First results from the SND@LHC experiment

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on behalf of SND@LHC collaboration

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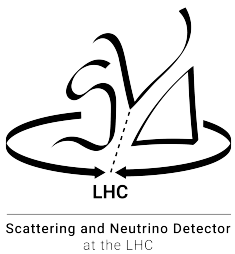


April 6, 2024

Physics Programme

- **Neutrino Interactions**
  - Detect neutrino interactions in unexplored TeV energy range
  - Measure NC/CC ratio as internal consistency check.
  - Large yield of ν_τ will be more than double existing data.
    - About 20 events observed by DONuT and OPERA
- **Heavy flavour physics**
  - 90 % of ν_e and $\overline{\nu}_e$ produced in SND@LHC come from charmed hadron decays. This provides opportunities to:
    - Measure $pp \rightarrow \nu_e X$ cross section.
    - Measure forward charm production through neutrinos.
    - Constrain gluon PDF at very small x.
- **Lepton 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).
- **Beyond Standard Model**
  - SND@LHC experiment can probe into large variety of Beyond Standard Model (BSM) scenarios describing Hidden Sector.

Scattering and Neutrino Detector @ LHC

Veto system

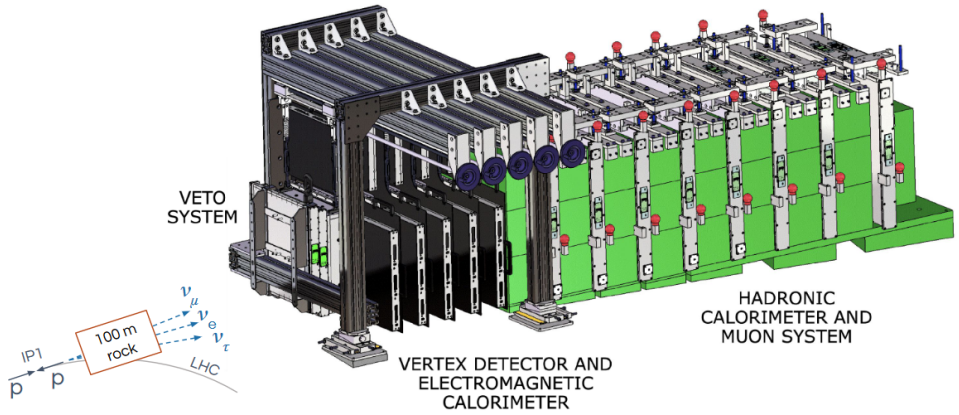
- 2+1 planes of stacked scintillator bars. (Additional vertical plane installed in 2024)
- Rejects charged particles entering the detector volume

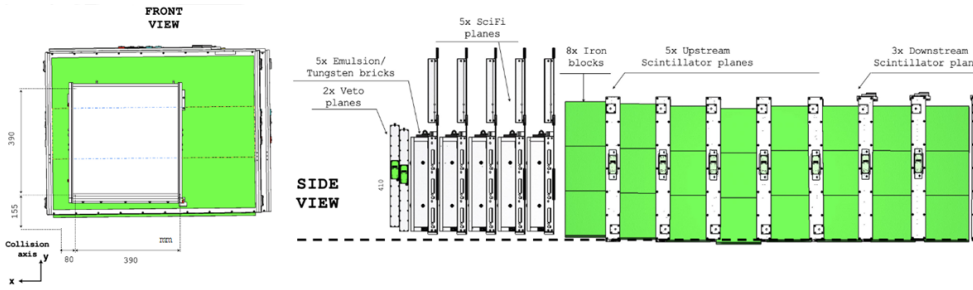
Target, Vertex detector and ECAL

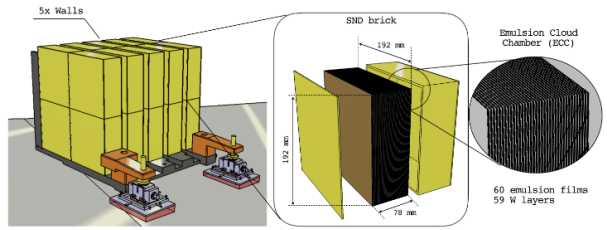
- 830 kg target made of tungsten.
- 5 walls with 4 Emulsion bricks
- Five scintillating fibre stations serve as ECAL, timestamp of vertices
- 84 X_0, 3 λ_{int}

HCAL and MUON system

- Eight plastic scintillator planes interleaved by 20 cm thick Fe blocks
- Last 3 downstream planes with higher granularity to track muons 9.5λ_{int}



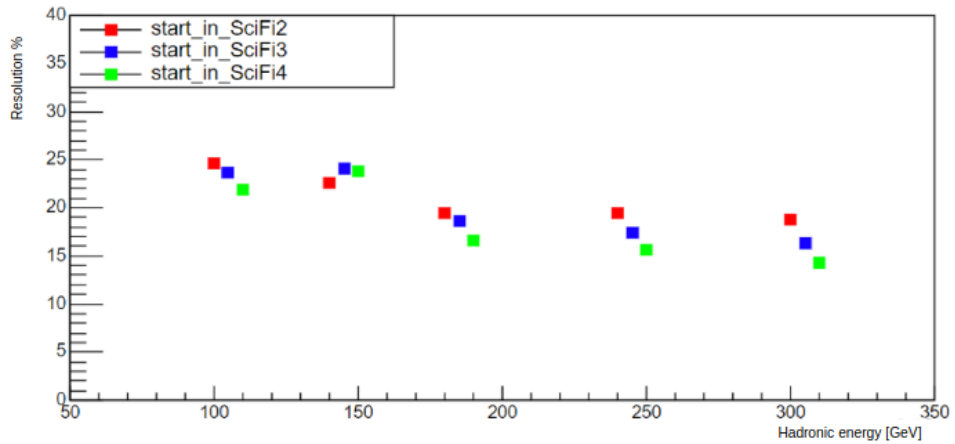


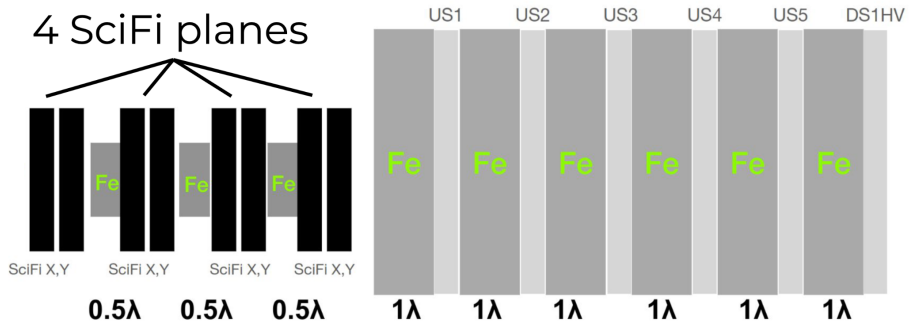


August 2023 Test Beam

- Test beam for hadronic energy calibration has been done in 2023.
- Exact same replica of HCAL together with downsize target

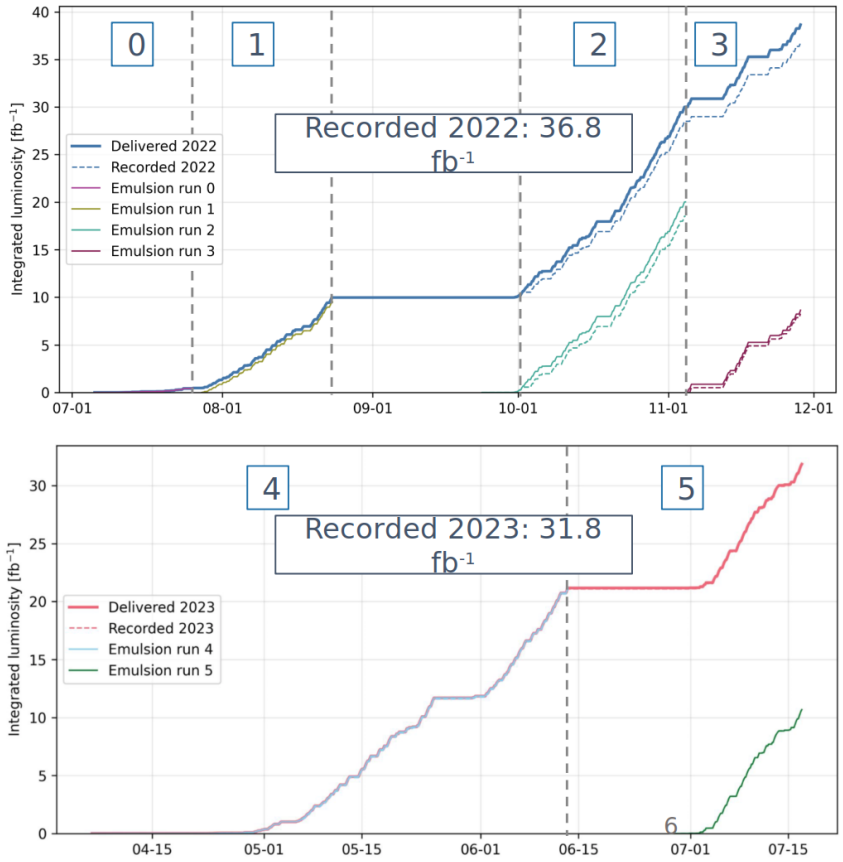
The resolution of hadronic energy is within 15-25 %





