METU

LHC
Scattering and Neutrino Detector
at the LHC

The SND@LHC Experiment @CERN-LHC

A. Murat Güler (METU)
On behalf of the SND@LHC Collaboration

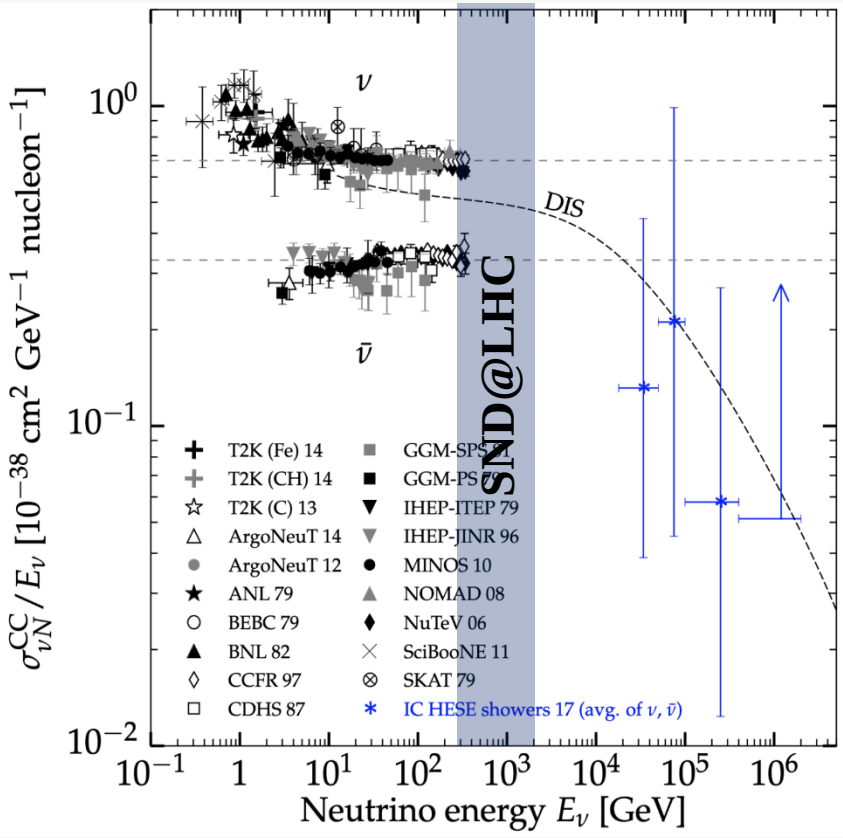
XVIII International Conference on Topics in Astroparticle and Underground Physics 2023
28 August - 1 September, University of Vienna

Detection of LHC neutrinos

- **LHC** operates as a **neutrino** factory
  - **Large** neutrino flux in the **forward** region.
  - **Highest** energy human-made neutrinos.
    - Neutrinos of **all flavours** can be observed by **a small-scale** experiment at the LHC
- **Idea** of detection of **LHC neutrinos** goes back to **80's**

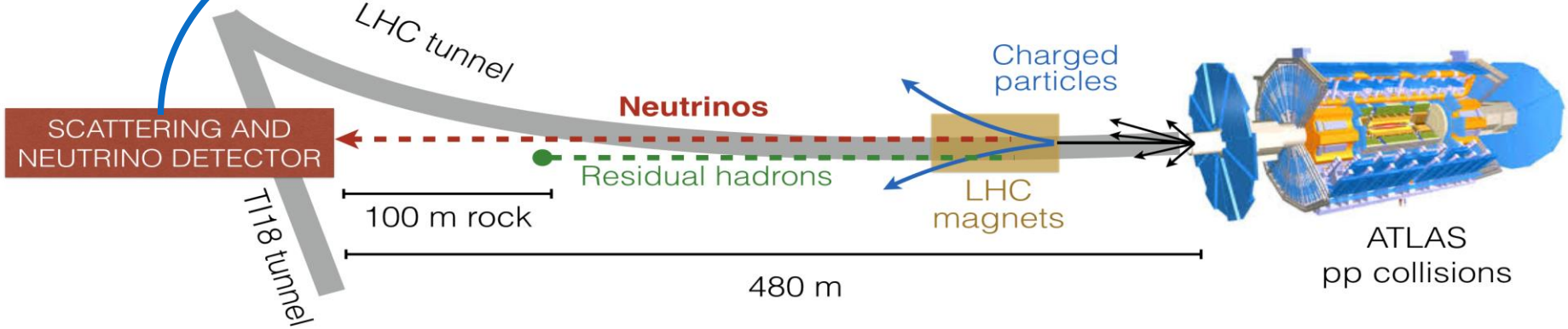
  CERN-1984-010-V-2.571; Nucl. Phys. B405, 80; LPNHE-93-03
  - seen as an opportunity to discover the ν_τ
- SND@LHC operates near the the ATLAS interaction point since **June 2022**.
  - Reported the **detection** of the LHC neutrinos

    Phys.Rev.Lett. 131 (2023) 3, 031802



Scattering and Neutrino Detector @ the LHC

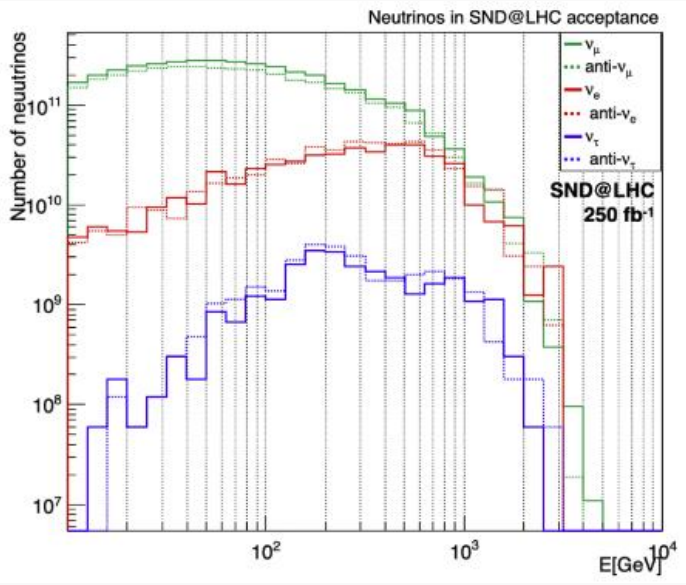
- It is located in the **TI18 tunnel**, former positron transfer line to LEP;
  - 480 m away from the ATLAS interaction point (IP1)
  - Covered angular acceptance of (**off axis**) **$7.2 < \eta < 8.4$**
  - Shielded by 100 m rock
- LHC magnet deflects charged particles
- Neutrinos and (if exist) feebly interacting particles (FIPs) interact in the detector



