A Scattering and Neutrino Detector at the LHC (SND@LHC)

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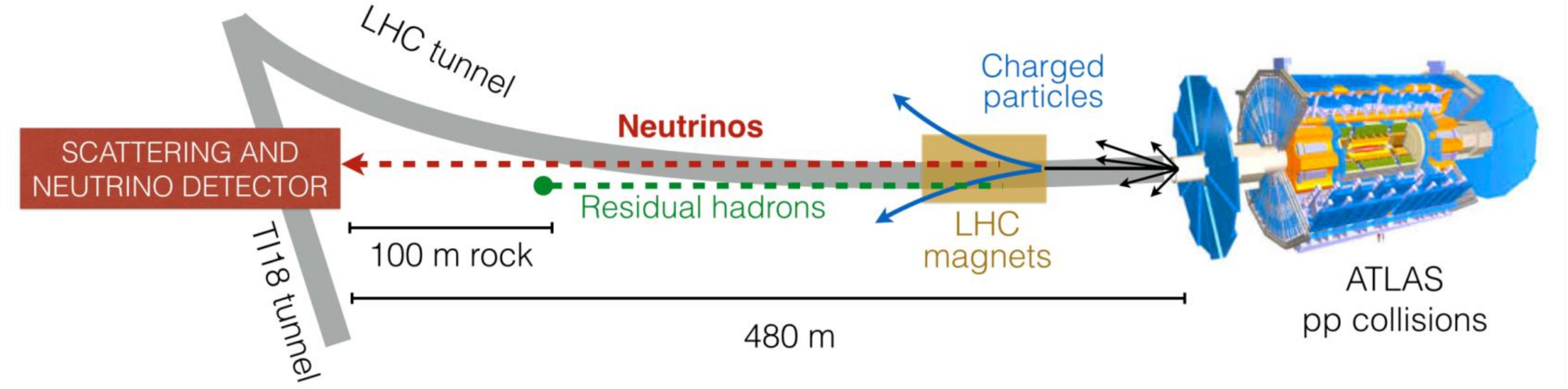
on behalf of the SND@LHC collaboration

SND@LHC experiment

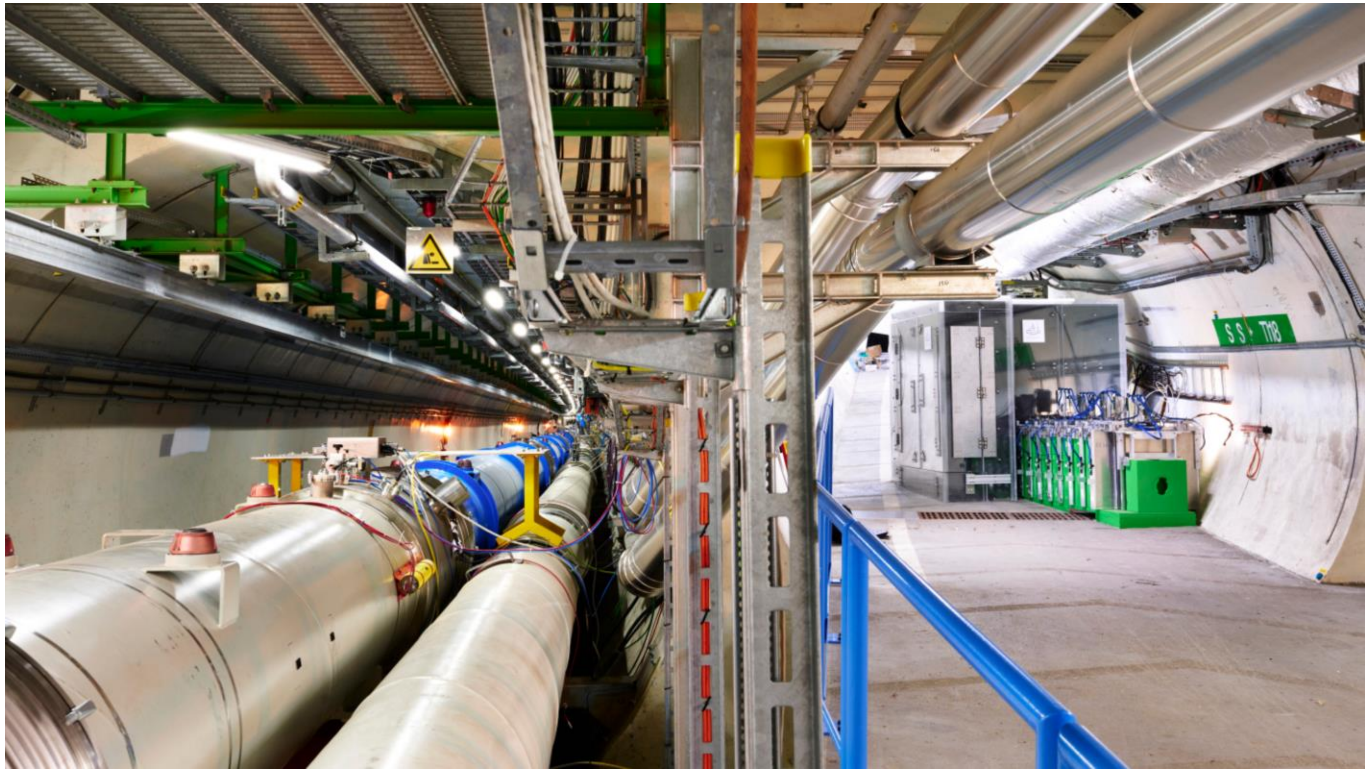
- The **S**cattering and **N**eutrino **D**etector at the LHC



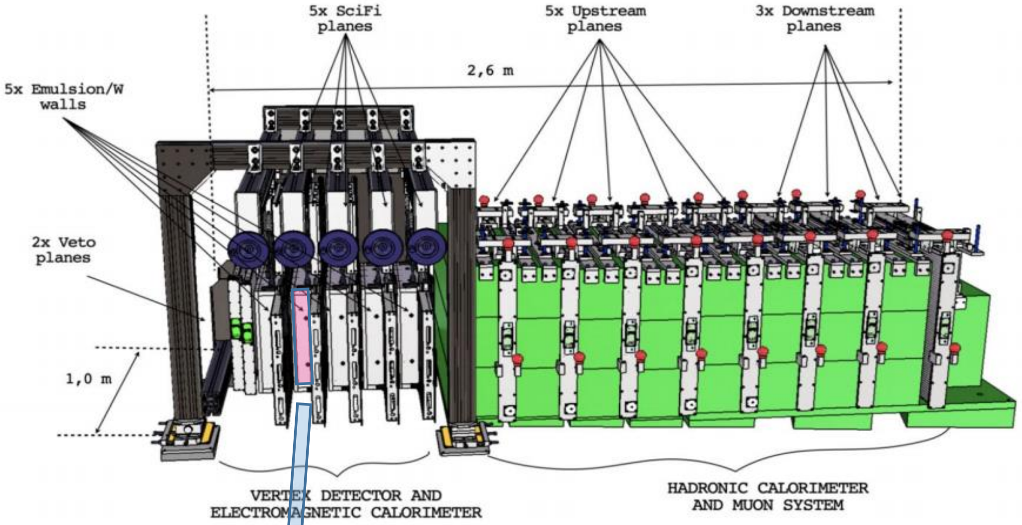
- Located 480 m downstream of the ATLAS interaction point along the beam collision axis
- Charged particles deflected by LHC magnets. 100 m rock absorbs residual hadrons
- However, neutrinos and (if exist) Feebly Interacting Particles can reach the detector
- The pseudo-rapidity range covered by the detector target **$7.2 < \eta < 8.4$** (unexplored before)

SND@LHC experiment

- Installed in TI18 tunnel and Taking Data (Run 3, 250 fb^{-1})



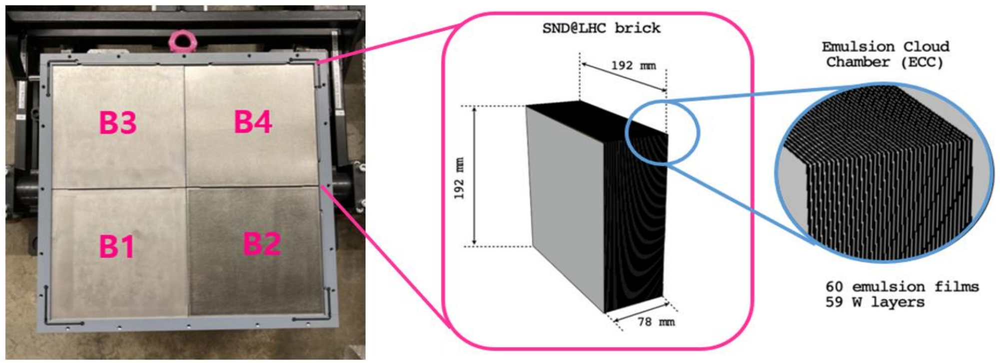
SND@LHC Detector

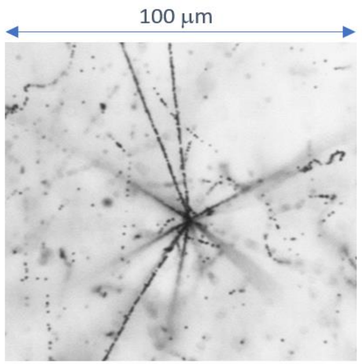


-Upstream Veto Planes
Two planes of scintillator bars
act as a veto for charged particles

