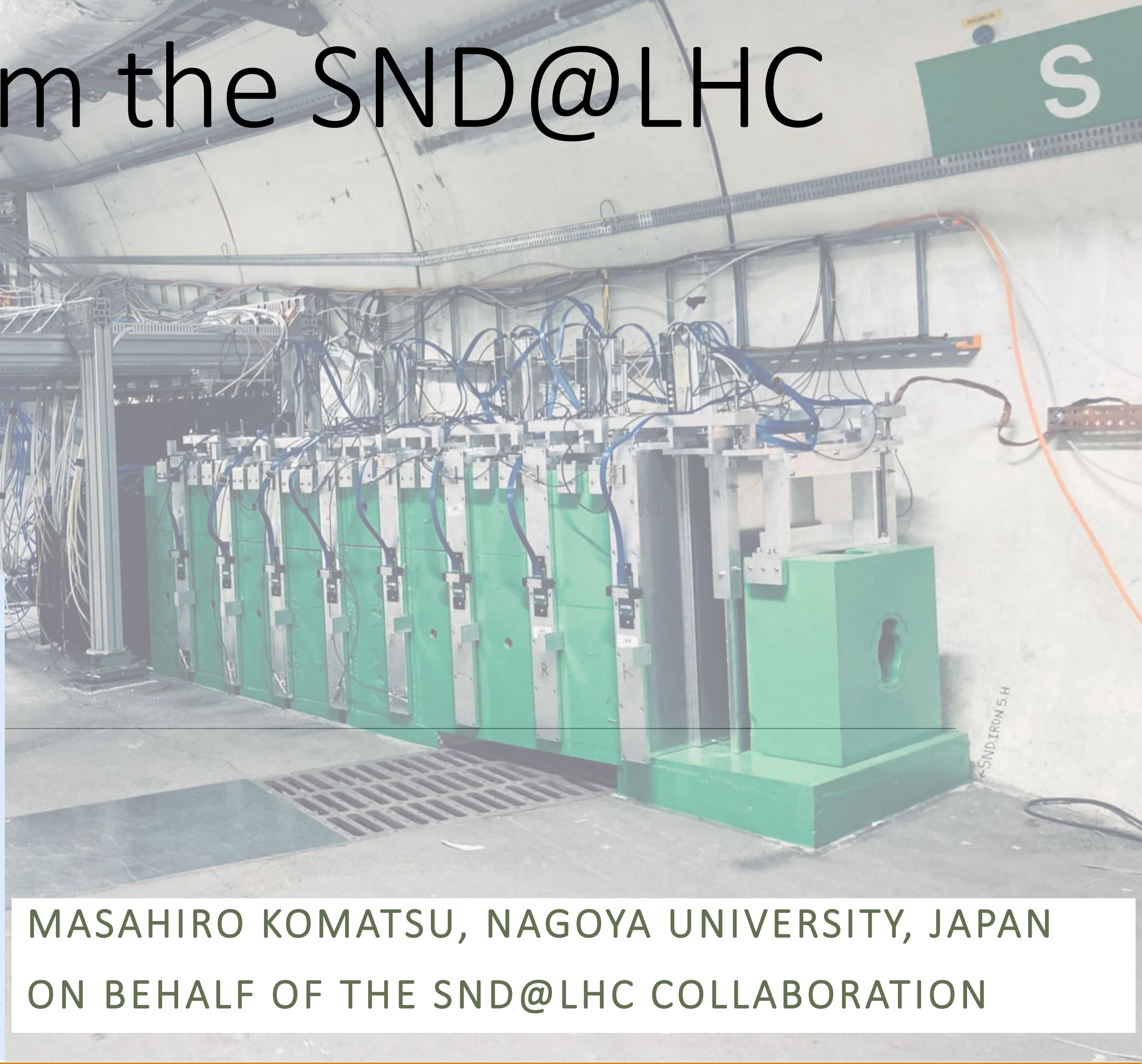
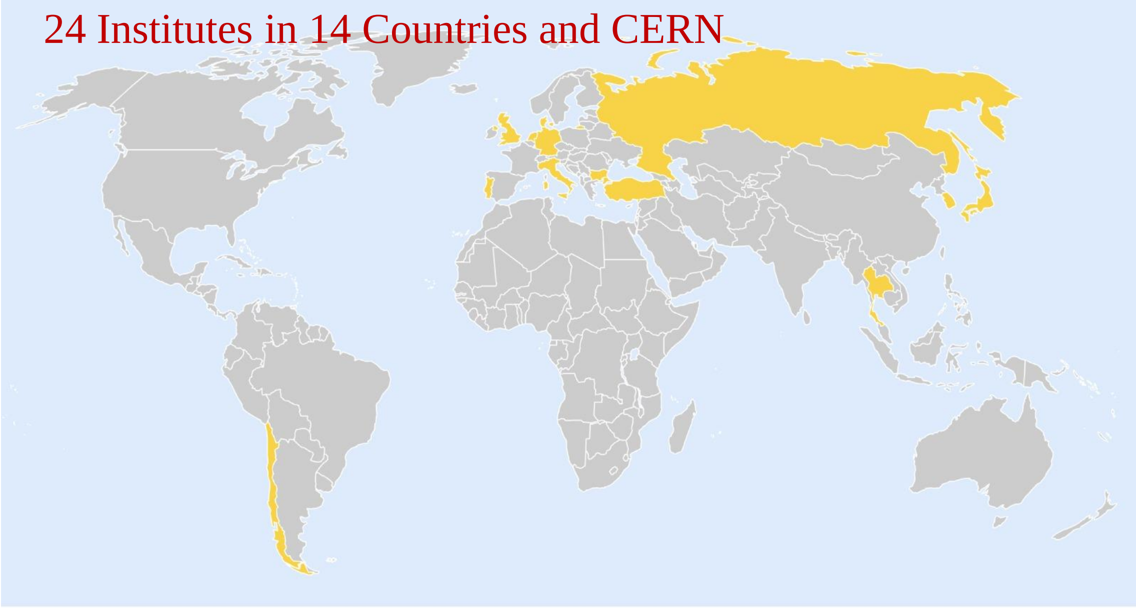
Recent results from the SND@LHC experiment

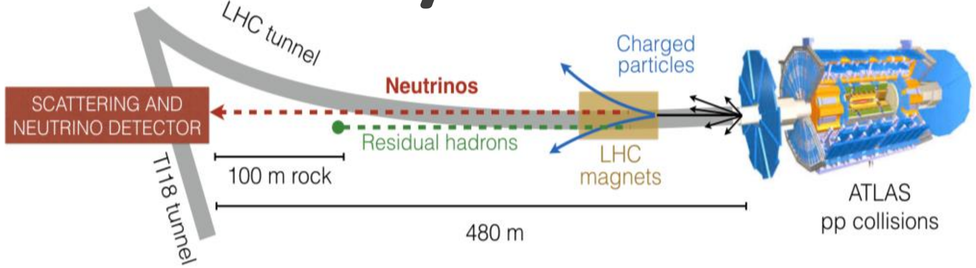


Collaboration: 150 members
24 Institutes in 14 Countries and CERN

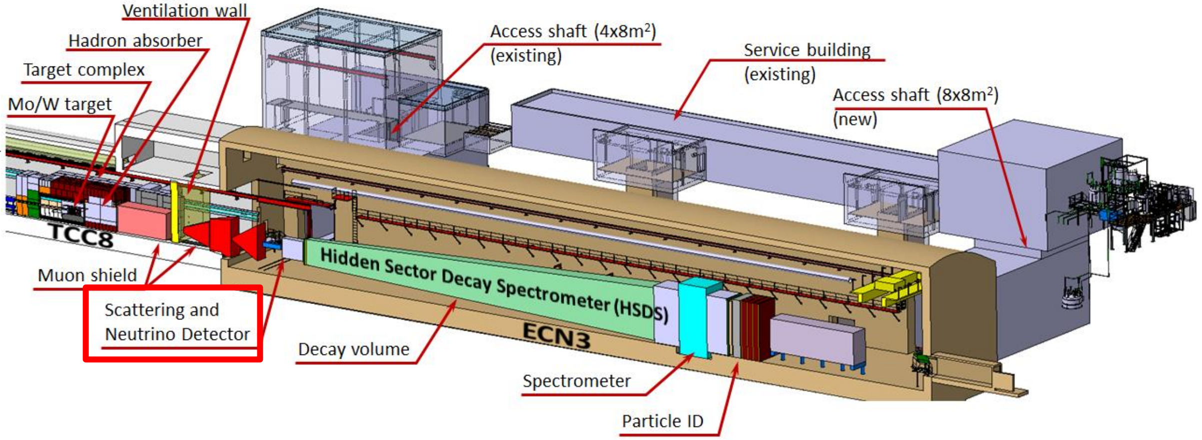


MASAHIRO KOMATSU, NAGOYA UNIVERSITY, JAPAN
ON BEHALF OF THE SND@LHC COLLABORATION

Brief history of the two experiments



SND@LHC



SHiP@ENC3 (Existing North Area Hall)

SHiP

- Proposal submitted on **April 2015** at new beam line for the experiment (ECN4). ESPP 2020 outcome was unfavorable for SHiP@ENC4.
- Looked for other existing location can host SHiP. CNGS, WANF and ECN3?
- **New proposal submitted** at existing hall (ECN3) and approved on March 2024.

SND@LHC

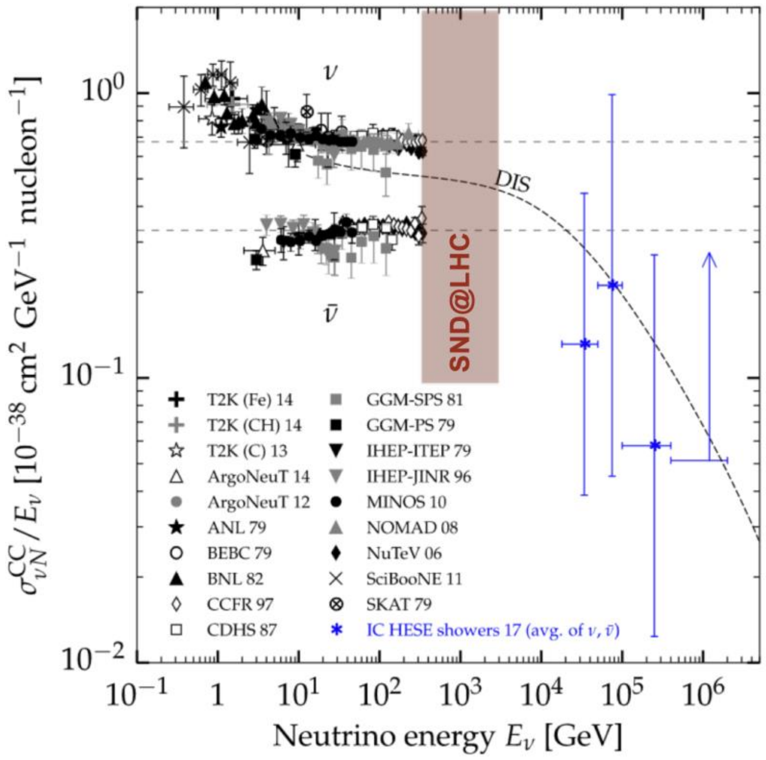
- **SND**(**S**cattering and **N**eutrino **D**etector)**@LHC** was approved on **March 2021**.
- Data taking started in April 2022.

Both beam provides all three(six) neutrino flavors.

Physics Motivation

1990, Klaus Winter pointed out possibility of tau neutrino detection at LHC neutrino

- The first tau neutrino detection done by Fermilab E872 DONUT with 800 GeV proton beam dump in 2000. (Phys.Lett.B 504 (2001) 218-224)
- Still number of observed tau neutrino interactions are limited (DONUT and OPERA)

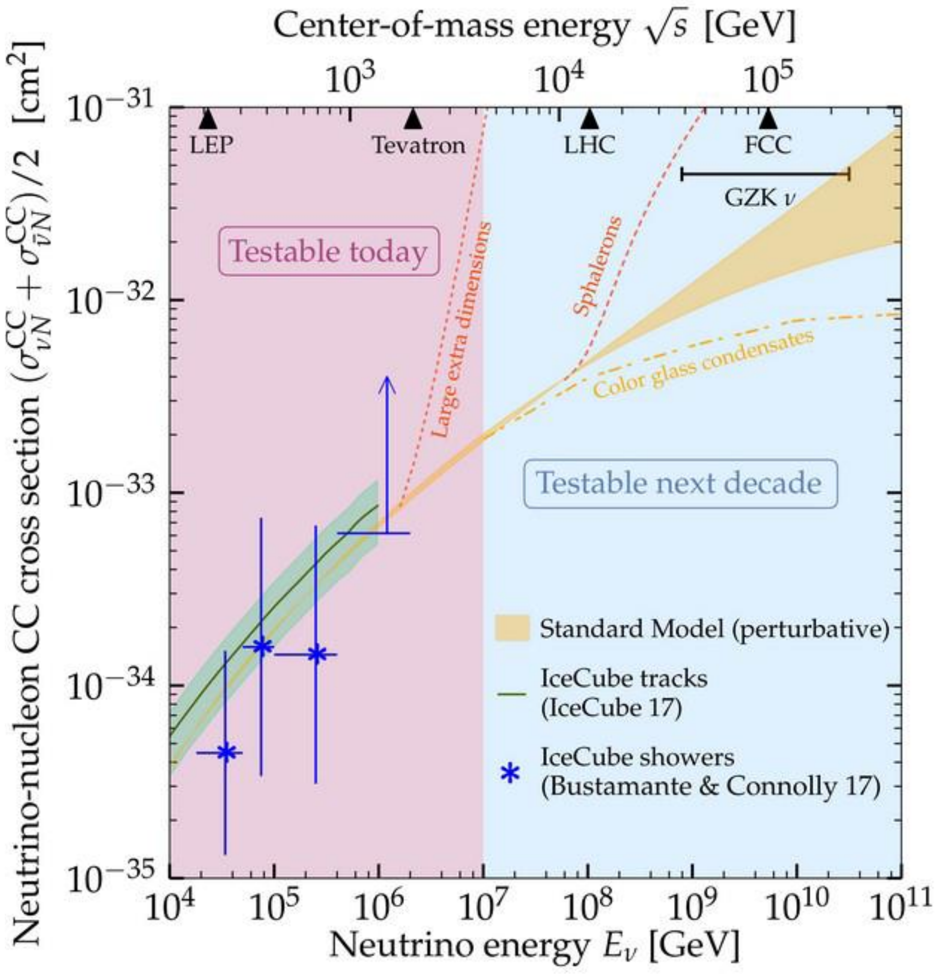


CERN is unique in providing high energy neutrinos in an unexplored energy region from LHC.