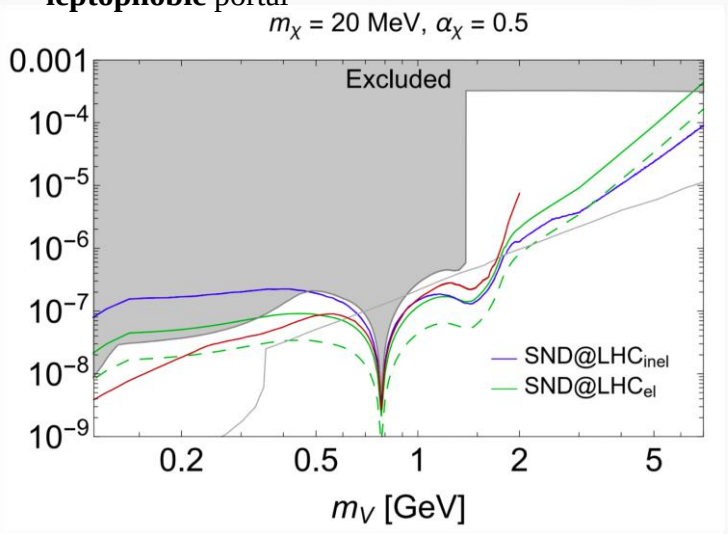
Physics Program

- **Neutrino interactions**
  - $\sigma_{pp} \rightarrow \nu$ X in $7.2 < \eta < 8.4$ range
  - NC/CC measurement for consistency check
- **QCD**
  - Decays of charm hadrons contribute significantly to the neutrino flux.
  - Measure forward charm production with neutrinos.
  - Constrain gluon PDF at very small x.
- **Lepton Flavour Universality**
  - Detection of all three types of neutrinos allows for tests of lepton flavour universality.
- **Beyond the Standard Model**
  - Search for feebly interacting, particles decaying within the detector or scattering off the target.

Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157
ν_e	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58
ν_τ	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



- Sensitivity of the experiment to the **leptophobic** portal

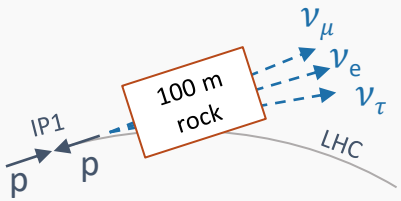


The SND@LHC Detector Layout

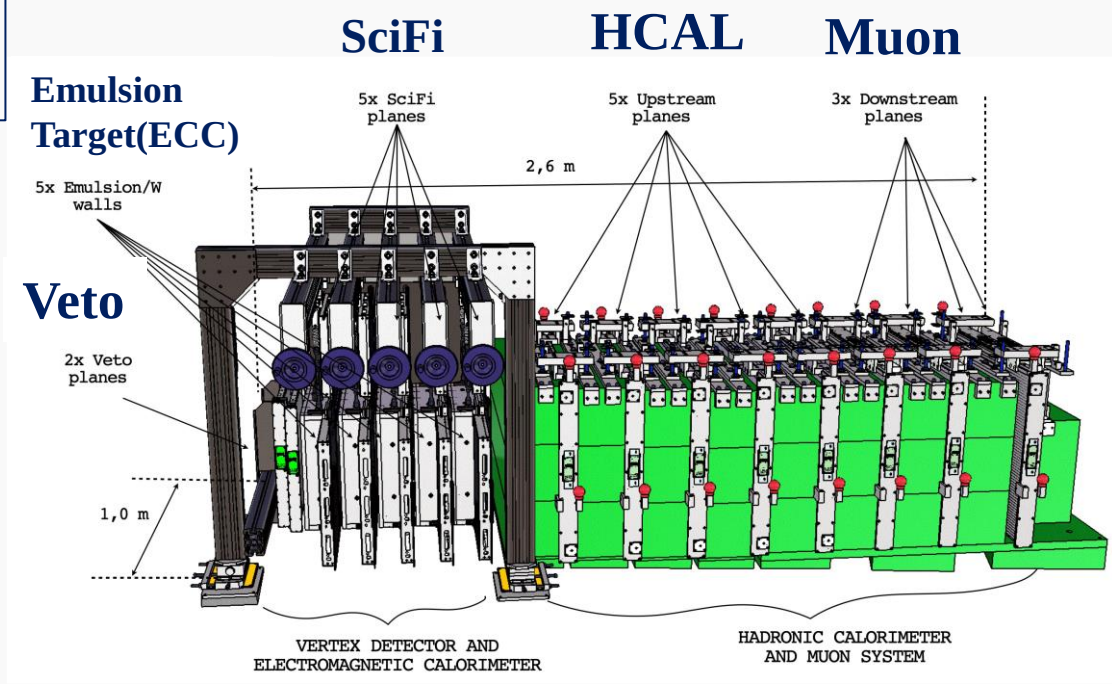
- **Veto** system
  - Two 1 cm thick scintillator planes.

- **Target, vertex** detector and **ECAL**
  - 830 kg tungsten target.
  - Five walls x 59 emulsion layers
  + five scintillating fibre stations.
  - 84 X_0, 3 λ_{int}

- **HCAL** and **MUON** system
  - Eight 20 cm Fe blocks
    + scintillator planes.
  - Last 3 planes have finer granularity to track muons, 9.5 λ_{int}



- Cross-sectional area: 40 x 40 cm^2
- Length: 2.6 m



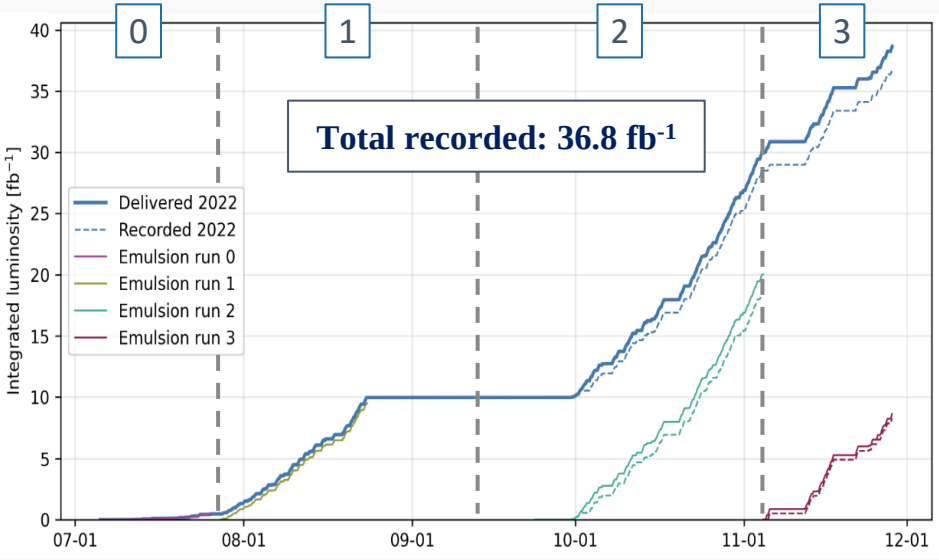
arXiv 2210.02784 to appear on JINST

Data Taking

August 2020: Letter of Intent published	**March 2021:** Approval by CERN Research Board	**December 2021:** Detector installed	**April 2022:** First data taken

- SND@LHC is operating since the start of **Run 3** of the LHC.
- Extremely successful data-taking campaigns in **2022**.
  - Electronic detectors uptime of **~95%.**
- Three emulsion detector exchanges in SND@LHC
- Additional ~**30 fb^{-1}** will be collected in **2023**.

