NEUTRINO INTERACTION STUDIES WITH SND@LHC DETECTOR

CSN1
24/11/2025

Giulia Paggi
Università e INFN Bologna
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

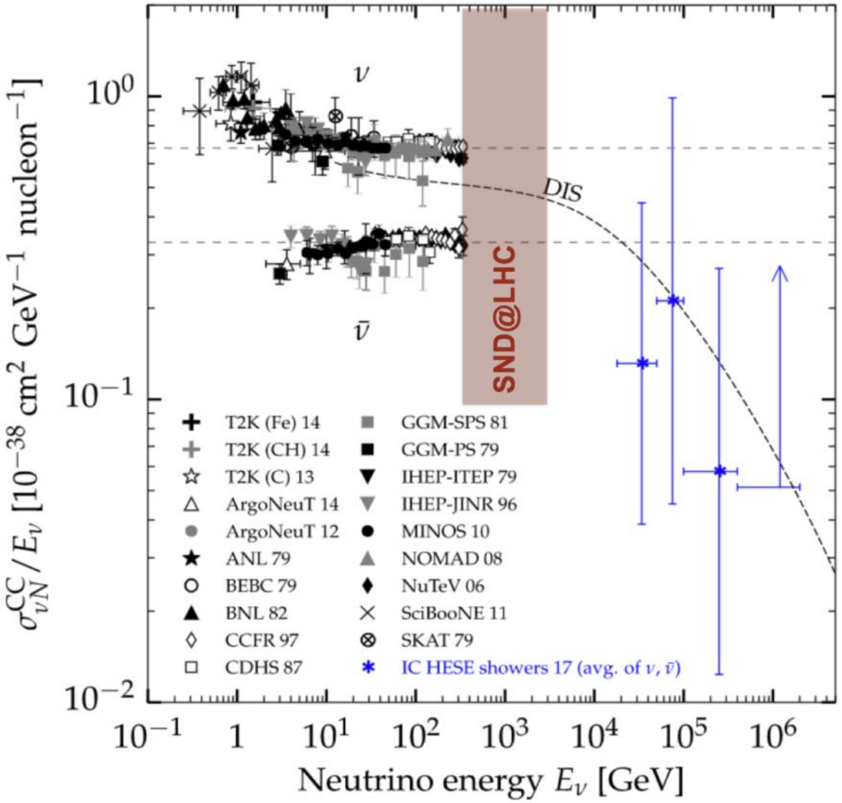
→ **Large ν flux** in forward region from pp collisions

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 ($gg \rightarrow cc$)

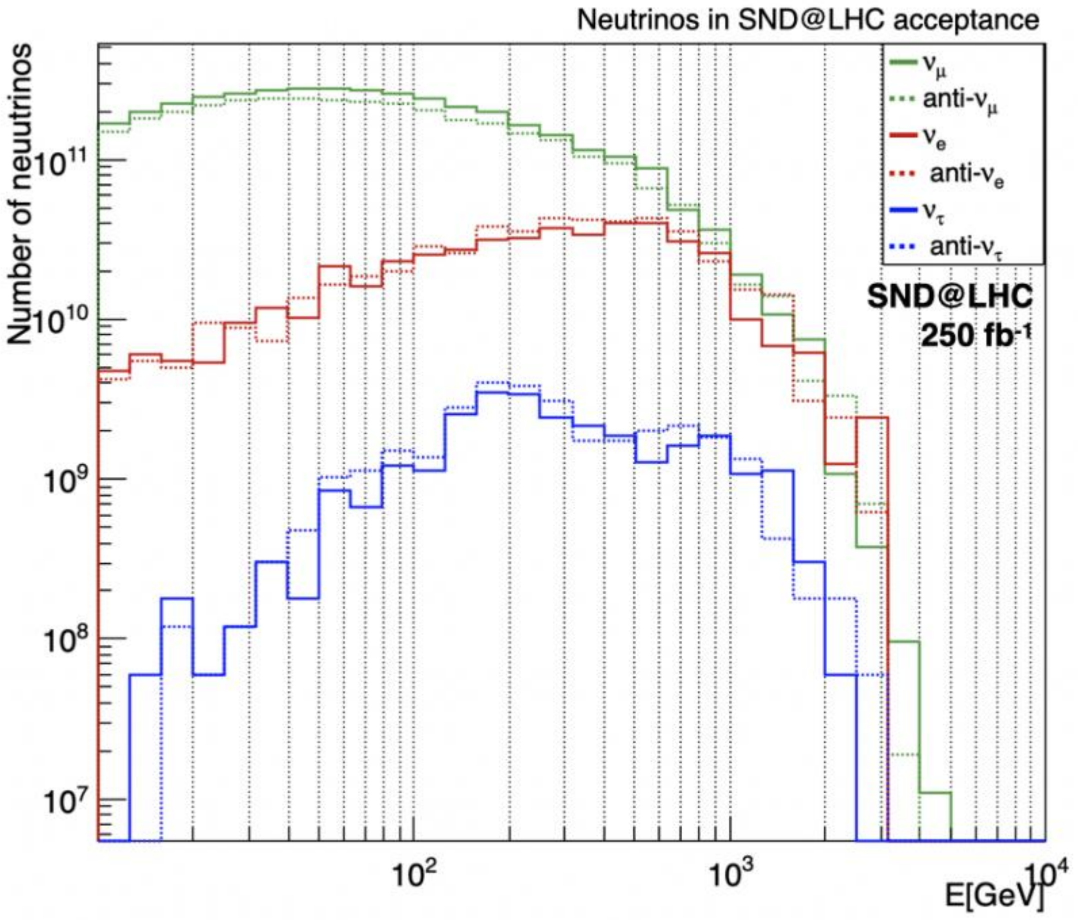
  → Given the η region, the majority of vs is from charmed hadrons decay

→ High-energy neutrino cross section measurements

→ ν_τ observations

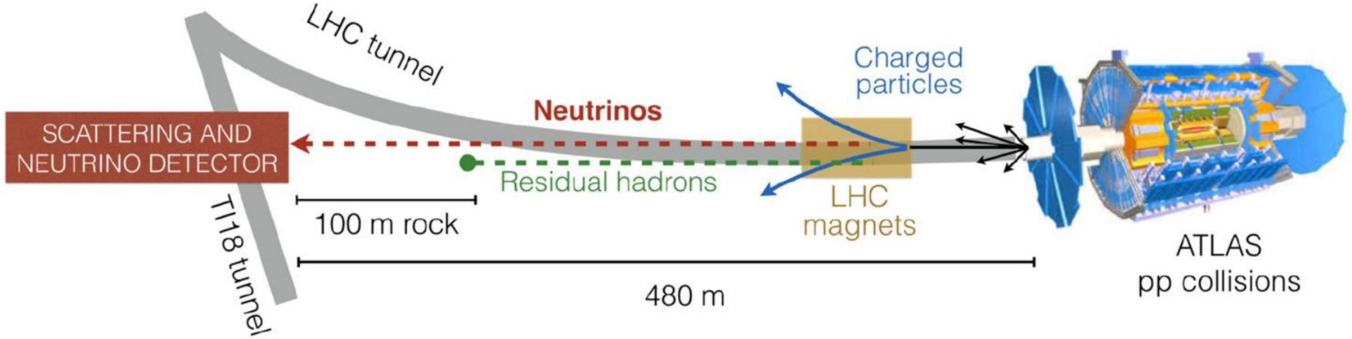
→ Test lepton **flavour universality** measuring ν_e/ν_μ and ν_e/ν_τ

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



The detector: location

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



→ Shielded by **100 m rock**

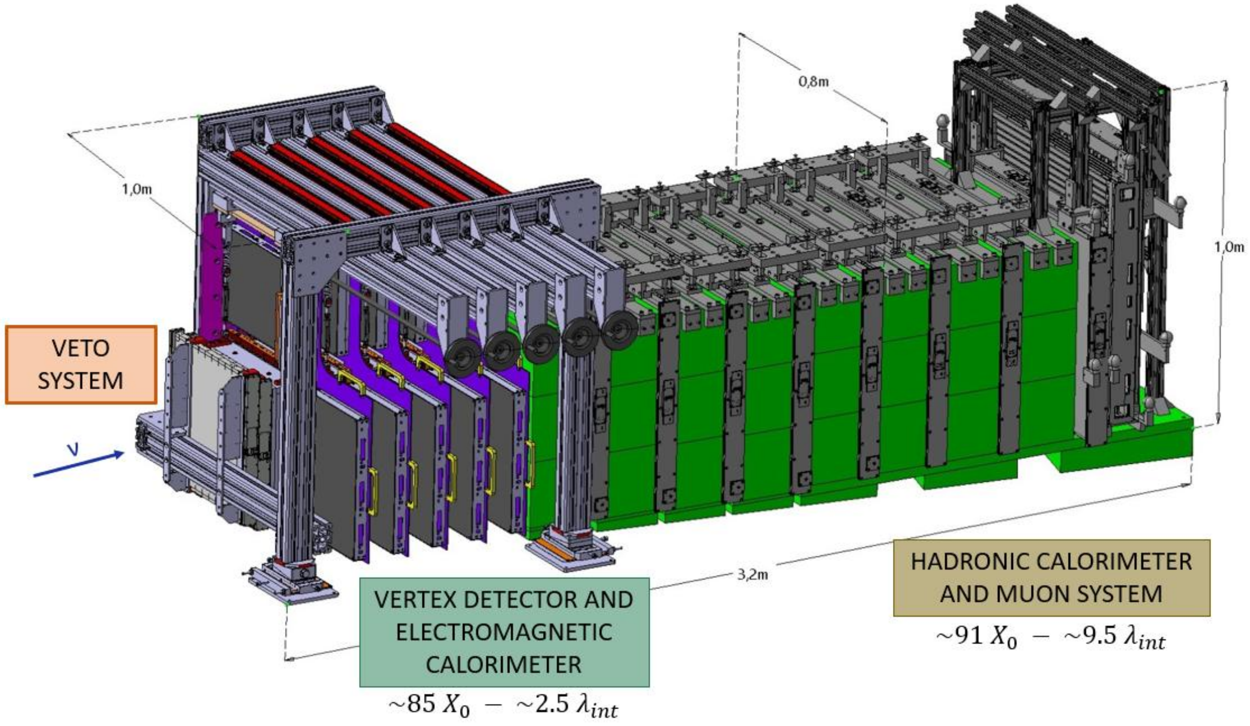
→ **LHC magnet** deflects charged particles

↓

Neutrinos and FIPs reach the detector

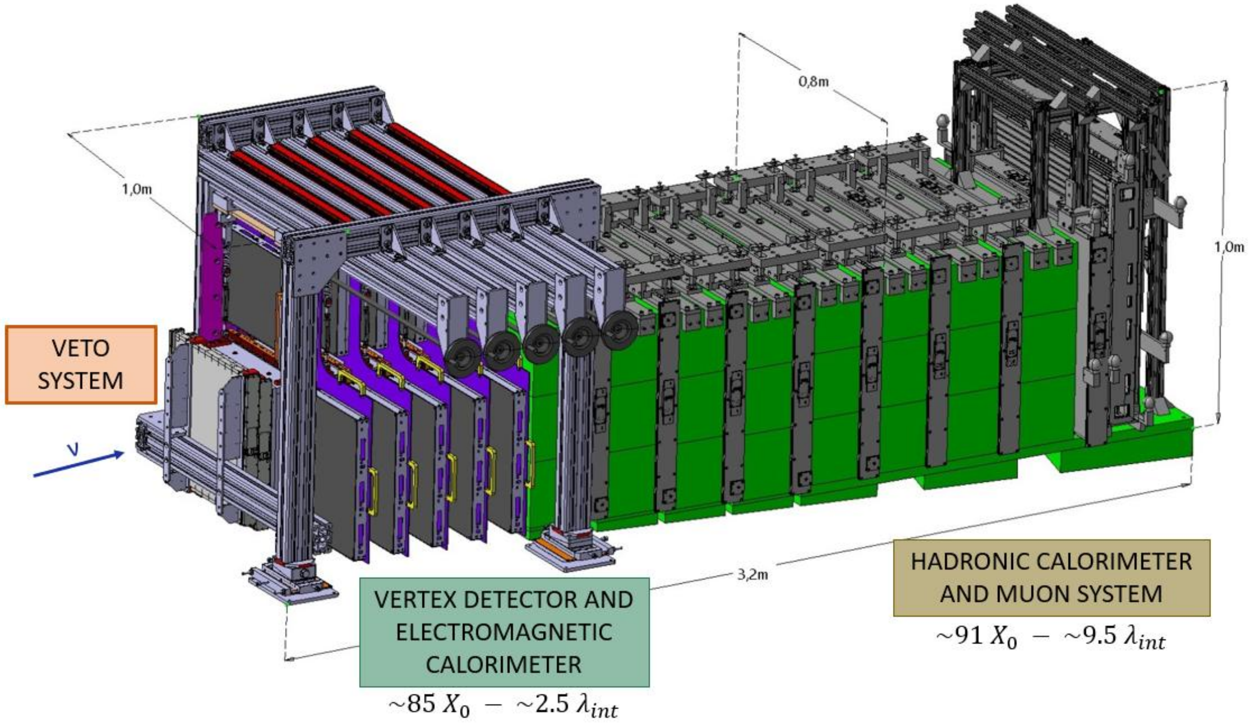
The detector

Hybrid detector composed of:



The detector

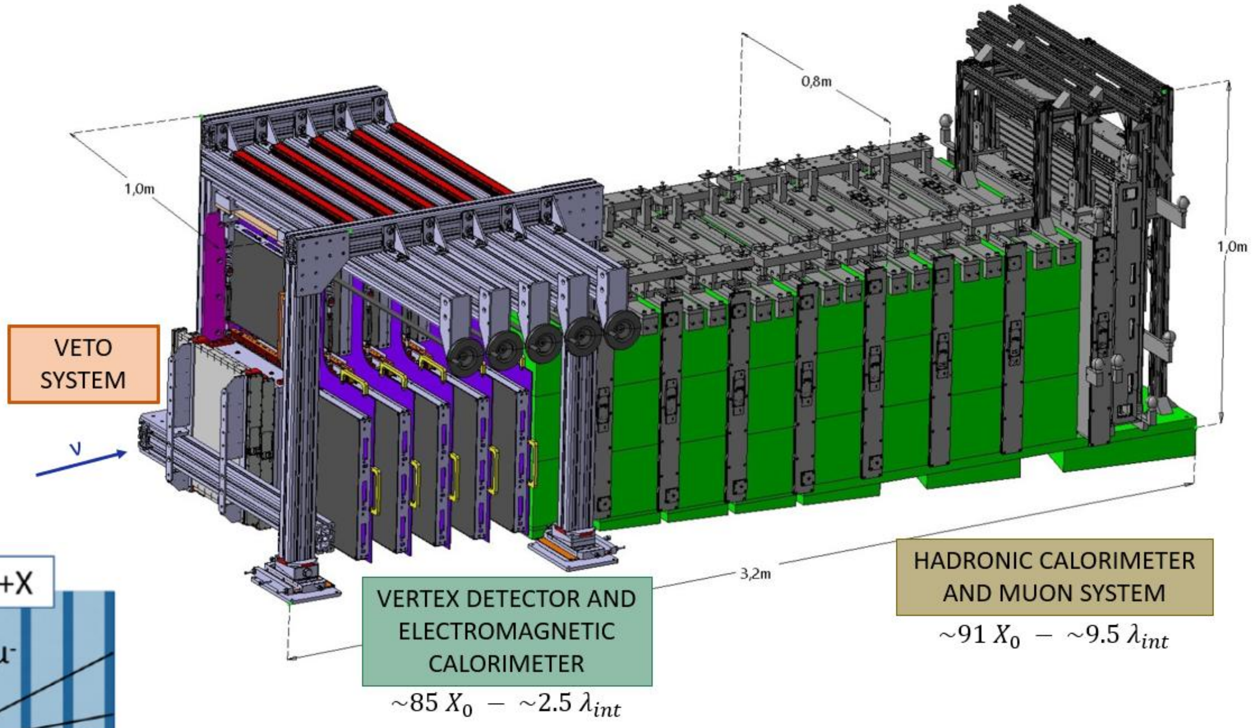
Hybrid detector composed of:
→ Veto system
  → Since 2024: **3** planes of scintillating bars **to tag incoming charged** particles

