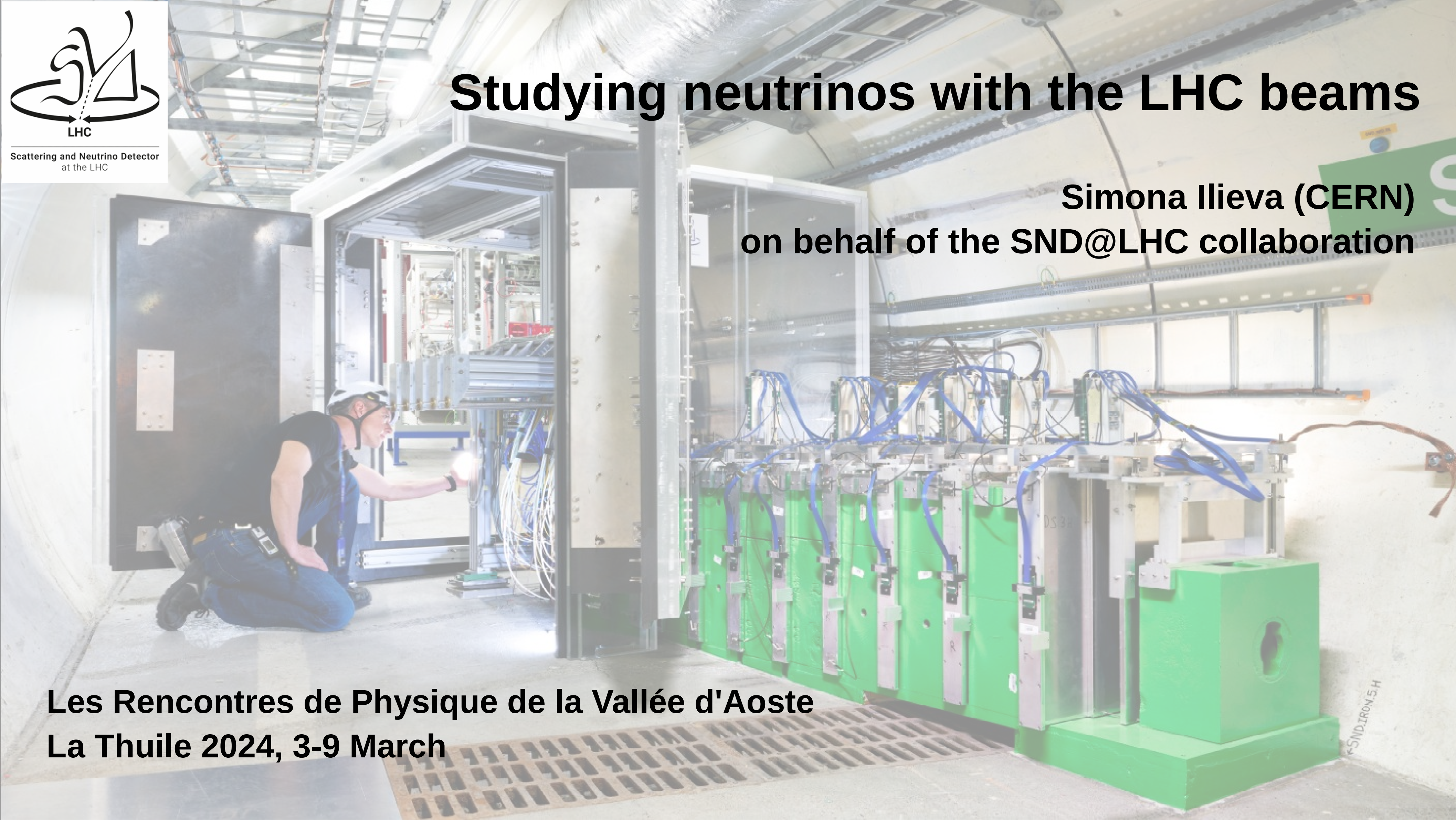
LHC
Scattering and Neutrino Detector
at the LHC

Studying neutrinos with the LHC beams

Simona Ilieva (CERN)
on behalf of the SND@LHC collaboration



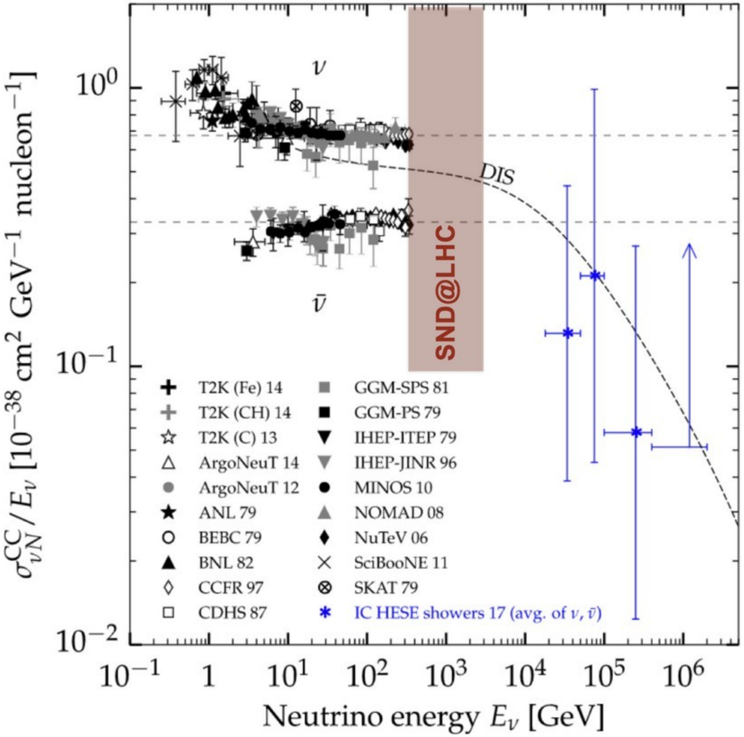
Les Rencontres de Physique de la Vallée d'Aoste
La Thuile 2024, 3-9 March

