Neutrino Physics with the SND@LHC Experiment

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on behalf of SND@LHC collaboration

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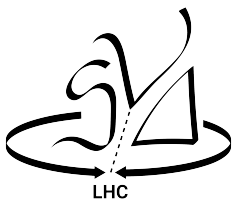
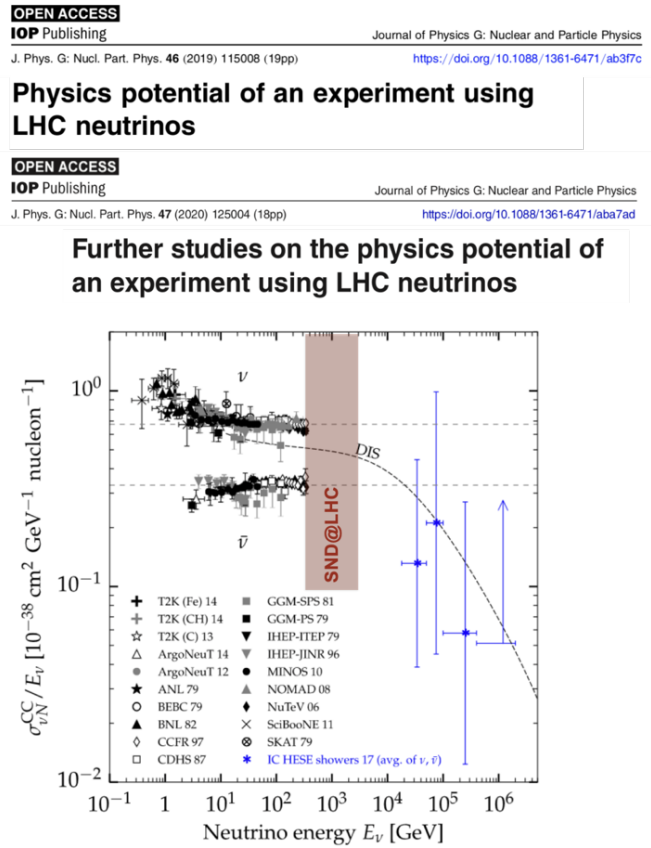
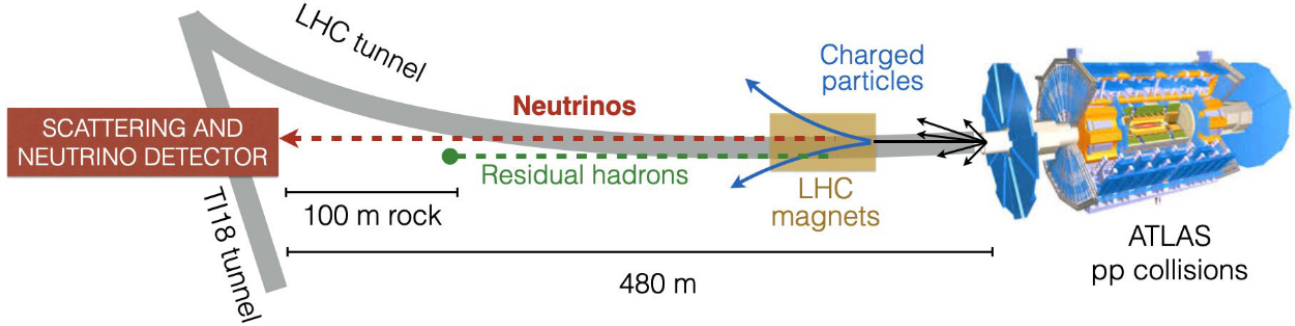
XIX INTERNATIONAL CONFERENCE
ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS
24-30 August 2025
XICHANG, SICHUAN, CHINA



Neutrinos at LHC

- The physics potential of neutrino experiments at the LHC was acknowledged in the early 1980s.
- Large neutrino fluxes in forward region from pp collisions.
- The highest energy human-made neutrinos.
- High neutrino energy and thus larger interaction cross section ($\sigma_\nu \propto E_\nu$)
- All three neutrino flavours can be observed at the LHC with a small-scale experiment
- Unexplored energy domain $E_\nu \in [10^2, 10^3]$ GeV
- **SND@LHC:** off-axis, $7.2 < \eta < 8.4$



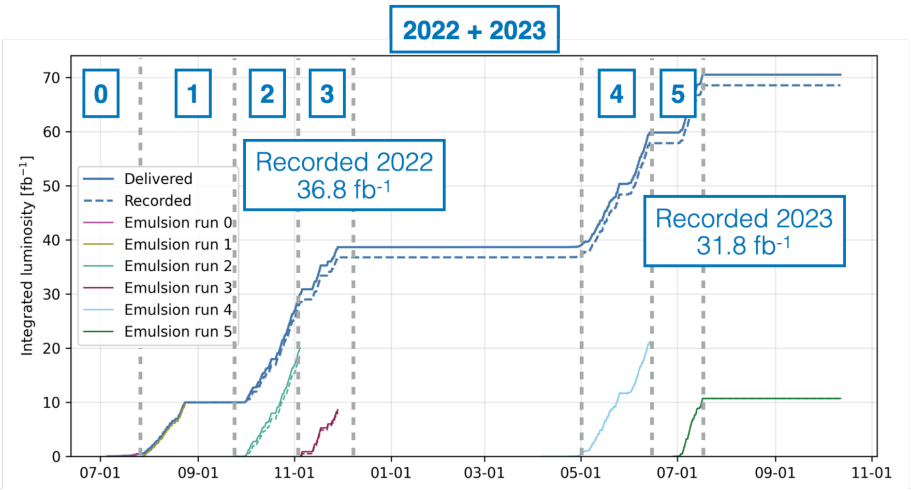


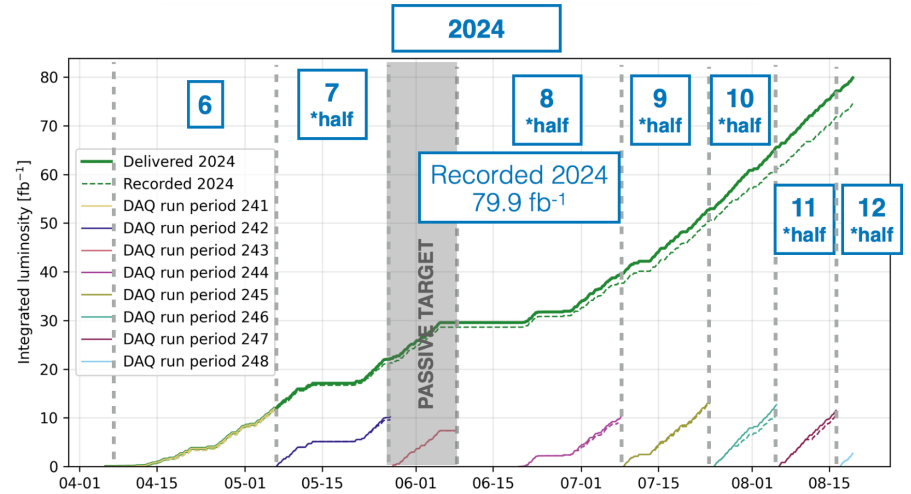
SND@LHC


SND@LHC
Veto
plastic scintillators
Target/ECAL
W+emulsions
SciFi tracker
HCAL/Muon System
Fe+plastic scintillators

Data Taking and Event Reconstruction

- Recorded lumi of pp collisions in **2022** and **2023** data taking campaigns: **68.6** fb^{-1}
  - Uptime of 97 %
  - Five emulsion target replacements.
    - Keep track density $< 4 \times 10^5$ tracks/cm^2
    - Limit the exposure to 20 fb^{-1}
- **2024:**
  - Instrument only the lower half target with emulsions
  - Exposure limited to 12 fb^{-1}
  - 79.9 fb^{-1} of *pp* collisions recorded by the electronic detector.
- **2025:** 49.3 fb^{-1} of luminosity was collected this year.