Two neutrino experiments, **SND@LHC** and **FASERν**, in operation at ATLAS interaction point. Good for forward heavy flavor production study.

LHC neutrino contains all three kinds of high energy neutrino useful to study lepton flavor universality.

Motivation

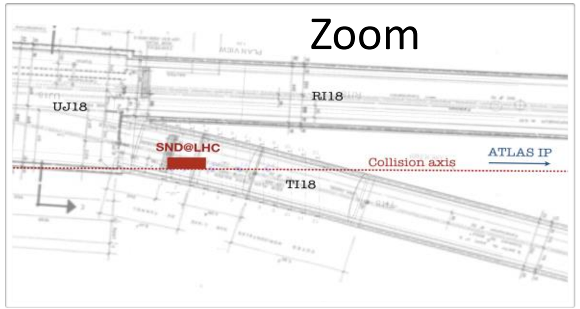


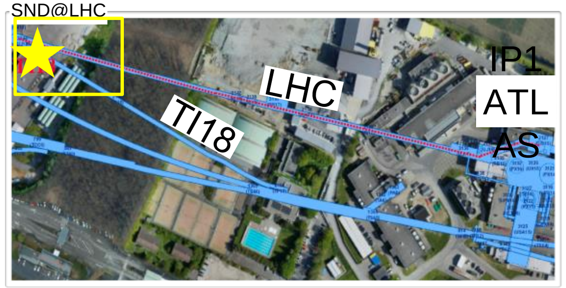
Unique in measuring pp→**ν**X, equivalent with 10^{17} eV (10^8 GeV) cosmic ray interaction which produce ultra high energy neutrinos.

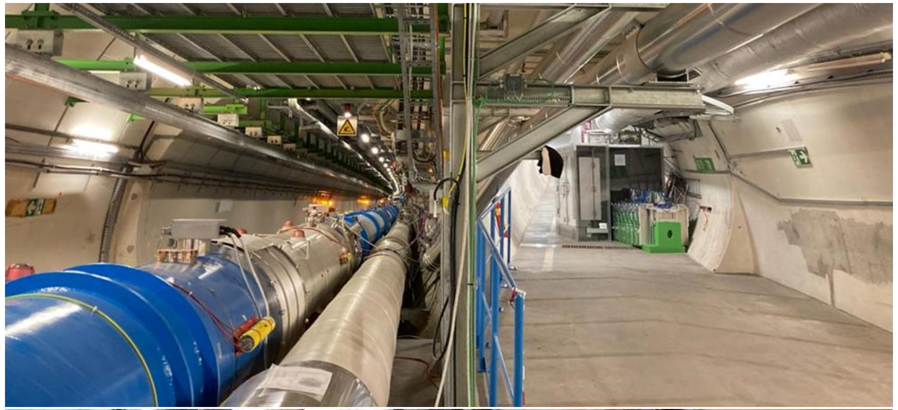
LHC neutrino allows us to reach forward region charm production where even LHCb ($2<\eta<5$) can not reach.

Neutrino is good probe for heavy flavors. LHCf can study forward neutral particles but those are mostly coming from light particles.

Location







About 480m away from the ATLAS IP

TI18 tunnel : former service tunnel connected SPS to LEP. Not used anymore.

Symmetric to TI12 tunnel where FASER is located.

Charged secondary particles deflected by LHC bending magnets

Shielded by 100 m of rock

Located slightly **off axis**

- Angular acceptance: **7.2<η< 8.4**
- FASER is placed on axis covering **η>8.8**

Aiming to collect 290 fb^{-1} (150 in proposal)

- More luminosity become available in RUN3

Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

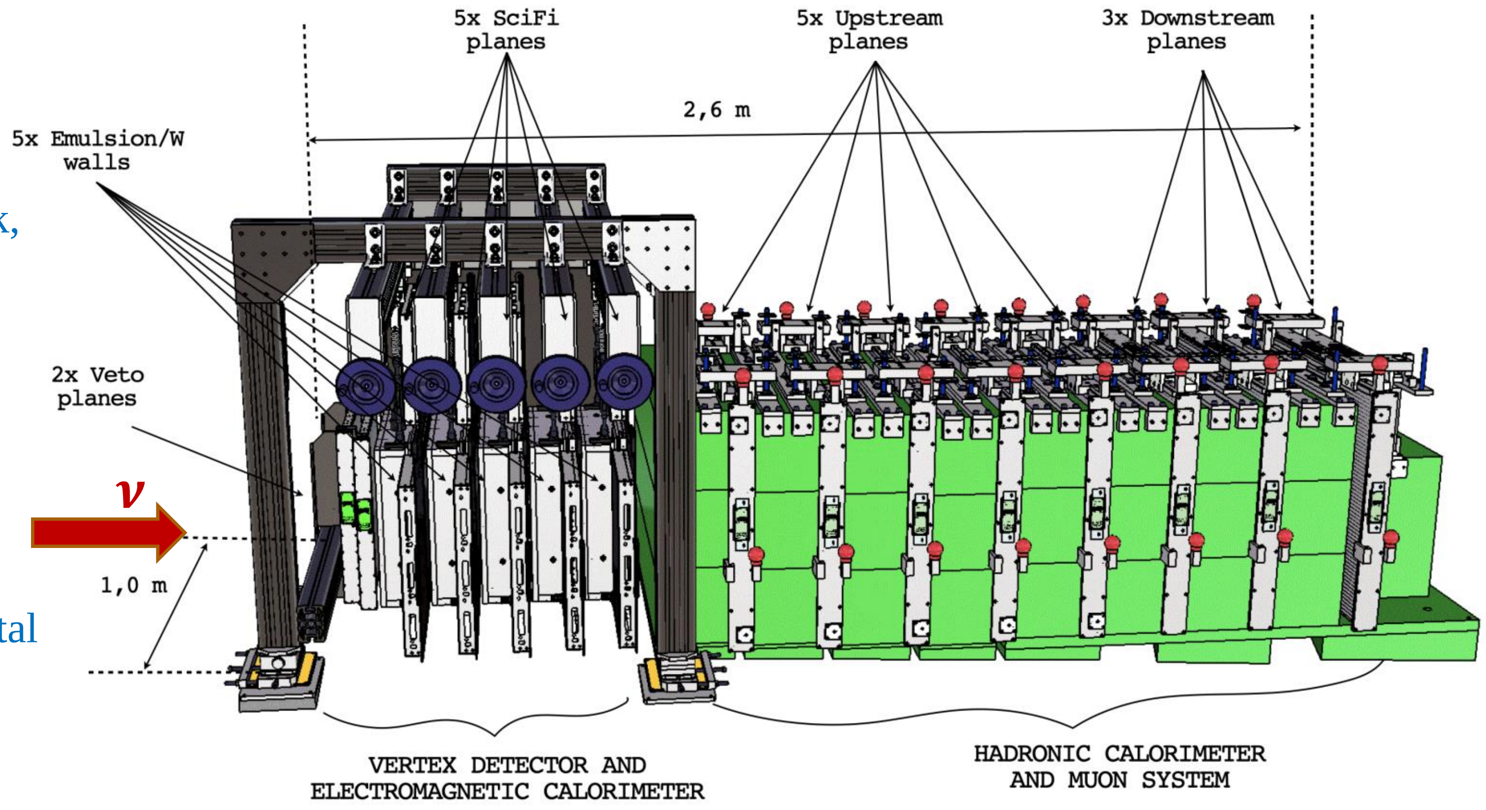
VETO PLANE:
tag penetrating muons

NEUTRINO TARGET & VERTEX DETECTOR:
- Emulsion cloud chambers (60 emulsion films, 300μm thick, interleaved by 1mm thick tungsten plates)

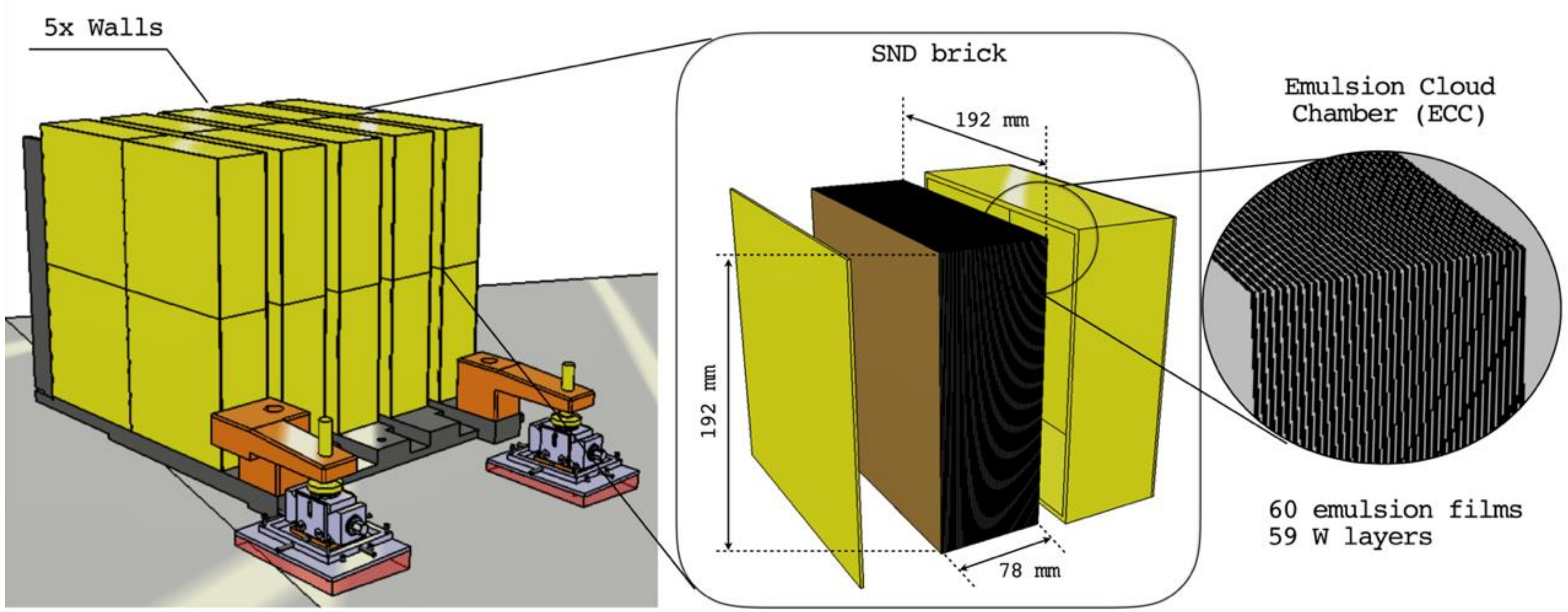
E.M. CAL
- 250μm Scintillating fibres for timing information and e.m. energy measurement

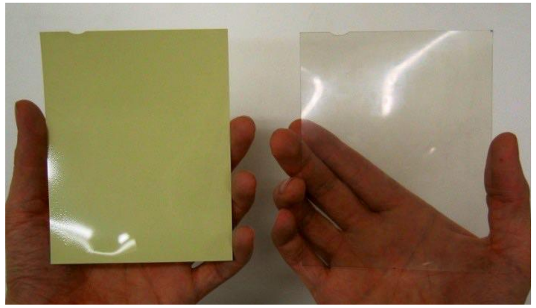
HADRONIC CALO:
iron walls interleaved with plastic scintillator planes for a total of about 11 λ

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

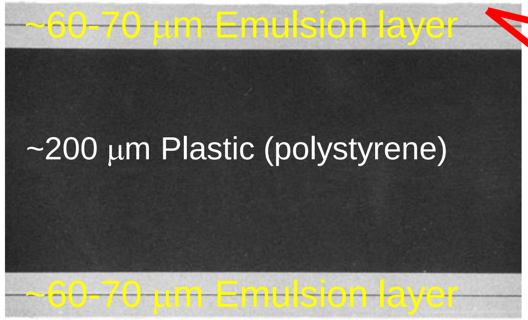


ECC target

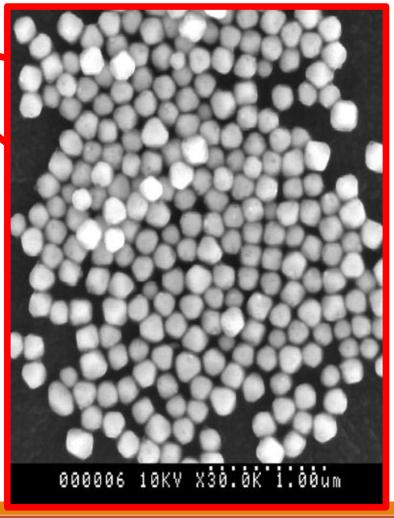




Before and after development



film cross section



Fine 3D tracking detector composed of 0.2 μm diameter AgBr crystal in gelatin.