Neutrino experiments at the LHC

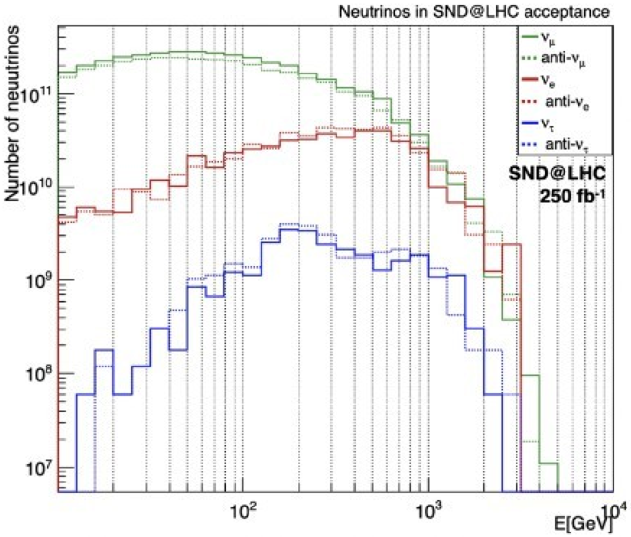
Potential of observing neutrinos at the LHC recognized in the early 80s

- Large neutrino fluxes in forward region from pp collisions
- High ν energy: E_ν [10^2 - 10^3] GeV, $\sigma_\nu \propto E_\nu$
- A small-scale LHC experiment can observe neutrinos of all three types
- Probe pp→ νX in an unexplored energy domain

PRL 122 (2019) 041101



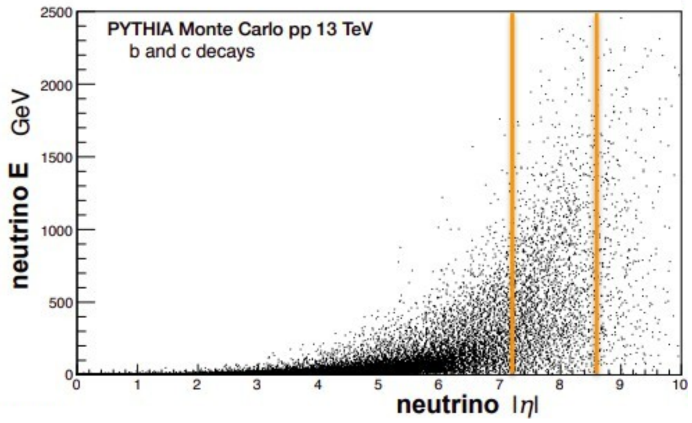
- Two experiments presently operating
  - FASERν on-axis (η>9)
    - enhances statistics
  - SND@LHC off-axis (7.2 <η< 8.4)
    - enhances charm parentage



SND@LHC physics programme

SND@LHC TP: LHCC-P-016

- Measure charm production at high η
  - Neutrinos in the detector acceptance are mostly coming from charmed hadrons decay
    J. Phys. G: Nucl. Part. Phys. 47 125004
- ν_e as a probe of forward charm quark production
  - constrain gluon PDF at very low momentum fraction ($x \sim 10^{-6}$)
- Lepton universality test: ν_τ/ν_e and ν_μ/ν_e
  - The detector is designed to distinguish all neutrino flavours
- Measurement of the NC/CC ratio
- Direct search for feebly interacting particles (FIP) through their scattering

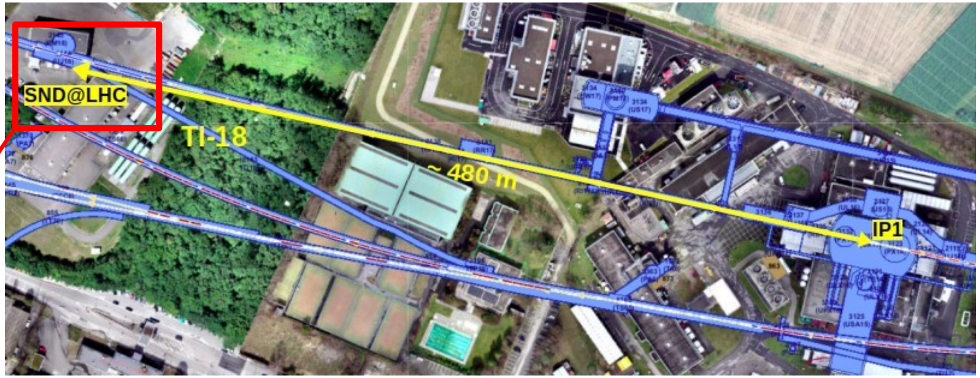


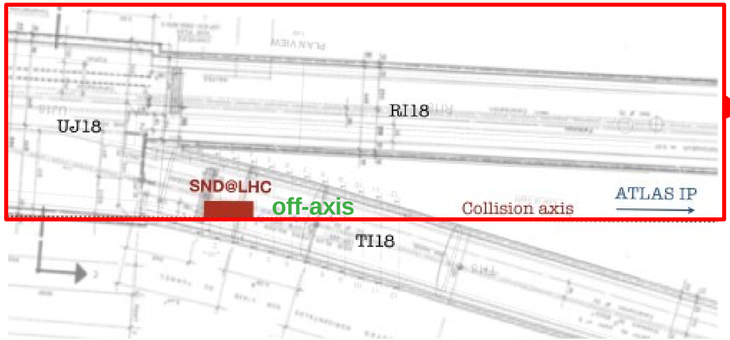
Run3: 250fb^{-1}

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

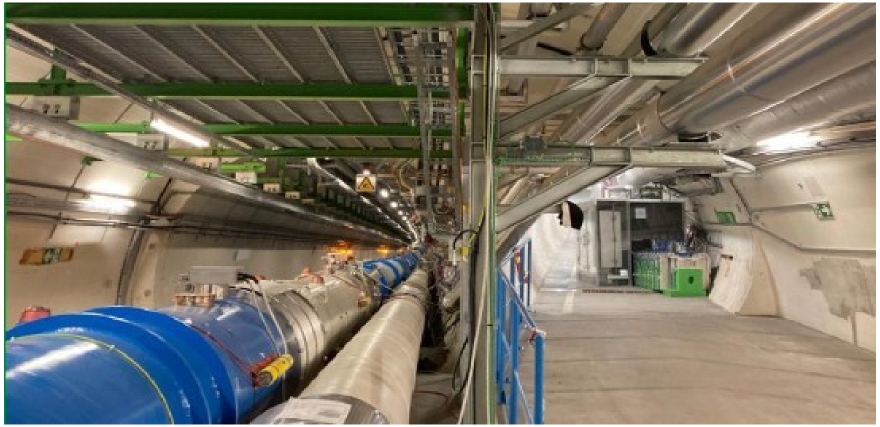
Detector location

- In the TI18 tunnel
  - former SPS to LEP transfer line
- ~ 480m away from ATLAS interaction point(IP1)