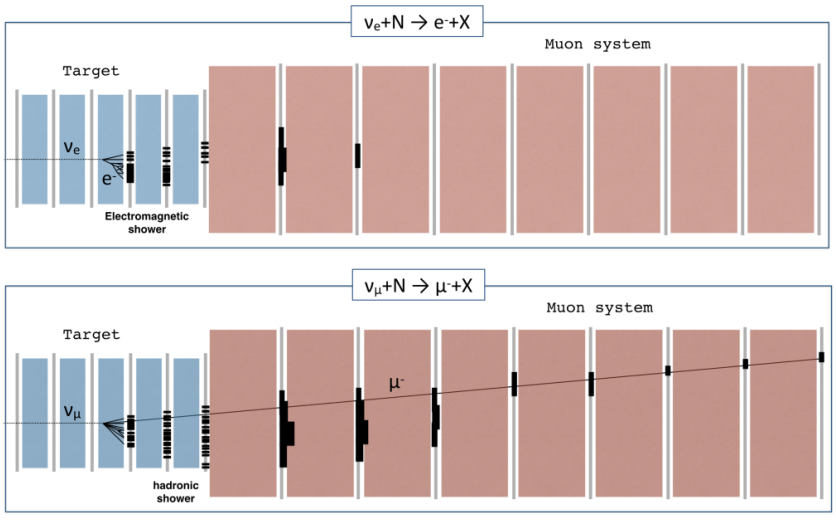




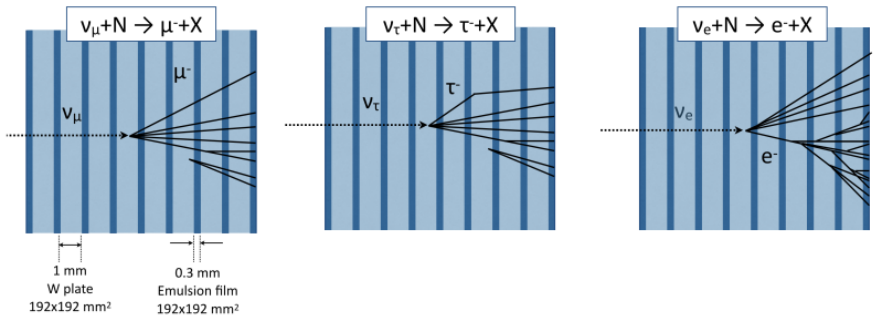
Data Taking and Event Reconstruction

Two phases of event reconstruction

- **Online with Electronic Detectors**
  - Identify signal candidates (neutrino or FIPs)
  - Tag muons (muon system)
  - Energy reconstruction through ECAL+HCAL

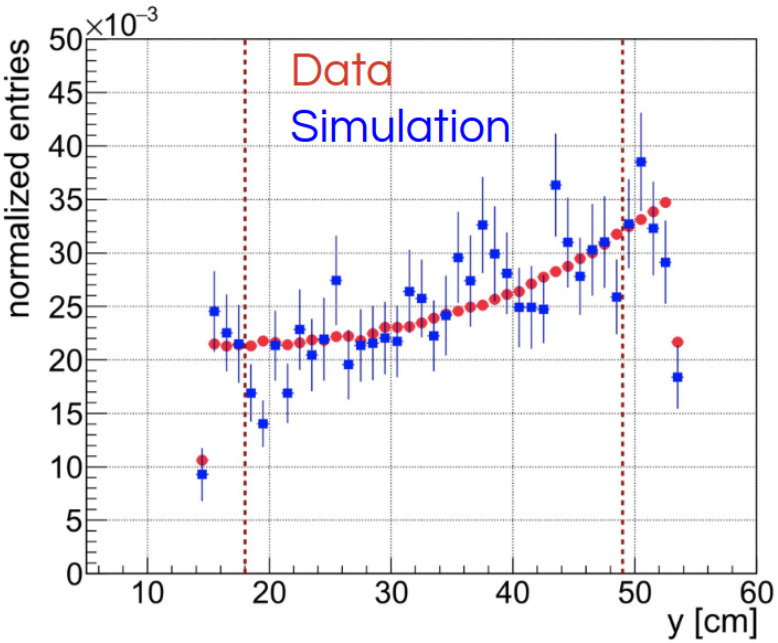


- **Offline with Emulsion Detectors**
  - Reconstruct vertices within micrometric resolution.
  - Match vertices with electronic data, get timestamp, reconstructed energy



Measurement of the muon flux at the SND@LHC experiment (Eur. Phys. J. C (2024) 84: 90)

- The IP1 muons constitute the main background source for SND@LHC.
- Dedicated muon flux measurement has been conducted.

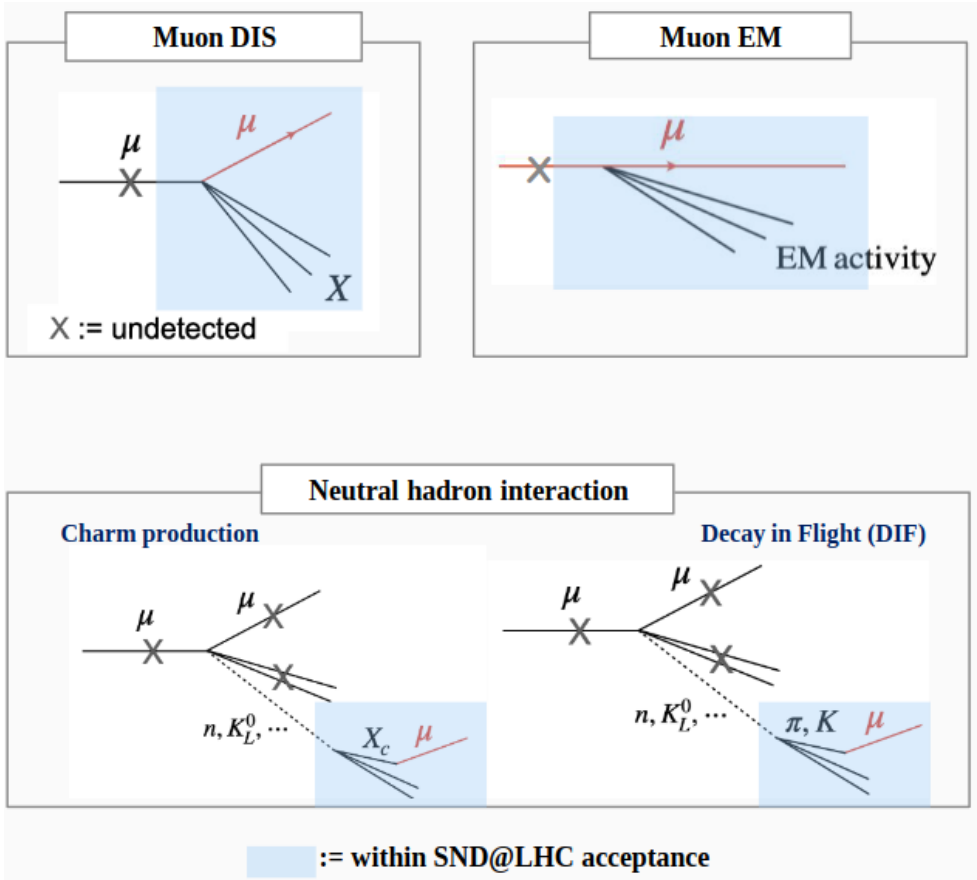


year	rate [Hz]	flux [trk/(fb/cm^{-2})]
2022–2023	557	1.8×10^4
2024	1154	3.8×10^4
2025	**782**	2.7×10^4

- Analysis of 2024 and 2025 data is ongoing.

Gradient along vertical direction observed in 2022-2023

Observation of Collider Muon Neutrinos with the SND@LHC Experiment (Phys.Rev.Lett. 131 (2023) 3, 031802)



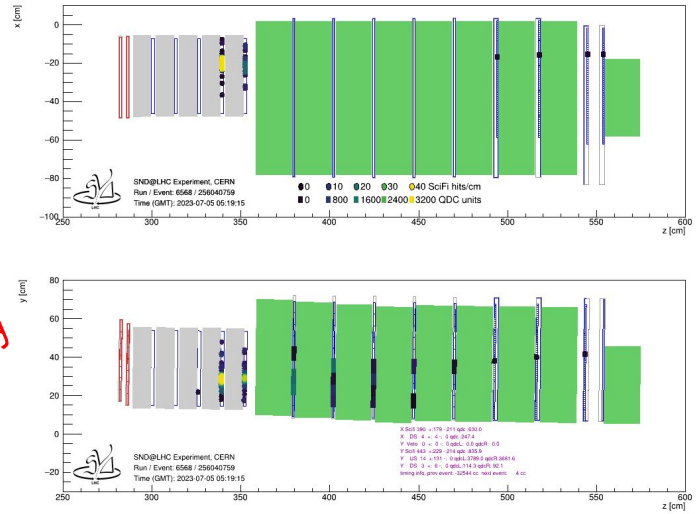
8 neutrino event candidates observed with a statistical significance of 6.8 σ

ν_μ Analysis Update

The search for ν_μ interactions is updated with extended fiducial volume and inclusion of 2023 data, results to be published.

