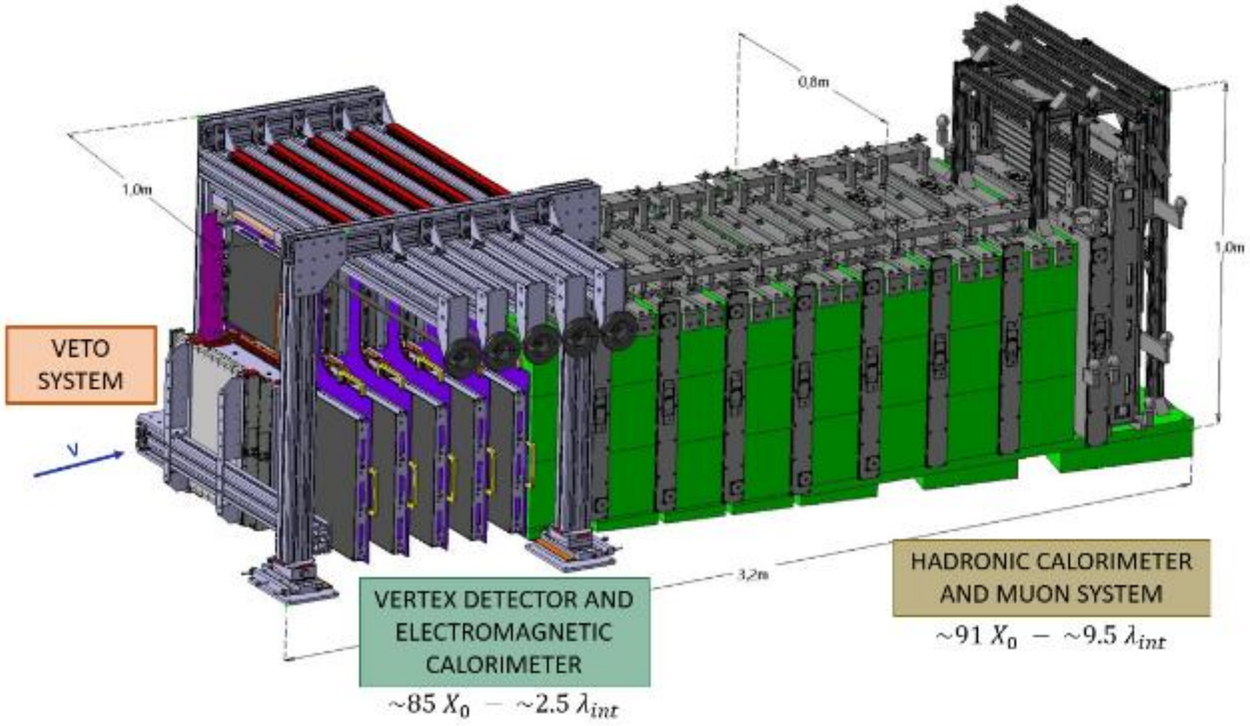


The detector

Hybrid detector composed of:

→ Veto system

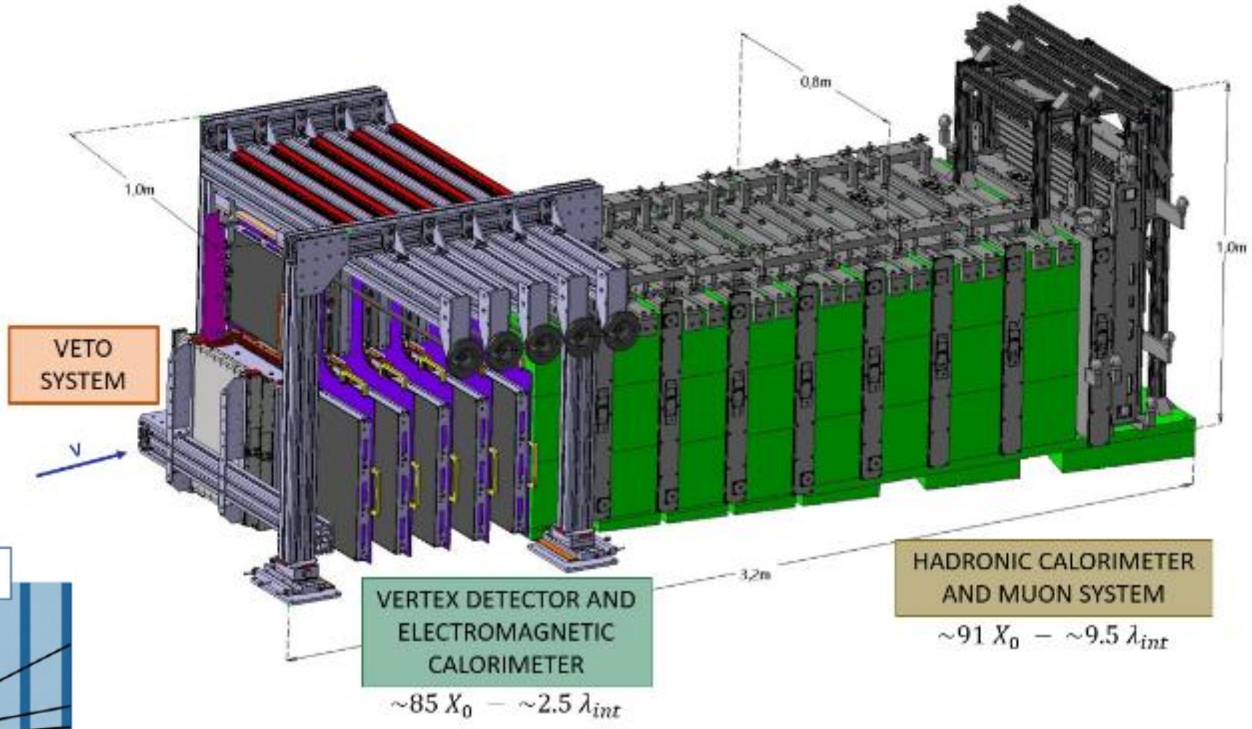
→ Since 2024: **3** planes of scintillating 6 cm wide bars **to tag incoming charged** particles, the original 2 with horizontal staggered bars, the latest one with vertical bars

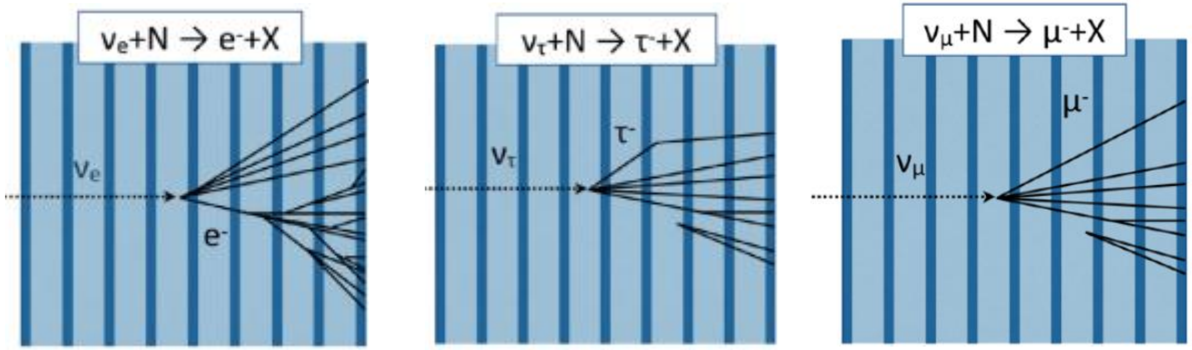


The detector

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 for **tracking and vertex identification**
  - → Scintillating fibers (SciFi) for **time and calorimetric information**





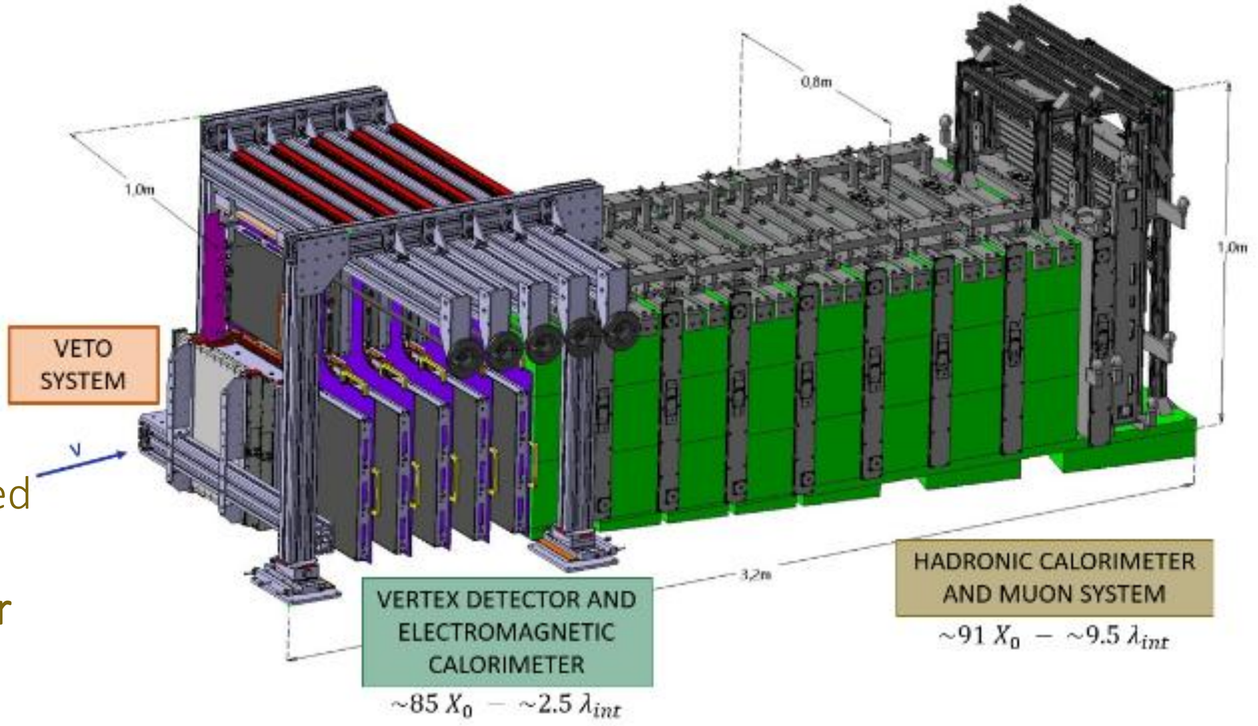
The detector

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 for **tracking and vertex identification**
  → Scintillating fibers (SciFi) for **time and calorimetric information**

→ 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 1 cm-thick, focus on **muon tracking**
  → **Since 2025: 2 MiniDTs,** small size replica of CMS DTs

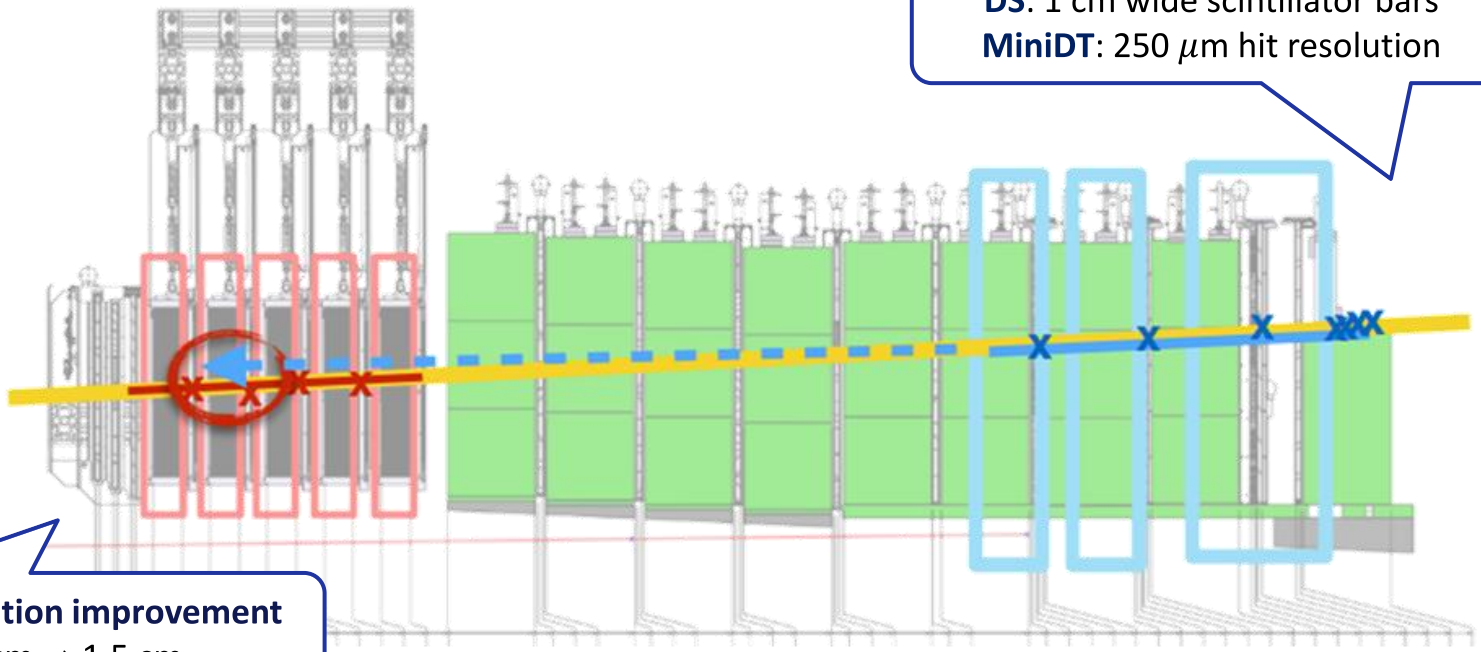


Upgrade of Muon system

Muon tracking :

- Identification of muons produced in ν_μ interactions
- Muon flux measurements sets the maximum exposure time for emulsions

DS: 1 cm wide scintillator bars
MiniDT: 250 μm hit resolution



2x **resolution improvement**
3 cm → 1.5 cm

March 2025

Hadronic calibration and Veto Upgrade

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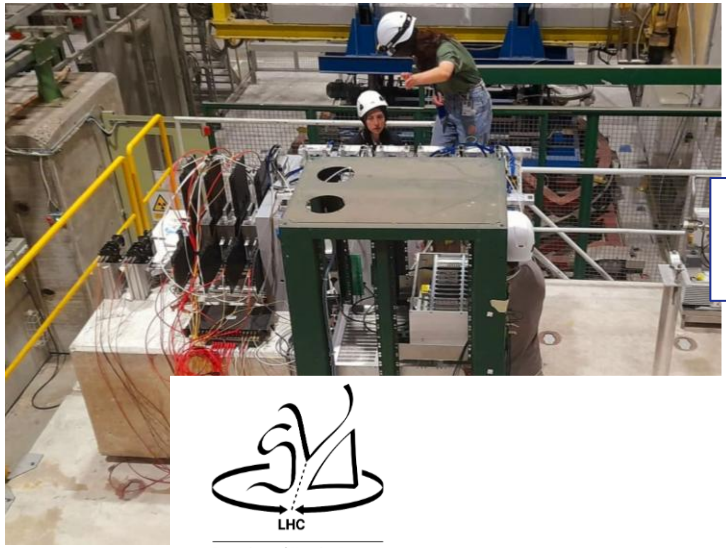
Before starting the ν_μ analysis 2024