Machine to IP1(left) - SND@LHC in TI18(right)



- Shielded by:
  - ~ 100m rock
  - LHC magnets deflecting charged particles
- Angular acceptance 7.2 < η < 8.4

Detector concept

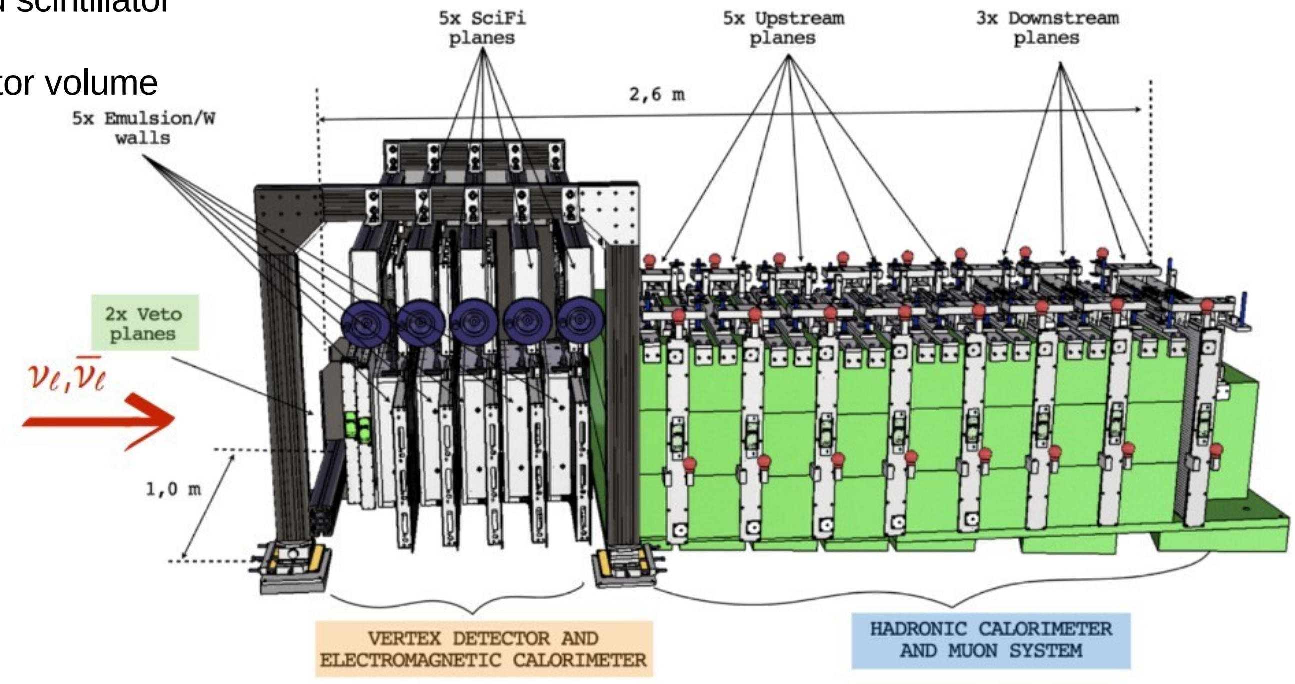
- Hybrid detector design
- Optimized for the identification of three ν flavours and feebly interacting particles.

- **Veto system**
  - 2+1 (installed in 2024) planes of stacked scintillator bars
  - tag charged particles entering the detector volume

- **Vertex detector + ECal**
  - **E**mulsion **C**loud **C**hambers(emulsion/W)
    - neutrino target mass ~830kg
  - ECC alternated with Scintillating fiber planes

- **HCal + MUON ID SYSTEM**
  - 5+3 plastic scintillator planes interchanged with 20-cm-thick iron walls
  - Last 3 planes (**D**ownstream **S**tations) have finer granularity to track muons