Data Taking and Event Reconstruction

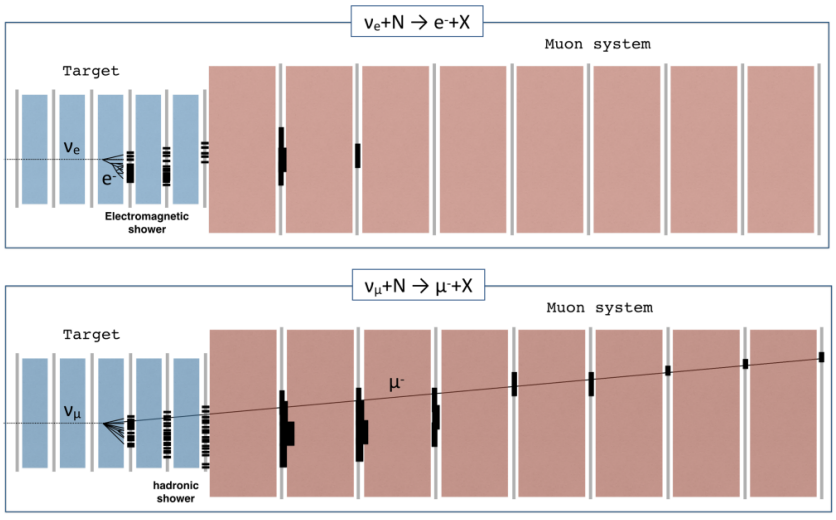
- Recorded lumi of pp collisions in **2022** and **2023** data taking campaigns: **68.6** fb^{-1}
  - Uptime of 97 %
- Emulsion wall extraction after few months of exposure.
  - Keep integrated tracks at a reasonable level later for analysis.
  - Scanning done in parallel in different laboratories after chemical development.



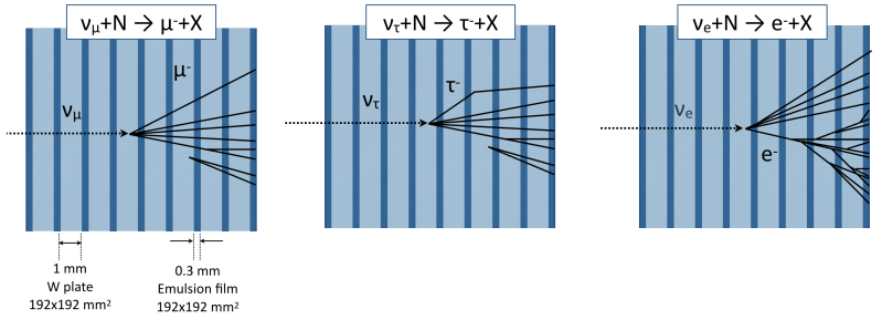
Data Taking and Event Reconstruction

Two phases of event reconstruction

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

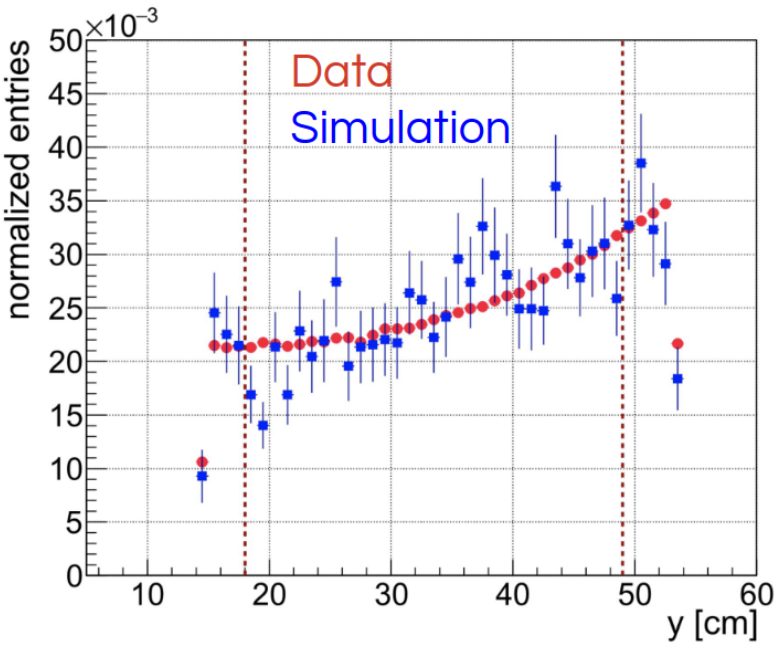


- **Offline with Emulsion Detectors**
  - Reconstruct vertices within micrometric resolution.
  - Match vertices with electronic data, get timestamp, reconstructed energy



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

- Muons from IP1 constitute the major background source for SND@LHC.
- Dedicated muon flux measurement has been conducted.

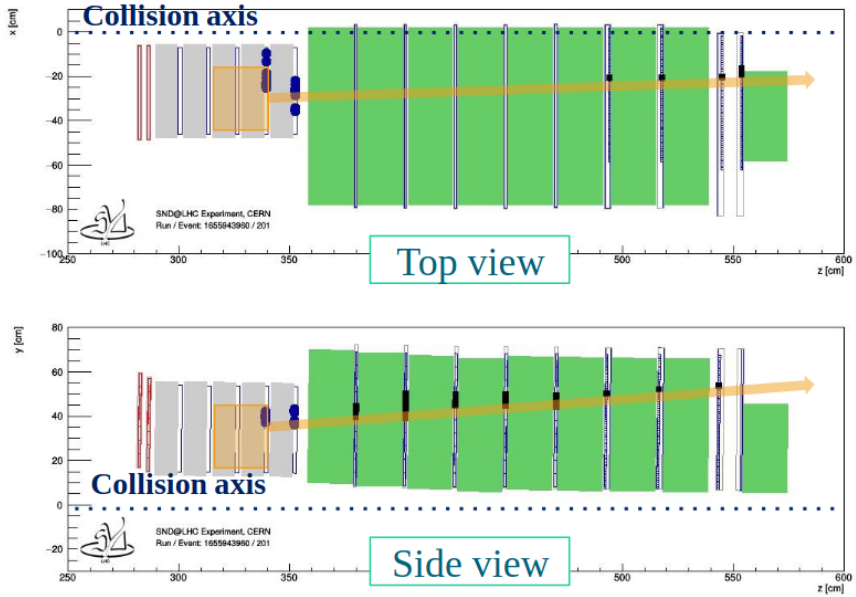


System	Muon flux ($[10^4 fb/cm^2]$)
SciFi	$2.06 \pm 0.01(stat.) \pm 0.12(sys.)$
DS	$2.02 \pm 0.01(stat.) \pm 0.08(sys.)$

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

Event Selection

- **Fiducial Volume**
  - Neutral vertex 3^{rd} or 4^{th} wall
  - Reject side-entering backgrounds
  - Signal acceptance: 7.5%
- ν_μ **identification**
  - Large ECAL and HCAL activity
  - Single muon track associated to the vertex
  - Signal selection efficiency: 36%



ν Simulation

- Neutrino Production : DPMJET
- Particle Transportation to SND@LHC: FLUKA
- Neutrino Interaction: GENIE

Number of ν_μ CC events expected in $36.8 fb^{-1}$ after cuts: 4.2

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

Backgrounds:

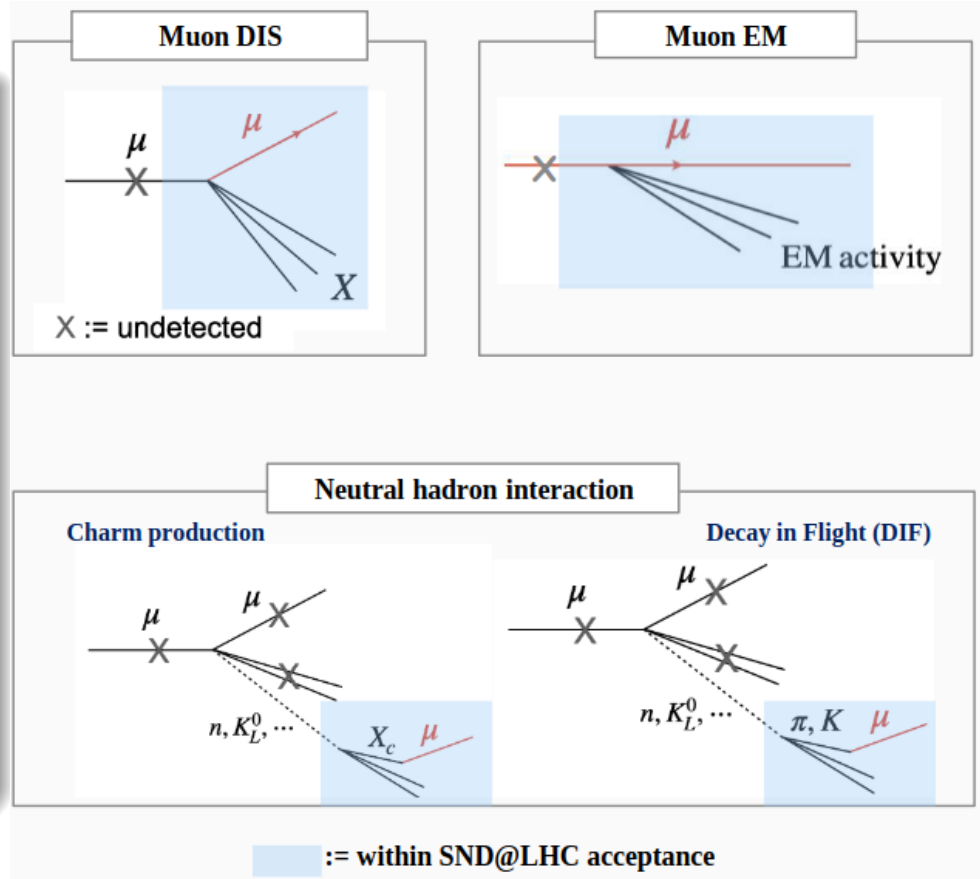
i. Passing through muons

- Incoming muon track might be missed due to veto inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5×10^{8}
- Detector inefficiency: 5×10^{-12}.
- Negligible background with tight fiducial cuts.

ii. Neutral hadrons

- Neutral hadrons produced in muon DIS with surrounding material.
- Expect a total of $(8.6 \pm 3.8) \times 10^{-2}$ background events due to neutral hadrons

Observed 8 neutrino event candidates with a statistical significance of 6.8 σ (Phys.Rev.Lett. 131 (2023) 3, 031802)



$$N_{\mu}^{bkg} = N_{\mu} \times (1 - \epsilon_{Veto}) \times (1 - \epsilon_{Scifi1}) \times (1 - \epsilon_{Scifi2})$$

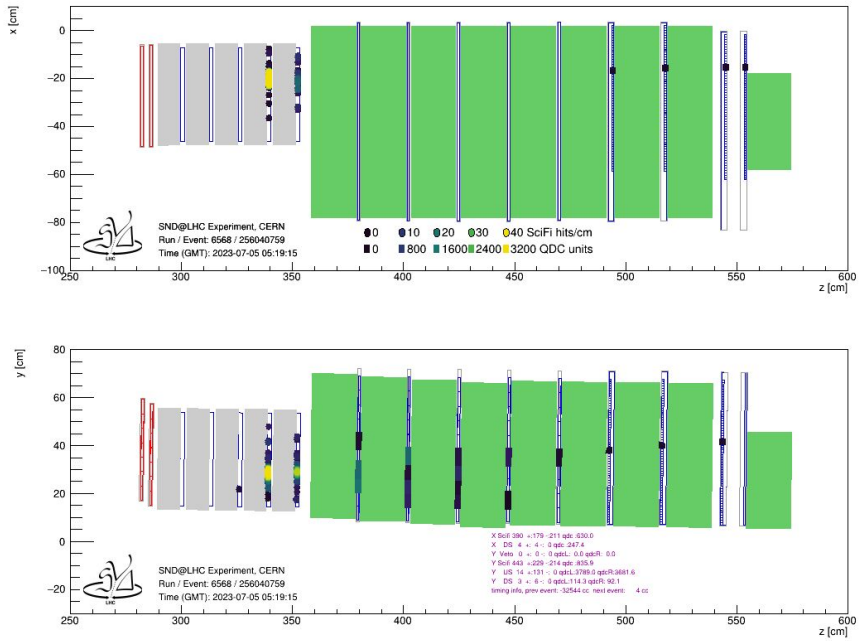
$$N_{neutrals}^{bkg} = N_{neutrals} \times P_{inelastic} \times \epsilon_{selection}$$

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

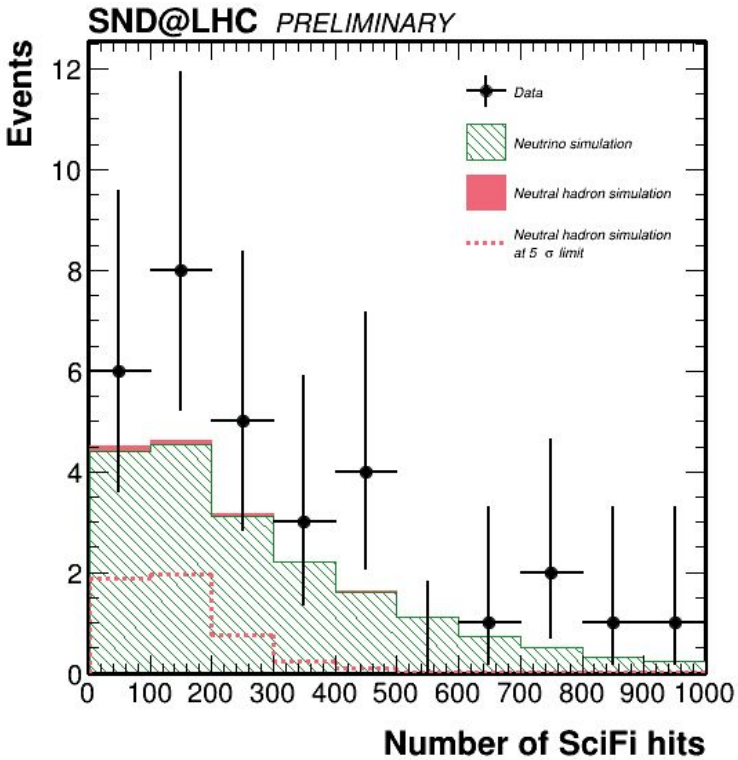
- **Fiducial Volume**
  - Reject only vertices in the first wall
  - Reject side-entering backgrounds
  - Signal acceptance: 18%
- **ν_μ identification**
  - Large ECAL and HCAL activity
  - Single muon track associated to the vertex
  - Signal selection efficiency: 36%

