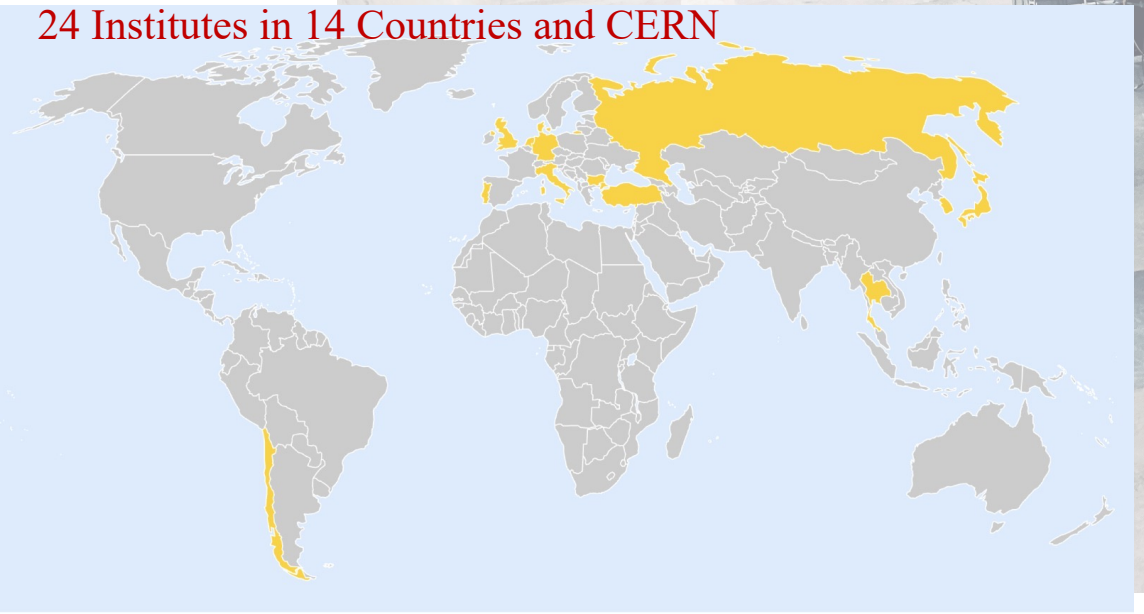
LHC

Scattering and Neutrino Detector
at the LHC

The SND@LHC experiment

Collaboration: 150 members

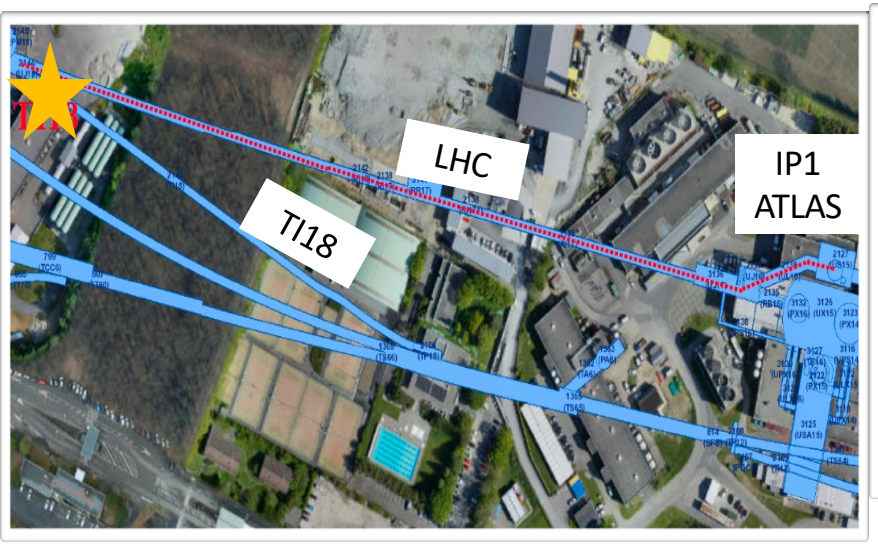
24 Institutes in 14 Countries and CERN

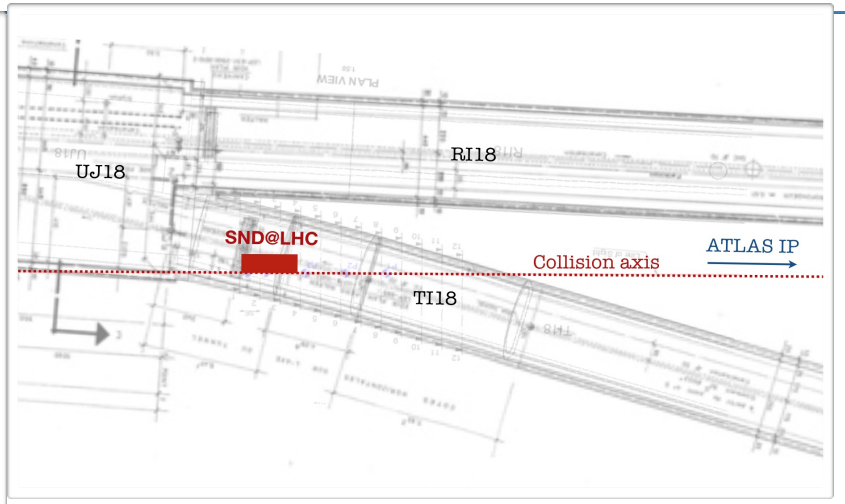


Giovanni De Lellis on behalf of the SND@LHC Collaboration

LHCC Open Session, November 29th 2023

SND@LHC REFRESHER



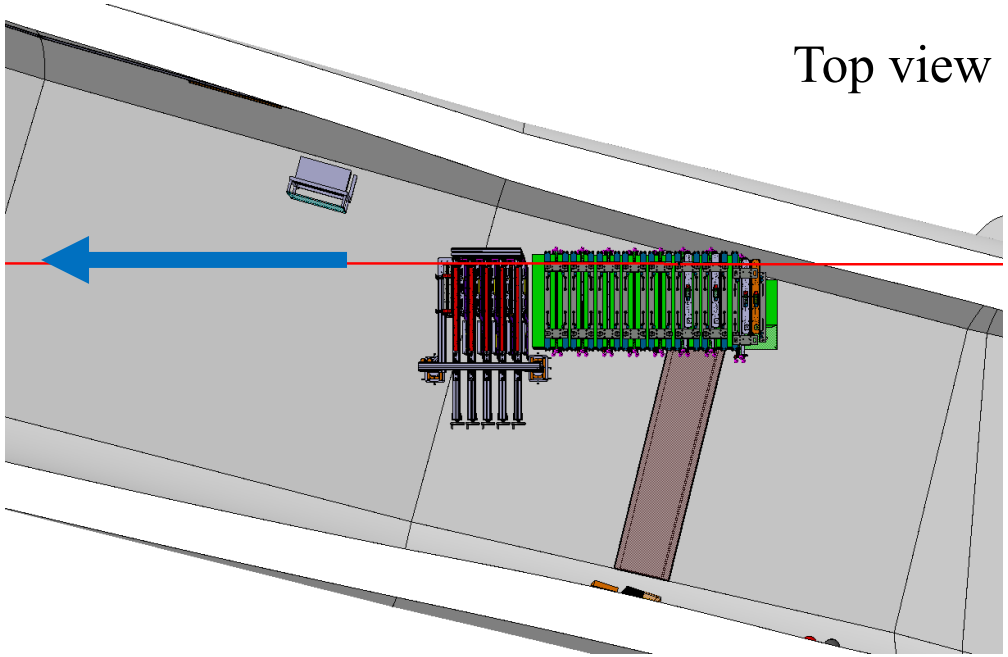


Physics motivation

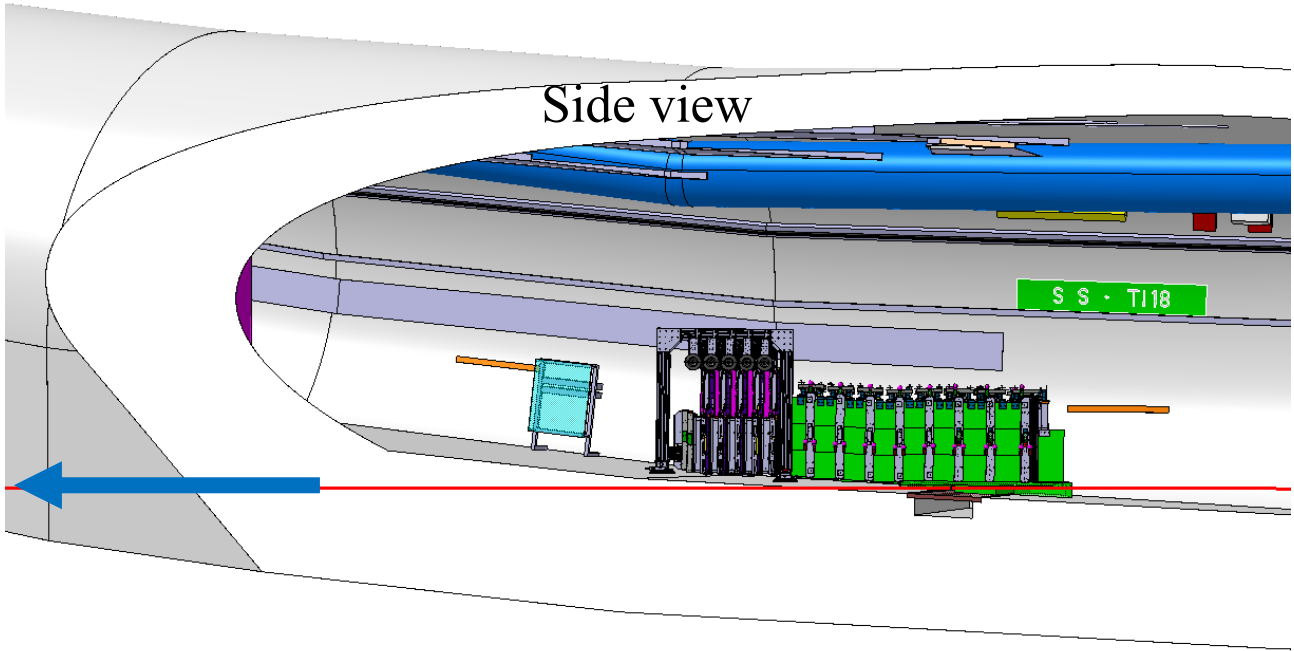
- Study neutrino interactions of all flavours at unexplored energy range
- Probe heavy flavour production with neutrinos at unexplored rapidity range
- Relevant for FCC detectors and νs from astrophysical sources
- LFU with neutrino interactions
- Search for recoil signatures of FIPs

$7.2 < \eta < 8.4$

Top view



Side view



Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

VETO PLANE:

tag penetrating muons

NEUTRINO TARGET & VERTEX DETECTOR:

- Emulsion cloud chambers (60 emulsion films, each 300μm thick, interleaved by 1mm thick tungsten plates)

E.M. CAL

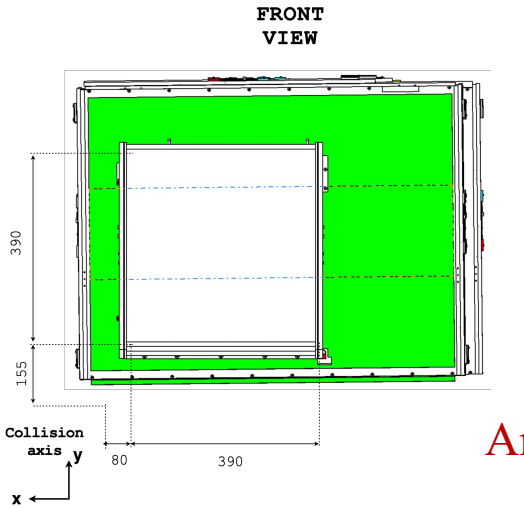
- 250μm Scintillating fibres for timing information and e.m. energy measurement

HADRONIC CALO:

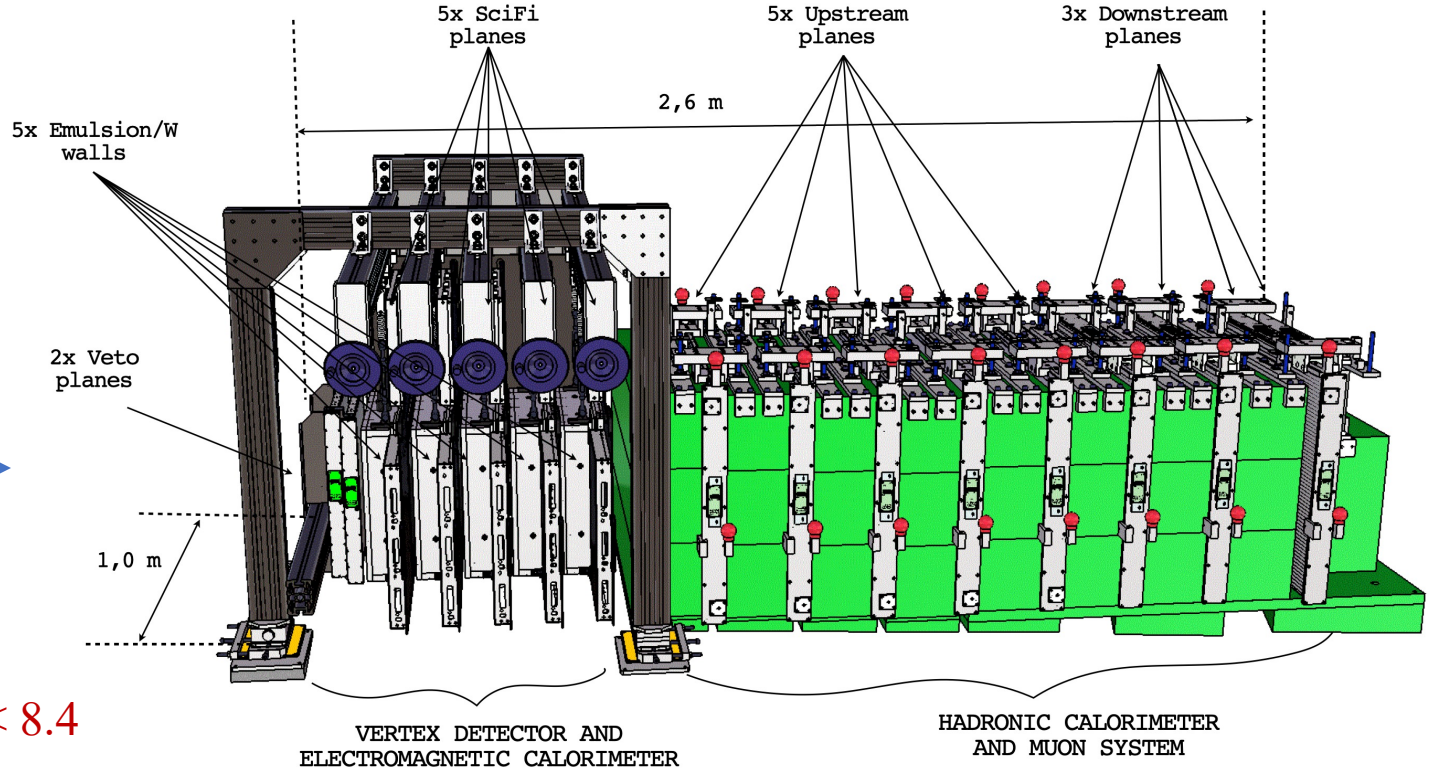
iron walls interleaved with plastic scintillator planes for ~11 λ

MUON IDENTIFICATION SYSTEM:

3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking

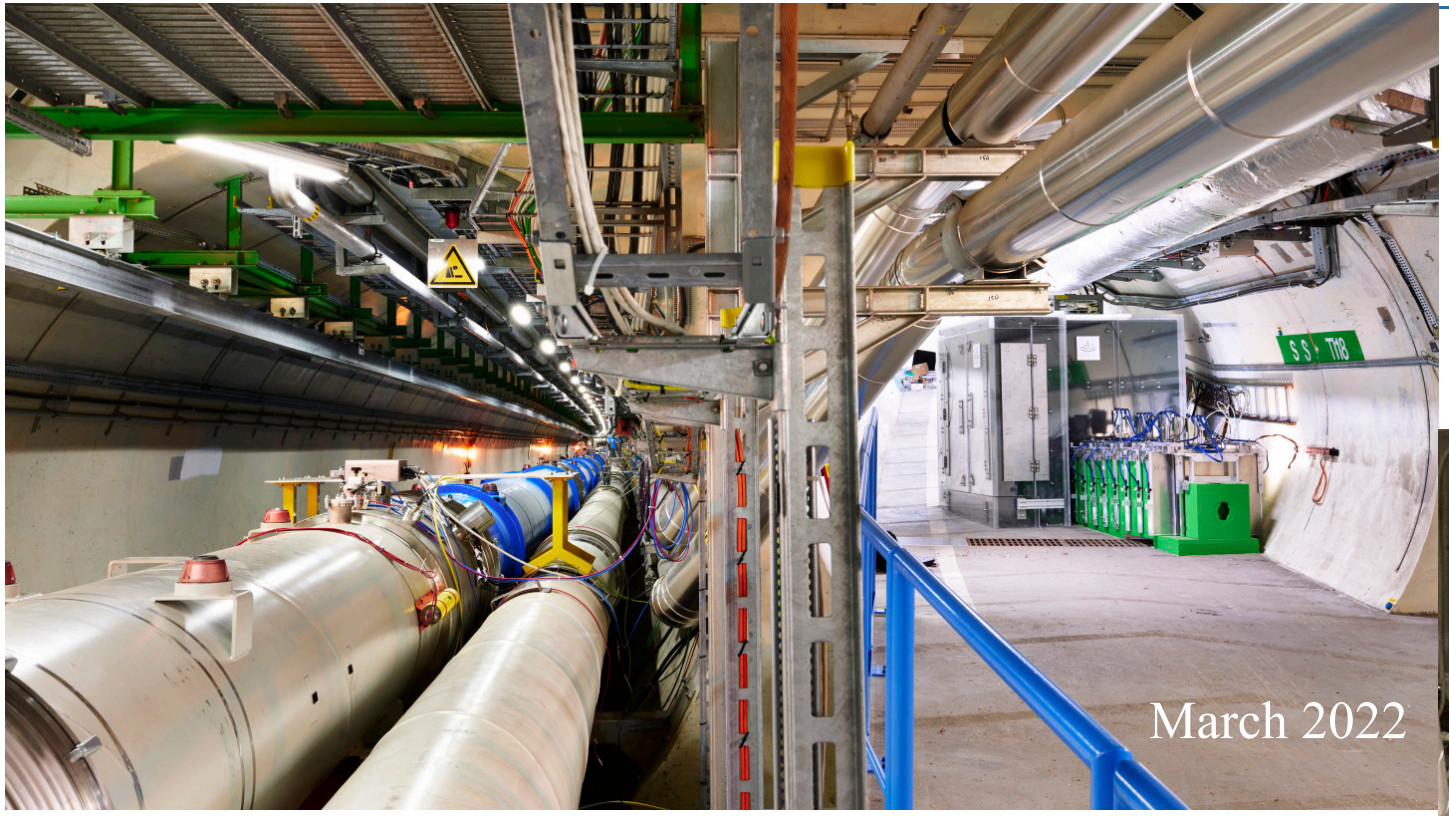


ν



Angular acceptance: $7.2 < \eta < 8.4$

Detector view in 2022 and in 2023



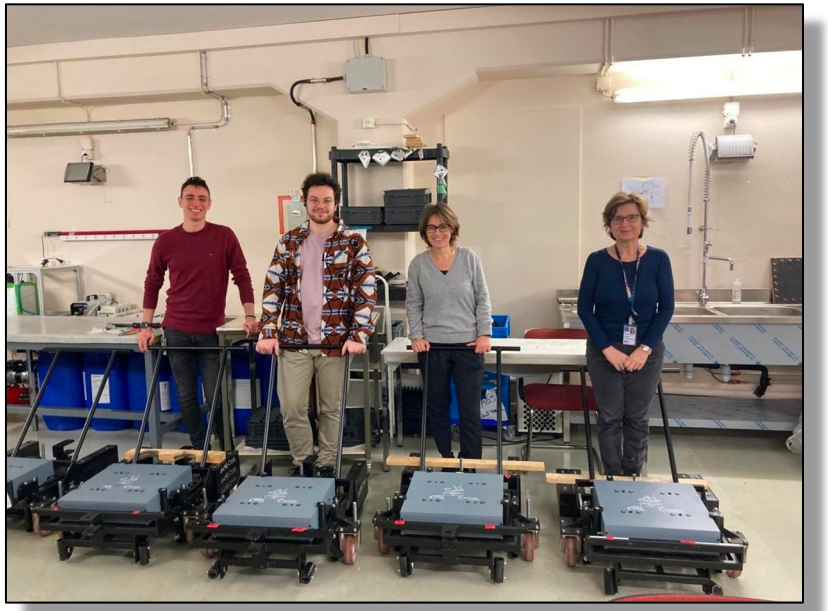
LoI: August 2020
Technical Proposal: Jan 2021
Approval in March 2021
Ready to take data in April 2022 when Run 3 started

Activities in 2023

EMULSION TARGET #4 and #5

- Mass of target #4: **797 kg**
- **1158** films (70% Nagoya+30% Slavich)
- Assembly: March 16th-19th
- Installation: **March 20th**
- Extraction: **June 23rd**
- Emulsion development: July 4th-17°
- Time for underground operation: 4 hours

- Mass of target #5: **784 kg**
- **1140** films (100% Nagoya)
- Assembly: March 16th-19th
- Installation: **June 23rd**
- Extraction: **July 27th**
- Emulsion development: August 12th-25th
- Time for underground operation: 4 hours

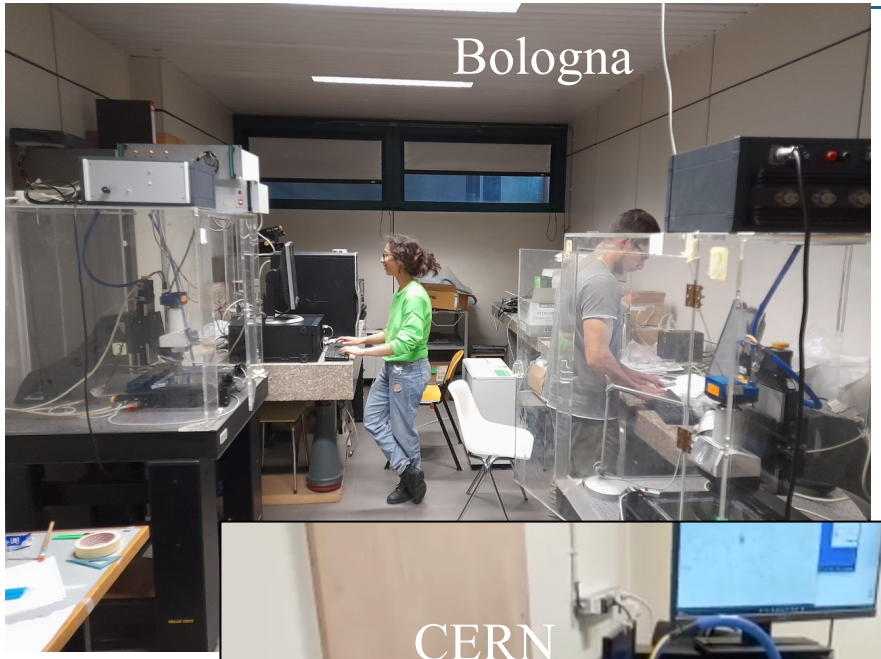


Target assembly

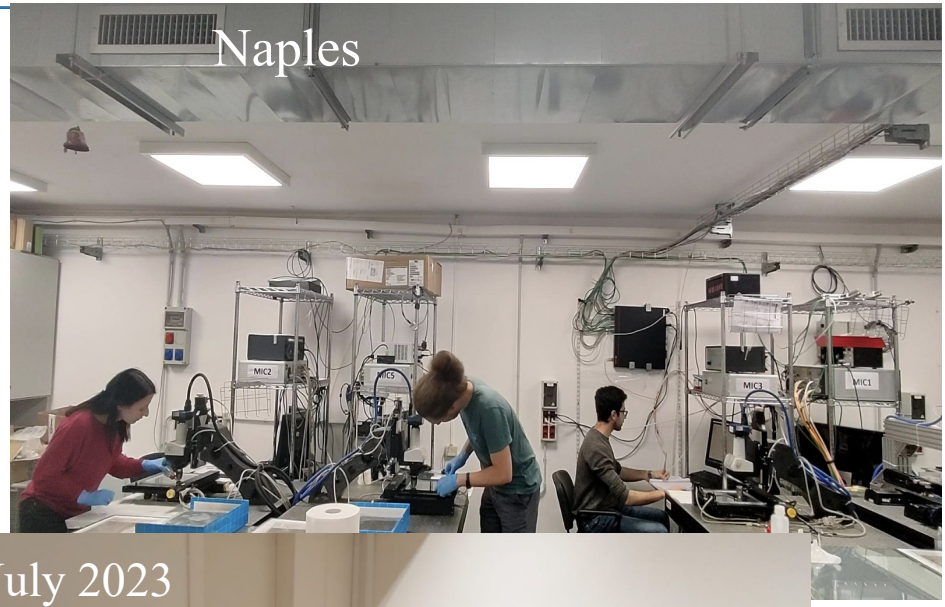
Target installation

Emulsion development

Strengthening the scanning station power

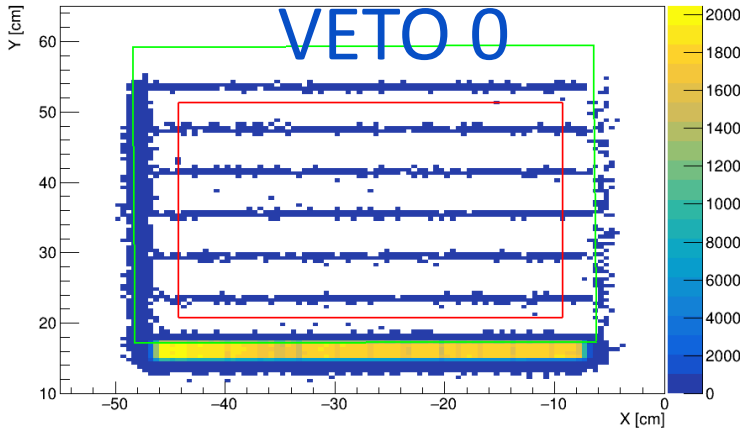


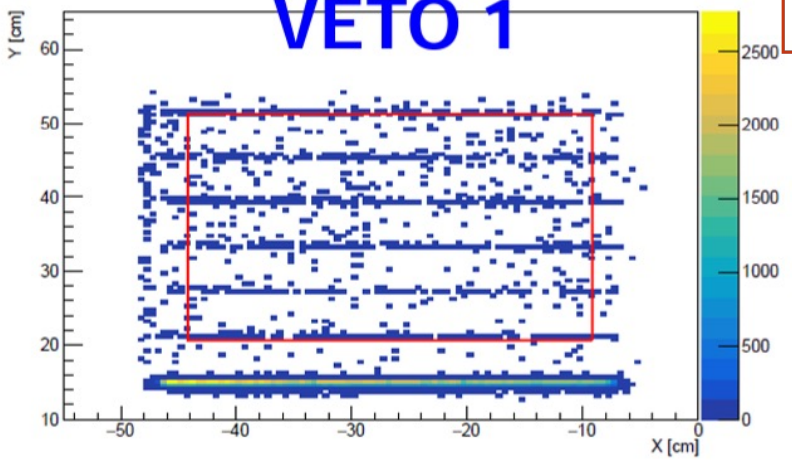
Bologna: 2 systems
Napoli: 2 systems
CERN: 2 systems + 2 upgrades operational in Dec