Run Period-2022	Target Mass(kg)	Integrated Luminosity(fb^{-1})
Run0(Apr.-July)	39	0.46
Run1(July-Sept.)	807	9.5
Run2(Sept.-Nov.)	784	20.0
Run3(Nov.Dec.)	792	8.6

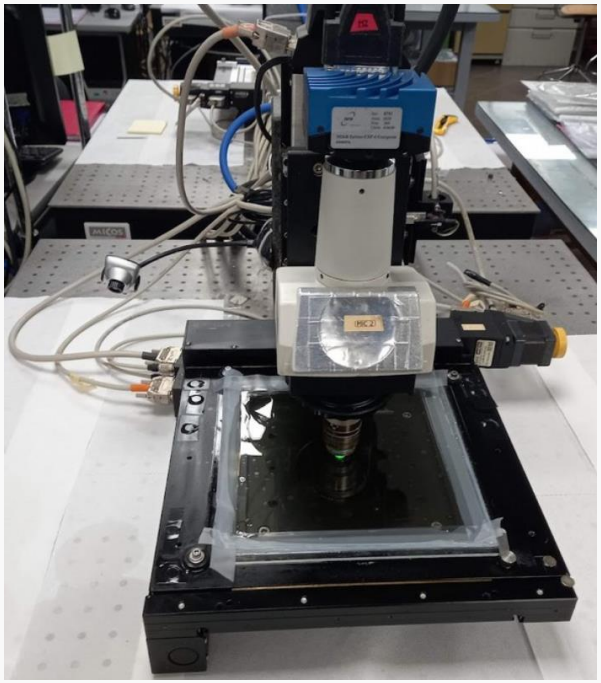


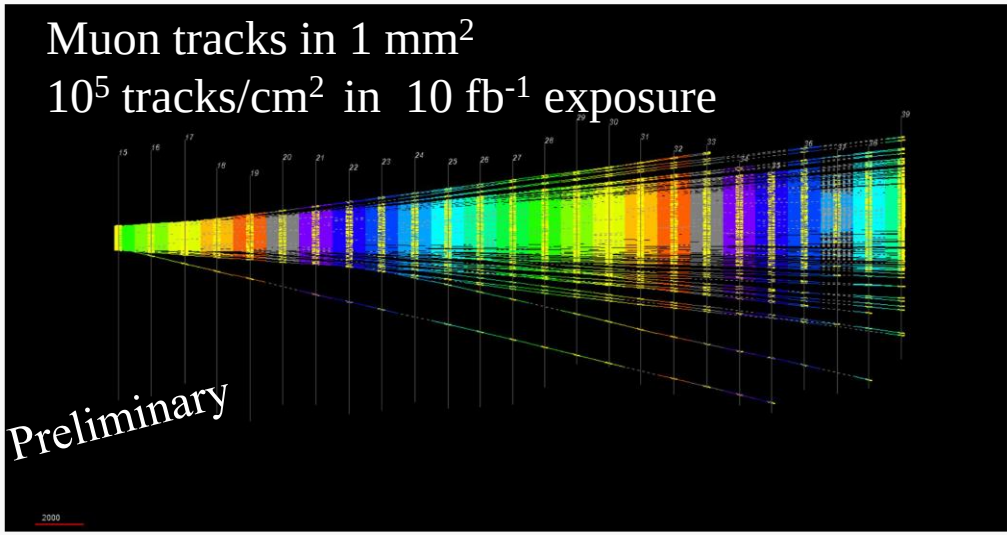
SND@LHC

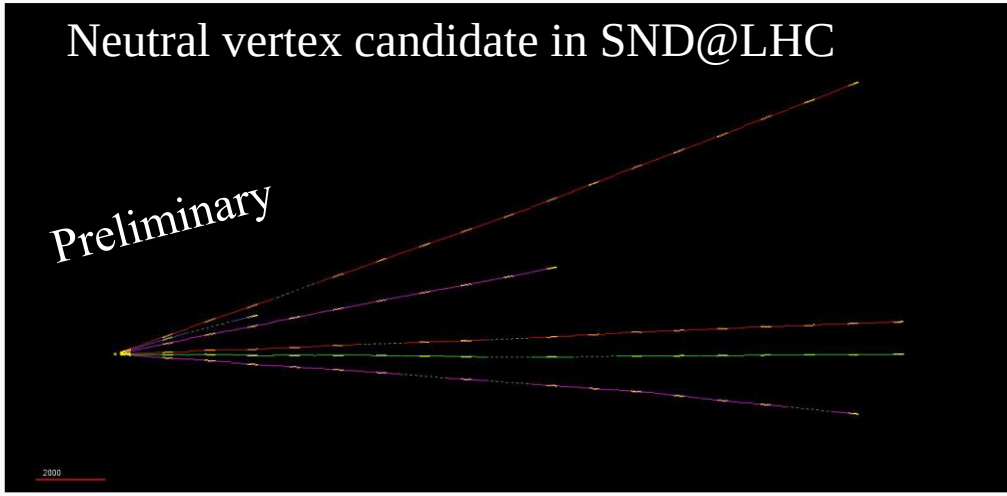
Emulsion Data

- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement

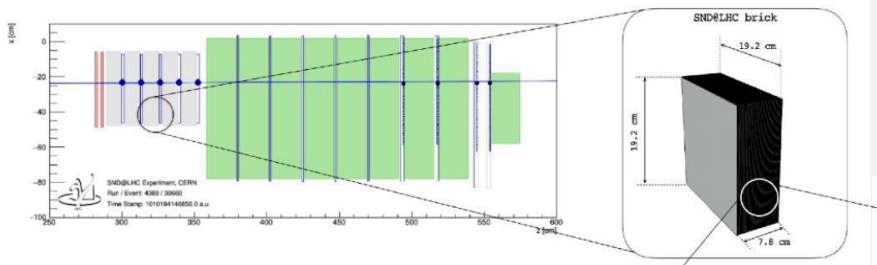
Emulsion scanning & analysis are ongoing