Event Selection

- **Fiducial Volume**
  - Reject only vertices in the first wall
  - Reject side-entering backgrounds
- **ν_μ identification**
  - Large ECAL and HCAL activity
  - Single muon track associated to the vertex

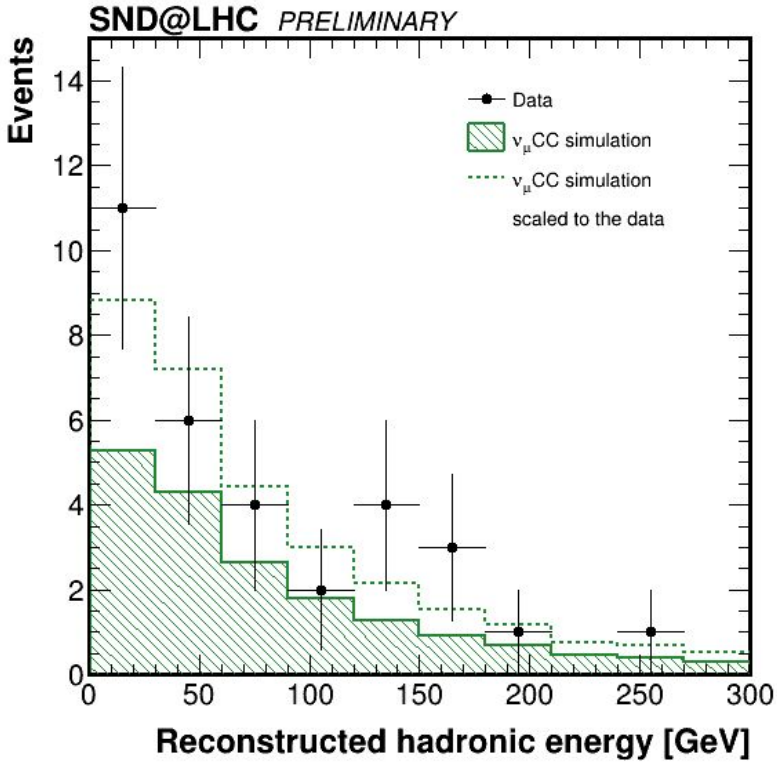


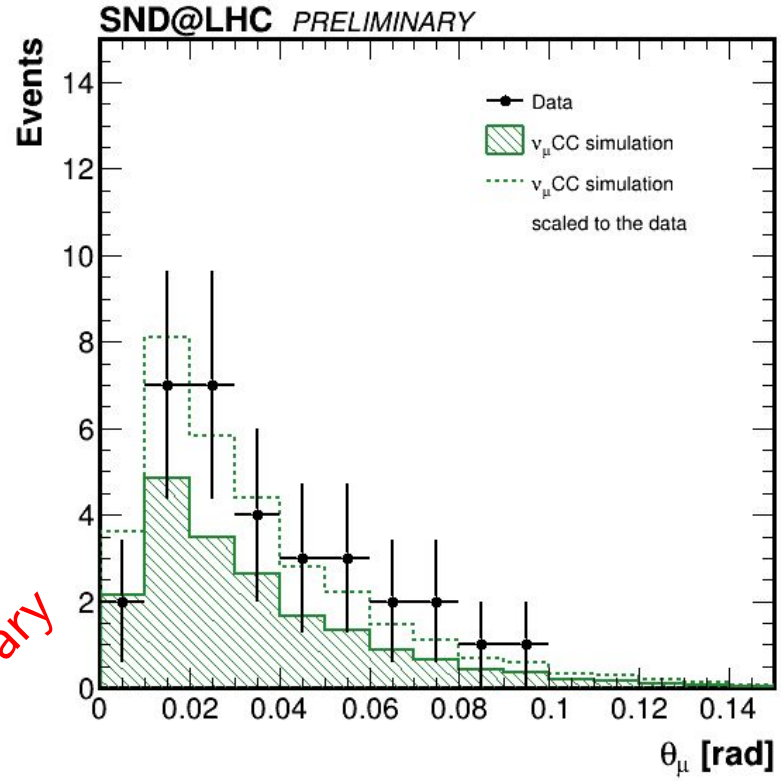
- Number of events expected in 68.6 fb^{-1} with extended fiducial volume
  - Signal: 19.1 ± 4.1
  - Neutral hadrons: 0.25 ± 0.06
  - Passing muons: 1.53

Number of events observed: 32

ν_μ Analysis Update

Kinematics of muon neutrino candidates agree with signal prediction.



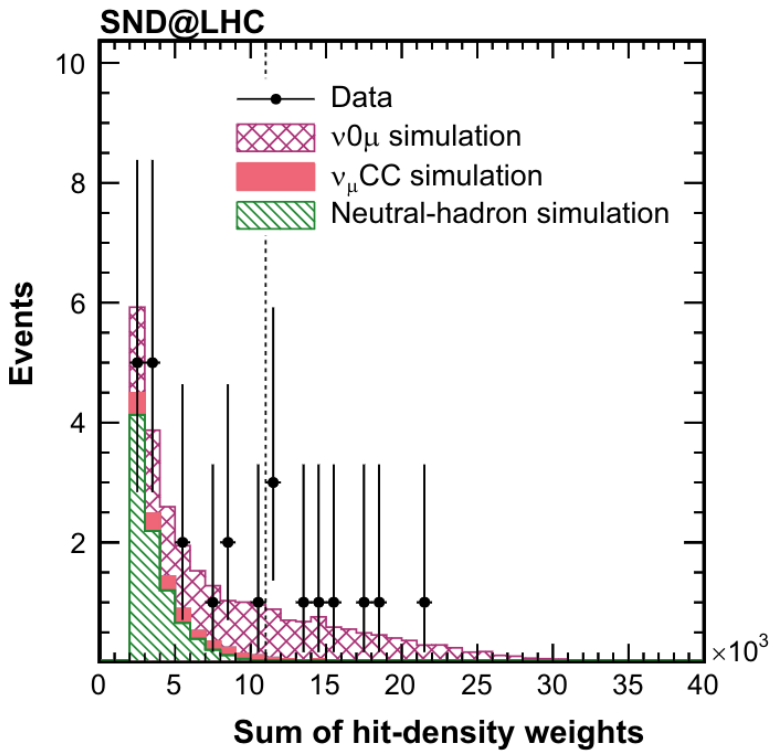


Preliminary

- 12-20 % energy resolution was achieved with the test beam campaign in 2023. [Paper submitted to JINST]

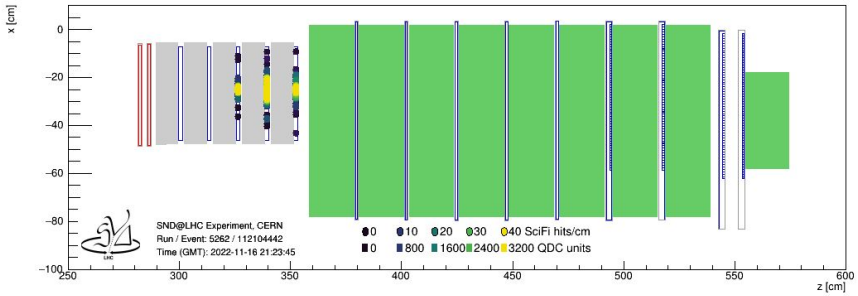
Observation of collider neutrinos without final state muons with the SND@LHC experiment (Phys. Rev. Lett. 134, 231802 – Published 13 June, 2025)

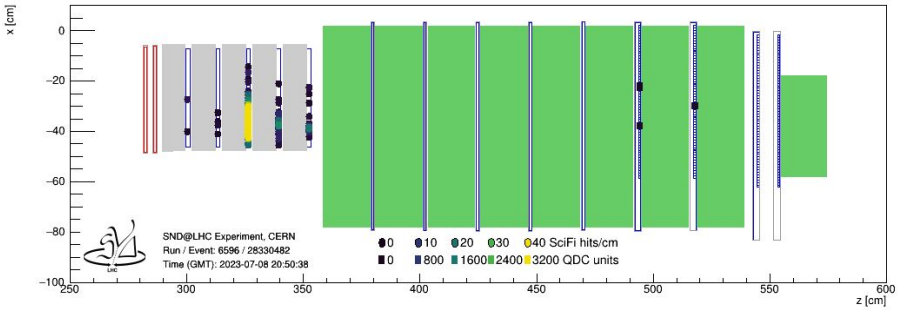
- **Signal** (0μ) : ν_e CC+ν_τ CC, NC
- **Backgrounds**
  - **Neutral Hadrons : 0.015**
    - cut on sum of hit-density weights at 11×10^3 maximizes the efficiency.
  - **Neutrino Background : 0.30**
    - Dominated by ν_μ CC
- **0μ Observation:**
  - **Expected signal:7.2 events**
    - 4.9 ν_e CC, 2.2 NC, 0.1 ν_τ CC
  - **Expected bkg: 0.32 $\pm$ 0.06**