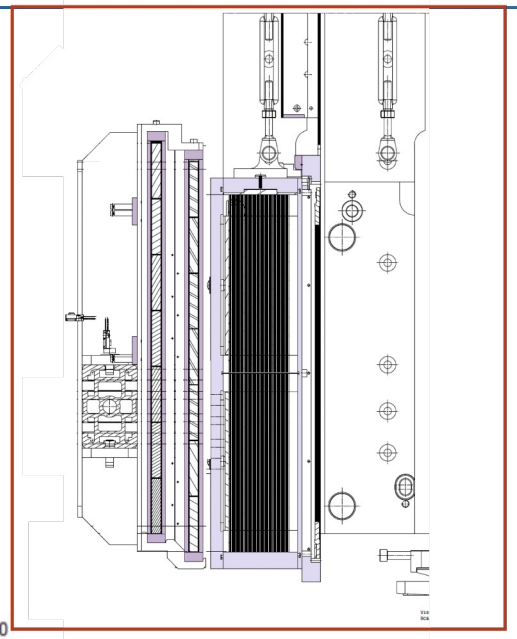


Upgrade of the veto system during next YETS

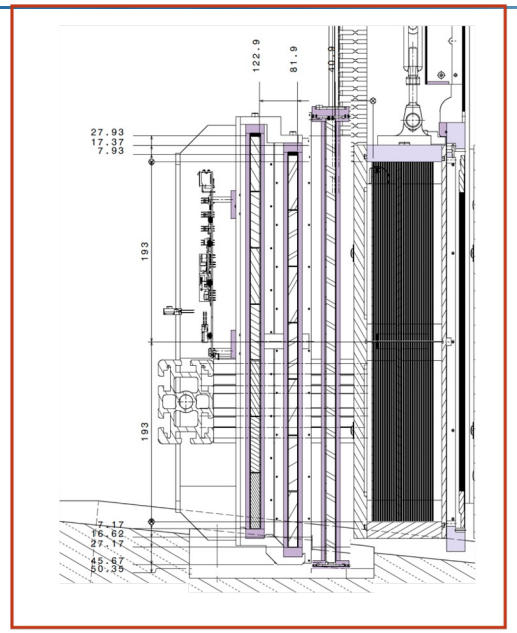
Extrapolated SciFi track position when no signal in Veto 0 or 1



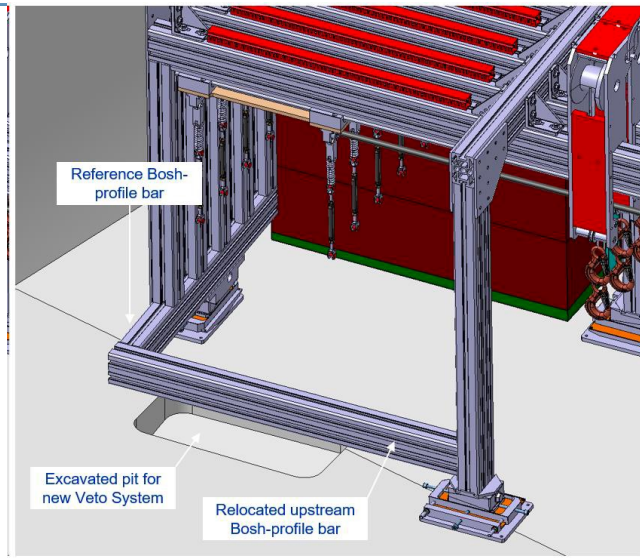




Current layout: two planes with H bars

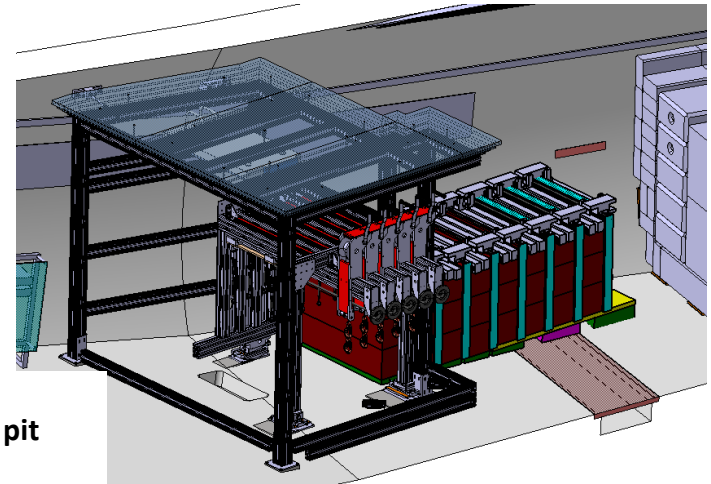


Upgraded layout: third plane with vertical bars



3D integration model (YETS 2023/2024)

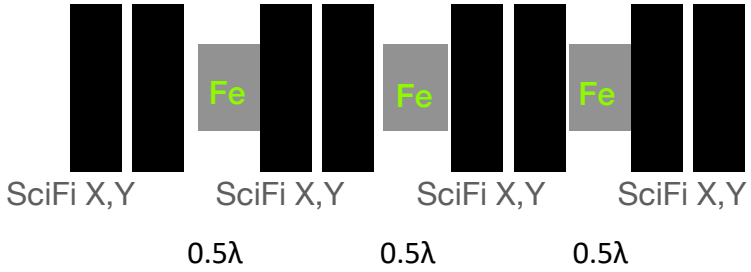
Recover fiducial volume, both longitudinally and in the transverse plane
Add a third layer to avoid loosing the first target wall and lower their position to cover the full transverse plane



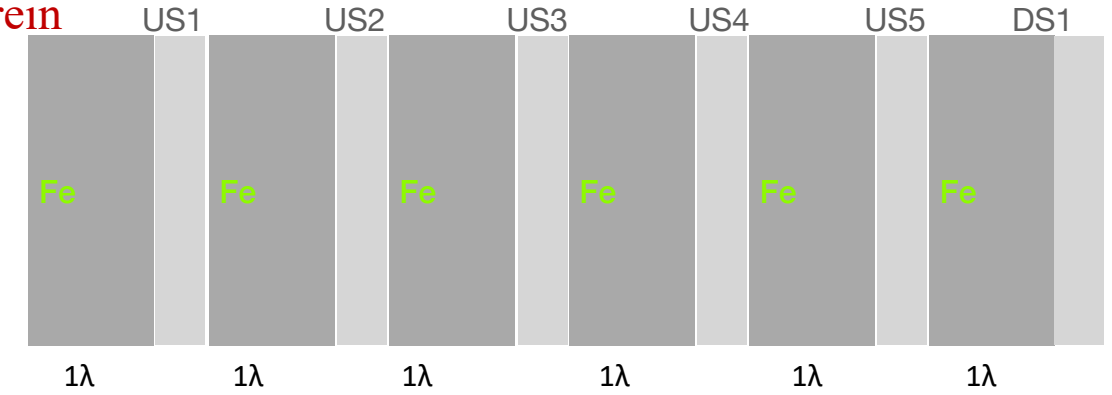
Excavated pit

Towards energy calibration

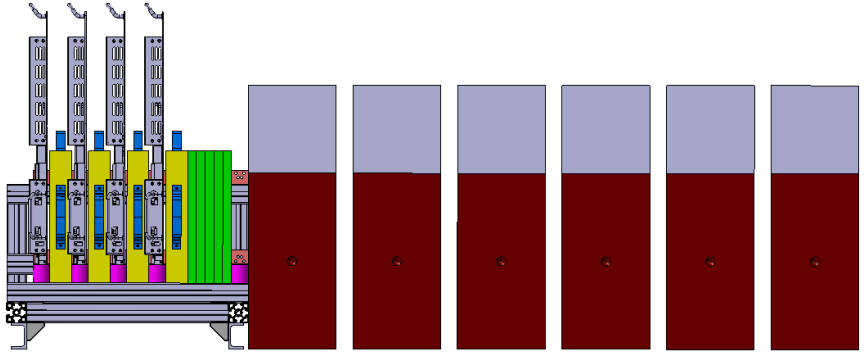
Target instrumented with SciFi stations to get the shower origin
And measure the energy deposited therein

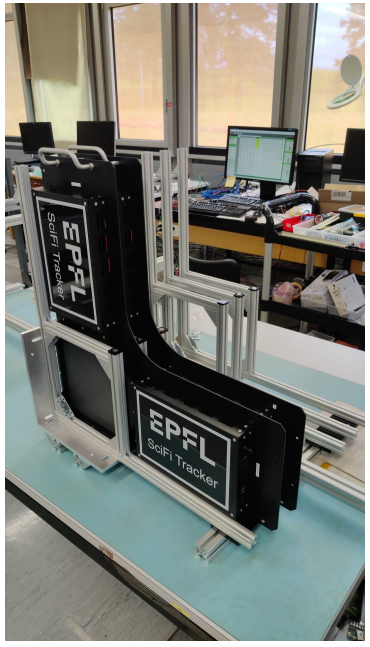


All 5 US stations and 1 DS



Successful data taking in H8 in August

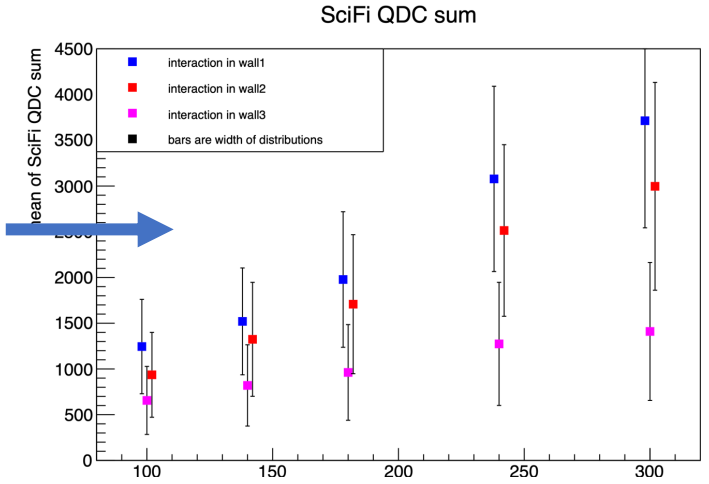




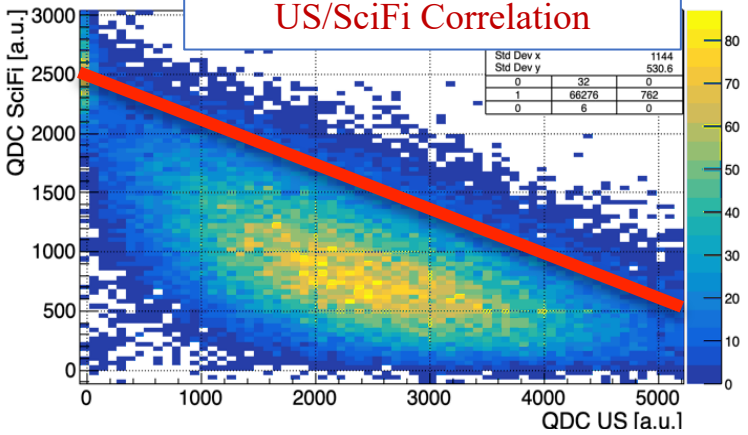
Preliminary calibration studies and energy resolution

Reconstruction of the total energy requires the estimate of the fraction lost in the target region. SciFi accomplishing also this task

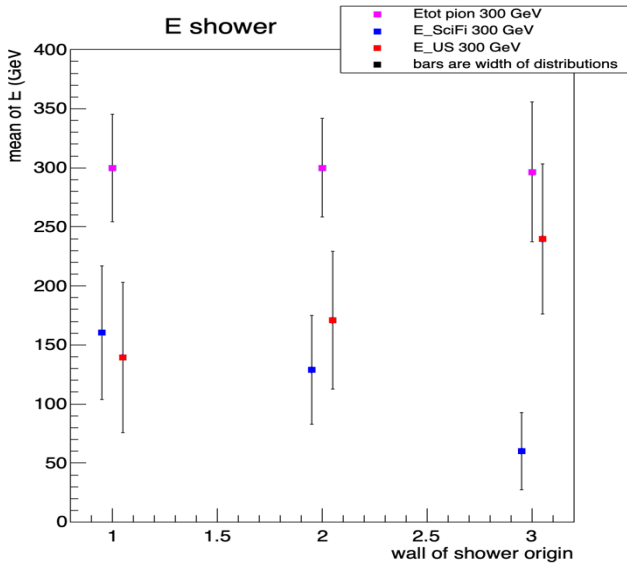
- Good proportionality of SciFi response to the particle energy
- Different calibration curves according to the (longitudinal) shower origin in the target



