

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



NEUTRINO INTERACTION STUDIES WITH SND@LHC DETECTOR

CSN1
24/11/2025

Giulia Paggi
Università e INFN Bologna
On behalf of the SND@LHC Collaboration

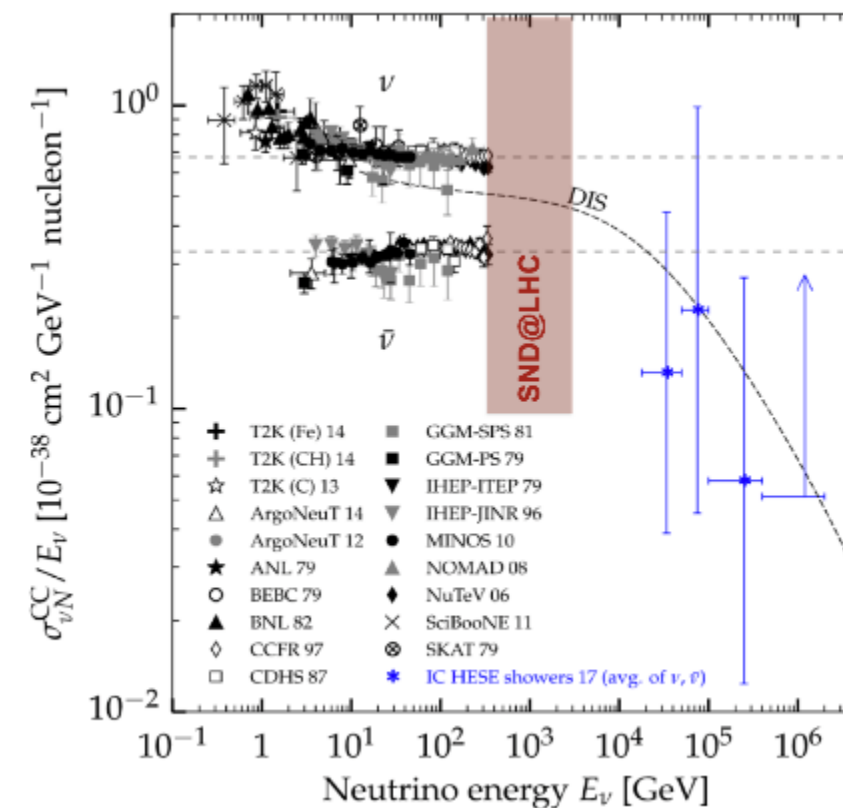
PRL 122 (2019) 041101

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

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

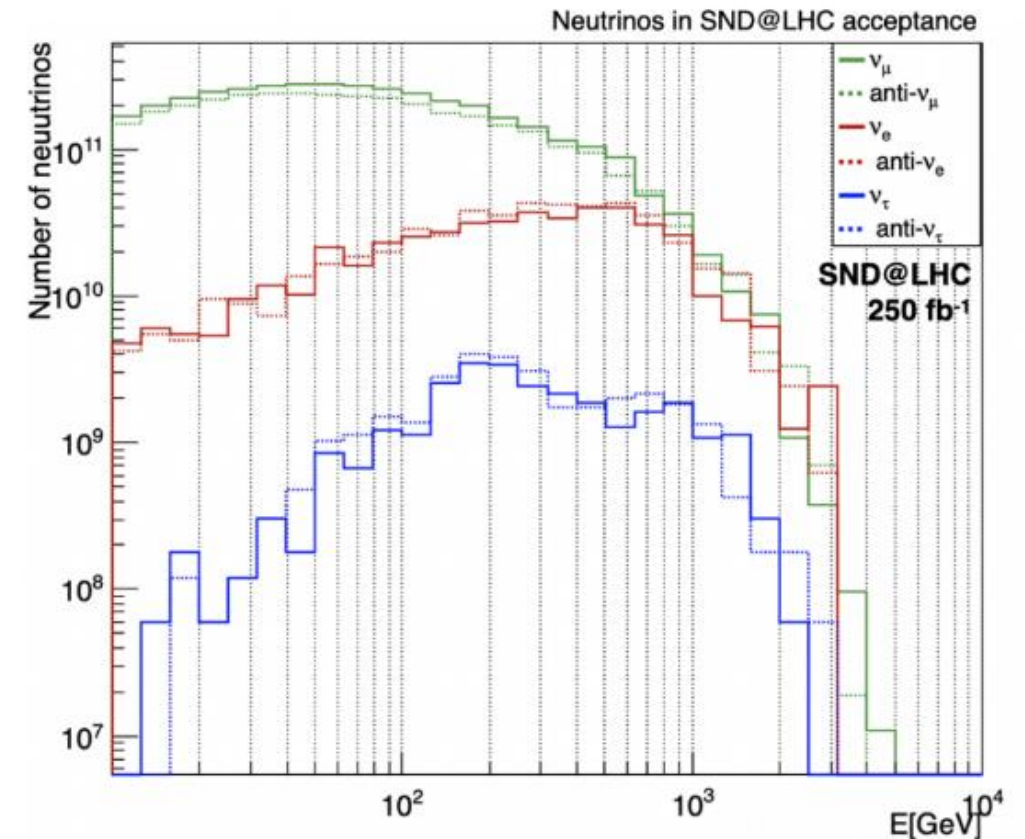
→ **High ν energies:** $E_\nu [10^2, 10^3] \text{ GeV}$

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



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

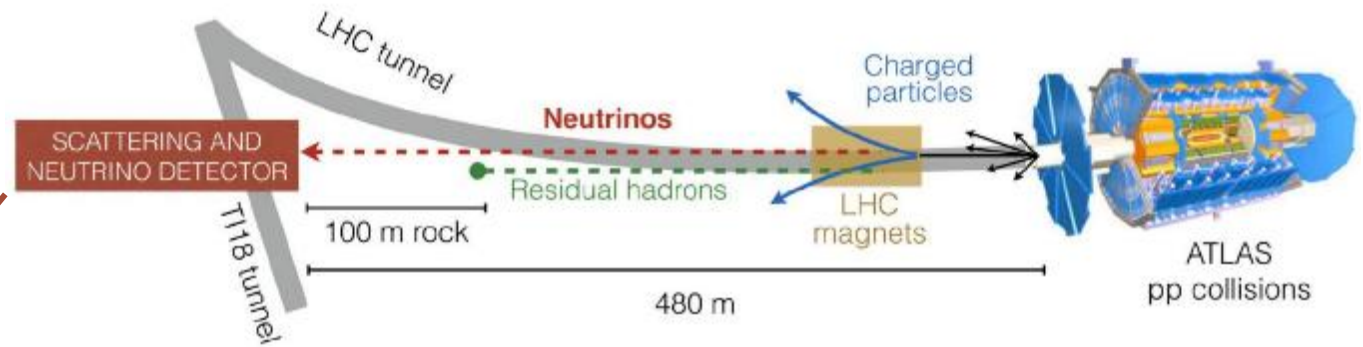
- Measure **charm production** at high η ($gg \rightarrow cc$)
 - Given the η region, the majority of ν s is from charmed hadrons decay
- High-energy neutrino cross section measurements
- ν_τ observations
- Test lepton **flavour universality** measuring ν_e/ν_μ and ν_e/ν_τ
- Direct search of **feebly-interacting particles** (FIPs)



THE DETECTOR

The detector: location

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

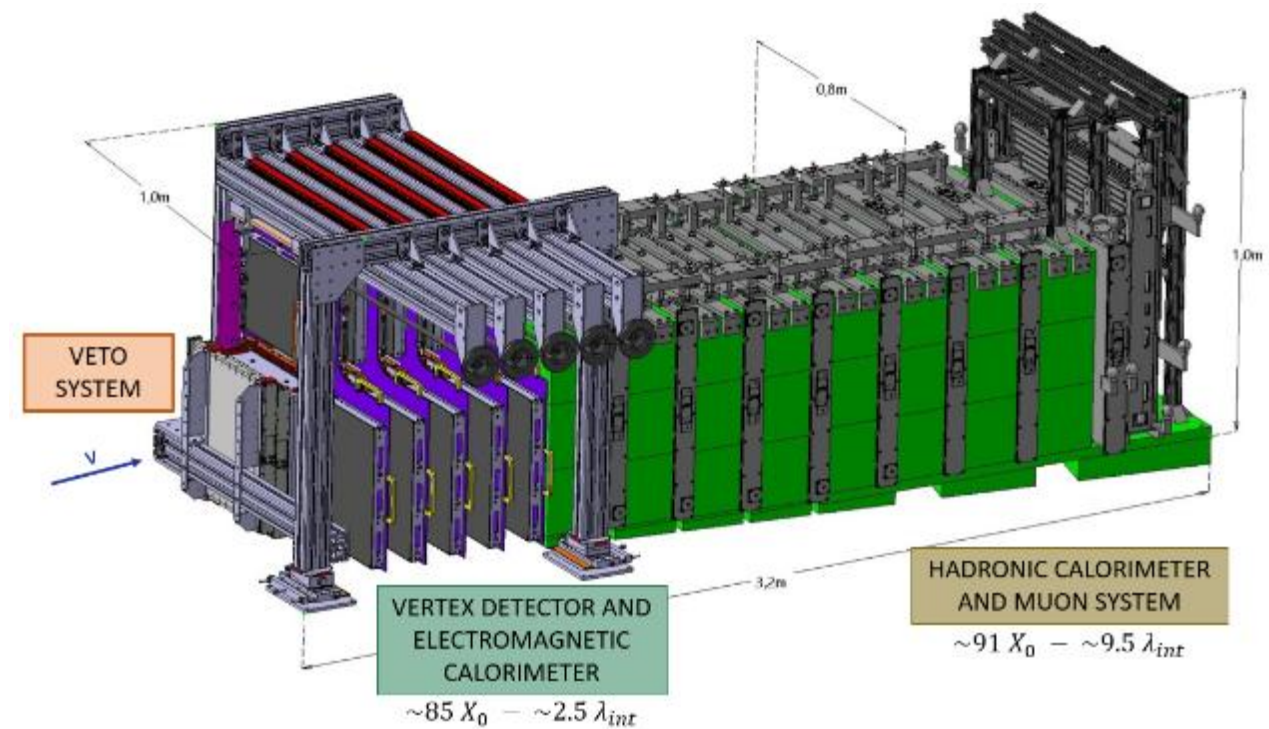


- Shielded by 100 m rock
- LHC magnet deflects charged particles

Neutrinos and FIPs reach the detector
Residual muon background

The detector

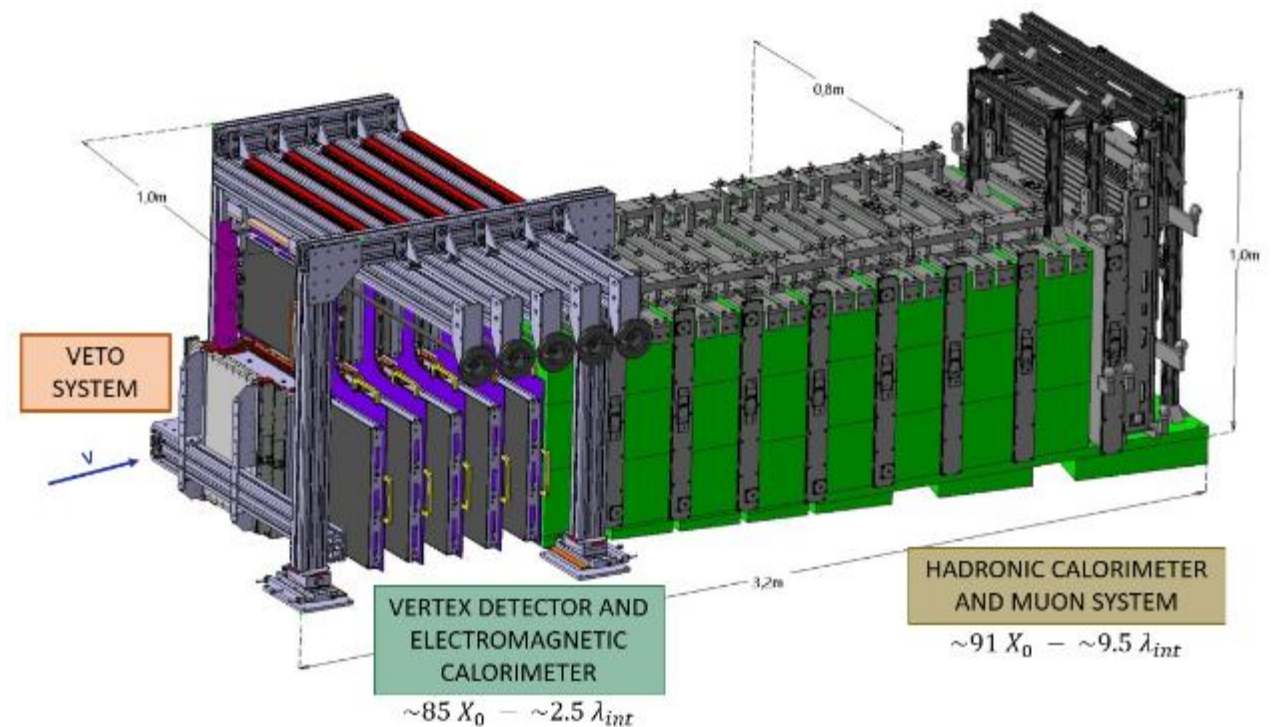
Hybrid detector composed of:



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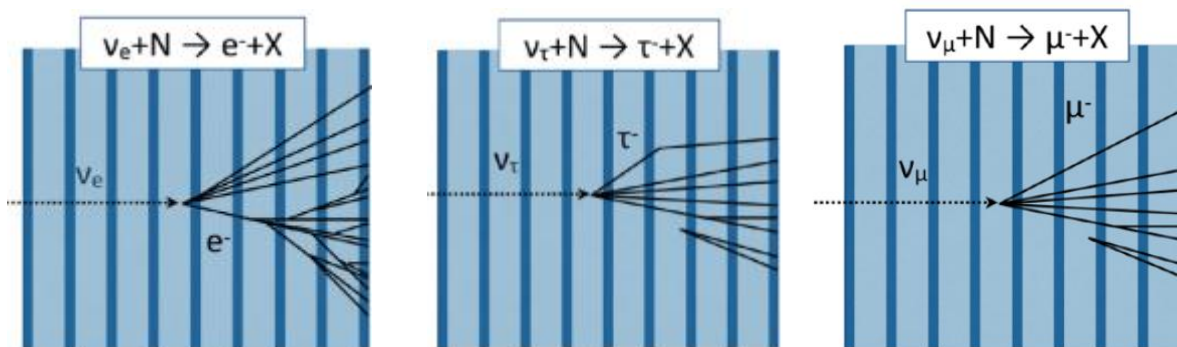
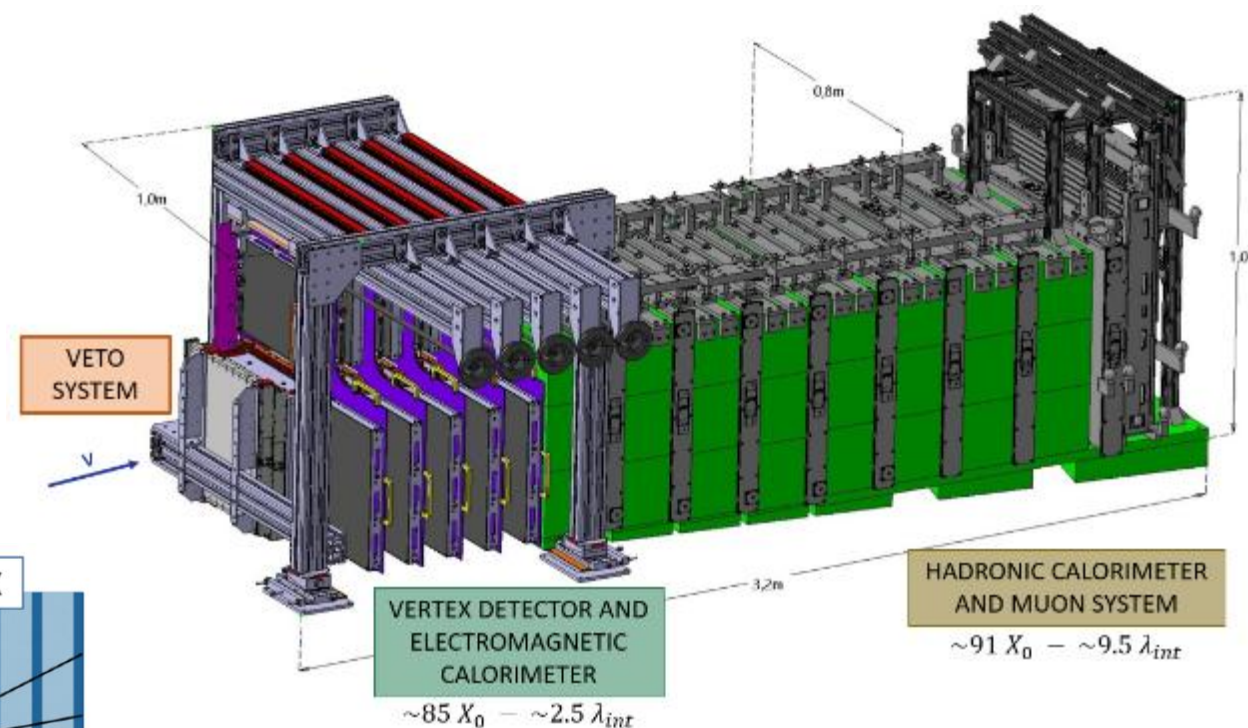
→ Veto system

→ 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



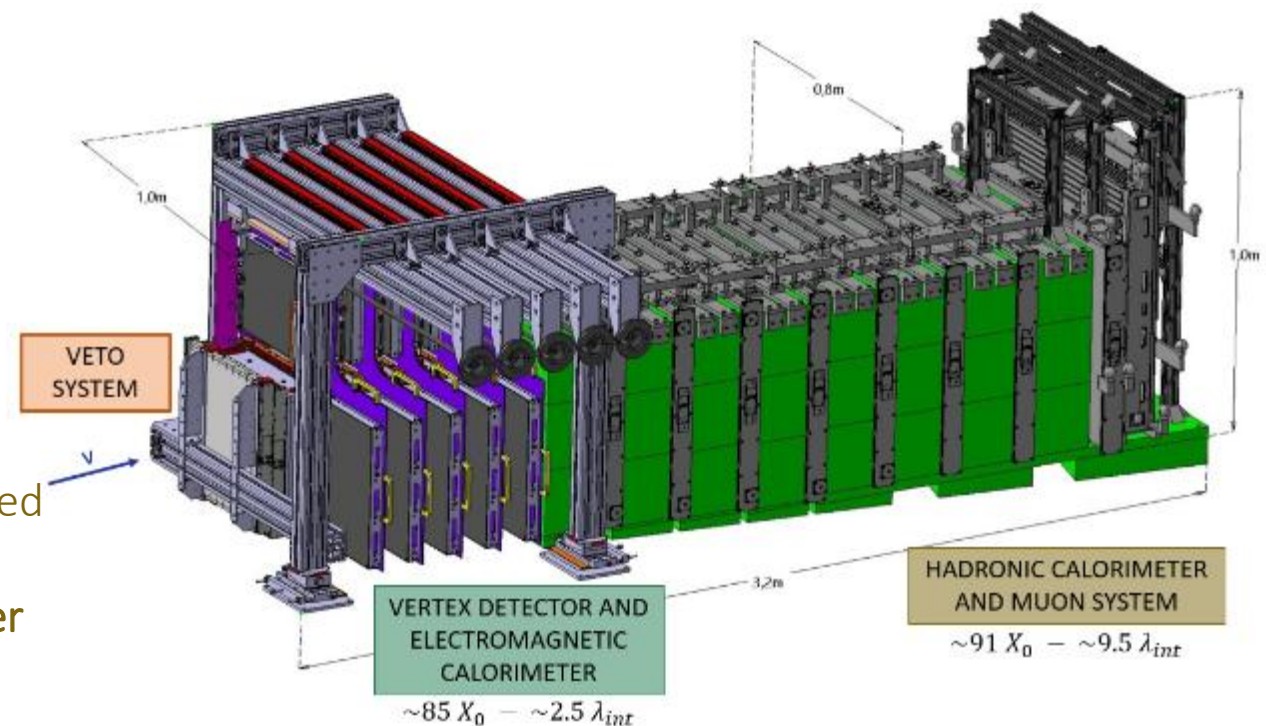
Hybrid detector composed of:

- 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



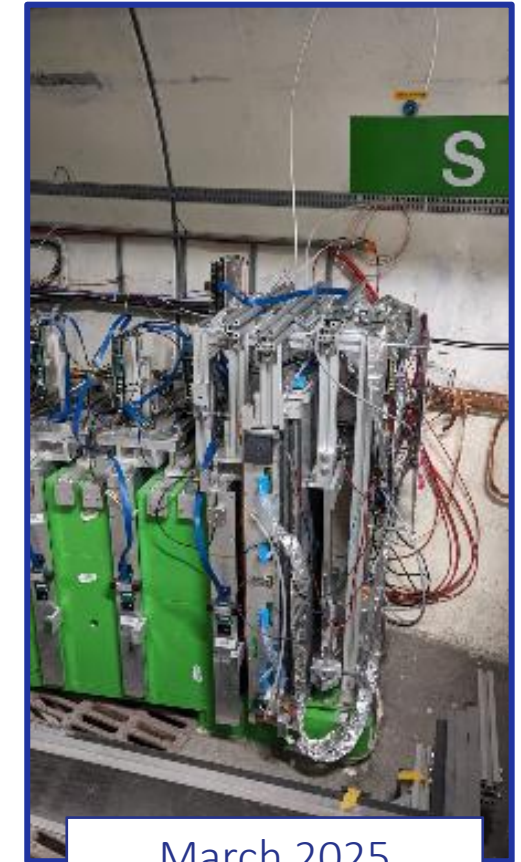
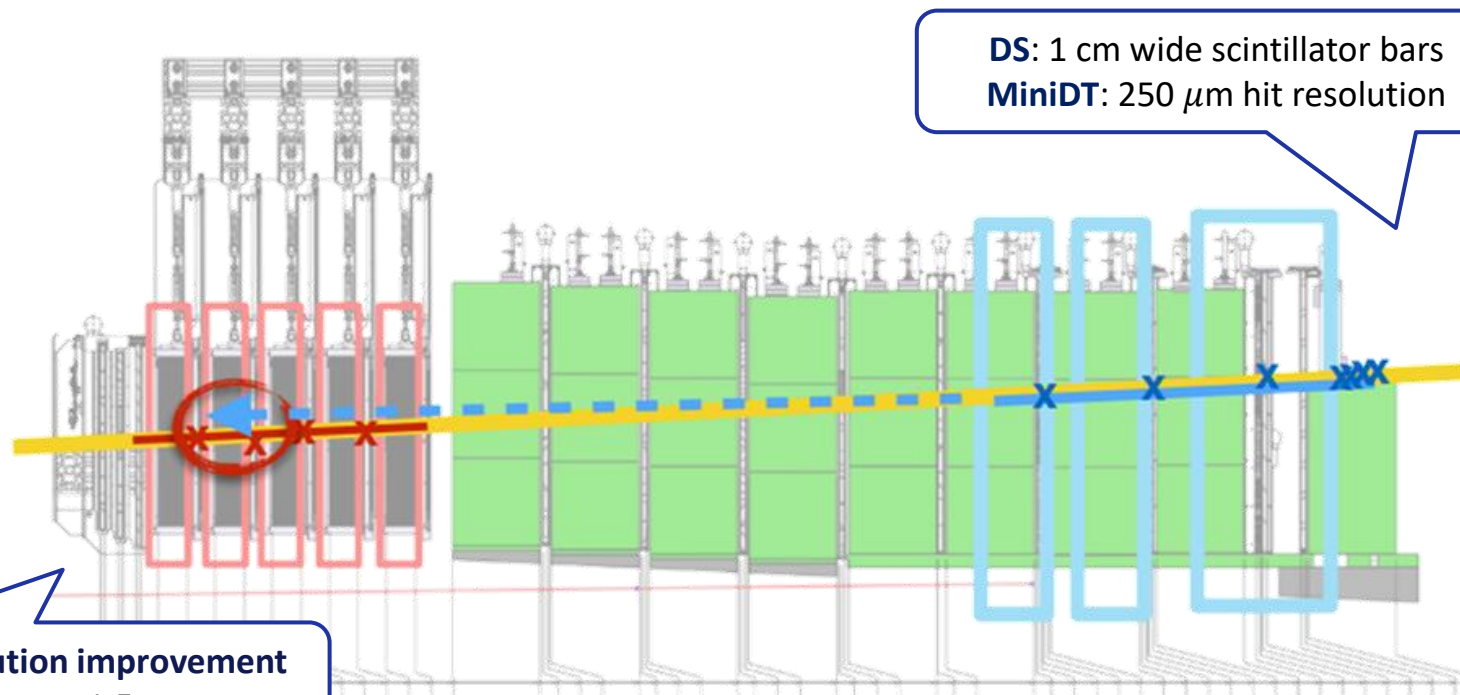
Hybrid detector composed of:

- 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



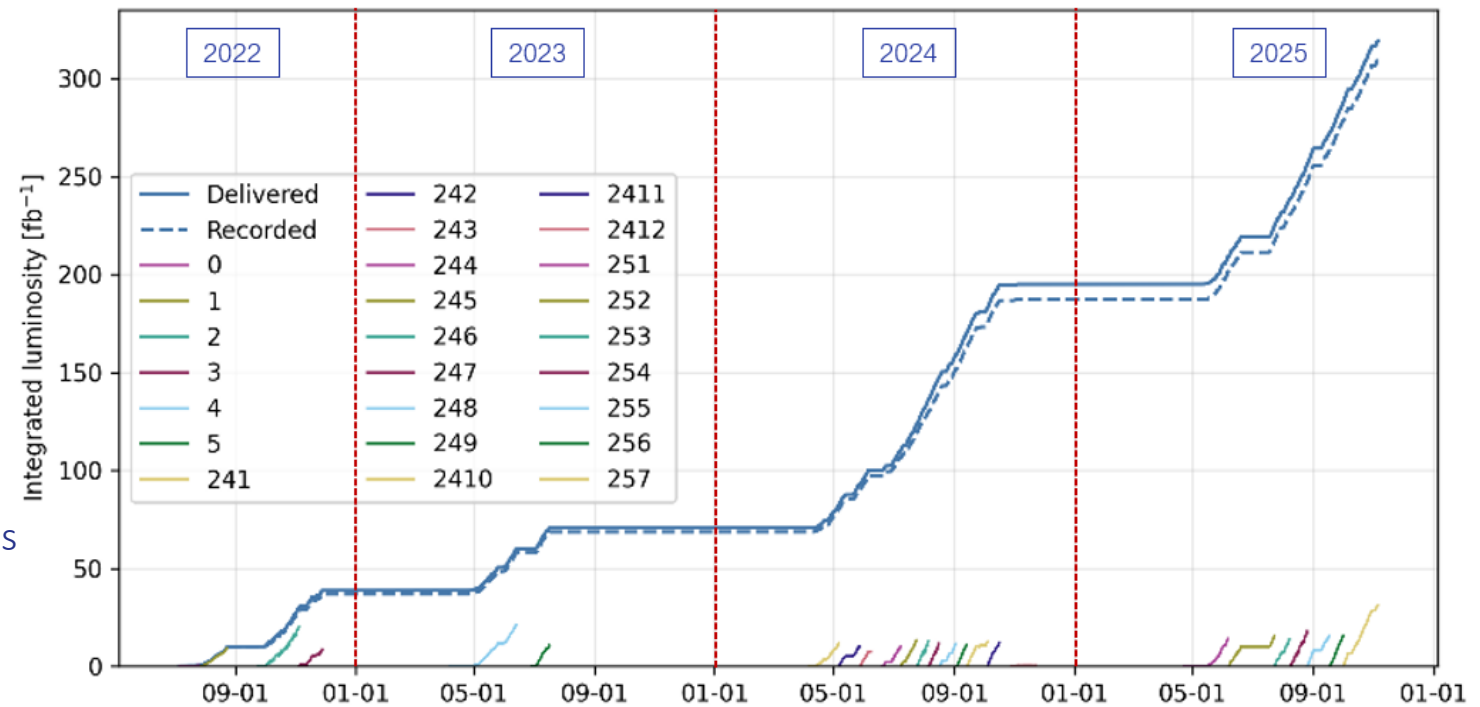
Muon tracking :

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



March 2025

- 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:
 - 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



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

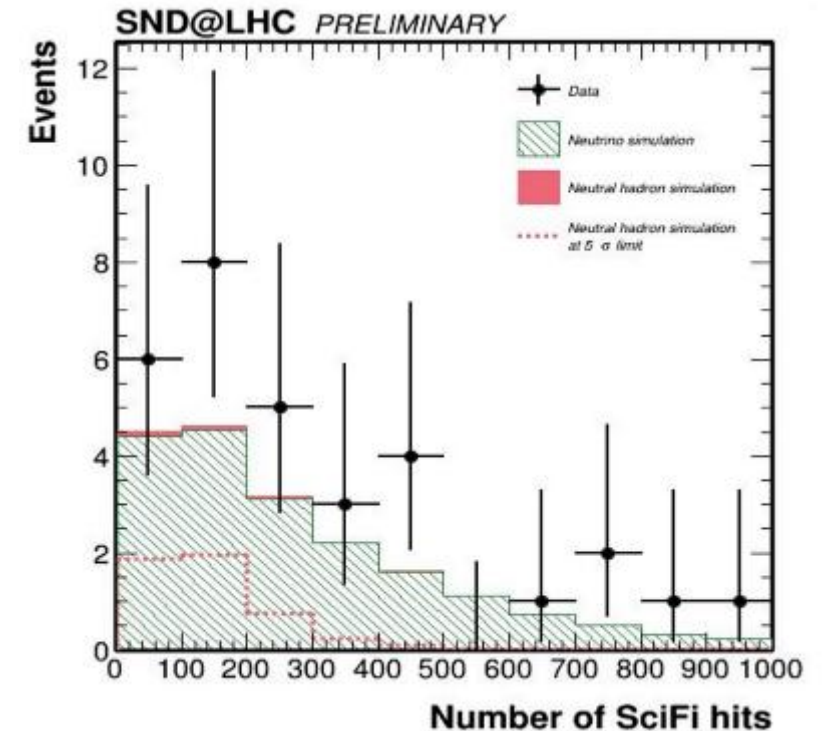
ν_μ ANALYSIS 2022+2023

- **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 $\rightarrow$ from 2 target walls to 4