Hadronic shower response calibration



Final publication
JINST 20 P10039 (2025)

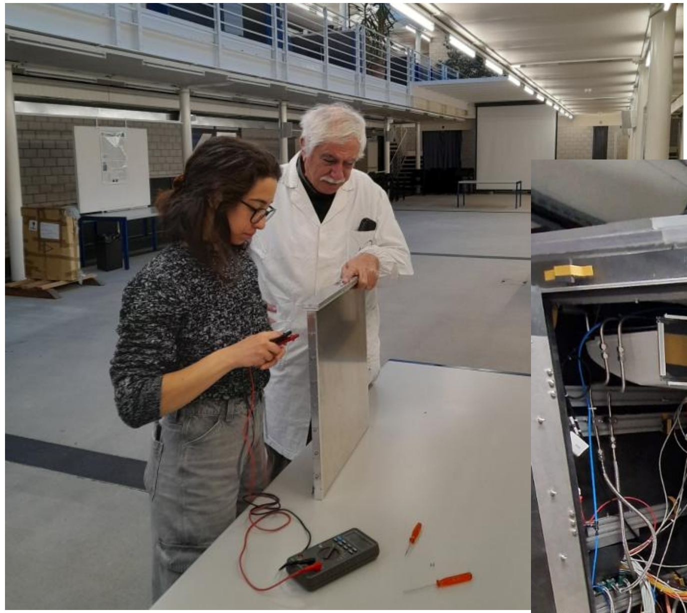
Scattering and Neutrino Detector at the LHC

CERN-SND@LHC-INT-2025-001
November 20, 2025

Studies of Hadronic Showers in SND@LHC

Chris Betancourt[1,*], Federico Cindolo[2], Matei Climescu[3], Andrew Conaboy[4], Gaetano Marco Dallavalle[5], Eric van Herwijnen[6], Simona Ilieva[7], Richard Jacobsson[7], Emil Khalikov[8], Lukasz Piotr Krzempek[7], Heiko Lacker[4], Anna Mascellani[10], Filippo Mei[2,5], Giulia Paggi[2,5], Guilherme Soares[9], Eduard Ursov[4], Ettore Zaffaroni[10]

Veto system inefficiency

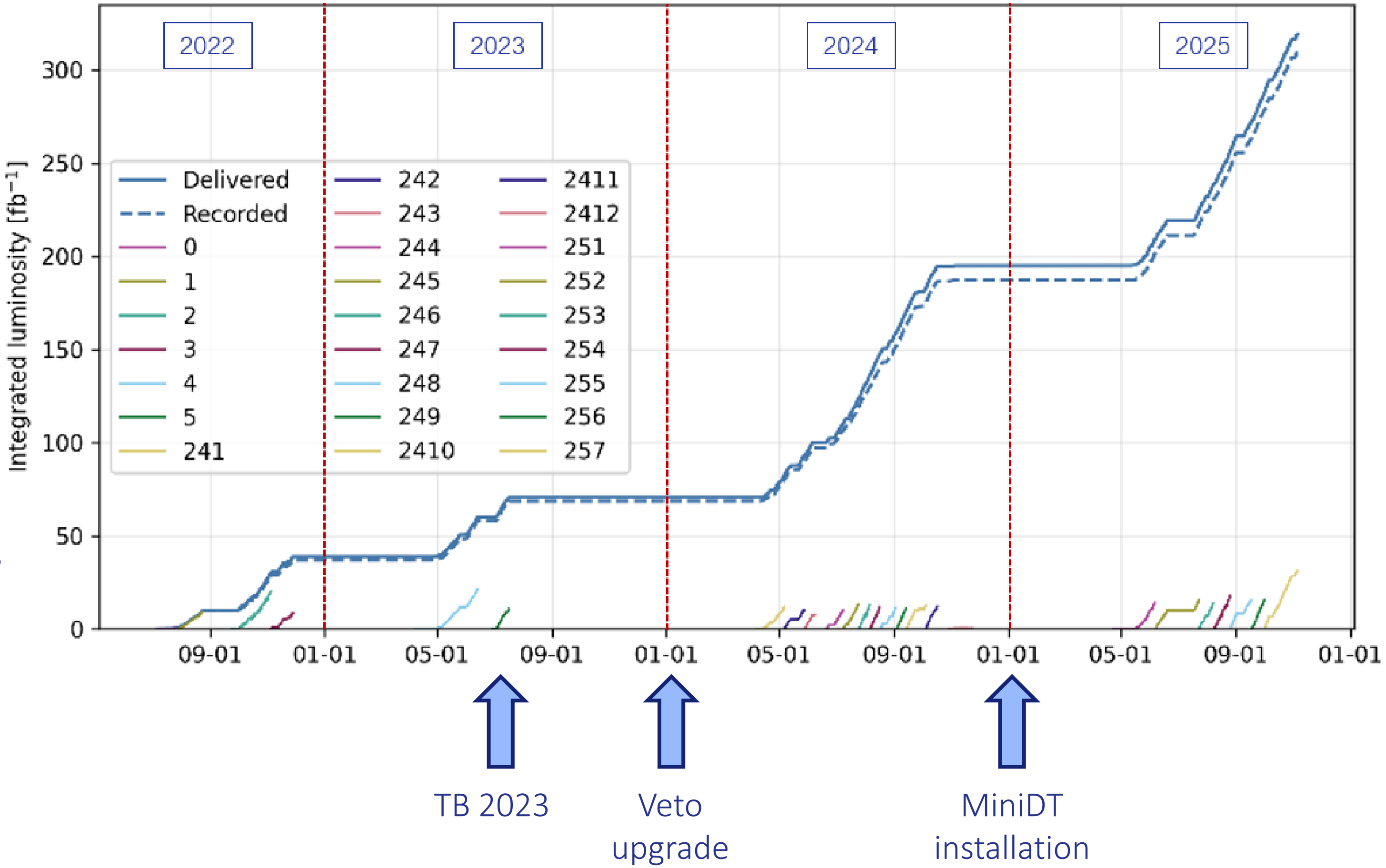


Corresponding author: JINST 20 P07011 (2025)

SND@LHC Data

- Electronic detectors:
  - 2025: 122 fb^{-1}, uptime 98%
  - 2024: 119 fb^{-1}, uptime 95%
  - 2023: 32 fb^{-1}, uptime 99%
  - 2022: 36.8 fb^{-1}, uptime 95%
- Total: ~309 fb^{-1}

- Emulsion:
  - 20 active target exposed
  - 11 partially instrumented targets to enhance signal/noise ratio in unexpectedly high background conditions
  - Total of ~264 fb^{-1} integrated



PHYSICS ANALYSES

Analyses with electronic detector

- **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:** $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$
- ***0 $\boldsymbol{\mu}$ final states***: the *first* observation of non-ν_{μ} CC neutrino interaction using electronic detectors at the LHC PRL 134 231802 (2025)

ν_μ ANALYSIS 2022+2023

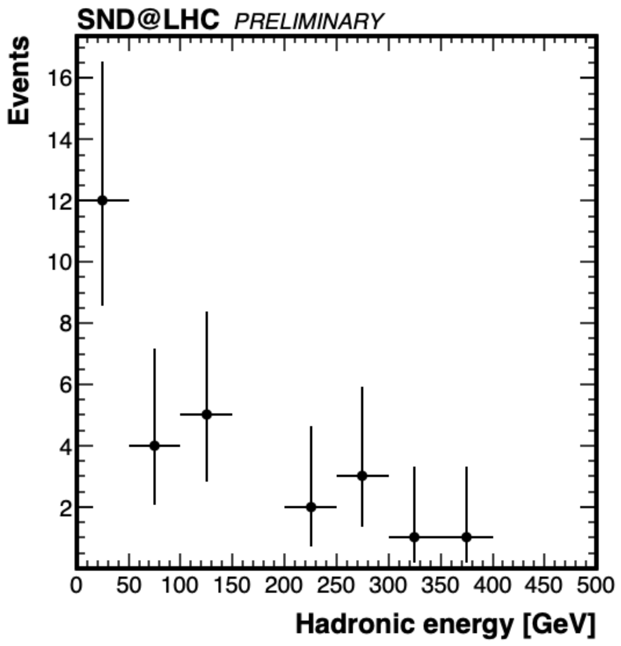
ν_μ analysis 2022+2023

- **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: 68.5 fb^{-1}
  - Optimized fiducial volume cuts → relax cuts to recover efficiency

Events expected in 68.6 fb^{-1}

- Signal: 21 ± 4.1 (prod) $^{+1.6}_{-2.9}$ (sel)
- Neutral hadrons: 0.25 ± 0.06
- Unidentified muons: 1.5 ± 0.3

28 events observed



ν_μ analysis 2022+2023

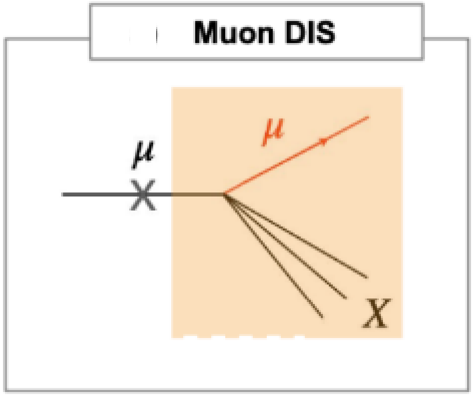
Step 1: Fiducial volume selection

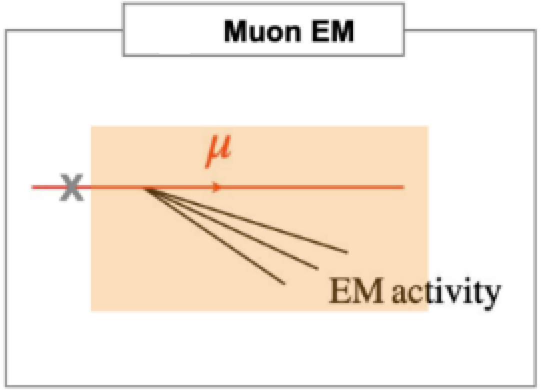
Cut	Description
A	Average SciFi channel in [200, 1200] (vert.) and [300, 1336] (hor.)
B	Average DS bar number in [10, 50] (vert.) and [70, 105] (hor.)
C	No veto hits
D	No hits in the 1$^{\text{st}}$ SciFi station

Define fiducial area of 25×26 cm^2
across the detector layers

Observation of ν_μ: background

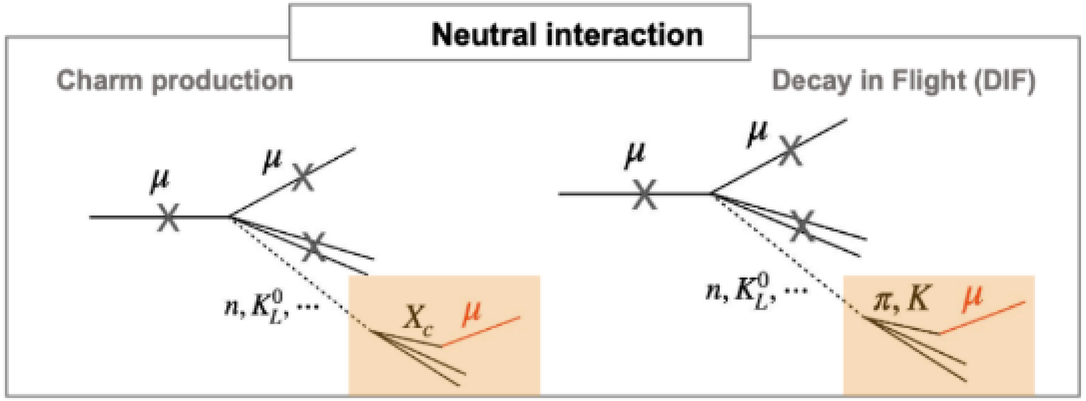
Undetected muon background





- Veto inefficiency
- Inclined trajectory

Muon-induced **neutral particles**



$$N^{\mathrm{bkg}}_{\mathrm{neutrals}} = N_{\mathrm{neutrals}} \times P_{\mathrm{inel}} \times \epsilon_{\mathrm{sel}}$$

↓

To be estimated from **simulations**

X = undetected

= in SND@LHC volume

ν_μ analysis 2022+2023

Step 1: Fiducial volume selection

Cut	Description
A	Average SciFi channel in [200, 1200] (vert.) and [300, 1336] (hor.)
B	Average DS bar number in [10, 50] (vert.) and [70, 105] (hor.)
C	No veto hits
D	No hits in the 1^{st} SciFi station

A, B → **Define fiducial area of $\mathbf{25} \times \mathbf{26}$ cm^2** across the detector layers

C → **No** incoming **charged particles**

D → **1^{st} SciFi** plane as **additional Veto** plane

ν_μ analysis 2022+2023

Step 2: neutrino candidate selection

Cut	Description
E	If there are DS hits, all US planes must be hit
F	Previous event more than 100 clock cycles away
G	Event has one reconstructed DS track
H	Latest DS hit time > earliest SciFi hit time
I	DS track intersects first SciFi plane > 5 cm away from detector edge
J	Sum of min(DOCA) of track to SciFi hits must be < 3 cm in both horizontal and vertical planes, per station
K	More than 35 SciFi hits
L	US total QDC larger than 600 (700) for data (MC)
M	Number of DS hits per projection < 10

→ Continuity of μ signal

→ Remove spurious events

→ Remove events with spurious hits

Track requirements

→ Track-SciFi hits compatibility

→ *Large* activity

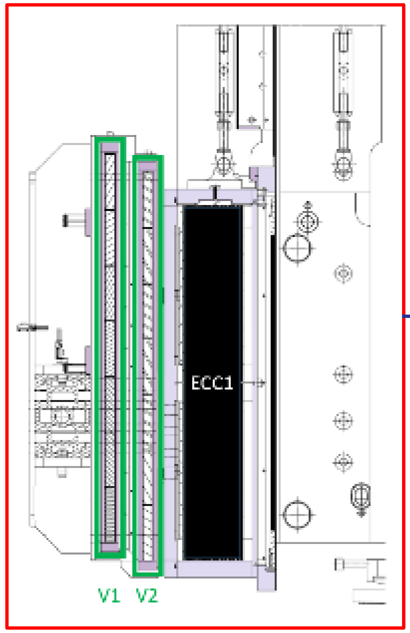
ν_μ ANALYSIS 2024

Veto System Upgrade

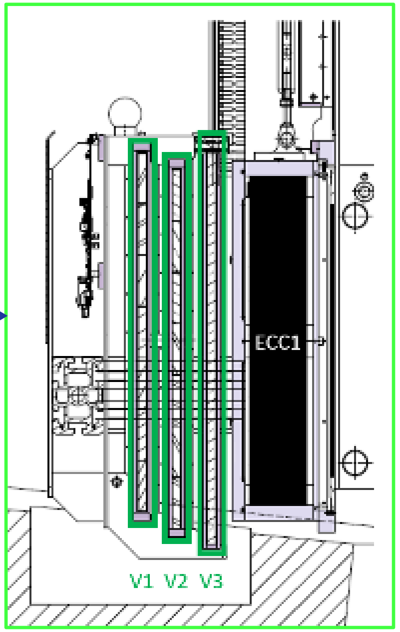
Inefficiency **optimal value** in the 2022-23 period was $(7.8 \pm 2.8) \times 10^{-8}$ achieved on a fiducial area of 35×35 cm^2 → target coverage of ~ 64%