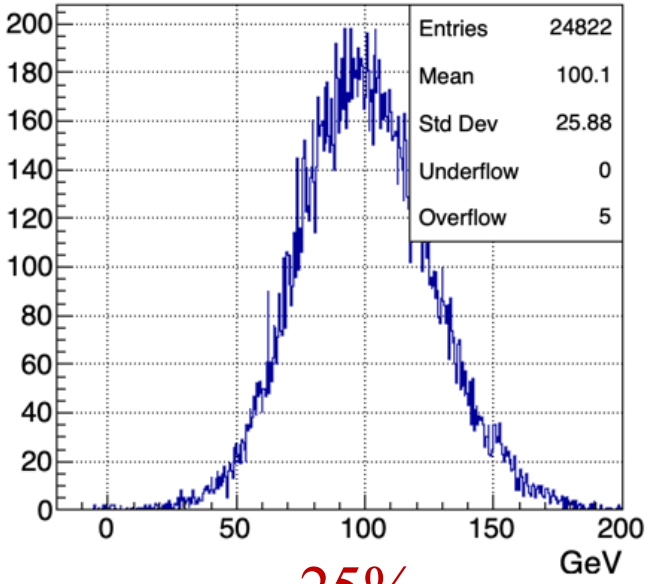
100 GeV π
US/SciFi Correlation



300 GeV π: energy sharing between SciFi and Upstream Station

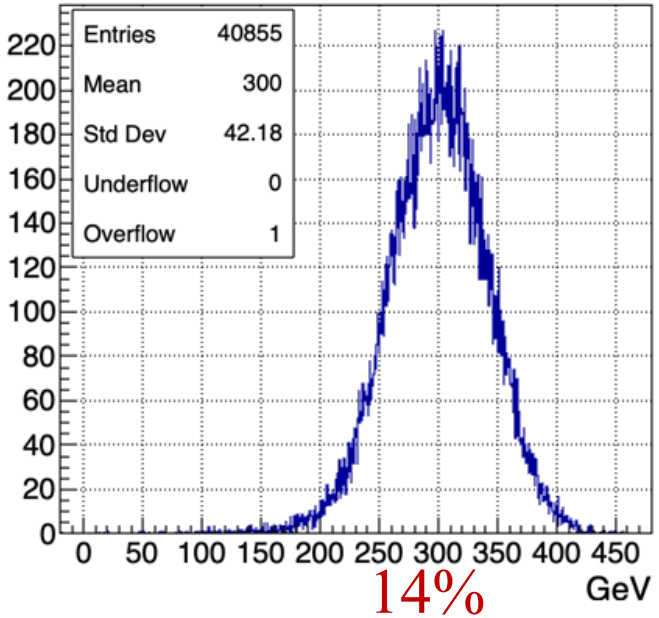


Reconstructed energy for 100 GeV π



25%

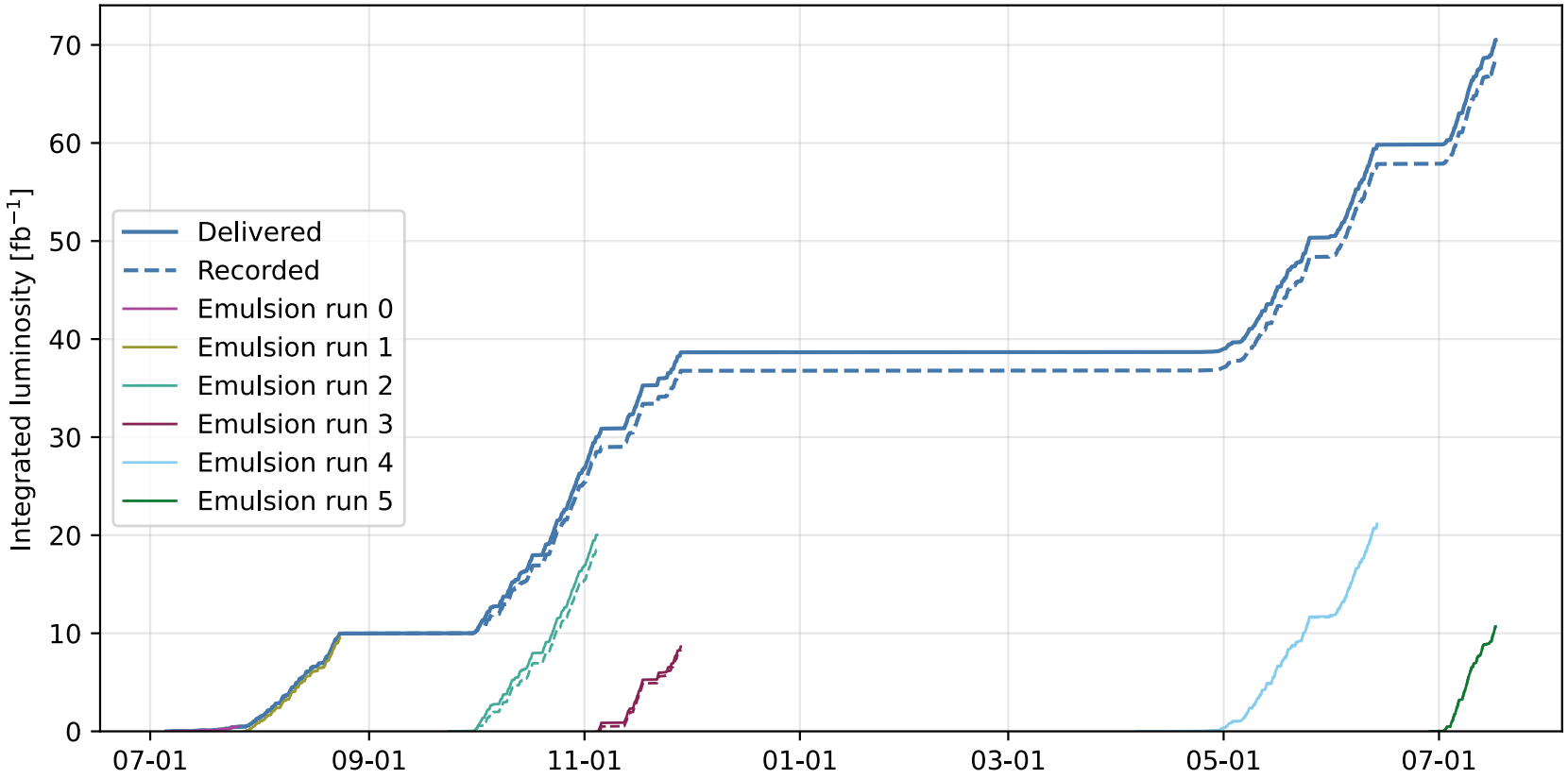
Reconstructed energy for 300 GeV π



14%

Data analysis

Integrated luminosity



Integrated luminosity: 70.5 fb^{-1}

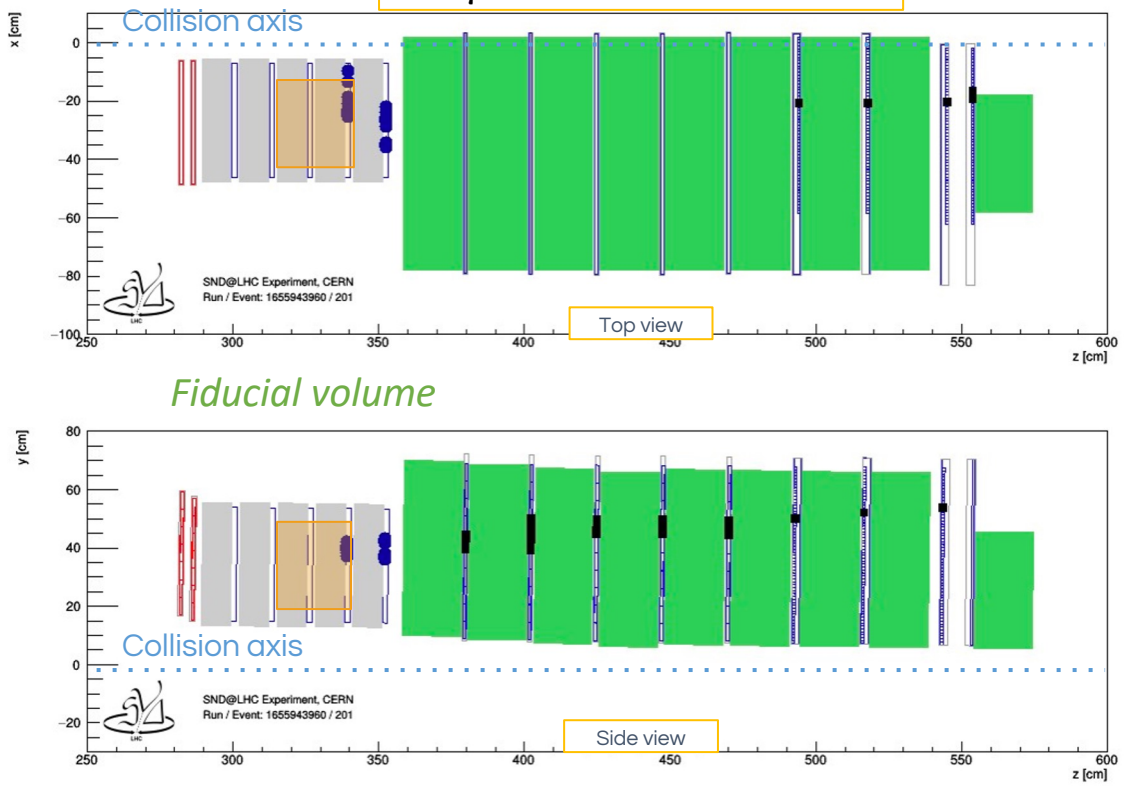
Recorded efficiency 97.3% (2022 95%, 2023 99.7%)

Neutrino observation with electronic detectors

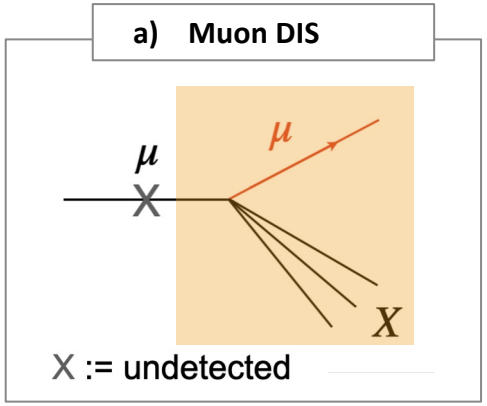
- Analysis strategy:
  - Full Run 3 **2022 dataset**: recorded luminosity of 36.8 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach: initial S/N ~ 10^{-8} down to 100
  - ~10^9 muon events: **strong rejection power** to reach negligible background level

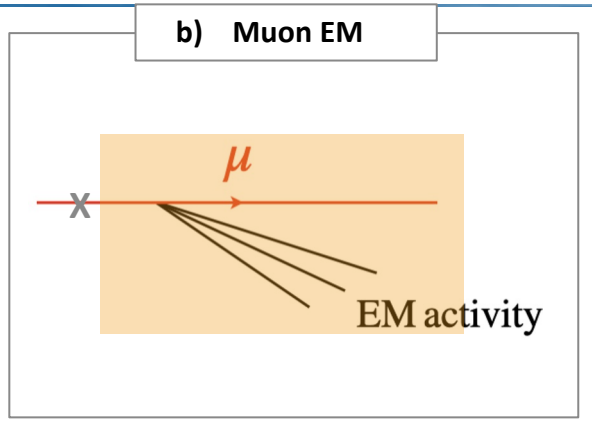
- Signal selection:
  - **Fiducial Volume (1, 2)** cuts
    - **Neutral vertex**, located in the 3rd or 4th target wall
    - Select fiducial cross-sectional area to reject background entering from the side
  - **Neutrino ID** cuts
    - Require "large" E.M. (SciFi) and hadronic activity (HCAL)
    - Event produced upstream (timing)
    - **Muon** reconstructed and **isolated** in the Muon system

ν_μCC simulation



Background evaluation



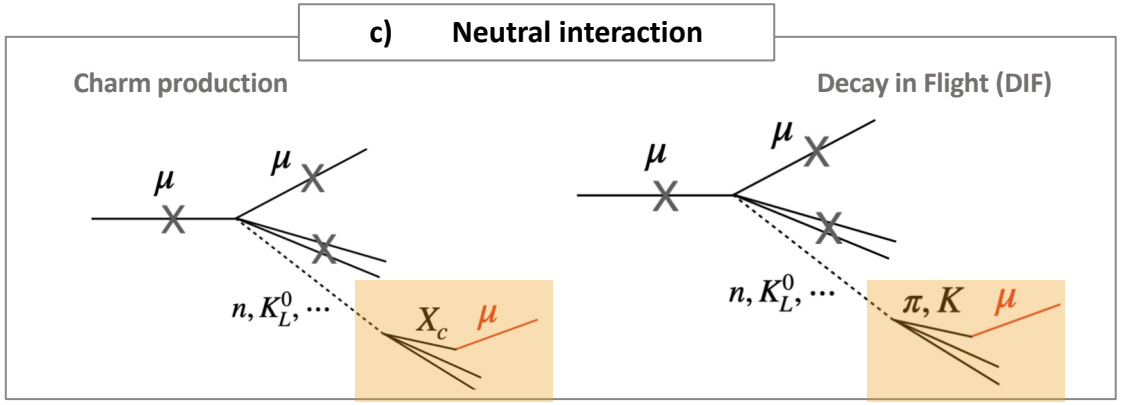


- Muon induced background: undetected muons entering the target (2022 Run3 data)