-TARGET REGION
Five walls of Emulsion Cloud Chamber
(Emulsion + Tungsten 830 kg),
each followed by a Scintillating Fiber
plane (timestamp)

-MUON SYSTEM
Eight iron slabs, each followed by
one or two planes of scintillating bars





Neutrino interaction in Emulsion

arXiv 2210.02784v3

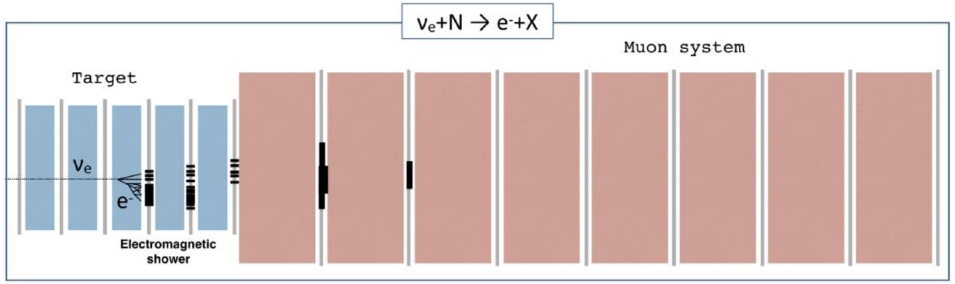
Event Reconstruction

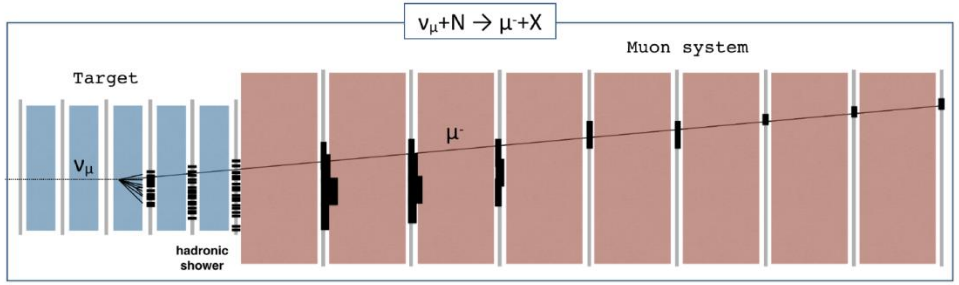
- Distinguish all three flavors of neutrinos.

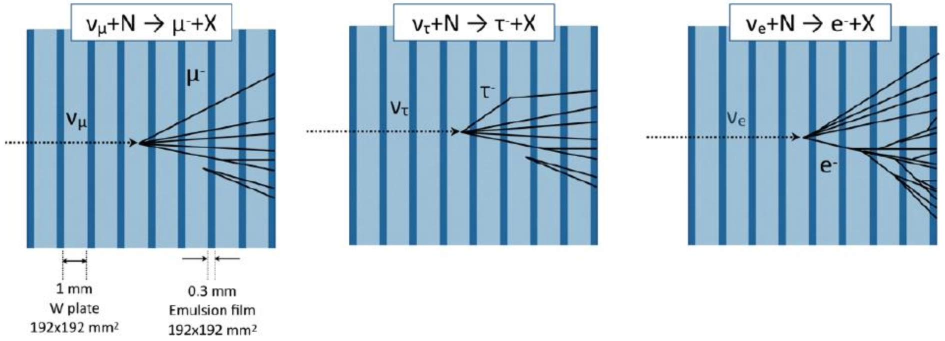
- Performed in two phases

- First Phase (electronic detectors)
  - ➢ Tagging incoming charged particles (veto planes)
  - ➢ Muon identification (SciFi, muon system)
  - ➢ Energy measurement (SciFi, HCAL)

- Second Phase (nuclear emulsions)
  - ➢ Extract and analyze emulsion data (~20 fb^{-1})
  - ➢ Reconstruct ν primary and secondary vertices
  - ➢ Match emulsion and electronics reconstruction

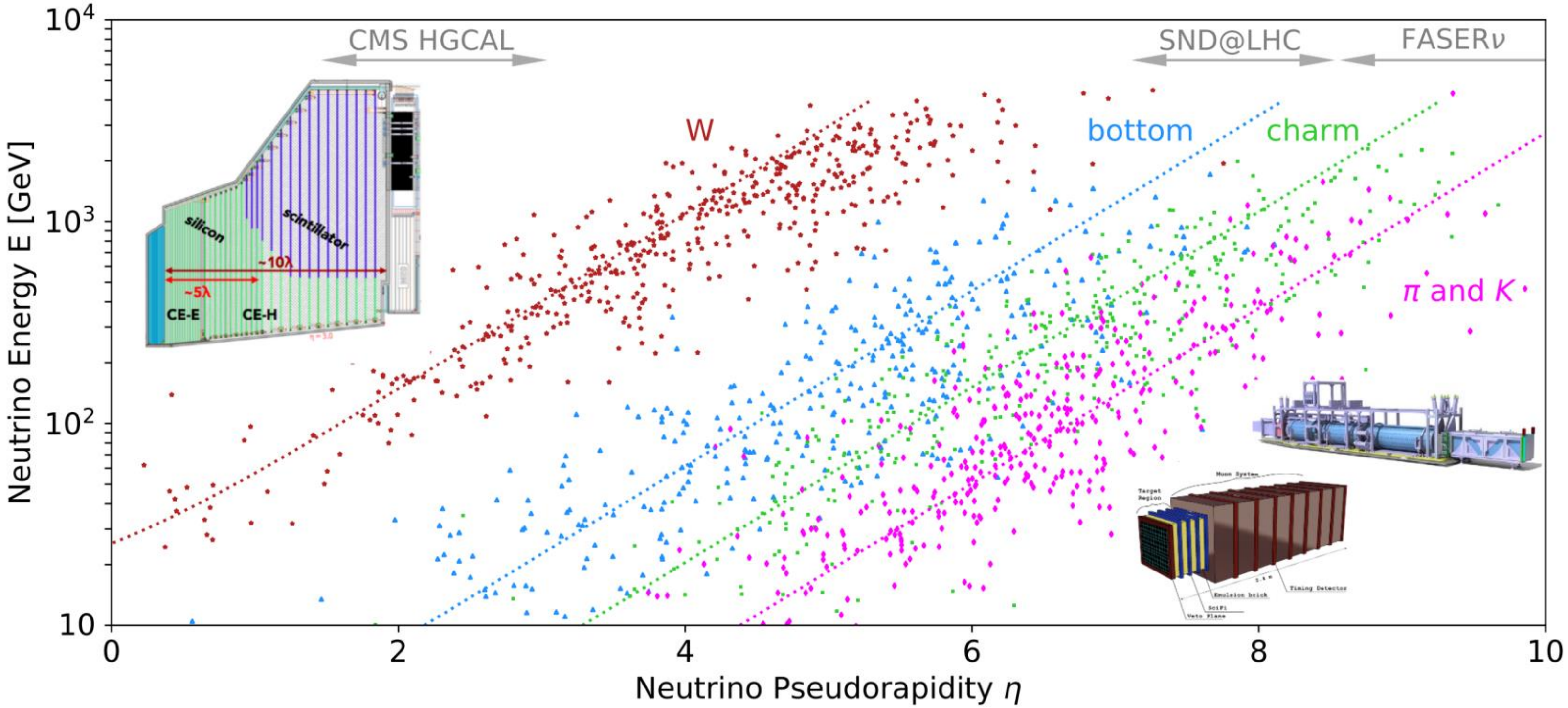






Neutrinos at the LHC

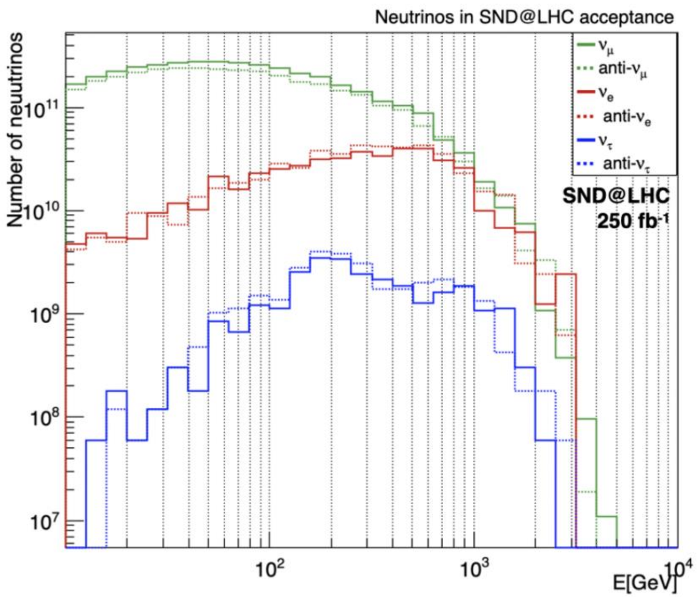
- Neutrinos at the LHC can originate from the weak decay of a variety of SM particles of different masses.