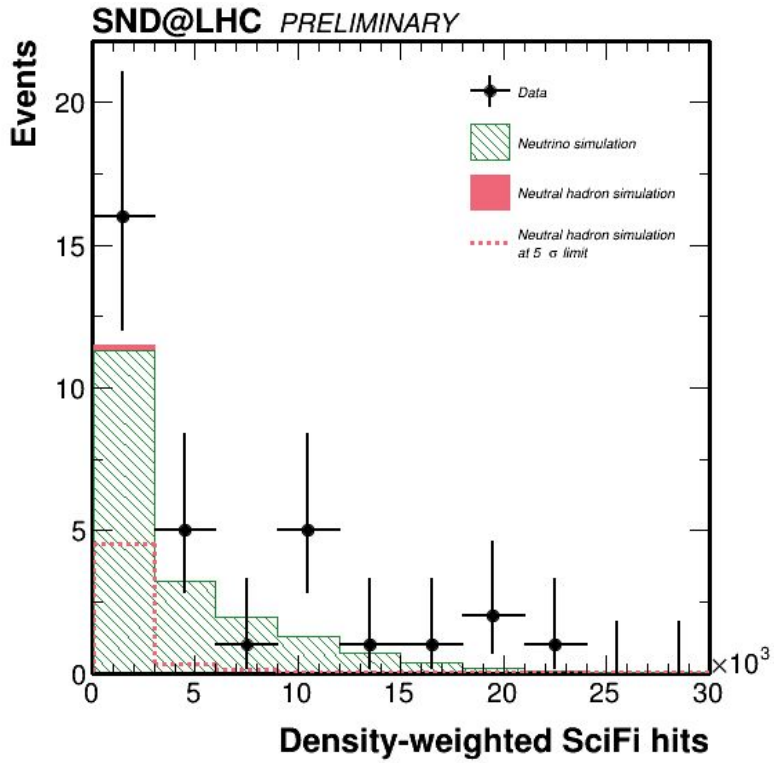


Updated ν_μ Search

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

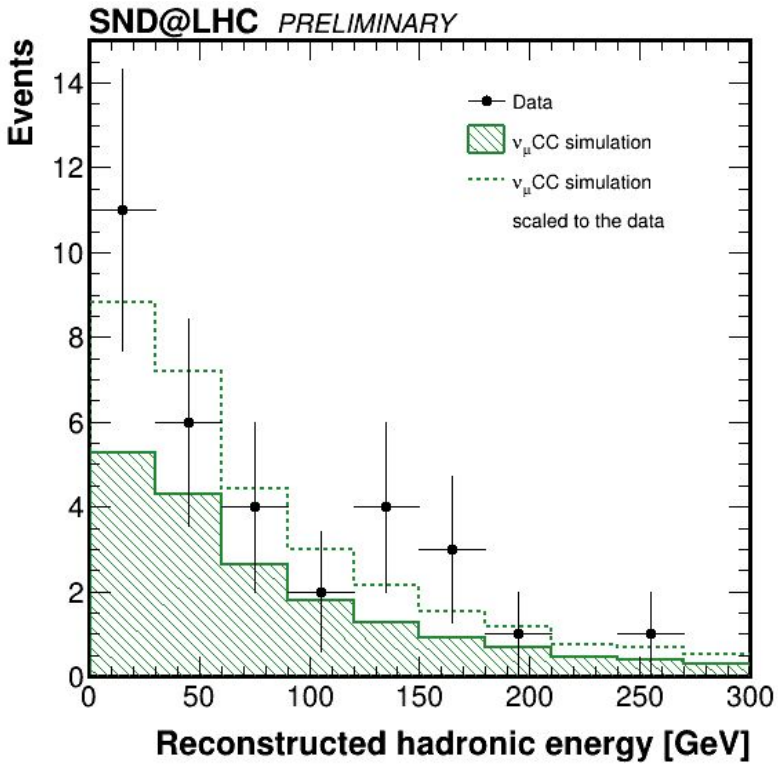
Number of events observed: 32

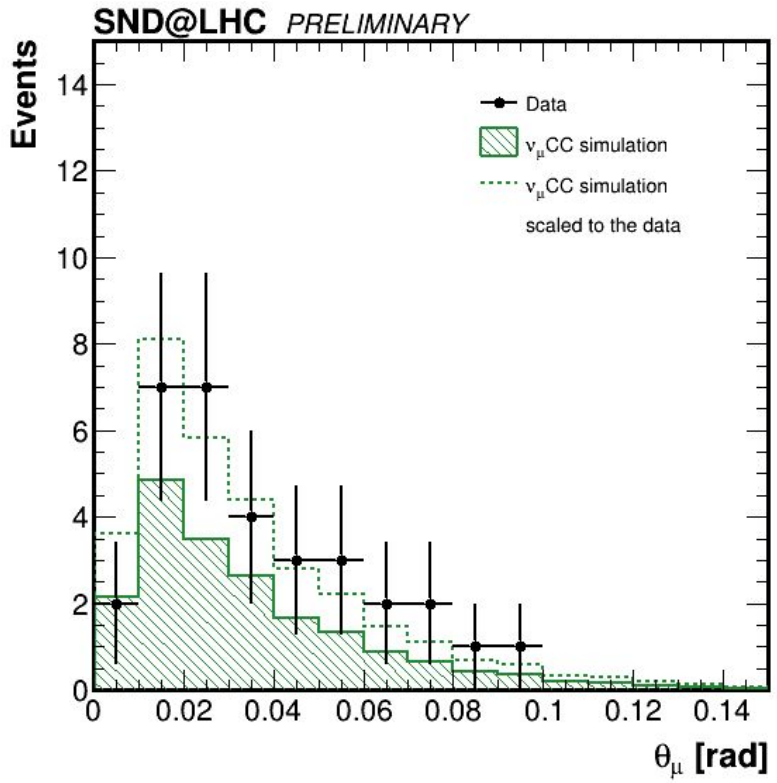




Updated ν_μ Search

Kinematics of muon neutrino candidates are in agreement with the signal prediction.





Search for 0μ Events

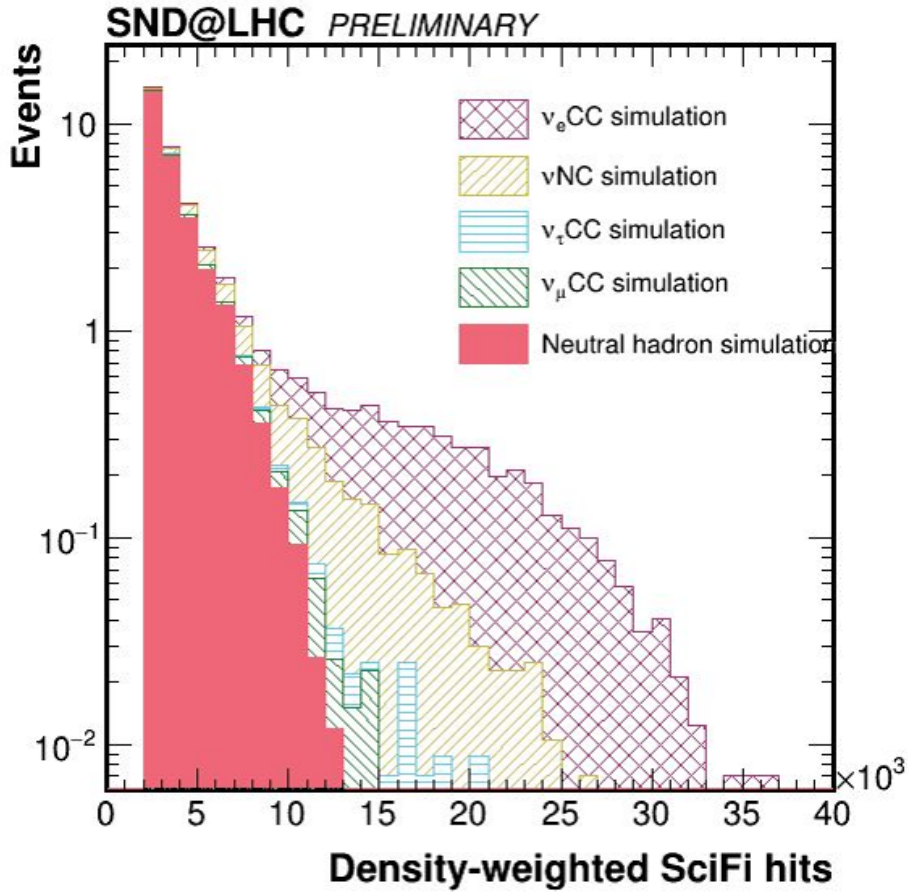
Search for shower-like events accounting for signal ν_e CC and NC interactions is ongoing.