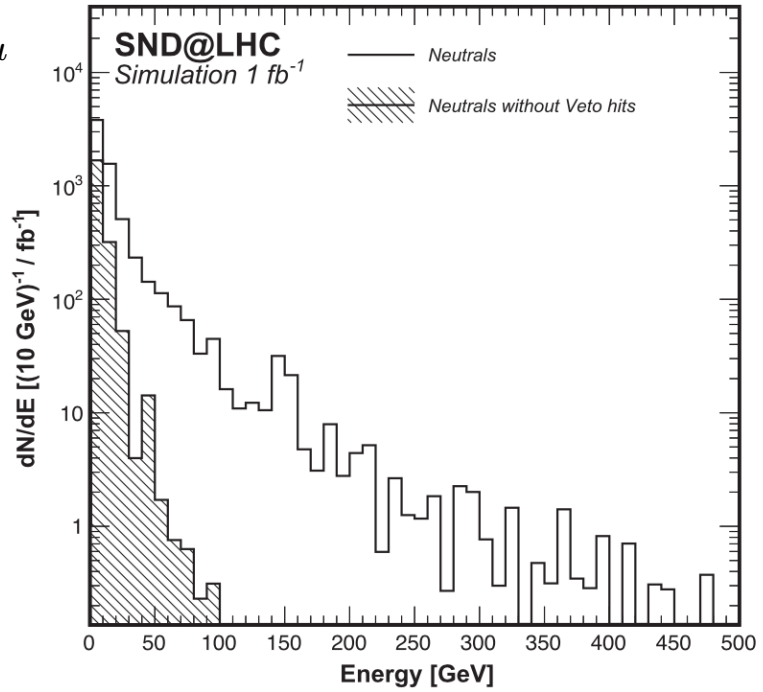
$$N_{bkg} = N_\mu\,(1-\varepsilon_{veto}) \times (1-\varepsilon_{SciFi1}) \times (1-\varepsilon_{SciFi2}) = 5.3 \times 10^{-12} N_\mu$$

$$N_\mu = 1.2 \times 10^9$$

Totally negligible



within SND@LHC acceptance

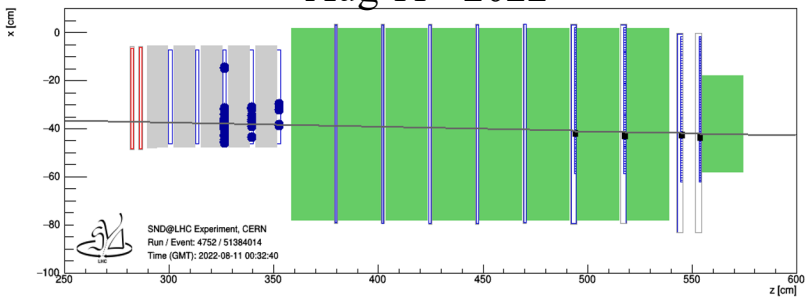


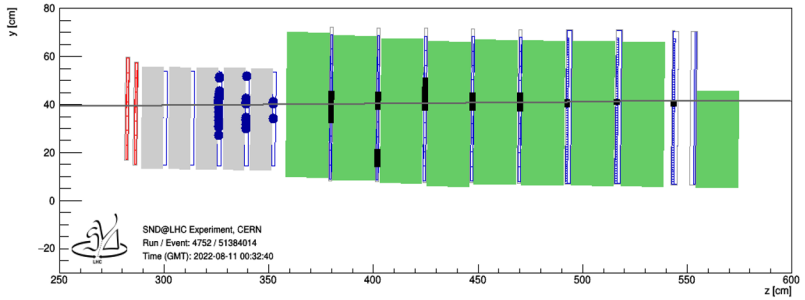
- Muon-induced neutral interactions

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

Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



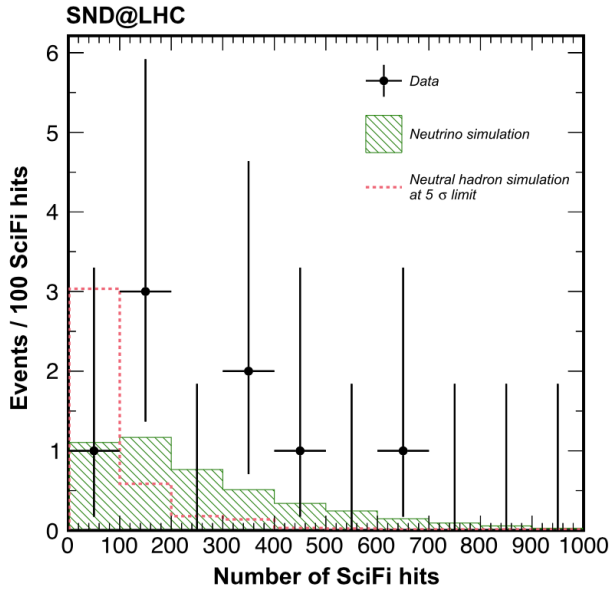


Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

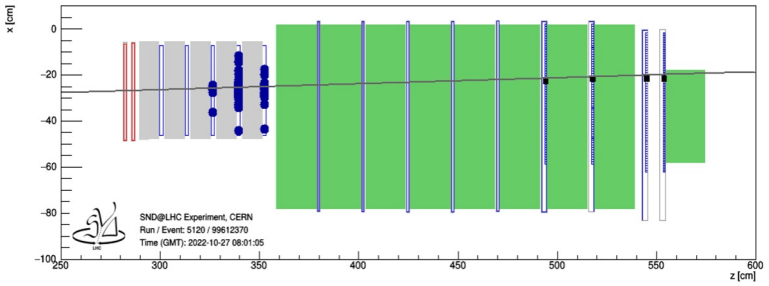
R. Albanese *et al.* (SND@LHC Collaboration)

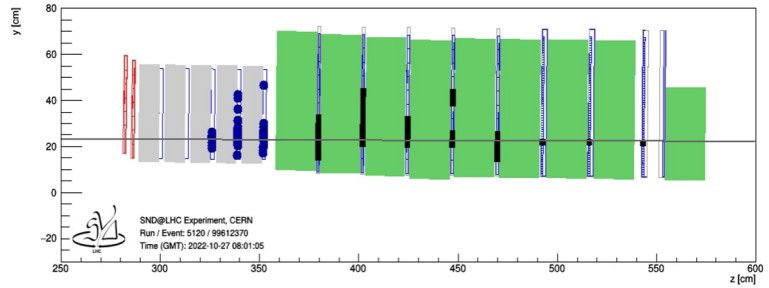
Phys. Rev. Lett. **131**, 031802 (2023) – Published 19 July 2023



Distribution of SciFi hits for ν_μ candidates with the MC expectation for ν events and background (augmented to the 5 sigma level)

Oct 27th 2022





8 observed events and an expected background

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

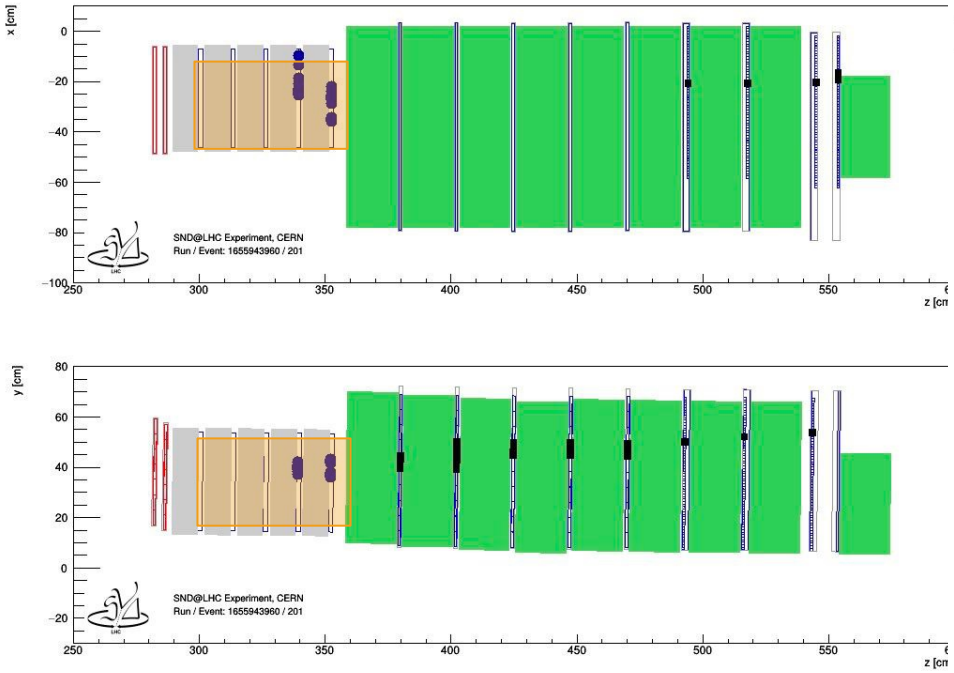
Background only hypothesis probability:

$$P = 7.15 \times 10^{-12}$$

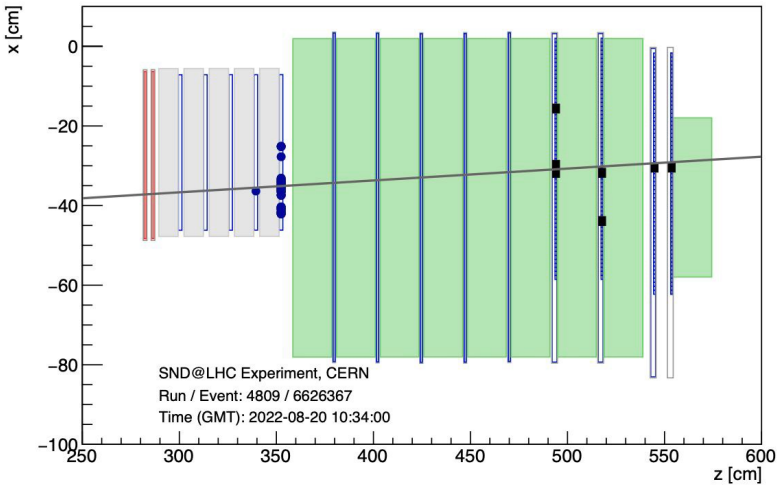
$6.8\ \sigma$ observation

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

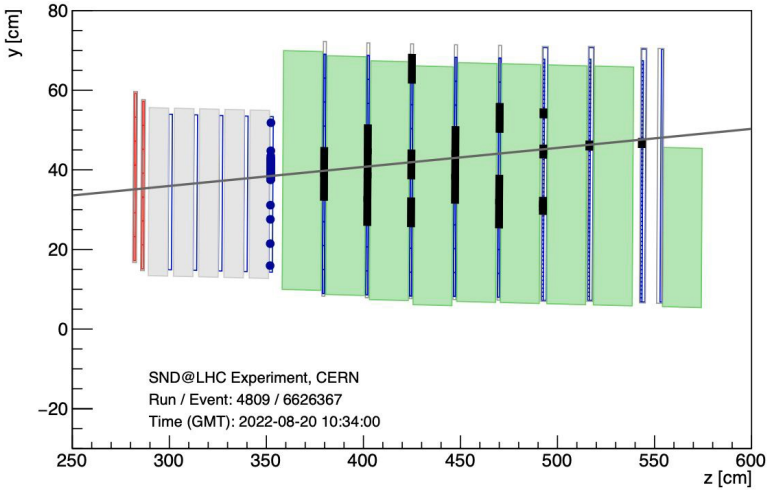
Muon neutrino selection with 2022-2023 data in an extended volume (wall 2 and 5 included)