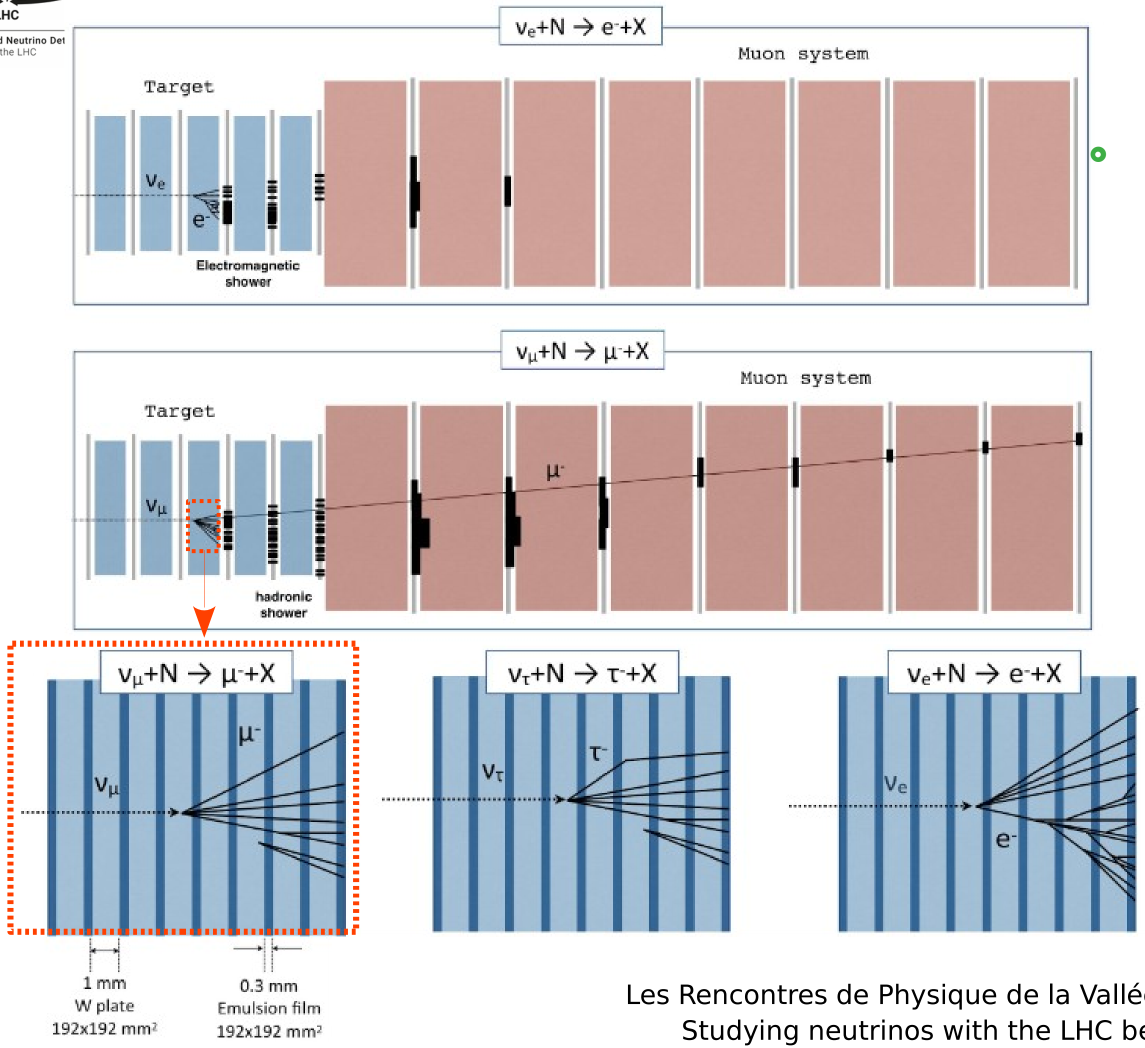
arXiv:2210.02784



~ 84 X_0, $3\lambda_{int}$

~10 λ

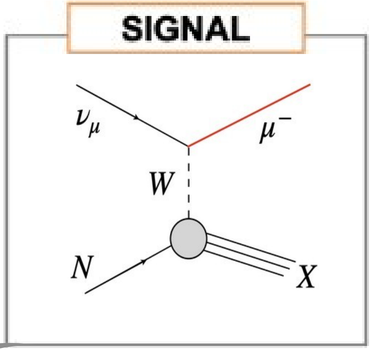
Neutrino interaction identification



- **First phase (online, electronic detectors)**
  - Identify signal candidates (neutrino or FIPs)
  - Tag muon tracks (muon system)
  - Measure showers with the Ecal and HCal
- **Second phase (offline, emulsion)**
  - Micrometric resolution for precise neutrino vertex reconstruction
  - No timing information – emulsions integrate signal over a few months to a maximum of 20 fb^{-1}
  - Limited energy measurement
  - Must be complemented with a **matched** electronic detector event

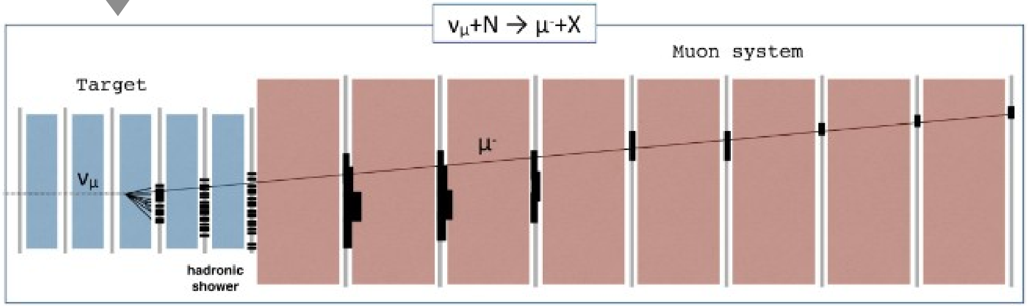
Observation of collider muon neutrinos with the SND@LHC experiment

PRL 131, 031802(2023)



Search for ν_μ **C**harged **C**urrent **D**eep **I**nelastic **S**cattering events in the electronic detector data

- Analysis of the 2022 dataset
  - corresponding to 36.8 fb^{-1}
- Expected signal: 157 ± 37
- Background from ~10^9 muons



- Select high-purity sample of candidate events
  - counting-based approach
- Maximize signal/background ratio
  - strong rejection power needed

Observation of ν_μ using electronic detectors

PRL 131, 031802(2023)

Fiducial volume cut

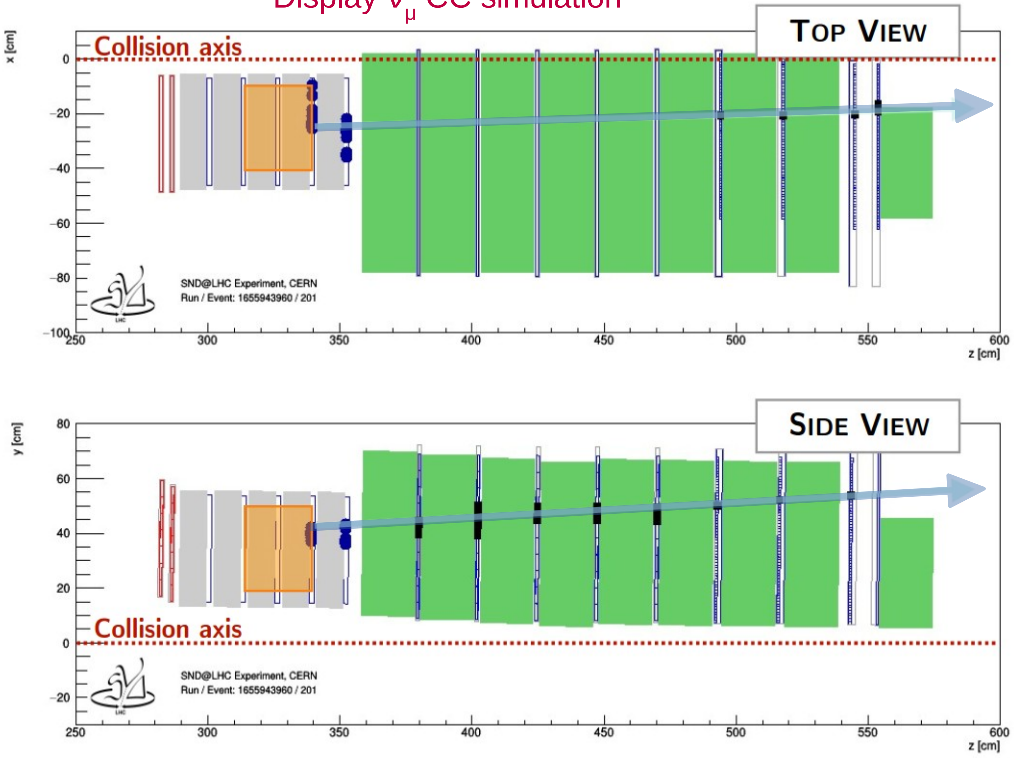
- Detector activity starts in the 3rd or 4th target wall
  - consistent with a neutral particle interaction
  - probing the ν_μ-induced shower already in SciFi
- Reject side-entering backgrounds
- Signal acceptance: 7.5%