Fiducial volume

- No hits in the veto detector.
- Reject side-entering events
- Signal acceptance: 12 %

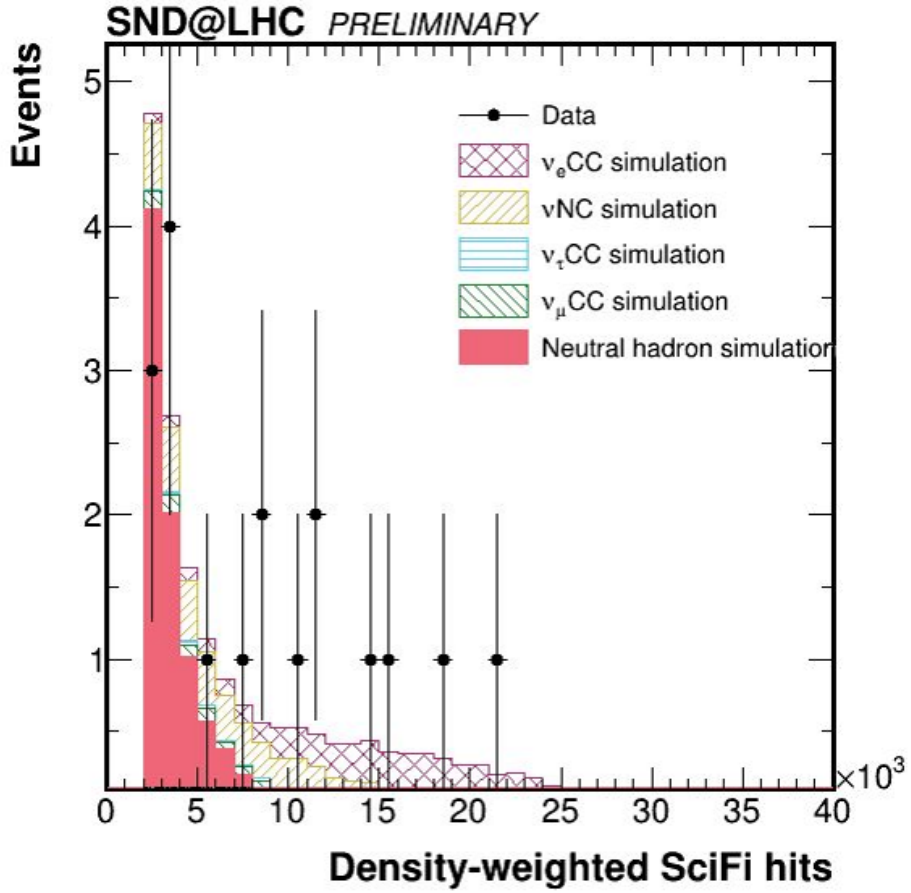
Signal Identification

- Large ECAL+HCAL activity
- No tagged muons
- Optimized Density-weighted number of hits in the most active station to maximize expected significance
- Signal selection efficiency: 42 %

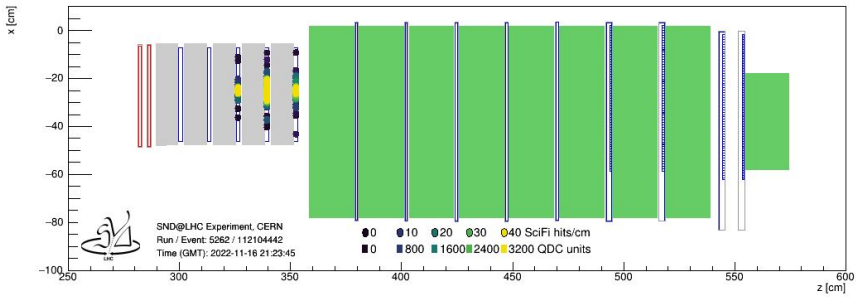


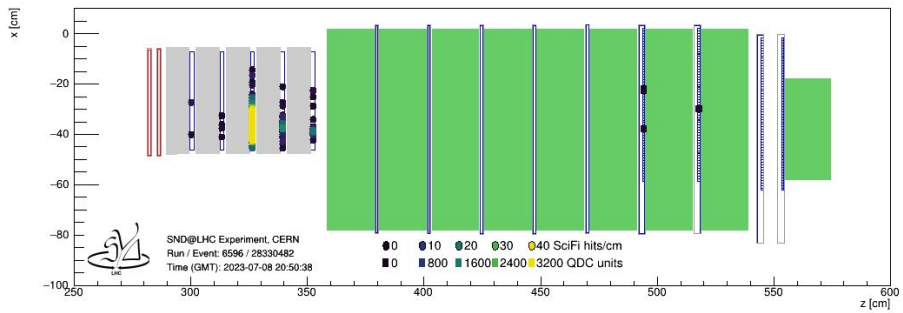
Search for 0μ Events

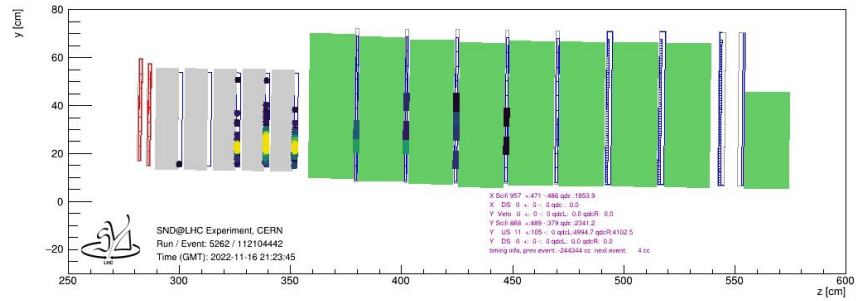
- Introduce control region (between 2×10^3-5×10^3)dominated by the neutral background to measure the background.
- Scale the number of expected background to the number of observed events in the control region.
  - Observed neutral hadron background is 1/3 of the expected value.
- Expected neutral hadron background in the signal region:0.01
- ν_μ CC interactions are the dominant background, expected:0.12
- Expected background from ν_τ CC interactions:0.07
- **Total expected background:** 0.20 ± 0.11 **events**
- **Expected signal: 4.66 events**