Events expected in 68.6 fb^{-1}

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

28 events observed

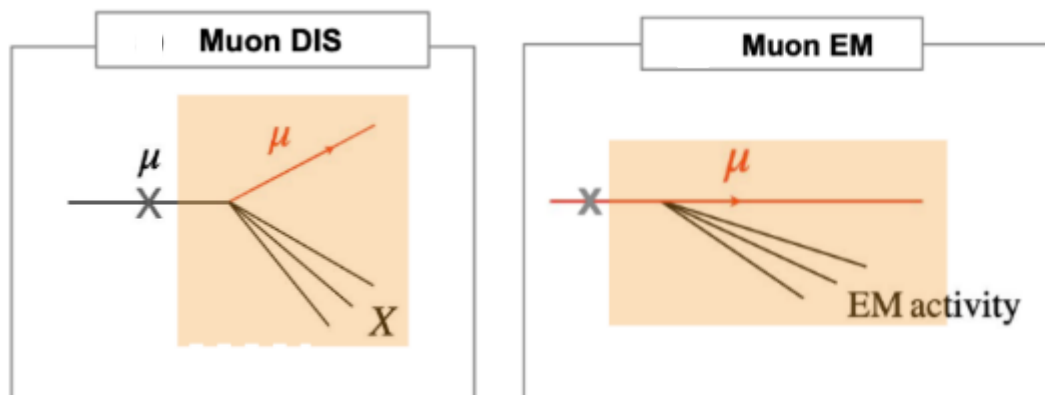


Step 1: Fiducial volume selection

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

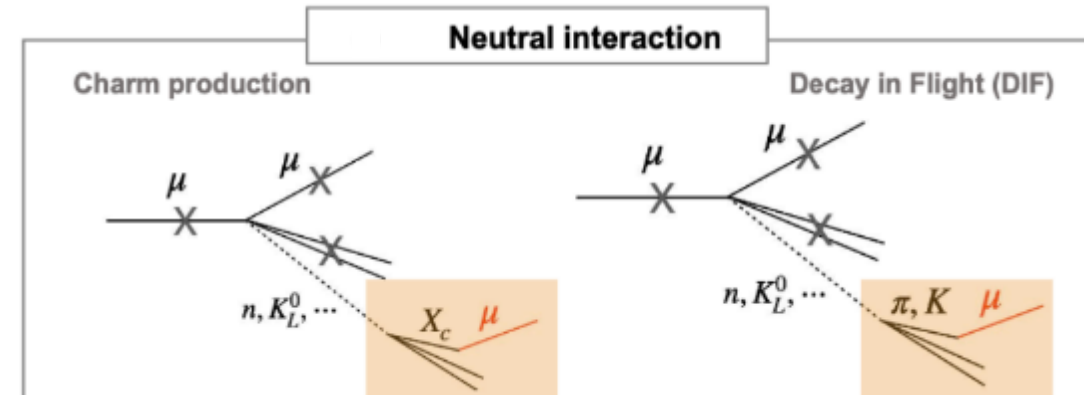
Define fiducial area of $25 \times 26 \text{ cm}^2$
across the detector layers

Undetected muon background



- Veto inefficiency
- Inclined trajectory

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

$X = \text{undetected}$
 = in SND@LHC volume

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

Define fiducial area of $25 \times 26 \text{ cm}^2$
across the detector layers

No incoming charged particles

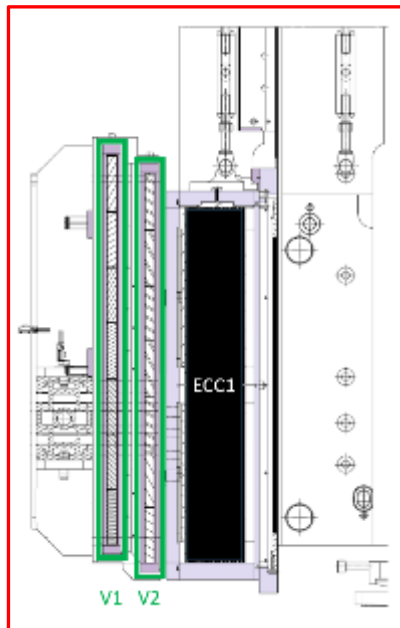
1st SciFi plane as additional Veto
plane

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 $35 \times 35 \text{ cm}^2 \rightarrow$ target coverage of $\sim 64\%$

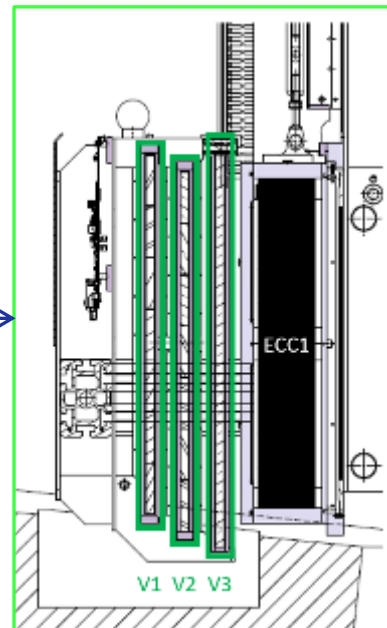
In YETS 2023-24 additional **3rd veto plane** + lowering of the whole system

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



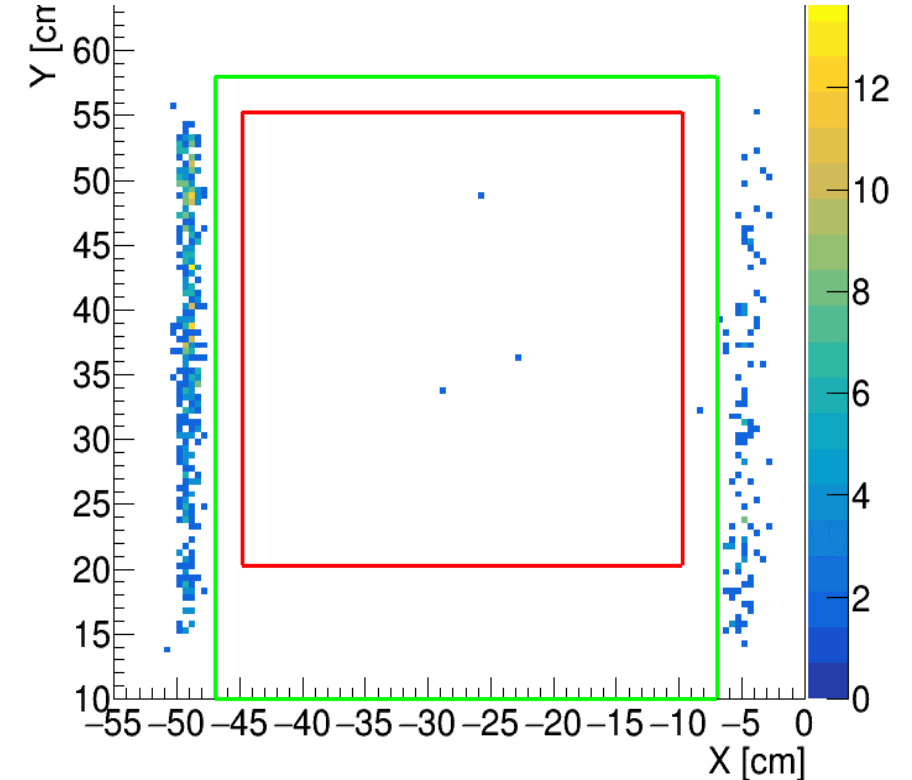
2022/23 veto system

CSN1



Updated veto system

G. Paggi



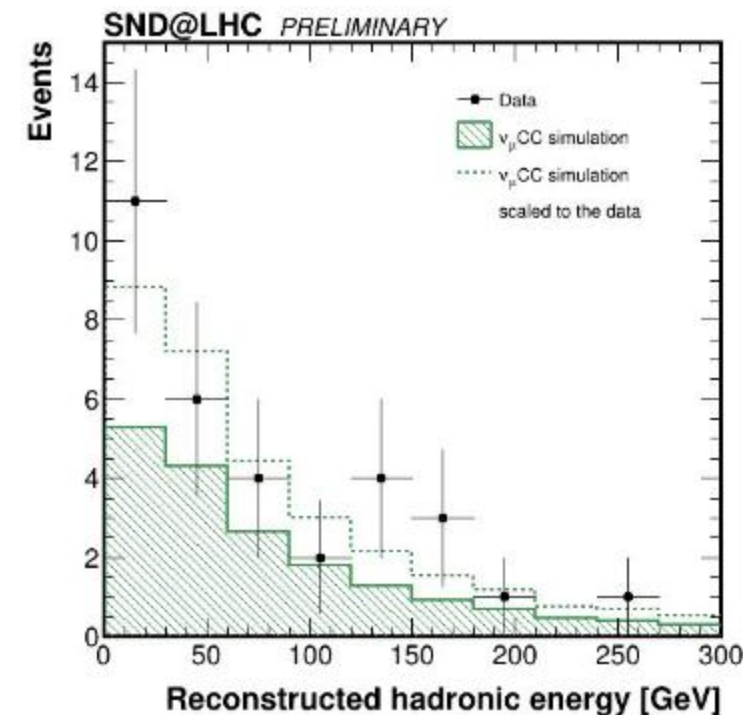
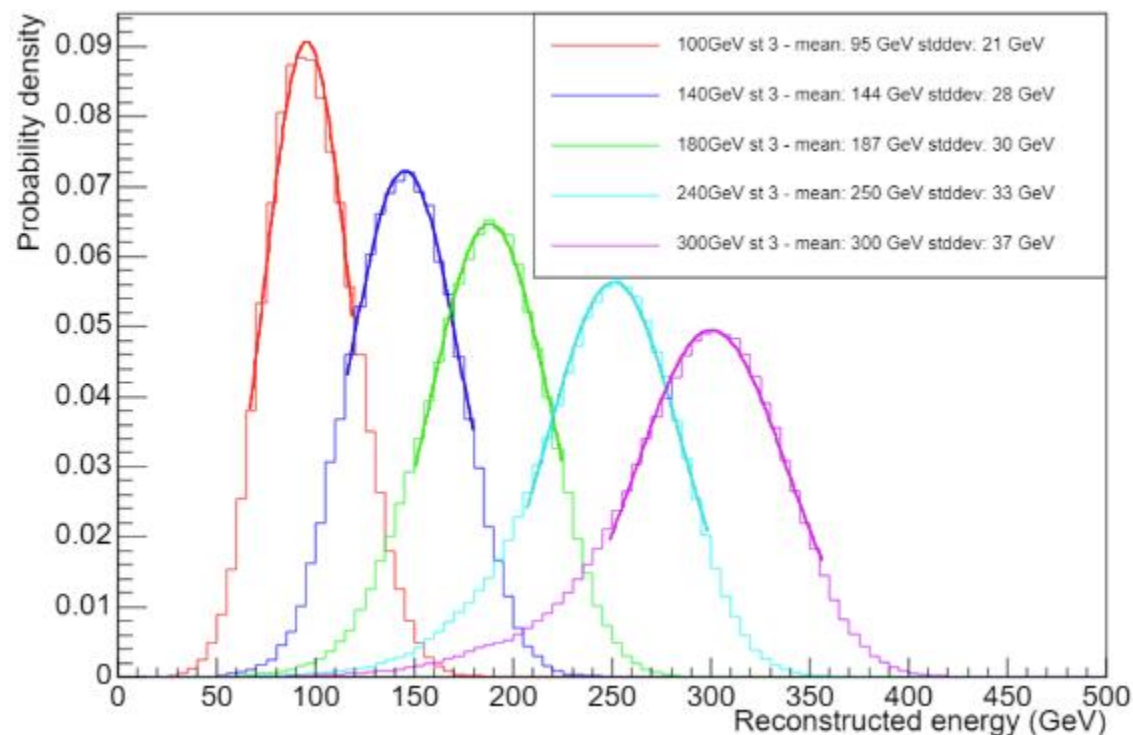
In the new configuration the inefficiency is $(4.9 \pm 1.9) \times 10^{-9}$ on the **full target area**

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 events with spurious hits
I	DS track intersects first SciFi plane > 5 cm away from detector edge	Track requirements
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	→ <i>Large</i> activity
L	US total QDC larger than 600 (700) for data (MC)	
M	Number of DS hits per projection < 10	

νN collisions produce hadronic showers $\rightarrow$ **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%**



ν_μ ANALYSIS 2024



2024 ν_μ update



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

- exploiting the upgraded veto system $\rightarrow$ 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 $\rightarrow$ 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

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

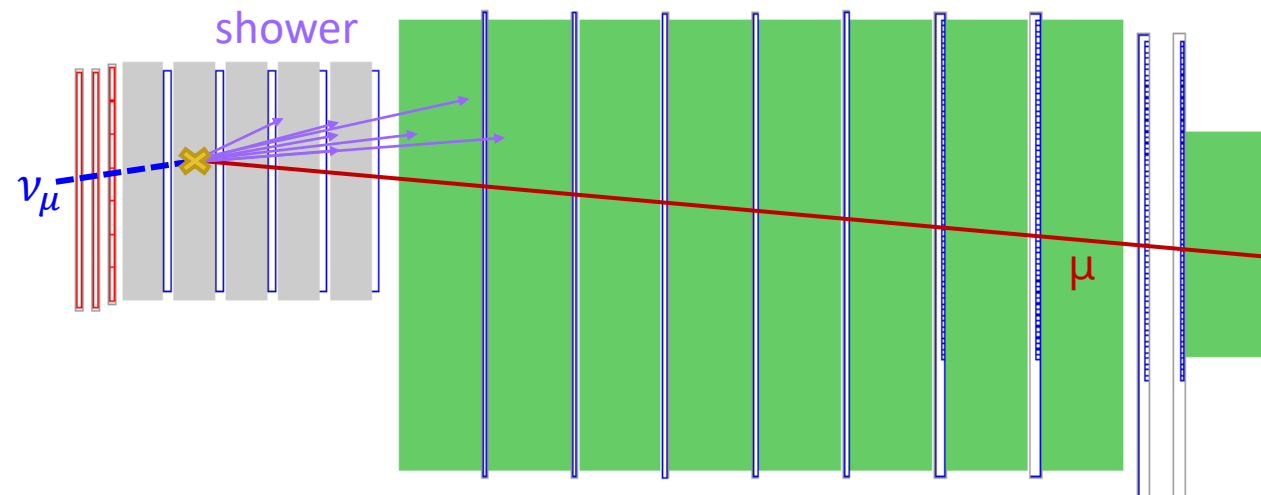
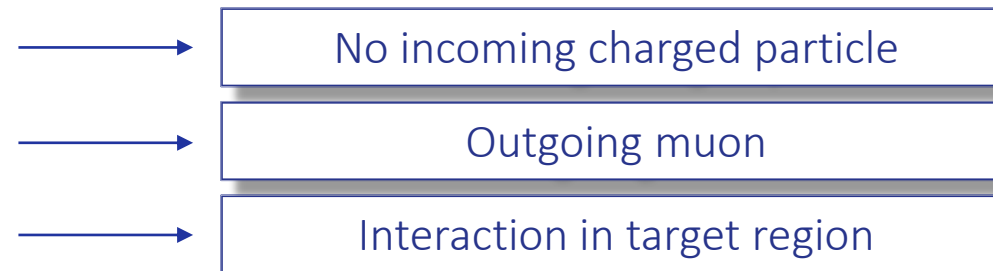
Work in progress!