Number of bricks : 20

- walls: 5
- Bricks per wall : 4

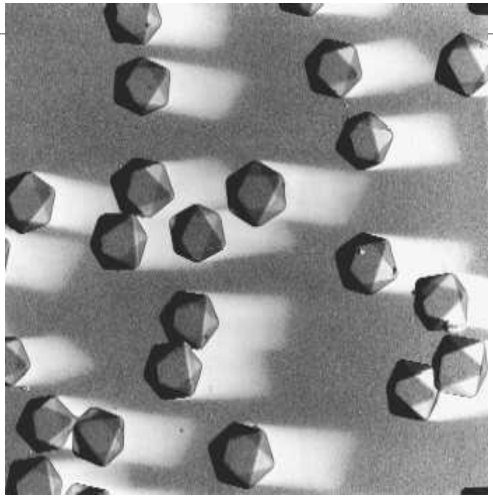
Brick surface: 192x192 mm^2

- Brick thickness: 78 mm
- 60 films + 59 W plate

Passive material : Tungsten

- Total mass : 830 kg
- Total emulsion surface : 44 m^2

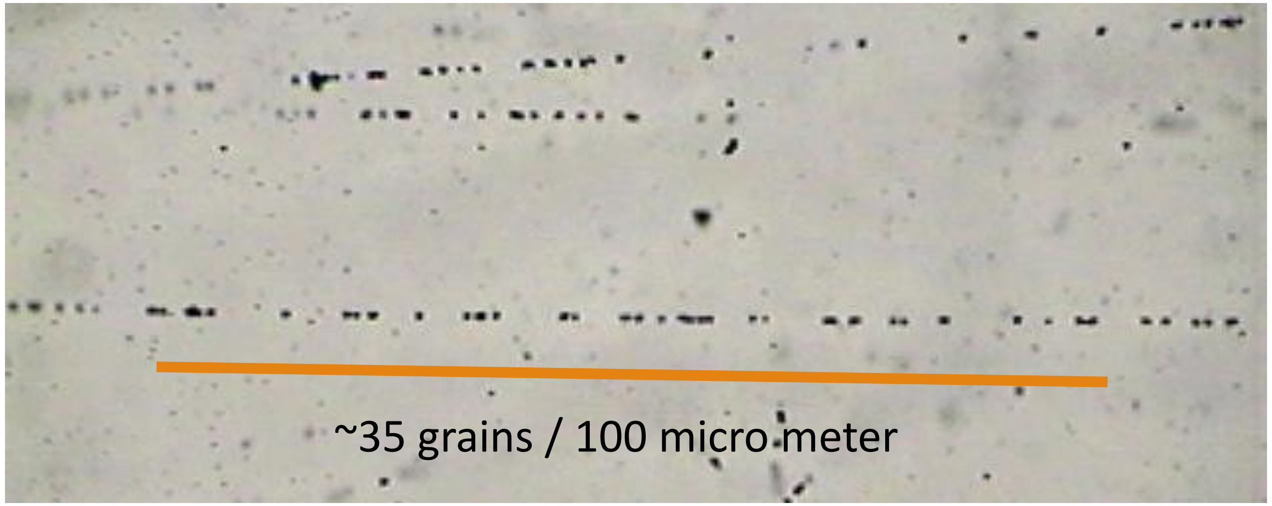
Nuclear emulsion



AgBr crystal : size 0.2 – 0.3 micro meter in diameter.

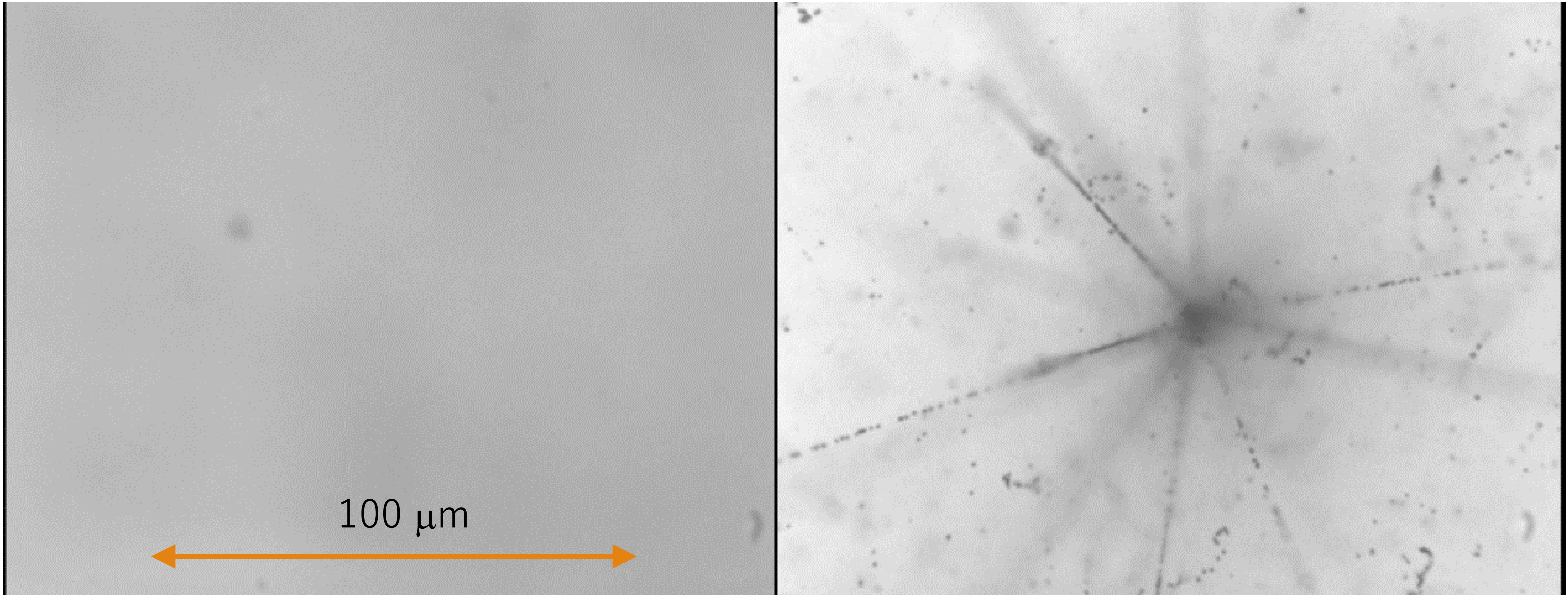
Charged particle produce latent image, developing process make Ag grain visible.

MIP



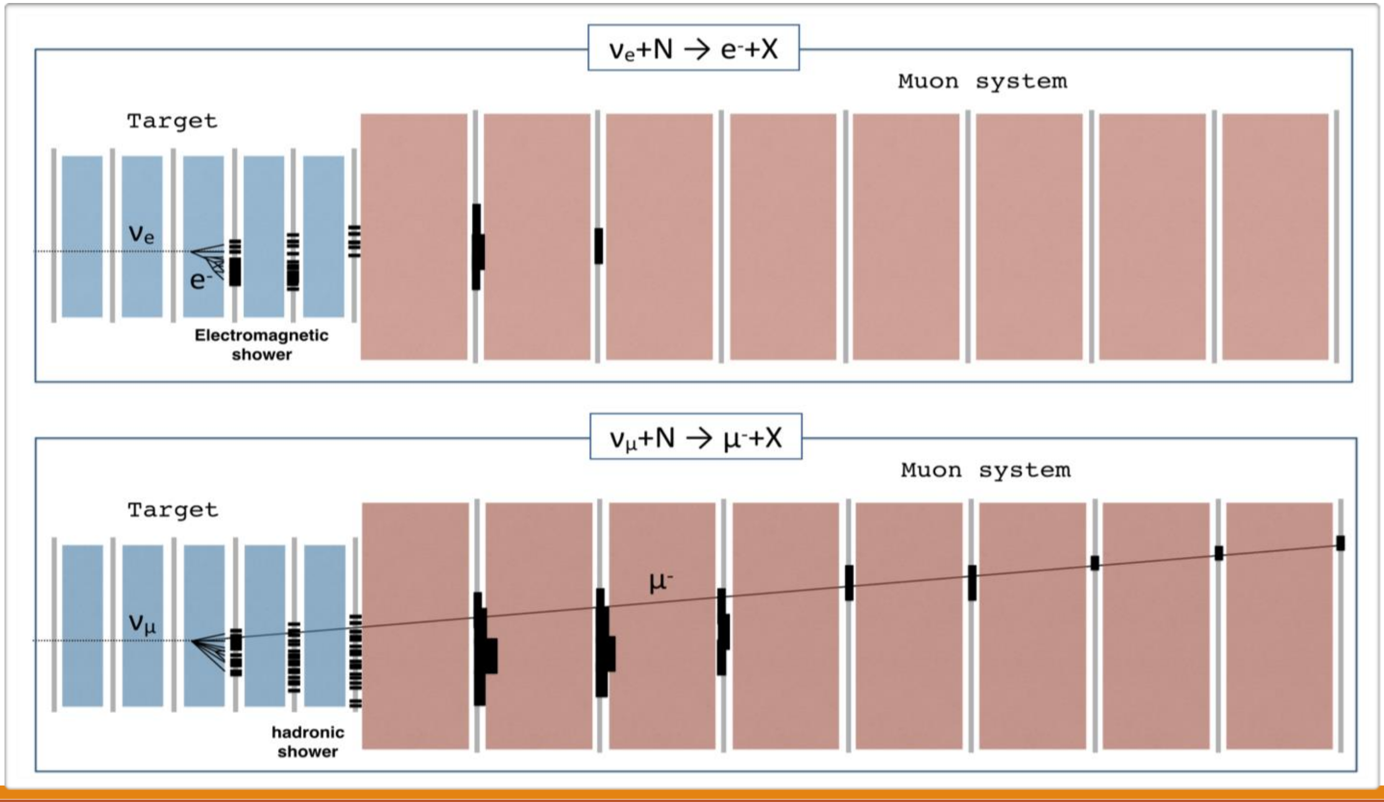
High energy interaction in emulsion

600 GeV π^- | Sulfur 200 GeV/nucleon

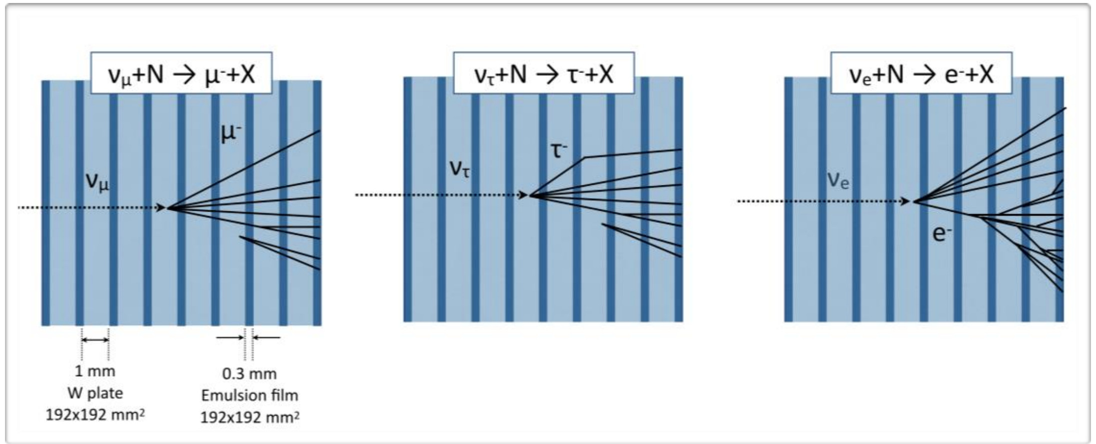


EVENT RECONSTRUCTION

- **FIRST PHASE: electronic detectors**
- Event reconstruction based on Veto, Target Tracker and Muon system
  - Identify neutrino candidates
  - Identify muons in the final state
  - Reconstruction of electromagnetic showers (SciFi)
  - Measure neutrino energy (SciFi+Muon)