In YETS 2023-24 additional **3rd veto plane** + lowering of the whole system

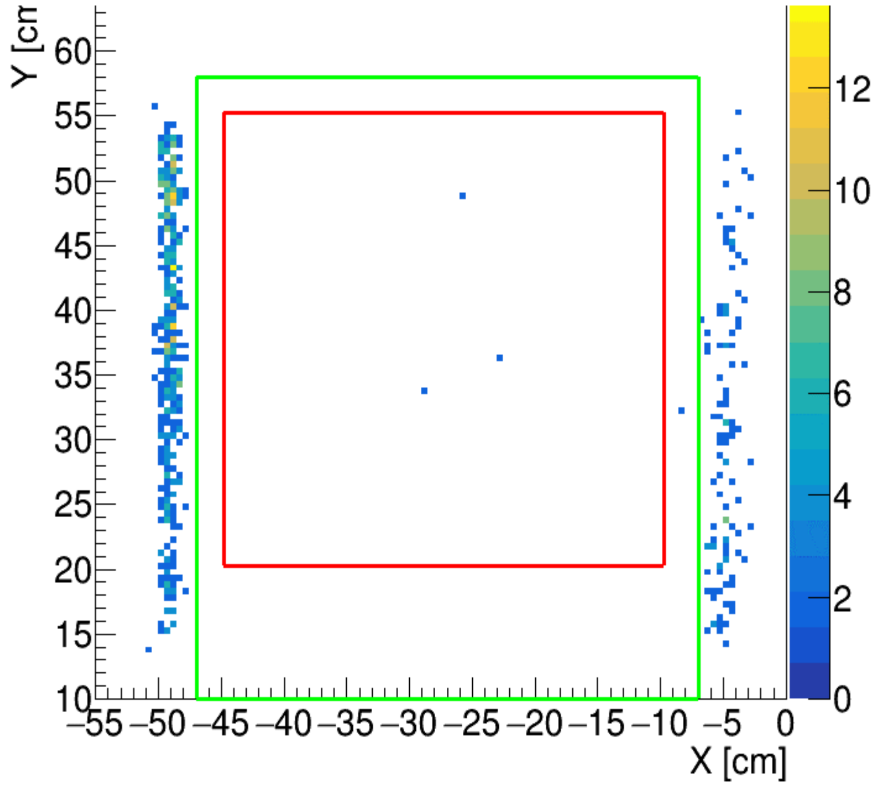
The 3rd plane has **vertical** bars to reduce overlapping area → minimizes signal loss due to spatial and temporal coincidences



2022/23 veto system



Updated veto system

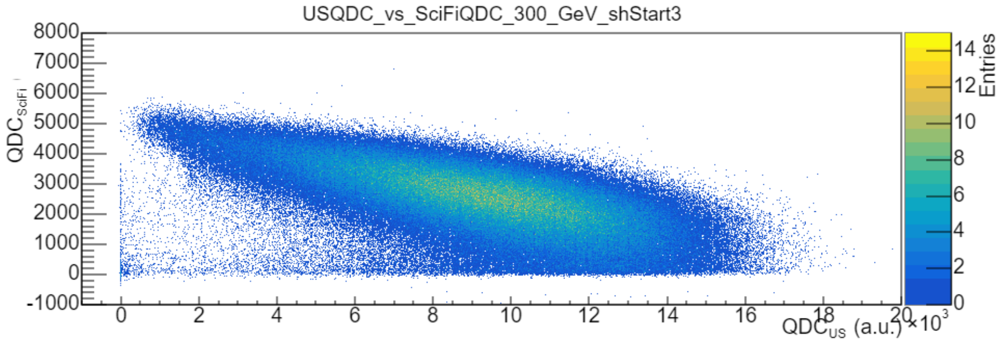


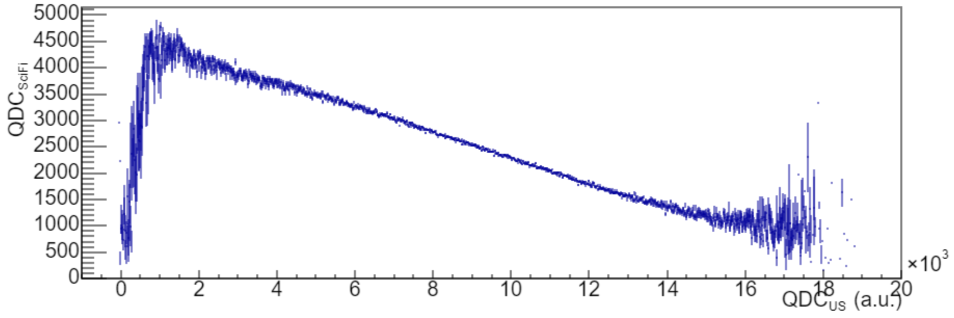
In the new configuration the inefficiency is $(\mathbf{4.9 \pm 1.9}) \times \mathbf{10^{-9}}$ on the full target area

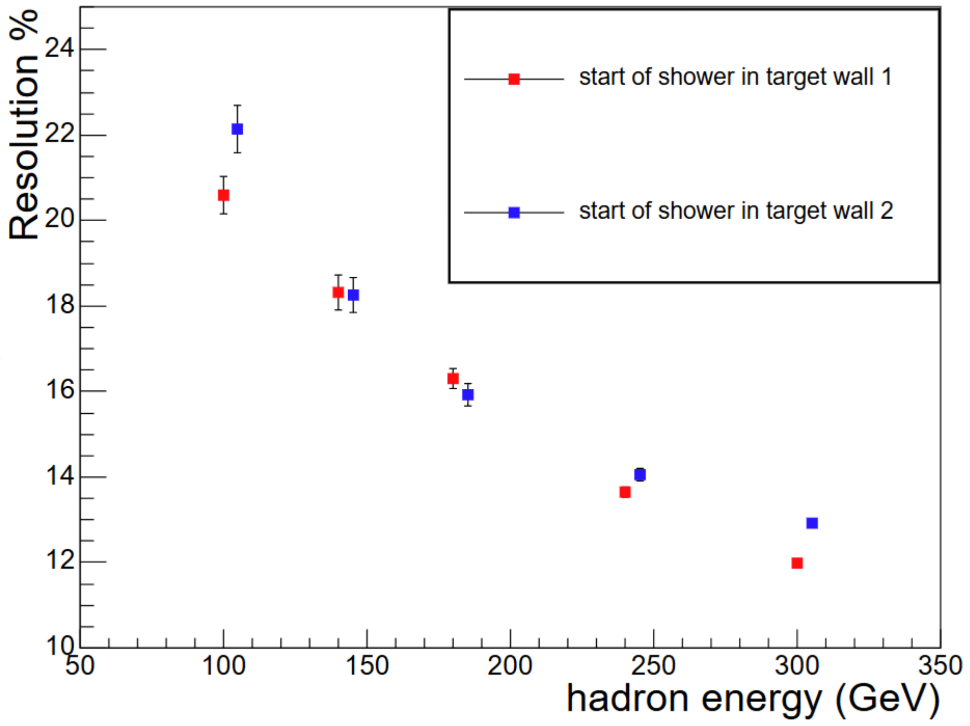
Corresponding author: JINST 20 P07011 (2025)

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%**







JINST 20 P10039 (2025)

2024 ν_μ update

Goal: upgrade the CC ν_μ study with the 2024 SND@LHC data: recorded 119 fb^{-1} → **1.75x dataset** 2022+2023

- exploiting the upgraded veto system → use all target walls + larger fiducial area: **2.2x volume 2022+2023**
- new algorithms developed on 2023 test beam data
  - shower tag
  - energy calibration + shower direction reconstruction → estimate incoming neutrino energy: **compute cross-section as a function of energy** thanks to larger statistic available
- more complex cuts thanks to better understanding of timing and QDC

Final goal: **identify a ν_μ sample** ($\sim 10^2$ expected events) **to compute rate** and **allow the first studies on ν_μ properties at LHC energies**

Large sample → selection method and background rejection are developed on a subsample of $\sim$20 fb^{-1} keeping the rest of the data blinded

Work in progress!

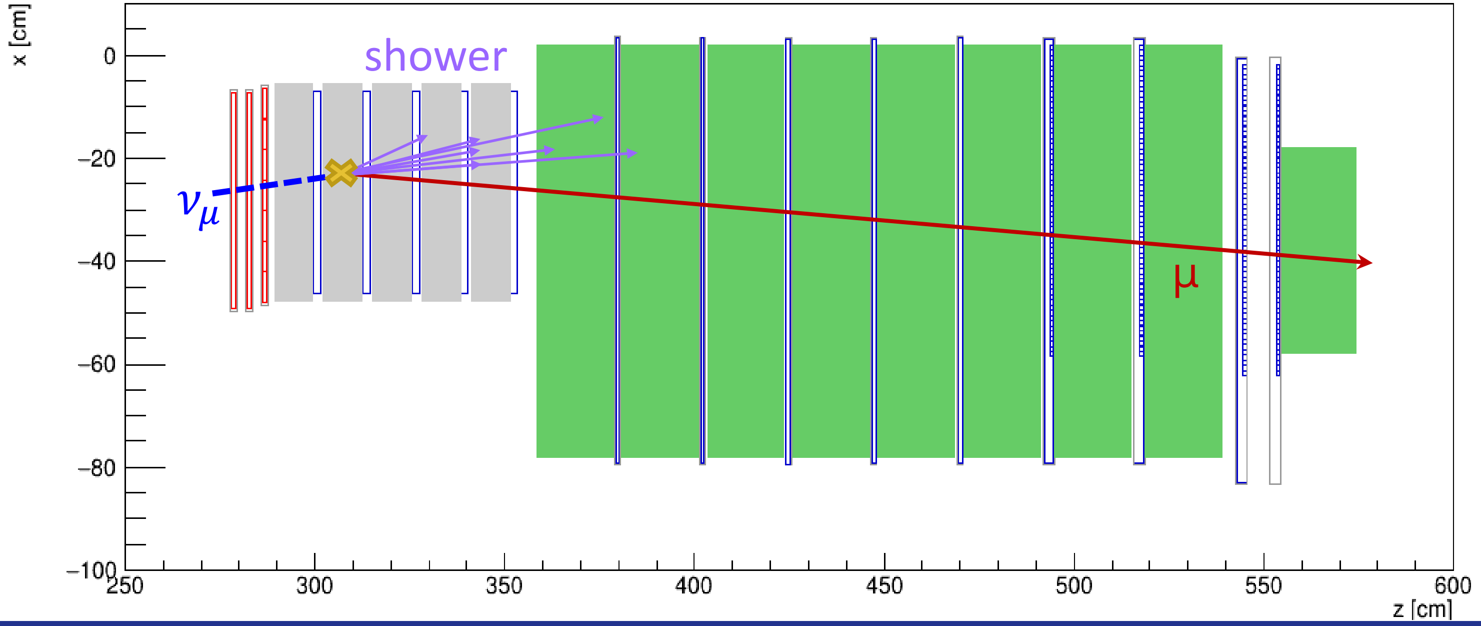
2024 ν_μ CC - Preselection

Work in progress!

Step 1: preselection with relaxed constraint

For ν_μ sample:

1. **No more than one** veto plane with signal → No incoming charged particle
2. At least 2 DS with > 1 (x,y) → Outgoing muon
3. A shower tagged → Interaction in target region

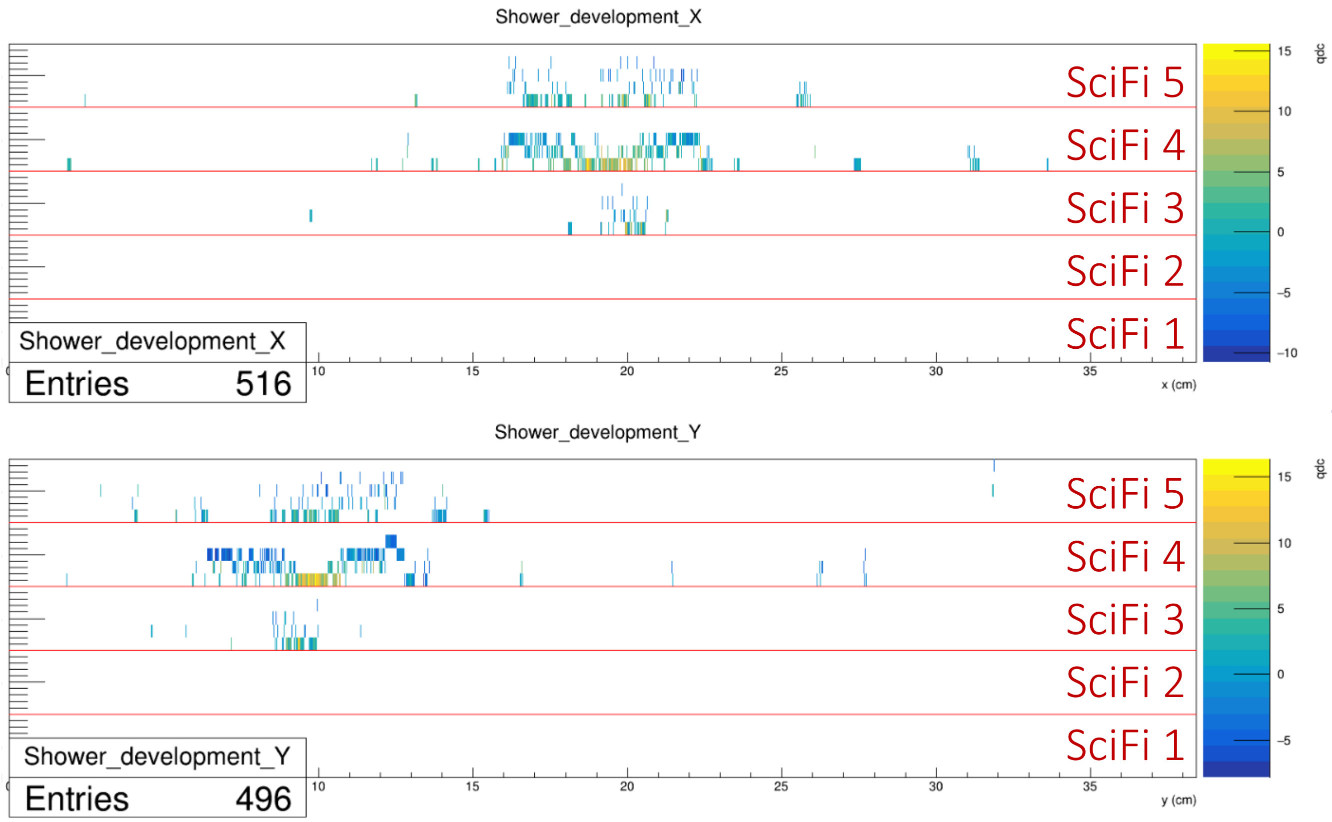


Shower tagging

Aim: find SciFi modules in which an hadronic shower is visible

→ constrain interaction vertex in preceding tungsten wall

Achieved by: requiring a minimum number of hits in a sliding window



X view

Y view

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

2024 ν_μ CC - Preselection

Work in progress!