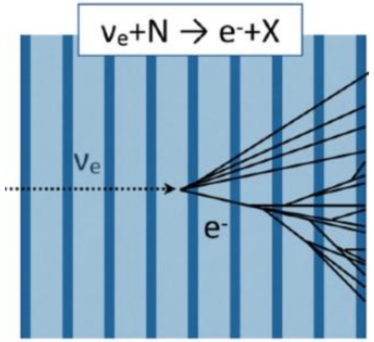


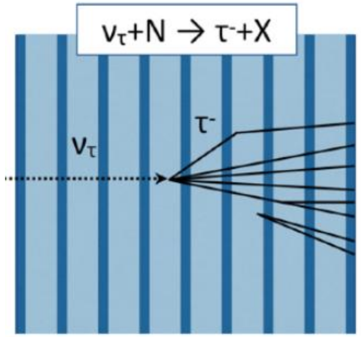
The detector

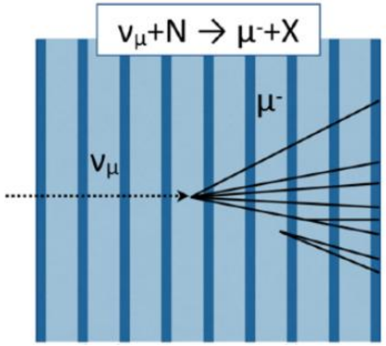
Hybrid detector composed of:

→ 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**









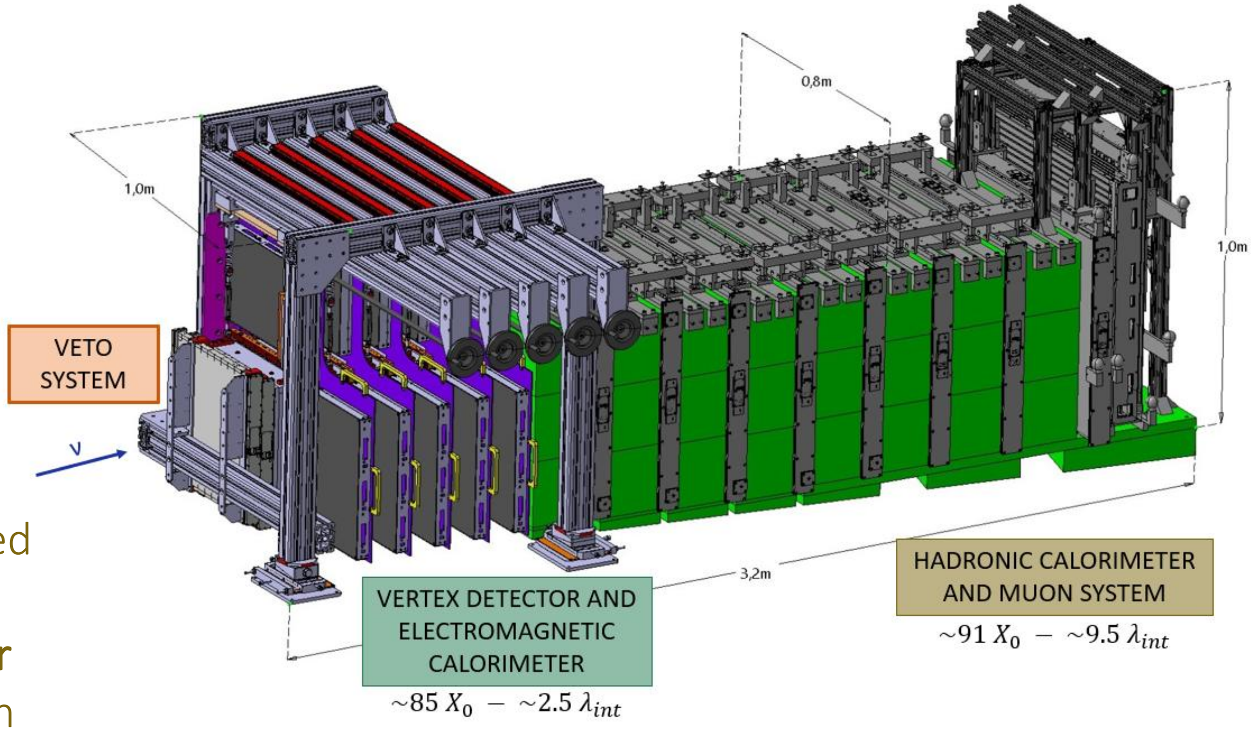
The detector

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, focus on **muon tracking**
  → **2 MiniDTs**: small size replica of CMS DTs



Upgrade of Muon system

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

Aim of **halving the muon reconstruction resolution**


Before

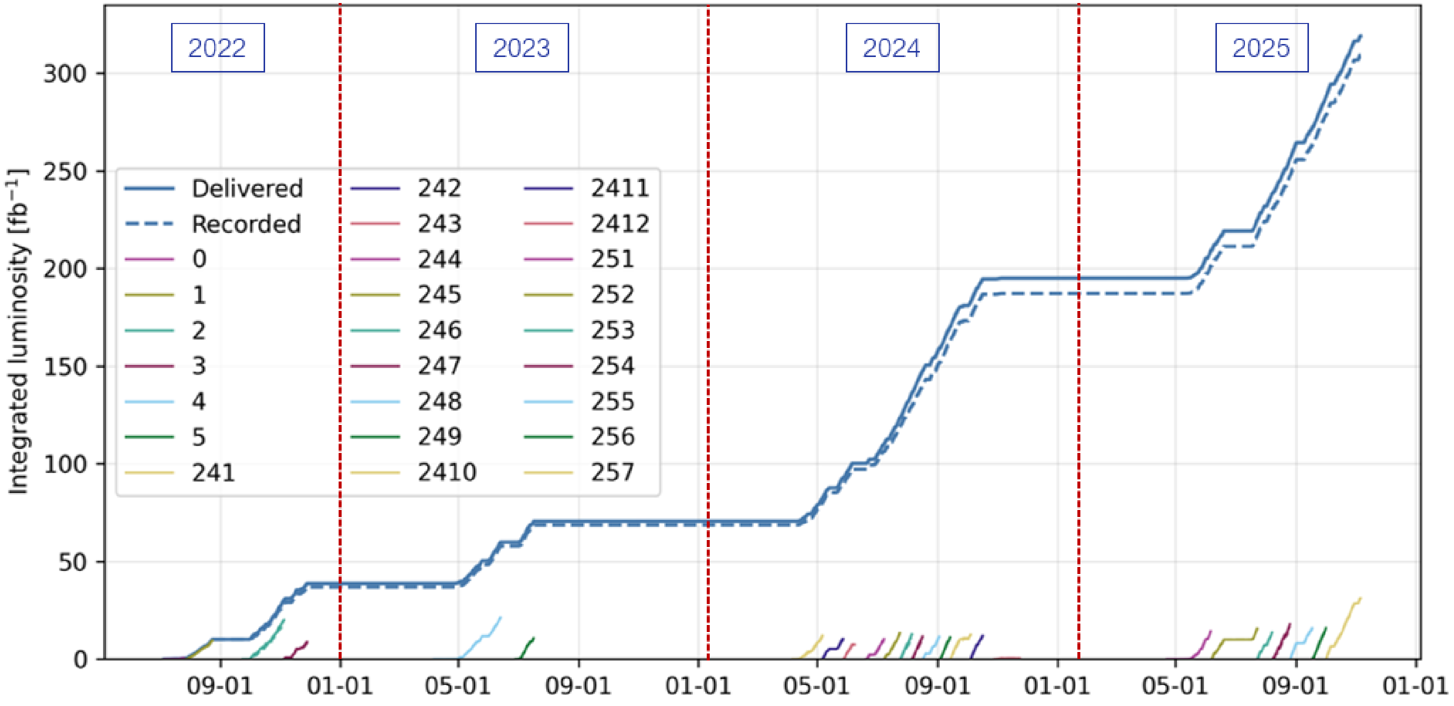
After

- Offline event matching validated
- Track reconstruction development ongoing

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%

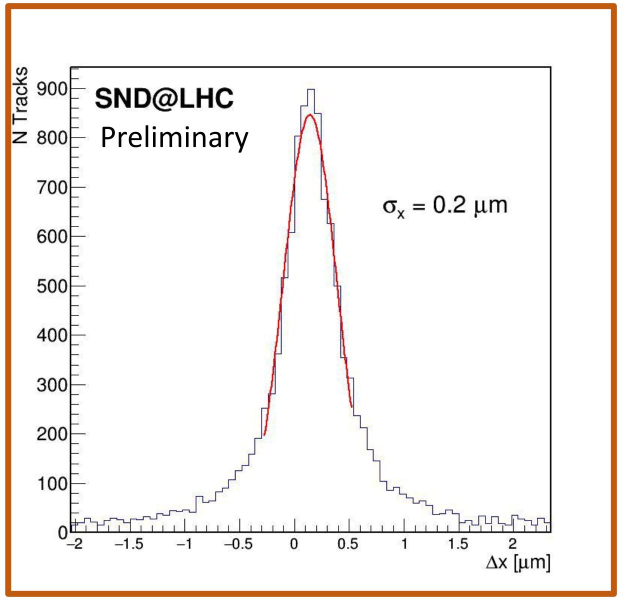
- Emulsion:
  - 2022-23: 5 full target
  - 2024-25: target was only partially instrumented unexpected increase in muon flux
  - 252 fb^{-1} integrated

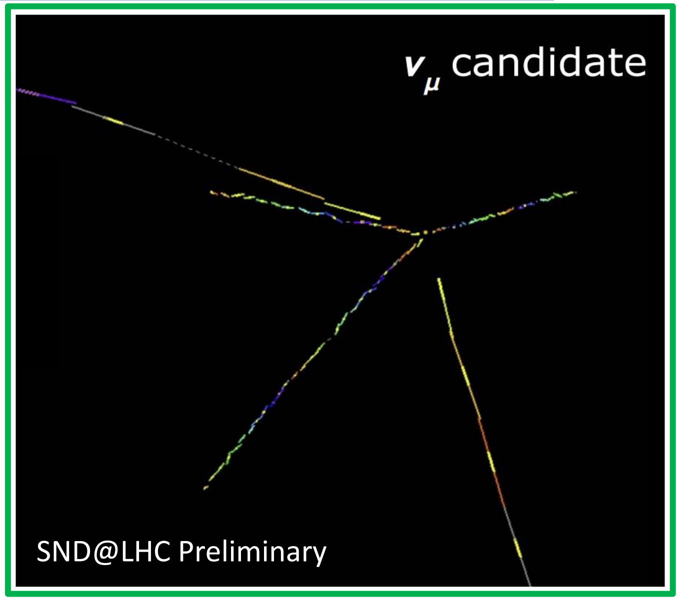


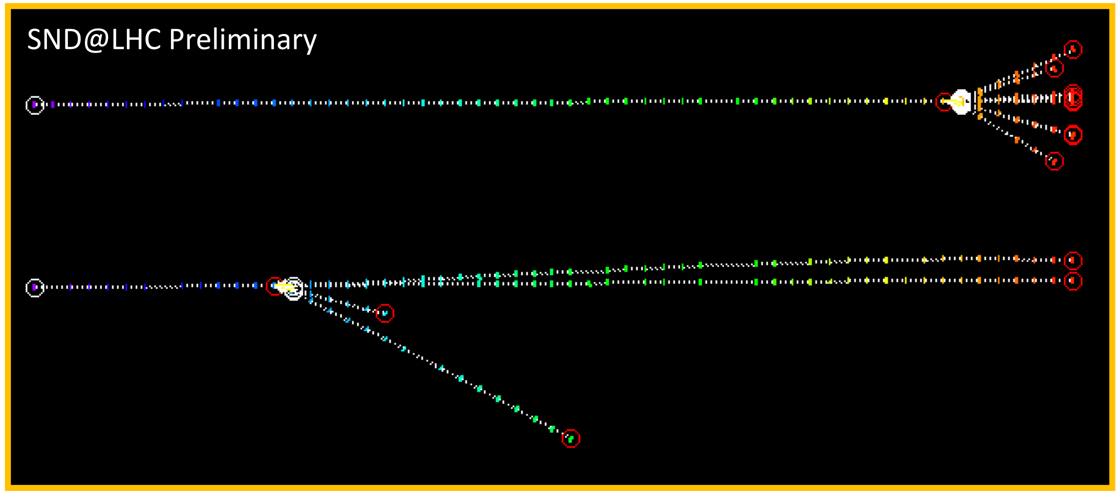
Emulsion data analysis

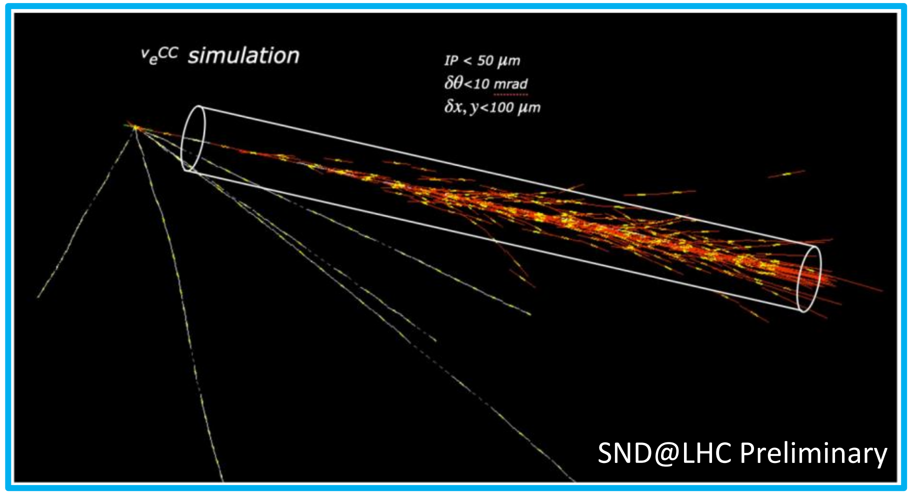
Emulsion data analyses:

- Achieved position resolution 0.2 μm
- Vertices search ongoing on reconstructed data
  - Muon neutrinos
  - Electron neutrino
  - Muon DIS









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**
- **Muon DIS in emulsion**