Work in progress!

Step 1: preselection with relaxed constraint

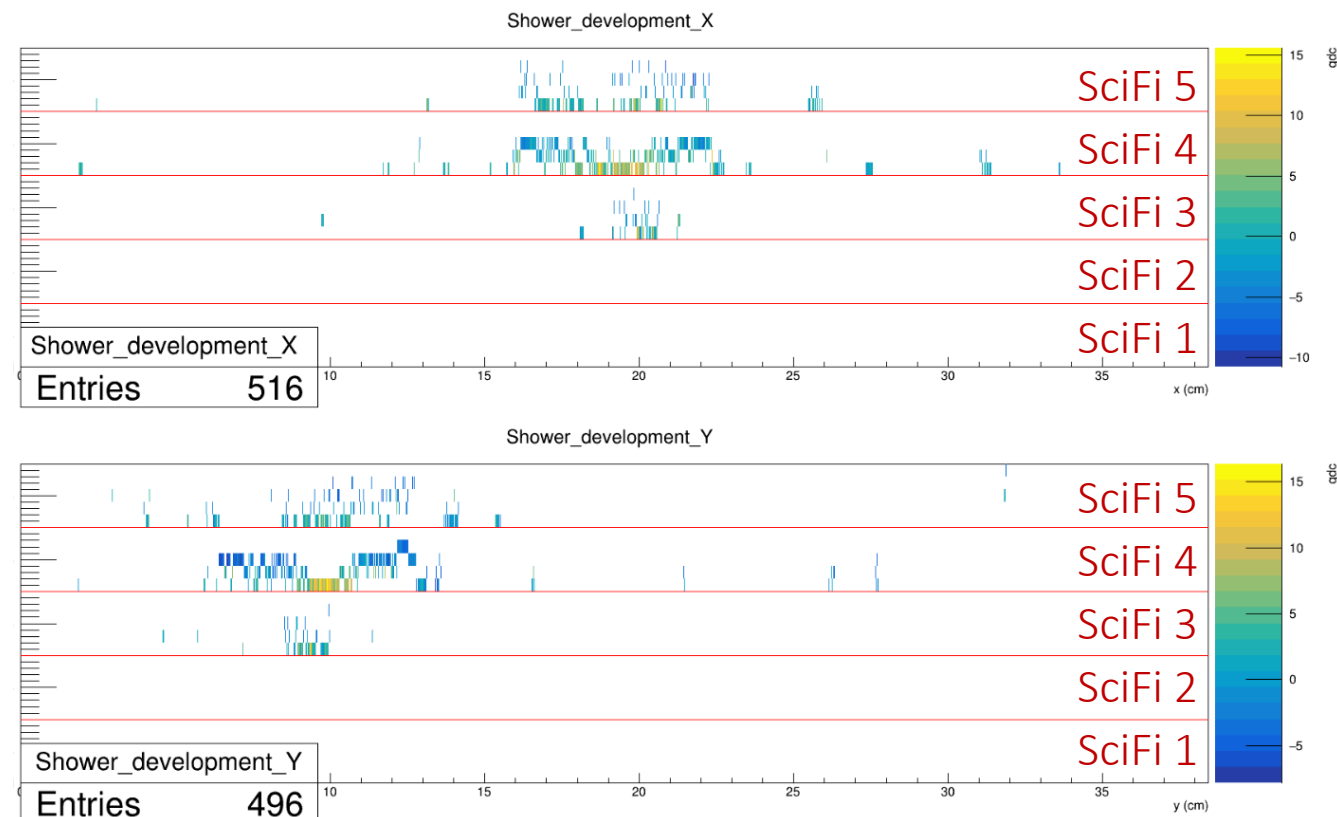
For ν_μ sample:

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



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

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



X view

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

Y view

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



2024 ν_μ CC - Preselection



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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 $\rightarrow 3.25 \times 10^5$ events

For μ sample:

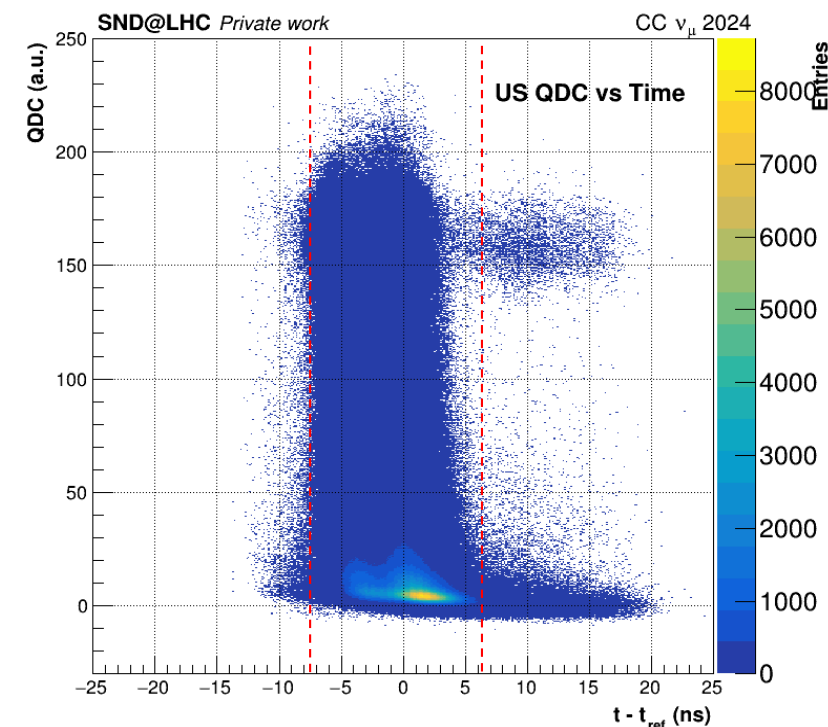
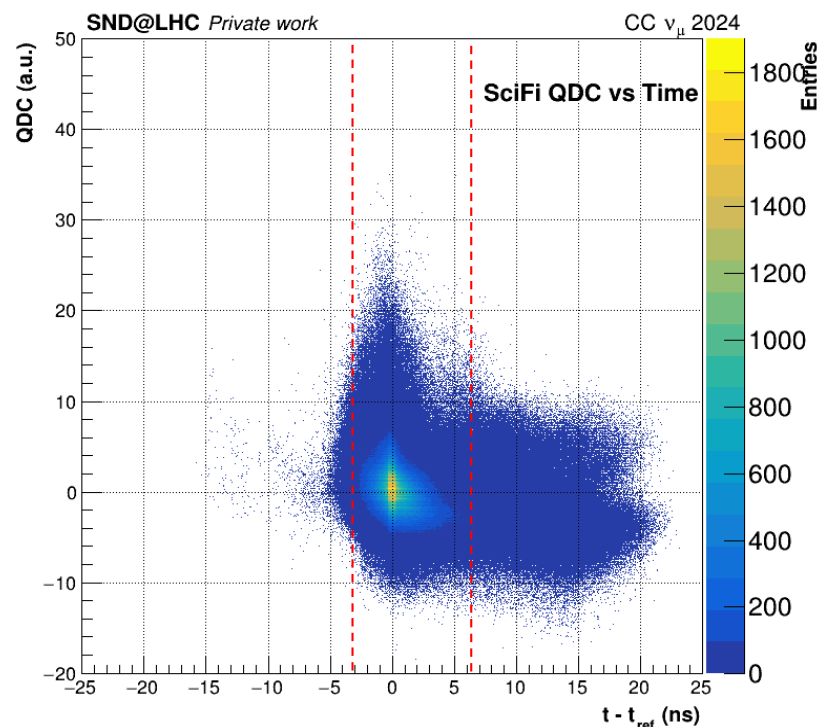
1. **No less than 2** veto planes with signal;
2. At least 2 DS with > 1 (x,y)
3. A shower tagged

12% of a single run ($\sim 0.1 \text{ fb}^{-1}$) $\rightarrow 1.34 \times 10^6$ events

Work in progress!

Step 2: Event selection criteria

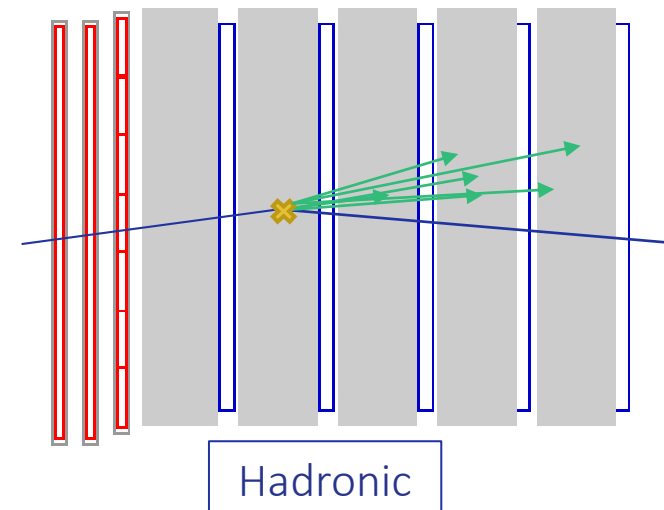
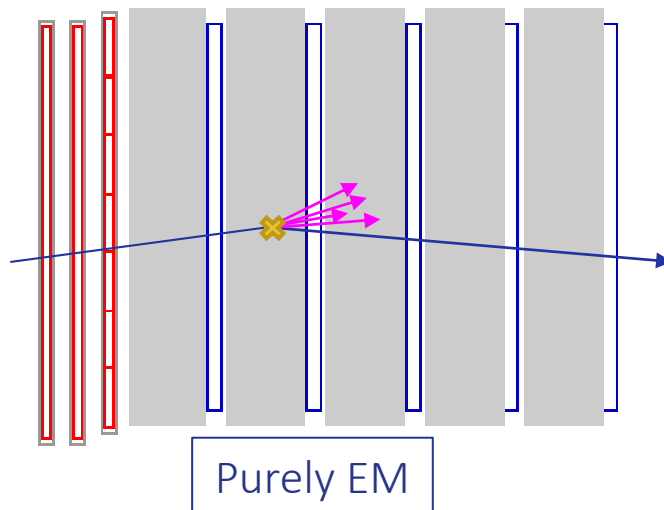
1. No hits in the veto system
2. Correct hit timing
 - $t_{ref} \equiv$ most probable value in SciFi



Work in progress!

Step 2: Event selection criteria

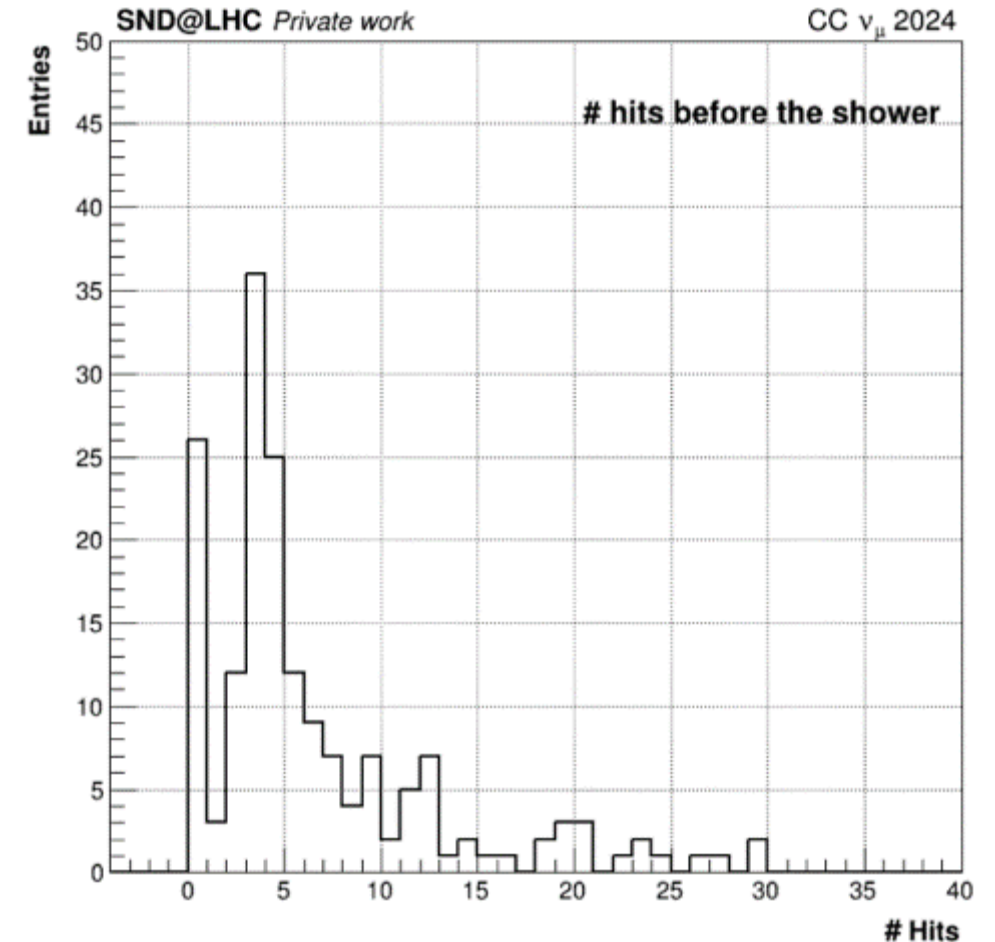
1. No hits in the veto system
2. Correct hit timing
3. Activity in all US planes → muon reaching DS planes
4. Shower tagged with the strict algorithm
 - Require two consecutive SciFi planes tagged → **suppress purely EM showers** exploiting longitudinal development difference



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 → passing muon show a peak at ~ 4 hits (2 per module)





2024 ν_μ CC – Selection: shower



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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 $\rightarrow$ 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 $\rightarrow \geq 7$ bars hit across US subsystem