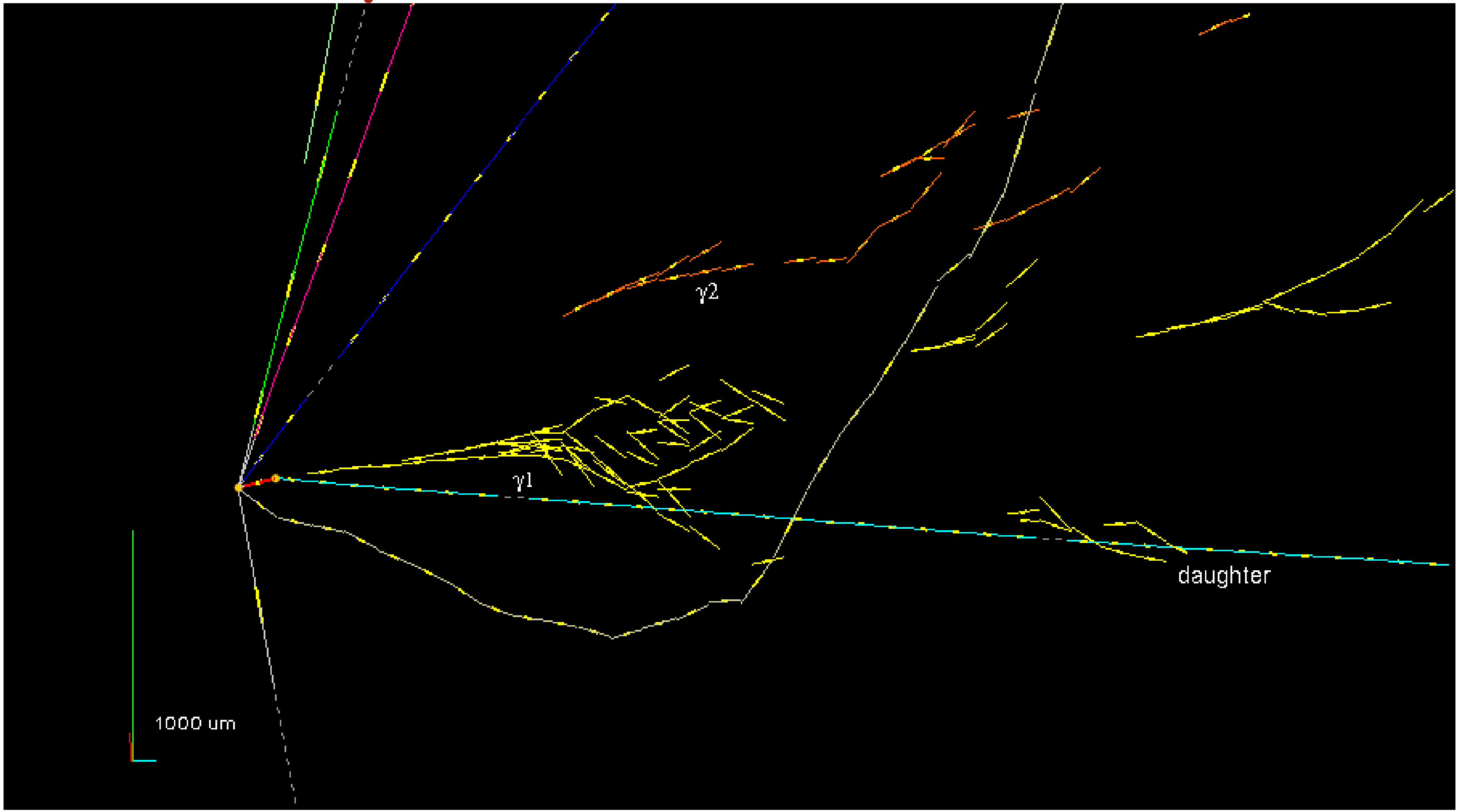


- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement



Flavor identification by ECC

THE FIRST ν_τ CANDIDATE IN OPERA

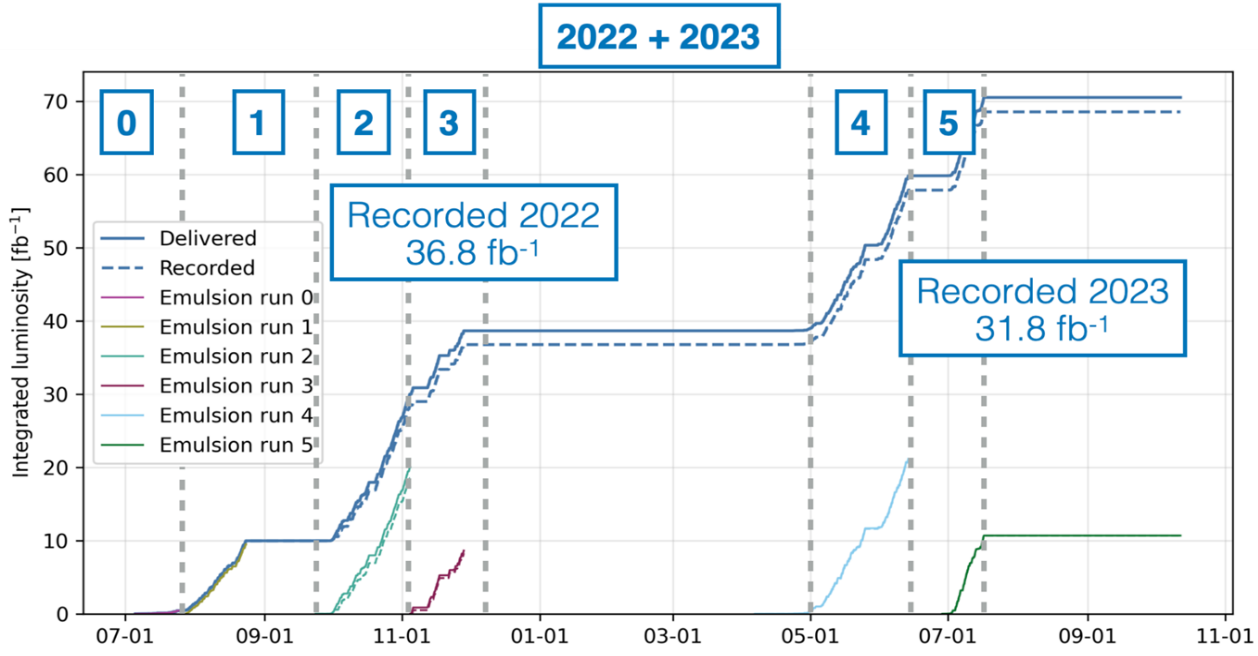


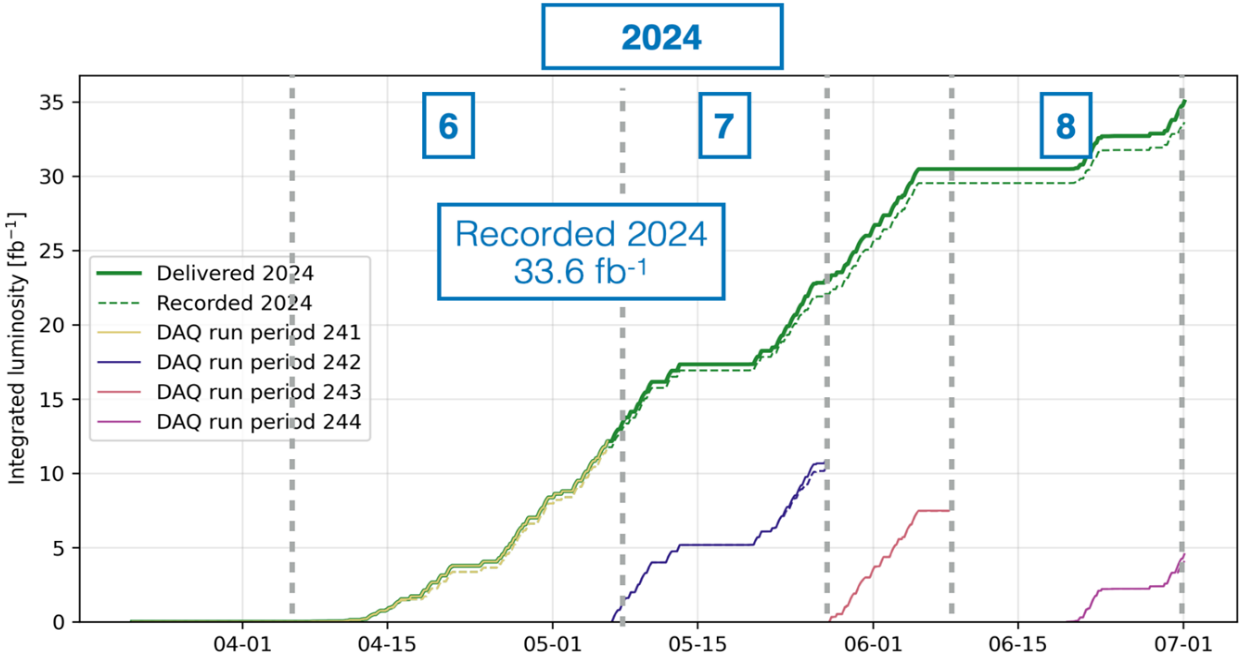
Physics Letters B691 (2010) 138

pp collision data

- **68.6 fb^{-1}** of proton-proton collisions recorded by the electronic detectors in **2022-2023**
  - 97% detector uptime
  - Five emulsion target replacements
    - Keep track density < 4×10^5 tracks/cm^2
    - Limit the exposure to 20fb^{-1}

- Unexpected increase in the muon flux in **2024**
  - New strategy for the emulsion target replacement:
    - Instrument only the lower half target with emulsions
    - Exposure limited to 12 fb^{-1}
    - Keep 65% of events
  - **33.6 fb^{-1}** of proton-proton collisions recorded by the electronic detectors up to now
  - Three emulsion target replacements performed, nine expected





Muon neutrino analysis update

Phys. Rev. Lett. 131, 031802

Updated analysis with 2023 data and extended fiducial volume

Event selection

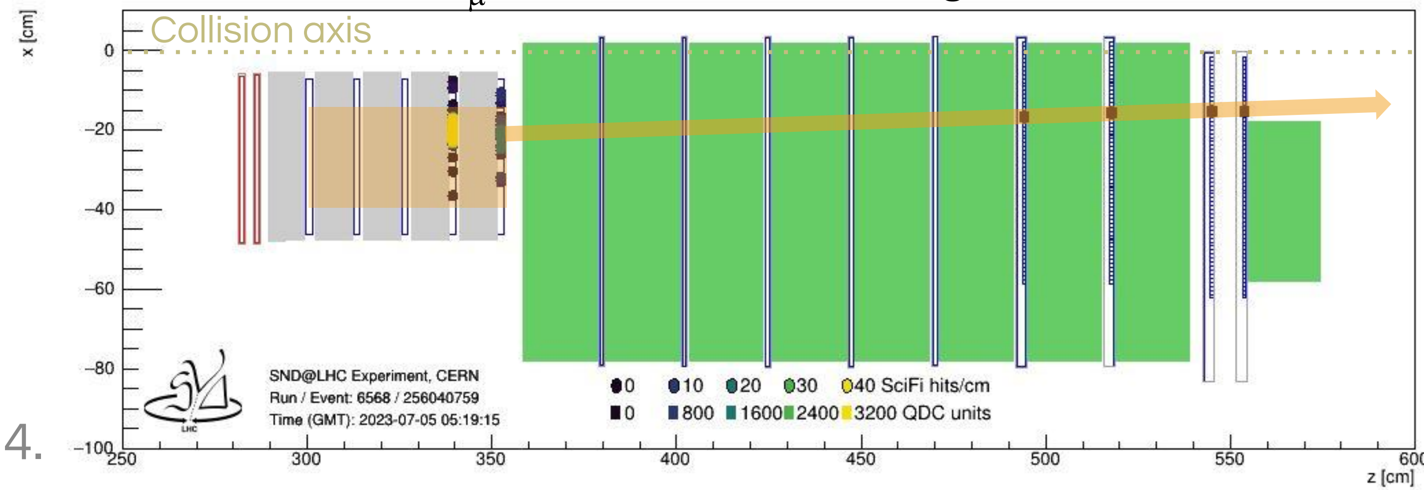
Fiducial volume

- Reject events in first wall.
    - Previously used only walls 3 and 4.
- Reject side-entering backgrounds.
- Signal acceptance: 18%
    - Up from 7.5%.