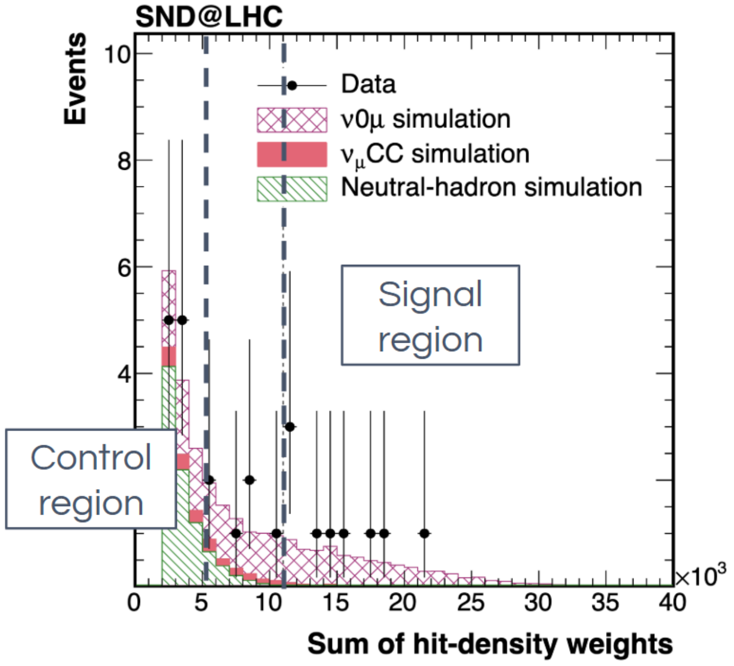
ν analysis with electronic detector

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: ν_e CC and NC interactions
  - Expected signal: 7.2 events → 4.9 ν_e CC, 2.2 NC, 0.1 ν_τ CC
  - 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 $\boldsymbol{\sigma}$

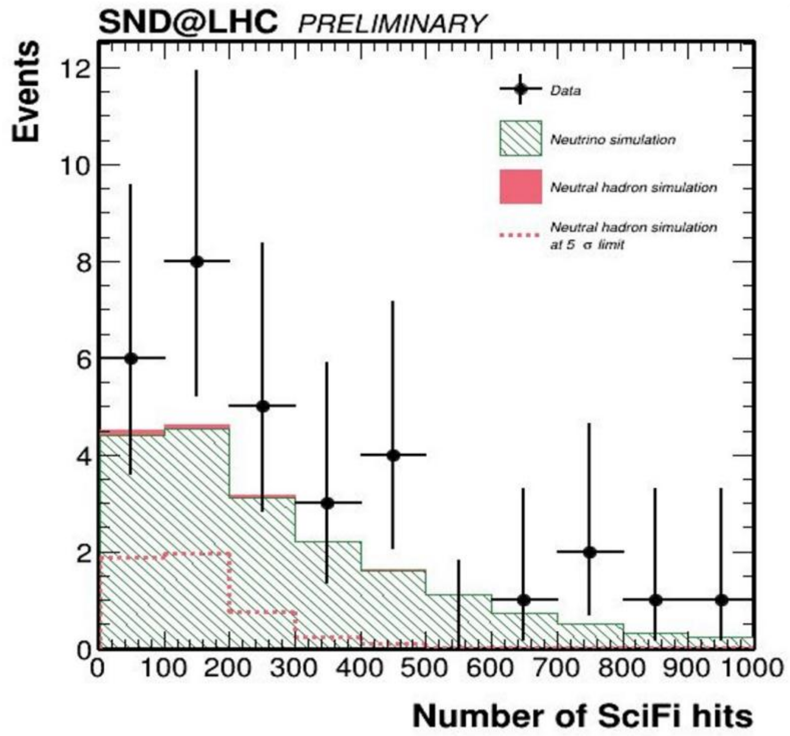


ν_μ analysis 2022+2023

Muon neutrino analysis

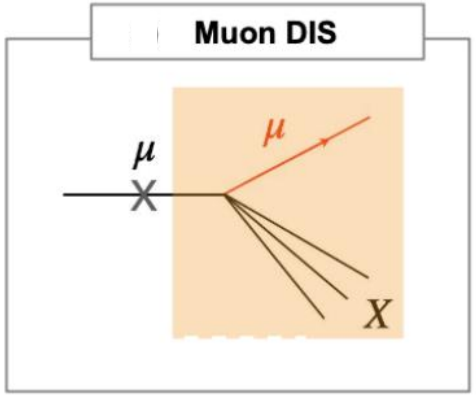
- **Published:** Observation of collider muon neutrinos with the SND@LHC experiment, PRL 131 031802 (2023)
  - On 2022 data, 36.8 fb^{-1}
  - Observed 8 ν_μ interaction candidates
- **Ongoing:** Update on 2022+2023 dataset
  - Larger statistic: 68.5 fb^{-1}
  - Optimized fiducial volume cuts → acceptance 18% up from 7.5%

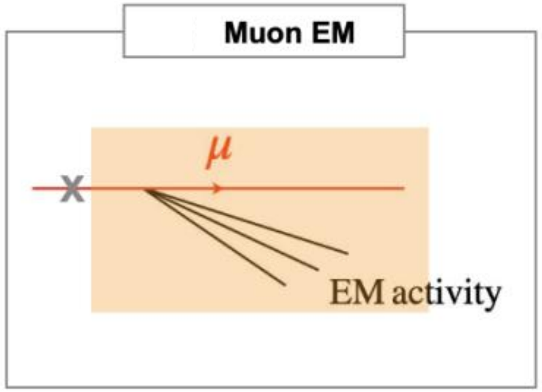
Number of candidates events: 32



Observation of ν_μ: background

Undetected muon background



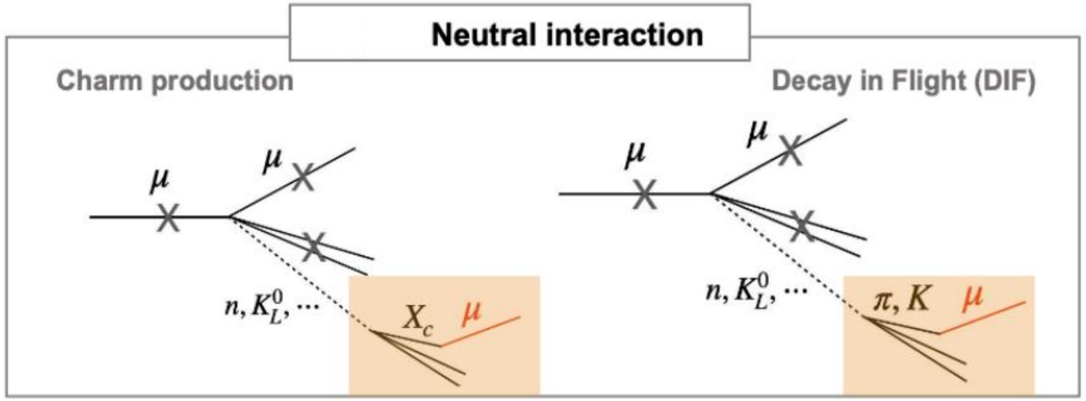


μ in target acceptance

$$N_\mu^{bkg} = \boxed{N_\mu} \times \boxed{(1-\epsilon_{Veto})}$$

Veto system inefficiency

Muon-induced **neutral particles**



$$N_{\text{neutrals}}^{\text{bkg}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}}$$

↓

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 1st SciFi station

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

No incoming **charged particles**

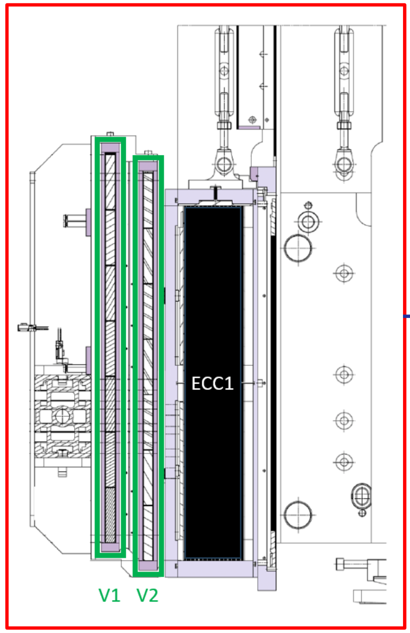
1st SciFi plane as **additional Veto** plane

Veto System Upgrade

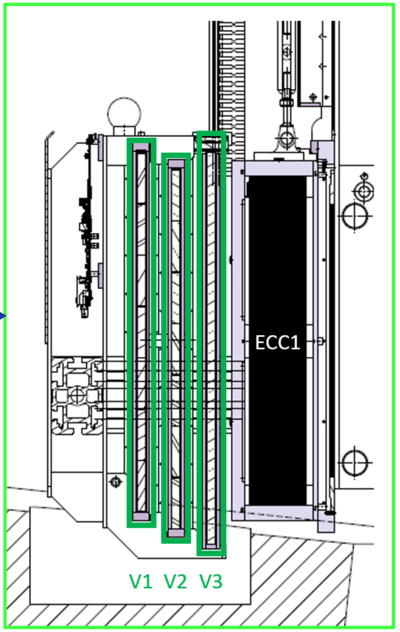
Inefficiency **optimal value** in the 2022-23 period was $(7.8 \pm 2.8) \times 10^{-8}$ achieved on a fiducial area of 35×35 cm^2 → target coverage of ~ 64%.

In YETS 2023-24 a 3rd **veto plane** was added

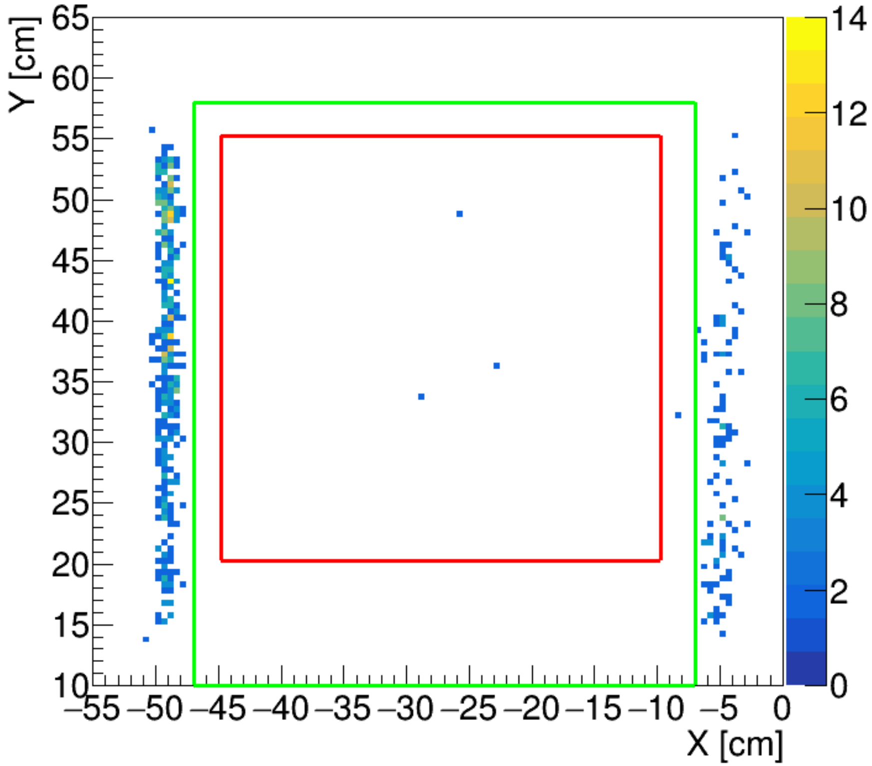
The 3rd plane has **vertical** bars to reduce overlapping area → minimizes signal loss due to spatial and temporal coincidences



2022/23 veto system



Updated veto system



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

↓

increase of 56% of observable neutrinos

On JINST!

ν_μ analysis 2022+2023

Step 2: neutrino candidate selection

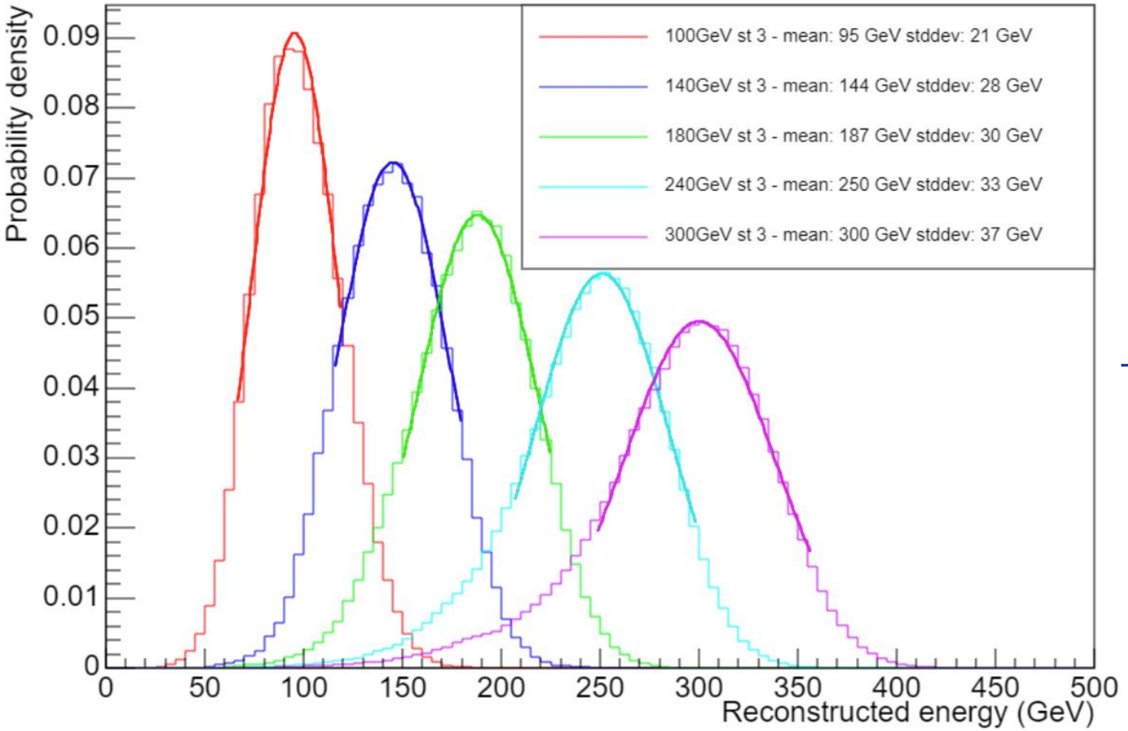
Cut	Description	
E	If there are DS hits, all US planes must be hit	→ Continuity of μ signal
F	Previous event more than 100 clock cycles away	→ Remove spurious events
G	Event has one reconstructed DS track	
H	Latest DS hit time > earliest SciFi hit time	→ Remove spurious events
I	DS track intersects first 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	→ Track compatibility
K	More than 35 SciFi hits	→ *Large* activity
L	US total QDC larger than 600 (700) for data (MC)	→ *Large* activity
M	Number of DS hits per projection < 10	

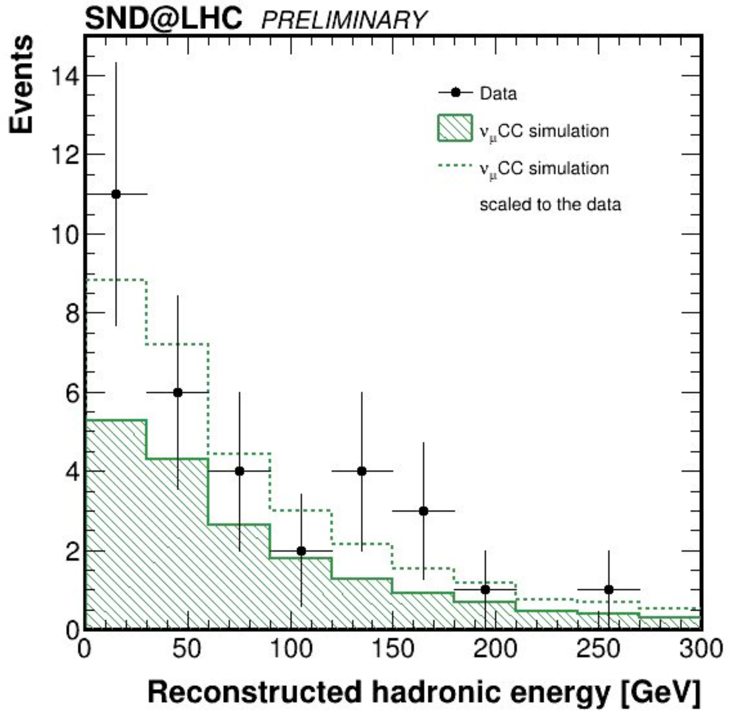
Track quality requirements

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%**





On JINST!