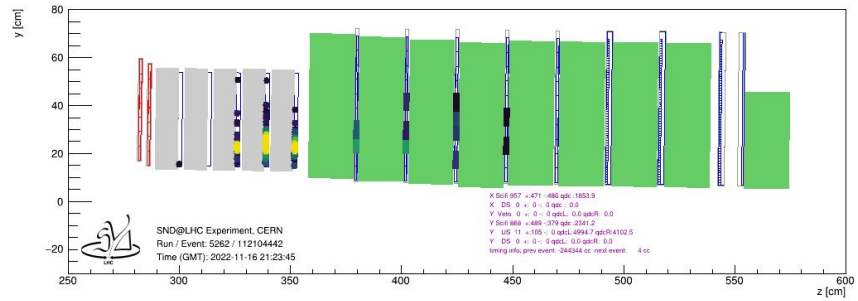


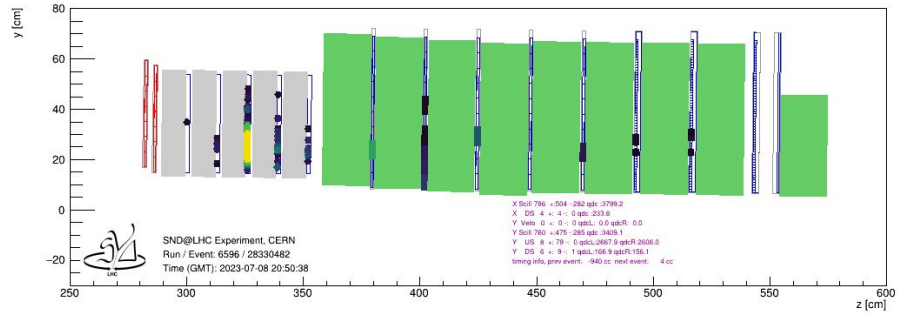
9 events observed with a significance of 6.4 σ

Search for 0μ Events



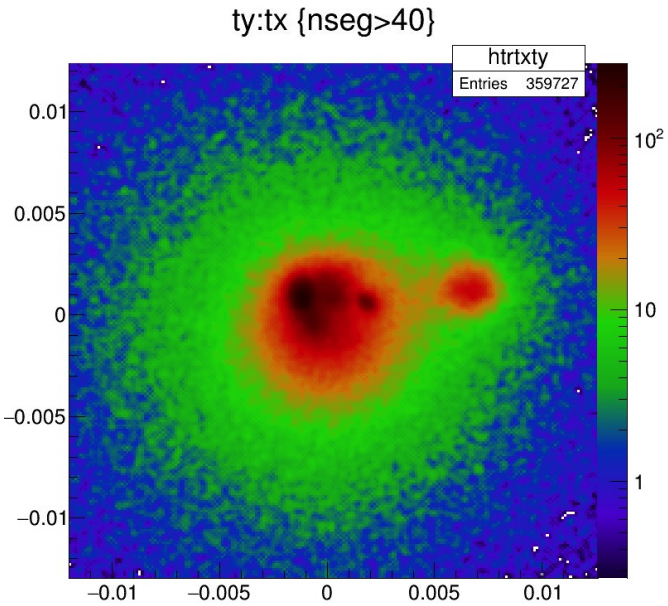


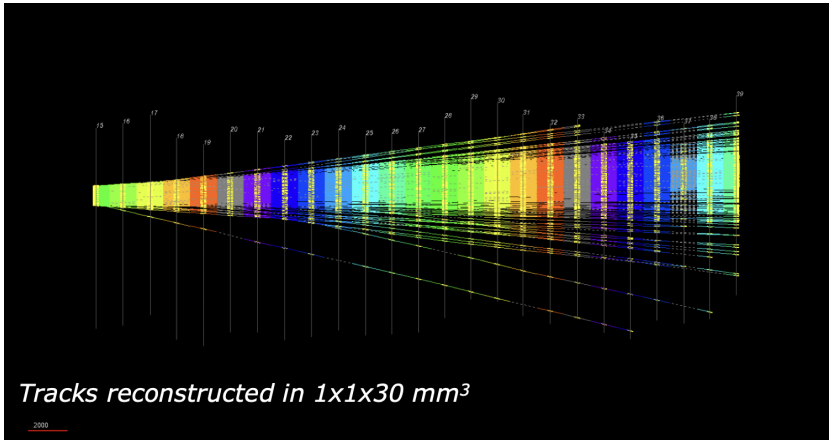


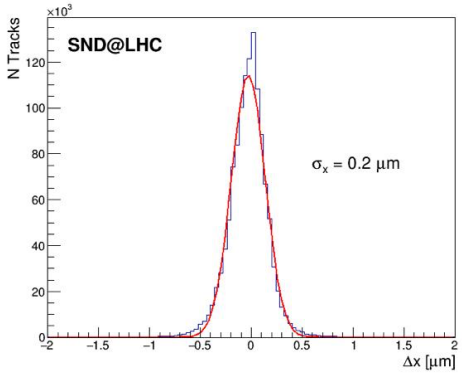


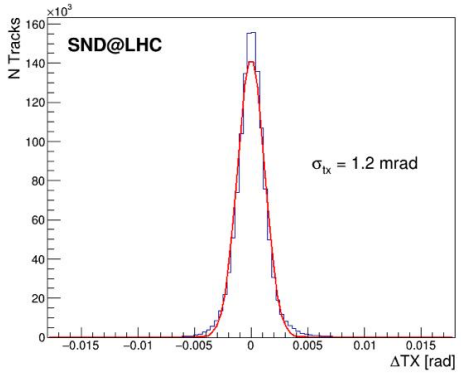
Emulsion Data Analysis

- Track density up to 4×10^5 tracks/cm^2 (factor 10^3 larger w.r.t. OPERA)
- Excellent tracking resolution achieved.