Step 1: *preselection with relaxed constraint*

For ν_μ sample:

1. **No more than one** veto plane with signal;
2. At least 2 DS with > 1 (x,y)
3. A shower tagged

From 1.14×10^{10} events → 3.25×10^{5} events

For μ sample for data-driven background estimation:

1. **No less than 2** veto planes with signal;
2. At least 2 DS with > 1 (x,y)
3. A shower tagged

12% of a single run (~0.1 fb^{-1}) → 1.34×10^{6} events

2024 ν_μ CC – Selection: timing

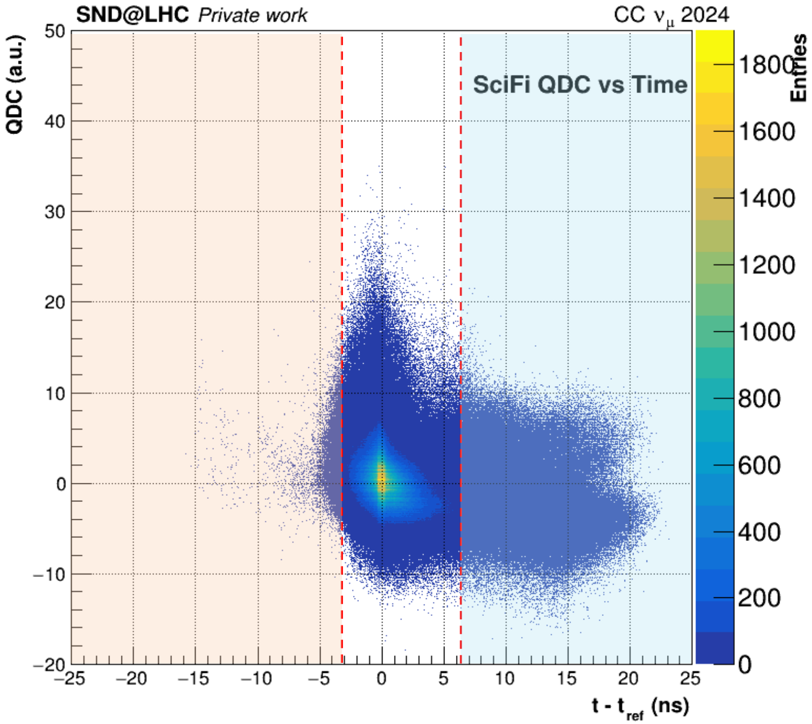
Work in progress!

Step 2: *Event selection criteria*

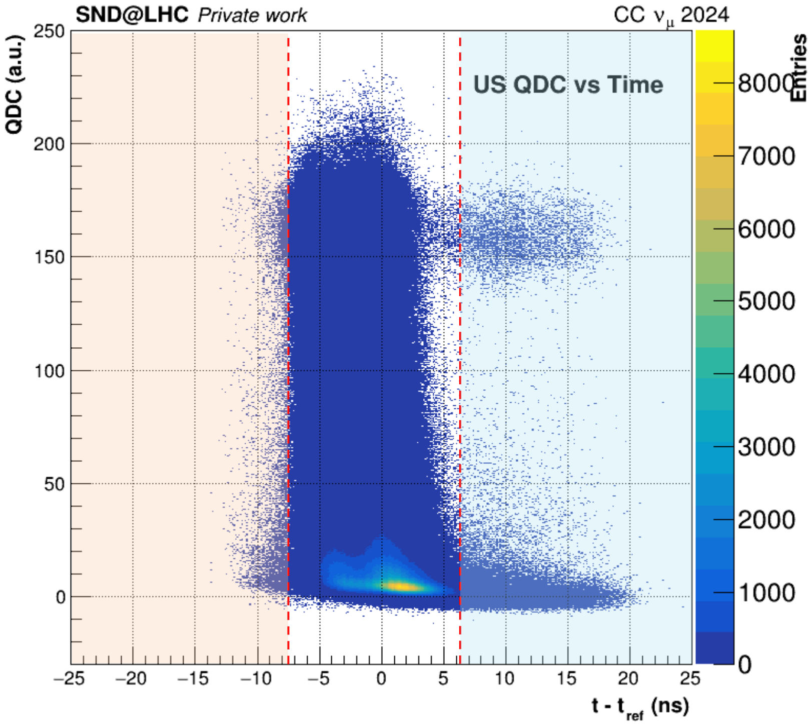
1. No hits in the veto system
2. Correct hit timing
   - $t_{ref} \equiv$ most probable value in SciFi
   - Scifi: [-3.125, 6.25] ns, US: [-7.5, 6.25]

Early hits: noise

Late hits: noise, cross-talk, afterglow



Candidates ν_μ sample

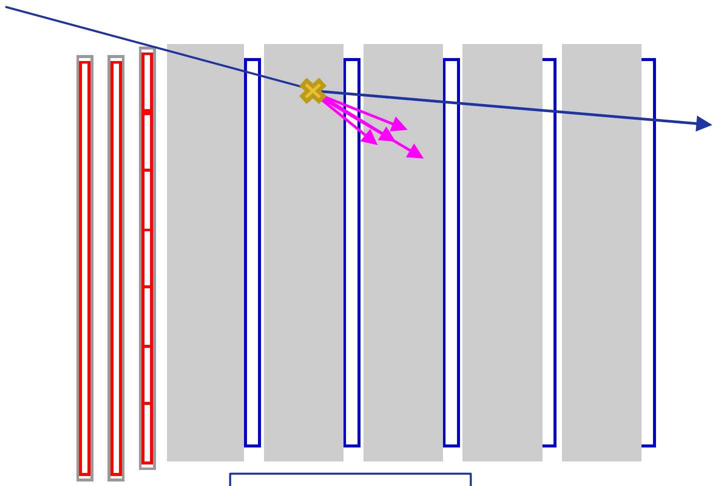


2024 ν_μ CC – Selection: shower

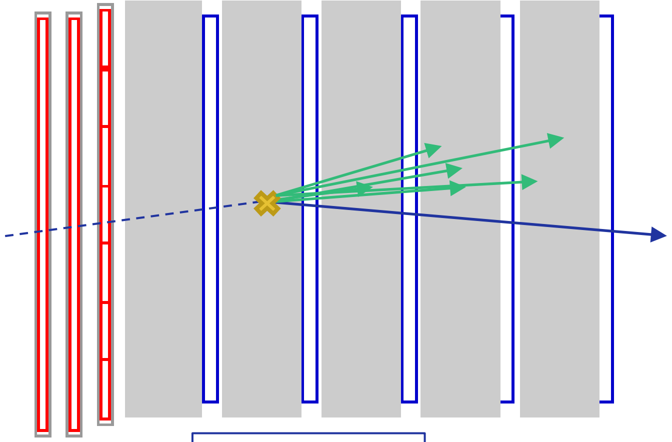
Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
   - Require two consecutive SciFi planes tagged → **suppress purely EM showers** exploiting longitudinal development difference



Purely EM



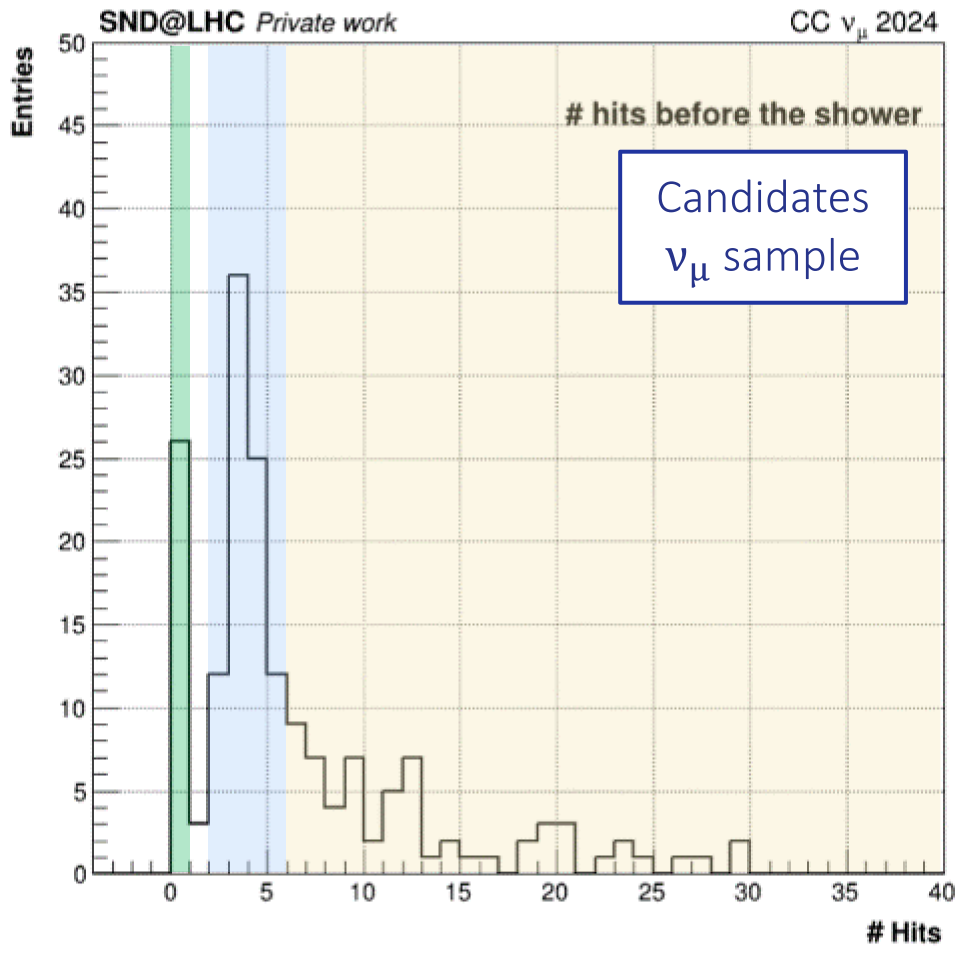
Hadronic

2024 ν_μ CC – Selection: shower

Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
   - Require two consecutive SciFi planes tagged
   - Reject events with 1 < hits < 7 before the shower → passing muon show a peak at ∼4 hits (2 per module)



no hit: expectation for incoming ν_μ

1 < hits < 7: passing muon peak

hits > 7: backscattering, early showers

2024 ν_μ CC – Selection: shower

Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
   - Require two consecutive SciFi planes tagged
   - Reject events with $1 < \text{hits} < 7$ before the shower
   - SciFi 1: background mitigation deferred to MC-based study
   - SciFi 5: cannot require 2 consecutive tags → ≥ 7 bars hit across US subsystem

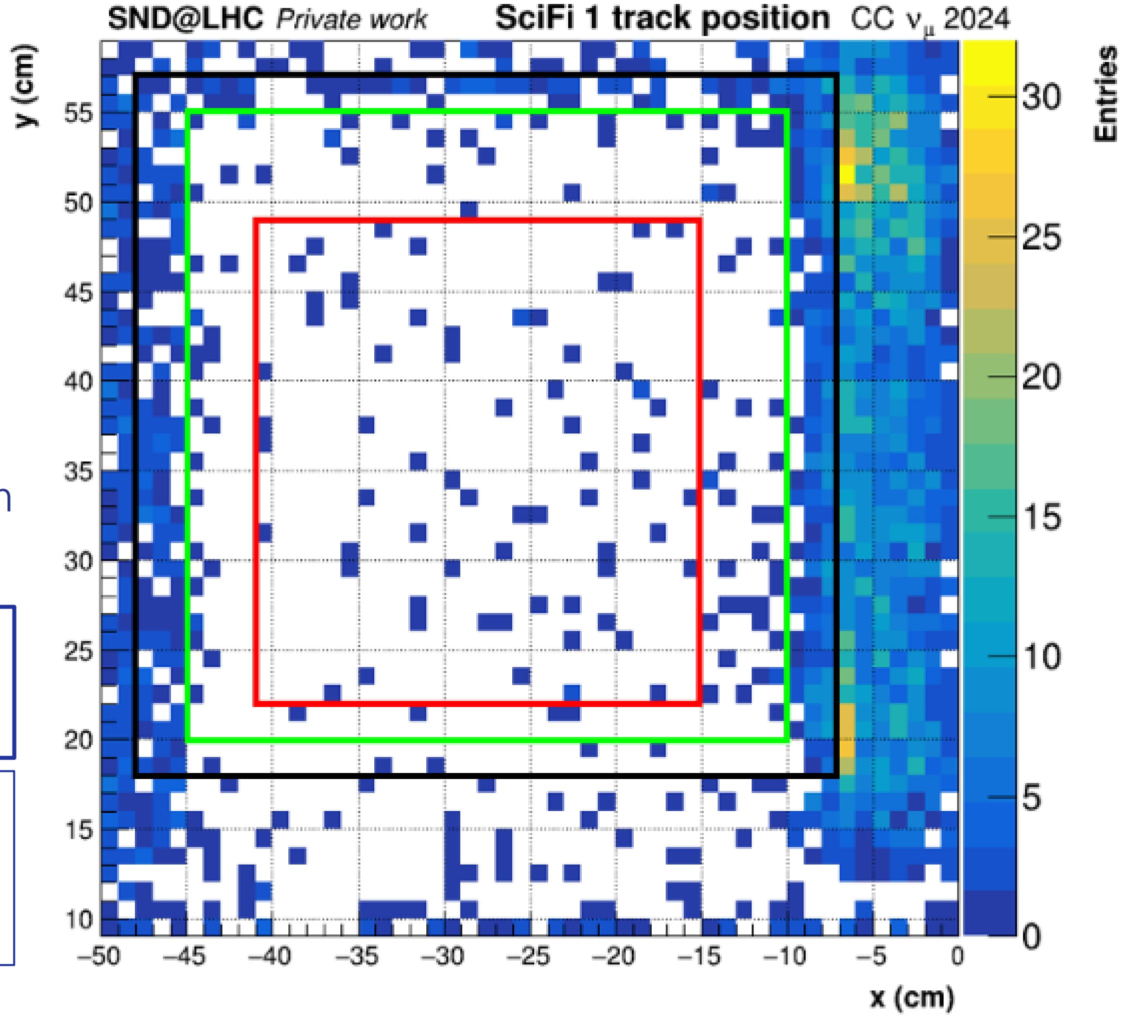
2024 ν_μ CC – Selection: track

Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
5. Check for a reconstructed track (with $\frac{\chi^2}{dof} \leq 5$) and check that the extrapolated (x,y) position:
   - to the shower start wall is inside the target region with fiducial cut of 2cm top/bottom, 3cm left/right