2024 ν_μ update

Work in progress!

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

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 muon background estimation → reverse veto requirements

2024 ν_μ update

Work in progress!

Step 1: preselection with relaxed constraint

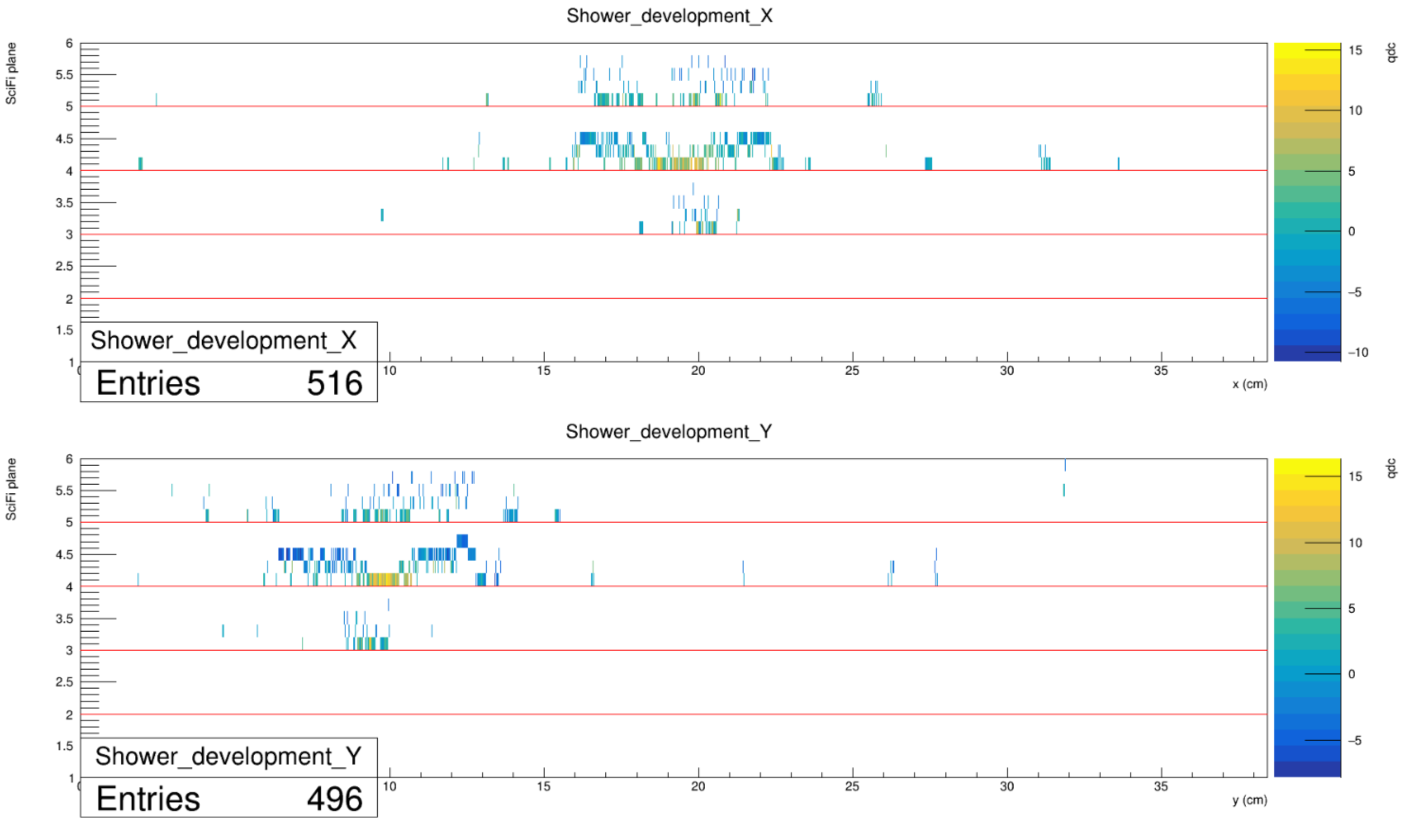
For ν_μ sample:

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

Shower tagging

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

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



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 update

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 **and** 1 y hit
3. A shower tagged

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

For μ sample:

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

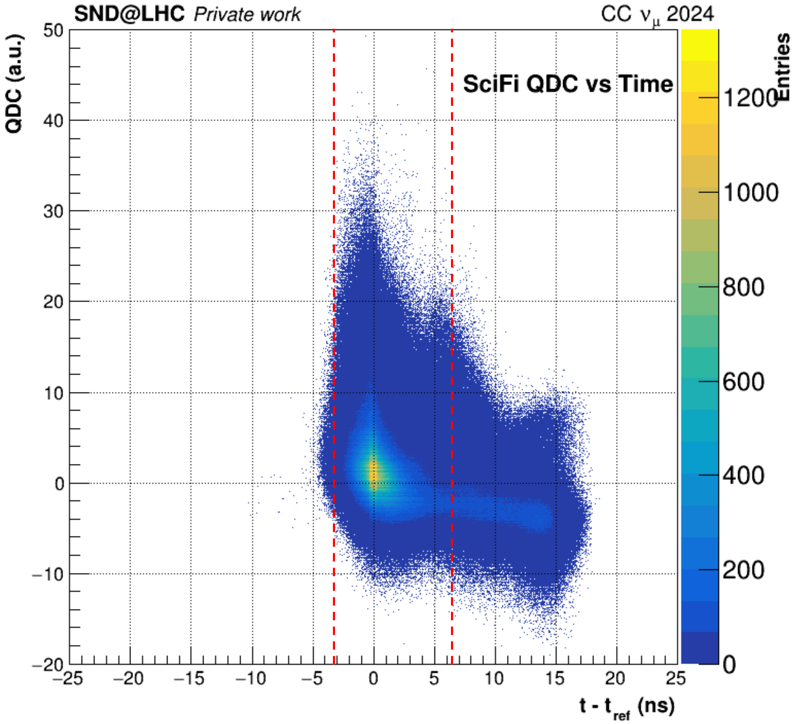
12% of a single run (~0.1 fb^{-1}) → 1.34×10^{6} events

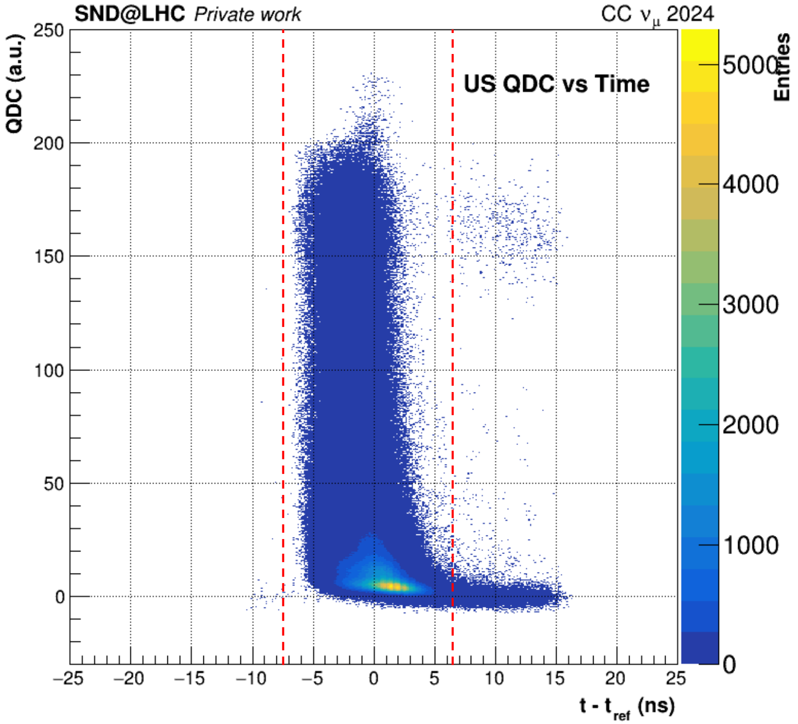
2024 ν_μ update: event selection

Work in progress!

Event selection criteria:

1. No hits in the veto system
2. Event synchronized with an interaction in IP1
3. Correct hit timing
   - $t_{ref} \equiv$ most probable value





2024 ν_μ update: event selection

Work in progress!

Event selection criteria:

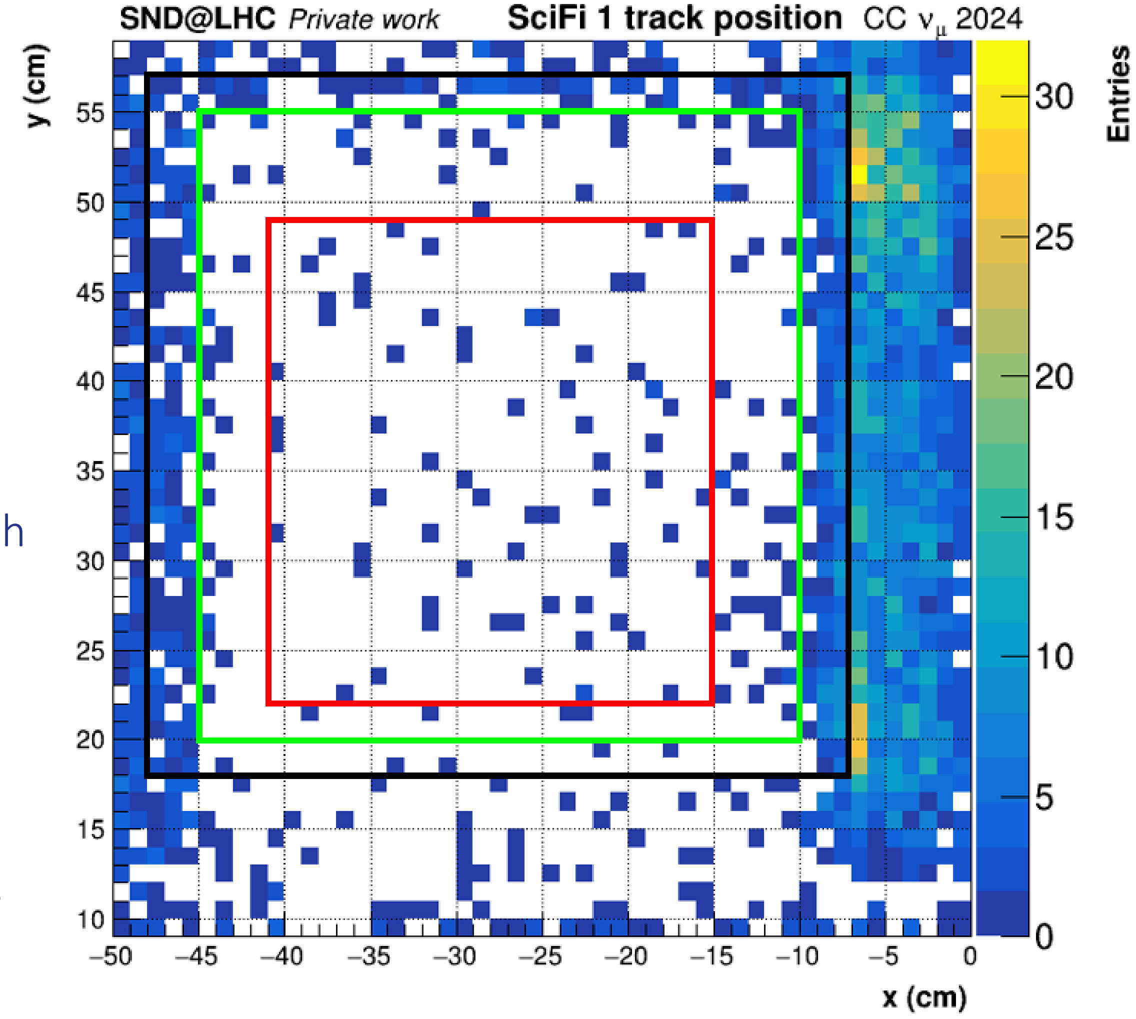
1. No hits in the veto system
2. Event synchronized with an interaction in IP1
3. Correct hit timing
4. Activity in all US planes → muon reaching DS planes
5. Shower tagged with the strict algorithm
   - Require two consecutive SciFi planes tagged → **suppress EM showers** exploiting longitudinal development difference
   - Reject events with $1 < \text{hits} < 7$ before the shower → passing muon show a peak at ~4 hits (2 per module)
   - 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 update: event selection

Work in progress!