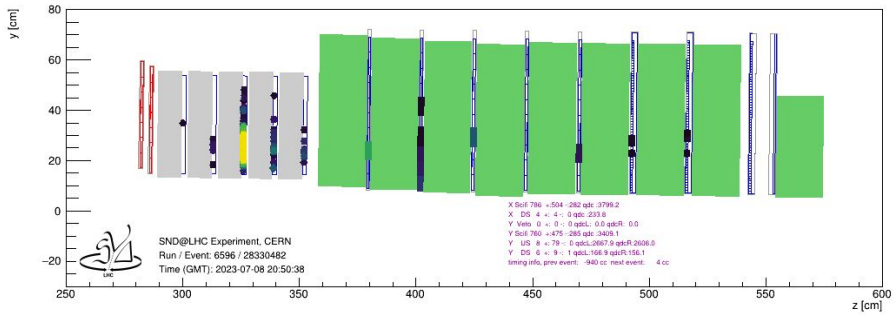


Search for 0μ Events





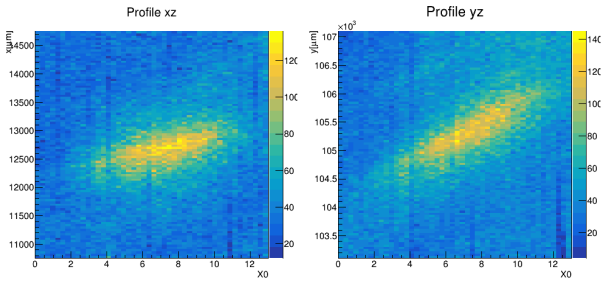


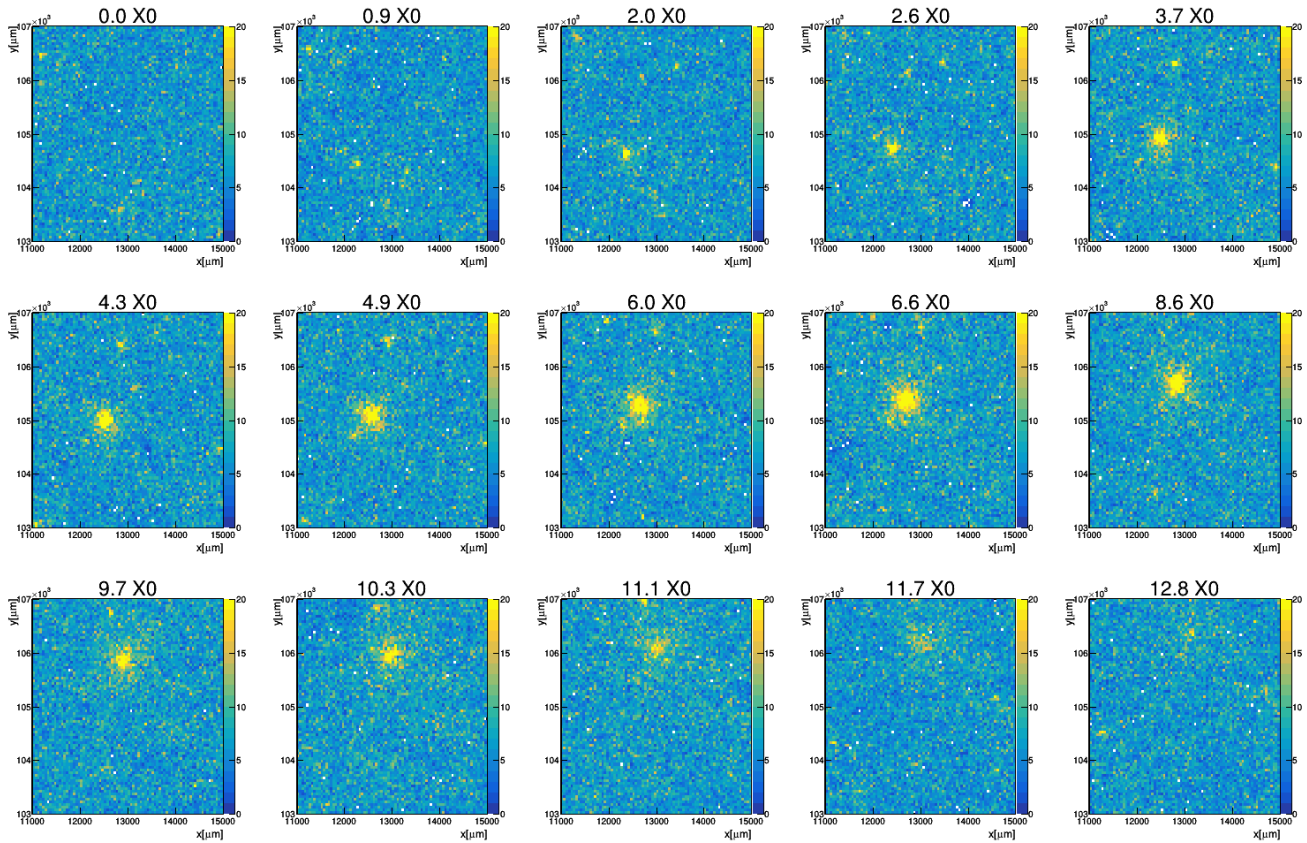


Observed: 6 events with 4.7 σ significance

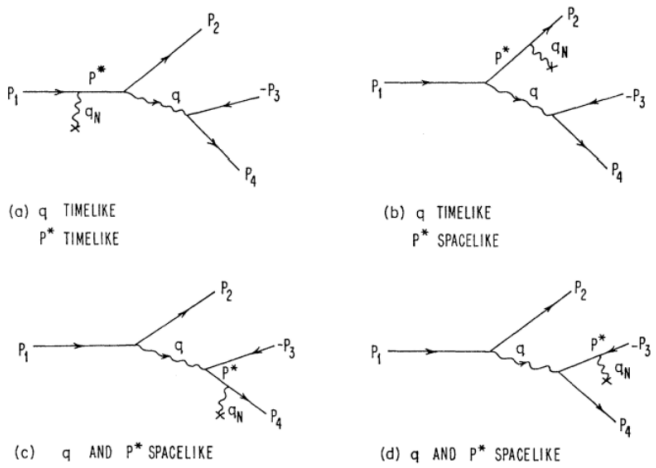
Search for ν_eCC with Emulsion Data

- Signal: Isolated shower pattern with neutral vertex.
- EM showers were identified, association with neutral vertices is ongoing.





Search for Multi Muon Events

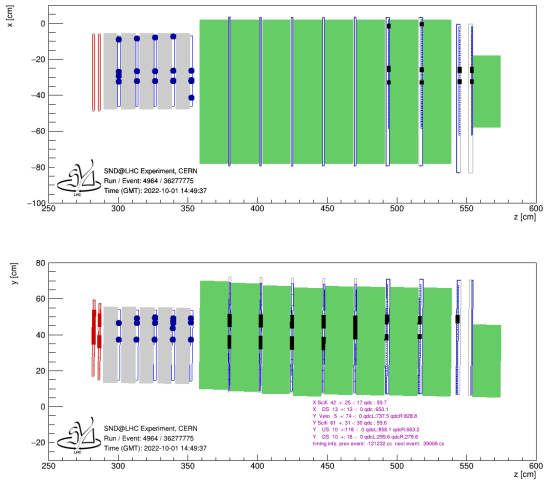


Two types of μ^3 events

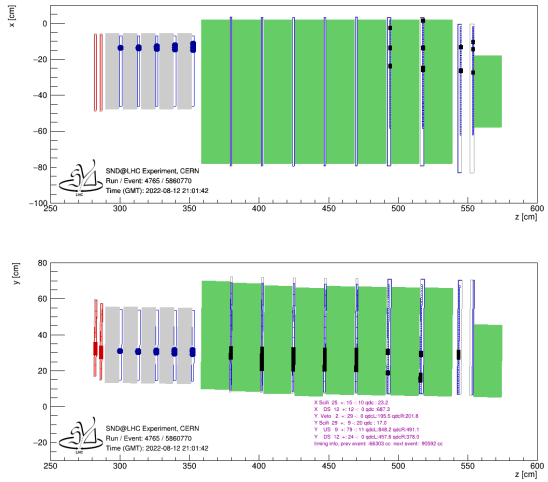
- A: Three tracks almost parallel
- B: Incoming tracks, vertex in the target, three outgoing tracks
- Possible explanations:
  - $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$ (The genuine trident)
  - $\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \gamma, \gamma + N \rightarrow N + \mu^{+}\mu^{-}$ (muon brems followed by γ conversion)

[Russell, J. J., Sah, R. C., Tannenbaum, M., Cleland, W. E., Ryan, D. G., & Stairs, D. G. (1970). Observation of Muon Trident Production in Lead and the Statistics of the Muon*. PhysRevLett.26.46]