Muon neutrino interaction ID

- Large hadronic activity in SciFi and HCal
- One muon track associated to the vertex
- Hit time consistent with an event originating from the IP1 direction
- Signal selection efficiency: 36%

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

Display ν_μ CC simulation



Background control: Muon flux measurement

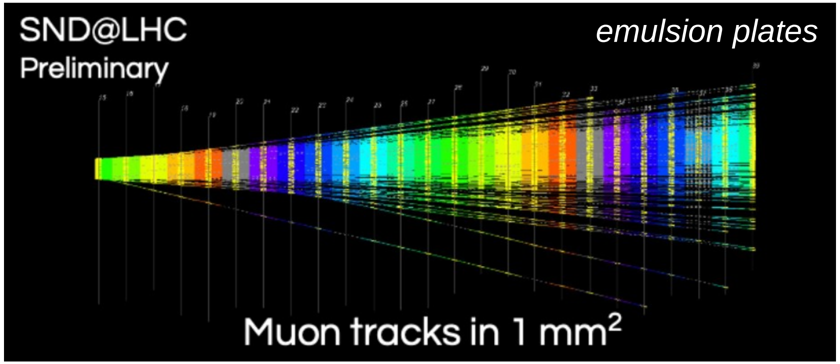
Eur.Phys.J.C 84 (2024)

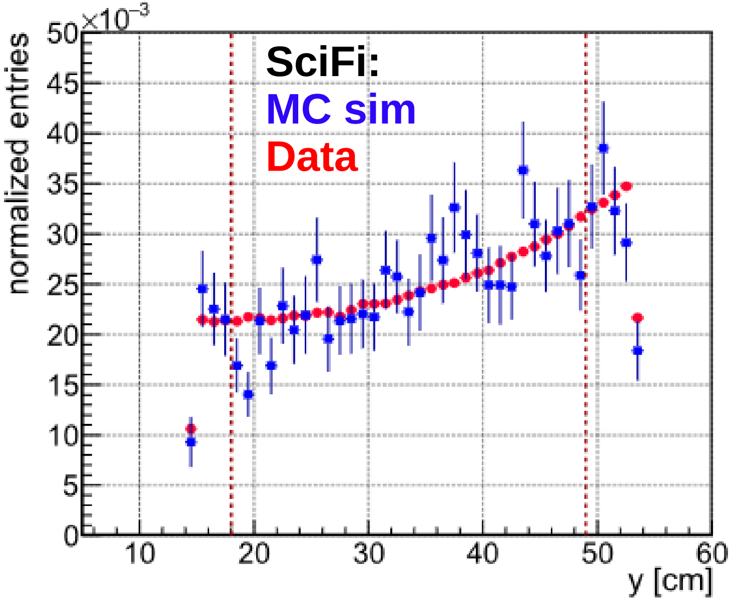
- A dedicated muon flux measurement using SciFi tracker and the Downstream Stations of the muon system
  - same fiducial area of size: 31x31cm^2

    SciFi: 2.06± 0.01(stat.) ± 0.12(sys.) ×10^4 cm^{-2}/fb^{-1}

    DS: 2.02 ± 0.01(stat.) ± 0.08(sys.) ×10^4 cm^{-2}/fb^{-1}

  - Control comparison with emulsion data shows good agreement too



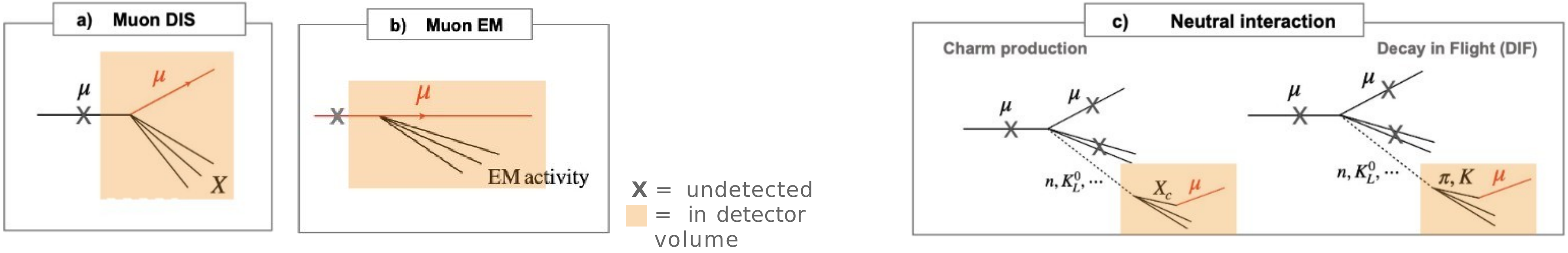


- Data/MC simulation agreement level 20-25%

Background assessment

PRL 131, 031802(2023)

- Muons reaching the detector location
  - Not vetoed, generate showers(bremsstrahlung, DIS in the detector) **(a,b)** – using the data
  - Interact in the surrounding material to produce neutral particles which can then mimic neutrino interactions in the target **(c)** – rely on simulations



~5.0x10[8] ~5.3x10[-12]

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

Total number of muons in target acceptance — *Veto inefficiency* — *SciFi plane inefficiency* — deemed negligible