Event selection criteria:

1. No hits in the veto system
2. Event synchronized with an interaction in IP1
3. Hit timing
4. Activity in all US planes → muon reaching DS planes
5. Shower tagged with the strict algorithm
6. Check for a reconstructed track (with $\chi^2 \leq 5$) 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



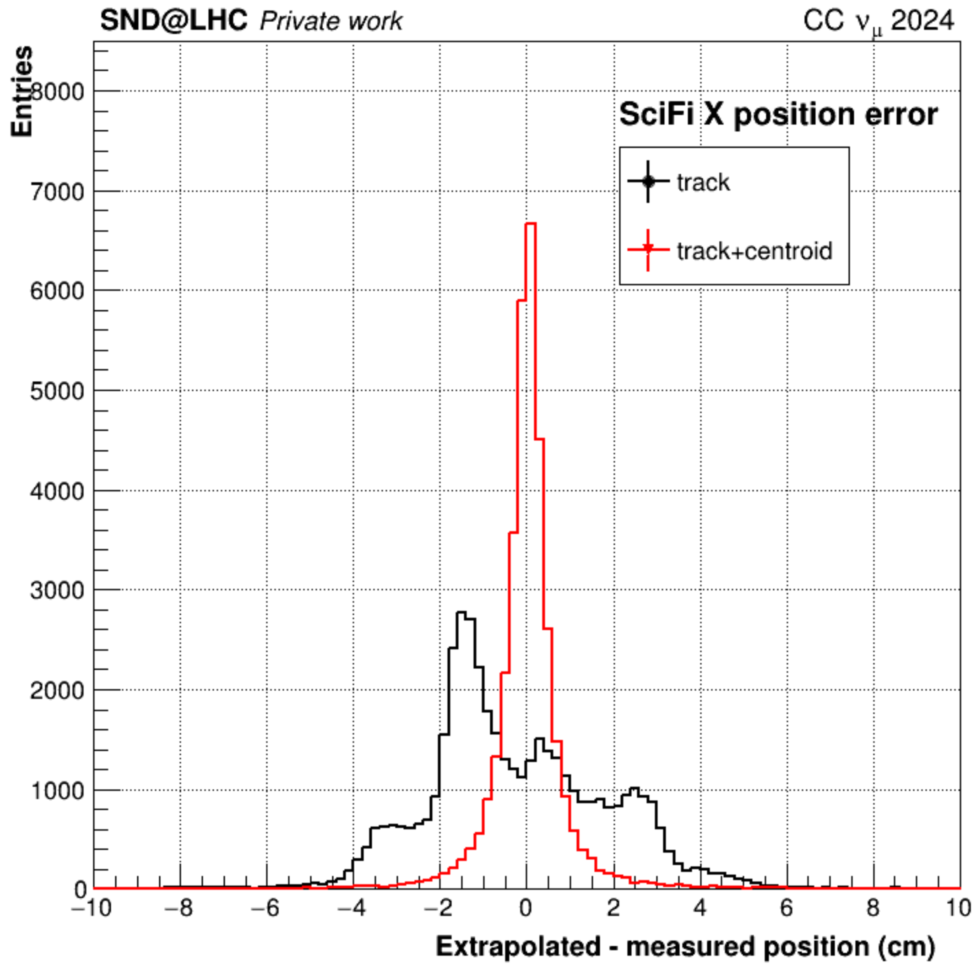
- SciFi module
- fiducial area 2024
- fiducial area 2022-23

2024 ν_μ update: event selection

Work in progress!

Event selection criteria:

1. No hits in the veto system
2. Event synchronized with an interaction in IP1
3. Hit timing
4. Activity in all US planes → muon reaching DS planes
5. Shower tagged with the strict algorithm
6. Check for a reconstructed track (with $\chi^2 \leq 5$) 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

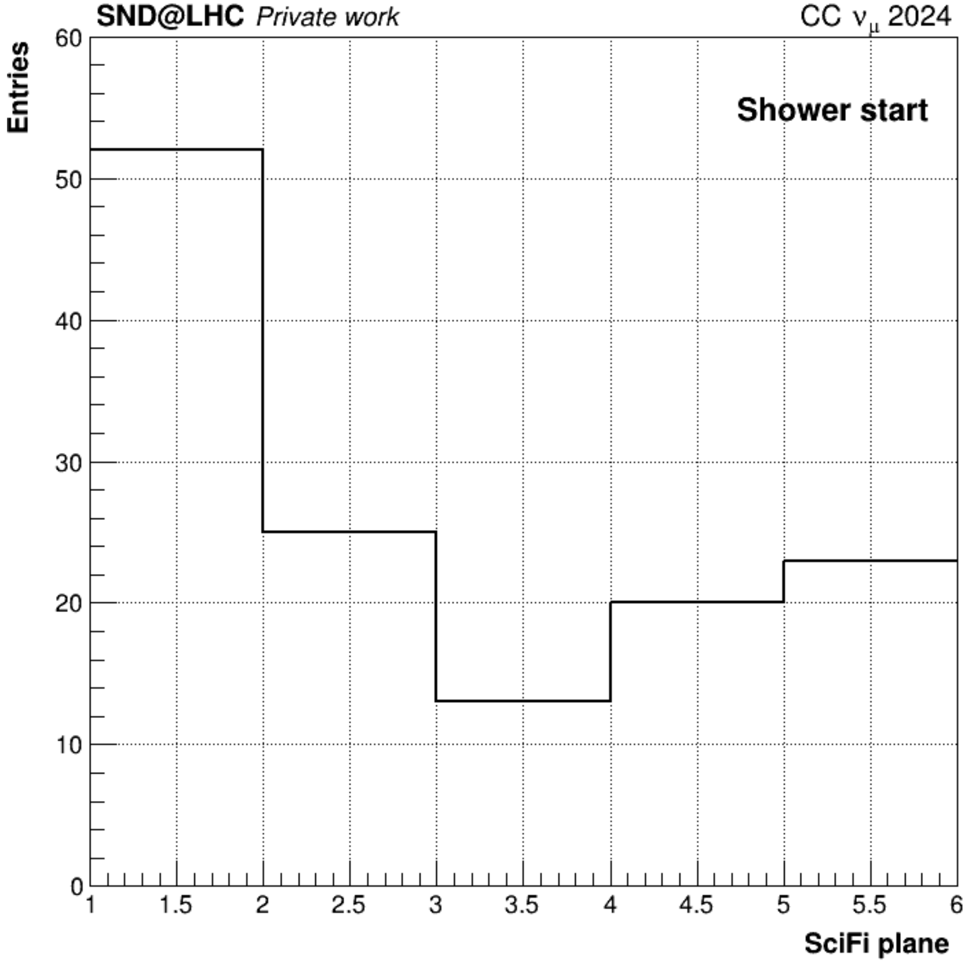


2024 ν_μ update: event selection

Work in progress!

Event selection criteria:

1. No hits in the veto system
2. Event synchronized with an interaction in IP1
3. Hit timing
4. Activity in all US planes → muon reaching DS planes
5. Shower tagged with the strict algorithm
6. Check for a reconstructed track (with $\chi^2 \leq 5$) and check that the extrapolated (x,y) position compatible with shower position



Summary and outlook

Analysis progressed substantially, but far from complete:

- Focus remains on optimising event selection, using:
  - 2024 preselected data sample
  - 2022/23 neutrino candidate samples
- Detailed studies of hit timing and event features greatly improved detector understanding

Next steps:

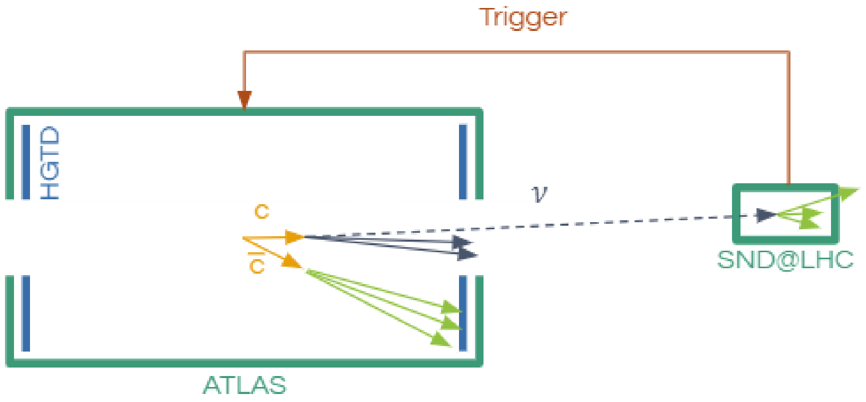
- Include shower direction reconstruction to estimate incoming particle energy
- Validation on MC was not achievable within thesis timeframe but will enable:
  - Validation of selection flow
  - Estimation of expected interaction rates and uncertainties
  - Assessment of backgrounds, including muons and neutral hadrons

THANKS FOR THE ATTENTION

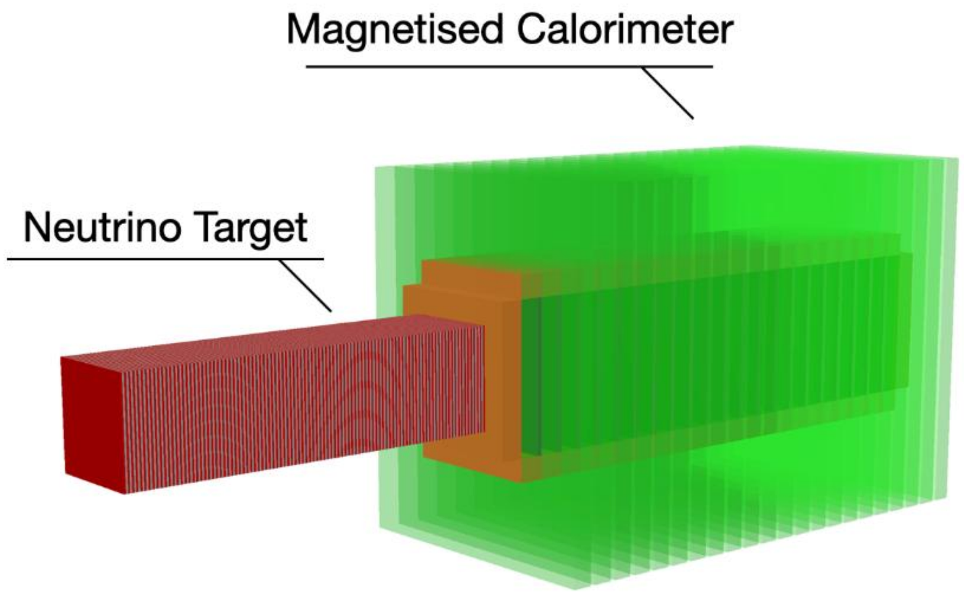
HL-LHC prospect

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**



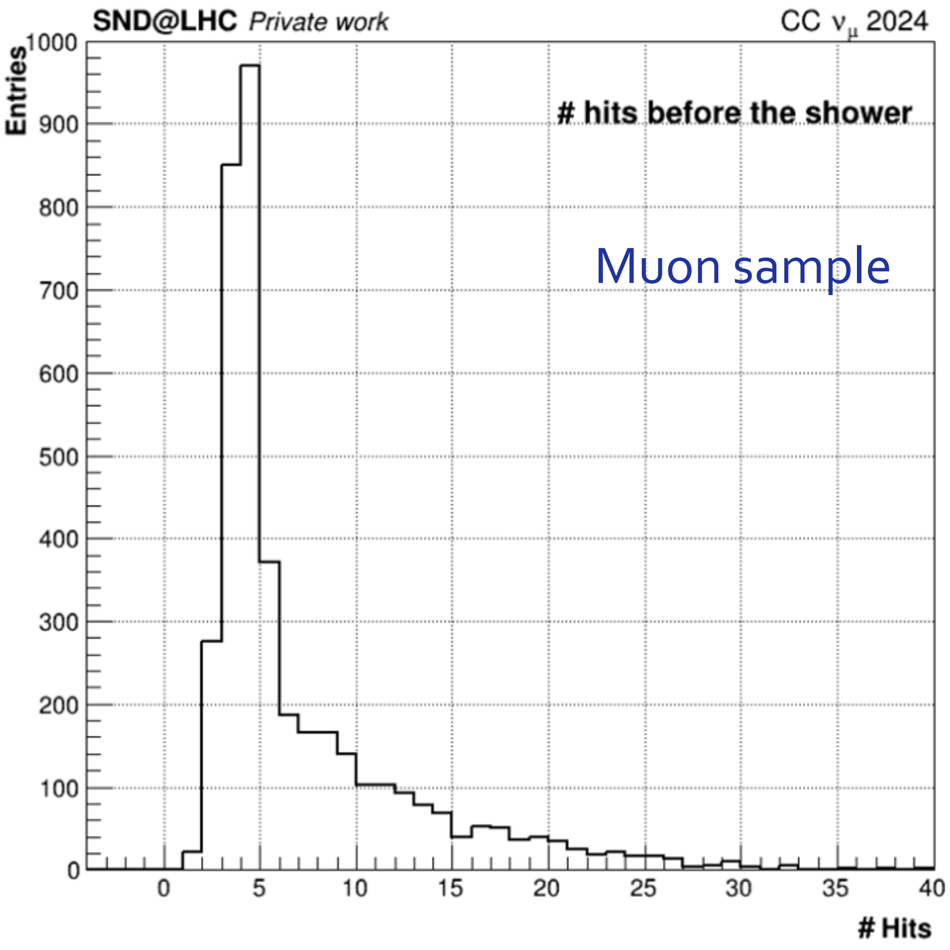
Measurement	Run 3 Uncertainty Stat.	Run 3 Uncertainty Sys.	HL-LHC Uncertainty Stat.	HL-LHC Uncertainty Sys.
Gluon PDF ($x < 10^{-5}$)	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	< 5%
ν_μ and $\bar{\nu}_\mu$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