Candidates ν_μ sample



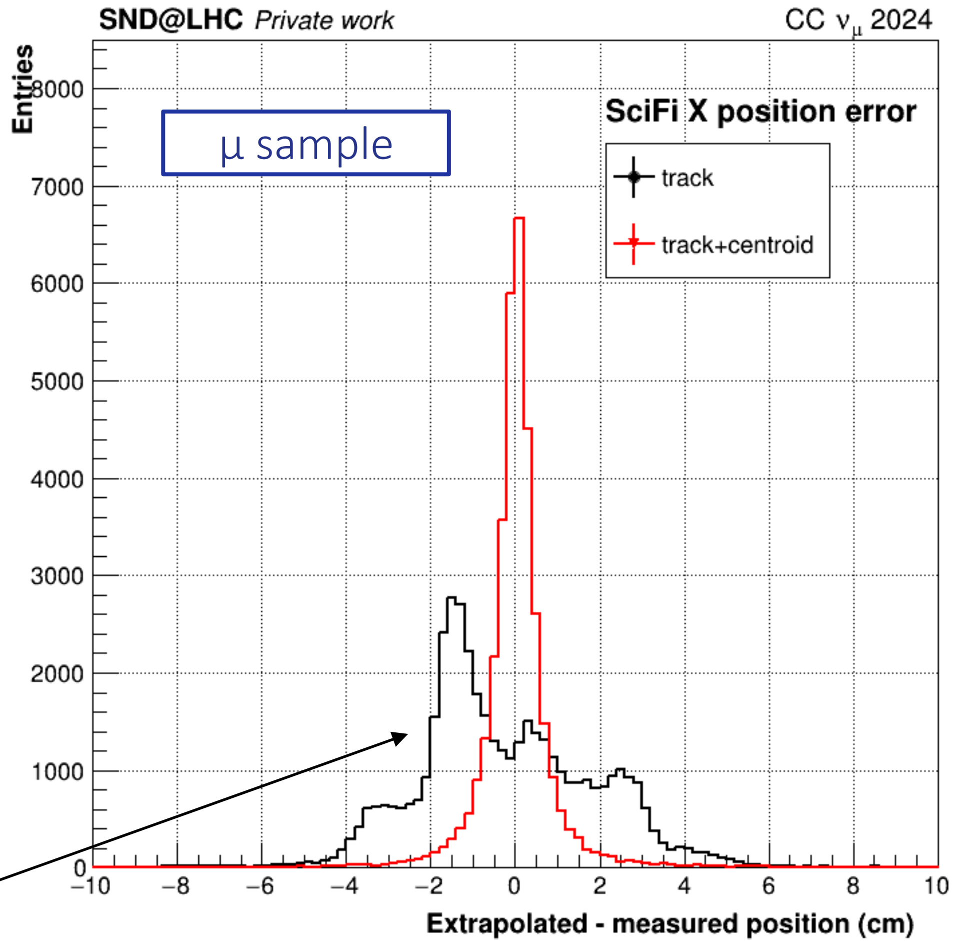
- ● SciFi module
- ● fiducial area 2024
- ● fiducial area 2022-23

2024 ν_μ CC – Selection: centroid

Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
5. Check for a reconstructed track (with $\frac{\chi^2}{dof} \leq 5$) and check that the extrapolated (x,y) position:
   - Distance < 3cm (DS extrapolation resolution) to **centroid** ≡ proxy for the interaction vertex, QDC-weighted position of hits
   - Add centroid to track points and re-fit
   - Extrapolate to veto the new track and require it to fall within active region, with a 1 cm margin from all edges



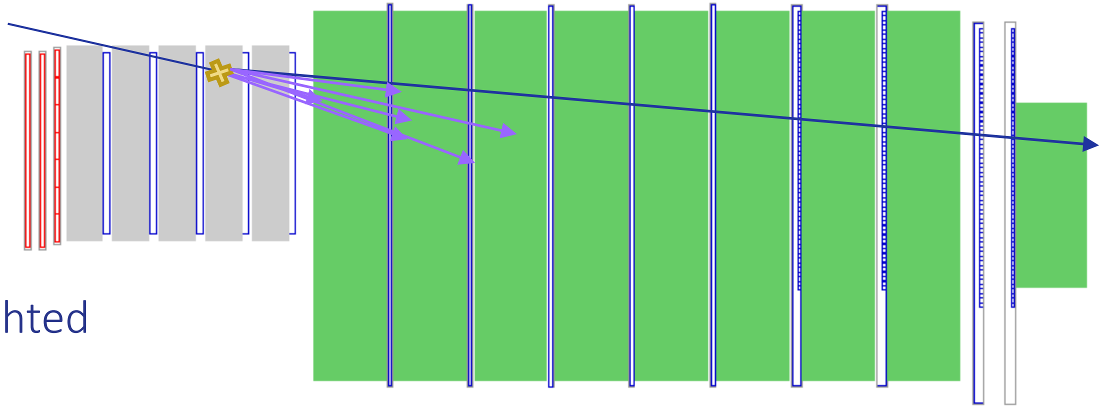
- Multi-peak: due to DS bar structure
- Asymmetry: due to detector geometry and DS-target relative position

2024 ν_μ CC – Selection: track

Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
5. Check for a reconstructed track (with $\frac{\chi^2}{dof} \leq 5$) and check that the extrapolated (x,y) position:
   - Distance < 3cm (DS extrapolation resolution) to **centroid** $\equiv$ proxy for the interaction vertex, QDC-weighted position of hits
   - Add centroid to track points and re-fit
   - Extrapolate to veto the new track and require it to fall within active region, with a 1 cm margin from all edges

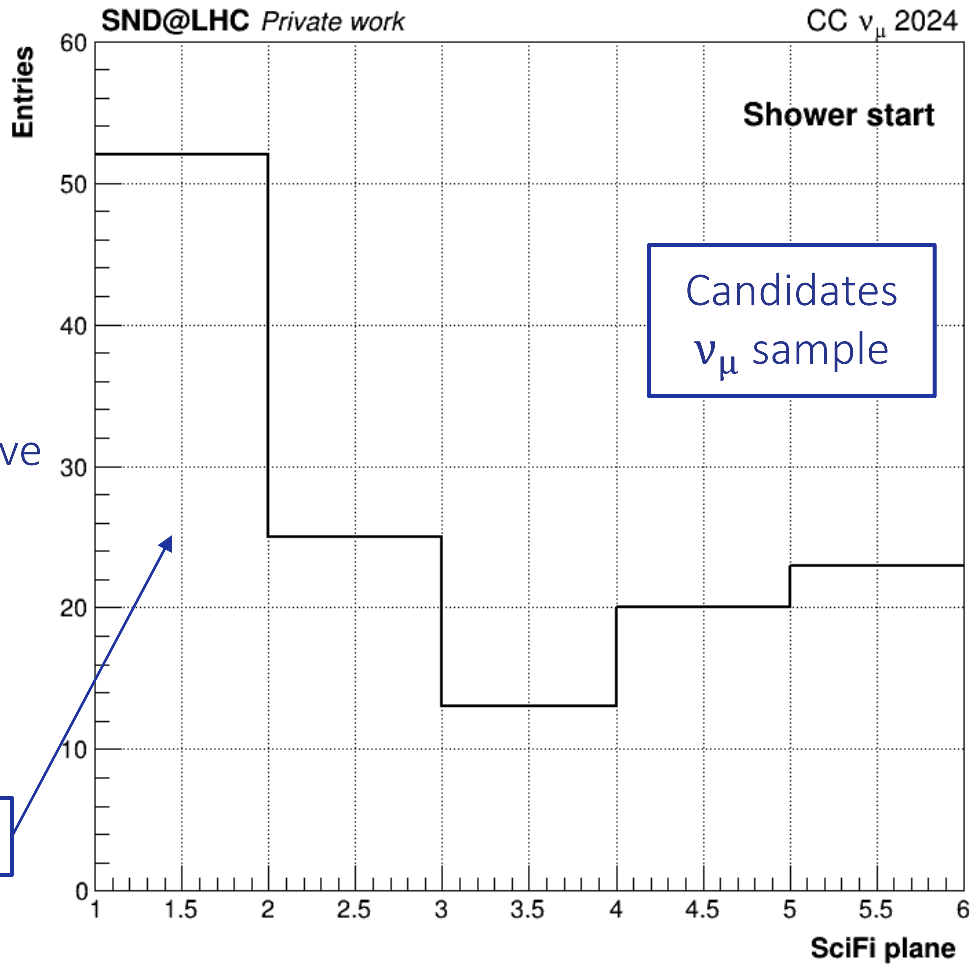


2024 ν_μ CC – Selected events

Work in progress!

Step 2: *Event selection criteria*

1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
5. Check for a reconstructed track (with $\frac{\chi^2}{dof} \leq 5$) and check that the extrapolated (x,y) position compatible with shower position, with the track pointing back to the veto active area



No condition on # hits in the previous wall → larger background

Summary and outlook

Status:

- Veto system upgraded to recover full volume
- Hadronic shower response calibrated
- Detailed studies of hit timing and event features

Next steps:

- Study on MC for validation of selection flow and evaluation of backgrounds (muons DIS and neutral hadrons)

Final goal on 2024 dataset : ν_μ rate measurement, which will lead to studies on cross-section and flux models thanks to the larger sample ($\sim 10^2$ expected events)

Further goals: include also 2025 and 2026 data, exploiting the enhanced muon tracks resolutions

After LS3: Recently approved (CERN-LHCC-2025-004) upgrade to run during HL-LHC:

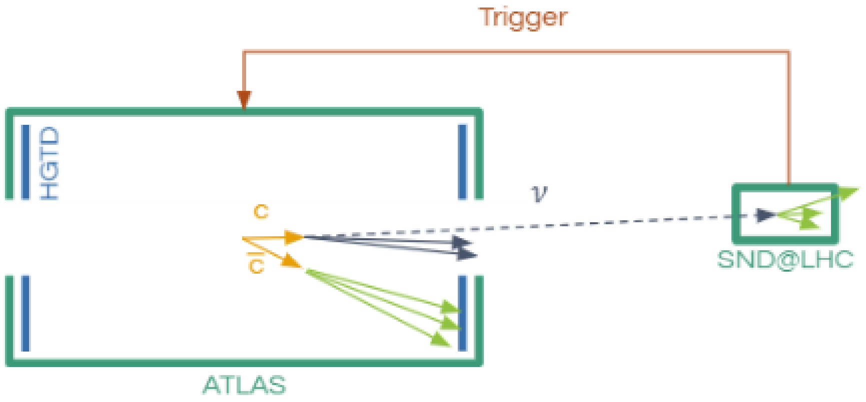
- first Si-based neutrino vertex detector
- magnetized calorimeter for charge and momentum measurement

THANKS FOR THE ATTENTION

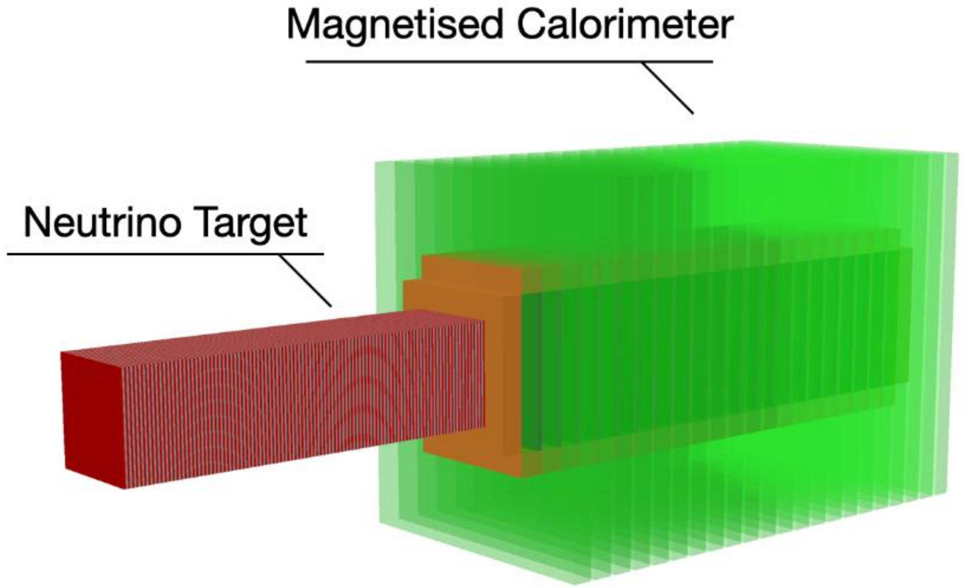
HL-LHC prospect

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**



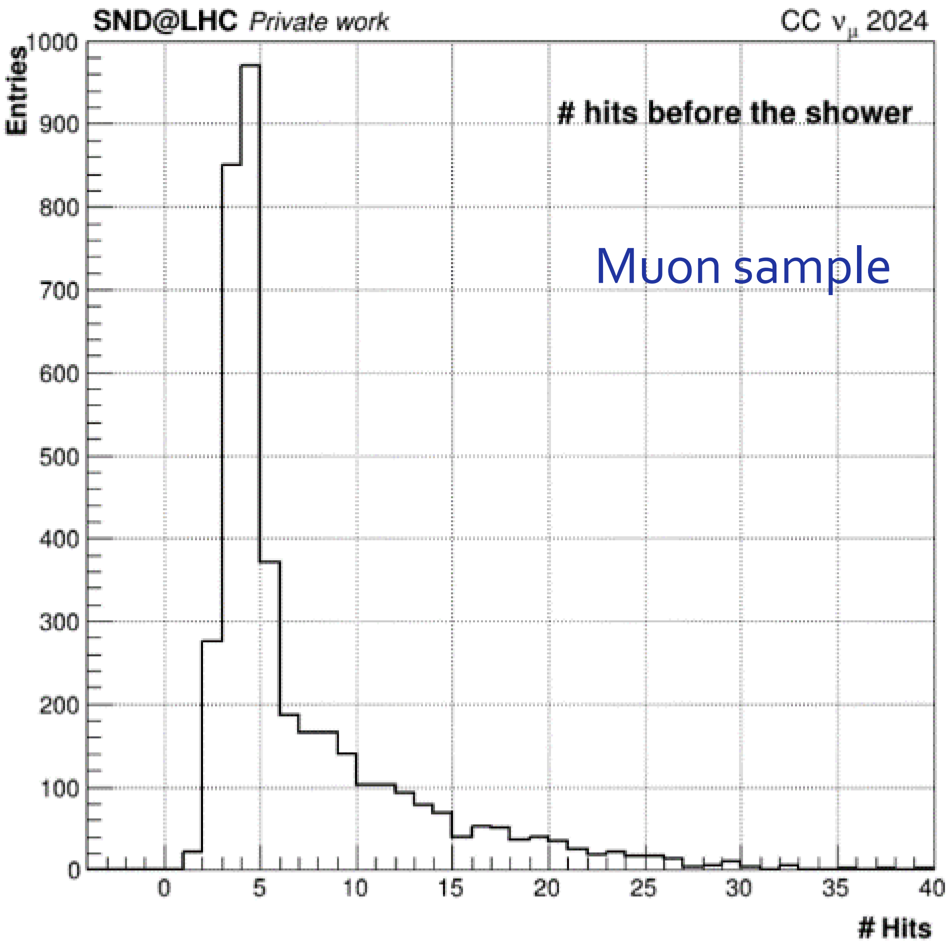
Measurement	Run 3 Uncertainty Stat.	Run 3 Uncertainty Sys.	HL-LHC Uncertainty Stat.	HL-LHC Uncertainty Sys.
Gluon PDF ($x < 10^{-5}$)	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	< 5%
ν_μ and $\bar{\nu}_\mu$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