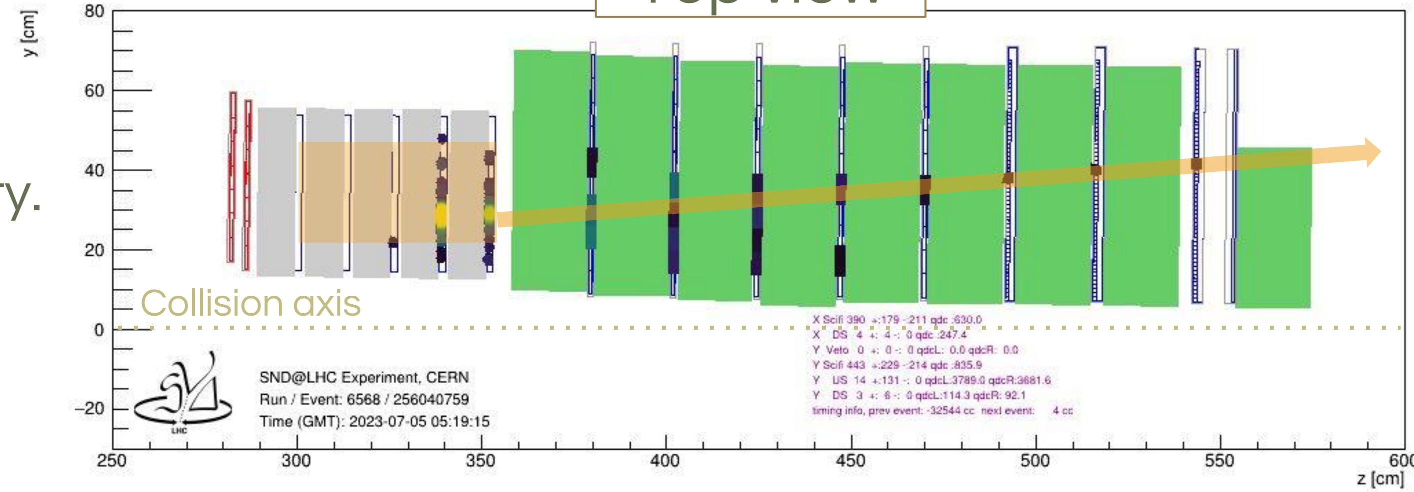
Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 35%

Observation of 8 ν_μ CC candidates with a significance of 6.8σ



Top view



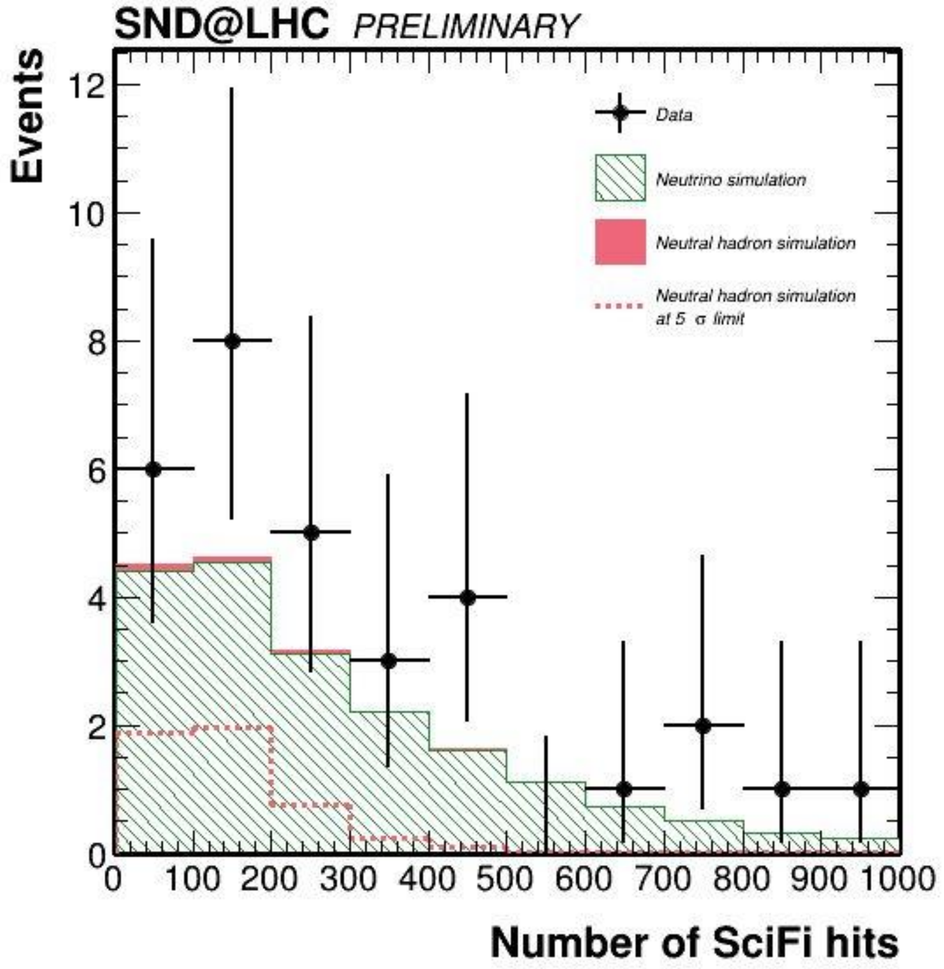
Side view

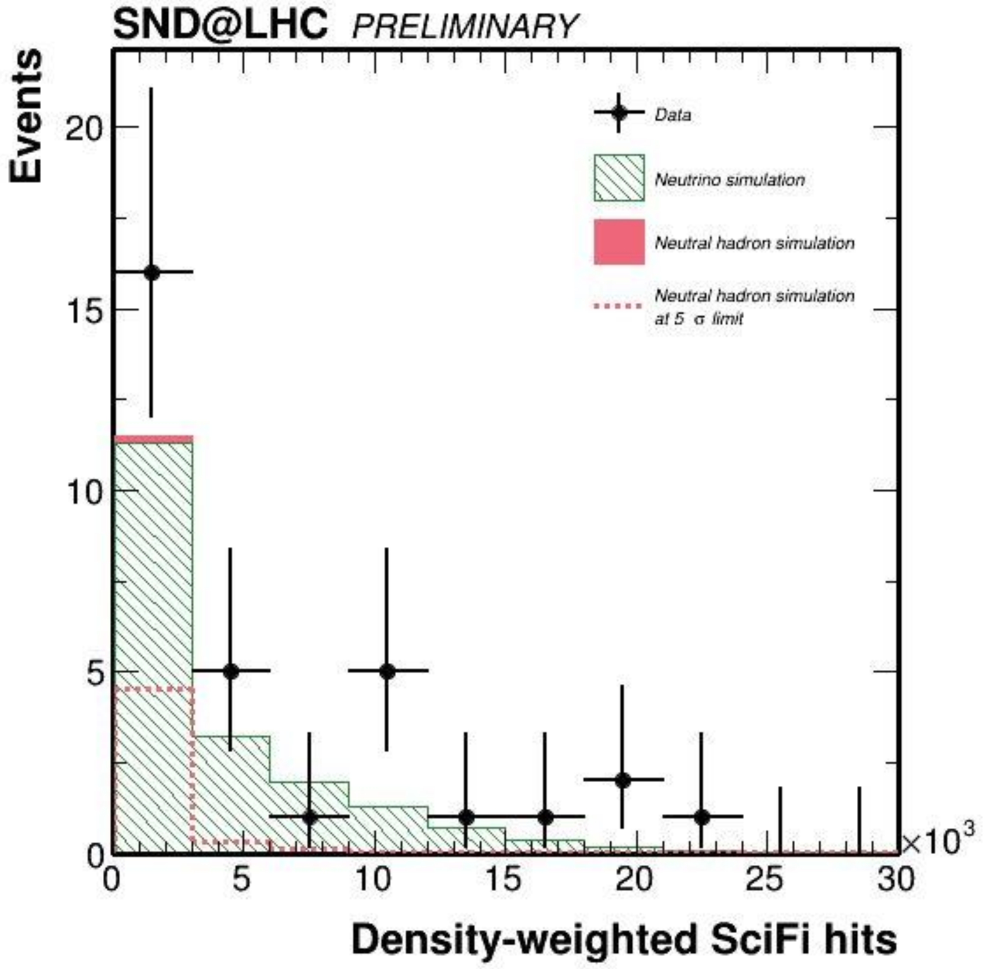
Updated muon neutrino results

Number of events expected in 68.6 fb^{-1}

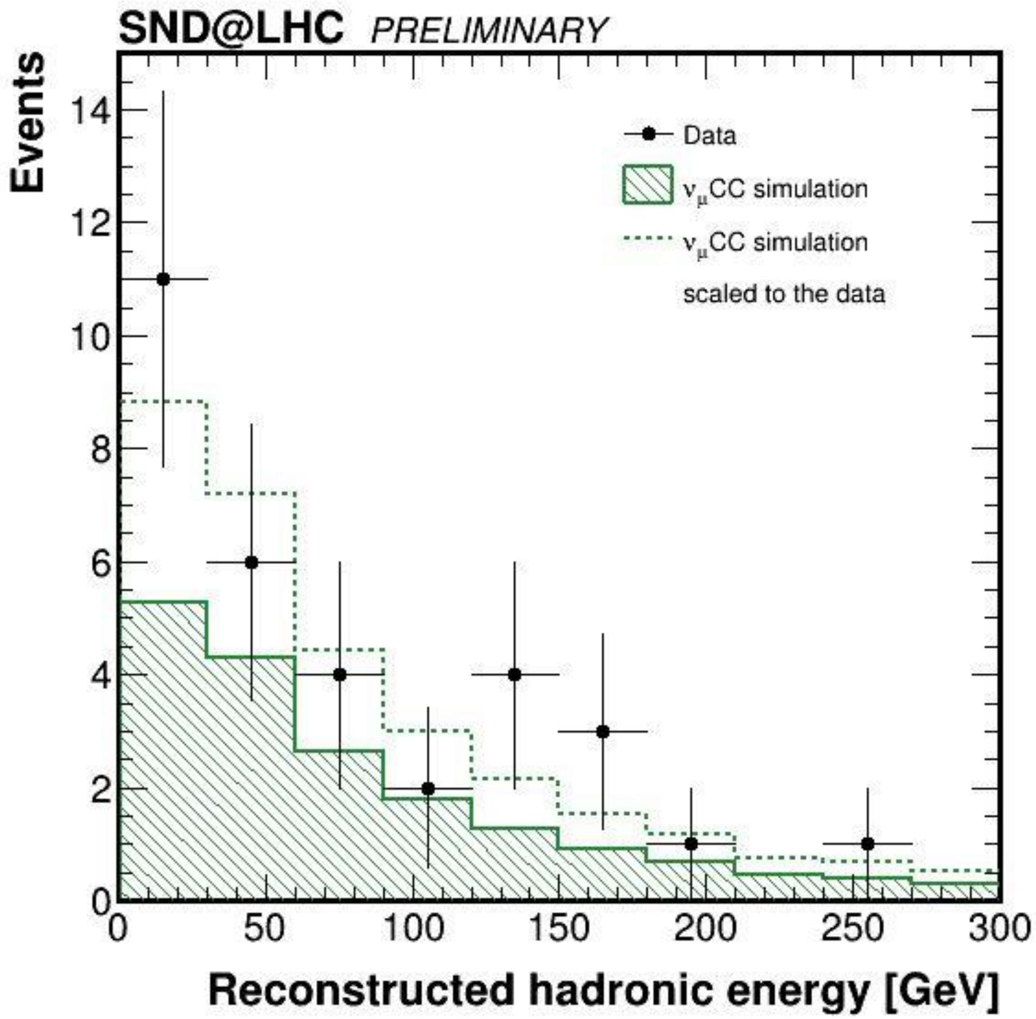
- Signal: 19.1± 4.1
- Neutral hadrons: 0.25 ± 0.06