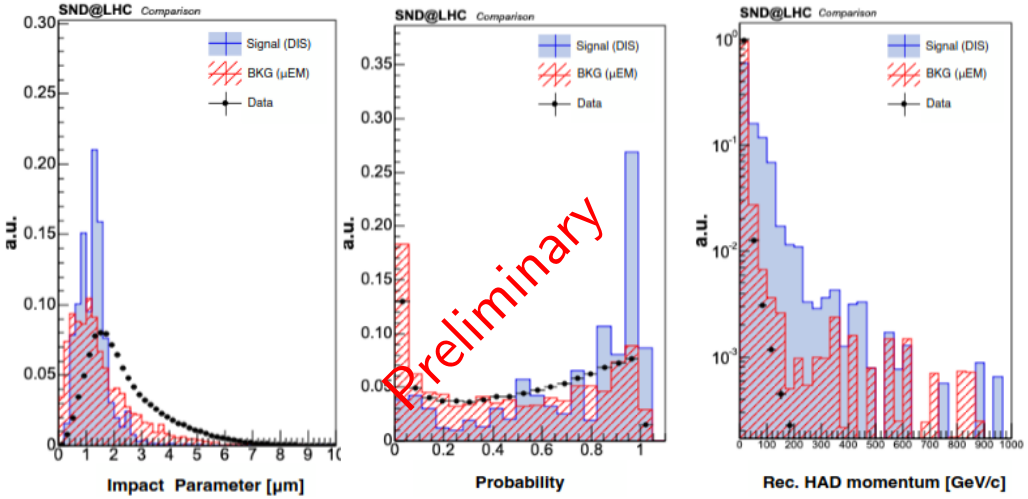


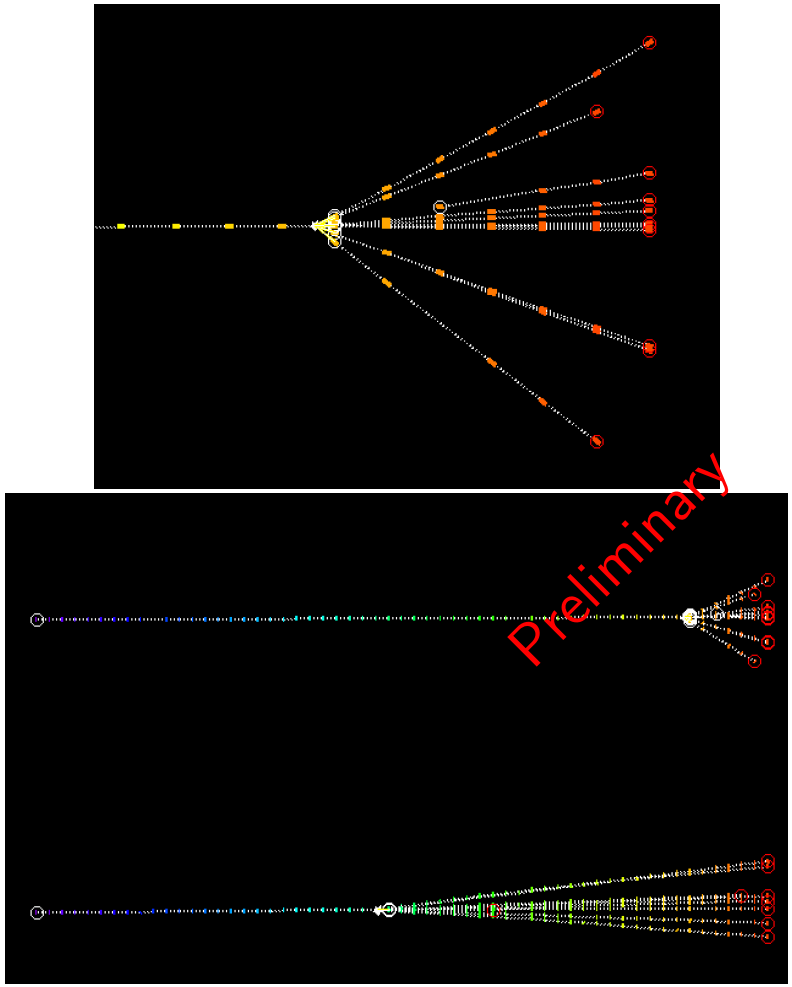




Observation of muon DIS in emulsion data

- The identification of muon DIS in the emulsion target was done with a cut-based approach on topological and kinematical parameters.