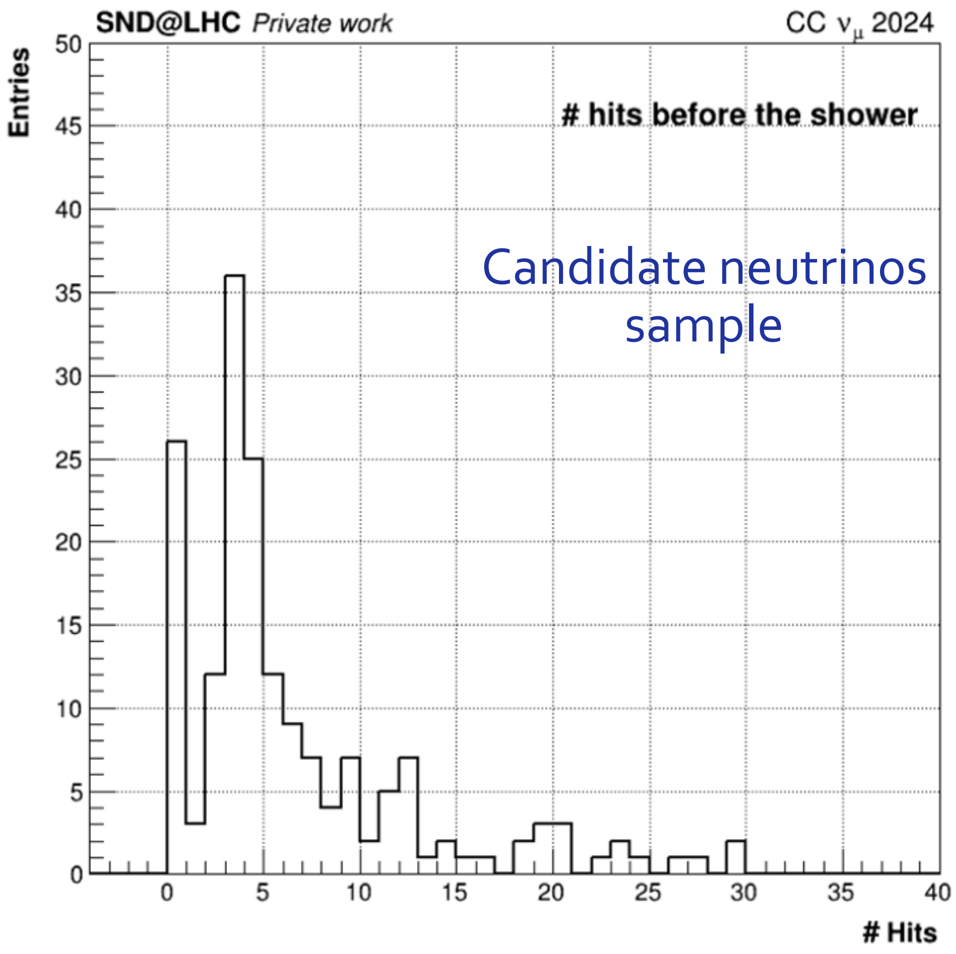


Preselection

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

Preselection

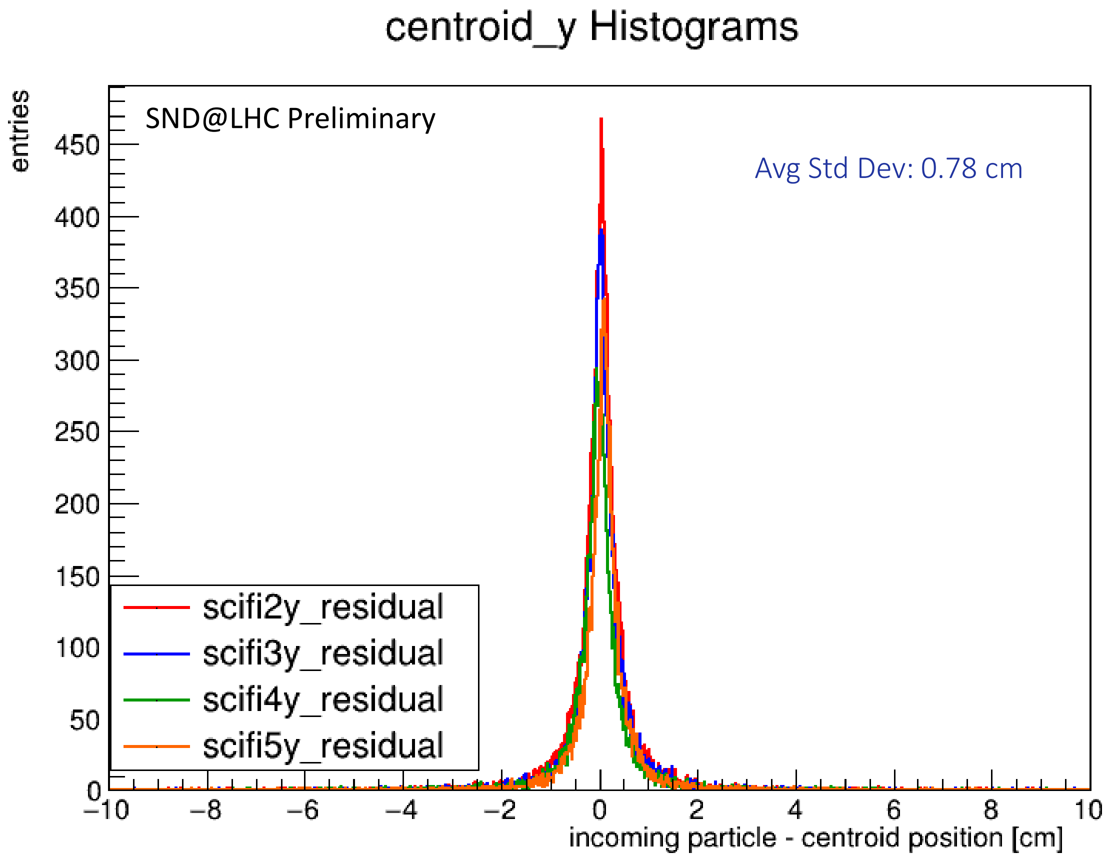


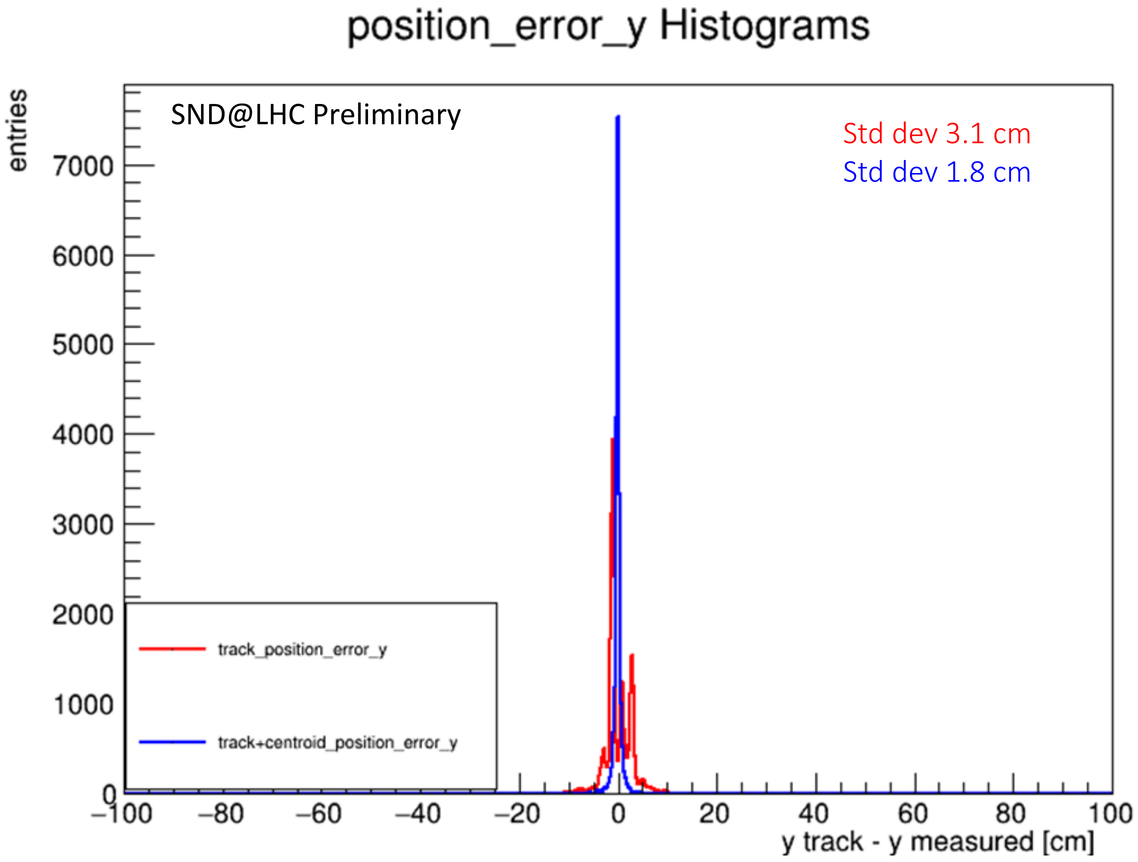


Validation of shower centroid

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

Aim: Validate centroid distribution using muon producing DIS showers

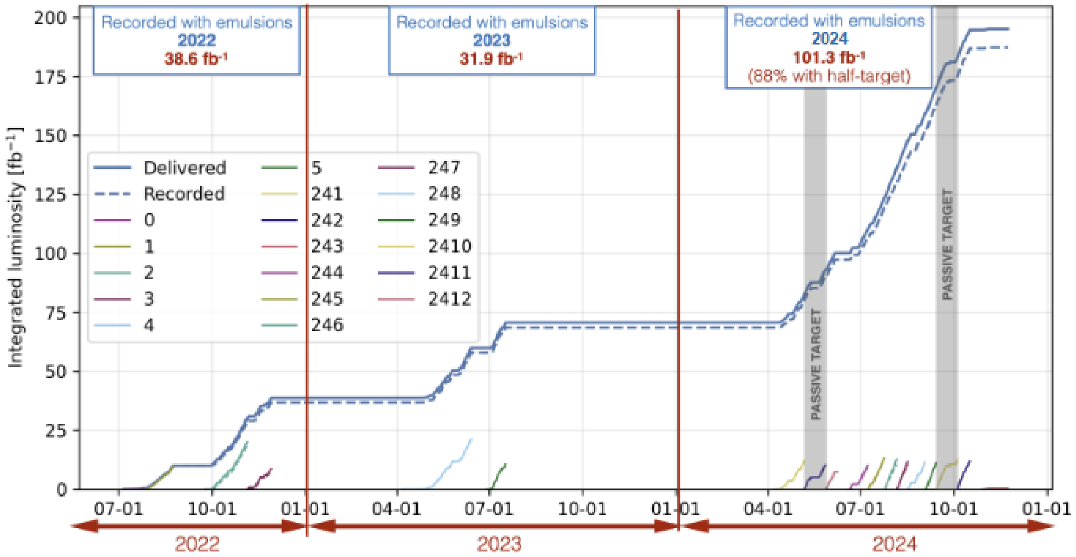




Backup

SND@LHC Data

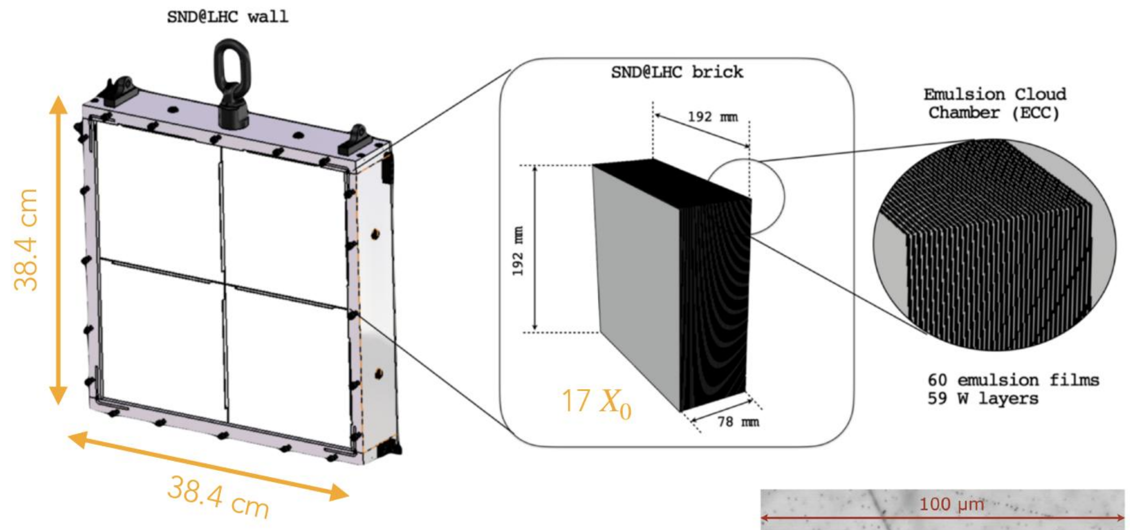
- Electronic detectors:
  - 2025 (so far): Recorded 10 fb^{-1}
  - 2022 – 2024: Recorded **187** fb^{-1}
    - **96%** uptime
- Emulsion detector:
  - **14** targets exposed in 2022 – 2024
  - **~170** fb^{-1} integrated
  - 5700 emulsion films (**210** m^2) exposed and developed
- Unexpected increase in the muon flux in **2024.**
  - Doubled the target replacement rate.
  - Instrumented only the lower half of the target.
    - Keep 65% of neutrino interactions.
  - Situation improved in 2025, but rates are still 40% higher than in 2022 and 2023.

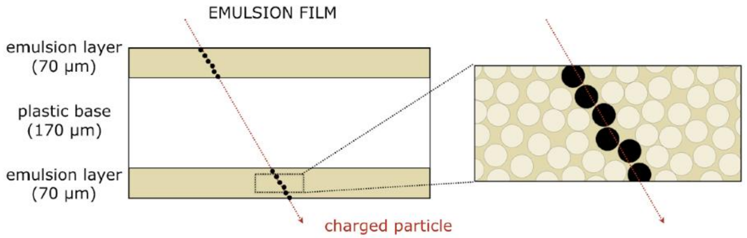


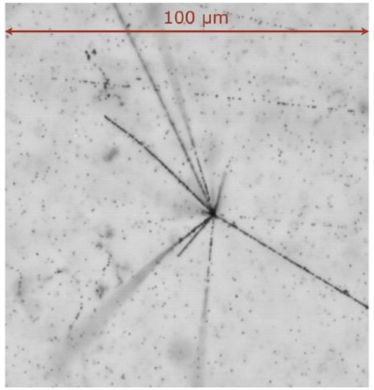
- Emulsion scanning is performed with fully automated microscopes in six laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Santiago
- Track density up to 4×10^5 tracks/cm^2

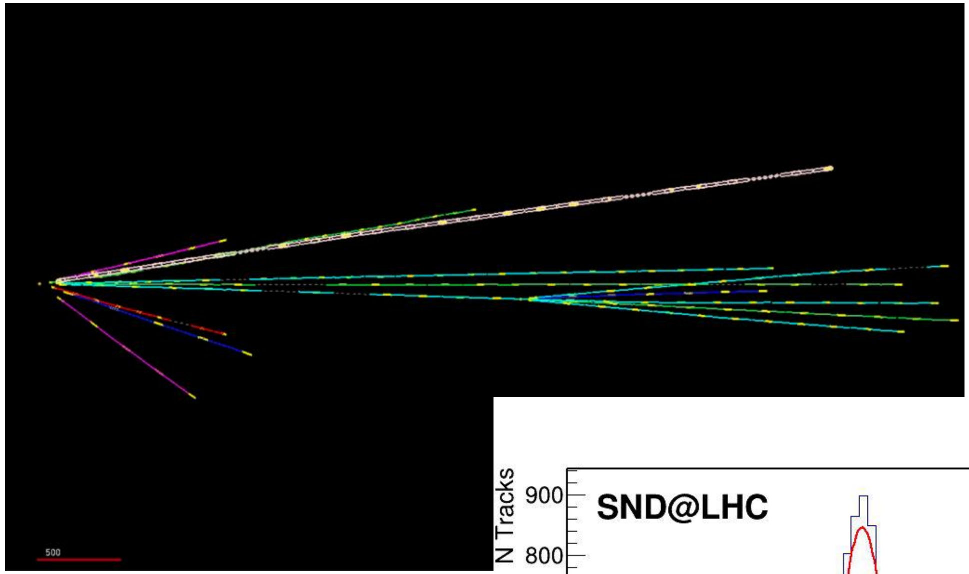
Status of emulsion scanning:
800 kg x 42 fb^{-1}

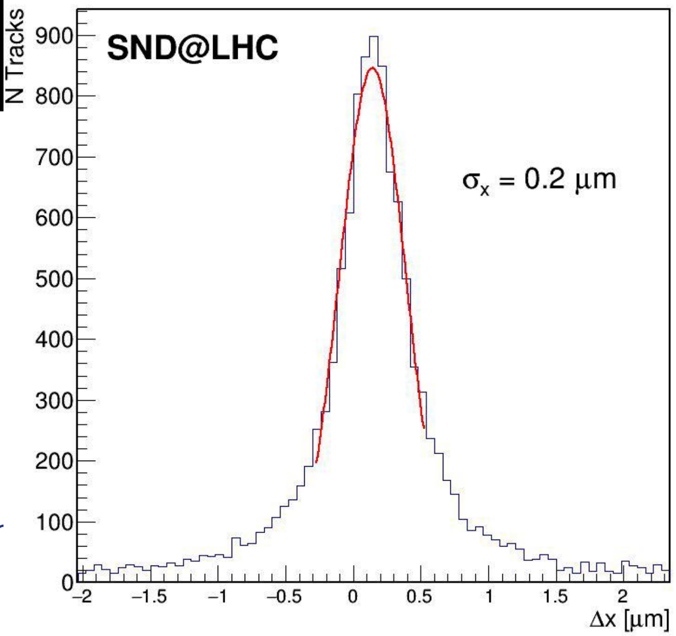
Backup







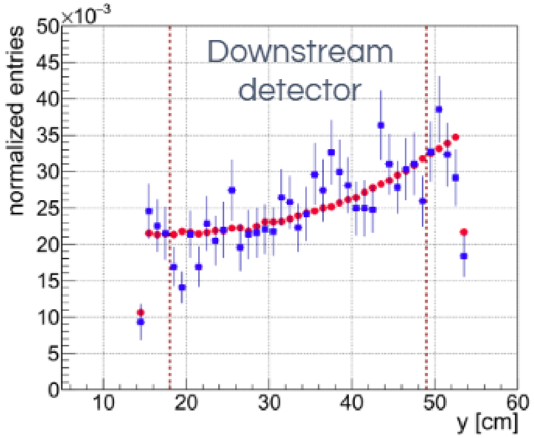




Position resolution 0.2 μm

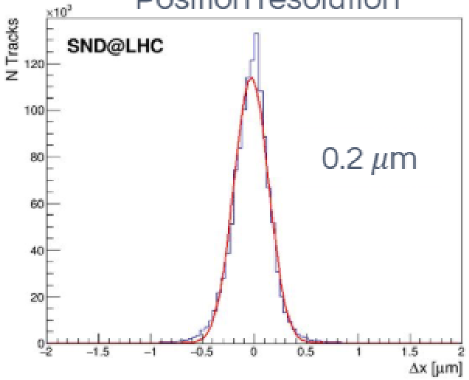
Passing muons

- 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.