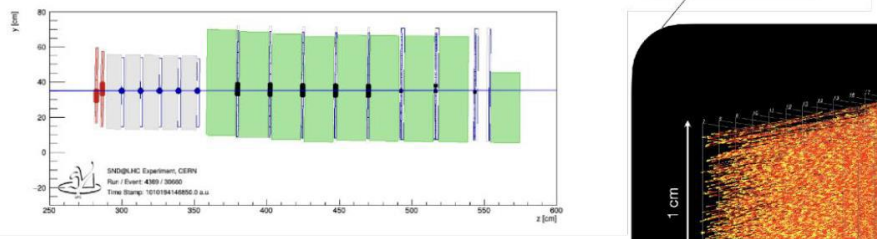


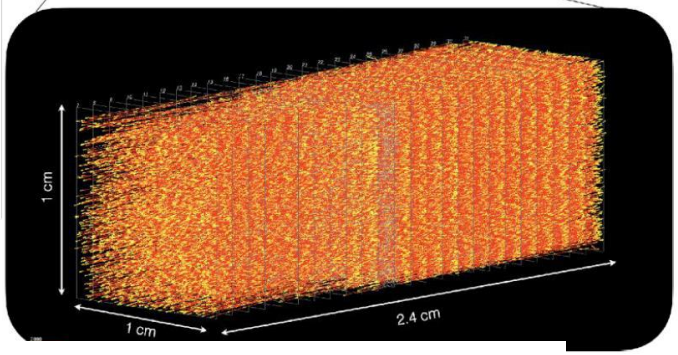




Muon Reconstruction



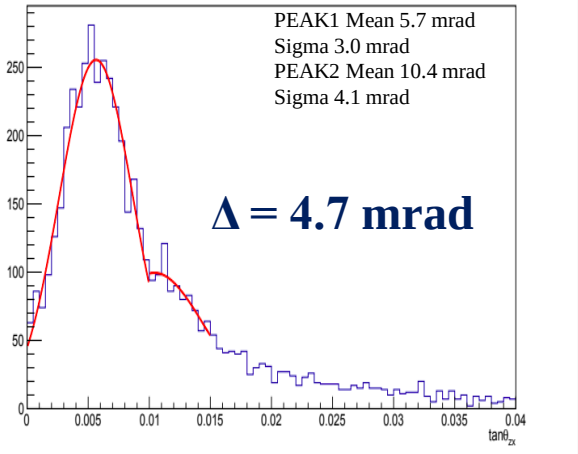




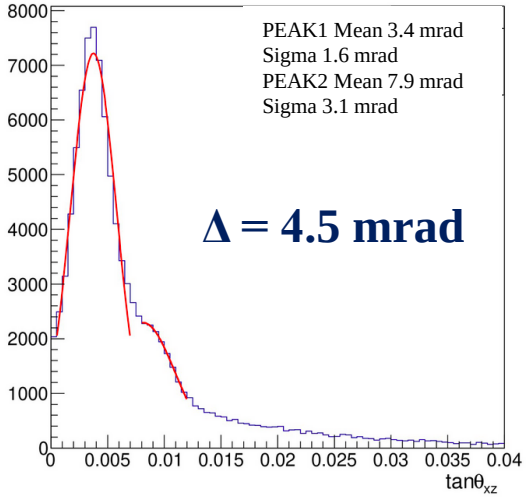
Emulsion Reconstruction
Muon tracks in 1x1cm^2
Integrated in Run0 of 0.51 fb^{-1} (07/04-26/07)

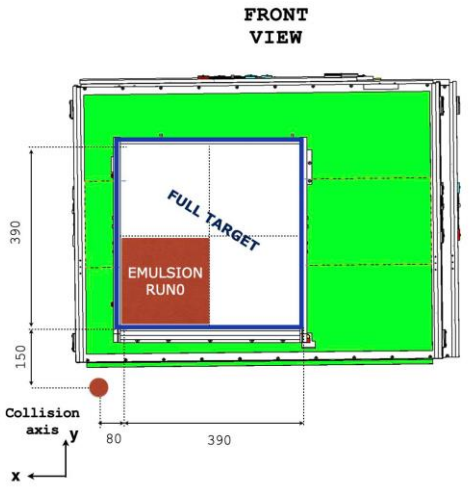
Emulsion/ SciFi distributions are agree within 10%

Emulsion tracks from RUN0



SciFi tracks from RUN0





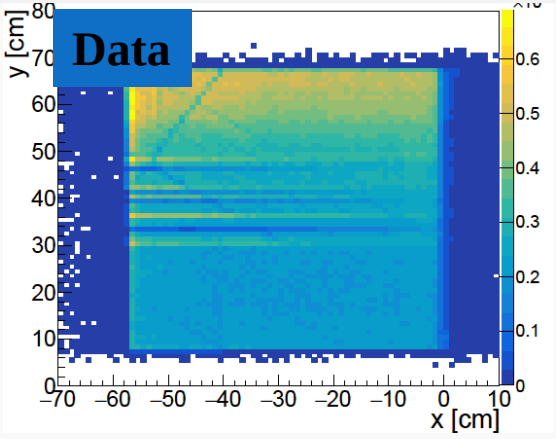
Muon Reconstruction

- Measurement of the muon, using the SciFi tracker and downstream muon detector

- Reconstructed DS tracks x − y profile at the upstream detector face

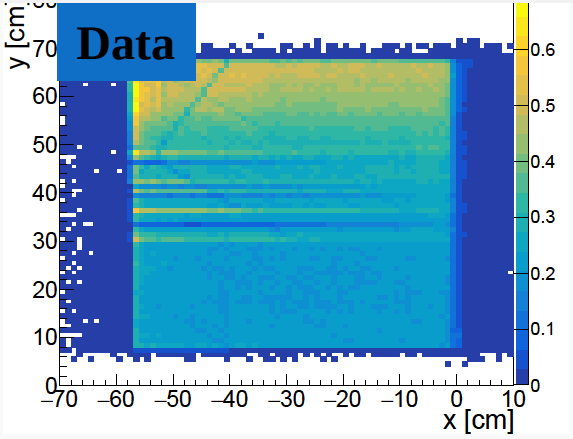
- Reconstructed SciFi tracks x − y profile at the upstream detector face

2.35 ± 0.01(stat) ± 0.08(sys) × 10^4 fb/cm²



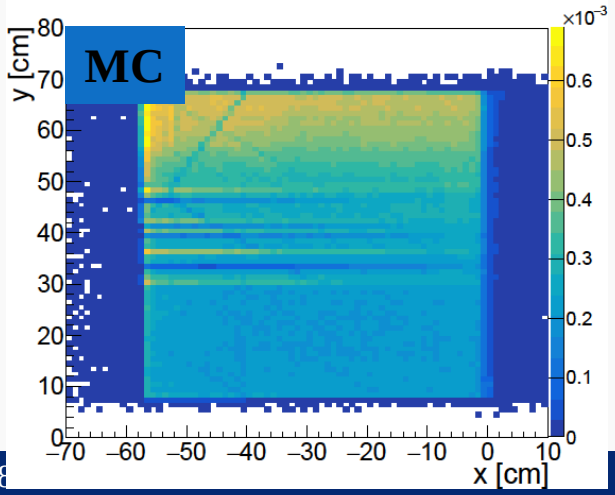
L_{int}[fb^{-1}]	N_{ev} [10^6]	t[h]
0.337	71	12.5
0.529	106	19.8