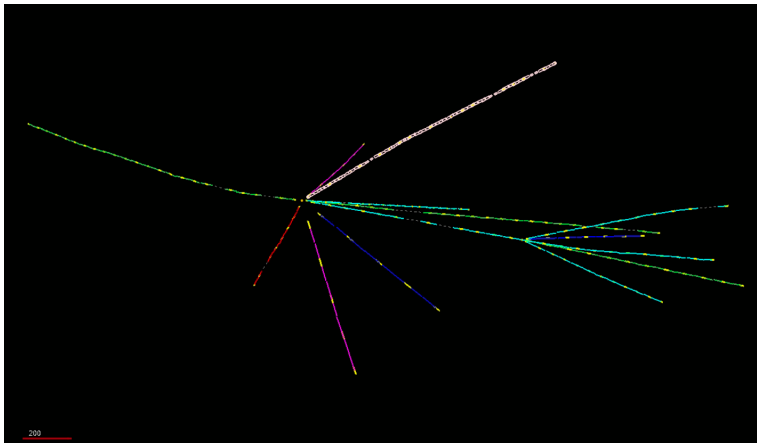


Observed: 992 ± 32

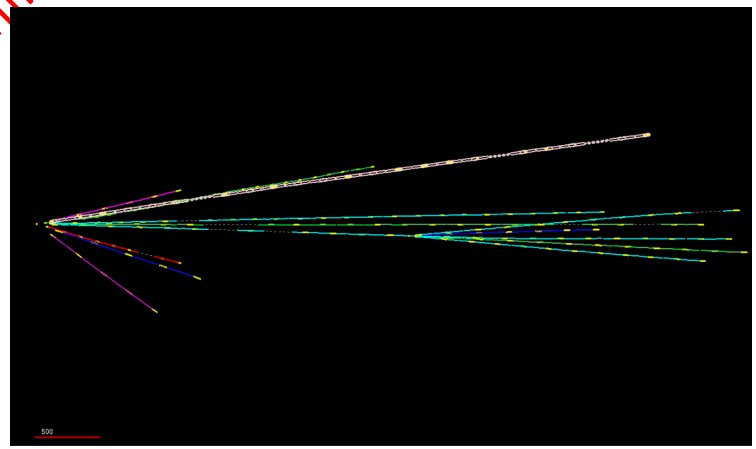
Expected: 1105 ± 69

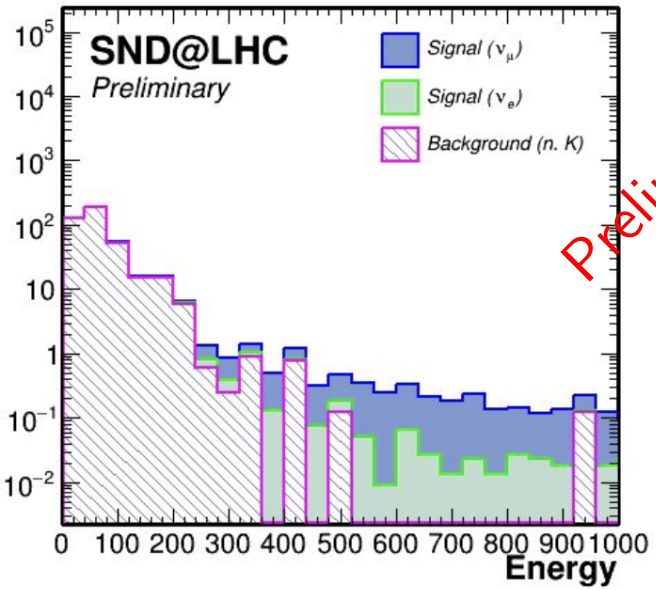
Neutrino Search in Emulsion Data

- Vertex search is ongoing

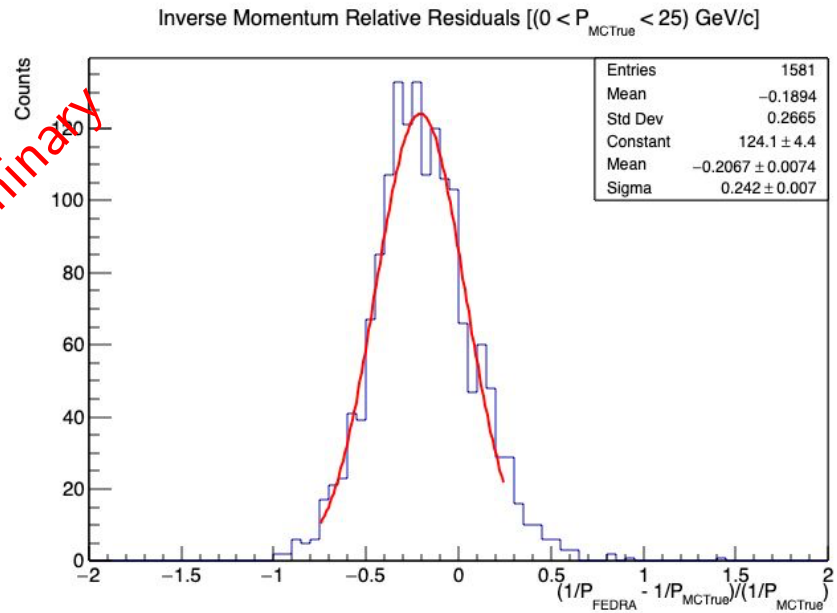


Preliminary



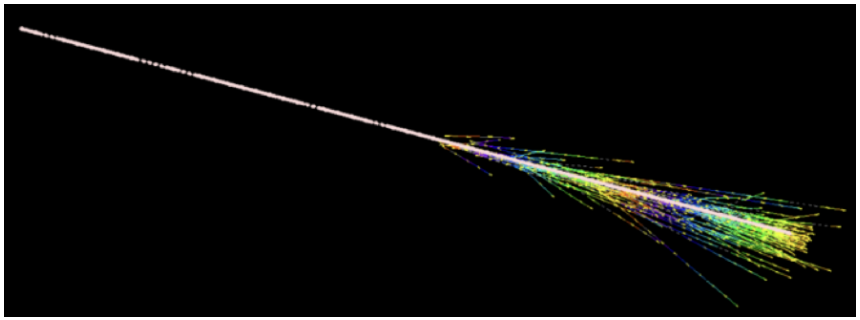


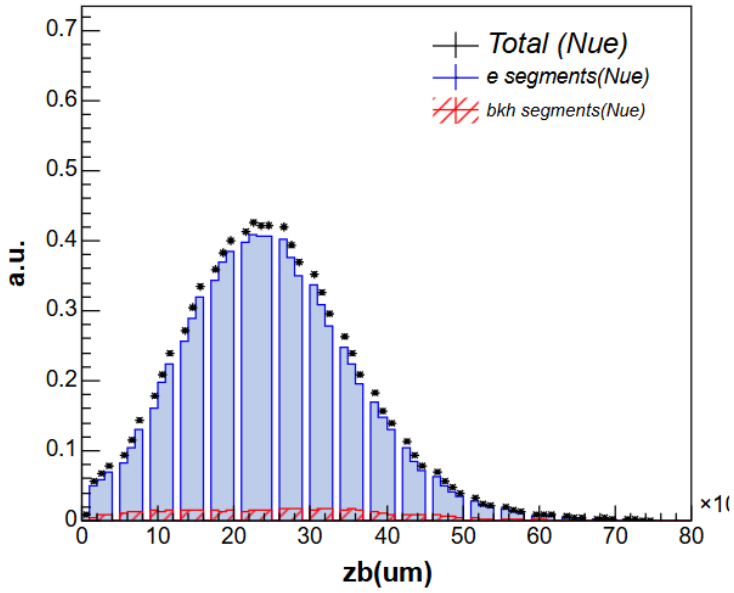
Preliminary



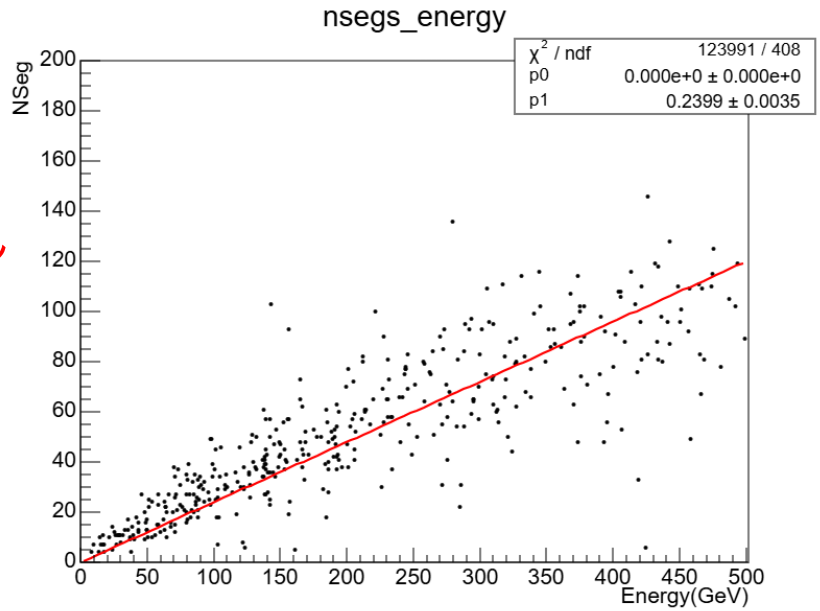
Electron Identification in Emulsion Target

- Electron ID based on EM shower identification
- Electron energy estimate based on number of segments at the shower maximum proportional to electron energy.

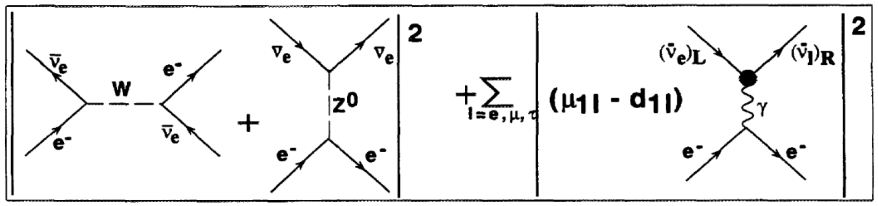




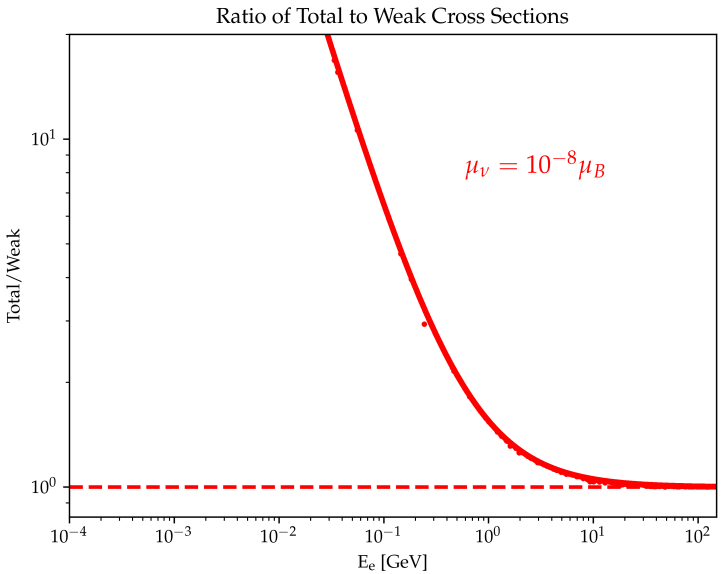
MC

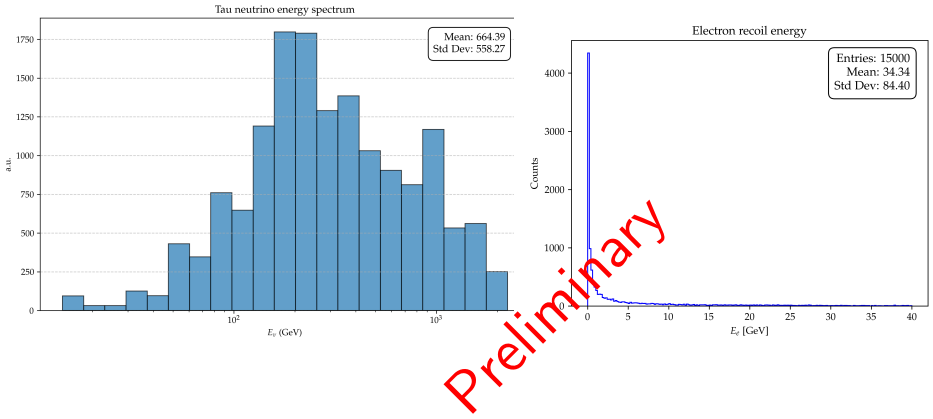


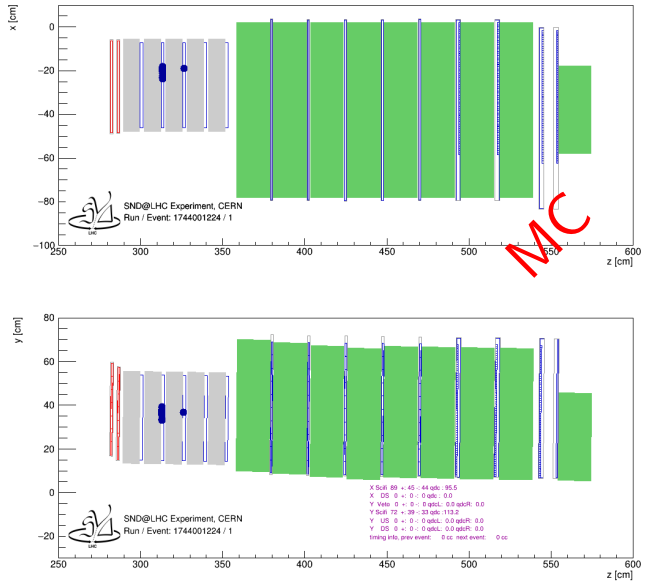
ν_τ Magnetic Moment



- The best limit on the magnetic moment of the tau neutrino has been established by the DONuT collaboration (2001) :
  $\mu_{\nu_\tau} < 3.9 \times 10^{-7} \mu_B$