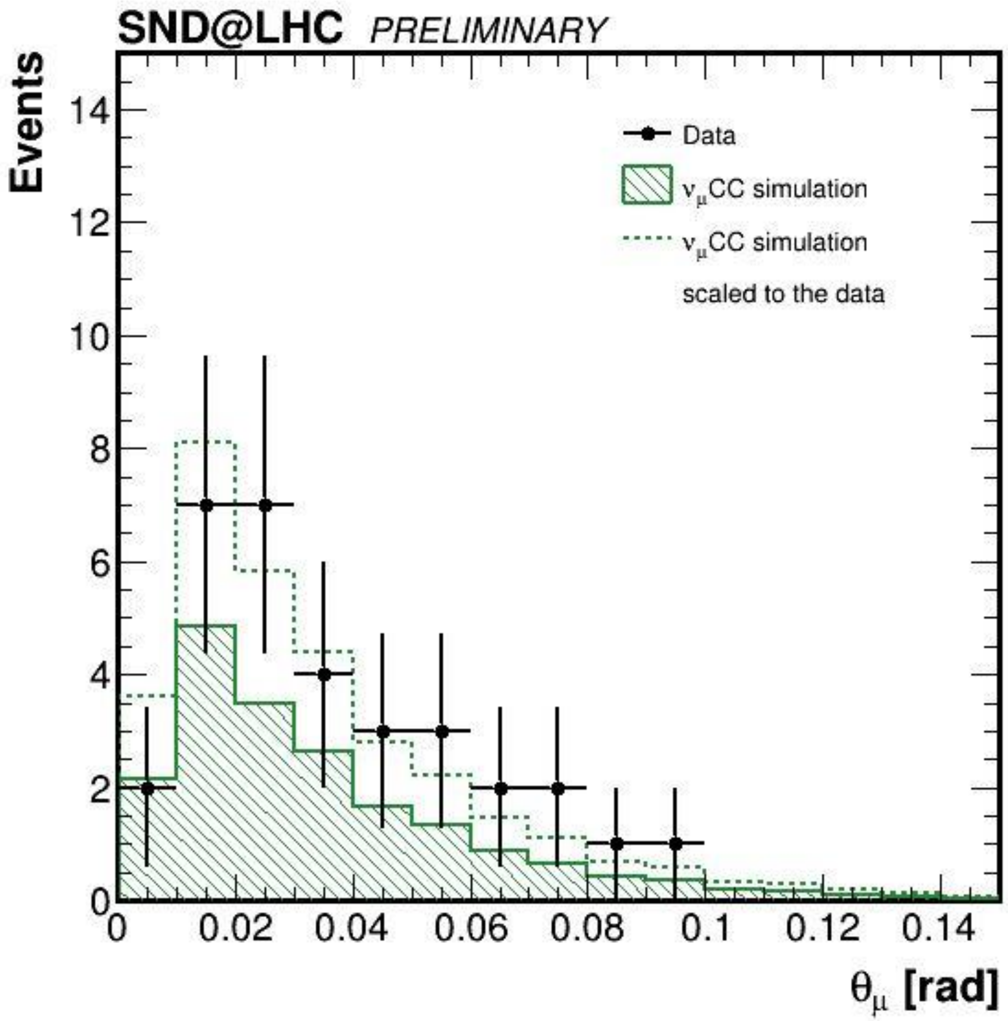
Number of events observed: 32





Muon neutrino event kinematics





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

Search for shower-like (0μ) neutrino events

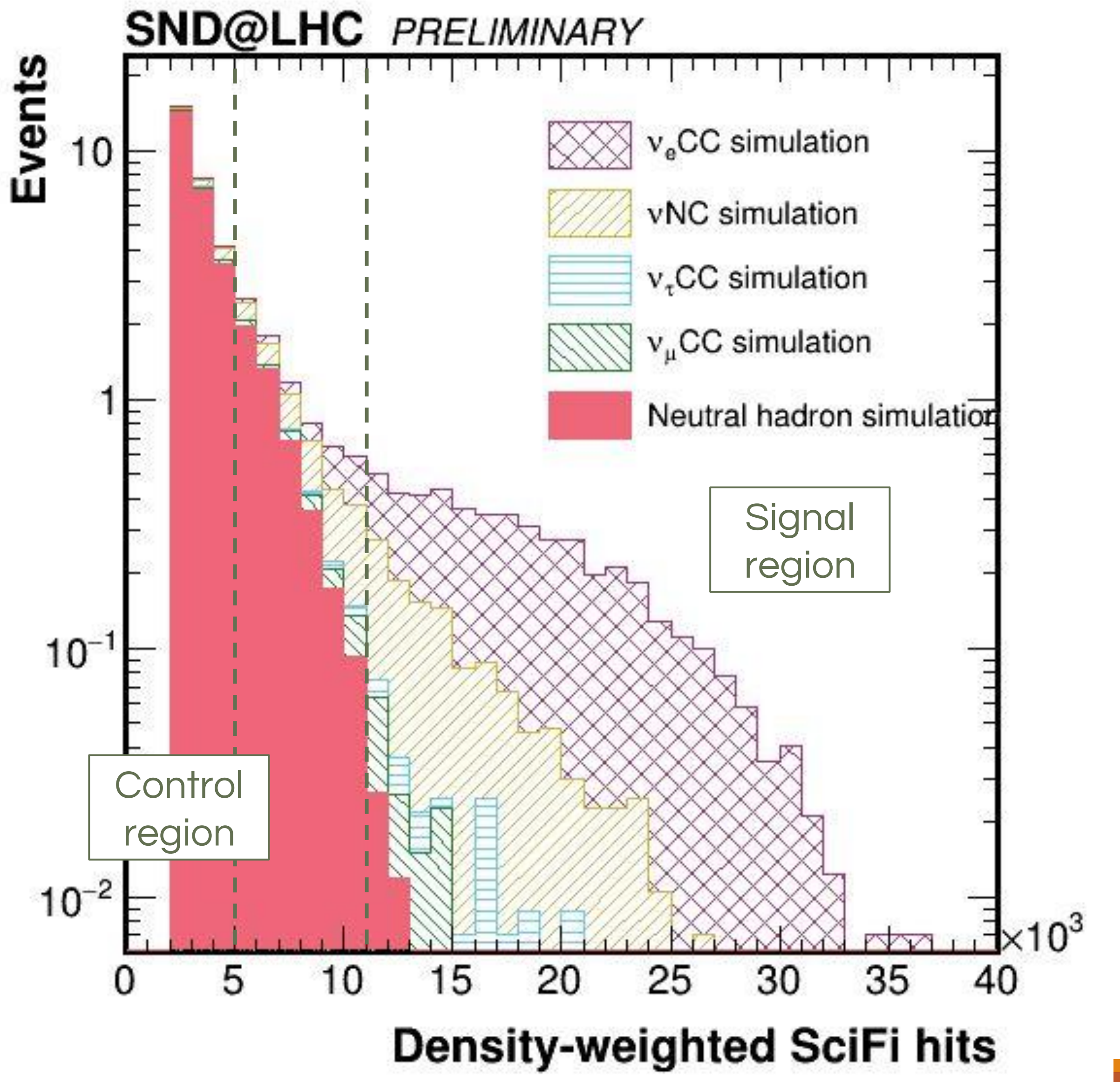
Signal: ν_eCC and NC interactions

Fiducial volume

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

0μ neutrino event identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- No hits in last two muon system planes.
    - No reconstructable muon.
- Density-weighted number of hits in most active station > 11x10^3.
    - Optimized for maximum expected significance
- Signal selection efficiency: 42%



Observation of 0μ events in SND@LHC

Neutral hadron background

- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
  - Observed neutral hadron background is ⅓ of the predicted value.
- Events **expected in signal region: 0.01**

Neutrino background

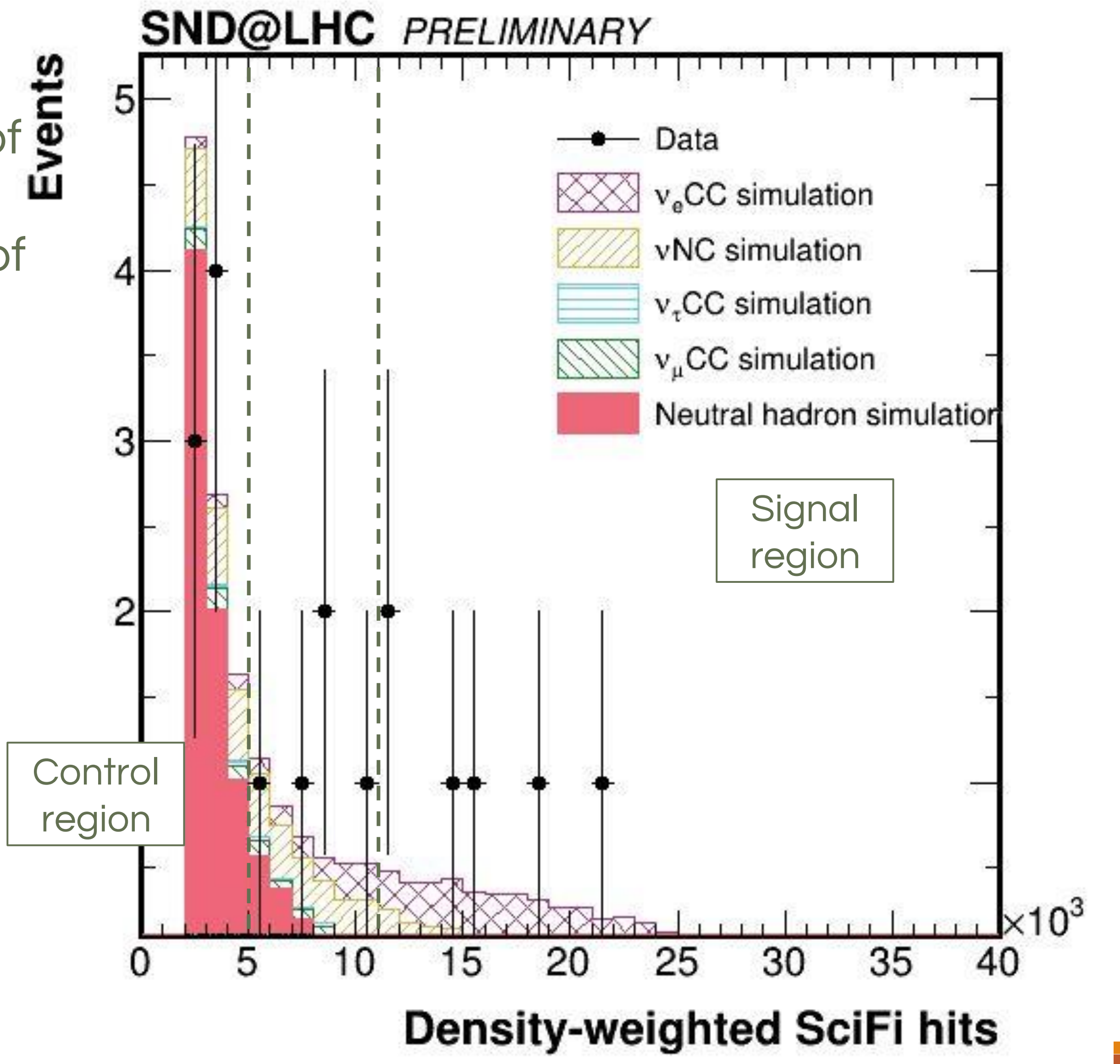
- Muon Neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC 1μ interactions expected: 0.002

0μ observation significance

- **Total expected background: 0.13 ± 0.11 events**
- **Expected signal: 4.7 events**
- **Expected significance: 4.9 σ**

Number of events observed: 6

Observation significance: 5.8 σ



Paper in preparation

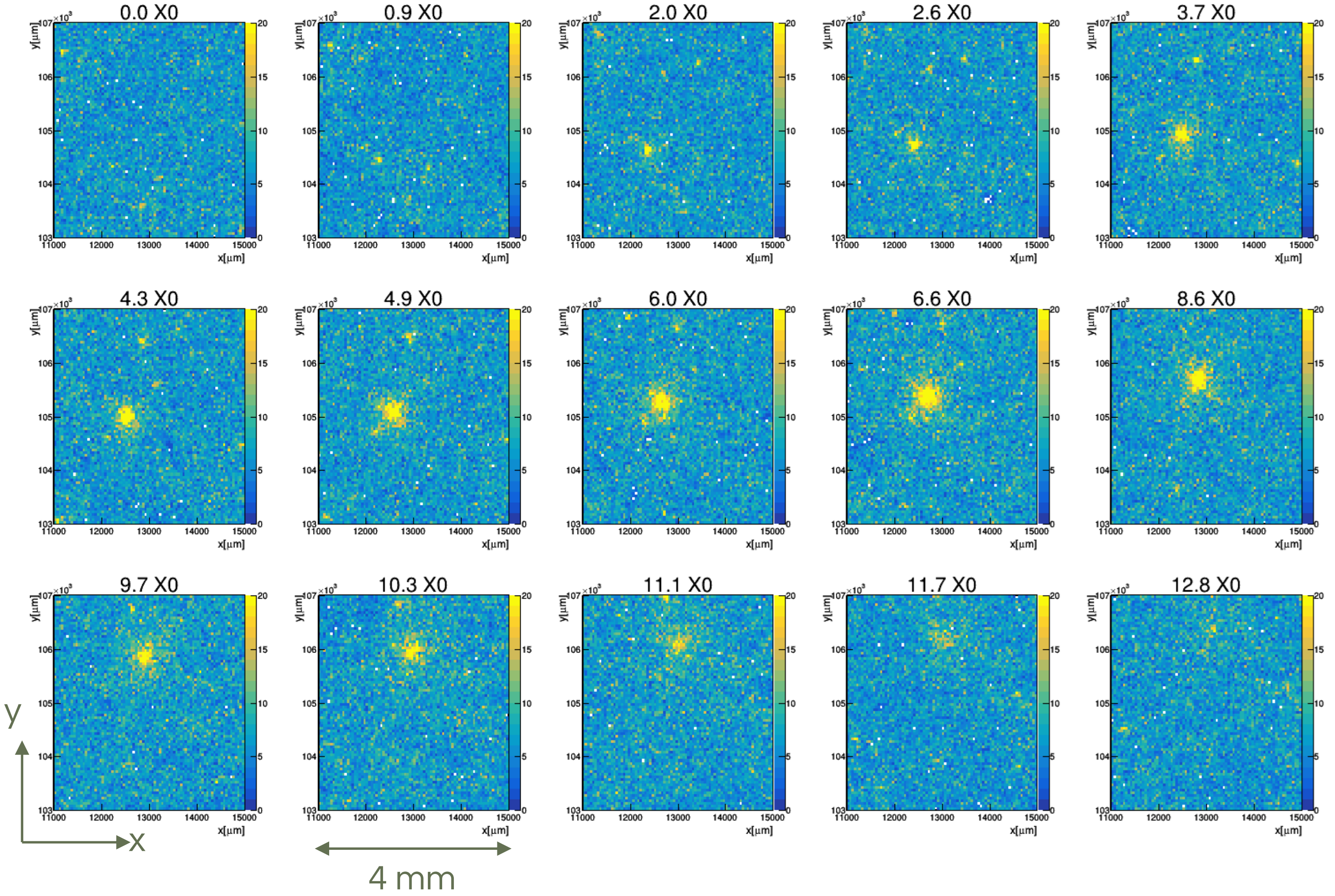
Search for ν_eCC interactions in the emulsion data

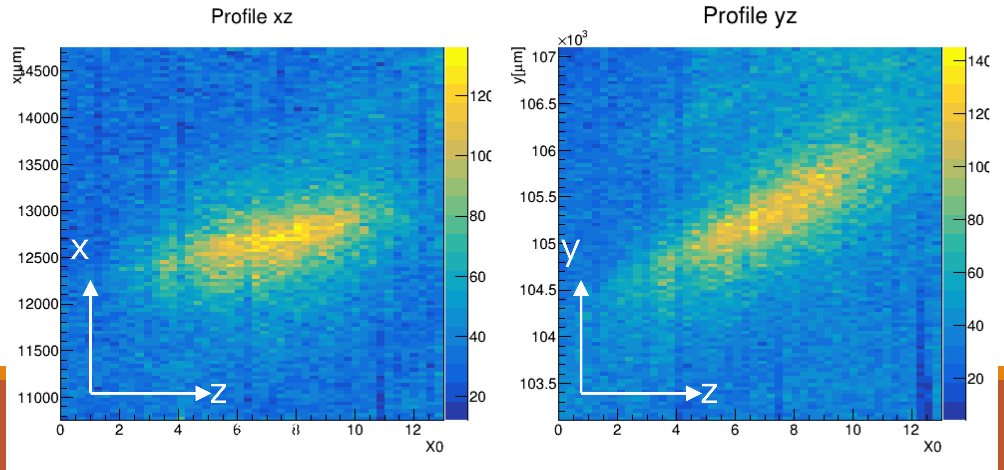
Strategy

- Identify regions of high track density in the emulsions.
- Consistent with the expectation of electromagnetic shower development.
- Search for neutral vertices associated to identified showers.