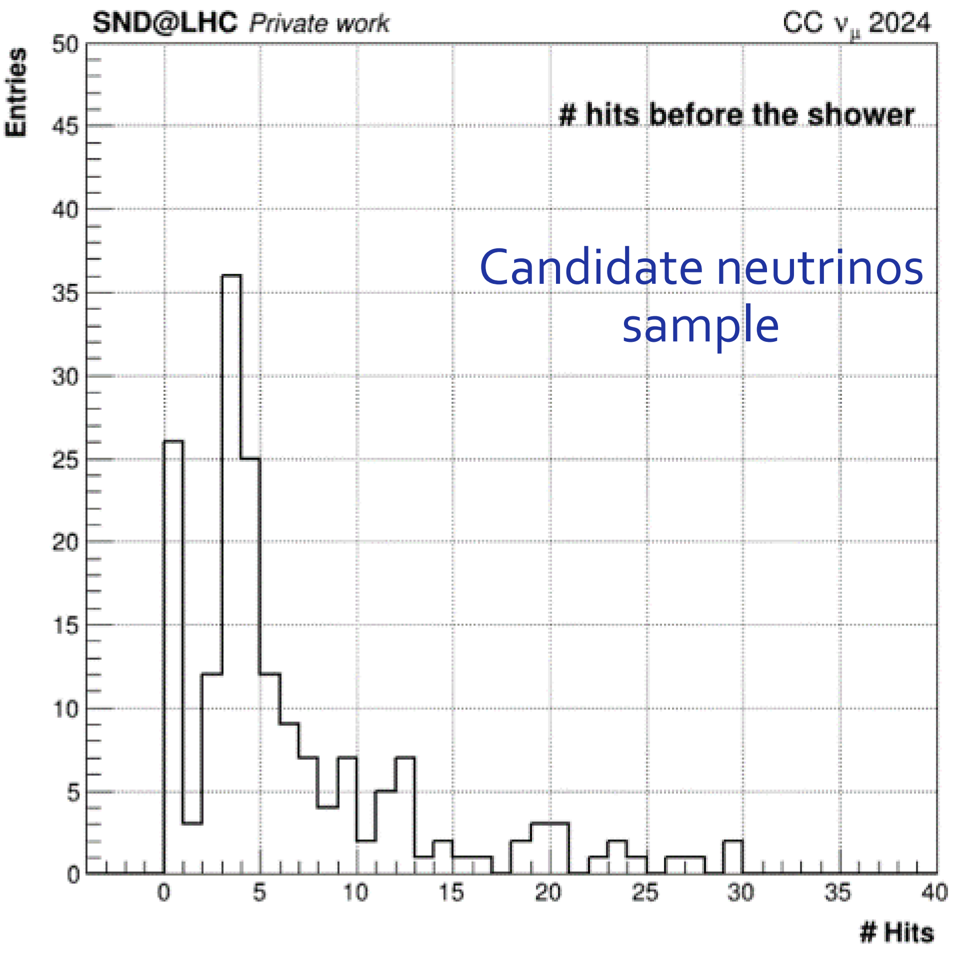


Preselection

Run	Emulsion target	Events	Luminosity [fb^{-1}]	Selected events	Selected events %
8285	1	4.12×10^8	0.6945	1.17×10^4	0.0028
8315	1	4.23×10^8	0.7400	1.19×10^4	0.0028
8320	2	4.48×10^8	0.7827	1.25×10^4	0.0028
8323	2	4.50×10^8	0.7900	1.22×10^4	0.0027
8638	3	6.05×10^8	1.0690	1.76×10^4	0.0029
8724	3	5.43×10^8	0.9128	1.58×10^4	0.0029
9015	4	4.76×10^8	0.8447	1.36×10^4	0.0029
9094	4	5.44×10^8	0.9650	1.56×10^4	0.0029
9258	5	5.07×10^8	0.8990	1.47×10^4	0.0029
9262	5	5.24×10^8	0.9320	1.51×10^4	0.0029
9288	6	5.14×10^8	0.9125	1.48×10^4	0.0029
9361	6	5.38×10^8	0.9420	1.55×10^4	0.0029
9411	7	5.32×10^8	0.9311	1.51×10^4	0.0028
9436	7	6.14×10^8	0.9080	1.76×10^4	0.0029
9562	8	5.33×10^8	0.9420	1.56×10^4	0.0029
9569	8	5.27×10^8	0.9350	1.51×10^4	0.0029
9622	9	7.04×10^8	1.2320	2.02×10^4	0.0029
9685	9	5.48×10^8	0.9771	1.57×10^4	0.0029
9715	10	3.36×10^8	0.6102	9.04×10^3	0.0027
9880	10	5.36×10^8	0.8814	1.55×10^4	0.0029
9885	11	5.31×10^8	0.9594	1.53×10^4	0.0029
9913	11	5.18×10^8	0.9361	1.48×10^4	0.0029
Total	–	1.14×10^{10}	19.7965	3.25×10^5	0.0029

N hit before shower

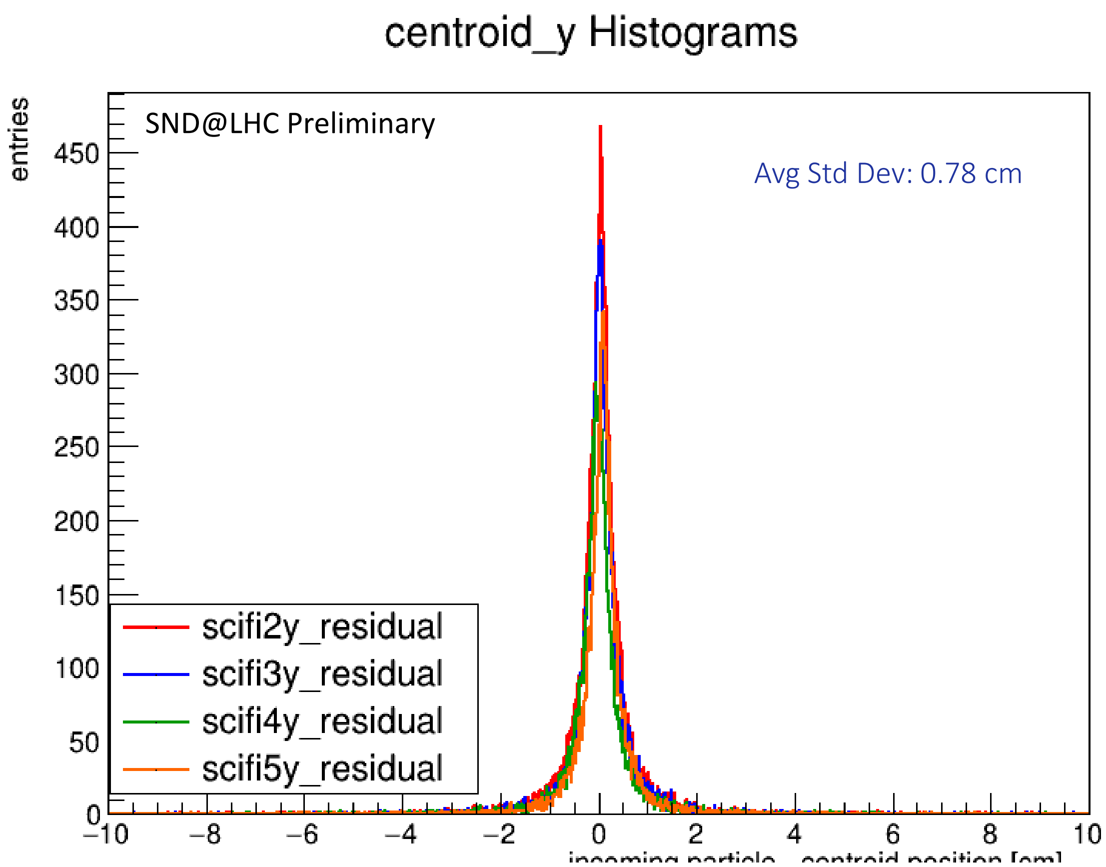


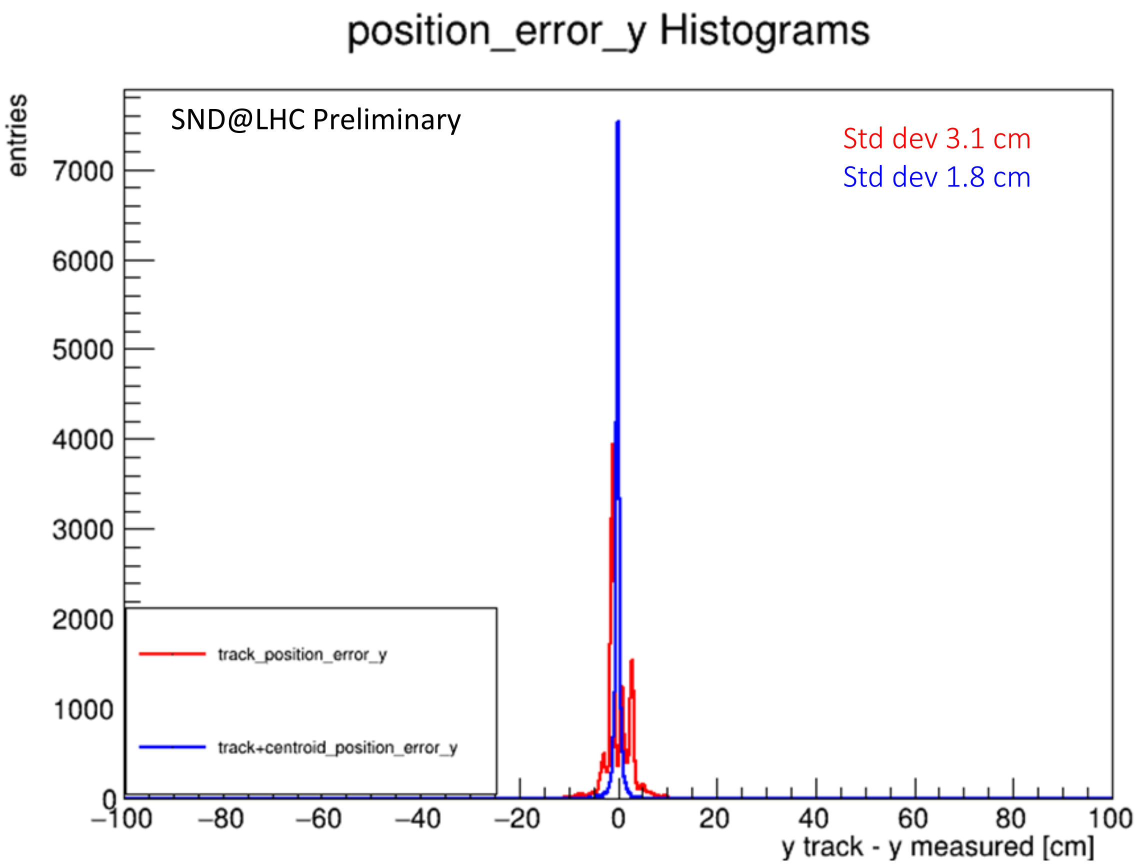


Validation of shower centroid

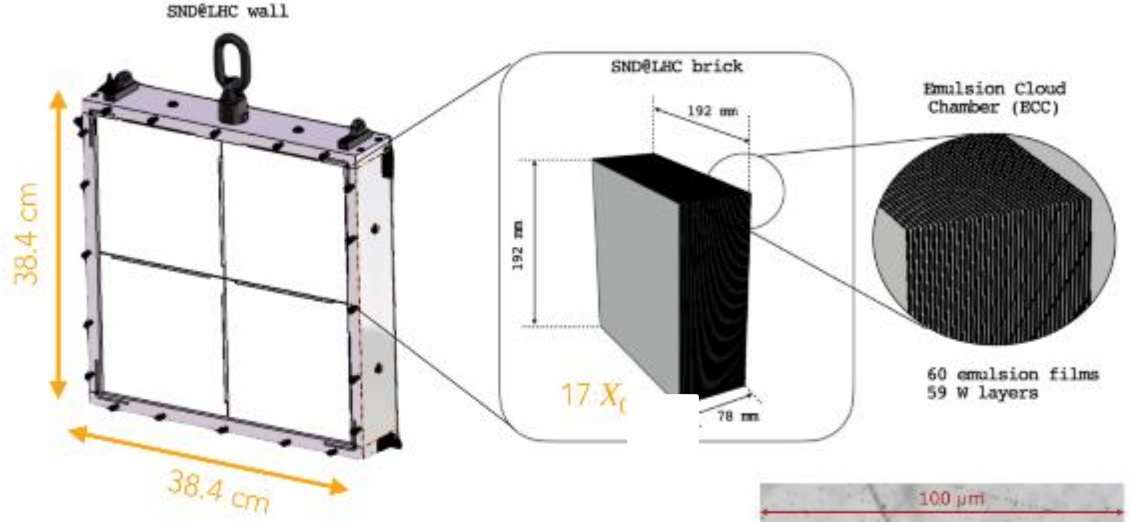
Centroid: Mean position averaged with qdc value. A minimum number of hits is needed

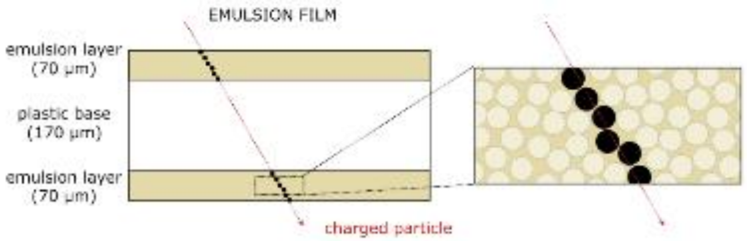
Aim: Validate centroid distribution using muon producing DIS showers

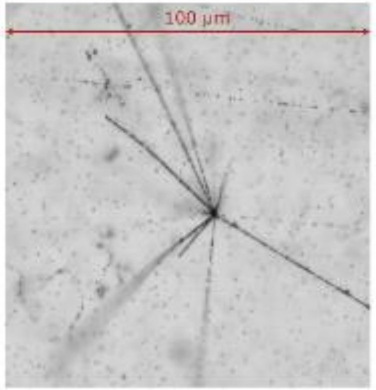




Backup

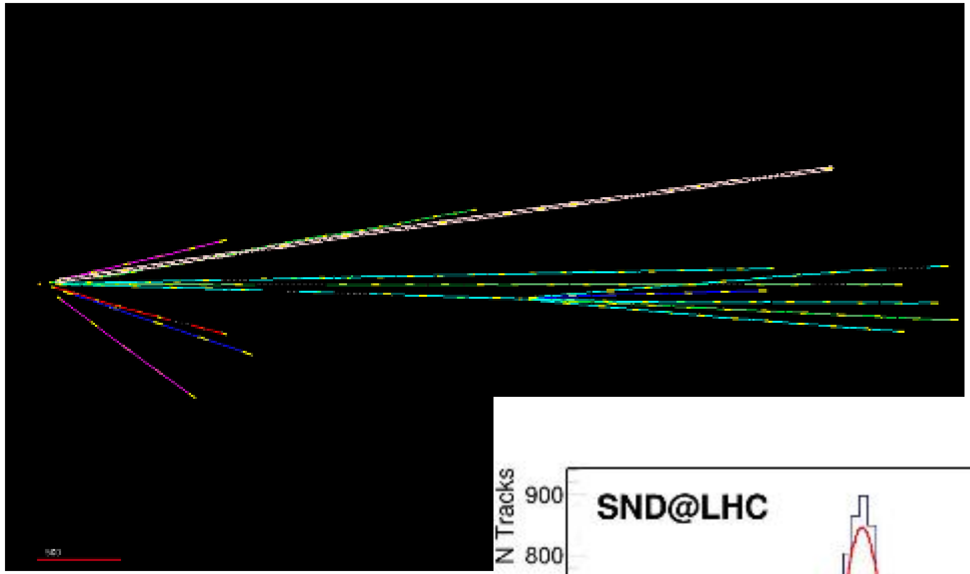


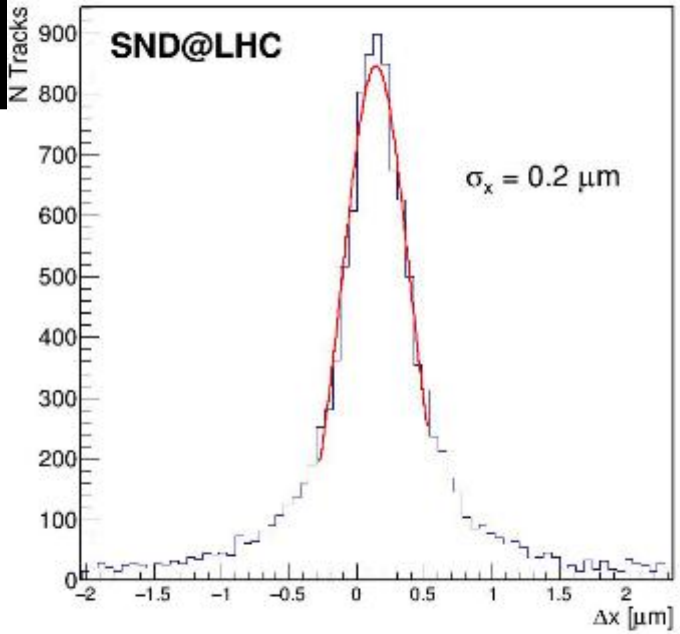




- Emulsion scanning is performed with fully automated microscopes in six laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Santiago
- Track density up to $4x10^5$ tracks/cm^2