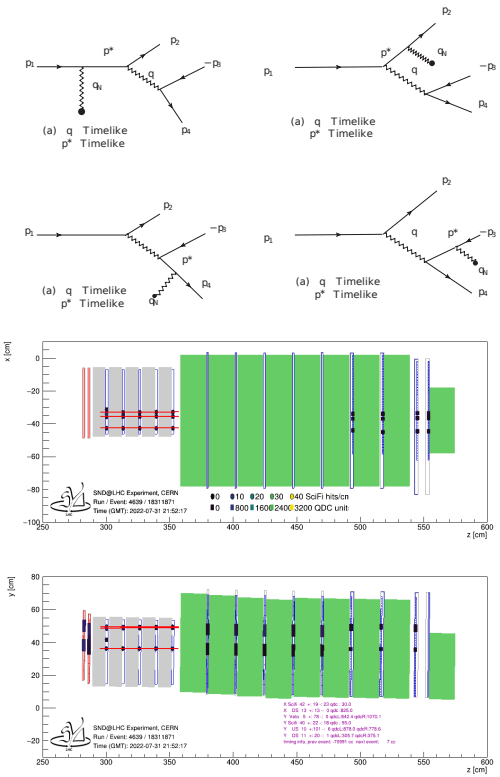


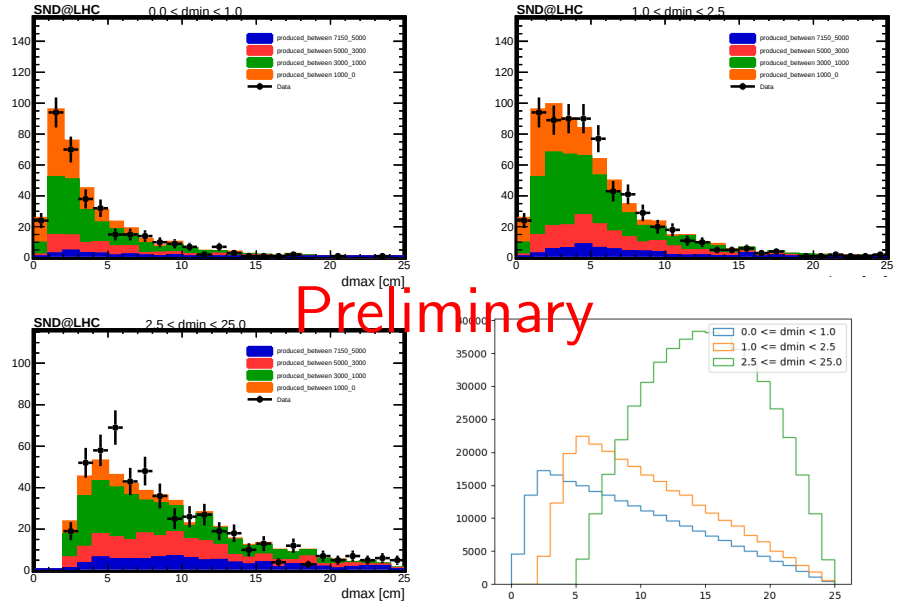


Non-Neutrino Physics

In addition to neutrinos, other physics analyses are ongoing

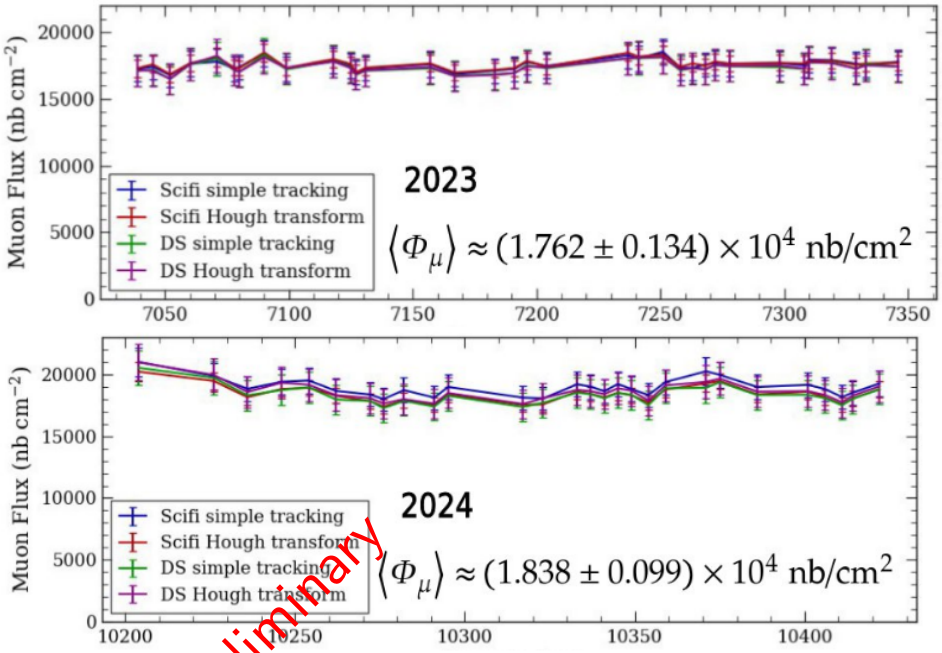
- Muonic Trident cross section measurement will be performed inside the rock.

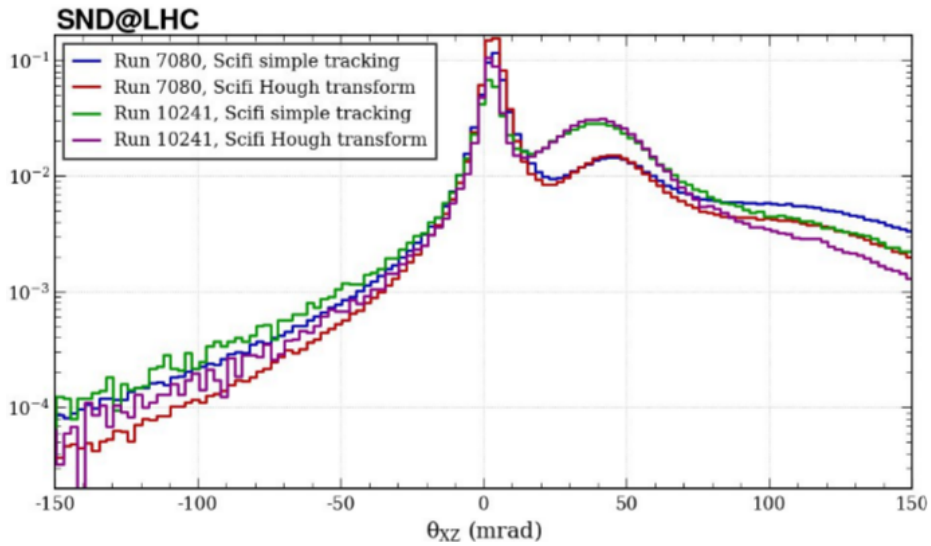




Non-neutrino physics

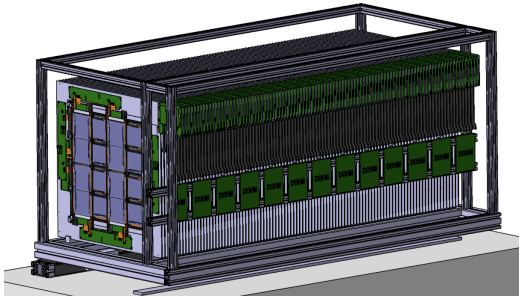
- Muon flux measurement with heavy ion runs. MC expectation : 1.56 $\pm$ 0.19 $\times$ 10^4 nb/cm^2, well agreement with measured flux.

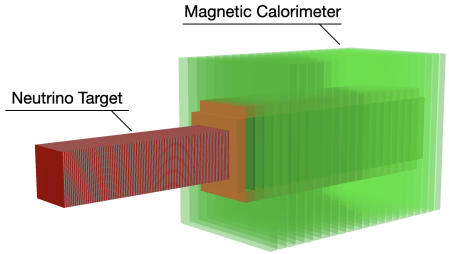




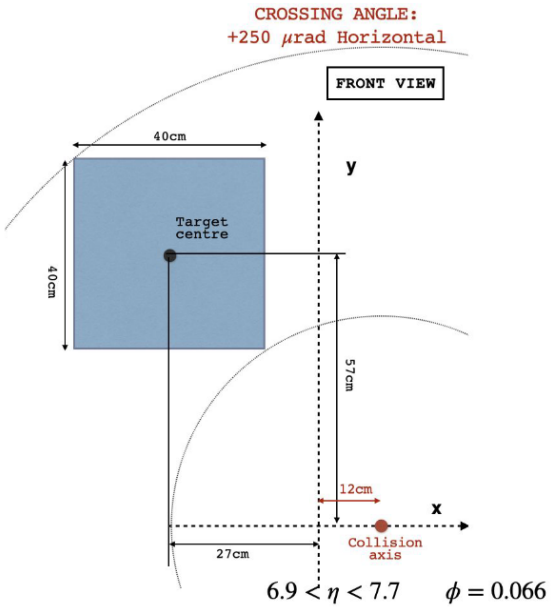
Future Upgrades: HL-LHC

- Iron core magnetic spectrometer identify ν_μ and $\overline{\nu}_\mu$
- Vertex detector with Si detector.
  - will be recycled from the CMS outer barrel tracker.
- Improved HCAL and timing detectors





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



Summary

- SND@LHC is running successfully since the start of LHC RUN3.
- Dedicated background studies have been done together with the measurement of the muon flux.
- First observation of neutrinos produced in *pp* collisions
- ν_μ CC analysis is ongoing with 2023 data.
- 9 non-ν_μ CC (ν_e CC+ν_τ CC+NC) neutrino events were observed and published in PRL.
- Excellent resolution is achieved in emulsion, and neutrino analyses are ongoing on the emulsion side.
- The search for muonic tridents and muon DIS are also being studied.
- The detector will be upgraded in LHC Run 4.