2.06 ± 0.01(stat) ± 0.11(sys) × 10^4 fb/cm²



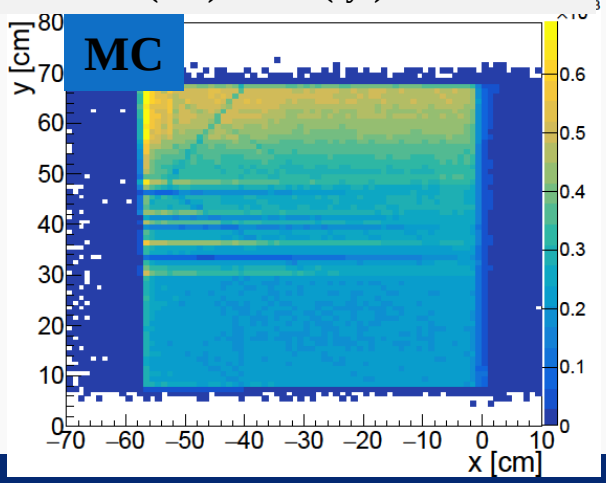
Data / MC agreement
@ 20-25 % level

1.79 ± 0.03(stat) ± 0.15(sys) × 10^4 fb/cm²



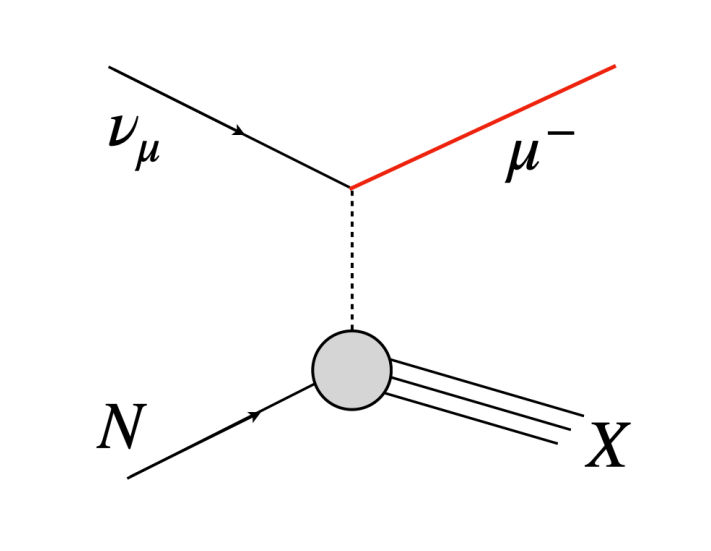
Muon flux from FLUKA
F. Cerutti, M.S. Gilarte
CERN-SY/STI

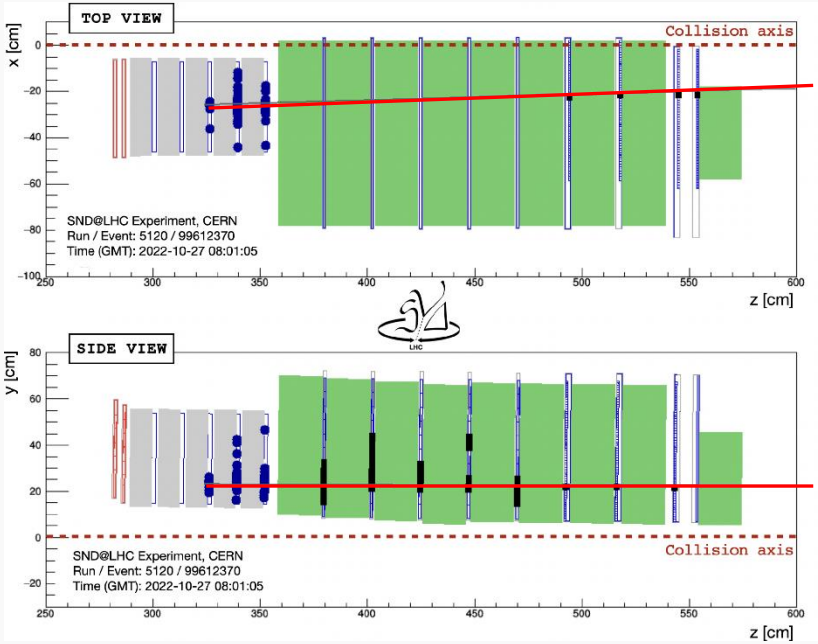
1.60 ± 0.05(stat) ± 0.19(sys) × 10^4 fb/cm²



Observation of Muon Neutrino Interactions

- **Analysis of 2022 dataset, corresponding to 36.8 fb^{-1}**
  - Expected signal yield ($\vartheta_\mu + \overline{\vartheta}_\mu$ interactions) : 157 ± 37
  - Challenge: background from ~ 10^9 muons
  - Counting-based approach
  - Use information from electronic detectors only





Event Selection

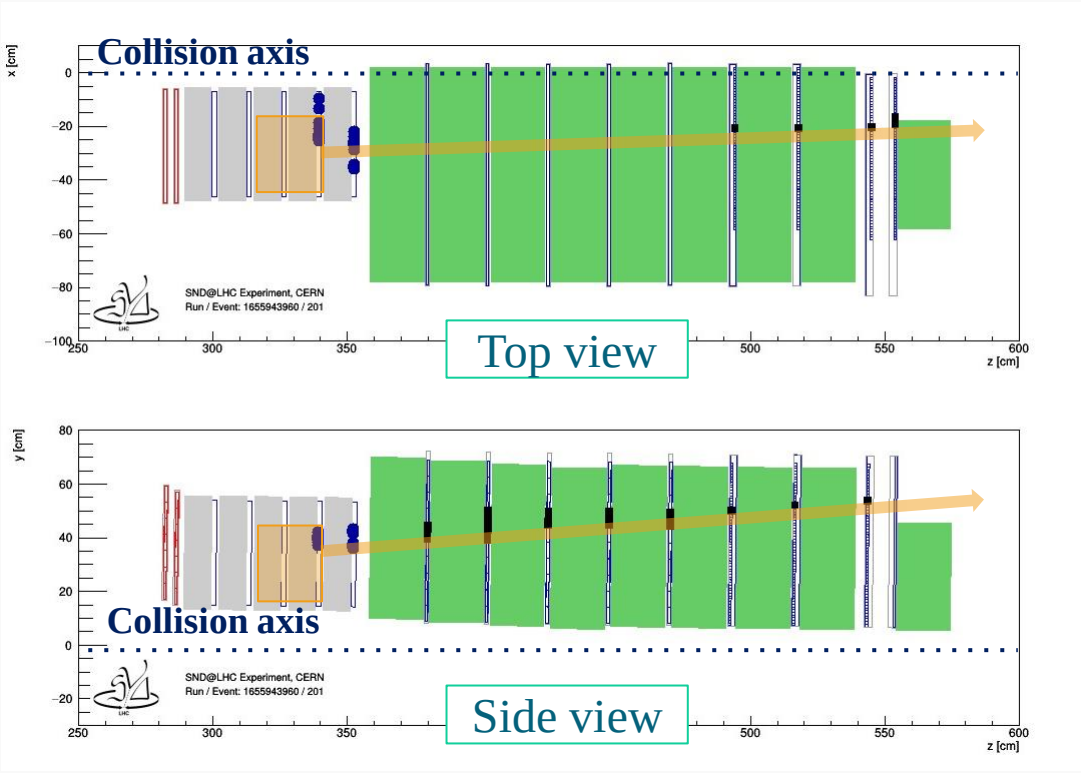
- Adopting a selection with strong rejection power, designed to yield a clean set of events

- **Fiducial volume**
  - Neutral vertex 3th or 4th wall.
  - Reject side-entering backgrounds.
  - Signal acceptance: 7.5%

- **Muon neutrino identification**
  - Large scintillating fibre detector activity.
  - Large HCAL activity.
  - One muon track associated to the vertex.
  - hit time distribution consistent with an event from IP1
  - Signal selection efficiency: 36%