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





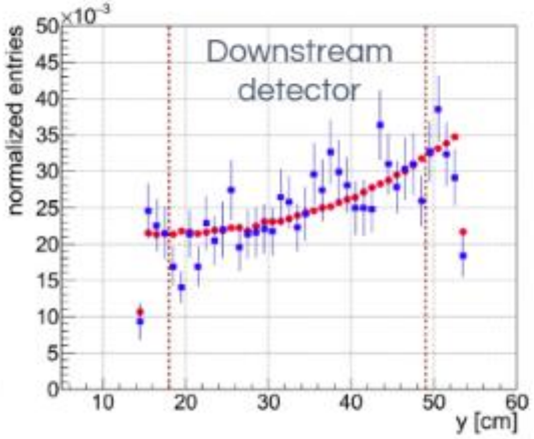
Position resolution 0.2 μm

Backup

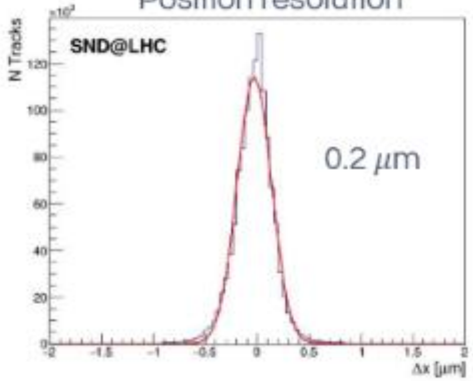
Passing muons

- 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.

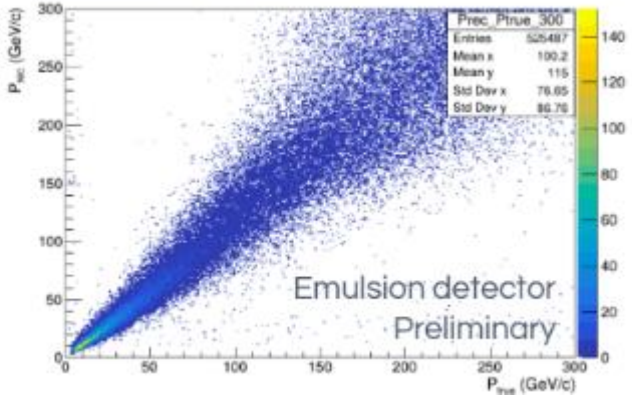
year	flux [trk/(cm^{-2}fb^{-1})]
2022	557
2024	1154
2025	**832**
MC	460



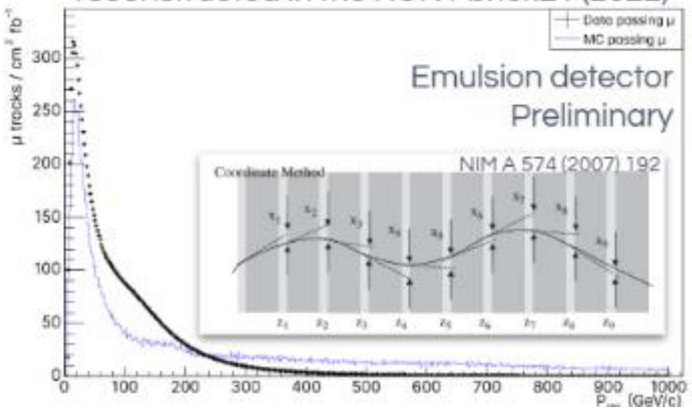
Position resolution



Reconstructed *vs* true muon momentum



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



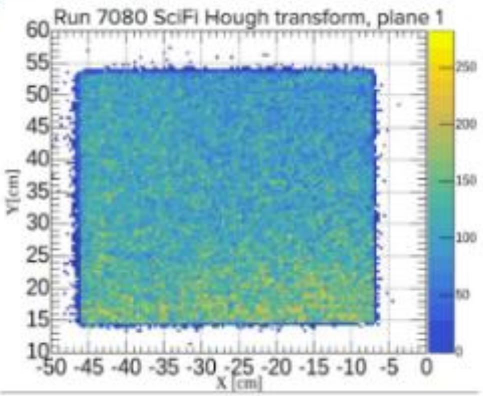
Passing muons in heavy ion runs

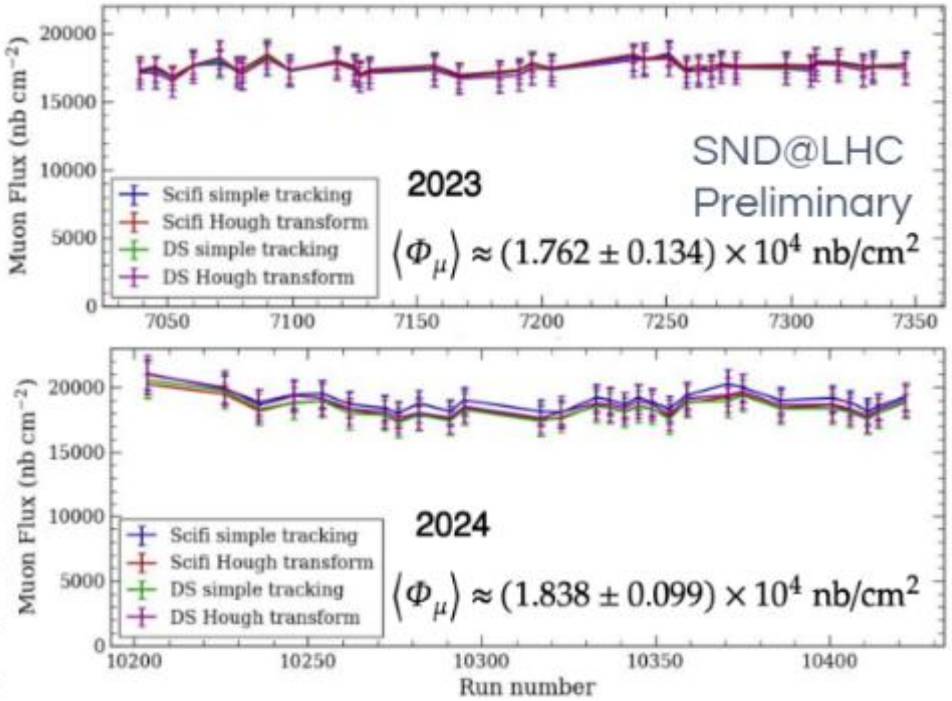
- Measurement of the muon flux in heavy ion collisions.
  - Different physics compared to pp.
    - Softer energy spectrum.
  - Different LHC optics compared to pp.

- 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

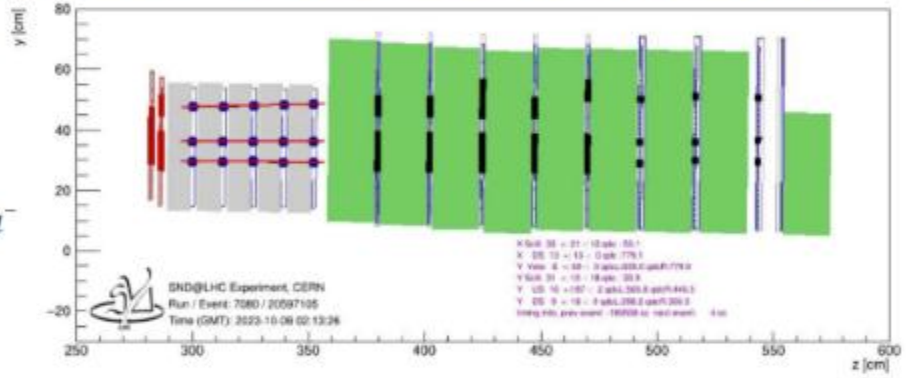
- PbPb/pp flux ratio: ~10^6
  - With different LHC optics





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

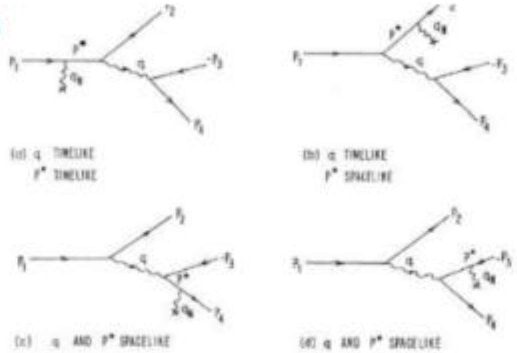
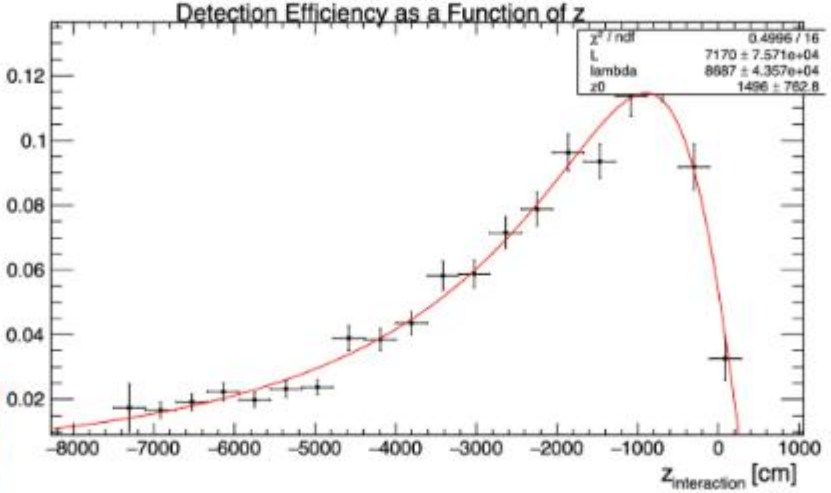
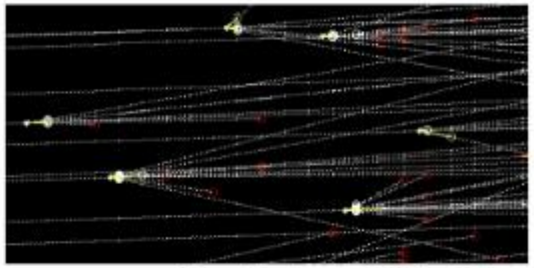


FIG. 1. The four Feynman diagrams for muon tridents (a) and (b) have timelike virtual photons while in (c) and (d) the virtual photon is spacelike. p^* is the four-momentum of the virtual muon; q is the four-momentum of the virtual photon and q_N is the nuclear recoil four-momentum.



Muon DIS in the emulsion

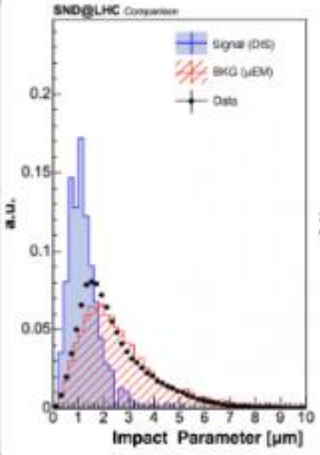
- Identification of **muon DIS** in the emulsion target with cut-based approach on topological and kinematical variables
- Data sample: vertices reconstructed in RUN1 brick 21: 32kg x 9.5fb^{-1}

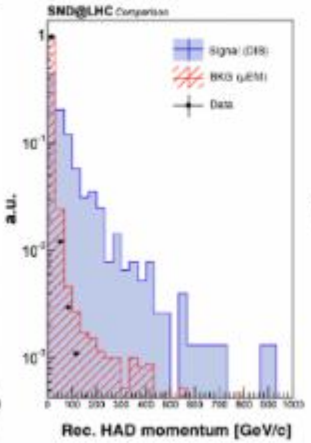


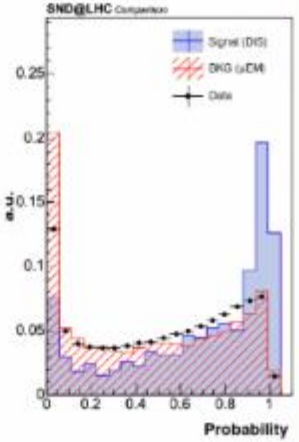
Simulated muon DIS in brick

Event selection criteria

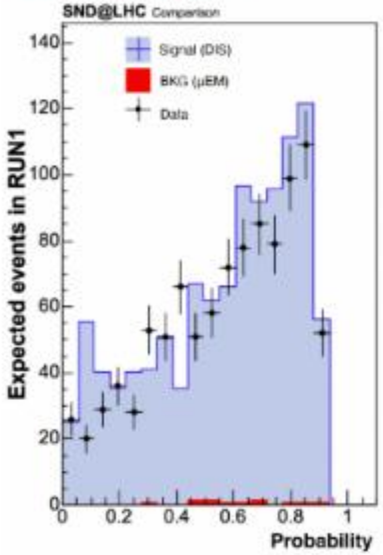
- charged vertex
- mean angular aperture > 13 mrad
- impact parameter<2.5μm
- fraction of rec. segments>0.87
- rec. hadron momentum > 16 GeV

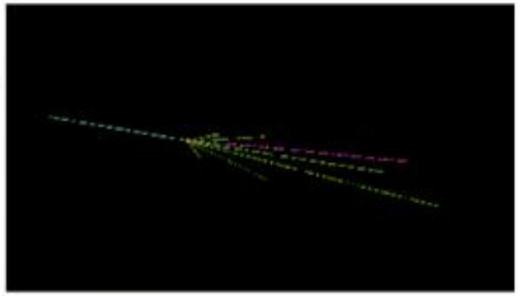






Signal region





Observed candidate in data

Observed: **992 ± 32**

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

Preliminary

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

Observation of 0μ events in SND@LHC

PRL 134 231802 (2025)

Signal: ν_e CC 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

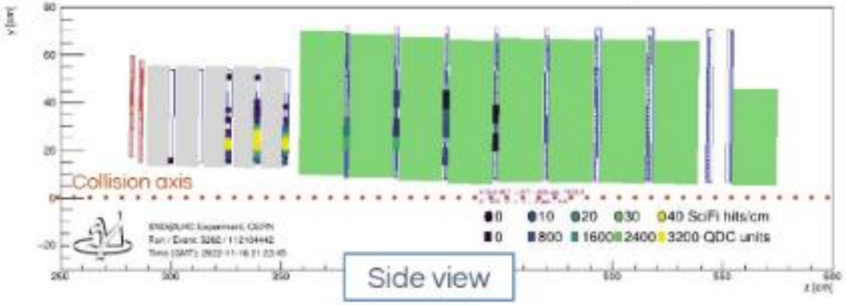
0μ observation significance

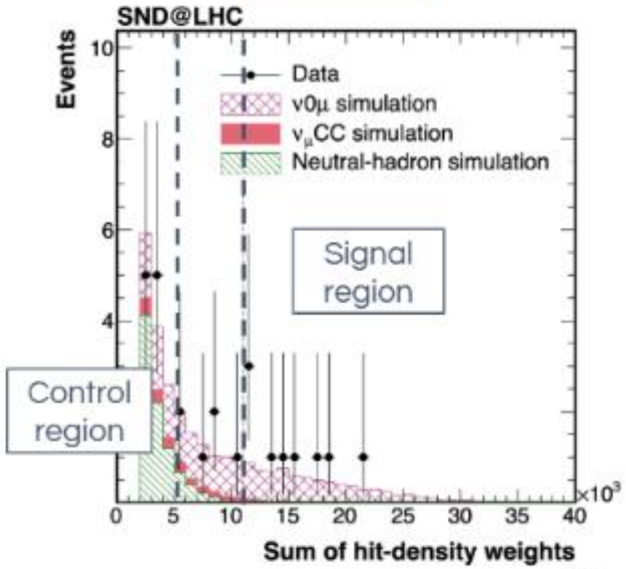
- **Total expected background: 0.32 ± 0.06 events**
- **Expected signal: 7.2 events**
  - 4.9 ν_eCC, 2.2 NC, 0.1 ν_τCC
- **Expected significance: 5.5 σ**

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.