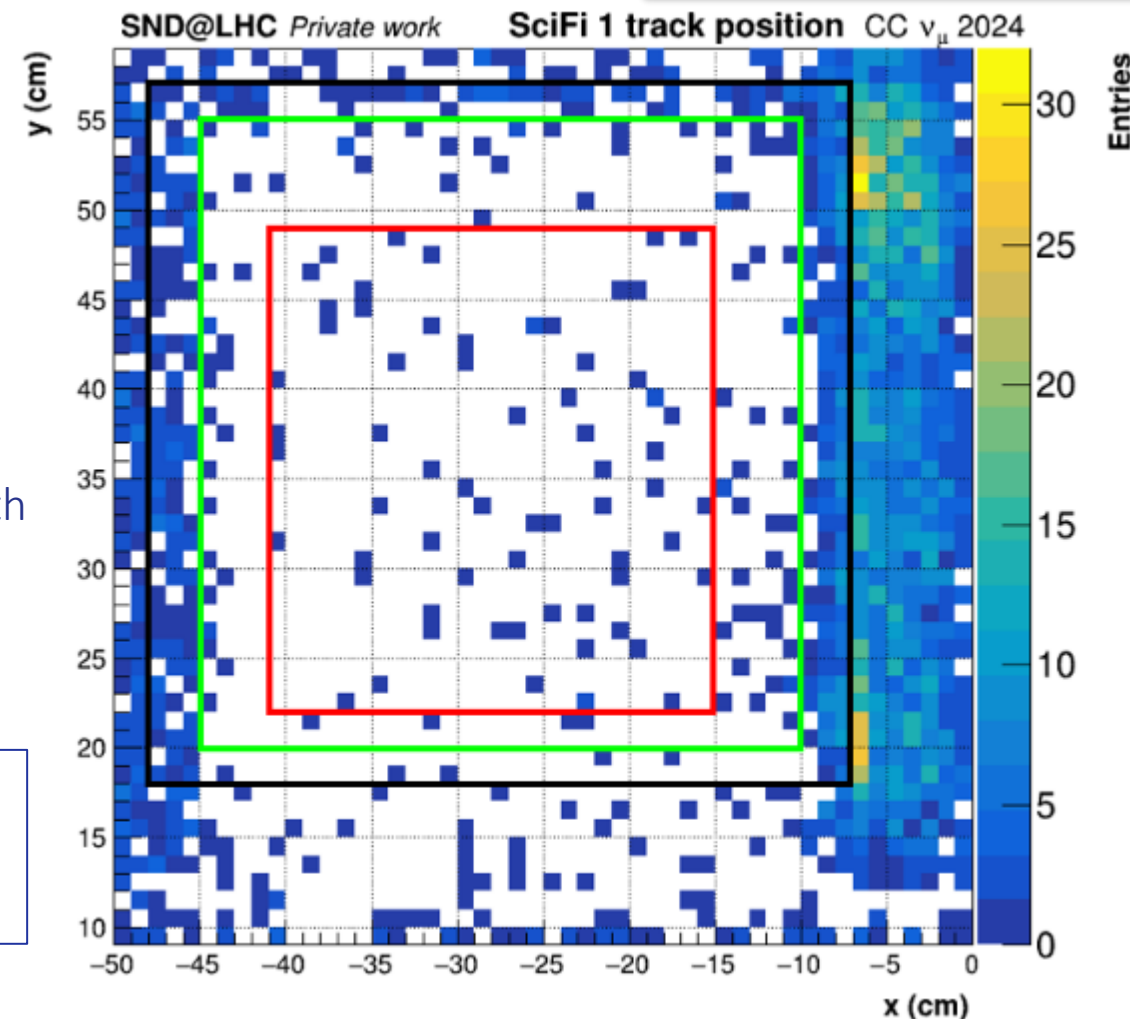
2024 ν_μ CC – Selection: track

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

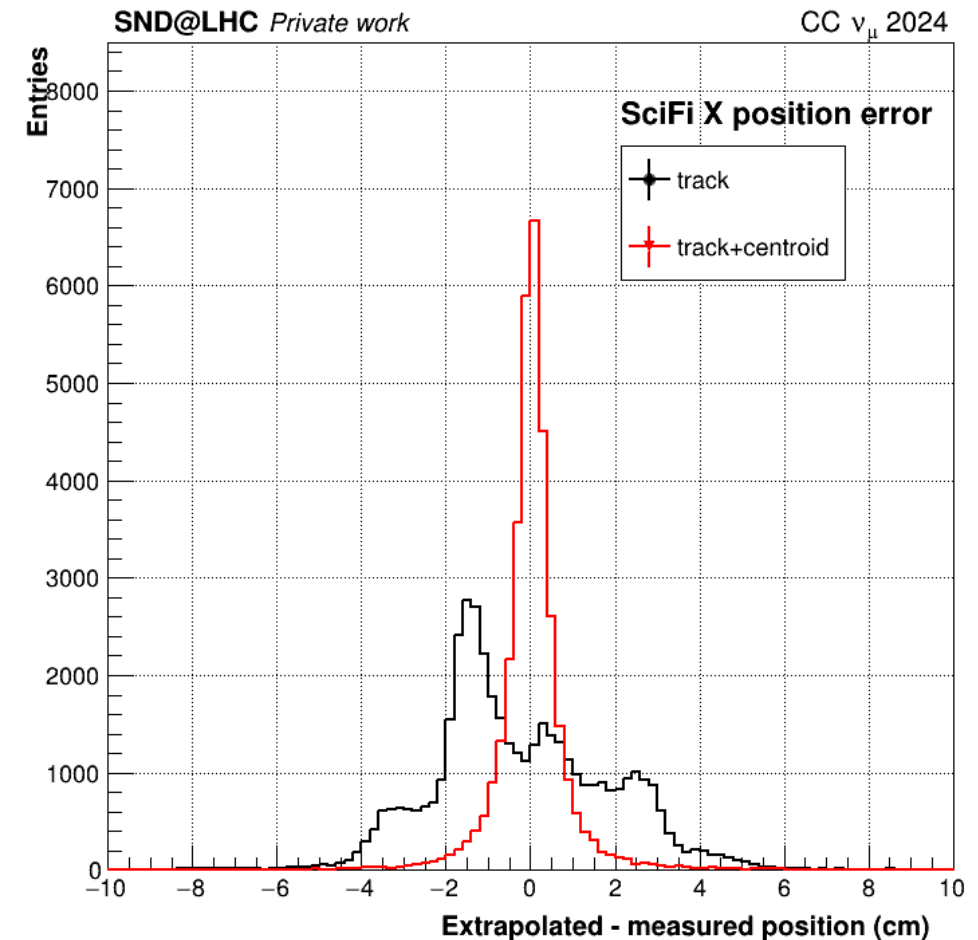
- SciFi module
- fiducial area 2024
- fiducial area 2022-23



Work in progress!

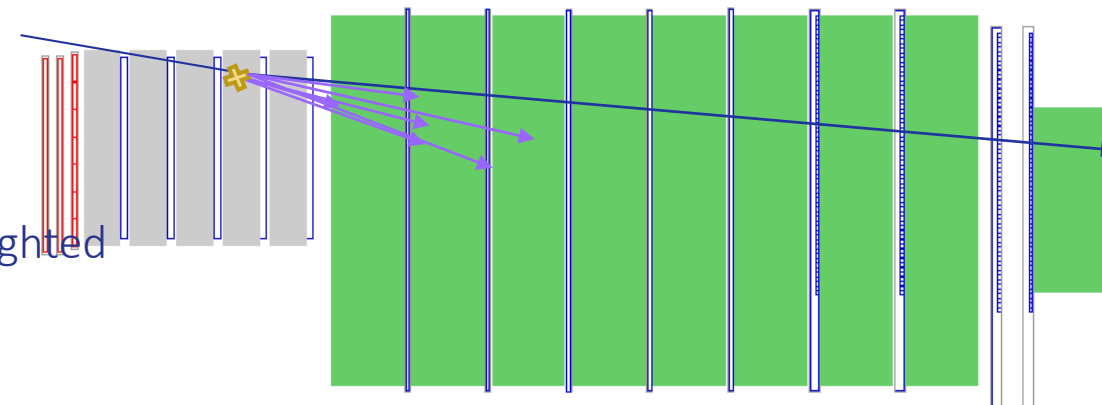
Step 2: Event selection criteria

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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



Step 2: *Event selection criteria*

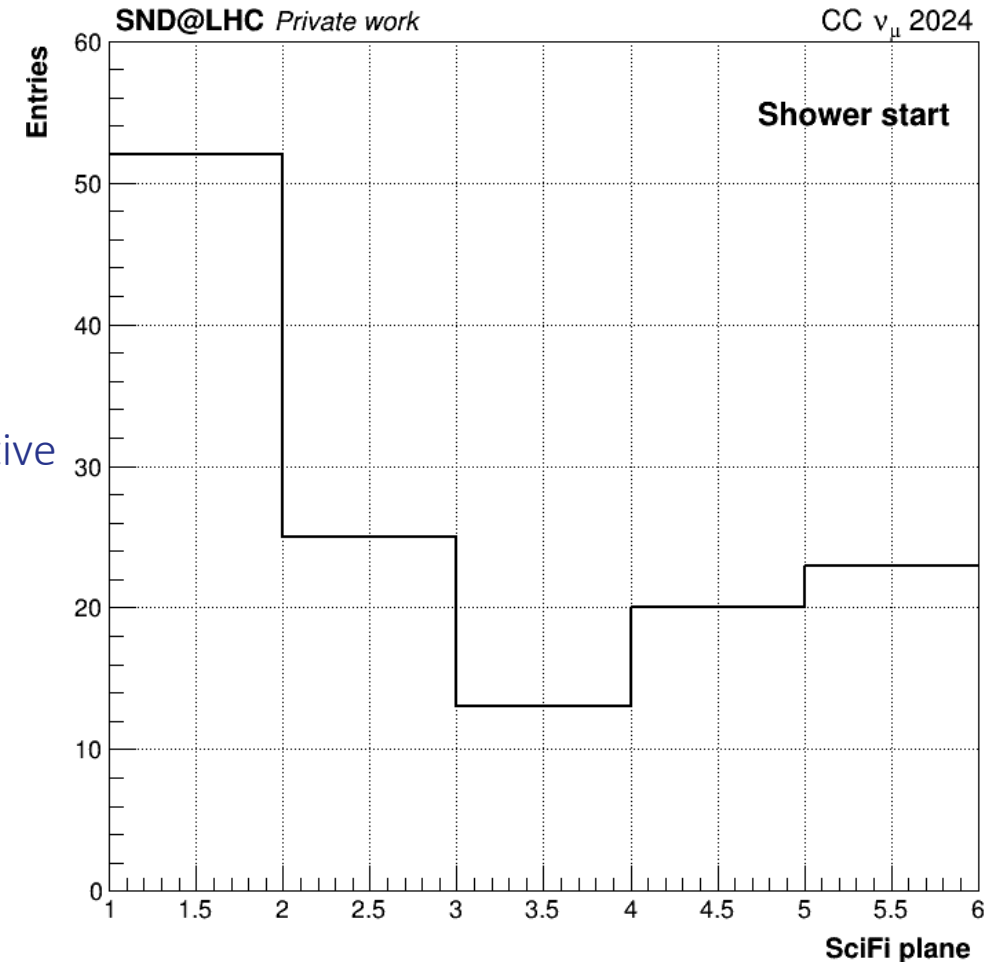
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 - Distance $< 3\text{cm}$ (DS extrapolation resolution) to **centroid** $\equiv$ proxy for the interaction vertex, QDC-weighted position of hits
 - Add centroid to track points and re-fit
 - Extrapolate to veto the new track and require it to fall within active region, with a 1 cm margin from all edges



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





Summary and outlook



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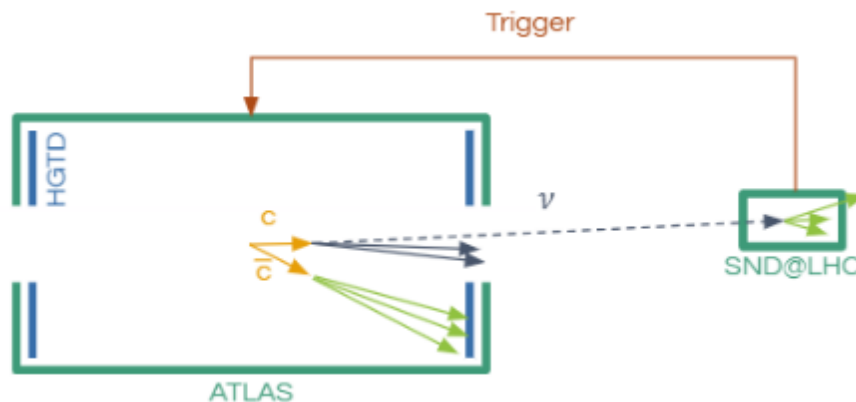
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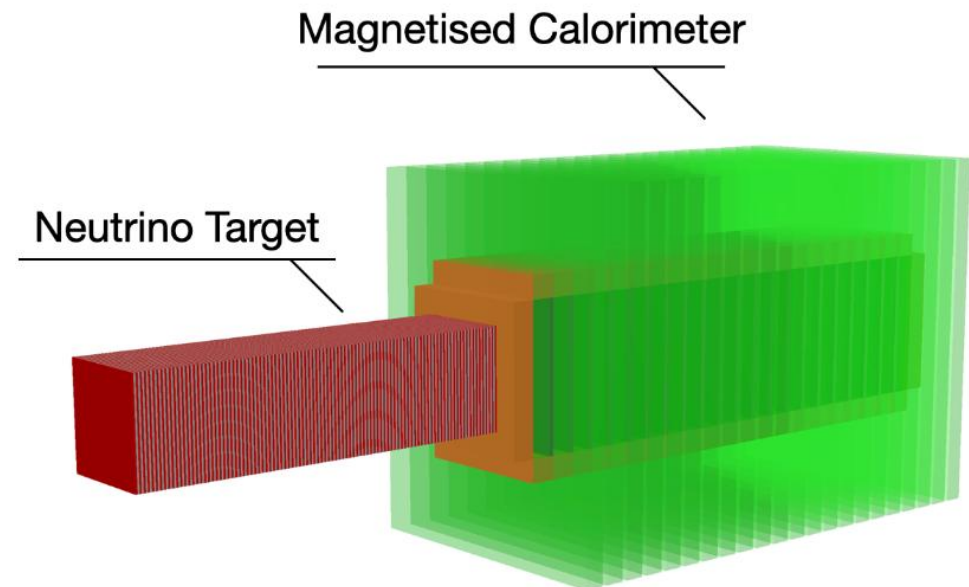
THANKS FOR THE ATTENTION

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		HL-LHC	
	Uncertainty Stat.	Uncertainty Sys.	Uncertainty Stat.	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



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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