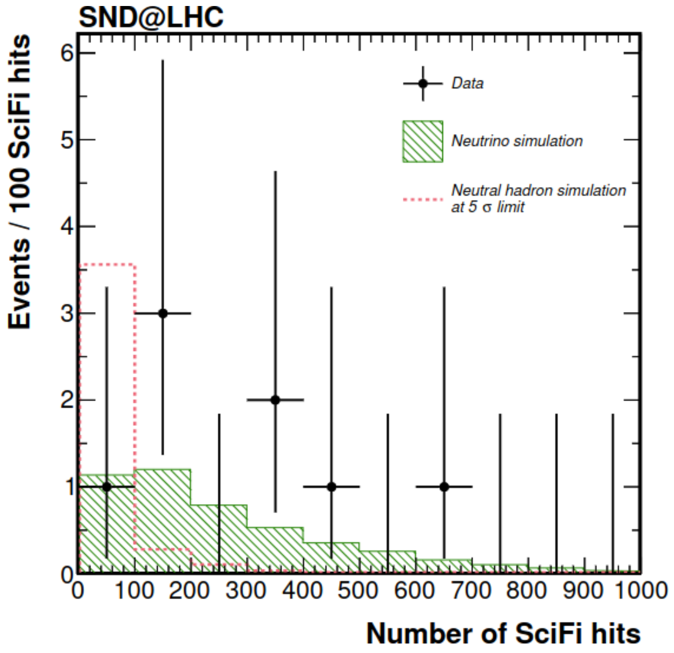
$$N_{\text{neutrals}}^{\text{bkg}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}}$$

$$= (8.6 \pm 3.8) \times 10^{-2}$$

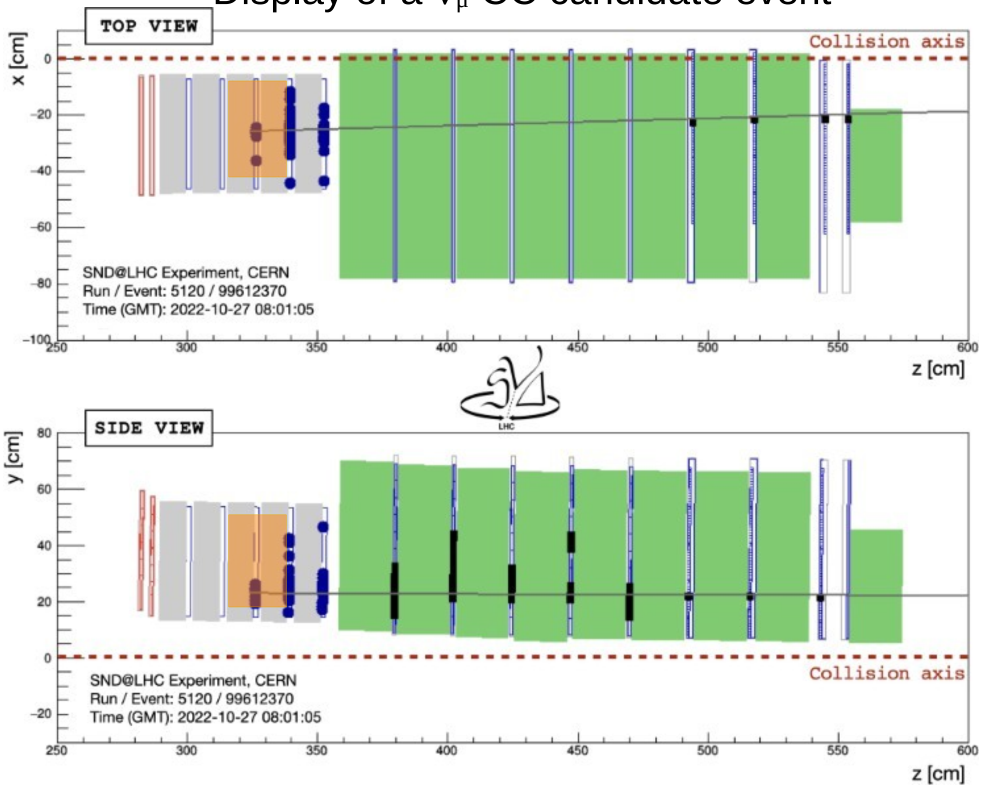
Observation of ν_μ using electronic detectors

PRL 131, 031802(2023)

Observed 8 ν_μ CC candidates with a statistical significance of 6.8σ



Display of a ν_μ CC candidate event



Ongoing searches in 2023/2024

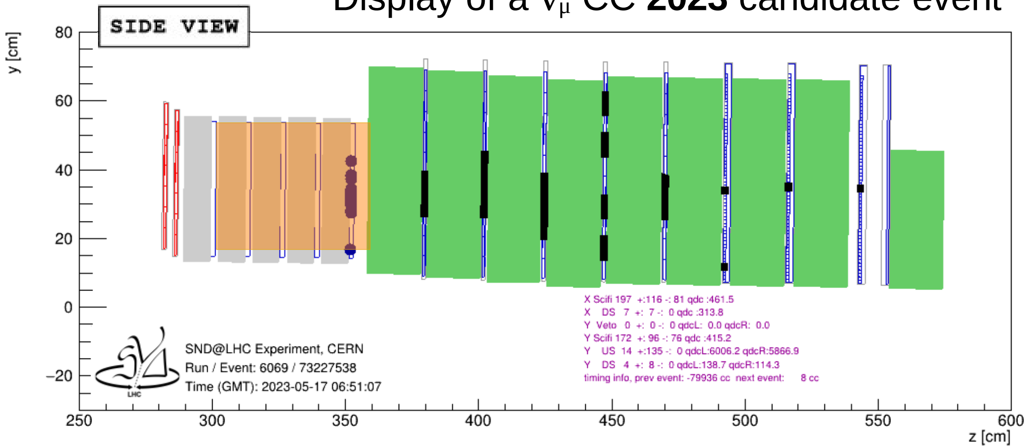
Preliminary

- ν_μ CC events search with 2022-2023 data in an extended target volume (walls 2 and 5 included):

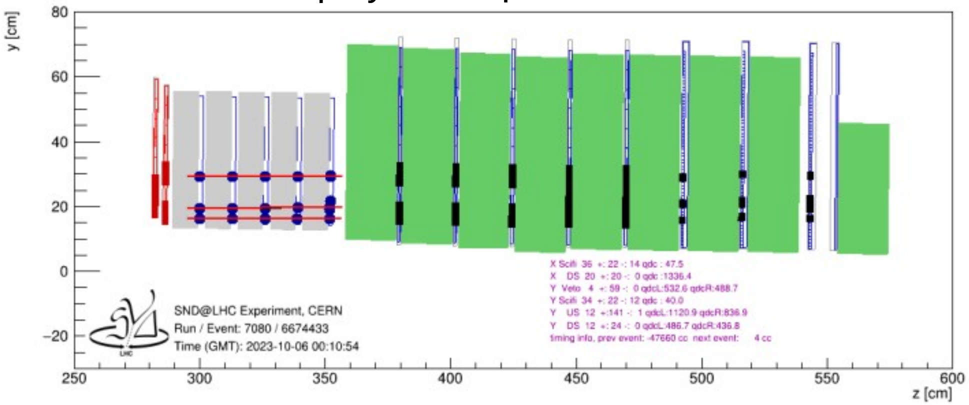
  32 events: 15 in 2022 and 17 in 2023

  - A factor of 2 gain from analysis improvements and another 2 from inclusion of the 2023 data w.r.t. PRL result
- Seeking charged current ν_e - DIS interactions using electronic detector data and emulsion
- Emulsion vertex matching to target tracker data
- Multi-muon event analysis in both proton and ion runs