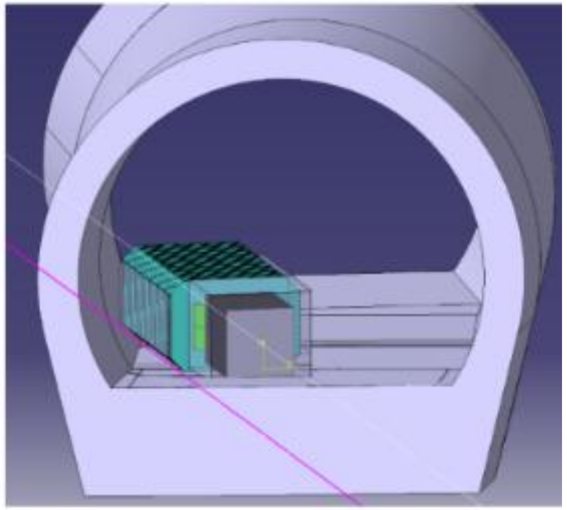


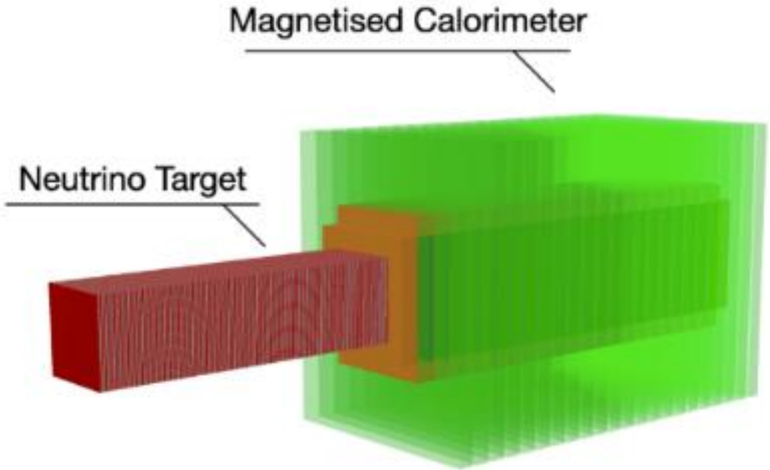


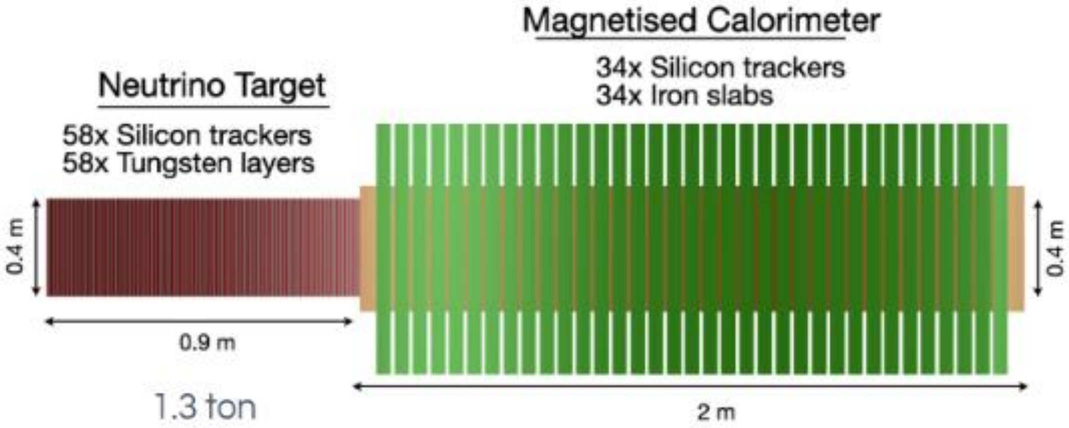
Backup

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.

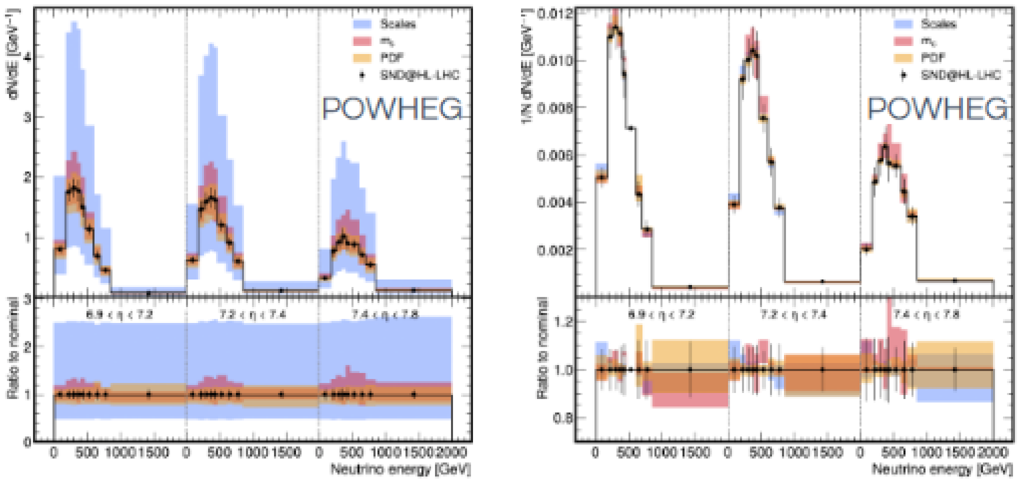


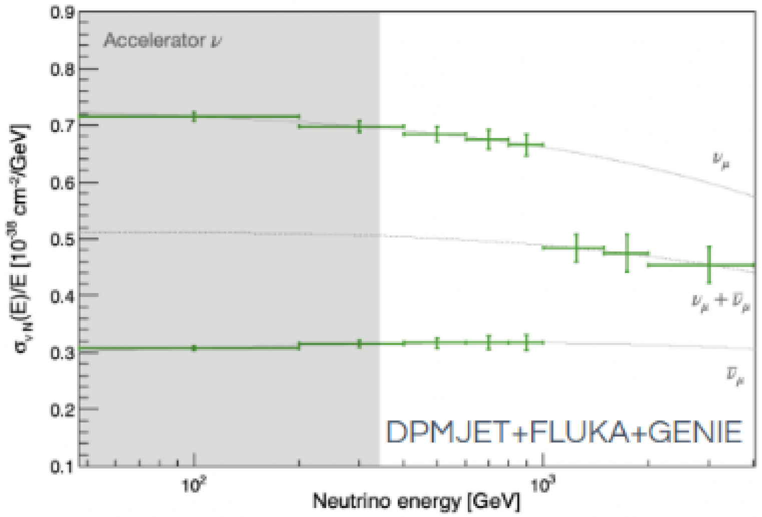




CERN-LHCC-2024-014

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%

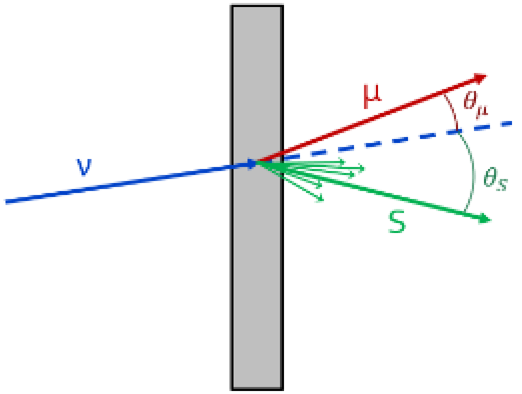
Shower direction reconstruction

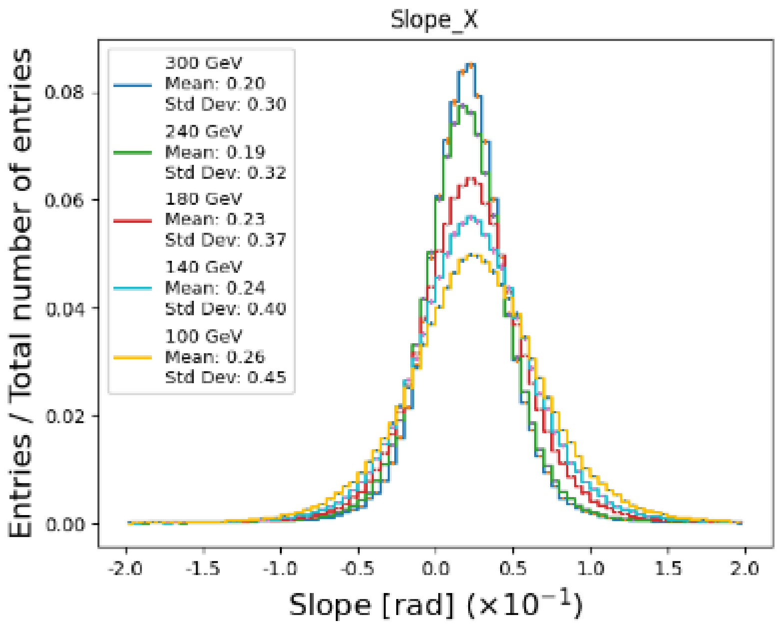
Aim: reconstruct shower direction → crucial for the ν_μ energy reconstruction as $E_\nu \sim E_S\left(1 + \frac{\sin(\theta_S)}{\sin(\theta_\mu)}\right)$

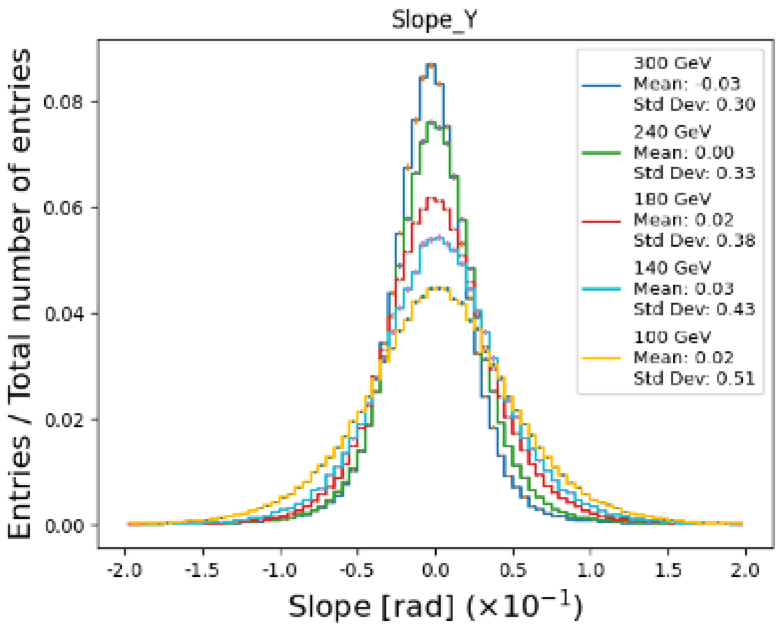
Idea:

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

Veto pre upgrade

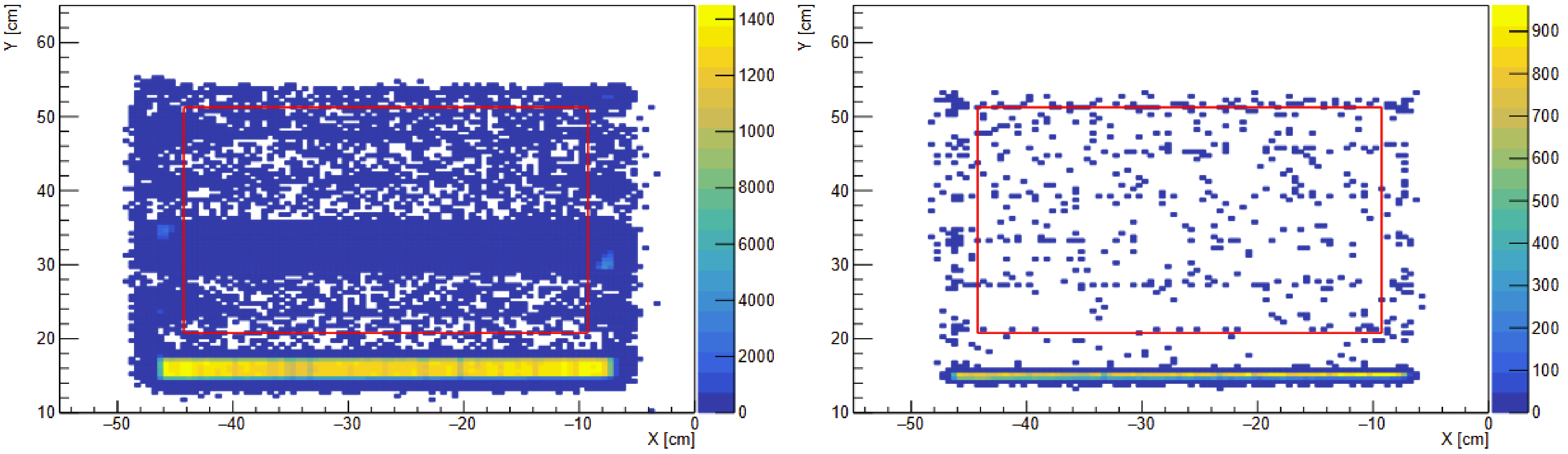


Figure 1: The extrapolated position of the reconstructed Scifi track at Veto plane 0 (left) and Veto plane 1 (right) for events with less than 13 fired Veto channels. The red square encloses the fiducial area used for the observation of neutrino interactions.

Veto per plane post upgrade