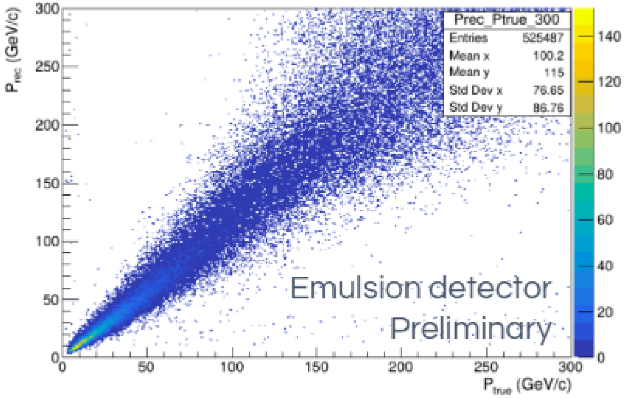


year	flux [trk/(cm^{-2}fb^{-1})]
2022	557
2024	1154
2025	**832**
MC	460

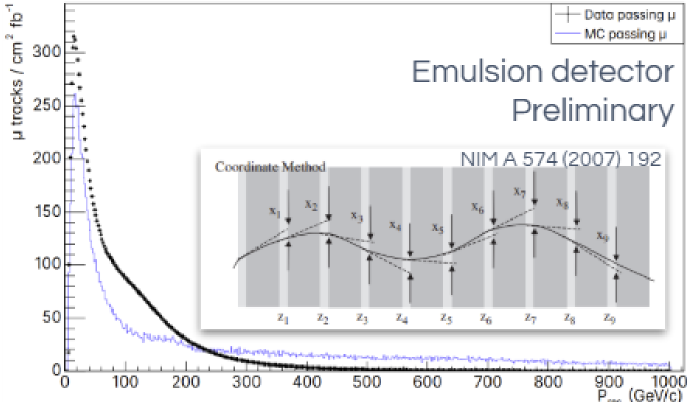
Position resolution



Reconstructed *vs* true muon momentum



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



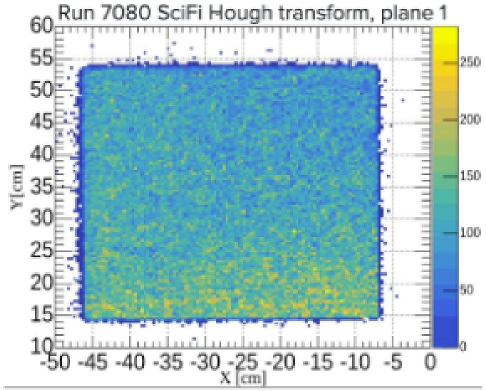
Passing muons in heavy ion runs

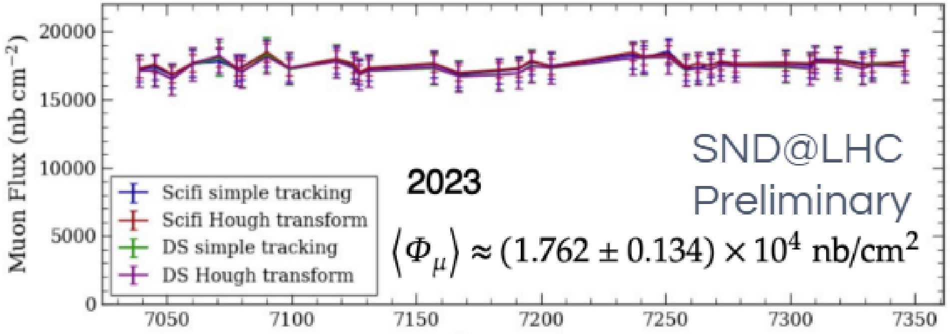
- Measurement of the muon flux in heavy ion collisions.
  - Different physics compared to pp.
    - Softer energy spectrum.
  - Different LHC optics compared to pp.

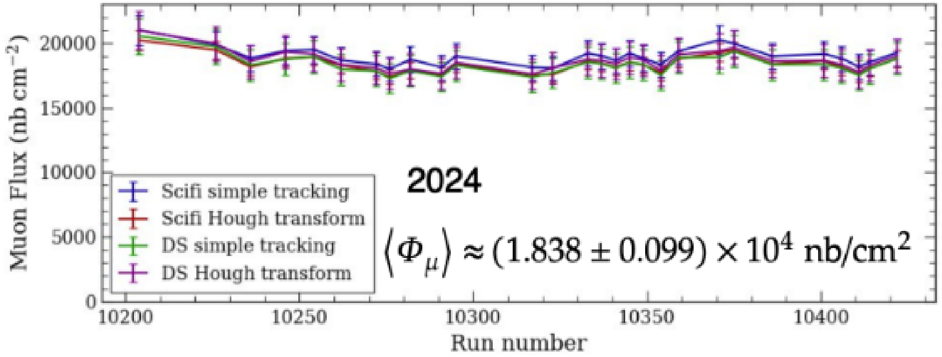
- Allows for further validation of the background model.
- Cross-check of detector performance.

- 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

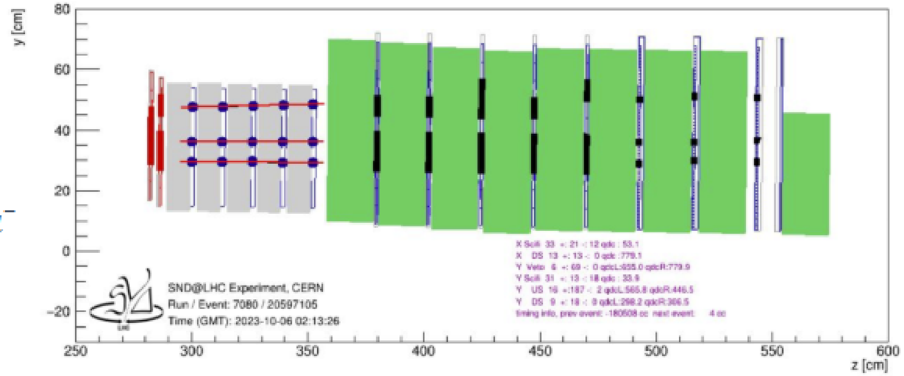






Muon trident cross-section measurement

- 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

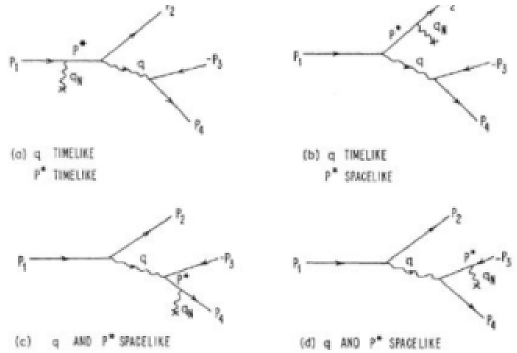
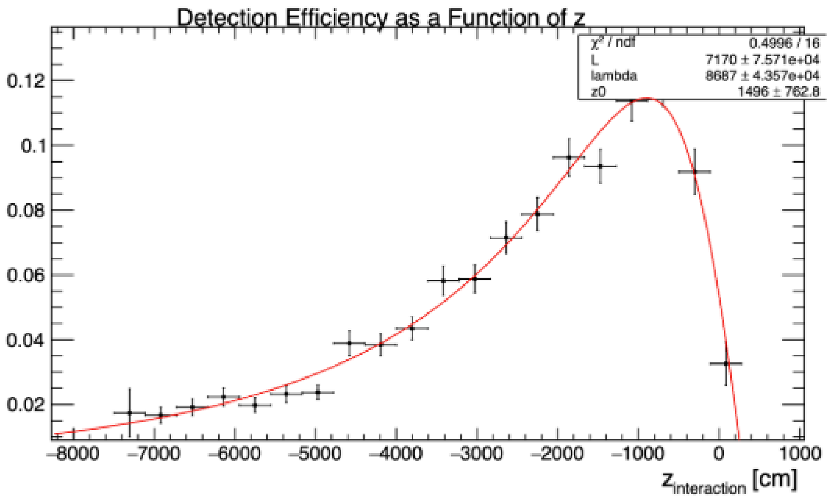


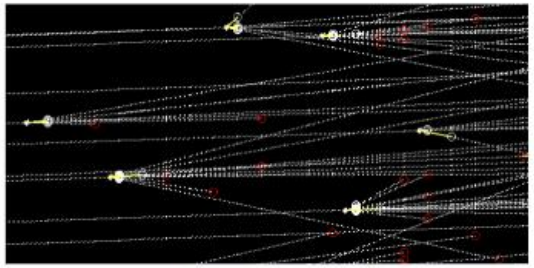
FIG. 1. The four Feynman diagrams for muon tridents (a) and (b) have timelike virtual photons while in (c) and (d) the virtual photon is spacelike. p^* is the four-momentum of the virtual muon; q is the four-momentum of the virtual photon and q_N is the nuclear recoil four-momentum.



Backup

Muon DIS in the emulsion

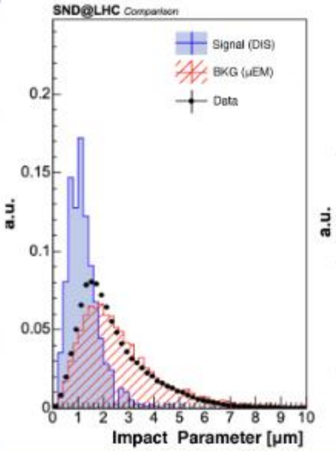
- Identification of **muon DIS** in the emulsion target with cut-based approach on topological and kinematical variables
- Data sample: vertices reconstructed in RUN1 brick 21: 32kg x 9.5fb^{-1}

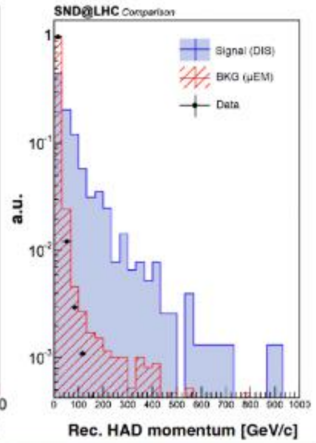


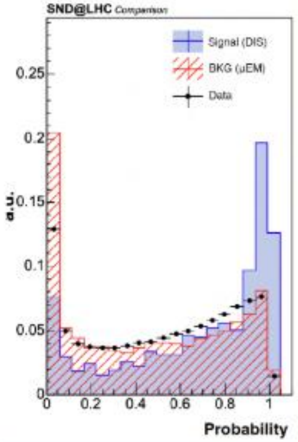
Simulated muon DIS in brick

Event selection criteria

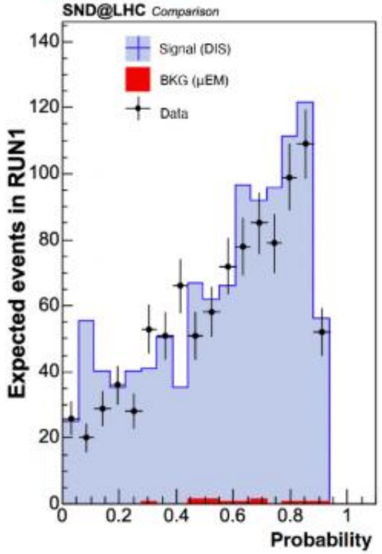
- charged vertex
- mean angular aperture > 13 mrad
- impact parameter<2.5μm
- fraction of rec. segments>0.87
- rec. hadron momentum > 16 GeV

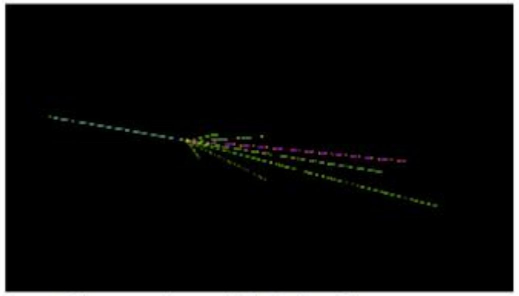






Signal region





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

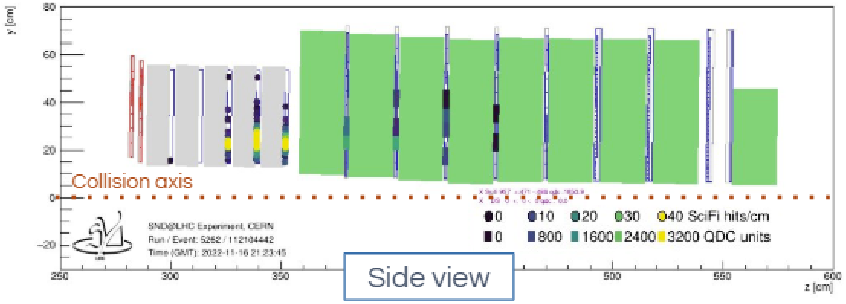
0μ observation significance

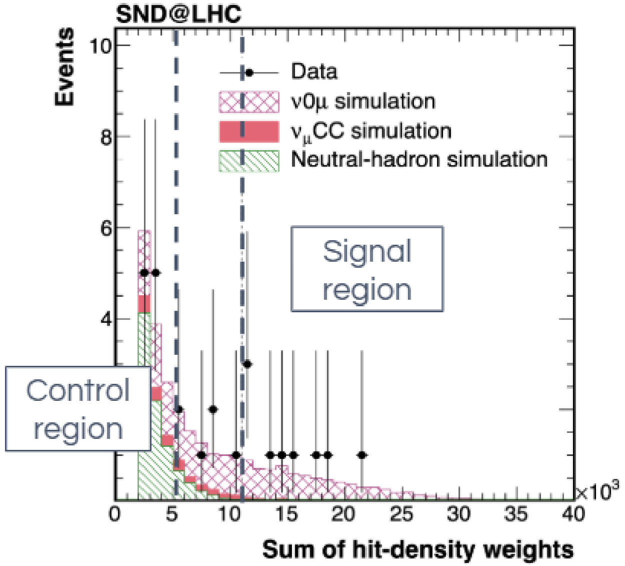
- **Total expected background: 0.32 ± 0.06 events**
- **Expected signal: 7.2 events**
  - 4.9 ν_eCC, 2.2 NC, 0.1 ν_τCC
- **Expected significance: 5.5 σ**

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.