P. Foldenauer,
F. Kling and P. Reimitz
[arXiv:2108.05370]

Neutrinos in SND@LHC acceptance

- O(7x10^{12}) neutrinos produced in the SND@LHC acceptance (250 fb^{-1})
- ~1690 CC neutrino interactions, ~555 NC interactions (tungsten 830 kg)



Flavour	Neutrinos in acceptance $\langle E \rangle$ [GeV]	Yield	CC neutrino interactions $\langle E \rangle$ [GeV]	Yield	NC neutrino interactions $\langle E \rangle$ [GeV]	Yield
ν_μ	130	3.0×10^{12}	452	910	480	270
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360	480	140
ν_e	339	3.4×10^{11}	760	250	720	80
$\bar{\nu}_e$	363	3.8×10^{11}	680	140	720	50
ν_τ	415	2.4×10^{10}	740	20	740	10
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10	740	5
TOT		4.0×10^{12}		1690		555

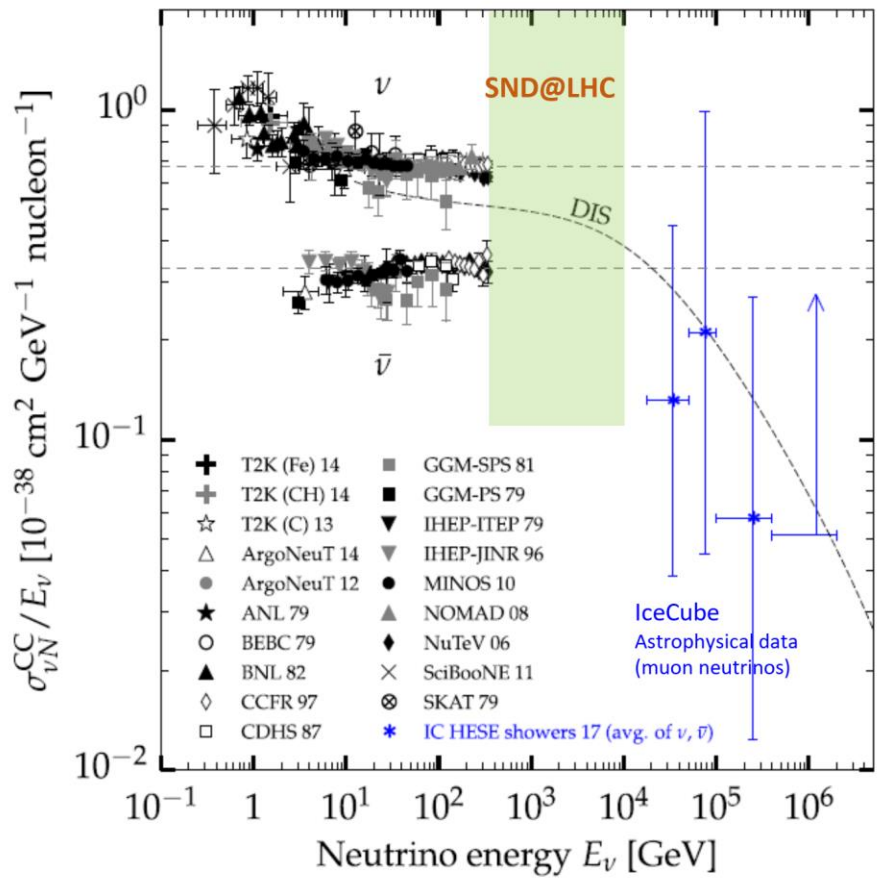
Ratio of NC/CC events ~ 0.33 : A consistency test of SM

Neutrinos at the LHC

- Neutrino energy range
  350 GeV < E < 10 TeV
  is currently unexplored.

- No **collider neutrinos** had ever been detected so far.

- SND@LHC and FASER now provide **the first detection** and study of the collider neutrinos in the unexplored energy range.

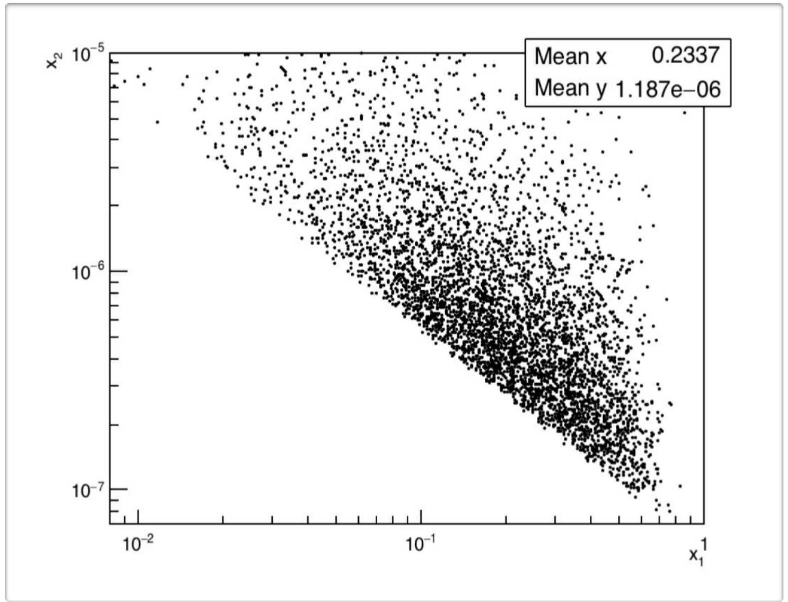


Physics in SND@LHC

- Measurement of the pp → ν X cross section
- Charmed-hadron production in pp collisions
- Lepton flavor universality in neutrino interactions
- Measurement of the NC/CC ratio
- Search for Feebly Interacting Particles

Charmed-hadron production at LHC

- Electron neutrinos mainly come from the decay of charmed hadrons produced in the LHC pp collisions.
- Measurement of pp → $\nu_e X$ cross-section provide insight into the heavy-quark production in an unexplored domain.



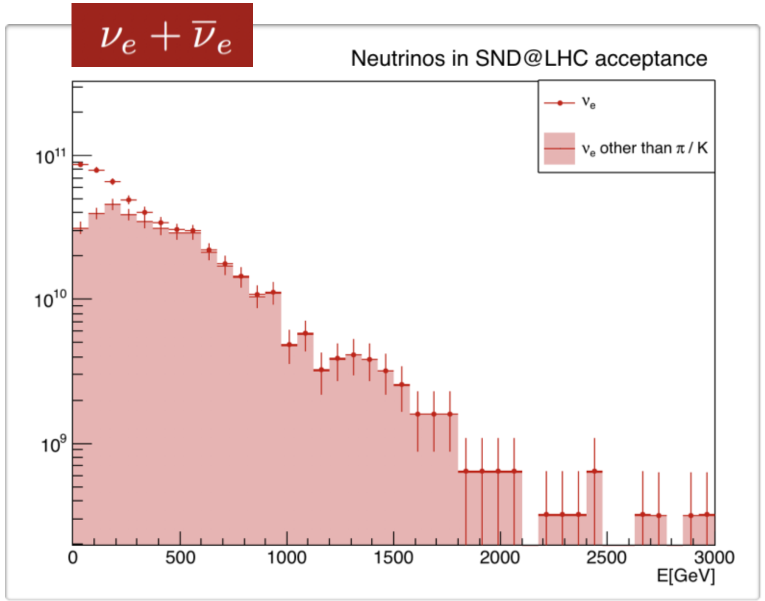
- The dominant partonic process for associated charm production at the LHC is gluon-gluon scattering

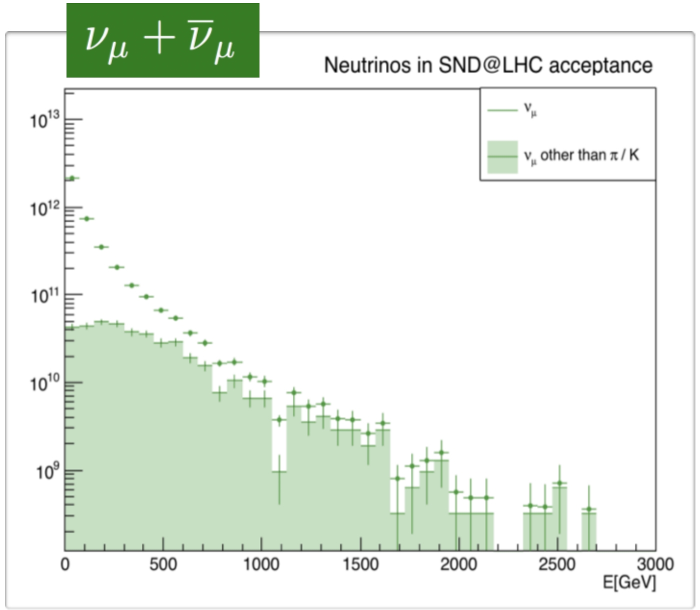
- Measurement of electron neutrinos can provide valuable constraints on the gluon PDF in small x region

Correlation between x1 and x2
for events with neutrinos in the SND@LHC acceptance

Lepton Flavor Universality

- The capability to identify all three flavors with the SND@LHC offers a unique possibility to test Lepton Flavor Universality in neutrino interactions
- The ν_e/ν_τ ratio is sensitive to the ν-nucleon interaction cross section ratio of the two neutrino species.