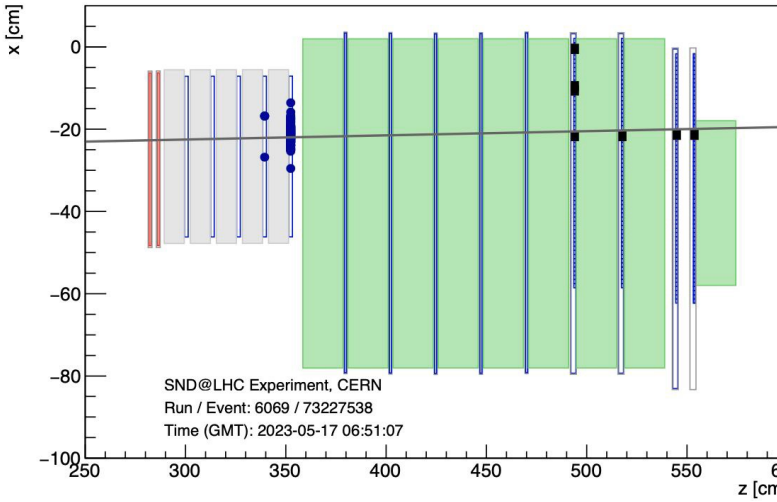


33 events: 16 in 2022 and 17 in 2023

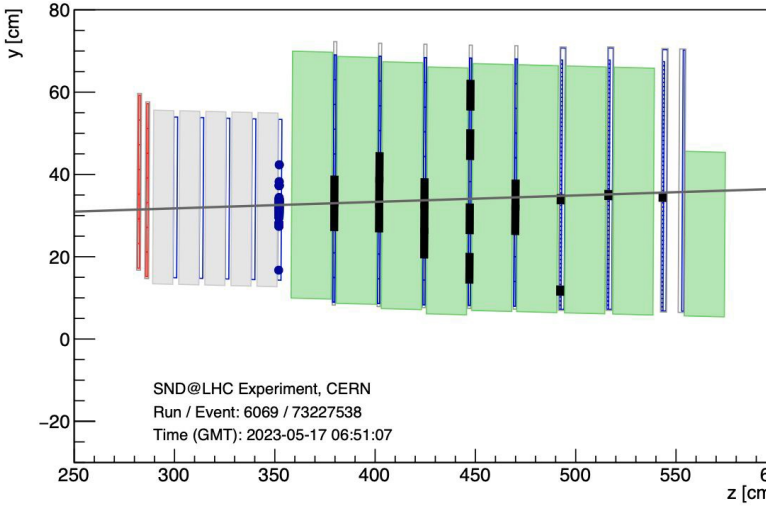


New 2022 event



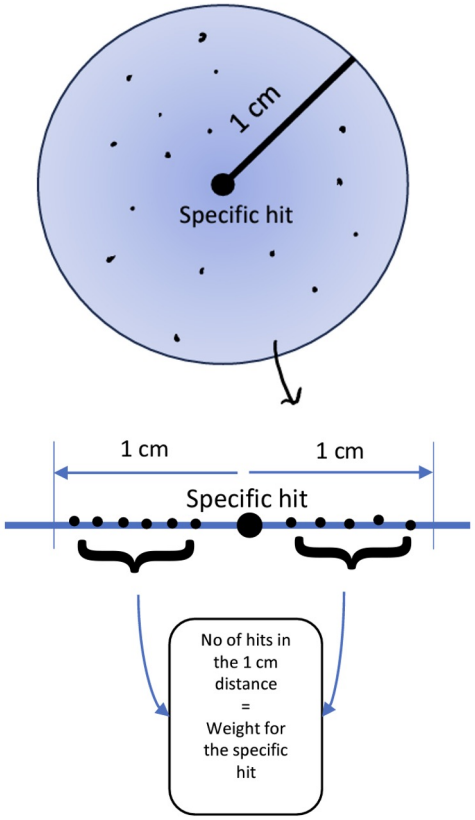


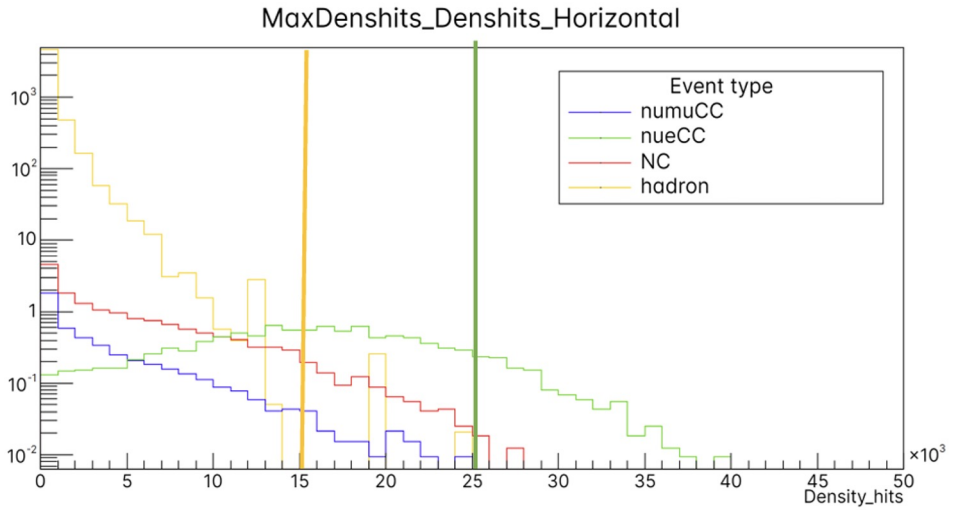
2023 event



Electron neutrino studies

- Signal selection based on topological and calorimetric information
- Discriminating variable: density of hits in SciFi





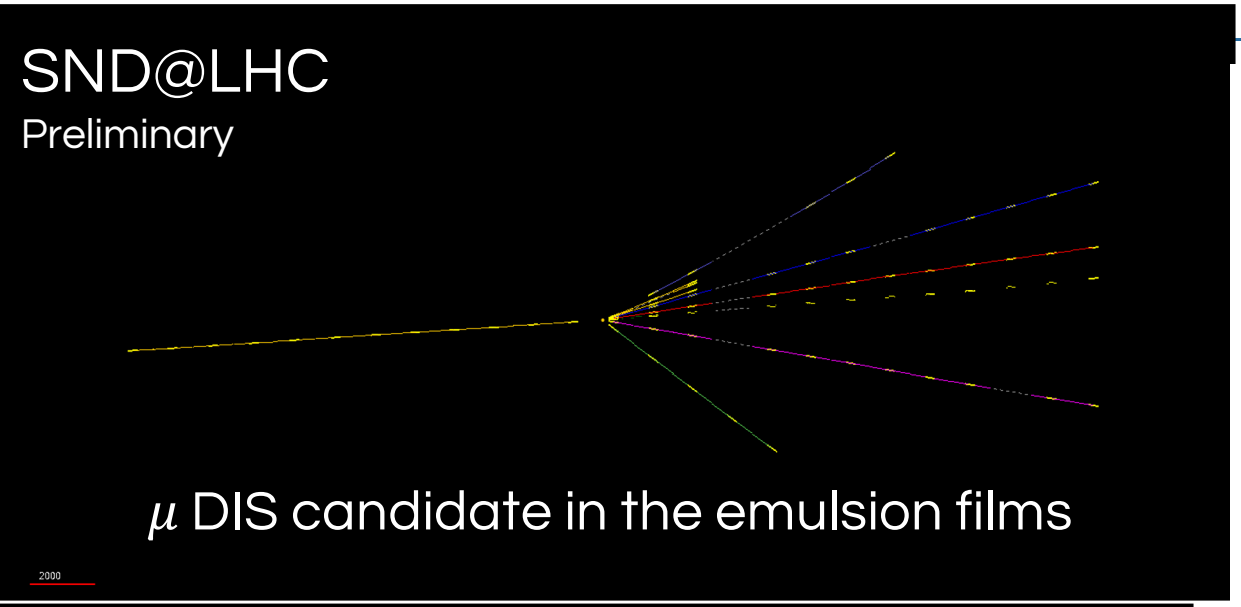
Events : 10000
Scaled to 70 fb^{-1}

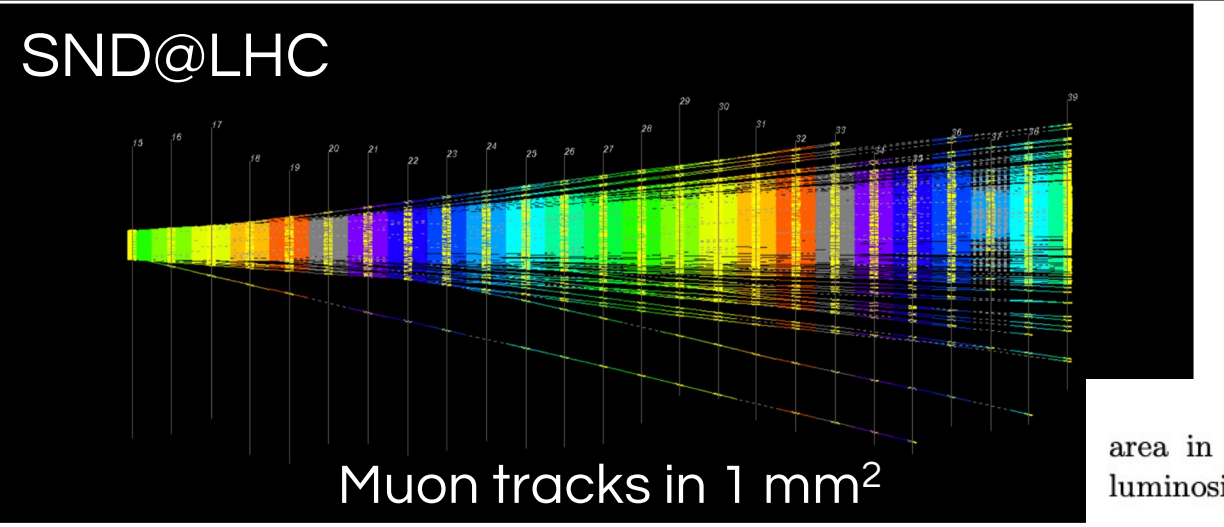
With a cut at 15000:
1.61 NC
0.29 ν_μ CC
7.1 ν_e CC

- Density of his > 15000
  - negligible neutral hadron background
- Density of hits > 25000
  - dominated by ν_e CC events

This study will profit from the ongoing energy calibration

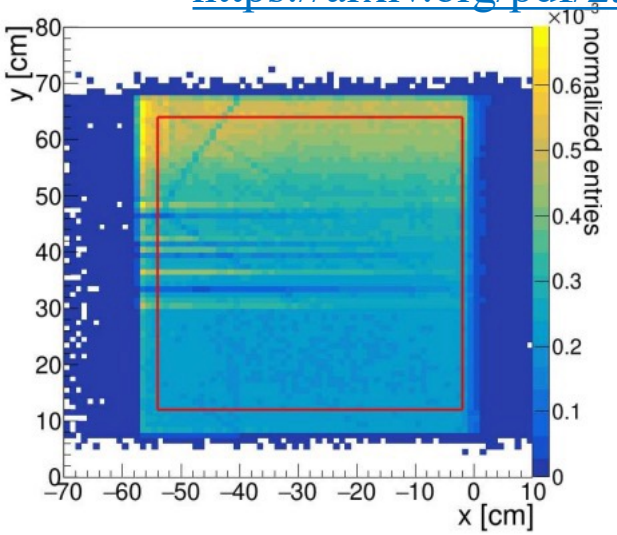
Muon flux measurement and emulsion analysis

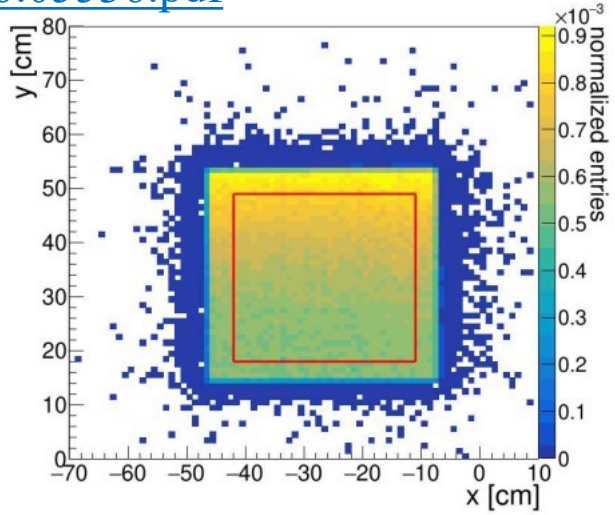




10^5 tracks/cm^2 in 10 fb^{-1} exposure

https://arxiv.org/pdf/2310.05536.pdf





SND@LHC measure muon flux in 3 different detector systems (emulsion, SciFi and Muon System).
Flux seen to increase with vertical distance from LOS.
FLUKA simulation estimate of flux ~20-25% lower than measurement.

The muon flux per integrated luminosity through an 18×18 cm^2 area in the emulsions is $\mathbf{1.5 \pm 0.1}(\text{stat}) \times \mathbf{10^4}$ fb/cm^2. The measured muon flux per integrated luminosity through a 31×31 cm^2 central SciFi area is

$$\mathbf{2.06 \pm 0.01}(\text{stat}) \pm \mathbf{0.12}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2,$$

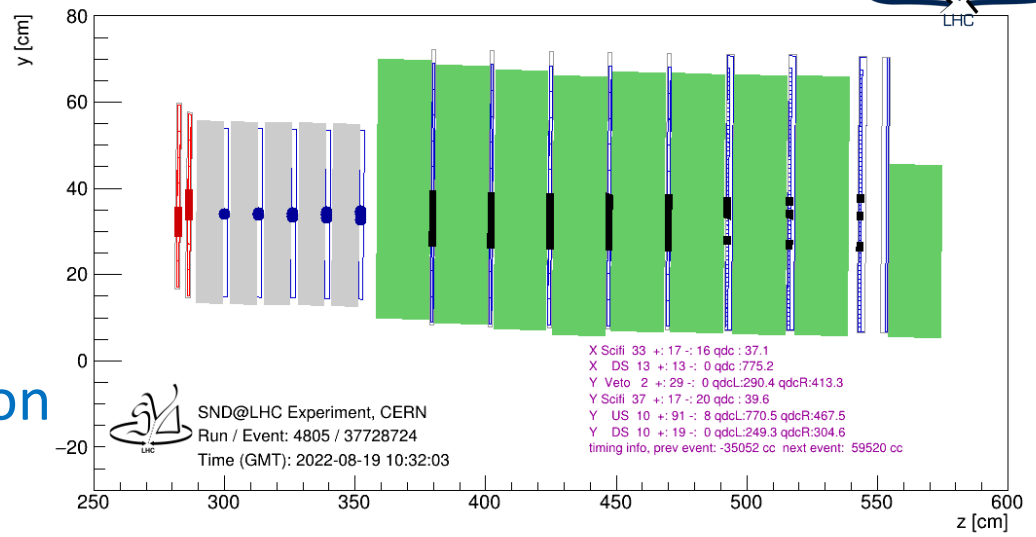
while for the downstream muon system the flux is

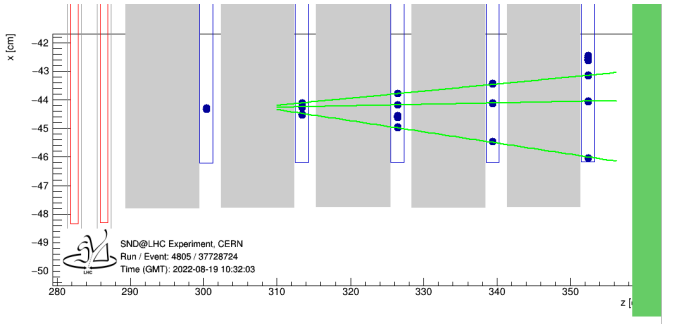
$$\mathbf{2.35 \pm 0.01}(\text{stat}) \pm \mathbf{0.10}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2$$

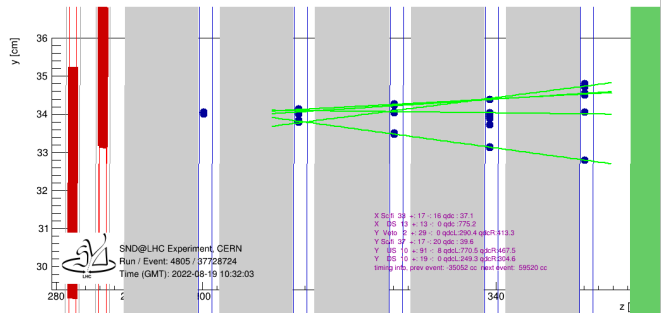
for a 52×52 cm^2 central detector region.