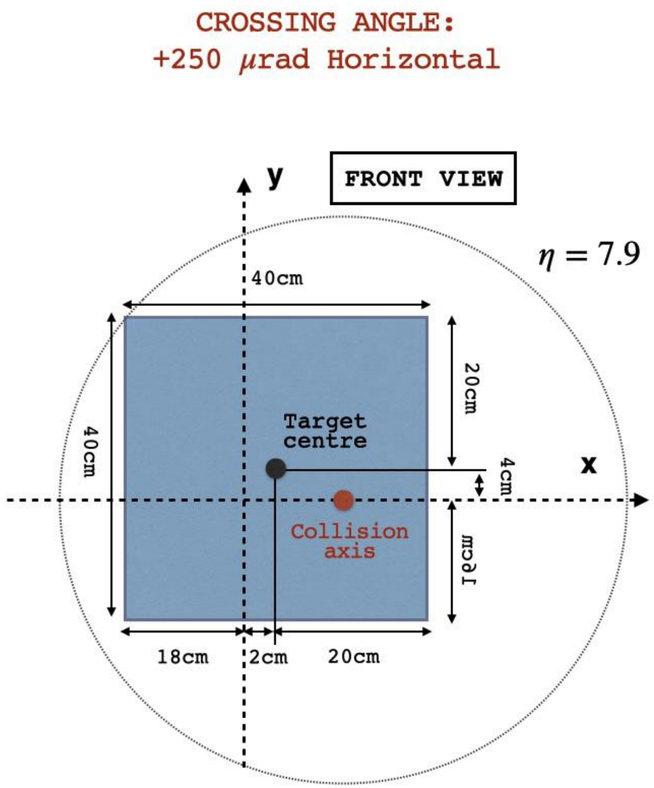
Status

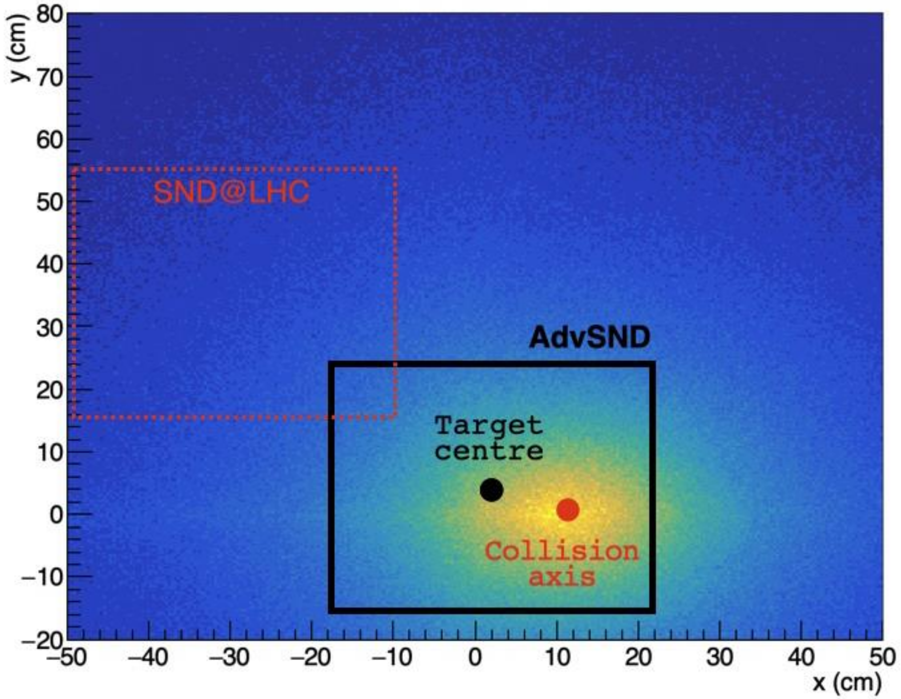
- Electromagnetic shower patterns identified.
- Vertex association ongoing.





Geometrical configuration in Run 4: off-axis with an improved acceptance to cope with statistical limitations of Run 3





Account for the crossing angle in the horizontal plane in Run 4

Main points of the upgrade:

Better transverse position while keeping the off-axis characterization (with some useful overlap with FASER)

Replace emulsion technology in the target to withstand the high μ-rate of HL-LHC without need for frequent access as it is in Run 3

Add a magnetised spectrometer for the muon charge and momentum measurement (energy and ν/ν-bar separation)

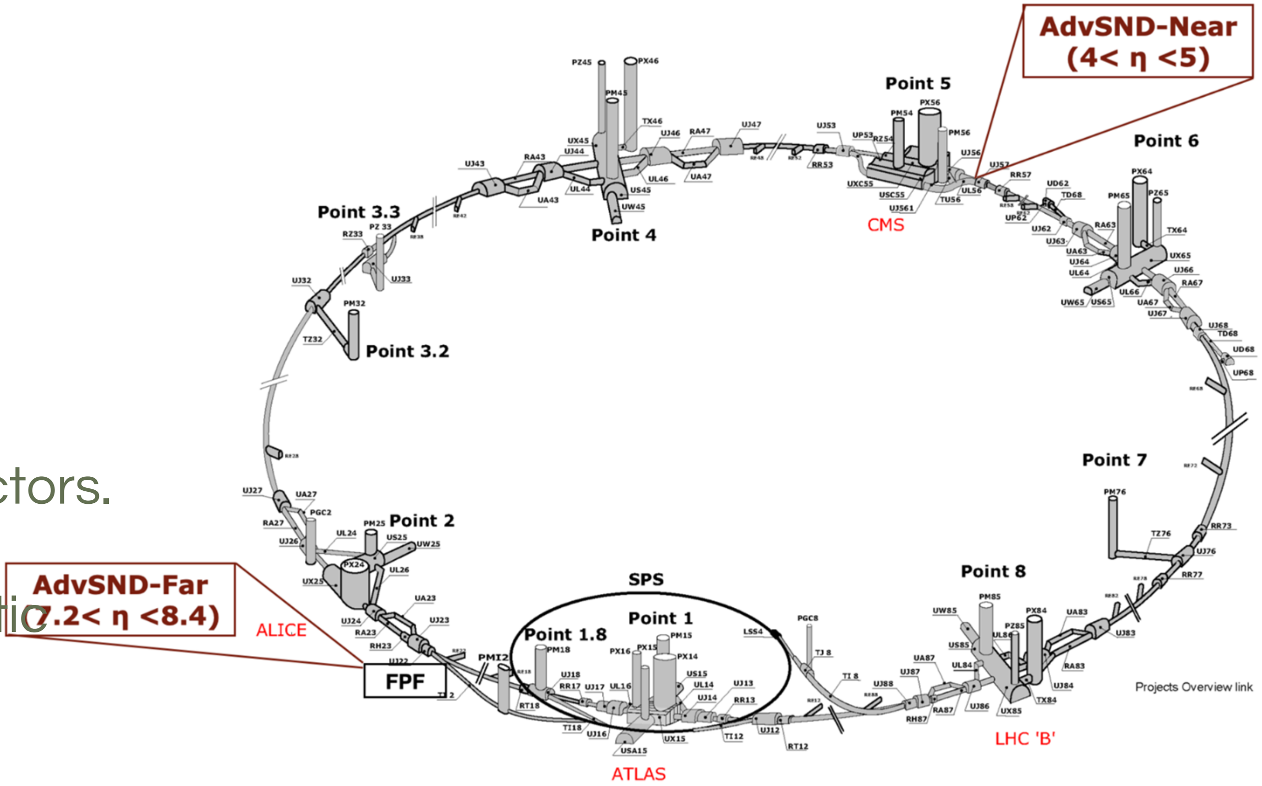
Upgrades beyond Run 3

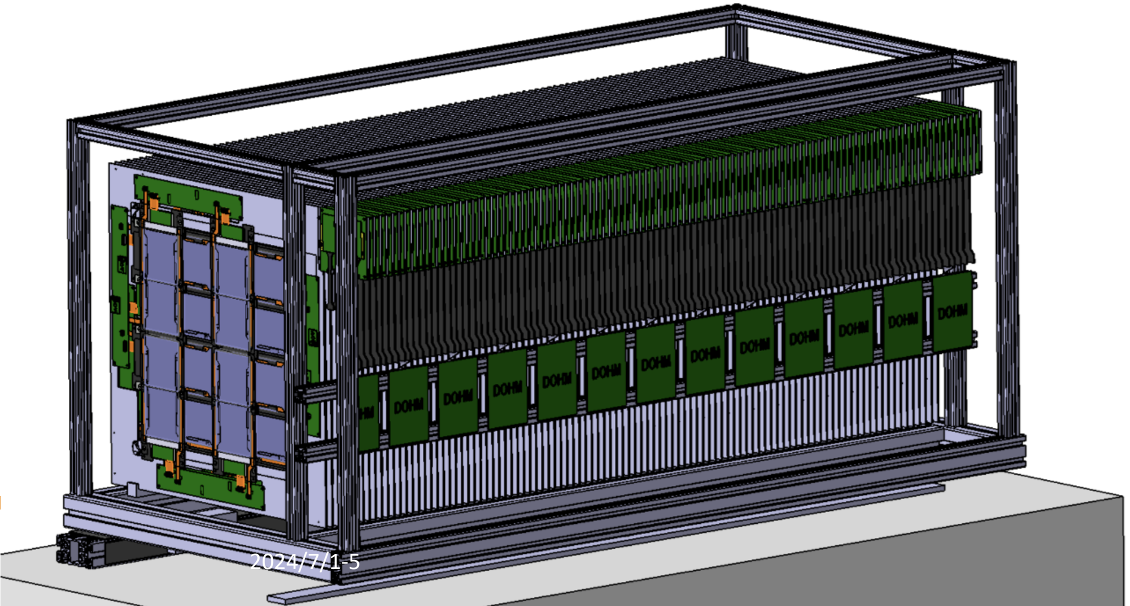
Run 4

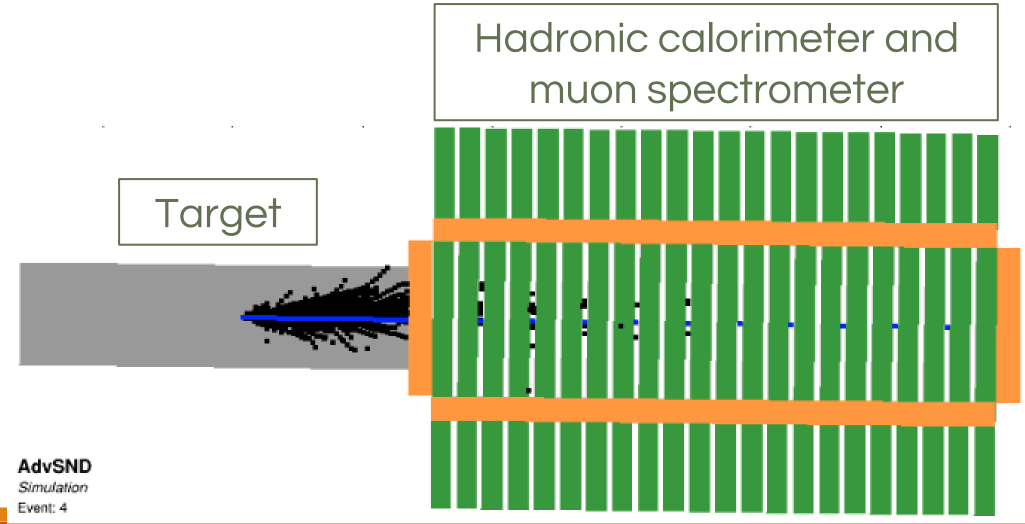
- Electronic **vertex detector**.
    - Si options under consideration.
- Iron-core **muon spectrometer**.
- Improved **hadron calorimeter** and **timing** detectors.

Beyond run 4

- **Near detector** at lower η to constrain systematic uncertainties in addition to **far detector** in the same η range as the current detector.







Summary

SND@LHC measures neutrinos in the forward region of pp collisions.

- Forward charm production, lepton flavor universality, neutrino interactions, …

The muon neutrino analysis was updated with an extended fiducial volume and 2023 data.

- The kinematic distributions of the 32 observed events are in agreement with the predictions.

Shower-like neutrino events were observed with a significance of 5.8 $\boldsymbol{\sigma}$. (Preliminary)

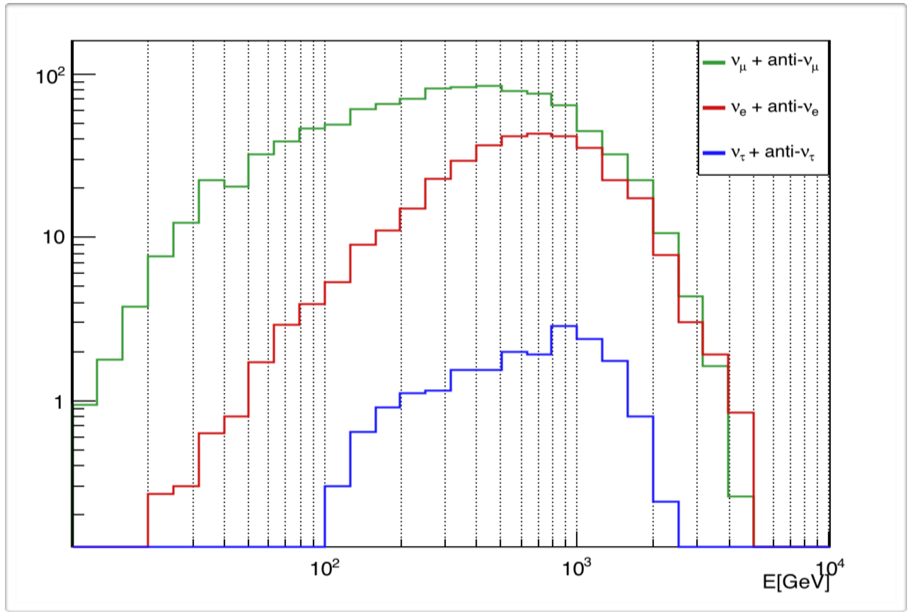
A search for electron neutrino interactions in the emulsion data is in progress.