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

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

contamination from π/k

The measurement of the R_{12} ratio can be used as a test of the LFU For E > 600 GeV

Measurement of the NC/CC ratio

- Lepton identification for the three different flavors allow to distinguish CC to NC interaction at SND@LHC.
- If differential neutrino and anti-neutrino flux are equal, the NC/CC ratio can be written as

$$P = \frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}}$$

- In case of DIS, *P* can be written as

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

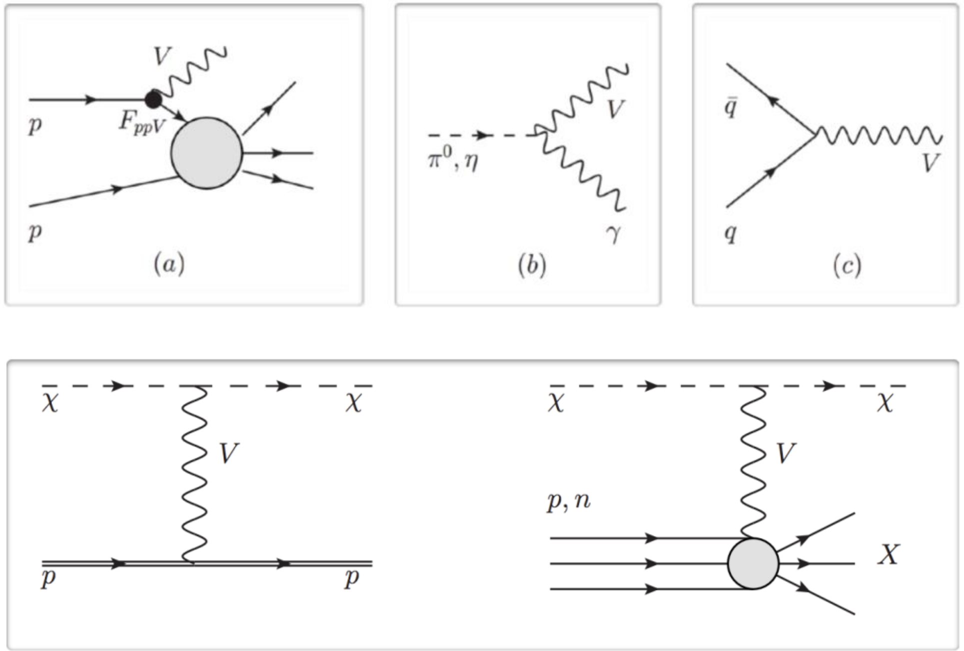
(For a Tungsten target λ=0.04)

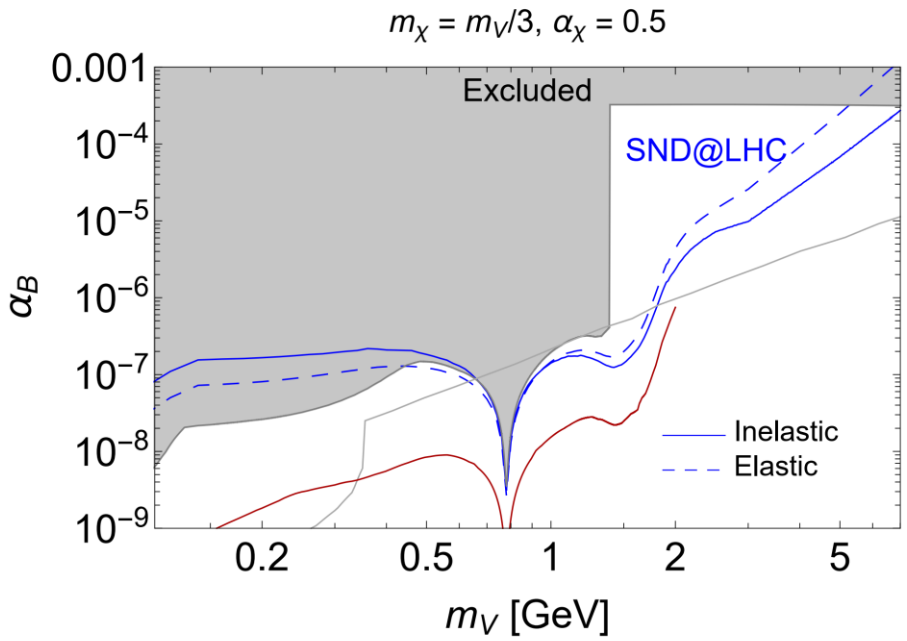
- SND@LHC plans to measure this ratio as a consistency test of the Standard Model

- The systematic uncertainty 10%
  The statistical error 5%

Search for Feebly Interacting Particles

- SND@LHC will also be capable of exploring models with FIPs.





First Physics Results

Observation of Collider Muon Neutrinos

- SND@LHC reported the first observation of muon neutrinos from the LHC collisions, **using exclusively data from the electronic detectors**.

PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

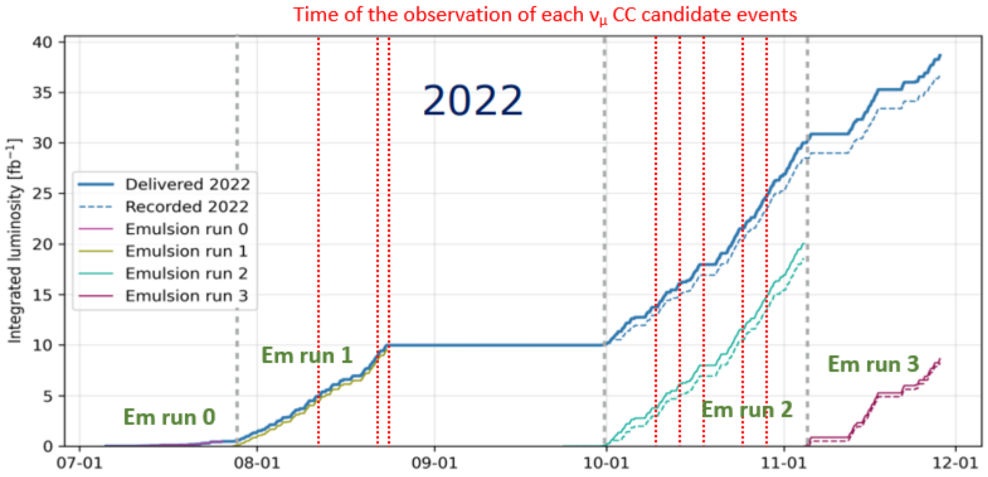
(Received 17 May 2023; revised 13 June 2023; accepted 20 June 2023; published 19 July 2023)

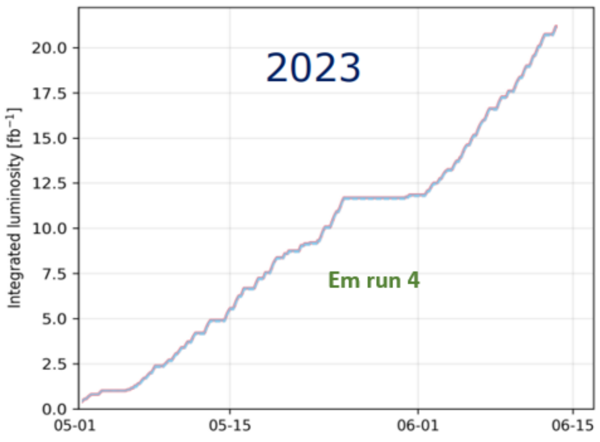
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_μ interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed ν_μ signal.

DOI: 10.1103/PhysRevLett.131.031802

Integrated Luminosity

- A data set of proton-proton collisions at 13.6 TeV collected in 2022 is used for ν_μ CC events search corresponding to an integrated luminosity of 36.8 fb^{-1}.