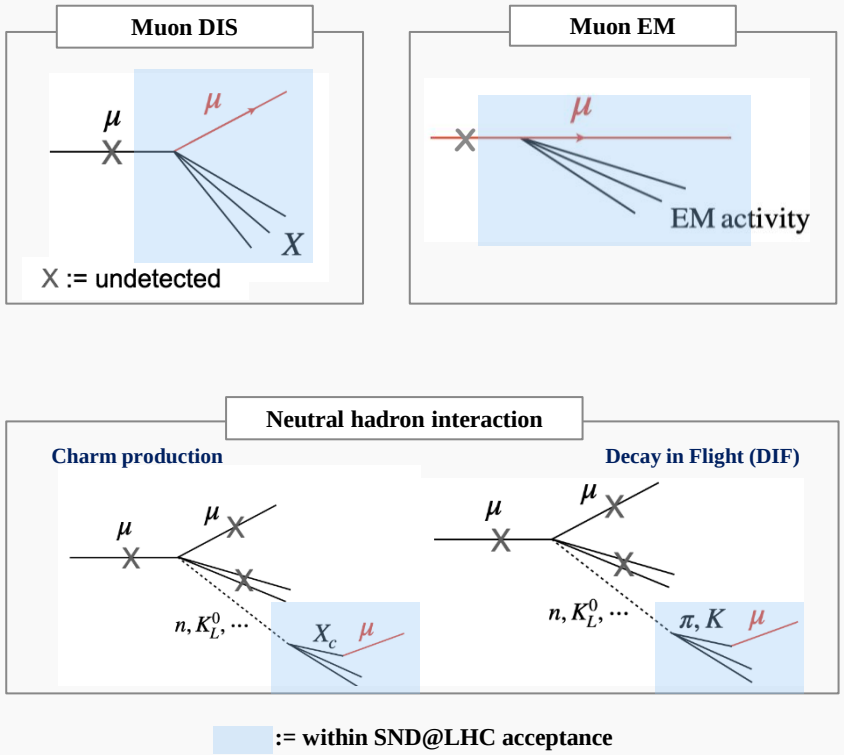
Number of ν_μCC events expected in 36.8 fb^{-1} after cuts: 4.2

ν_μCC simulation

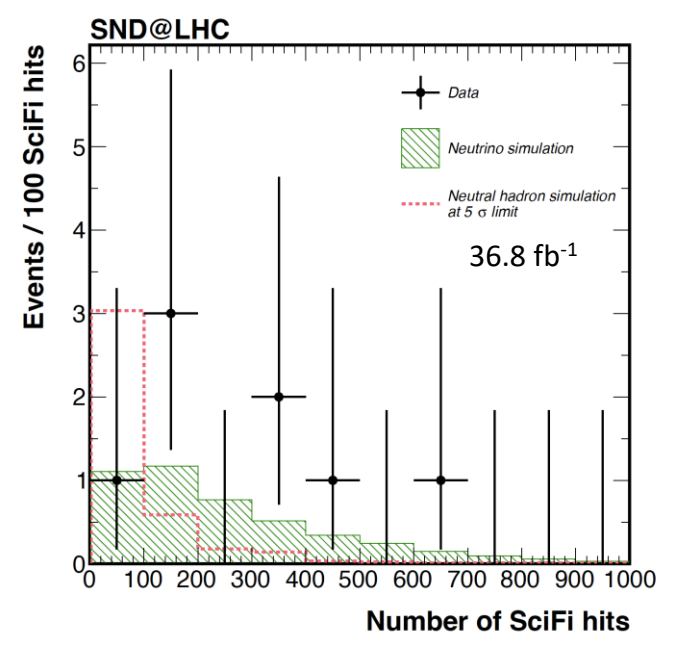


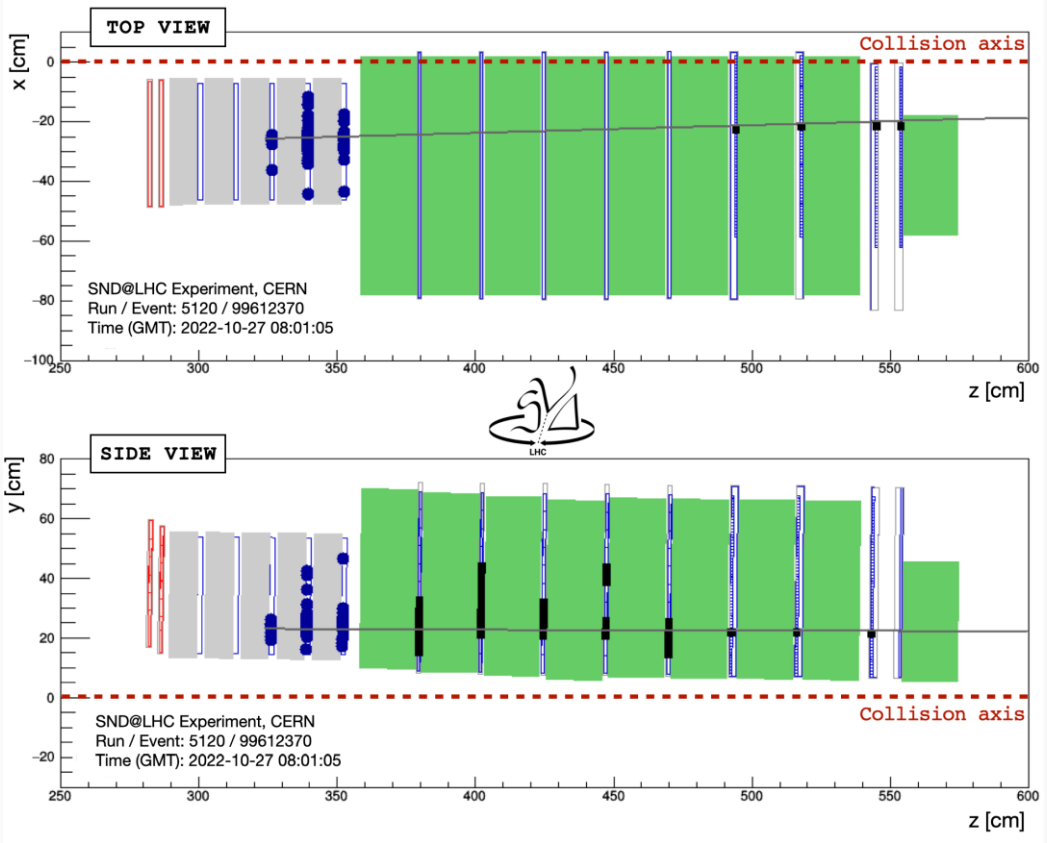
Backgrounds

- Entering muons
  - Incoming muon track may be missed due to detector inefficiency.
  - Shower induced by DIS or EM activity.
  - Number of muons in acceptance: 5 x 10^{8}
  - Detector inefficiency: 5 x 10^{-12}
    - Two veto and two scintillating fibre planes.
  - Negligible background with tight fiducial volume.
- Neutral hadrons
  - Neutral hadrons are produced in muon DIS in materials upstream of the detector.
  - Muon from pion decay-in-flight or charm production.
  - Expect a total of (8.6 ± 3.8) x 10^{-2} background events due to neutral hadrons.