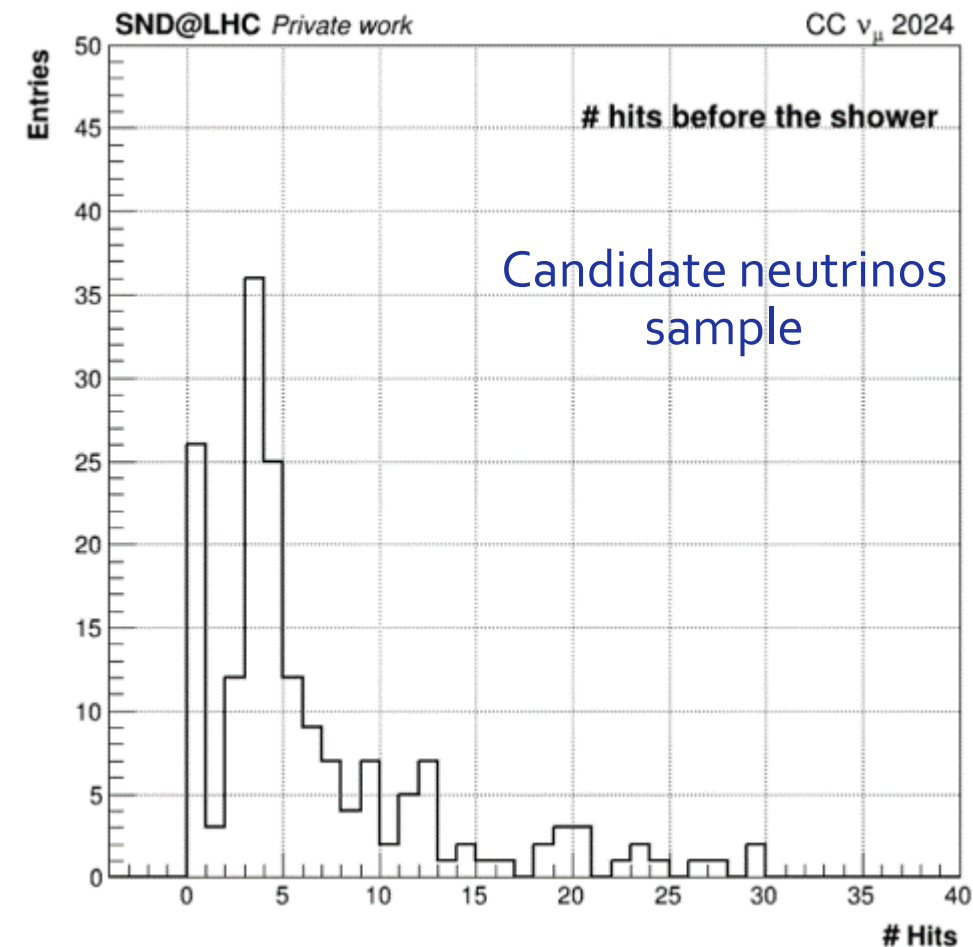
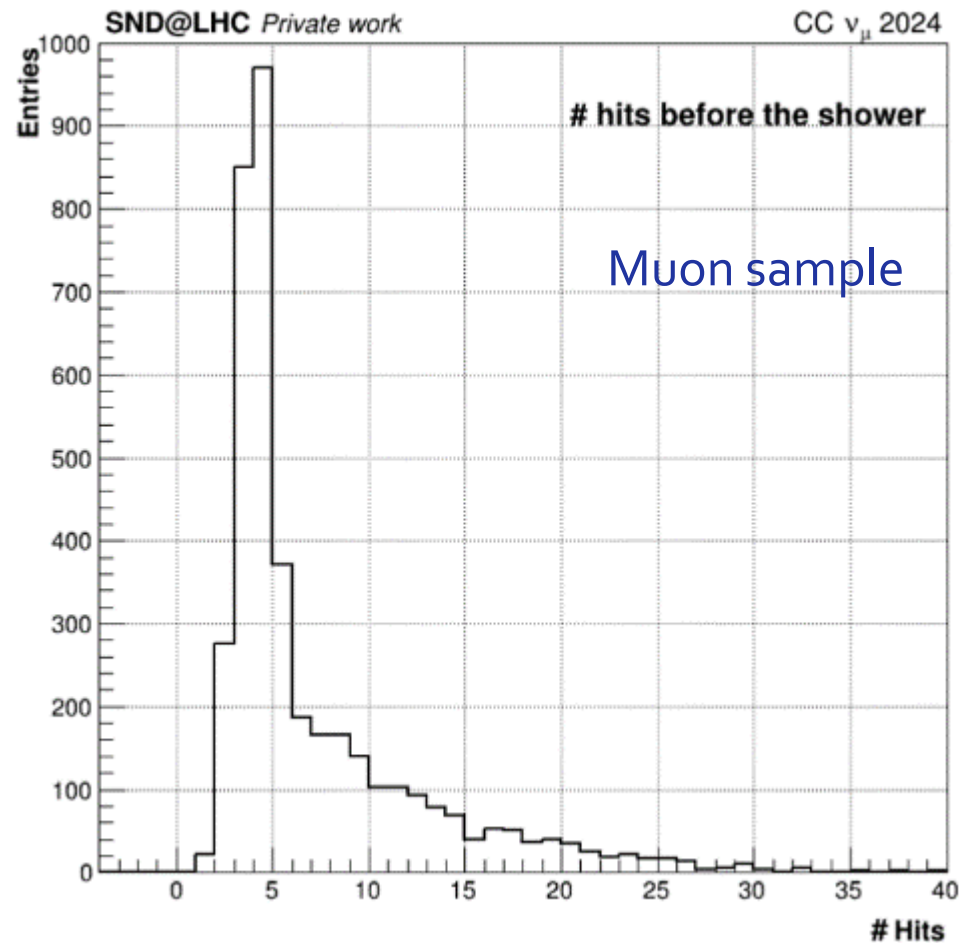
N hit before shower



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Istituto Nazionale di Fisica Nucleare
Sezione di Bologna





Validation of shower centroid



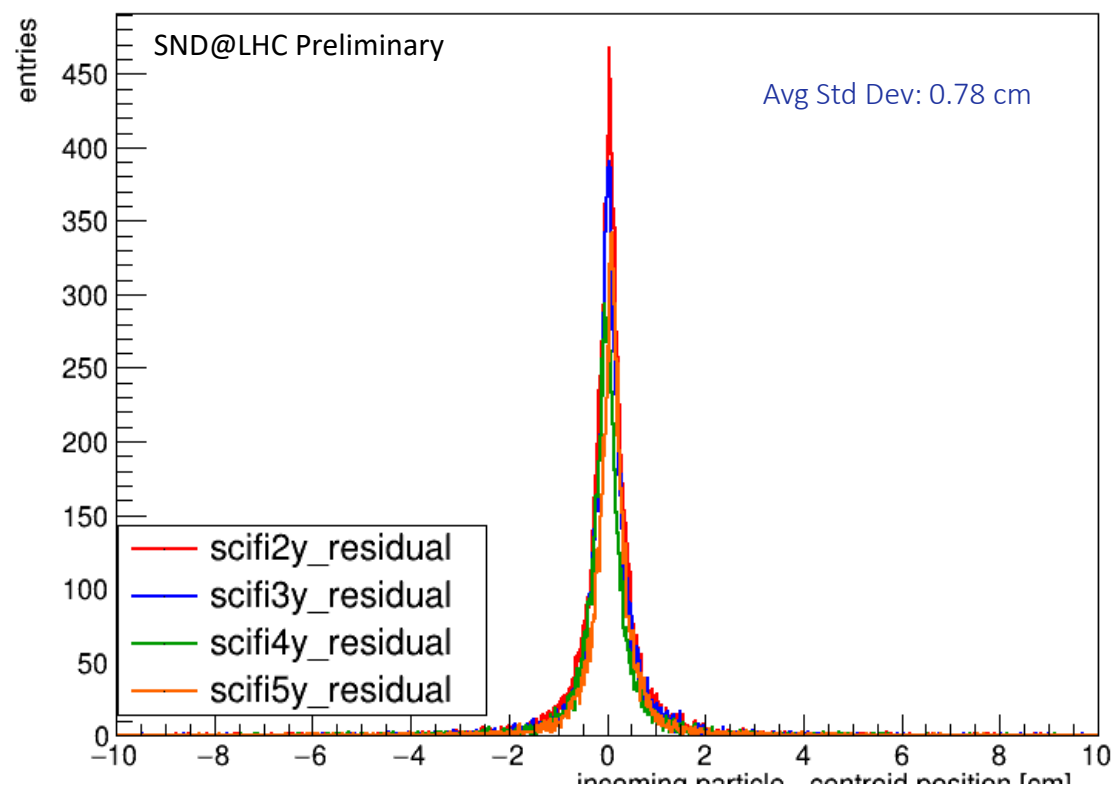
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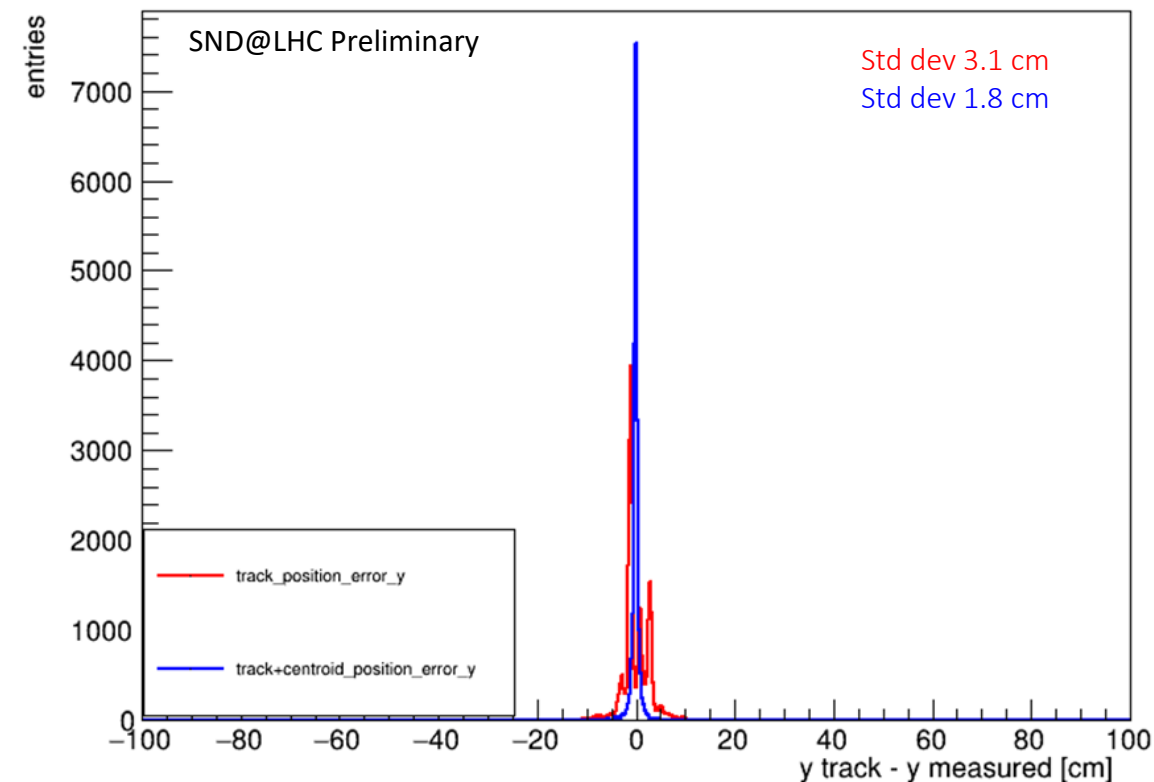
Centroid: Mean position averaged with qdc value. A minimum number of hits is needed

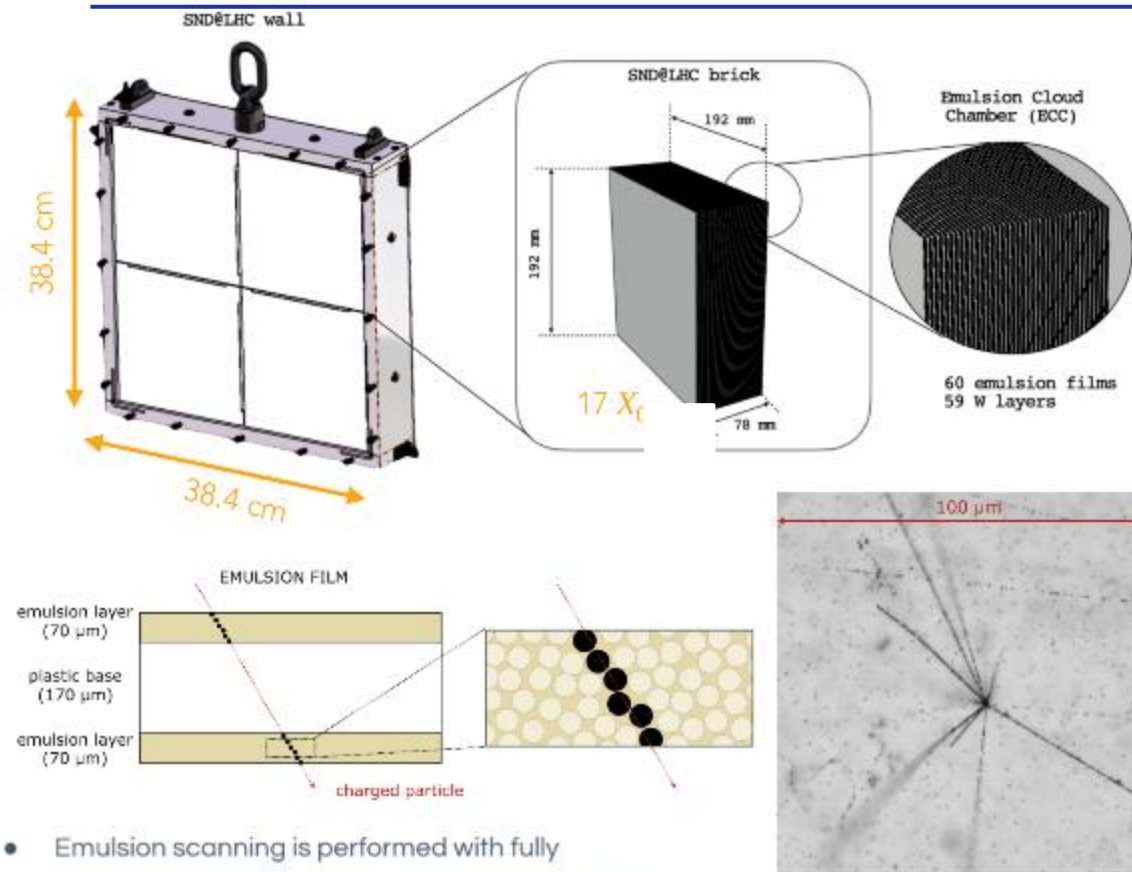
Aim: Validate centroid distribution using muon producing DIS showers

centroid_y Histograms



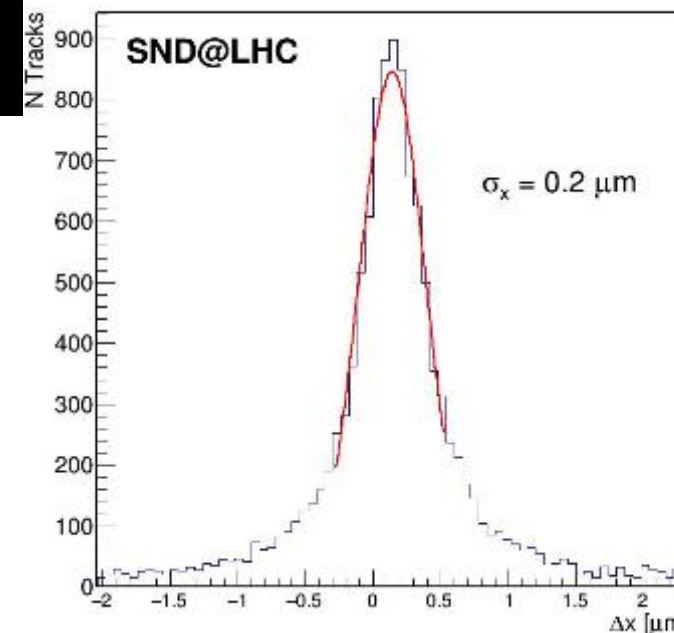
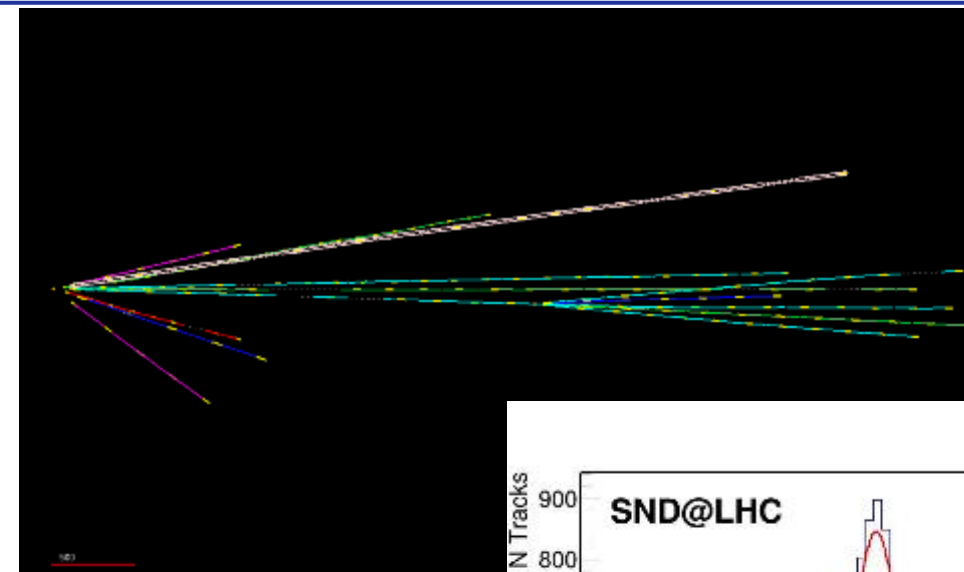
position_error_y Histograms