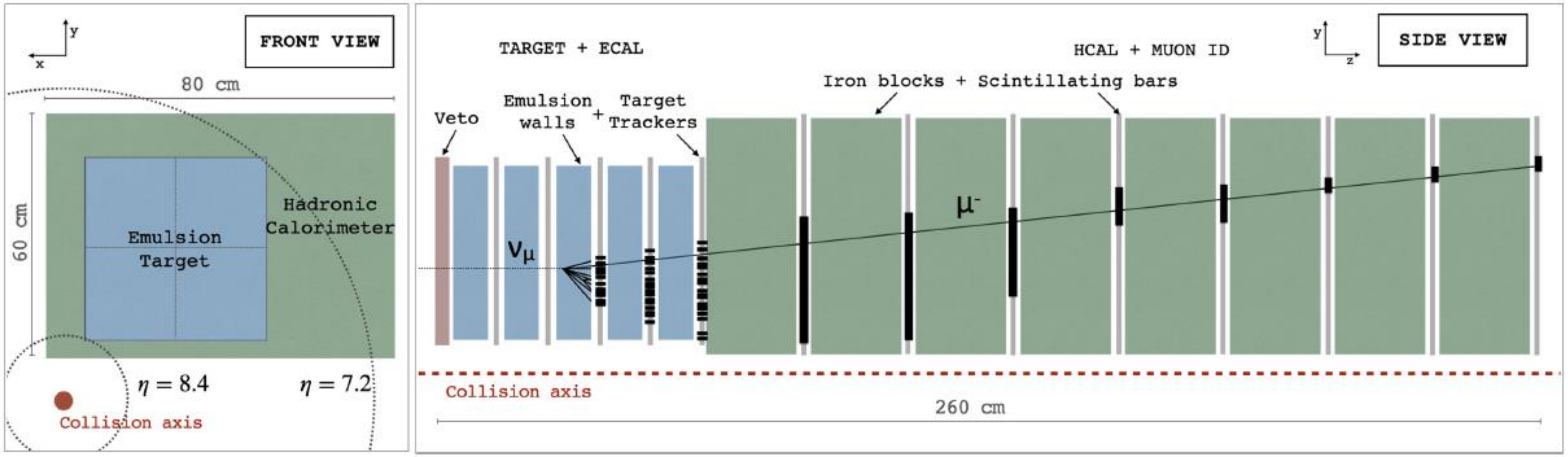


2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN0													39 kg	0.46 fb^{-1}
EMULSION RUN1													807 kg	9.5 fb^{-1}
EMULSION RUN2													784 kg	20.0 fb^{-1}
EMULSION RUN3													792 kg	8.6 fb^{-1}

2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN4													797 kg	21.2 fb^{-1}
EMULSION RUN5														18 fb^{-1}
EMULSION RUN6														18 fb^{-1}
EMULSION RUN7														18 fb^{-1}

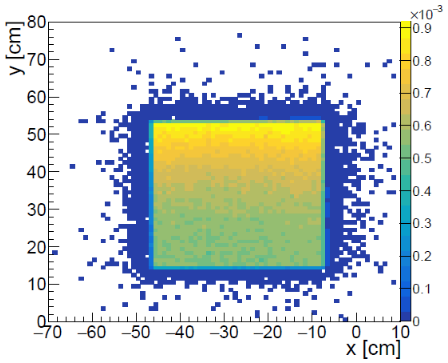
Signature of muon neutrino interaction

- In SND@LHC the dominant CC process occurring for muon neutrinos is deep inelastic scattering.
- The signature of these interactions includes an isolated muon track in the muon system, associated with a hadronic shower (SciFi and HCAL)

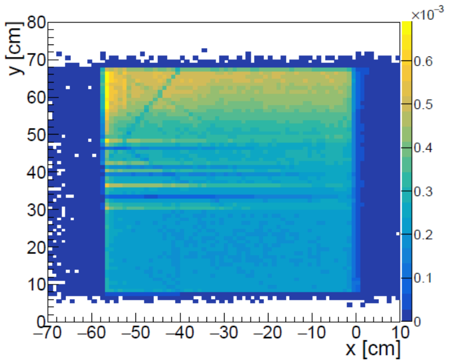


Analysis strategy

- Expected number of ν_μ signal ~ 157±37 (target mass 792 kg, 36.8 fb^{-1})
- Background : ~ 10^9 muons reaching the detector location.



SciFi tracks

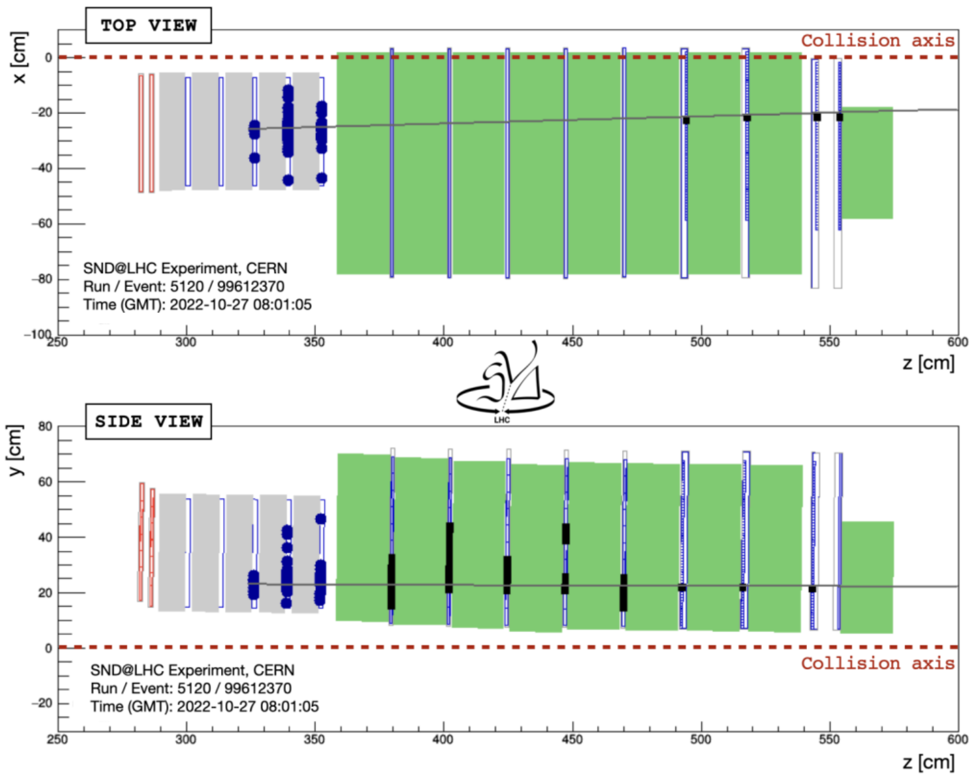


DS tracks

- ➢ Muon flux measured using electronic detectors ~ 2.07 x 10^4 cm^{-2}/fb^{-1}
- ➢ The expected muon flux in the fiducial area ~ 1.69 x 10^4 cm^{-2}/fb^{-1}

- Need a selection with strong rejection power for very clean events.

Signal Selection



Display of a ν_μ CC candidate event

- **Fiducial volume cut** : identify events happening in a fiducial region of the target and reject charged particles entering from the front and sides of the detector.

- A Neutral vertex event in the 3rd or 4th target walls
- Detector activity constrained in an inner XY region (25x26 cm^2)

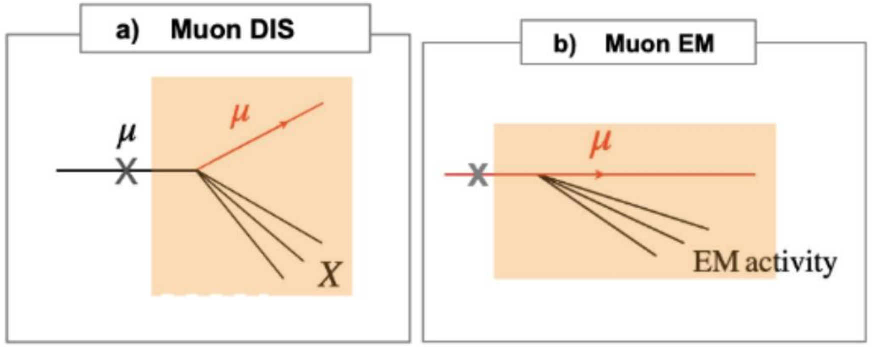
- **Neutrino ID cut** : select signal-like signature patterns.

- A Large hadronic activity in the calorimetric system
- A clean outgoing muon track in the muon system
- Hit time consistent with an event from the IP1 direction

➢ Overall efficiency on signal (MC) ~ 2.7 %
➢ Overall efficiency on data ~ 10^{-9}

Backgrounds

- **Penetrating Muon background** : enter in the fiducial volume without being vetoed and generate showers via DIS or bremsstrahlung

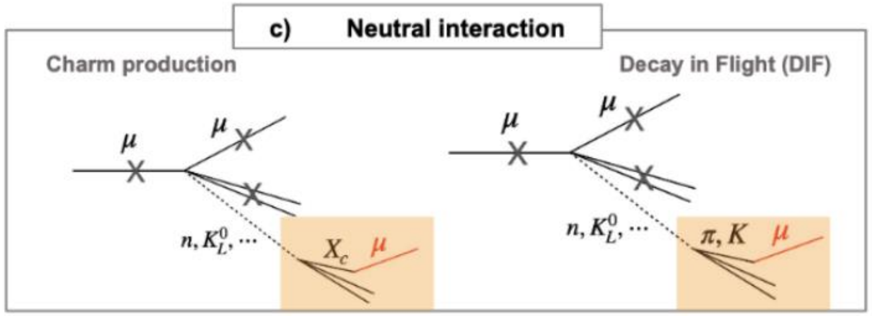


$$N_{\mu}^{bkg} = N_{\mu} \times \underbrace{(1-\epsilon_{Veto}) \times (1-\epsilon_{SciFi1}) \times (1-\epsilon_{SciFi2})}_{\sim 5.3 \times 10^{-12}} \sim 3 \times 10^{-3}$$