SND@LHC neutrino observation





Observed eight neutrino event candidates with a statistical significance of 6.8 σ

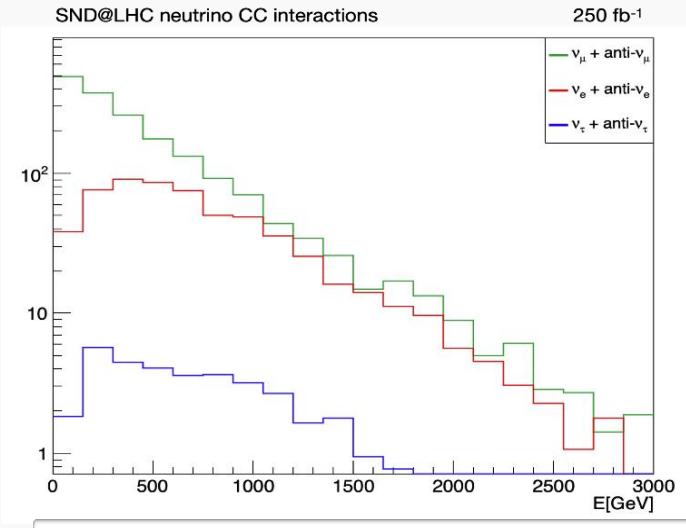
PRL 131, 031802 (2023)

Summary

- **Neutrinos** produced in **proton-proton collisions** have been detected for the first time!
- **8 ν_μ CC** candidates are identified in the CC interaction with the electronic detectors while the estimated backgrounds are **0.2**.
  Phys.Rev.Lett. 131 (2023) 3, 031802
- This marks the start of an exciting new era of **neutrino** measurements at the **LHC**.
  - Neutrino physics measurements
  - Heavy Flavour production,
  - Lepton Flavour Universality with neutrinos
  - Feebly Interacting Particles searches

Physics Motivation

- **Neutrino interactions**
  - Measure ν interactions in unexplored ~TeV energy range
  - Measuring the NC/CC ratio
  - Large yield of ν_τ will more than double existing data.
    - About 20 events observed by DONuT and OPERA.

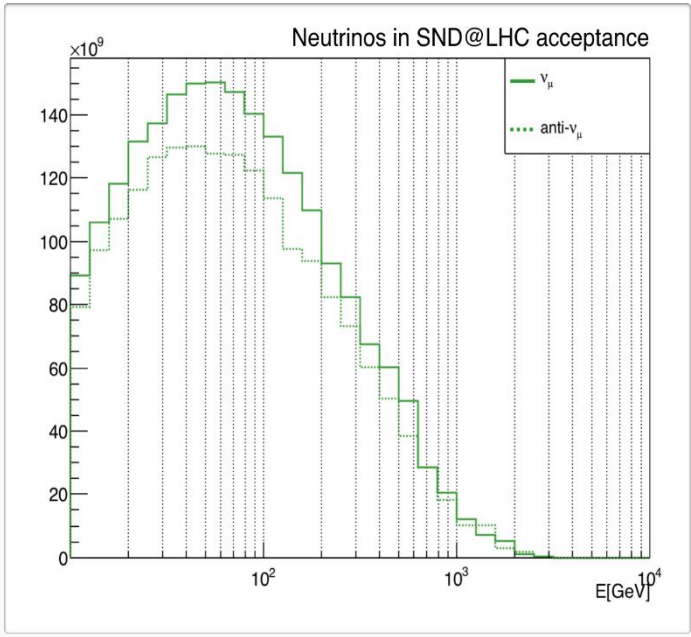


- The NC/CC ratio in case of DIS can be written as

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

Rept.Prog.Phys. 79 (2016) 12, 124201

- P measurement used as an internal consistency check



Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
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TOT		7.3×10^{12}		1930		625

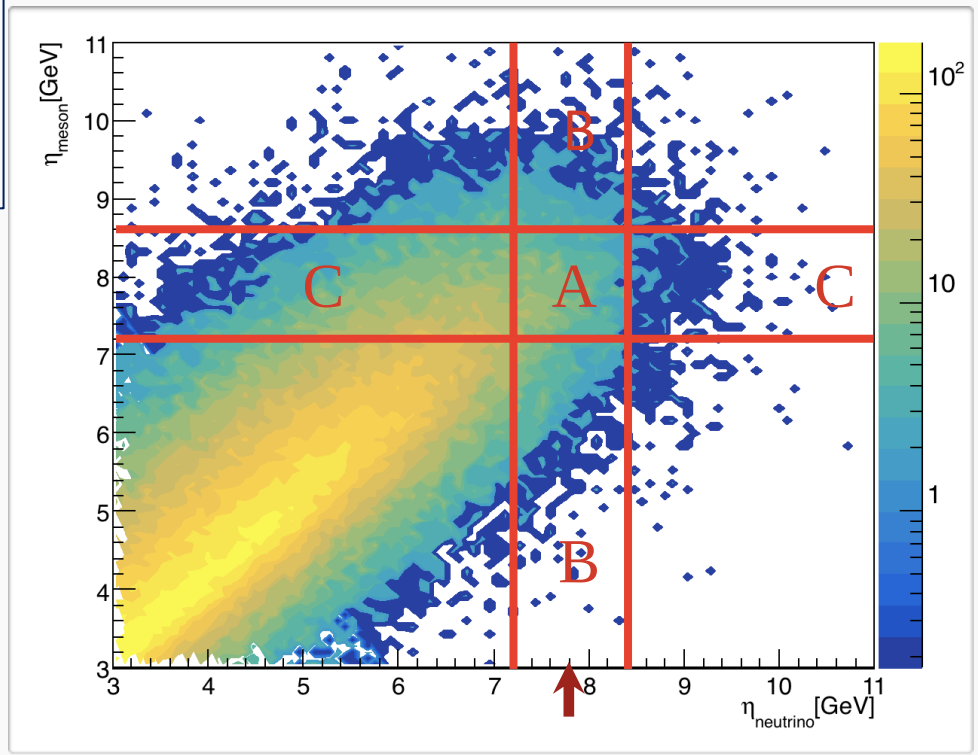
Physics Motivation

Heavy flavor Physics:

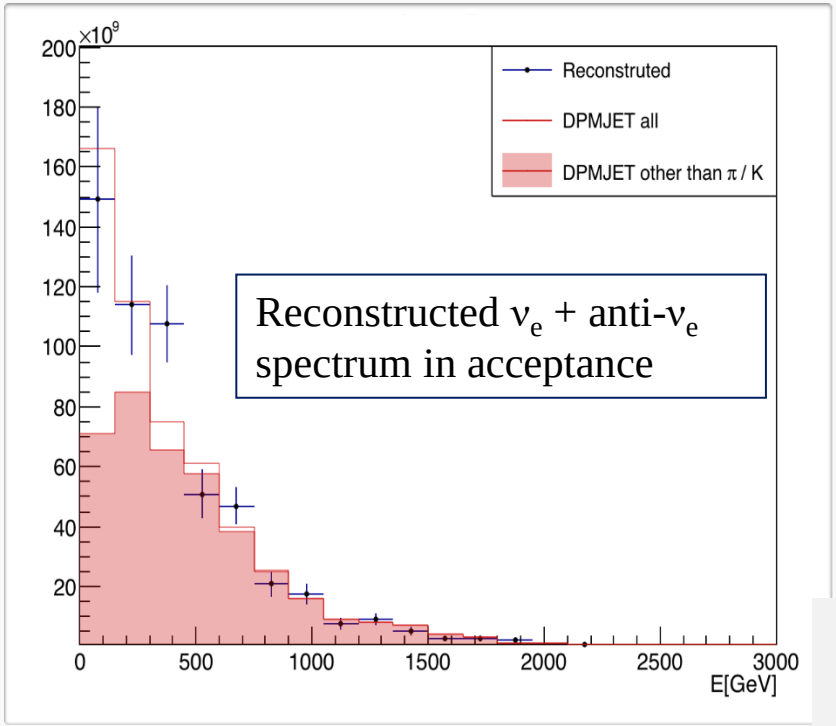
- 90% of ν_e and anti-ν_e produced in SND@LHC comes from charmed hadron decay.
  - This provides opportunities to:
  - Measure the $pp \rightarrow \nu_e X$ cross section
  - Measure forward charm production with neutrinos