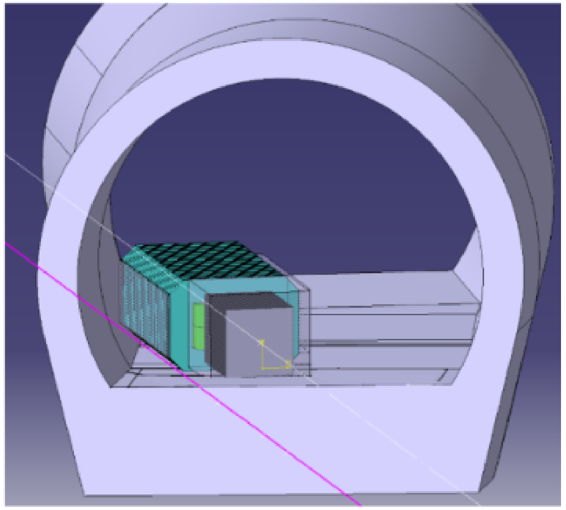


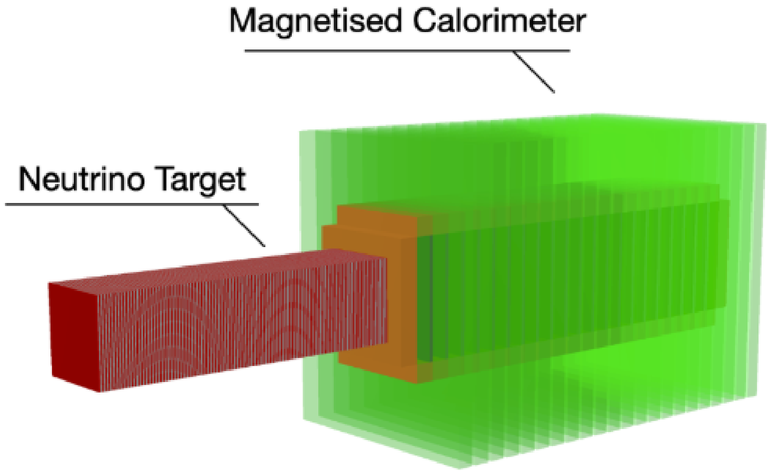


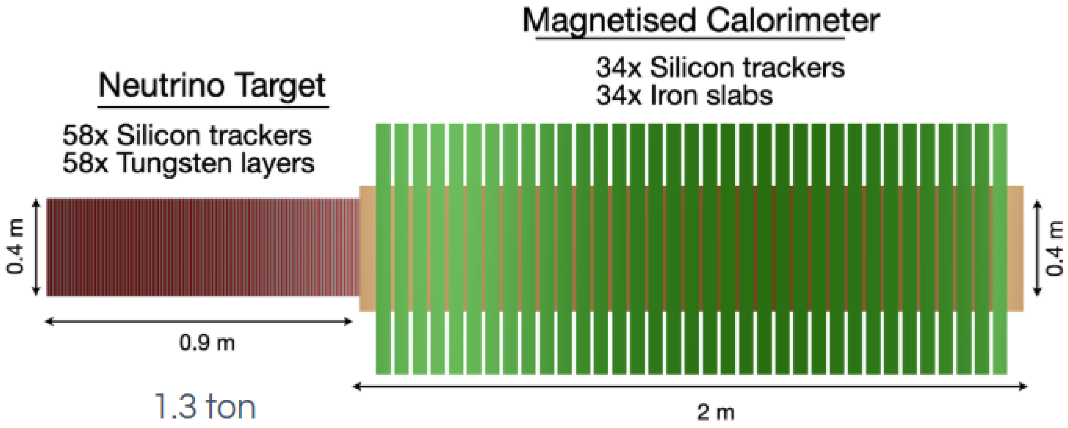
Backup

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.

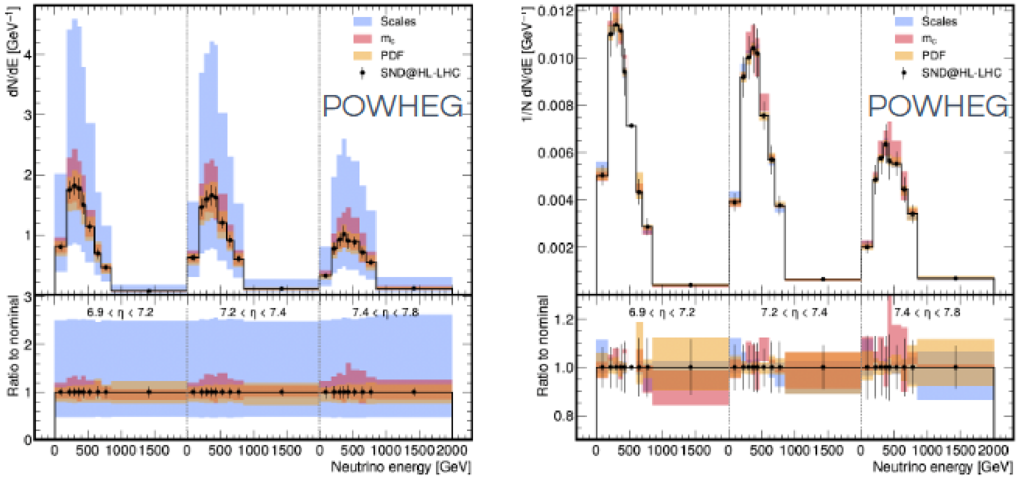






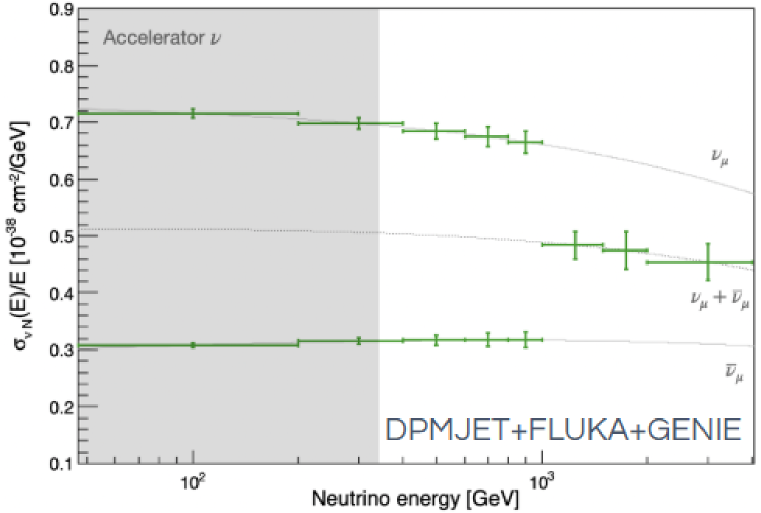
CERN-LHCC-2024-014

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

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 $\overline{\nu}_\mu$ cross-section	-	-	1%	5%



Extending ν cross-section measurements to a few TeV

[Technical Proposal for Run 4](https://cds.cern.ch/record/2926288)
https://cds.cern.ch/record/2926288

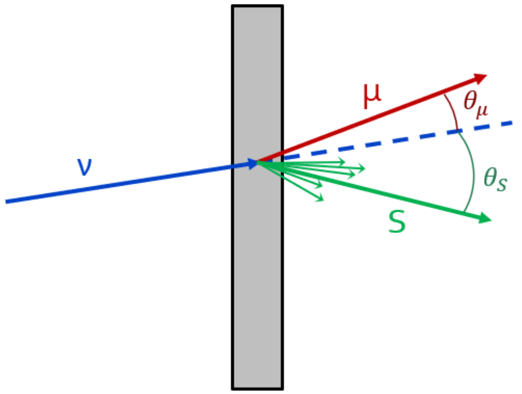
ESPPU Input

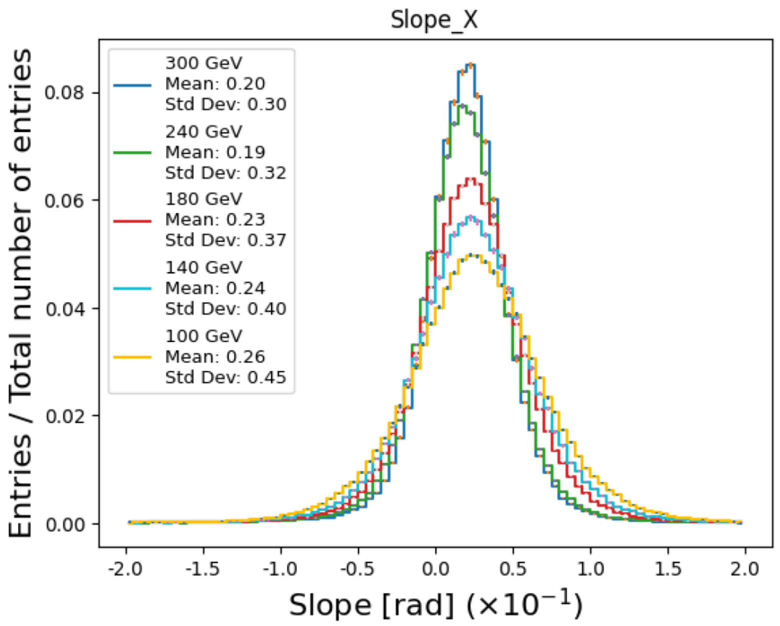
Backup: Shower direction reconstruction

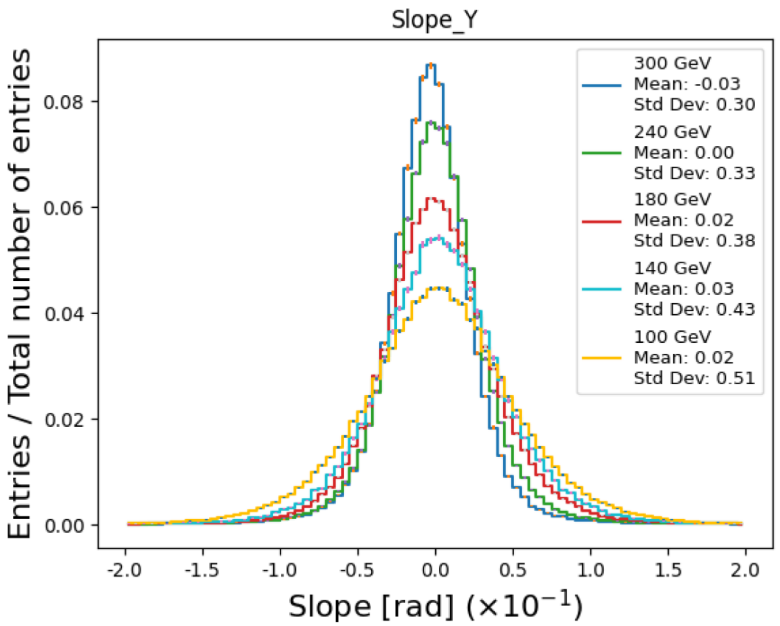
Aim: reconstruct shower direction → crucial for the ν_μ energy reconstruction as $E_\nu \sim E_S\left(1+\frac{\sin(\theta_S)}{\sin(\theta_\mu)}\right)$

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



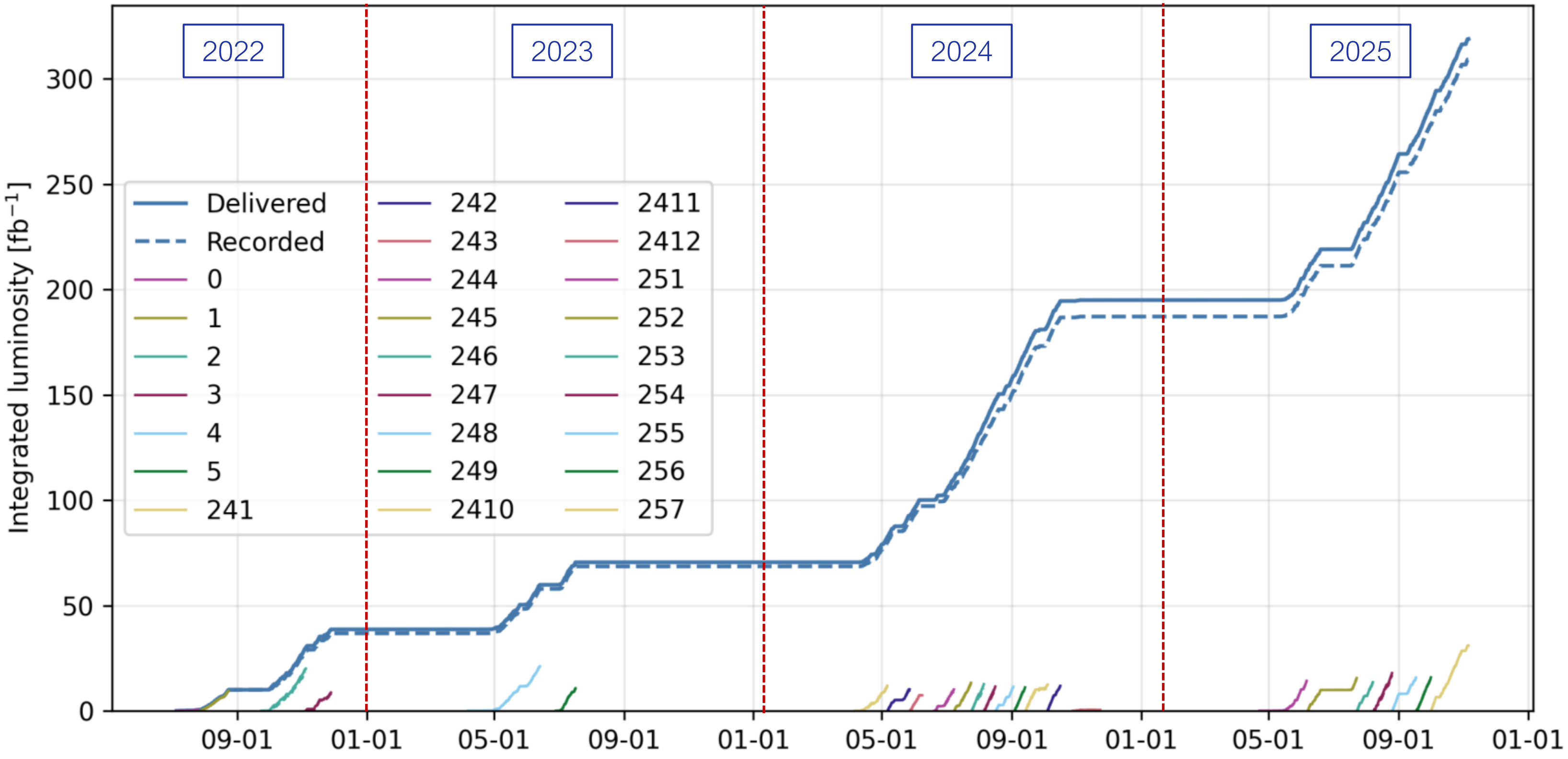




This was validated to be a good method but

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

SND@LHC Data



2022
2023
2024
2025
Integrated luminosity [fb^{-1}]
Delivered
Recorded
0
1
2
3
4
5
241
242
243
244
245
246
247
248
249
2410
2411
2412
251
252
253
254
255
256
257
0
50
100
150
200
250
300
09-01
01-01
05-01
09-01
01-01
05-01
09-01
01-01
05-01
09-01
01-01