Total number of muons in target acceptance ($\sim 5.0 \times 10^{8}$)

Electronic detectors inefficiencies

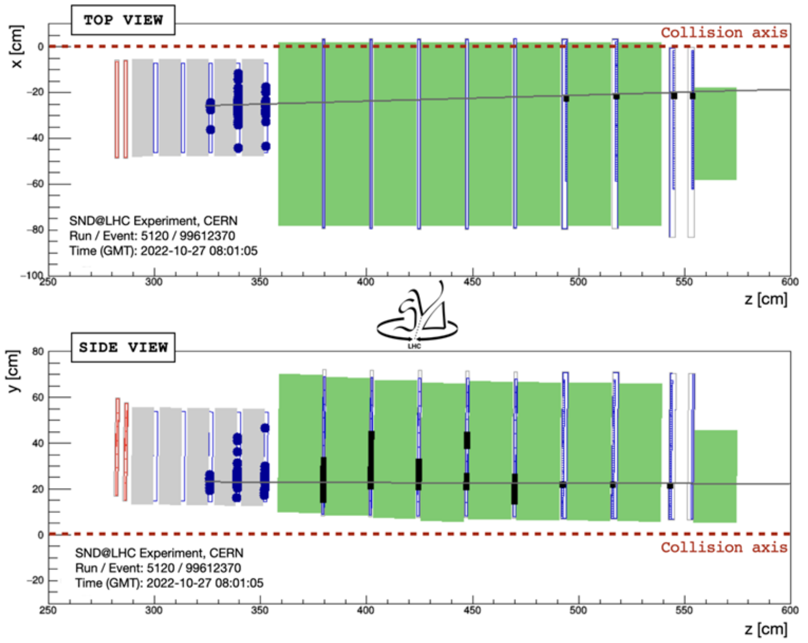
- **Muon-induced neutral particles** : Muons can interact in surrounding material, producing neutral particles which mimic neutrino interactions

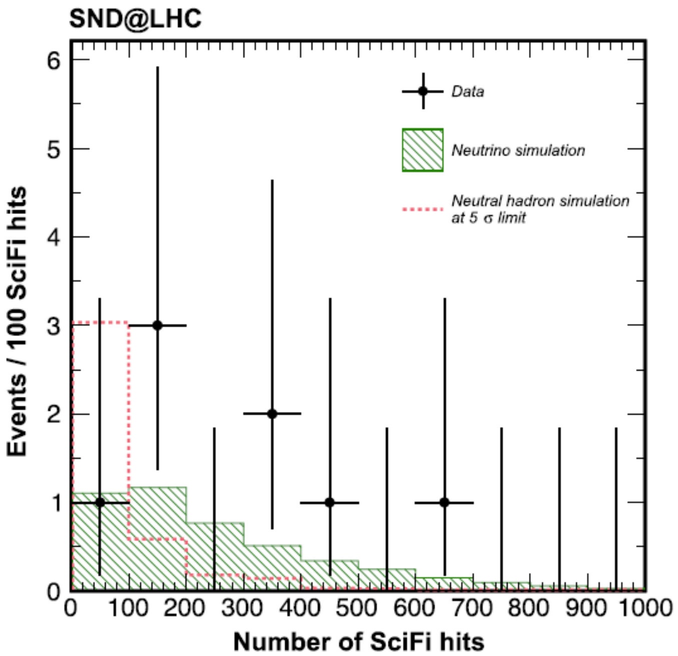


$$N_{neutrals}^{bkg} = N_{neutrals} \times P_{inel} \times \epsilon_{sel} = (8.6 \pm 3.8) \times 10^{-2}$$

Observation of muon neutrinos

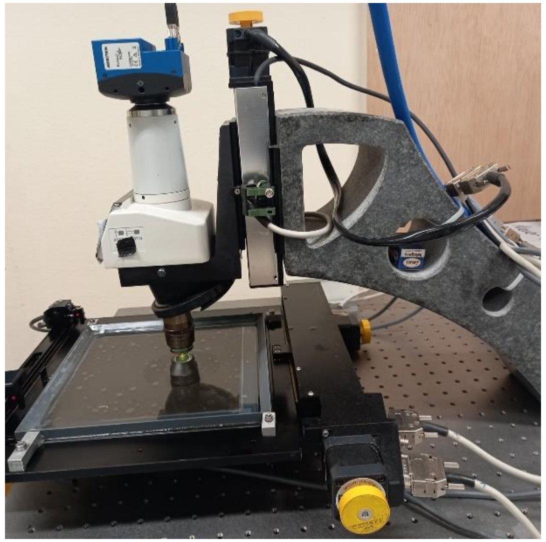
- After selection cuts, 8 ν_μ interaction candidate events remain (4.2 expected)
- An estimated background of 0.086 events
- A significance of 6.8 standard deviations for the observed ν_μ signal

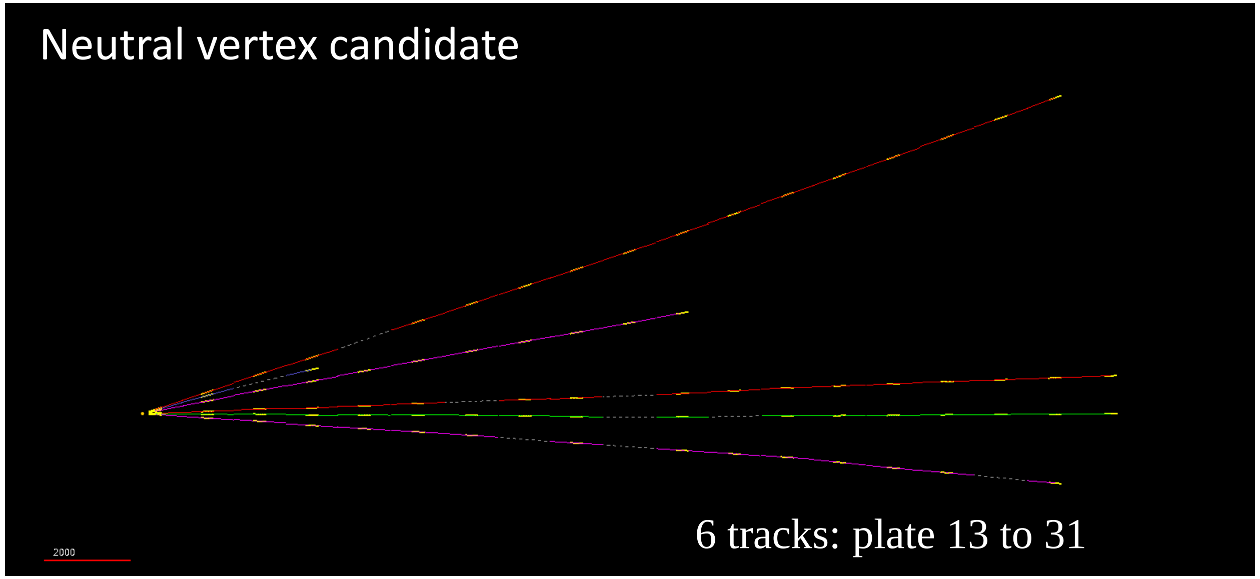


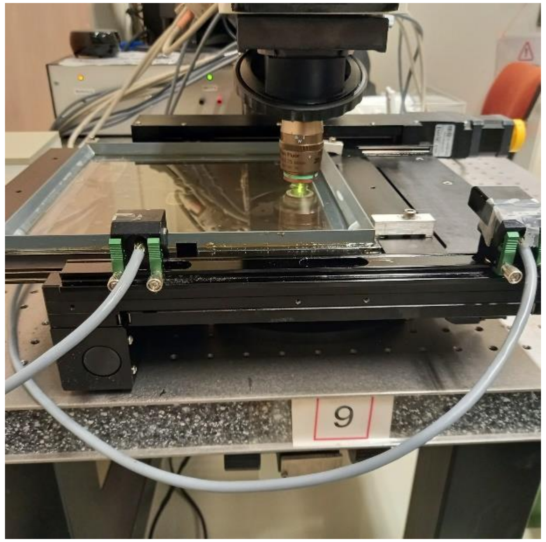


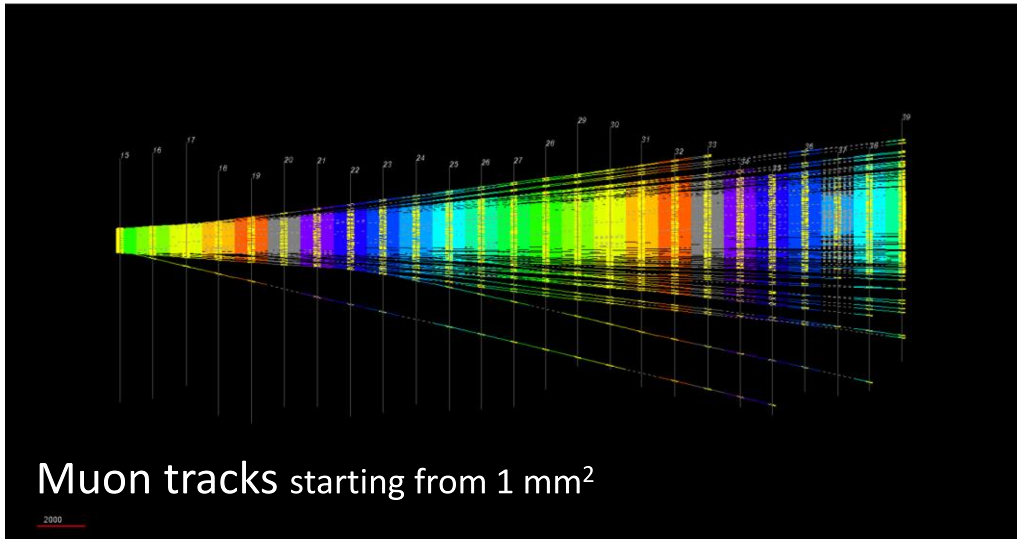
Nuclear Emulsion Scanning

- The analysis of the emulsions data is currently ongoing.