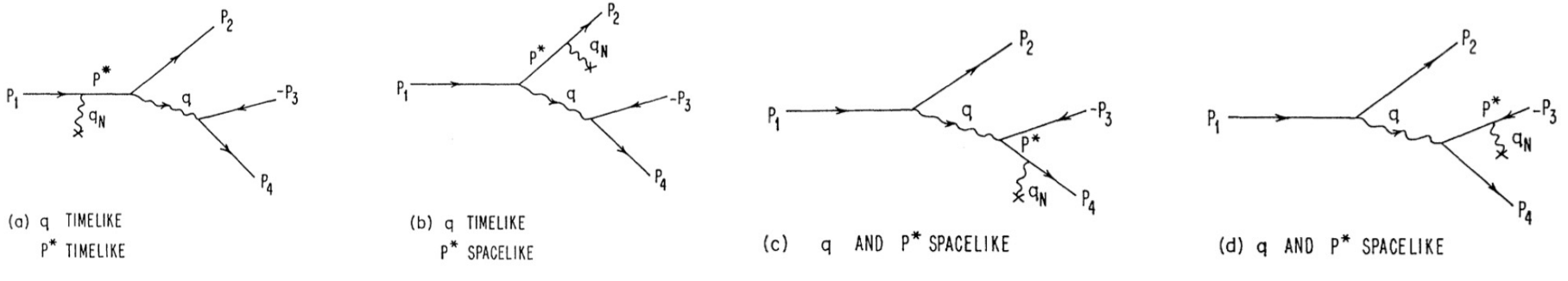
Trident process in the neutrino target

- $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$
  - Studied in the 60's and 70's, Muon Tridents, J.D. Bjorken(SLAC), M.C. Chen, Observation of Muon Trident Production in Lead and the Statistics of the Muon
  - Due to identical muons, sensitive to Fermi statistics
  - With 10 GeV muon beam, measured 60 nb per lead nucleon
- "Background": bremsstrahlung followed by γ-conversion
  $$\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \gamma, \gamma + N \rightarrow N + \mu^{+}\mu^{-}$$
- Process introduced in GEANT4 in 2022
- In 2022 data, 137 events observed with 3 tracks and 1 vertex
- Expect from simulation 85 events (2/3 due to γ-conversion and 1/3 genuine trident)







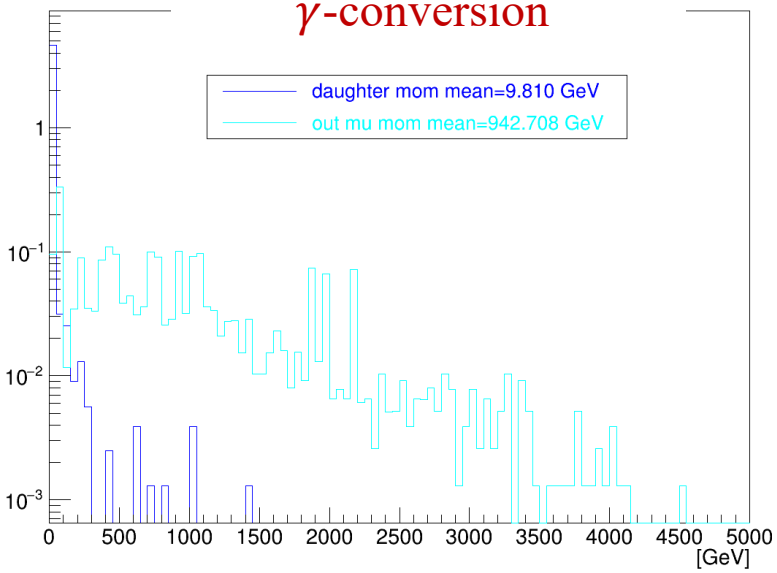


Trident events induced in the upstream rock

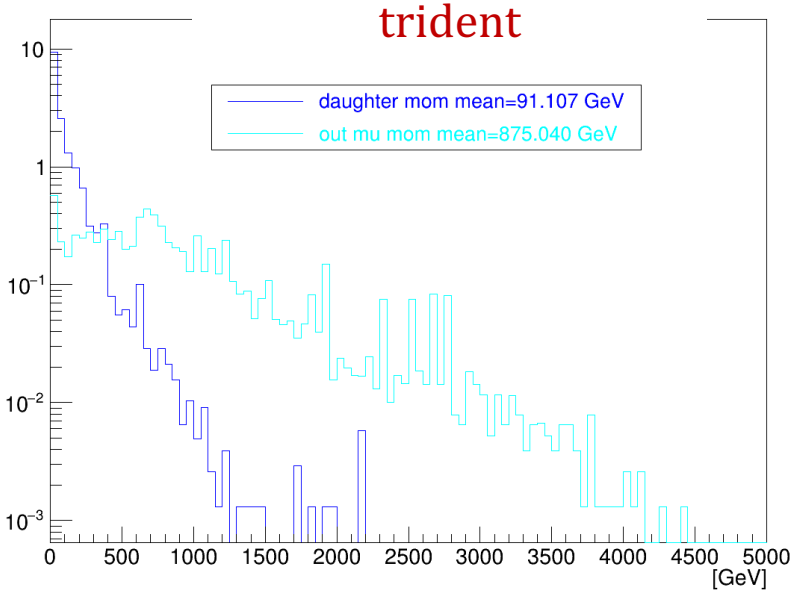
439 candidates in 2022 data

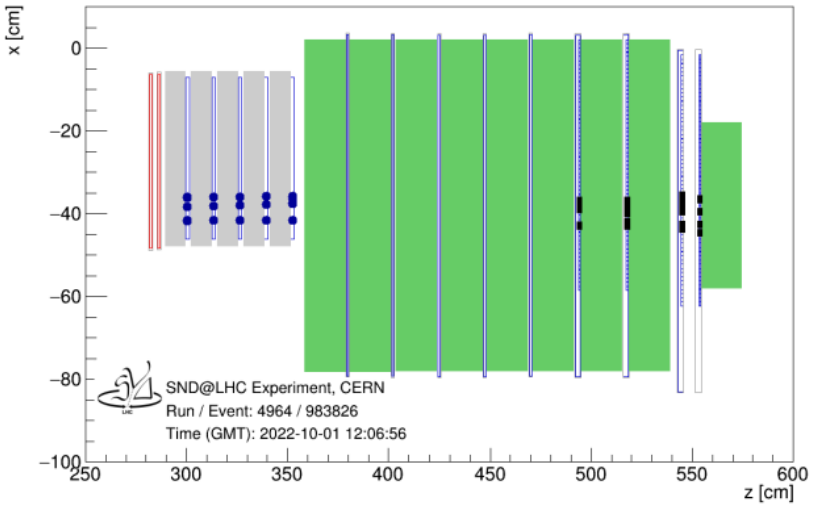
1032 expected from MC

Momentum distribution γ-conversion

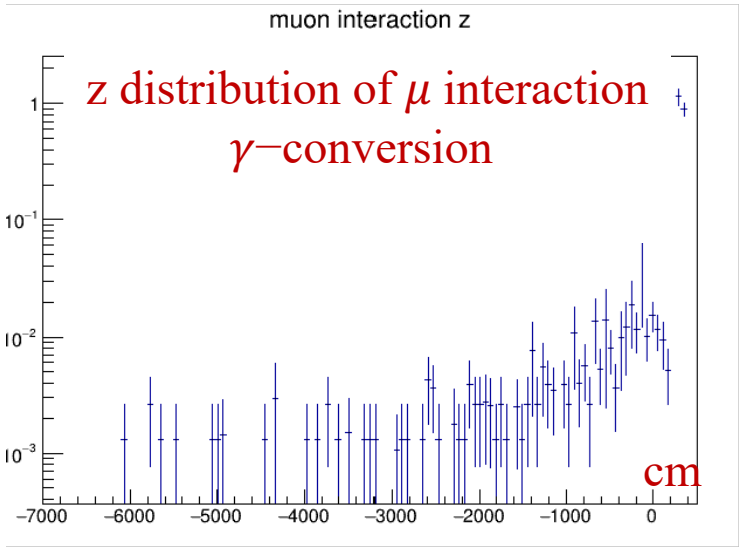


Momentum distribution trident

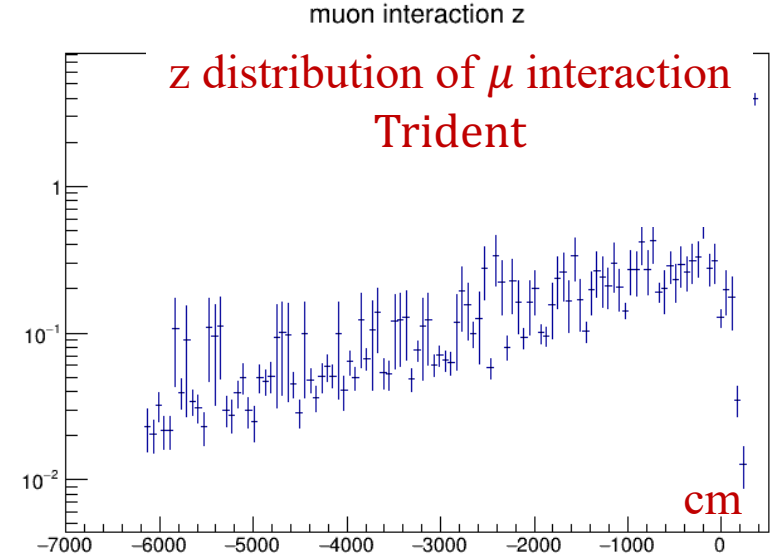


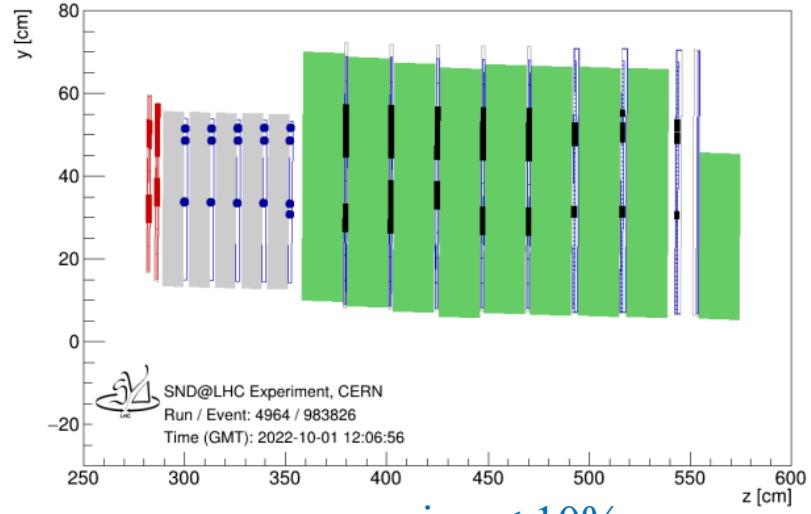


z distribution of μ interaction γ–conversion



z distribution of μ interaction Trident





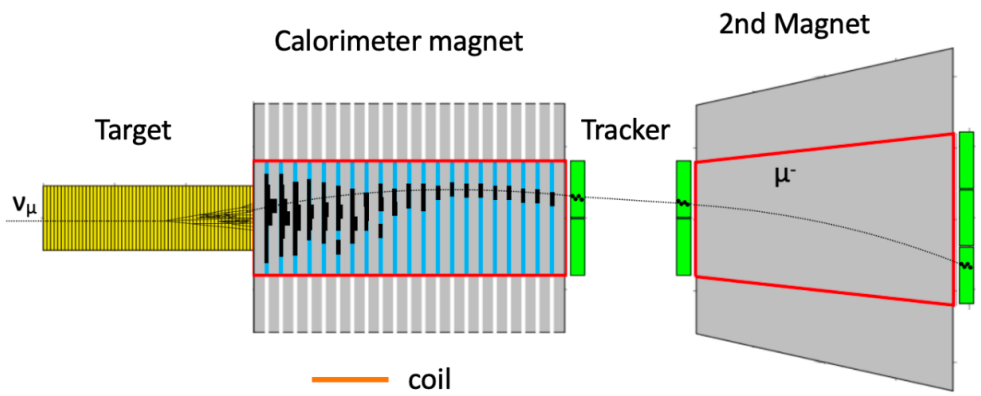
γ–conversion < 10%

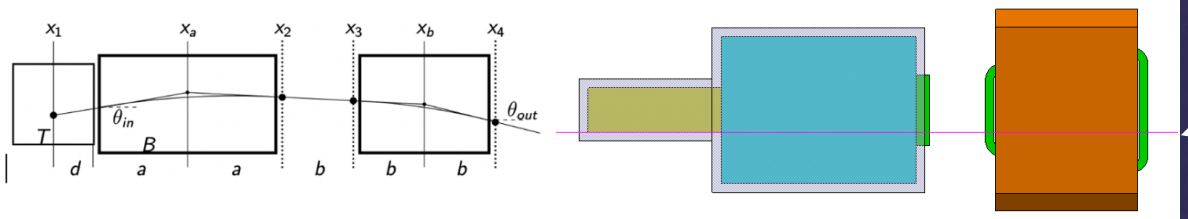
Improving the detector for the High Luminosity run