Display of a ν_μ CC **2023** candidate event

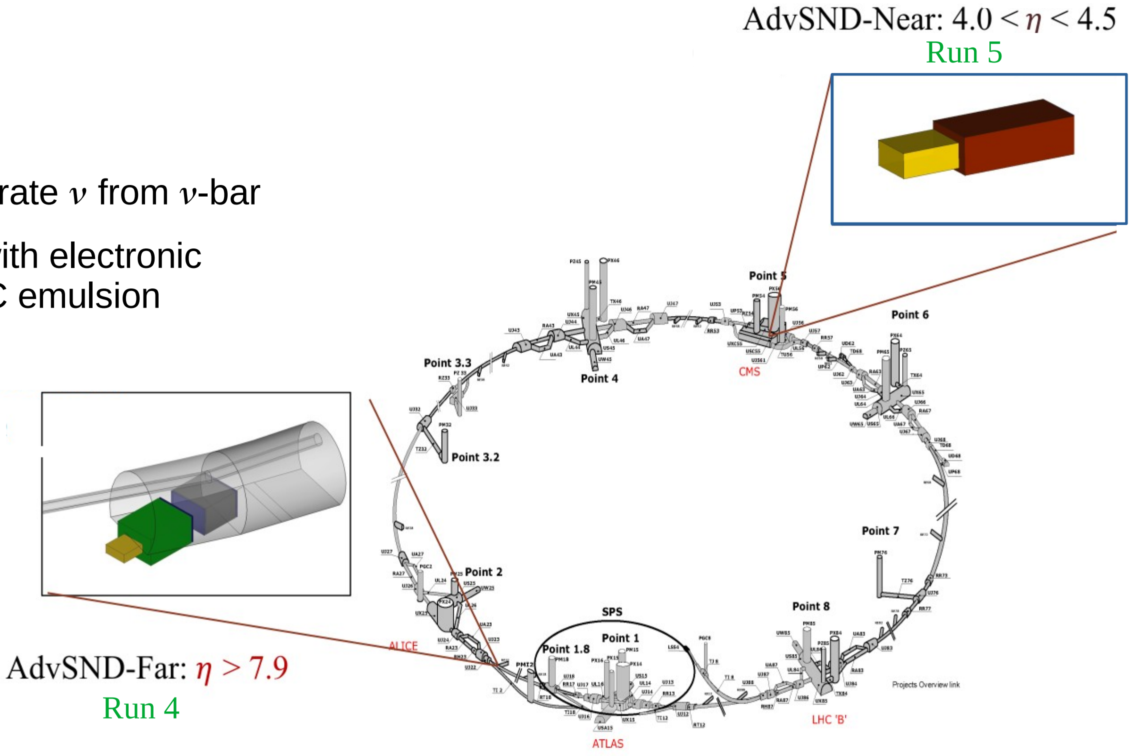


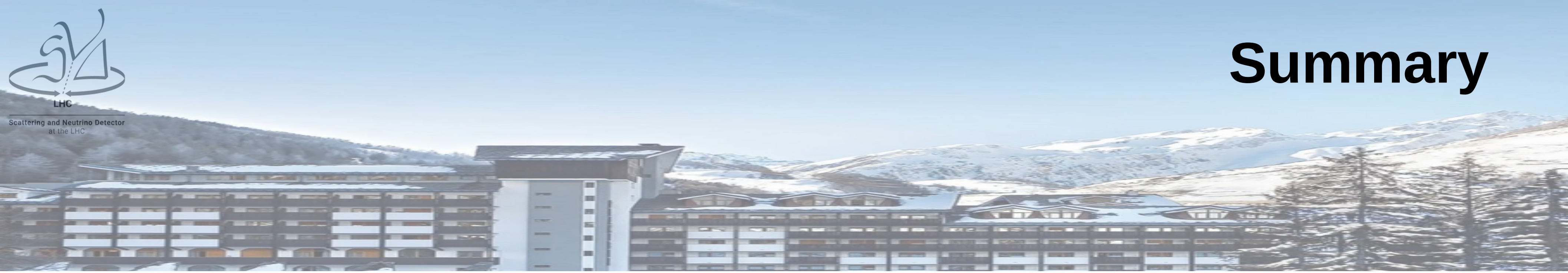
Display of a 3-μ event in the 2023 ion run



Advanced SND (AdvSND)

- Letter of intent in preparation
- Detector upgrades
  - Tag muon sign with magnet to separate ν from ν-bar
  - Replace emulsion vertex detector with electronic technology (Si pixels) since HL-LHC emulsion replacement rate is unfeasible





Summary

- SND@LHC detector is operating since the start of the LHC Run 3
  - has collected 36.8 fb^{-1} in 2022 and 34fb^{-1} in 2023
- Measurement of the muon flux in the detector
  - Validating MC simulation with 20-25%
- Observed 8 ν_μ CC candidates with 6.8σ significance
- Increasing the acceptance, selected 15(2022) and 17(2023) ν_μ CC candidate events
- ν_e search and emulsion analysis on the way
- Planning for the future in HL-LHC era