[J. Phys. G: Nucl. Part. Phys. 47 125004

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



Neutrinos in SND@LHC acceptance

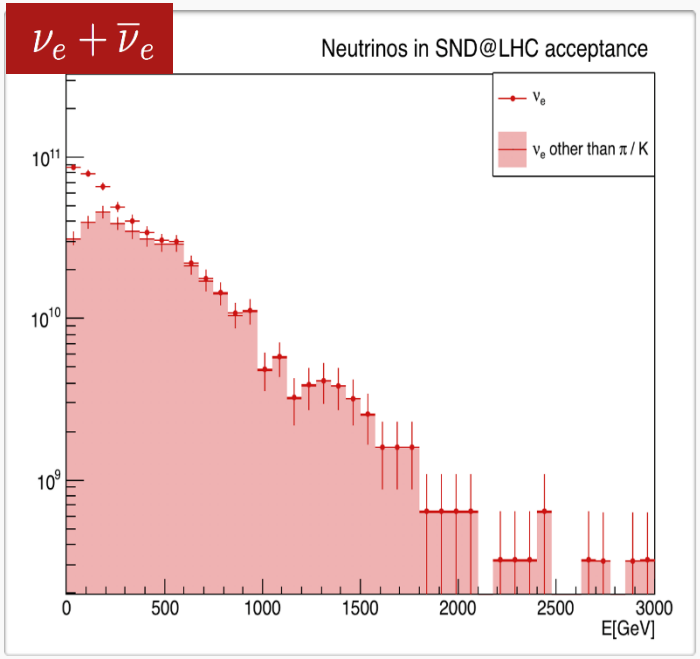


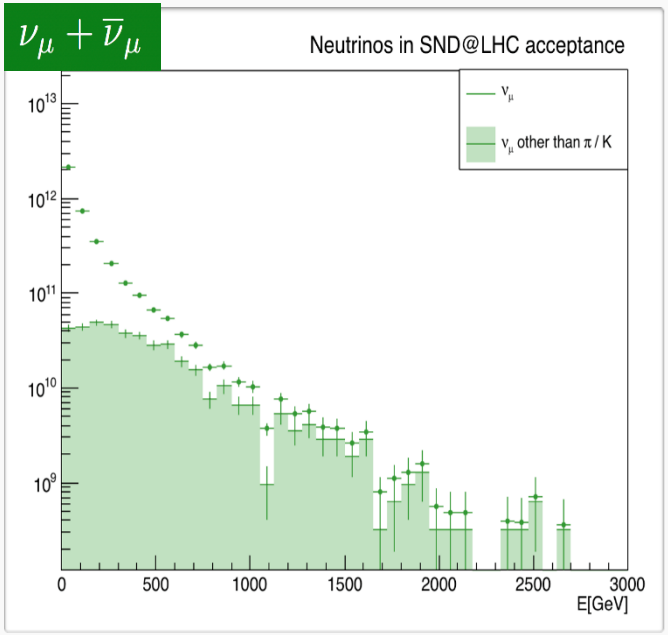
Reconstructed ν_e + anti-ν_e spectrum in acceptance

$$N(c-mesons) = N(\vartheta_e + \overline{\vartheta}_e) x \frac{f_{AB}}{f_{AC}} x \frac{1}{Br(c \rightarrow \vartheta_e)}$$

Physics Motivation

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





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

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

contamination from π/k

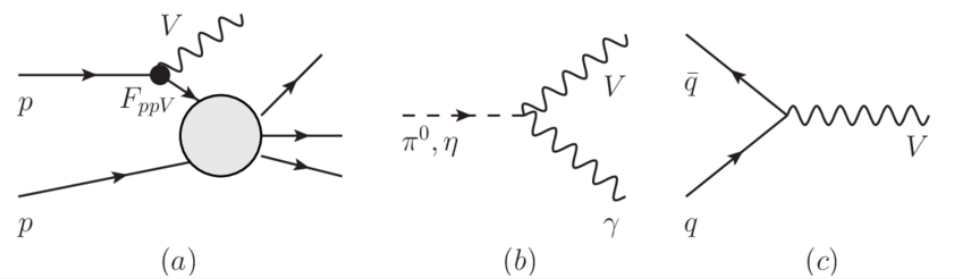
- Sensitive to ν-nucleon interaction cross-section ratio of two neutrino species

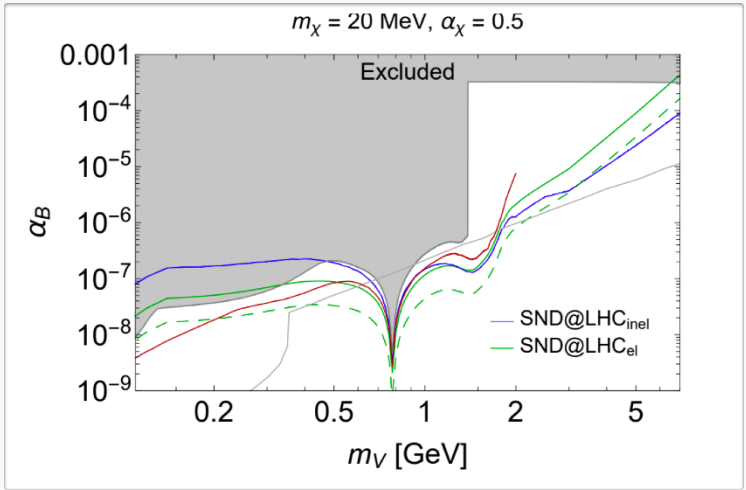
- The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU for E>600 GeV

Physics Motivation

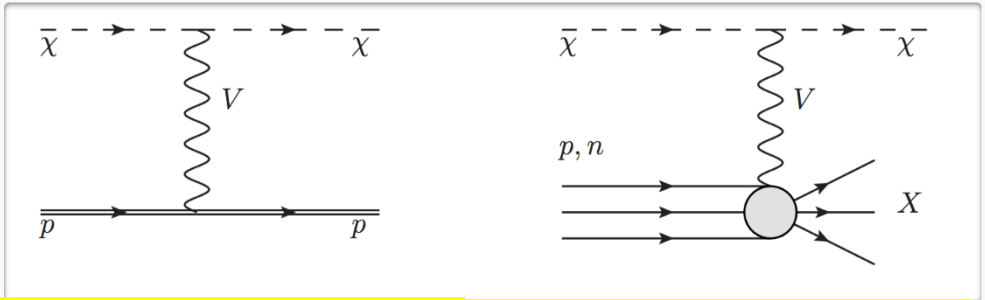
- SND@LHC experiment can explore a large variety of Beyond Standard Model (**BSM**) scenarios describing **Hidden Sector**

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





- FIPs **scattering** (*e.g. Light Dark Matter*)



ELASTIC SCATTERING **INELASTIC SCATTERING**

- FIPs **decay**
  - **HNL**, **Dark Scalar**, **Dark Photon** decaying into a pair of charged tracks, pointing back to the IP