Letter of Intent was submitted to the LHCC (CERN-LHCC-2024-007) for AdvSND in run4

NEUTRINO DIS INTERACTIONS

$7.2 < \eta < 8.4$, $0.4 < \vartheta < 1.5$ mrad

- **DPMJET3** embedded in FLUKA for neutrino production @ LHC
- Particle propagation towards the detector through the LHC **FLUKA** model
- **GENIE** used to simulate neutrino interactions in the detector target



Interacting Neutrinos

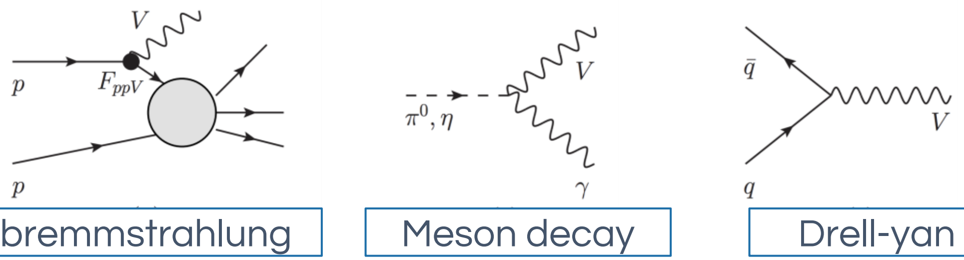
- Expectations in 290 fb^{-1} (43/57 upward/downward crossing angle)

	CC neutrino interactions		NC neutrino interactions	
Flavour	⟨E⟩ [GeV]	Yield	⟨E⟩ [GeV]	Yield
ν_μ	450	1028	480	310
$\bar{\nu}_\mu$	480	419	480	157
ν_e	760	292	720	88
$\bar{\nu}_e$	680	158	720	58
ν_τ	740	23	740	8
$\bar{\nu}_\tau$	740	11	740	5
TOT		1930		625

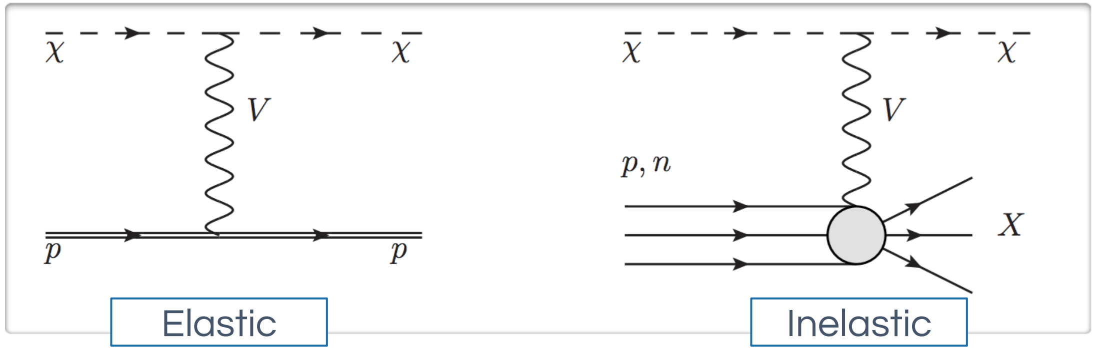
~ 30 ν_τ CC interactions expected

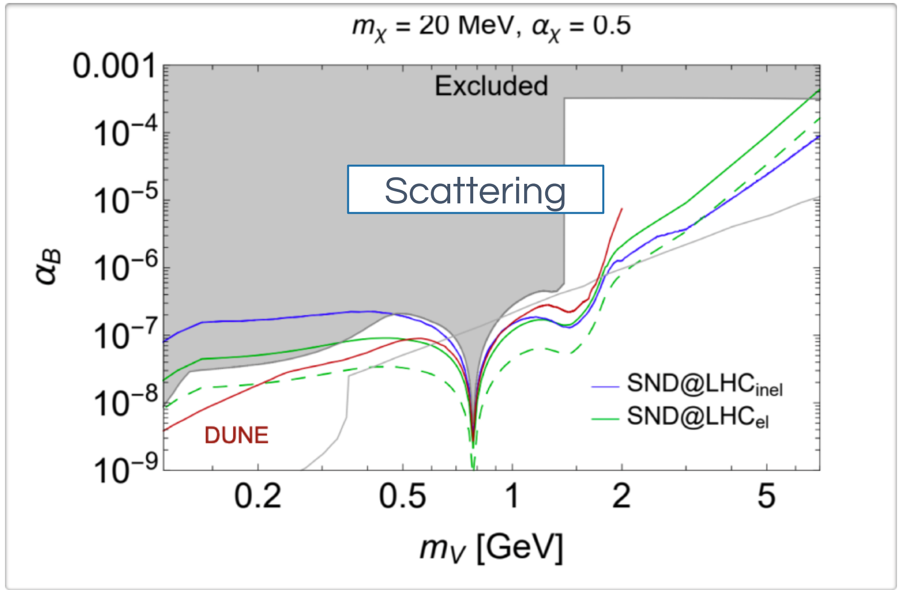
Feebly interacting particles

- SND@LHC is sensitive to new **dark sector** particles.

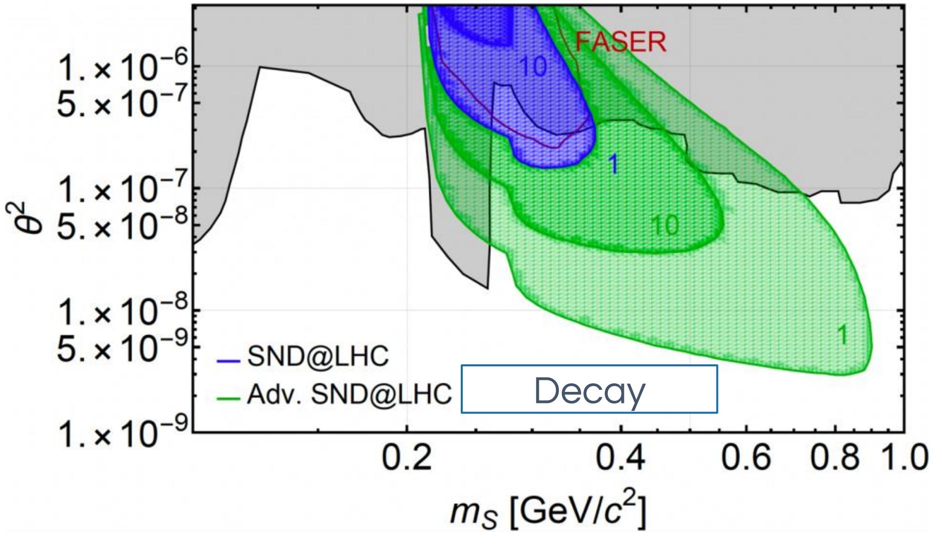


  - **Scattering** in the detector.
    - E.g., scalars interacting with nucleons via a leptophobic portal.





  - **Decaying** in the detector.
    - Dark scalars, heavy neutral leptons or dark photons decaying into a pair of charged tracks.



J. High Energ. Phys. **2022**, 6 (2022)

Feebly interacting particles

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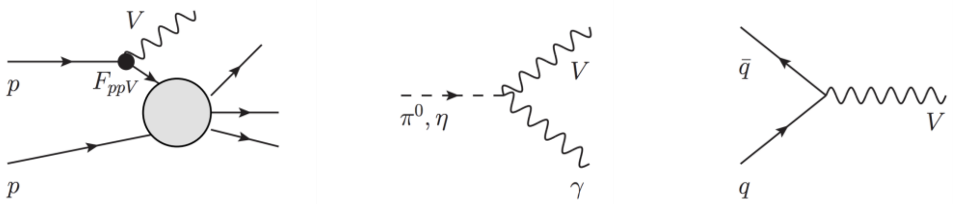
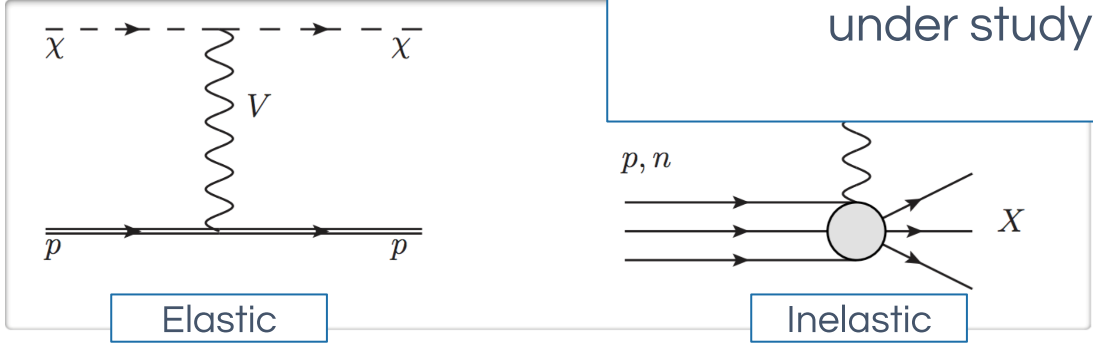


p bremmstrahlung | Meson decay | Drell-yan

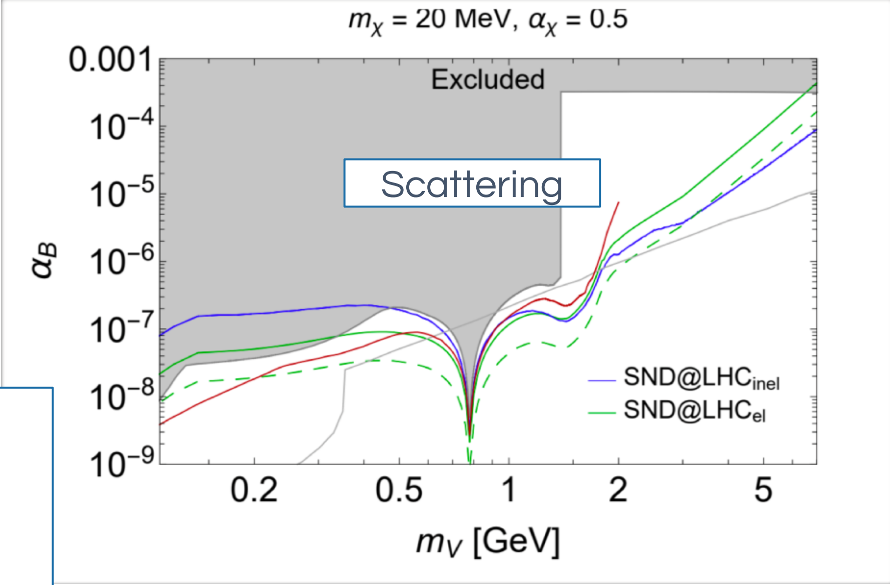
  - **Scattering** in the det
    - E.g., scalars in
      via a leptophol

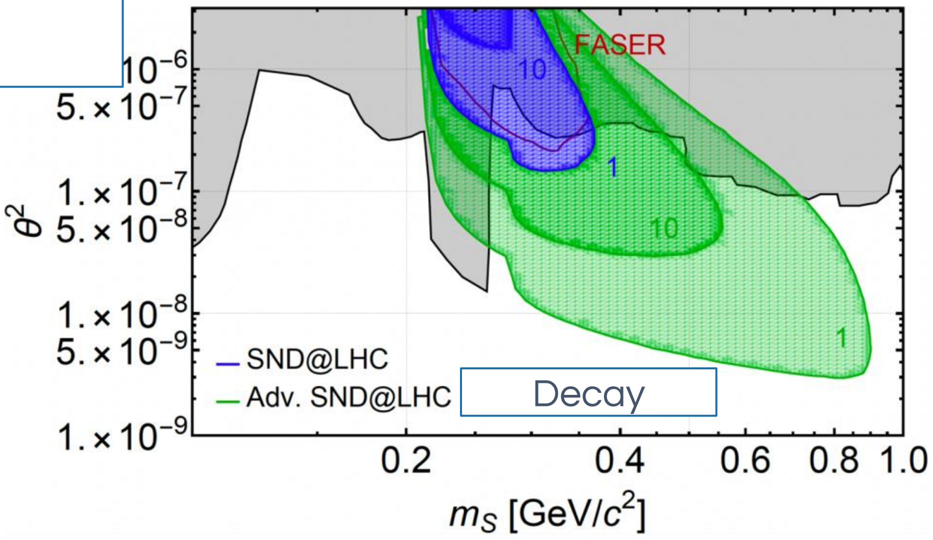
Signal efficiencies and backgrounds (neutrinos!) under study.



Elastic | Inelastic

  - **Decaying** in the detector.
    - Dark scalars, heavy neutral leptons or dark photons decaying into a pair of charged tracks.





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