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

Status of emulsion scanning:
800 kg x 42 fb⁻¹

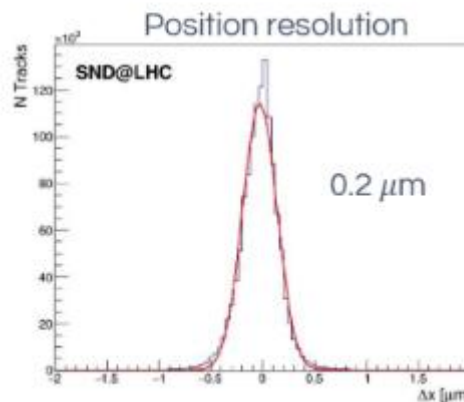
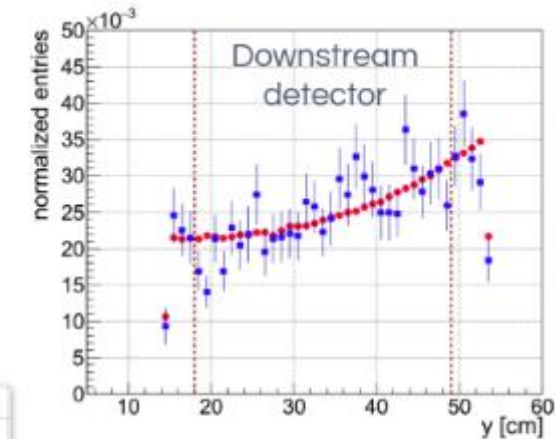


Position resolution 0.2 μm

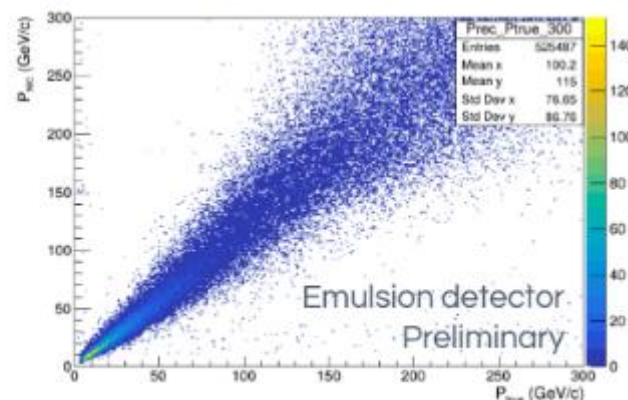
Passing muons

- 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.

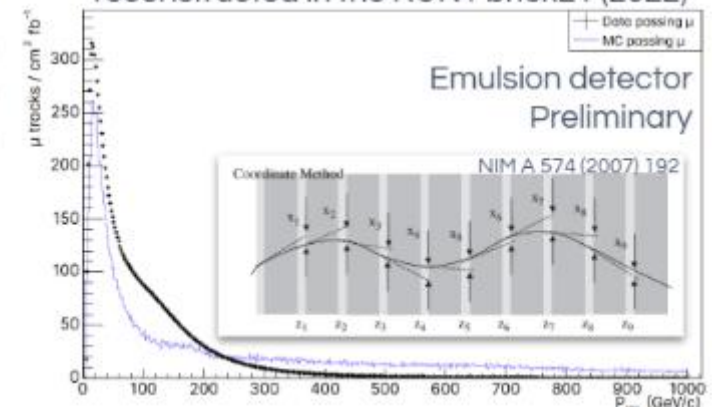
year	flux [trk/(cm ² fb ⁻¹)]
2022	557
2024	1154
2025	832
MC	460



Reconstructed vs true muon momentum

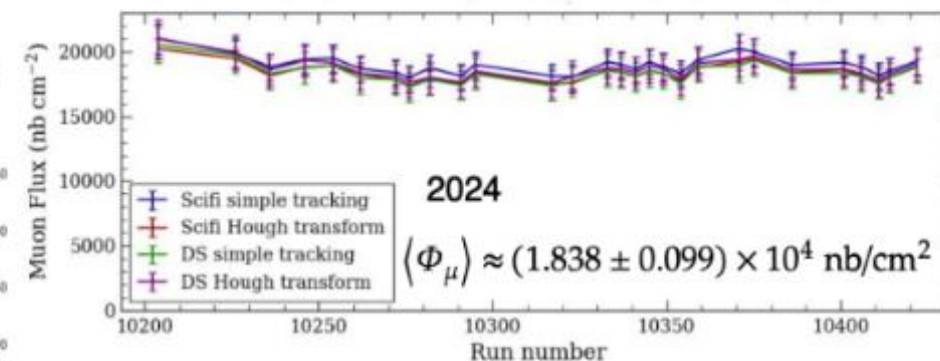
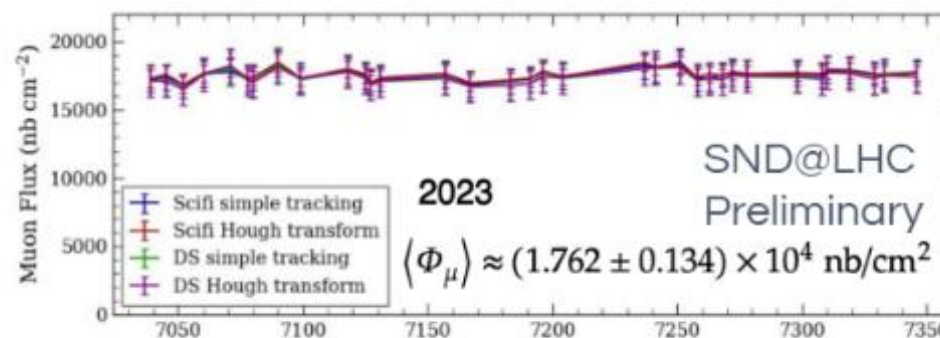
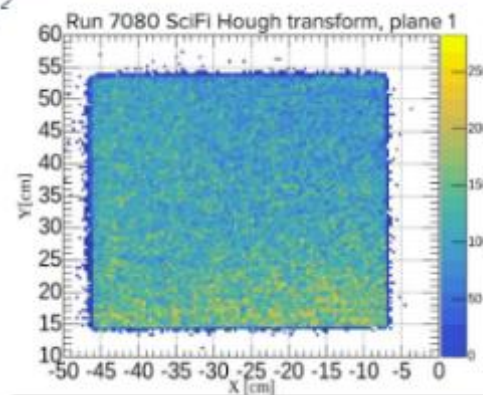


Momentum measurement for muons
reconstructed in the RUN1 brick21 (2022)



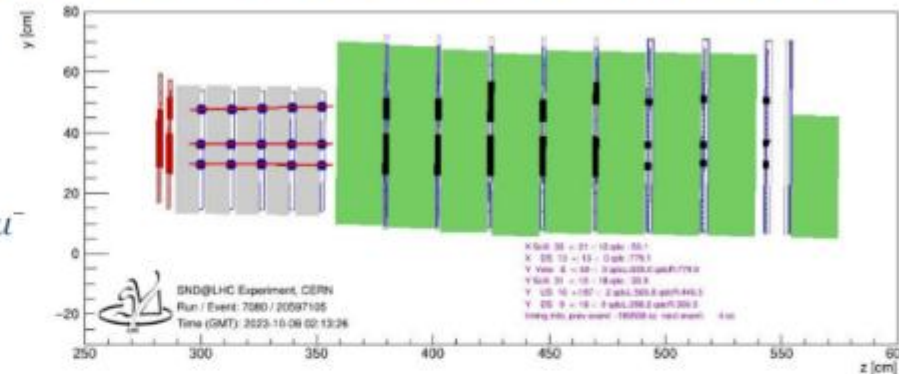
Passing muons in heavy ion runs

- 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:
 - $1.56 \pm 0.19 \times 10^4 \text{ nb/cm}^2$
- PbPb/pp flux ratio: $\sim 10^6$
 - 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: $\mu^\pm + N \rightarrow \mu^\pm \mu^\mp \mu^\pm + N$
 - 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

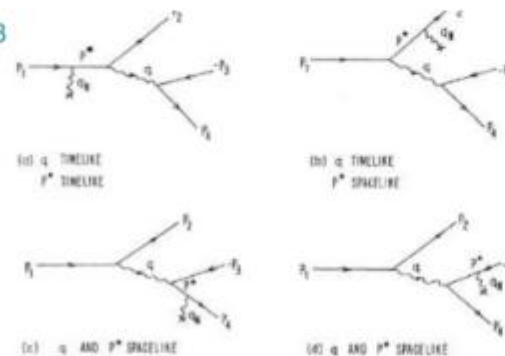
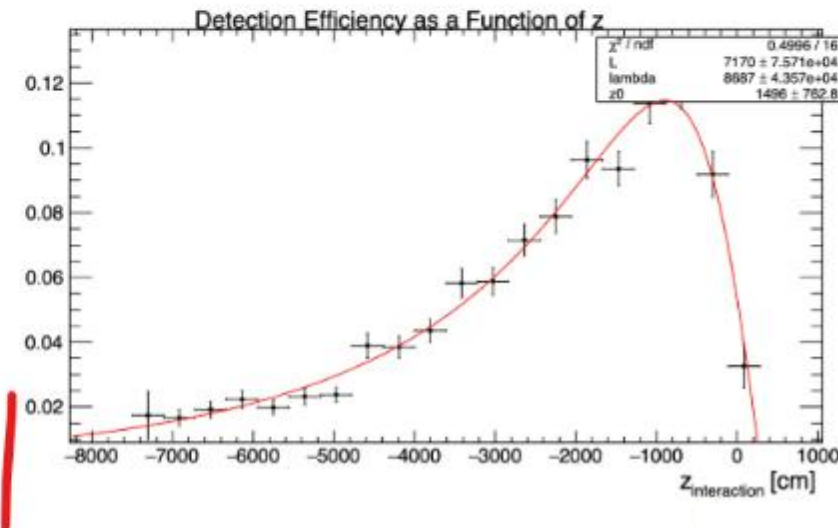
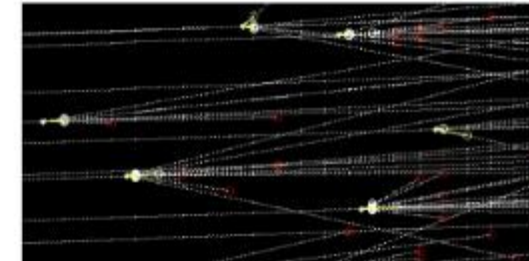


FIG. 1. The four Feynman diagrams for muon trident (a) and (b) have timelike virtual photons while in (c) and (d) the virtual photon is spacelike. p^* is the four-momentum of the virtual muon; q is the four-momentum of the virtual photon and q_N is the nuclear recoil four-momentum.



Muon DIS in the emulsion

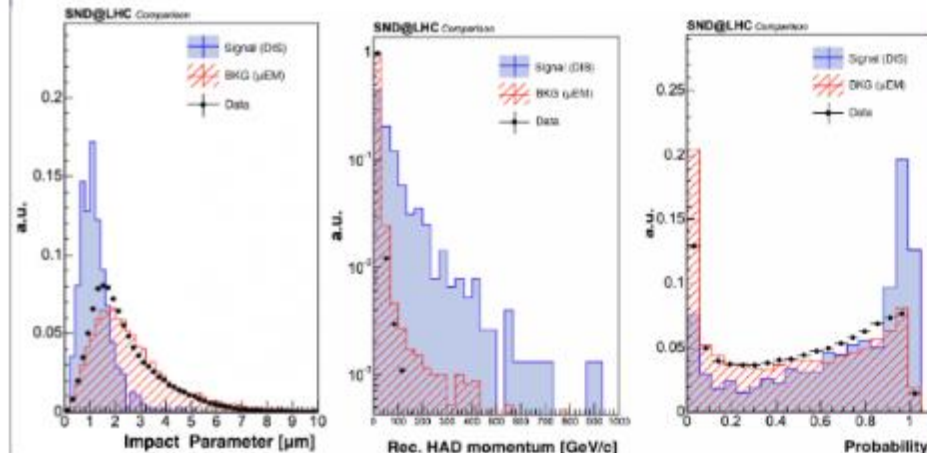
- Identification of **muon DIS** in the emulsion target with cut-based approach on topological and kinematical variables
- Data sample: vertices reconstructed in RUN1 brick 21: $32\text{kg} \times 9.5\text{fb}^{-1}$



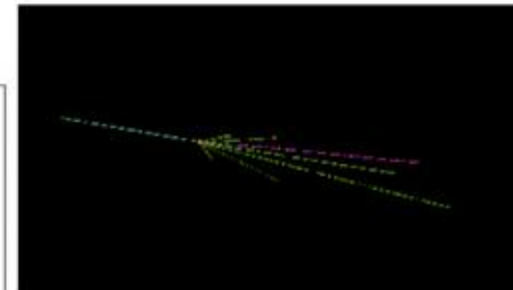
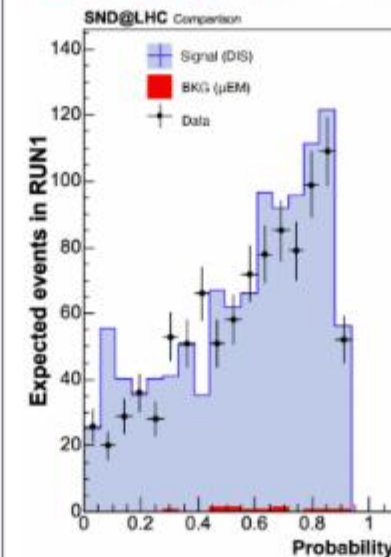
Simulated muon DIS in brick

Event selection criteria

- charged vertex
- mean angular aperture > 13 mrad
- impact parameter $< 2.5\mu\text{m}$
- 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