Track density per 10 fb^{-1} → ~10^5 tracks/cm^2

Conclusions

- The SND@LHC is a new experiment designed to perform measurements with neutrinos produced at the LHC.
- Taking data since the start of the LHC Run3.
- Reported the first direct observation of ν_μ CC interactions at collider, using electronic detectors, with 36.8 fb^{-1}.
- After selection cuts, 8 signal candidate events was observed with a significance of 6.8σ.
- Analysis of the emulsion data is currently being processed. Please stay tuned!

Backup slides

SND@LHC Collaboration

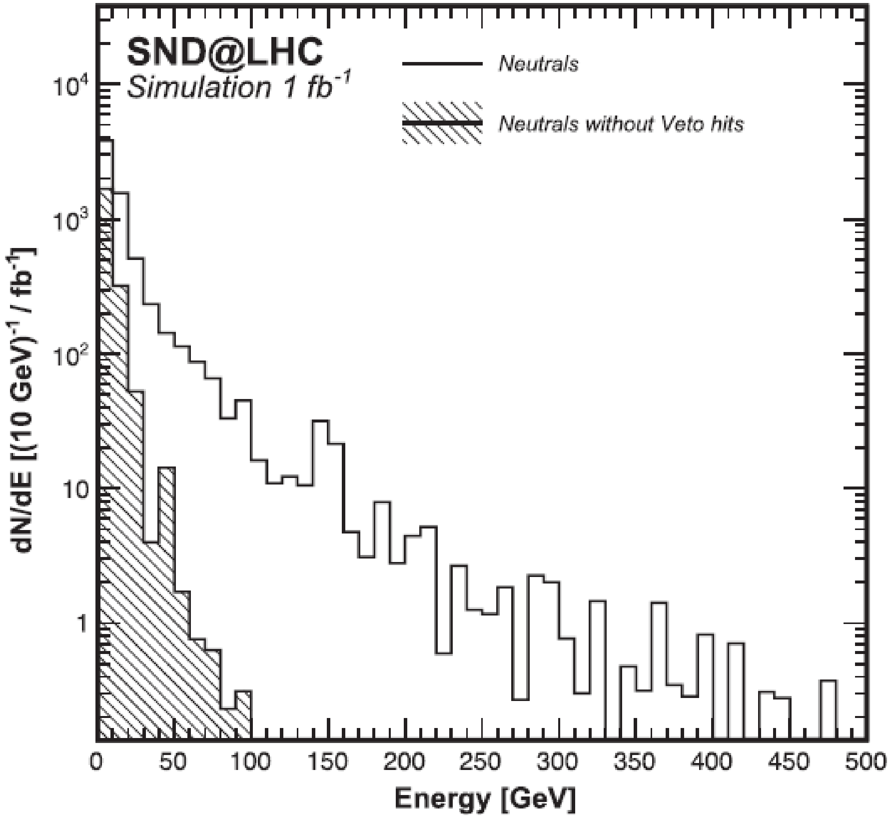
- Bulgaria
- Denmark
- Germany
- Italy
- Japan
- Korea
- Russia
- Switzerland
- Turkey
- United Kingdom
- Portugal
- Chile
- Brazil
- CERN

180 members, 24 institutes
13 countries & CERN

Summary of SND@LHC performances

Measurement	Uncertainty	
	Stat.	Sys.
$pp \rightarrow \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	20%
ν_e/ν_μ ratio for LFU test	10%	10%
Measurement of NC/CC ratio	5%	10%

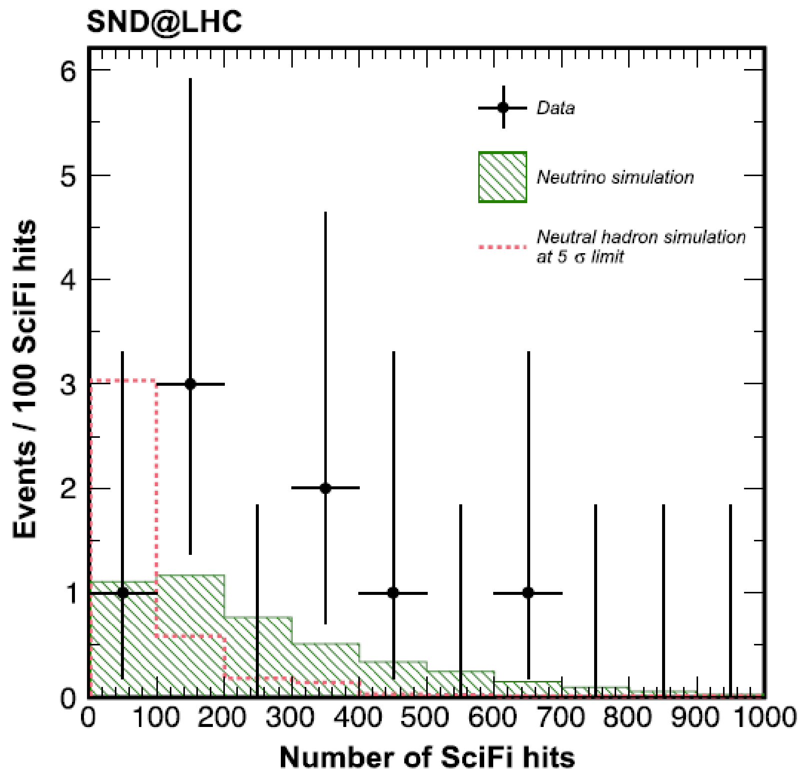
Energy spectrum of neutral hadrons



The rate of neutral hadron events with energies above 100 GeV is heavily suppressed by using the veto system to tag the accompanying charged particles (most often the scattered muon).

FIG. 4. Energy spectrum of neutral hadrons produced by muon interactions in the rock and concrete entering the SND@LHC acceptance. The shaded area shows the spectrum after rejecting events with hits in the veto detector.

Distribution of SciFi hits for candidate events

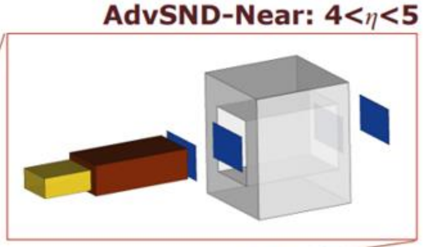


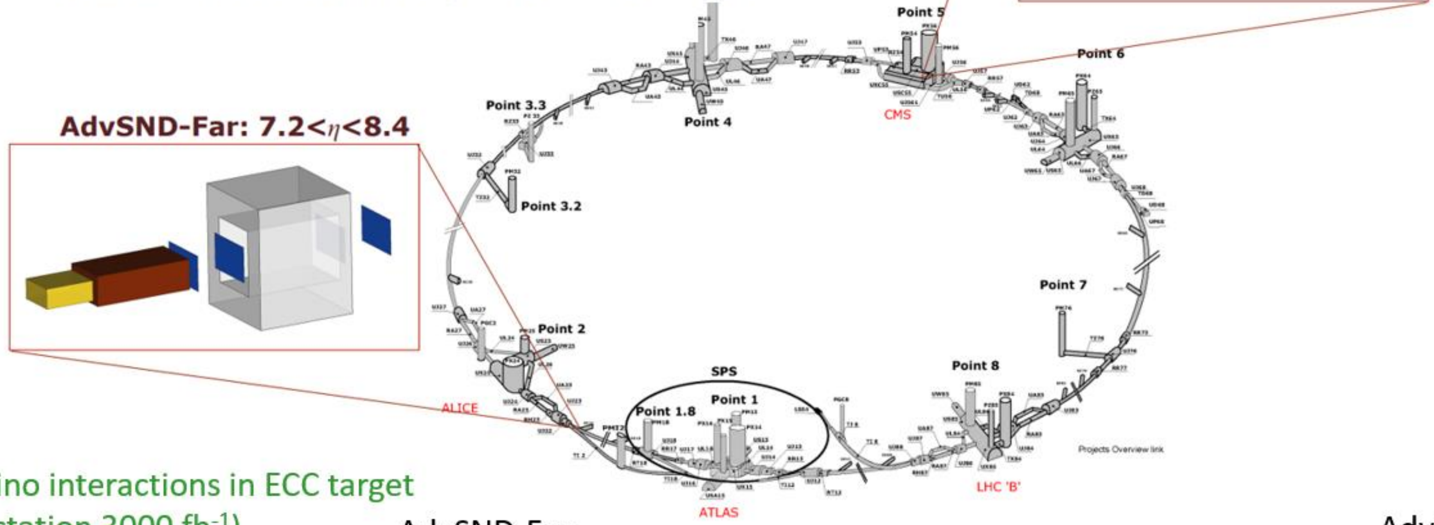
The lower energy of the neutral hadrons compared to the neutrino signal results in fewer hits in SciFi.