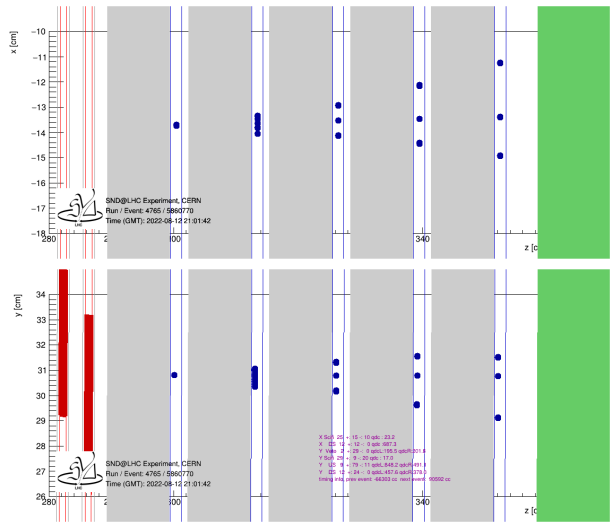
μ^3 Events



A: Interaction outside target



B: Vertex inside target

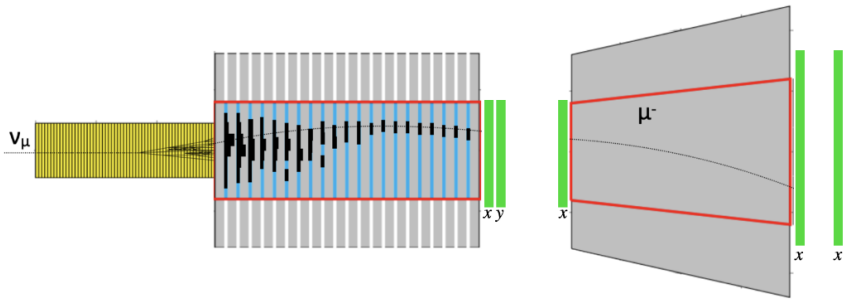


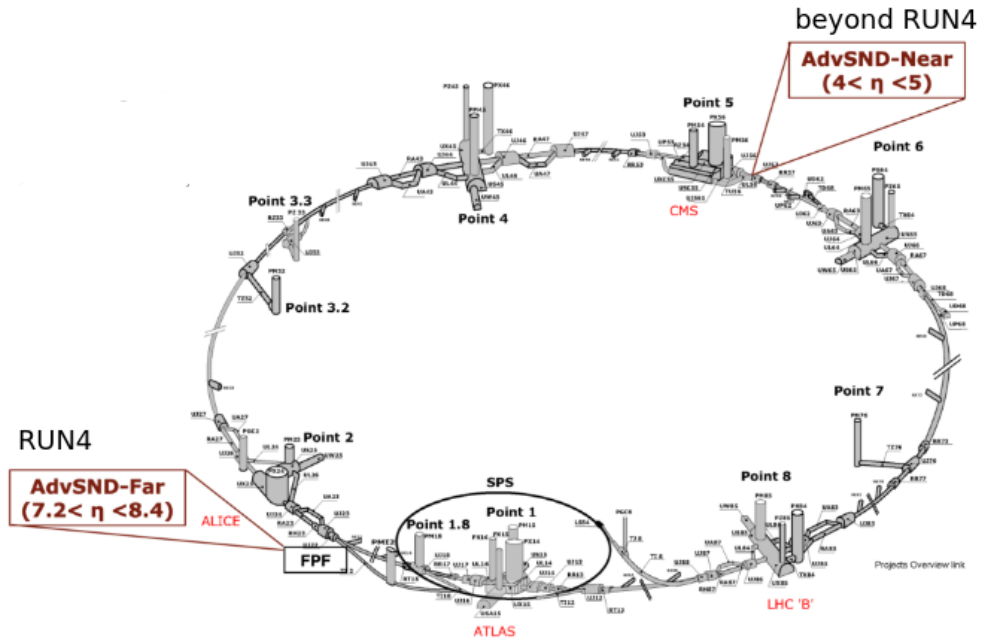
B: Vertex inside target zoomed

Future Upgrades: AdvSND

- Iron core magnetic spectrometer identify ν_μ and $\overline{\nu}_\mu$
- Vertex detector with Si detector
- Improved HCAL and timing detectors

Far detector, LHC RUN4 : The same η range with the current detector.





Near detector, beyond LHC RUN4: Smaller η range to reduce systematic uncertainities in the charm production

Summary

- SND@LHC is running successfully since the start of LHC RUN3.
- Dedicated background study has been done together with the measurement of the muon flux.
- First observation of neutrinos produced in pp collisions
- 32 ν_μ CC interactions have been observed together with 2023 data, yet to be published.
- 0μ neutrino events were observed, results will be published soon.
- Search for Multi Muons and Muon DIS are also being studied.
- **New era of LHC neutrino experiments has begun !**

Back up slides

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
- Currently, two neutrino experiments are operating at LHC

  IP1:
  - SND@LHC, off-axis, enhances neutrino flux from charm production, $7.2 < \eta < 8.4$
  - FASERν, on-axis, $\eta > 9$, enchances statistics

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **46** (2019) 115008 (19pp)
https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

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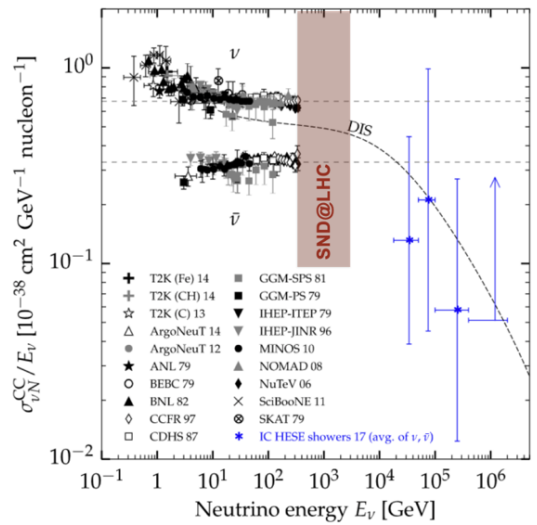
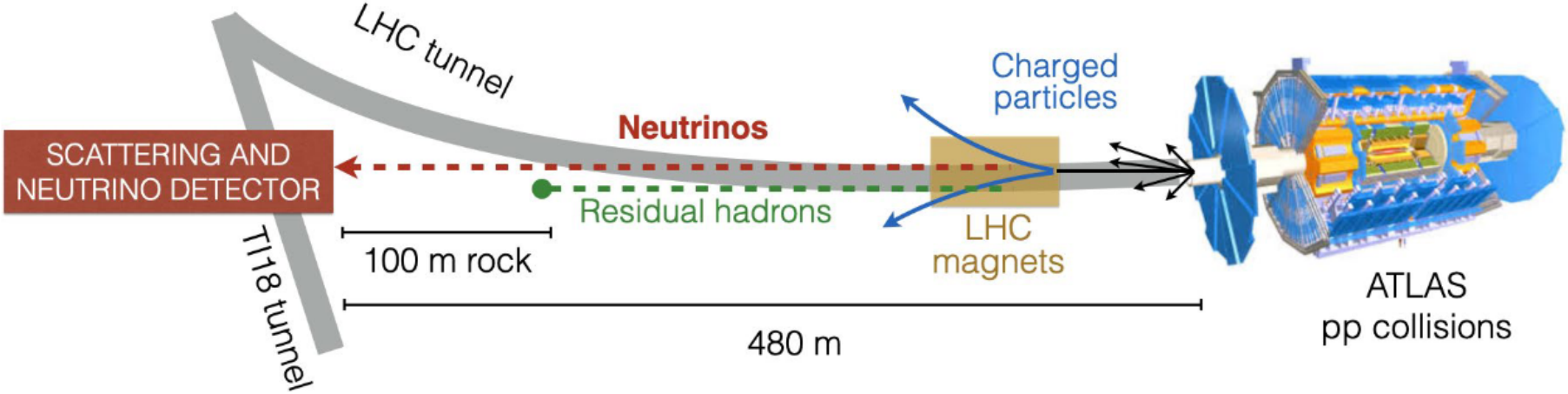
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **47** (2020) 125004 (18pp)
https://doi.org/10.1088/1361-6471/aba7ad

Further studies on the physics potential of an experiment using LHC neutrinos



Scattering and Neutrino Detector @ LHC



- The detector is located in the TI18 tunnel former transfer line from SPS to LEP
  - 480 m away from the ATLAS interaction point (IP1)
  - Covering pseudo rapidty range $7.2 < \eta < 8.4$
  - Shielded by 100 m rock
- LHC magnet deflects charged particles
- Neutrinos and FIPs interact in the detector

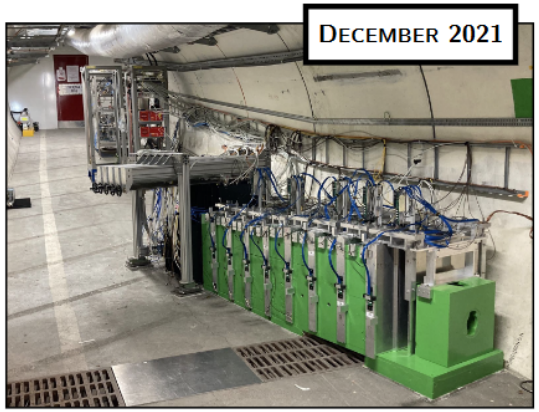
Data Taking and Event Reconstruction

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
- Successful data-taking campaings in 2022 and 2023

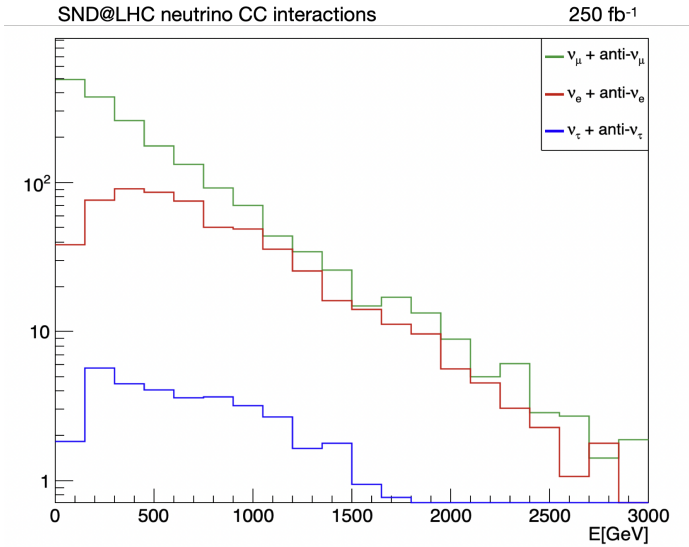
Neutrino Interactions

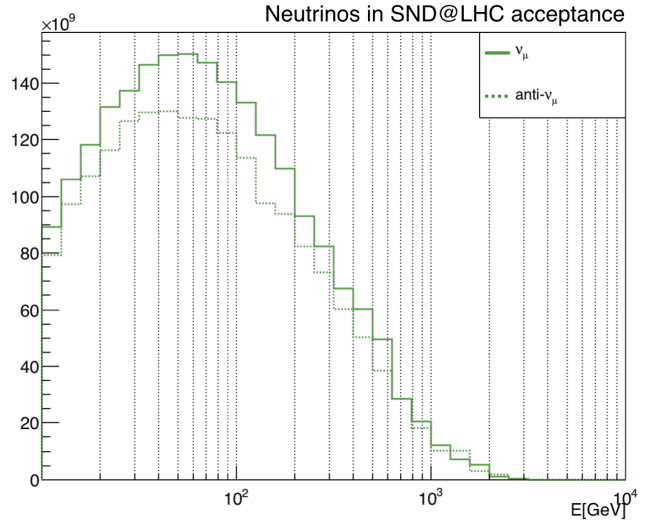
- **Neutrino interactions**
  - Measure neutrino interactions in unexplored TeV energy scale
  - Measuring NC/CC ratio
- The NC/CC ratio in case of DIS can be written as