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

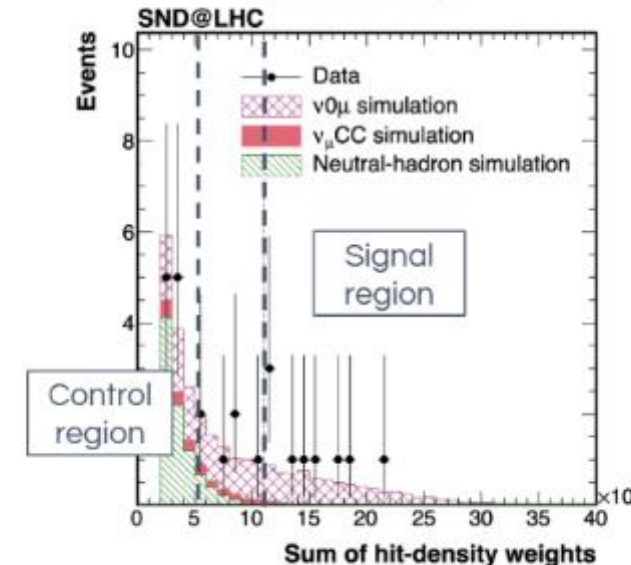
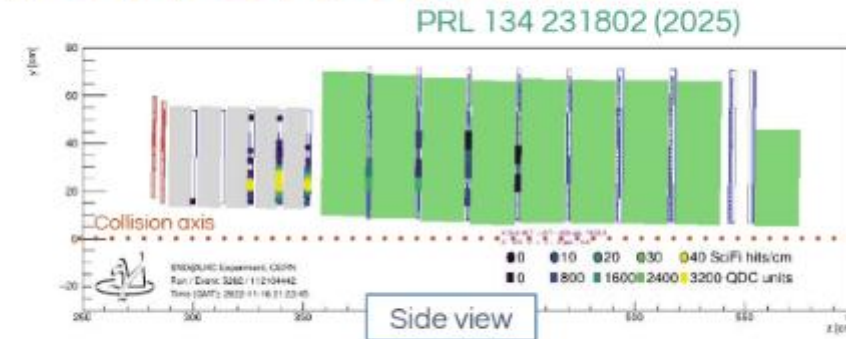
- Total expected background: 0.32 ± 0.06 events
- Expected signal: 7.2 events
 - 4.9 ν_e CC, 2.2 NC, 0.1 ν_τ CC
- Expected significance: 5.5σ

Number of events observed: 9

Observation significance: 6.4σ

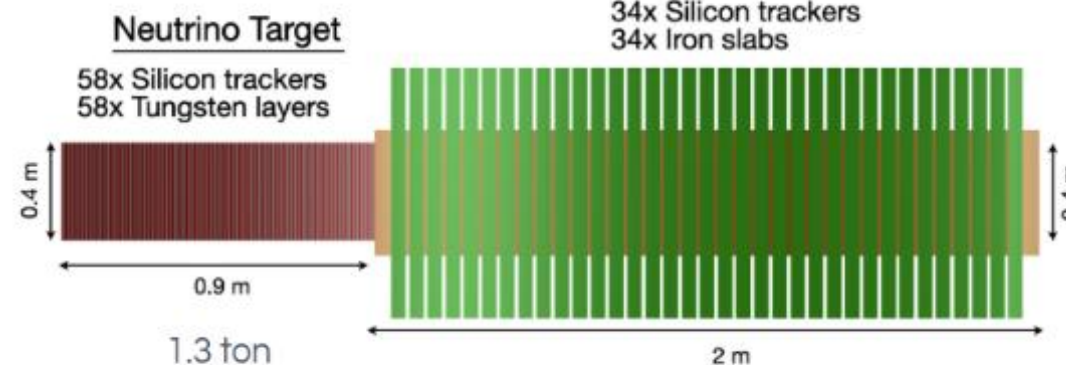
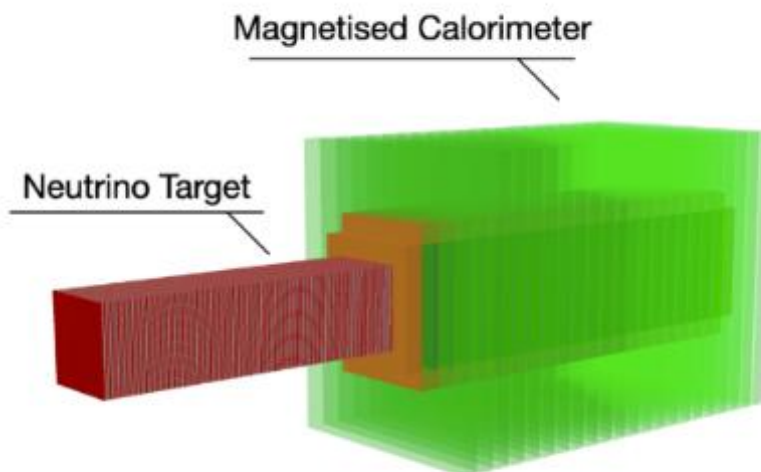
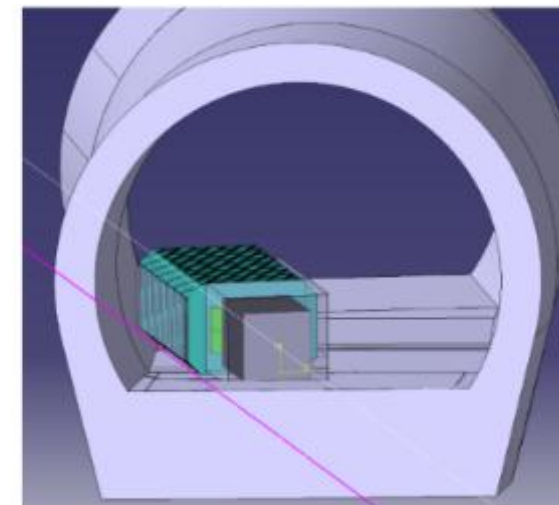
ν_e CC observation significance: 3.7σ

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

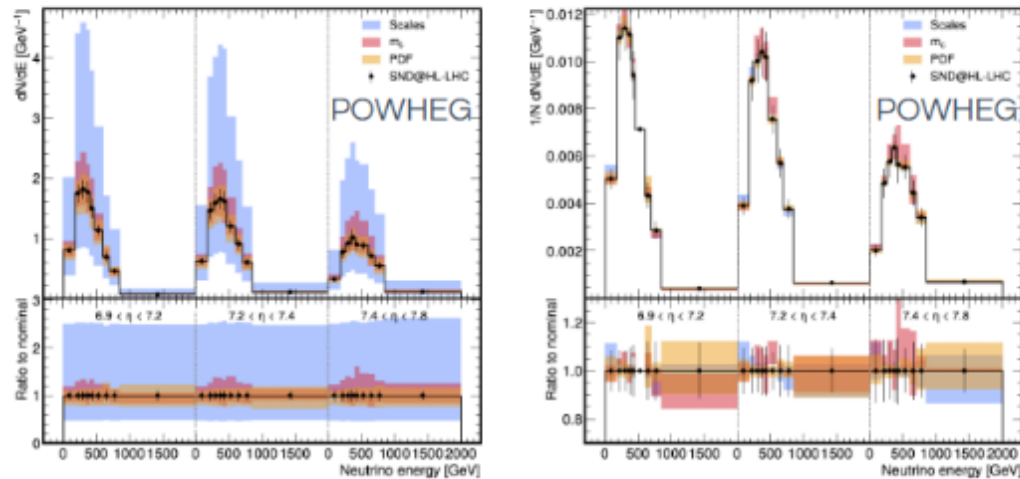


SND@HL-LHC

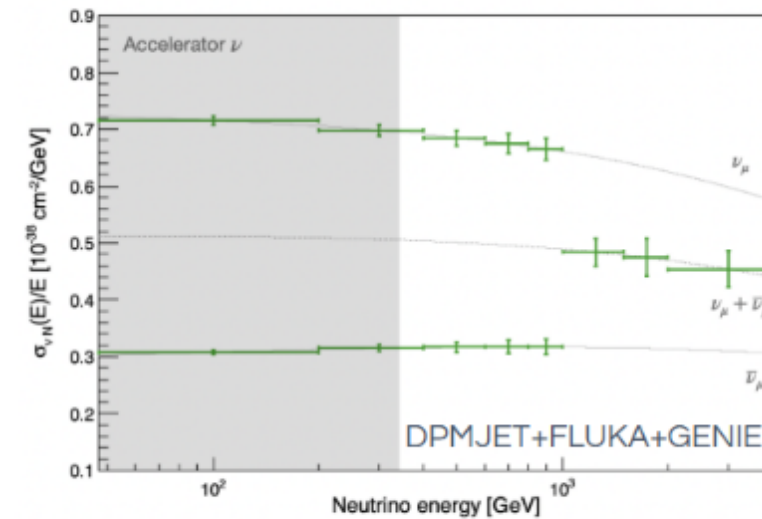
- Running the emulsion detector during the HL-LHC is unfeasible.
- HL-LHC phase of the experiment will use silicon-strip instrumentation.
 - First Si-based neutrino vertex detector!
- The calorimeter will be magnetised for muon momentum and charge measurement.



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>

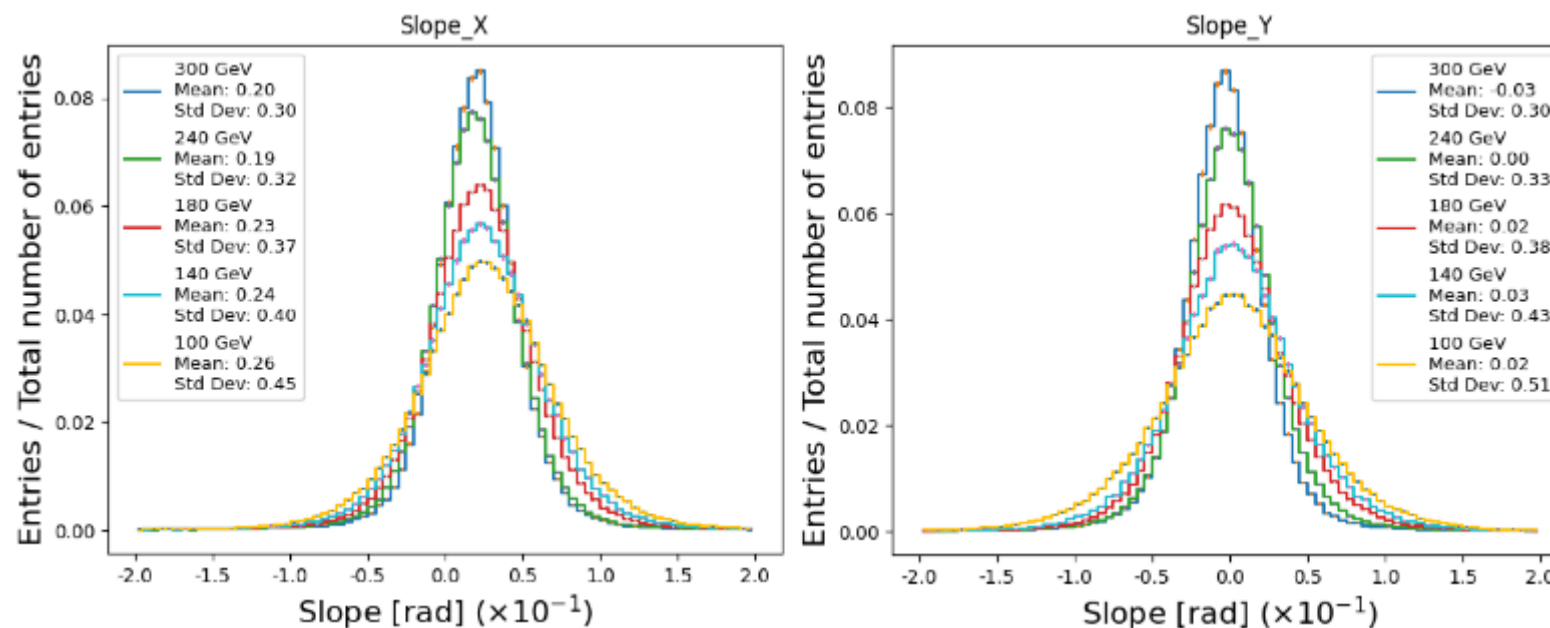
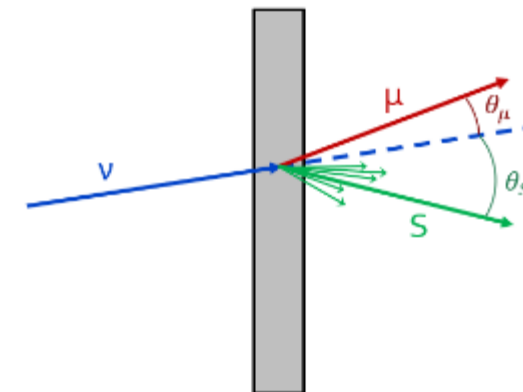
ESPPU Input

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

Aim: reconstruct shower direction $\rightarrow$ 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 $\rightarrow$ 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

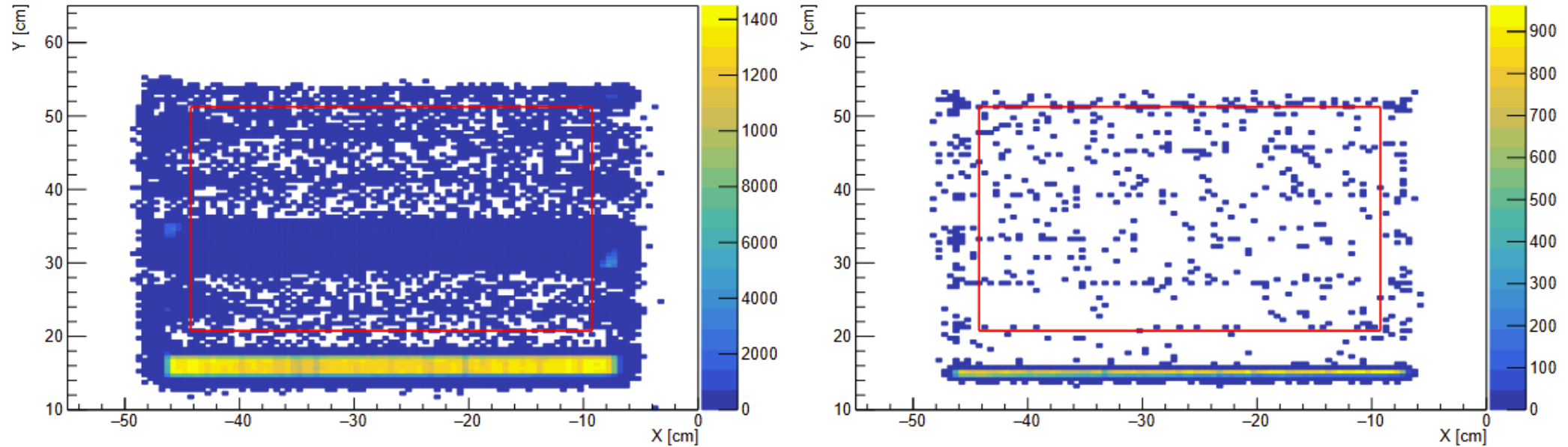


Figure 1: The extrapolated position of the reconstructed Scifi track at Veto plane 0 (left) and Veto plane 1 (right) for events with less than 13 fired Veto channels. The red square encloses the fiducial area used for the observation of neutrino interactions.



Veto per plane post upgrade



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