FIG. 3. Distribution of SciFi hits for candidate events, along with the expectation from the neutrino signal. The dashed line shows the background-only hypothesis scaled up to a deviation from the nominal expectation at a level of 5 standard deviations. The vertical bars represent 68.3% confidence intervals of the Poisson means.

Future plan - Advanced SND@LHC

- Upgrade of SND@LHC in view of an extended run during Run 4:
  - Extension of the physics case
  - New technologies and detector layout
  - Two detectors
    - AdvSND-Far ($7.2<\eta<8.4$)
      Possible locations: TI18, Future Forward Facility
    - AdvSND-Near ($4<\eta<5$)
      Possible locations: existing caverns close to IP





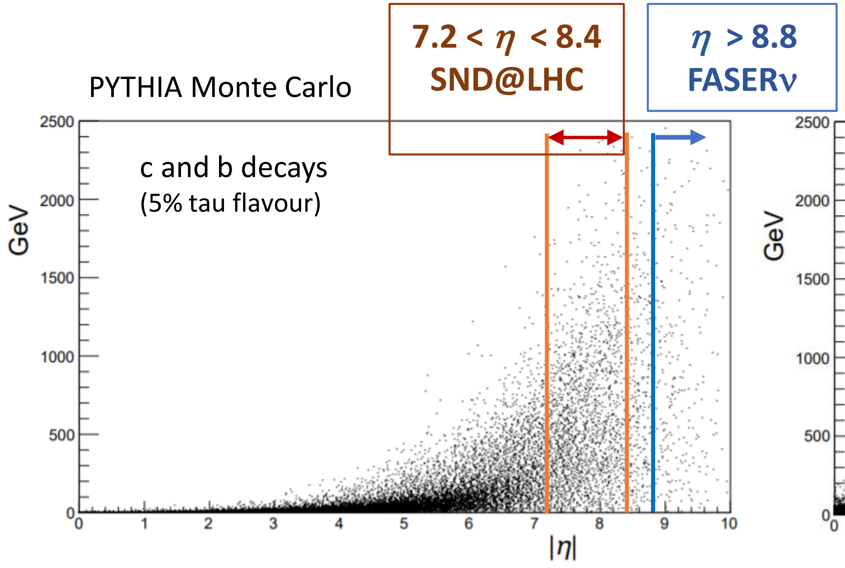
Neutrino interactions in ECC target
(Expectation 3000 fb^{-1})

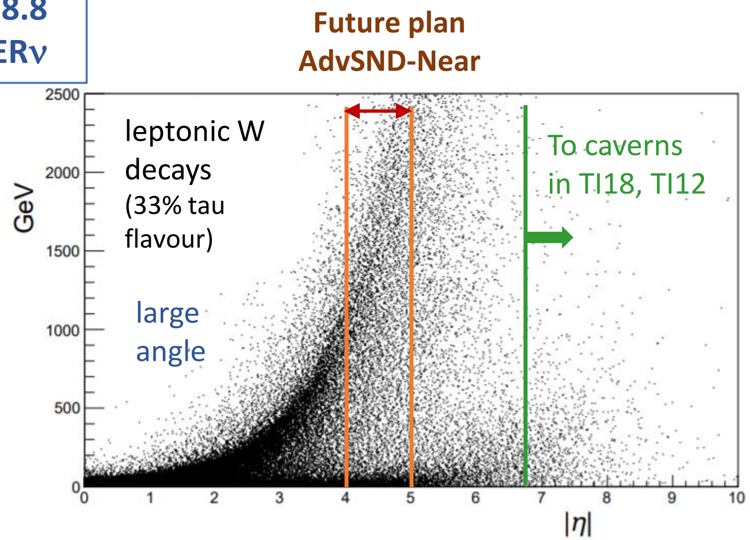
AdvSND-Far

Flavour	ν in acceptance		CC DIS	
	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	6.3×10^{12}	1.5×10^{11}	1.2×10^{4}	200
$\nu_e + \bar{\nu}_e$	6.7×10^{12}	1.7×10^{11}	1.2×10^{4}	220
$\nu_\tau + \bar{\nu}_\tau$	7.1×10^{11}	4.7×10^{10}	880	40
Tot	1.4×10^{13}		2.5×10^{4}	

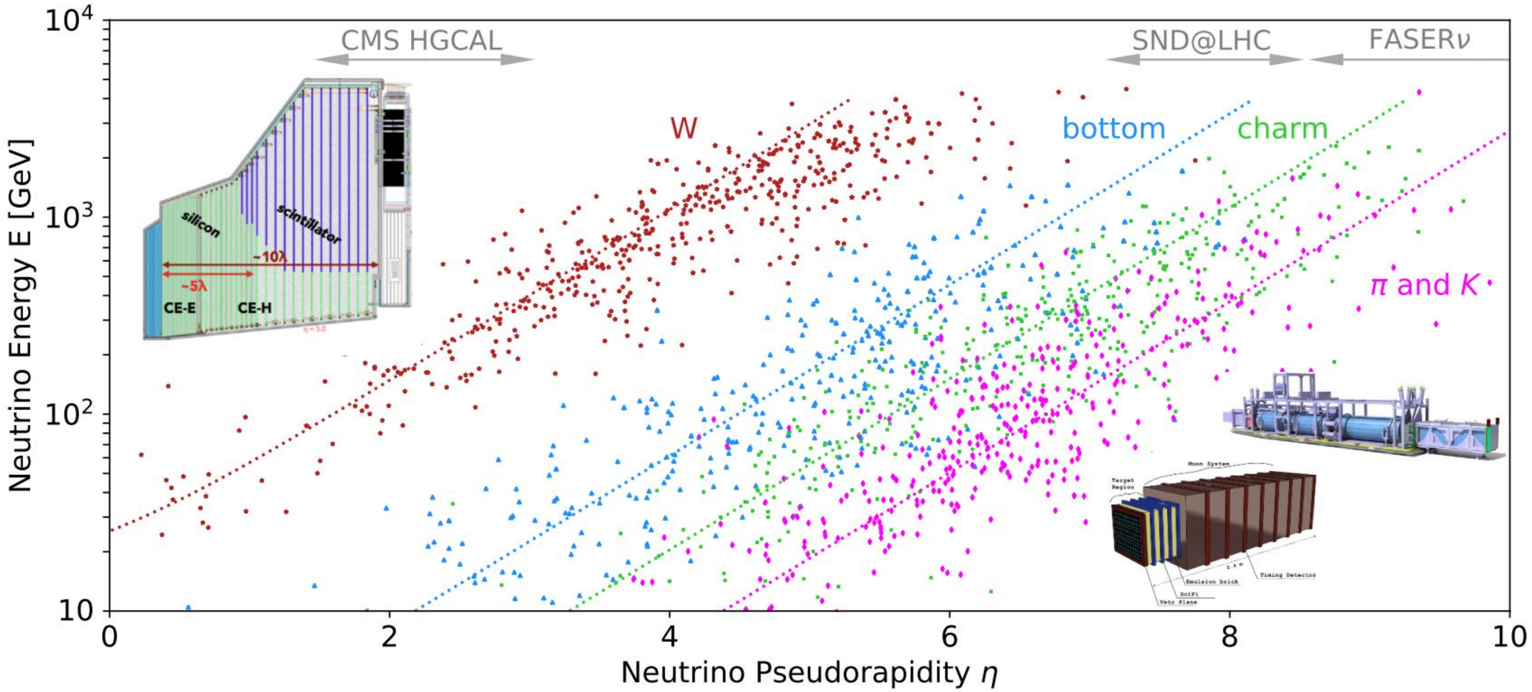
AdvSND-Near

Flavour	ν in acceptance		CC DIS	
	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	2.1×10^{12}	3.3×10^{11}	980	200
$\nu_e + \bar{\nu}_e$	2.2×10^{12}	3.3×10^{11}	1000	200
$\nu_\tau + \bar{\nu}_\tau$	2.7×10^{11}	1.4×10^{11}	80	50
Tot	5.4×10^{12}		2.5×10^{3}	





N. Beni, G. De Lellis, A. Di Crescenzo et al., *J. Phys. G* 46 (2019) 115008 [arXiv:1903.06564]



P. Foldenauer, F. Kling and P. Reimitz, [arXiv:2108.05370v1]