Back up slides

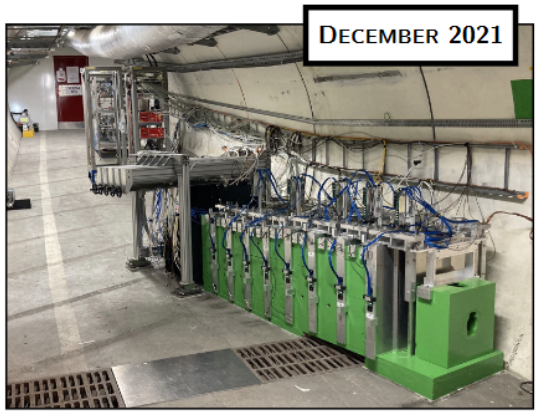
Data Taking and Event Reconstruction

August 2020: Letter of Intent published

March 2021: Approvel by CERN Research Board

December 2021: Detector installed

April 2022: First data taken



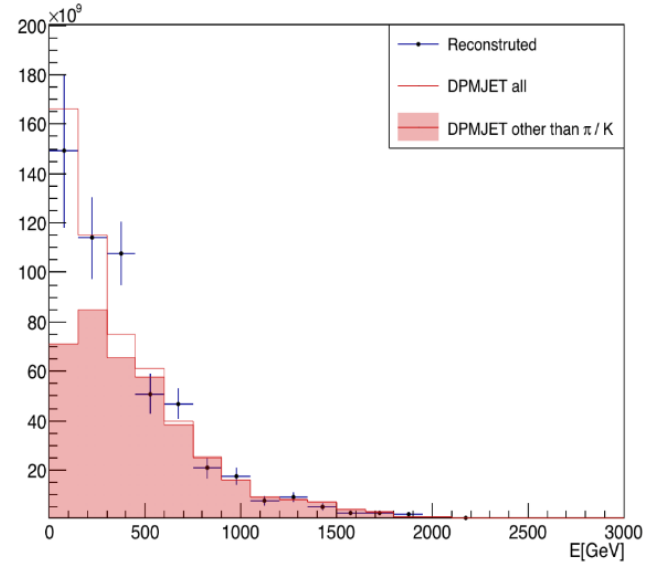
- SND@LHC is operating since the start of LHC RUN3

Physics Motivation

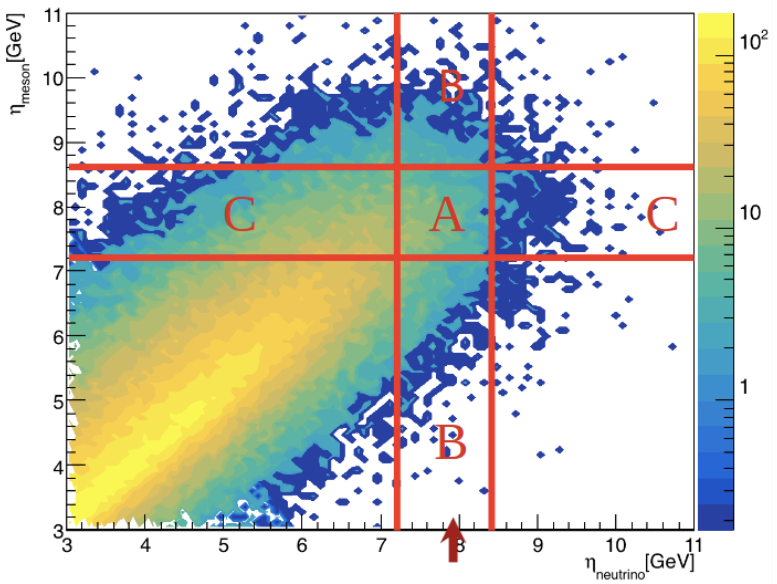
Heavy Flavour Physics

- 90 % of ν_e and $\bar{\nu}_e$ produced SND@LHC come from charmed hadron decays. This provides opportunities to:
  - Measure $pp \to \nu_e X$ cross section.
  - Measure forward charm production through neutrinos
  - Constrain gluon PDF at very small x

Reconstructed nue nue energy spectrum in acceptance

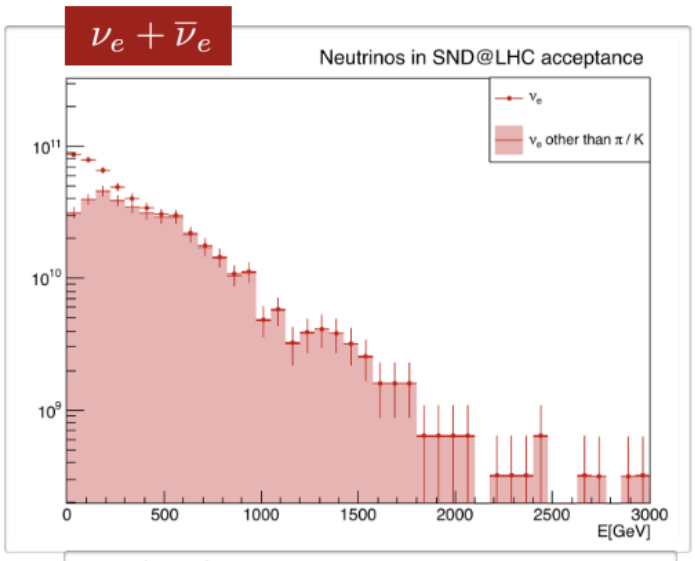


Correlation between pseudo-rapidity of the (anti-) electron neutrino and the parent charmed hadron

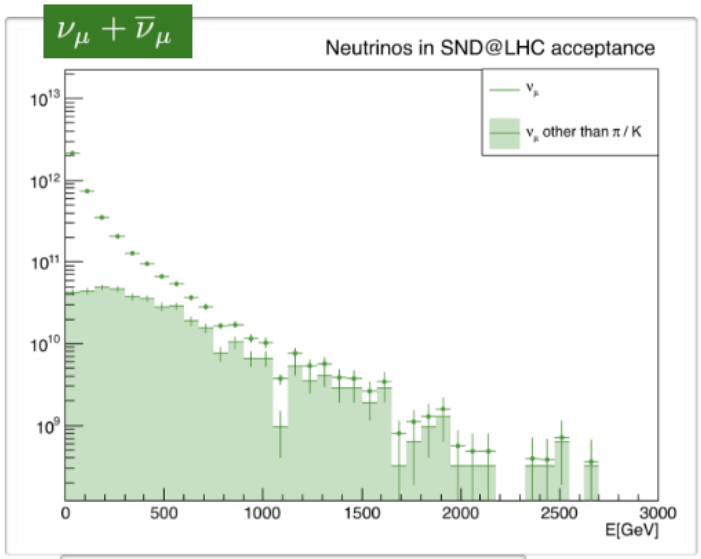


Physics Motivation

- **Lepton Flavor Universality Test (LFU)**
  - The identification of three neutrino flavours in the SND@LHC detector offers a unique possibility to test the Lepton Flavor Universality(LFU).



$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$



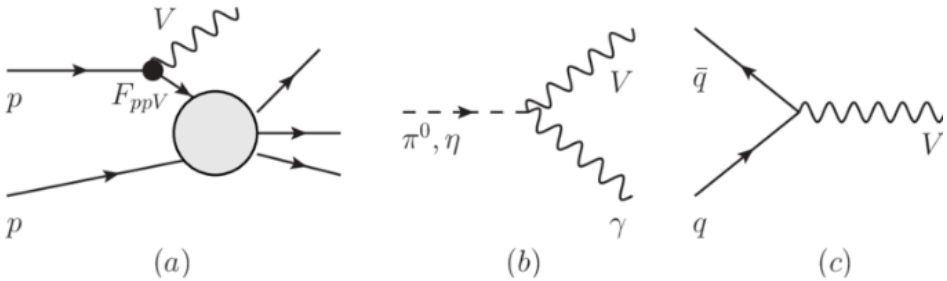
$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

π/K contaminati

Physics Motivation

SND@LHC experiment can probe into large variety of Beyond Standard Model (BSM) scenarios describing Hidden Sector

- FIPs production mechanisms (Bremsstrahlung (a), Meson Decay(b) and Drell-Yan (c))



- FIP interaction: Elastic Scattering(Left), Ineastic Scattering (Right)