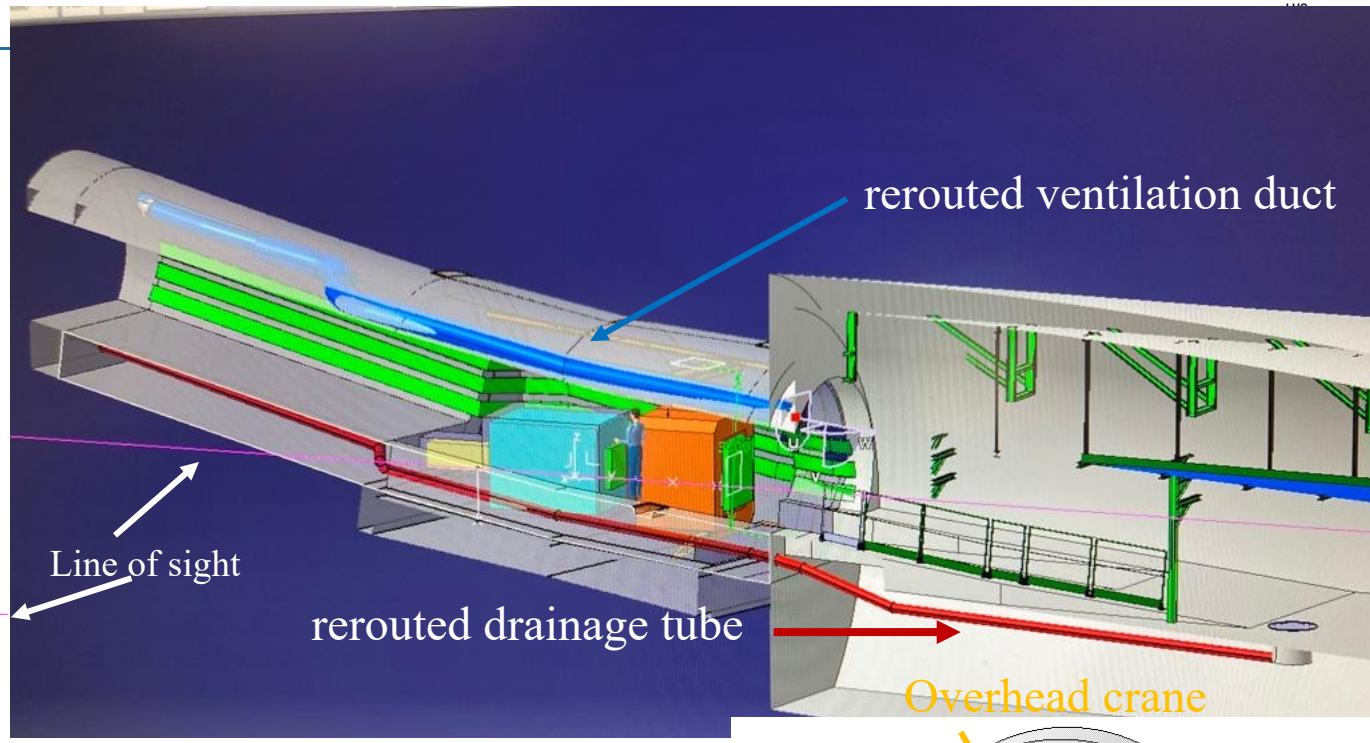
AdvSND-Far in TI18

- Improve statistics, reduce systematics
- Separate ν from ν-bar
- Charm production measurements
- LFU

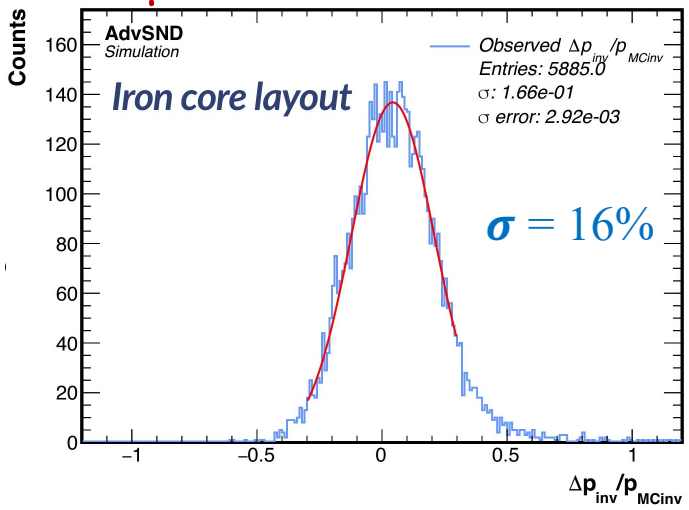
Adding a magnet for ν/νbar separation and improved energy resolution



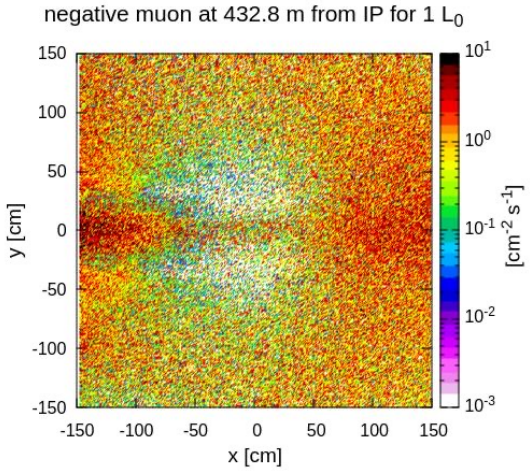


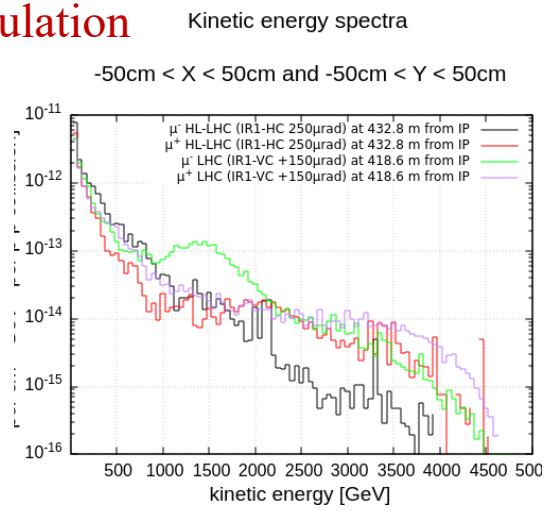


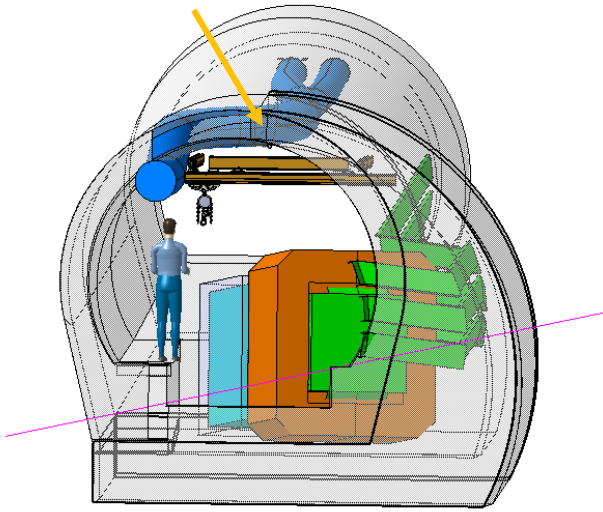
μ momentum resolution



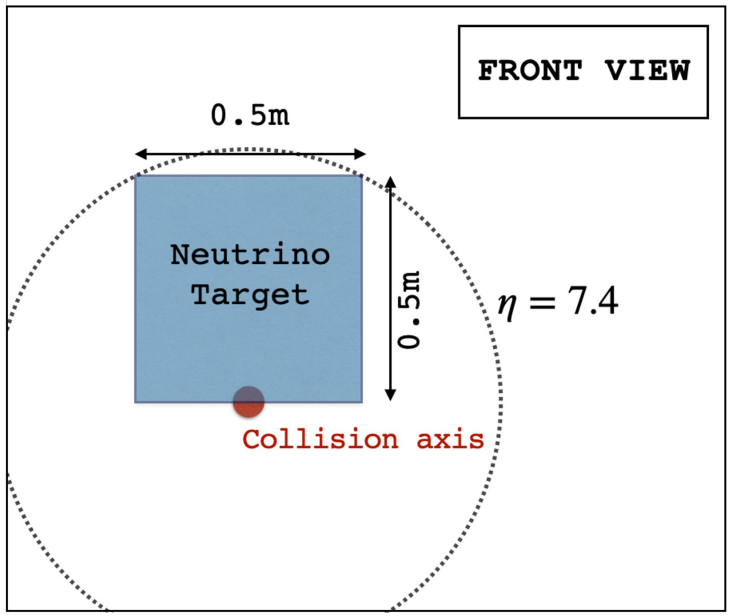
FLUKA HL simulation





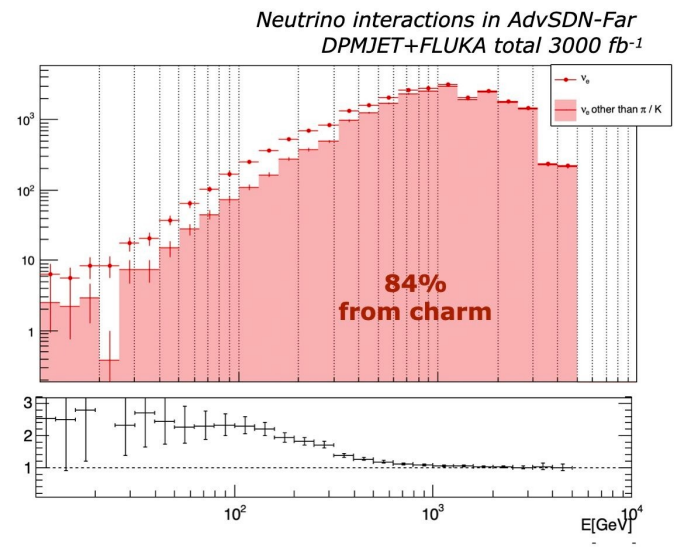


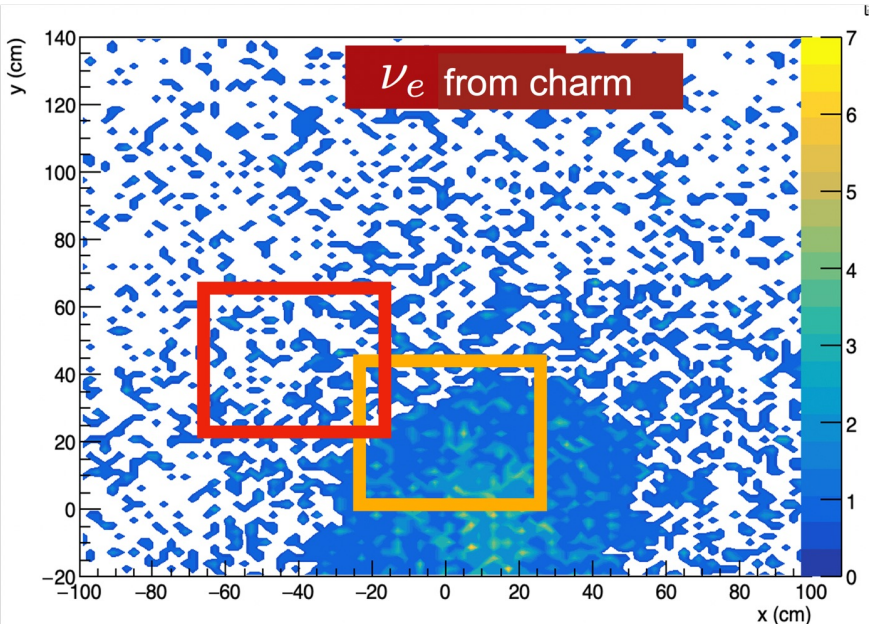
Off-axis configuration



Flavour	CC neutrino interactions Yield	NC neutrino interactions Yield
ν_μ	6.9×10^4	2.0×10^4
$\bar{\nu}_\mu$	2.5×10^4	9.0×10^3
ν_e	2.1×10^4	6.5×10^3
$\bar{\nu}_e$	1.0×10^4	4.0×10^3
ν_τ	950	300
$\bar{\nu}_\tau$	580	240
TOT	1.3×10^5	4.1×10^4

Active surface: ~50 × 50 cm^2
Tungsten mass ~ 2 tons





Lowered by ~15 cm
Partial overlap with FASER useful for data comparison/systematics
Gain in statistics × 4 w.r.t. current location for equal luminosity
> 150k ν interactions

Vertex detector: agreement with CMS Tracker
to re-use their TOB silicon trips (122 μm pitch)
Ongoing studies on optimal configuration and e/π^0 separation performance

A few concluding remarks

- Observation of collider muon neutrinos published on PRL in July 19th
- Muon flux measurement being published on EPJC
- Smooth operation with record efficiency of 99.7% in 2023
- Improvements on the energy measurement/calibration: successful test beam in August, preliminary calibration studies
- Improvements on the veto identification system during next YETS to recover fiducial volume losses (bottom part in particular)
- Strengthening emulsion scanning power at CERN (also to cope for Russian difficulties)
- Extend the physics case during HL-LHC