$$P = \frac{1}{2}\left\{1 - 2\sin^2\theta_W + \frac{20}{9}\sin^4\theta_W - \lambda(1 - 2\sin^2\theta_W)\sin^2\theta_W\right\}$$

- P measurement used as an internal consistency check

	Neutrinos in acceptance		CC neutrino interactions		NC neutrino interactions	
Neutrino flavour	$\langle E\rangle$[GeV]	Yield	$\langle E\rangle$[GeV]	Yield	$\langle E\rangle$[GeV]	Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
ν_e	125	3.0×10^{12}	480	419	480	157
ν_τ	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_\mu$	230	4.4×10^{11}	680	158	720	58
$\bar{\nu}_e$	400	2.8×10^{10}	740	23	740	8
$\bar{\nu}_\tau$	380	3.1×10^{10}	740	11	740	5
TOT		7.3×10^{12}		1930		625



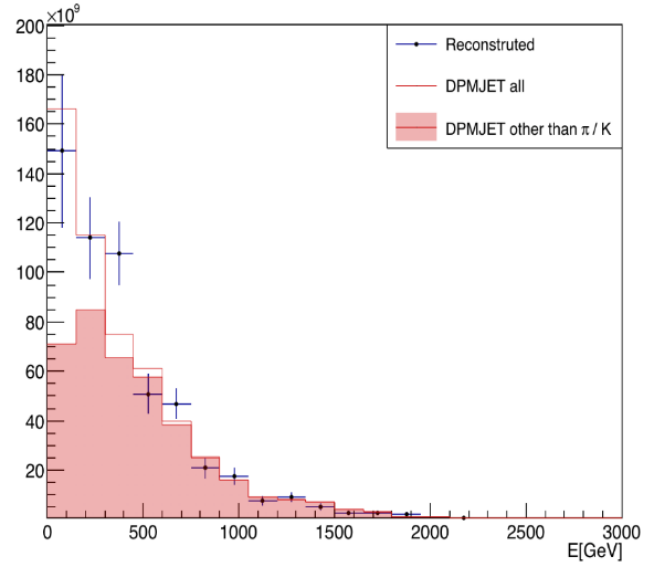


Physics Motivation

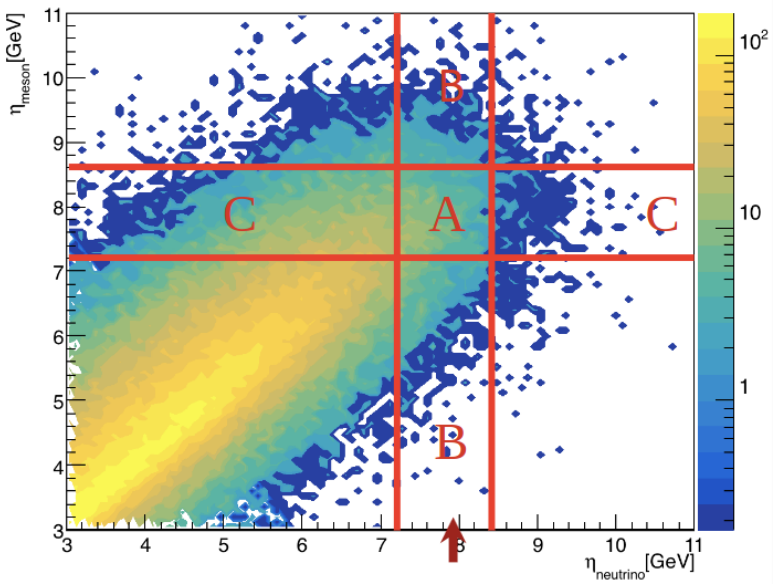
Heavy Flavour Physics

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

Reconstructed nue nue energy spectrum in acceptance

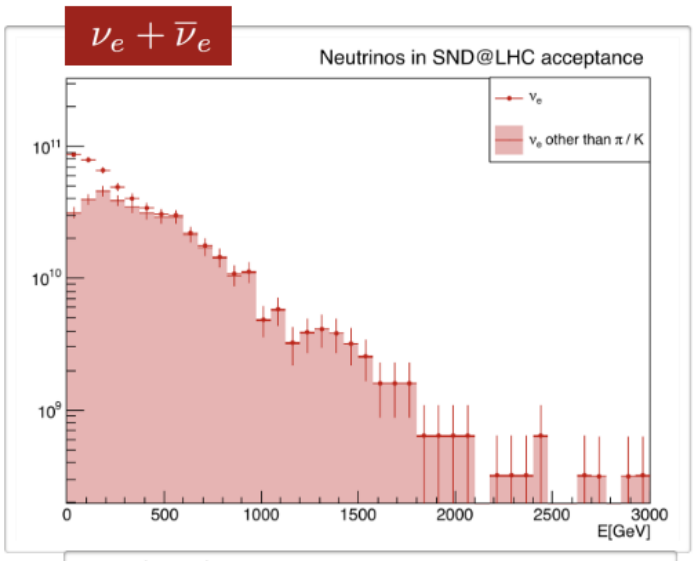


Correlation between pseudo-rapidity of the (anti-) electron neutrino and the parent charmed hadron

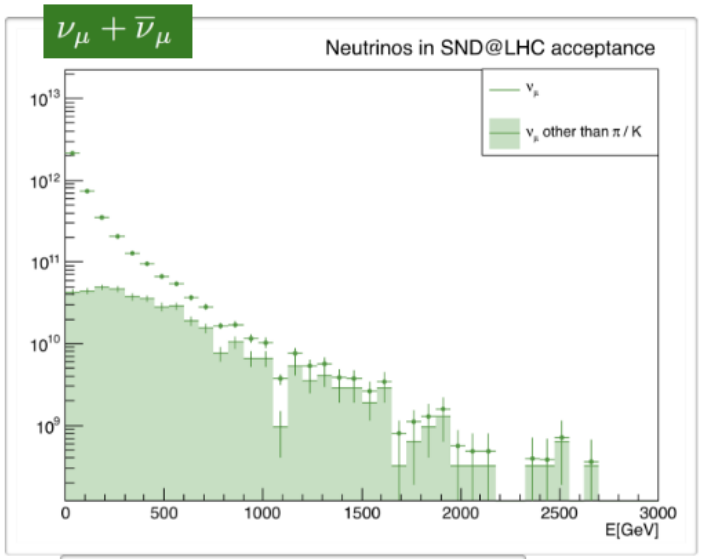


Physics Motivation

- **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).



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



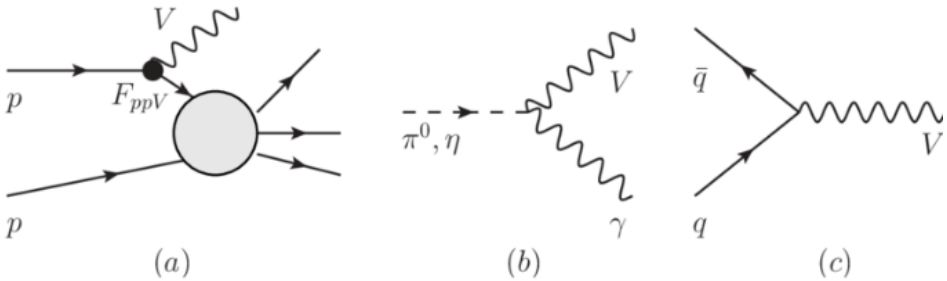
$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

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)