Backup slides

Experiment timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

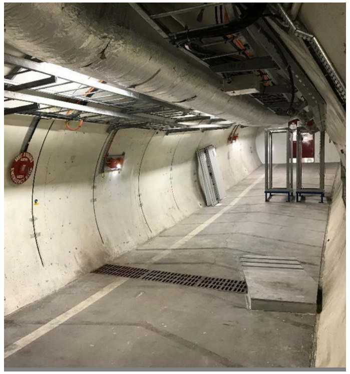
SND@LHC

January 2021

CERN approves new LHC experiment

SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

March 2021

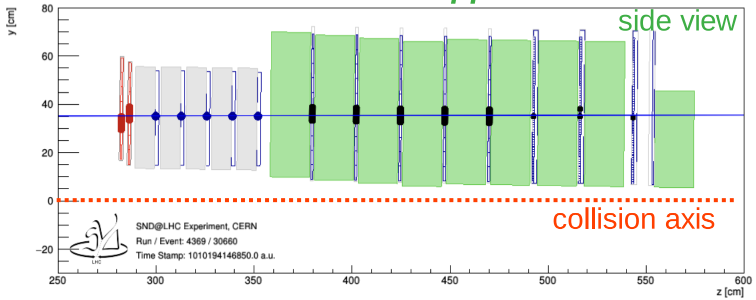


September 2021

December 2021

March 2022

Muon from 13.6 TeV pp collision

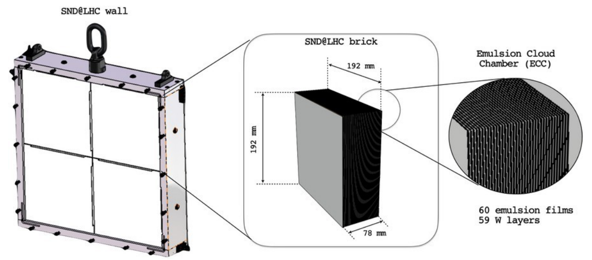


6^{th} July 2022

Detector components

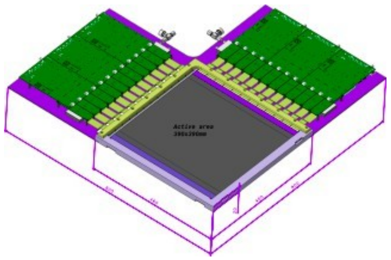
Emulsion Cloud Chambers

- Goal: tracking and vertex ID
- Sub-micrometric resolution
- Geometry
  - 5 walls of 2x2 bricks
- Shielding(protect from neutrons, stabilise T and humidity)
- Brick layout
  - 60 layers of 300 μm-thick emulsions
  - Interleaved by 1 mm tungsten plates
- Target mass ~830 kg



SciFi

- Goals:
  - Precise timing information (~350 ps time resolution)
  - EM energy measurement
  - Spatial information (<100 μm spatial resolution)
- Geometry
  - 5 planes of scintillating fibres mat pairs (x-y)
  - Mats built of 6 layers of staggered fibres

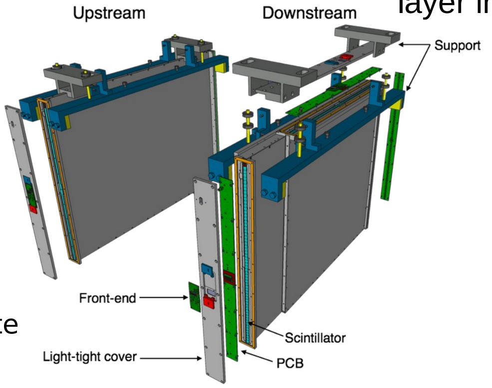


Hadronic calorimeter

- Goals:
  - Timing information
  - Hadronic energy measurement
  - Spatial information
- Geometry
  - 5 stations of horizontal scintillation bar layers
  - Readout on both ends of a bar

Muon ID system

- Goals:
  - Timing information
  - Muon tracking and isolation
- Geometry
  - 3 stations of orthogonal scintillation bar layer pairs
  - Horizontal bars read out on both ends
  - Vertical bars read out on one end (one additional layer in last station)

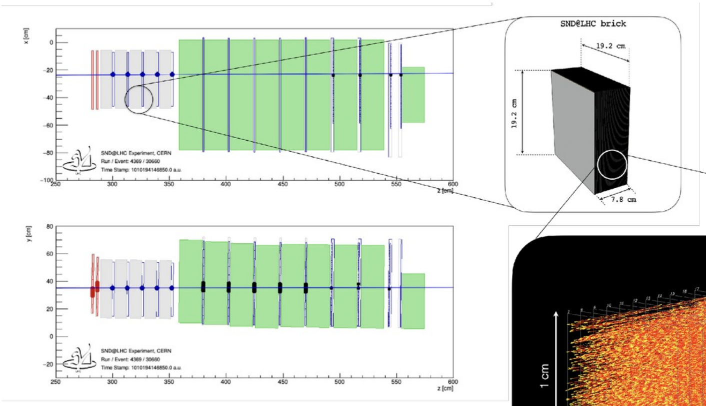


Muon flux

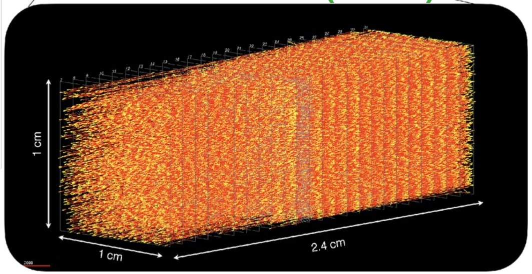
Using data from SciFi and DS, the muon flux is

- **SciFi**: 2.06×10^{4} cm^{-2}/fb^{-1} **DS**: 2.35×10^{4} cm^{-2}/fb^{-1} **Eur.Phys.J.C 84 (2024)**
- 2% deviation of SciFi and DS fluxes in the same acceptance range
  - while systematic error is 3%(SciFi) and 5%(DS) on muon flux per detector
- data/MC simulation agreement level 20-25%

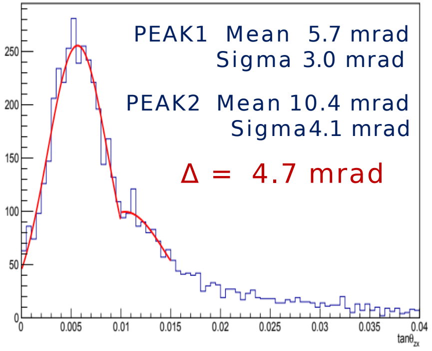
- Comparison of Emulsions/SciFi distributions with early data in good agreement, preliminary flux measurement agree within 10%
  - Input to target replacement strategy definition



Emulsion tracks: 1 cm² x-y section RUN0 (0.5 fb^{-1})



Emulsion tracks: RUN0



SciFi tracks: RUN0