LHC

Scattering and Neutrino Detector at the LHC

SND@LHC status and results

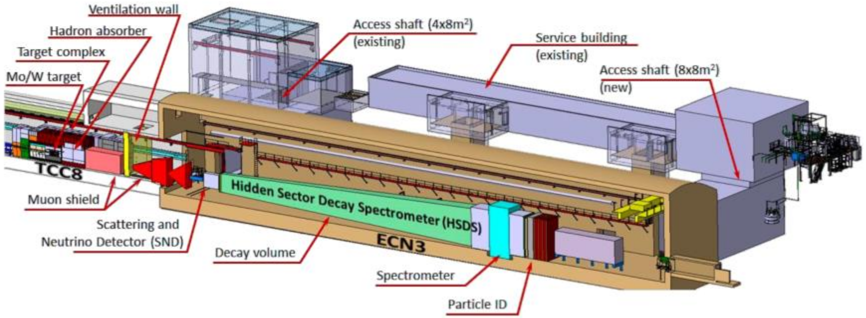
Valeri Tioukov

on behalf of SND@LHC collaboration

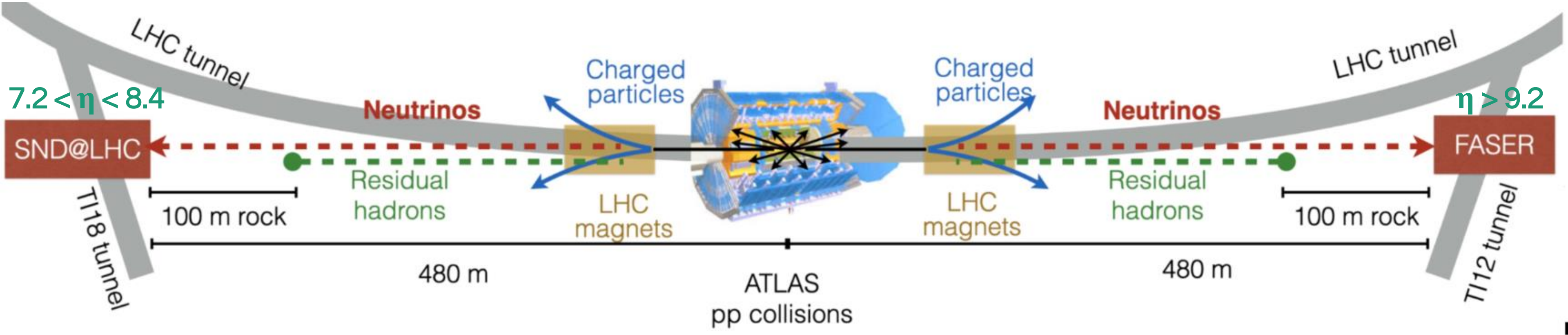
Neutrino experiments at CERN

SND@LHC taken data since 04/2022

SHiP proposed in 2015, approved in 2024
SPS beam dump



FASER taken data since 2022



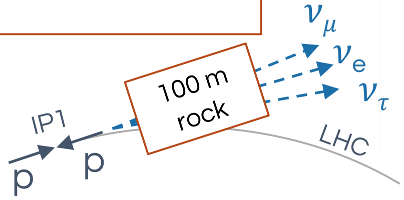
Scattering and Neutrino Detector at the LHC

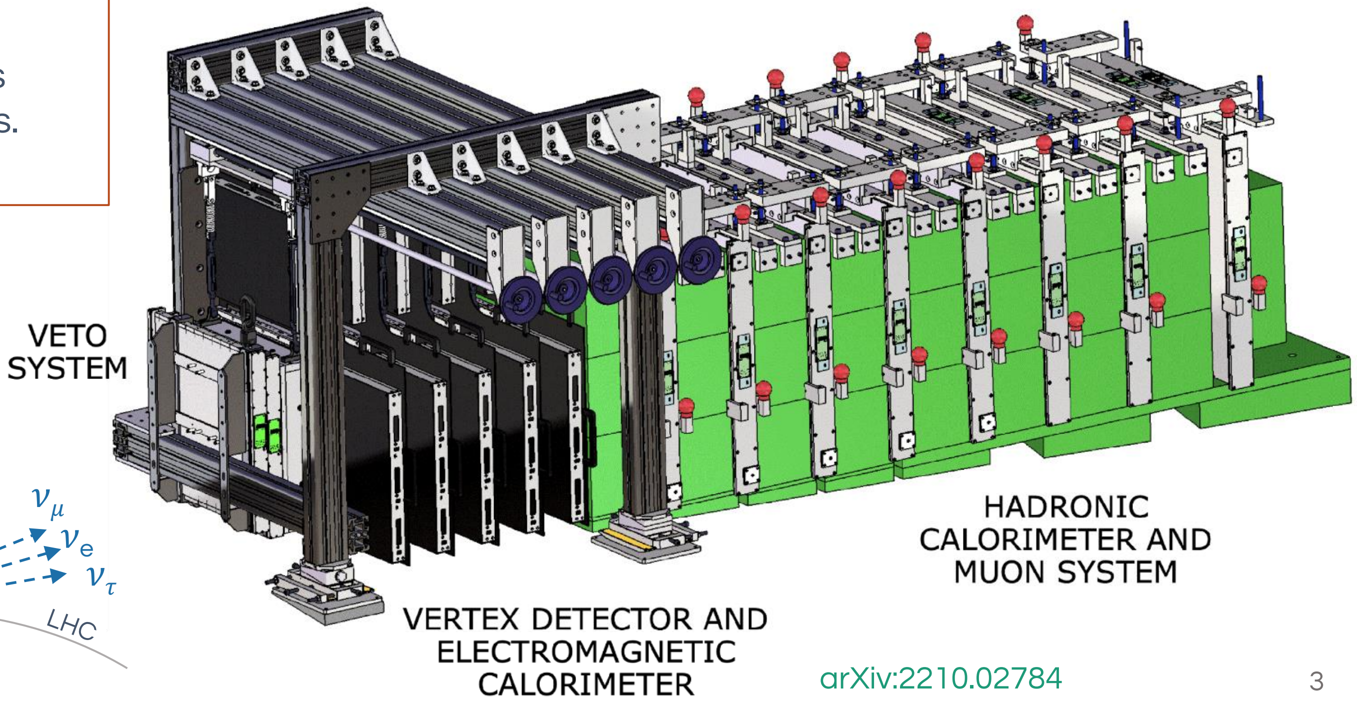
Veto system
2 (2022 – 2023) / 3 (2024 -) 1 cm thick scintillator planes.

Off-axis: $7.2 < \eta < 8.4$
Enhances the flux with charm origin.

Target, vertex detector and ECal
830 kg tungsten target.
Five walls x 59 emulsion layers
+ five scintillating fibre stations.
$84\ X_0$, $3\ \lambda_{int}$

HCal and muon system
Eight 20 cm Fe blocks
+ scintillator planes.
Last 3 planes have finer granularity to track muons.
$9.5\ \lambda_{int}$





arXiv:2210.02784

SND@LHC physics goals

QCD

- Decays of **charm** hadrons contribute significantly to the neutrino flux in SND@LHC.
  ⇒ Measure **forward charm production** with ν_es.
  ⇒ Constrain **gluon PDF** at very **small x**.

Flavour

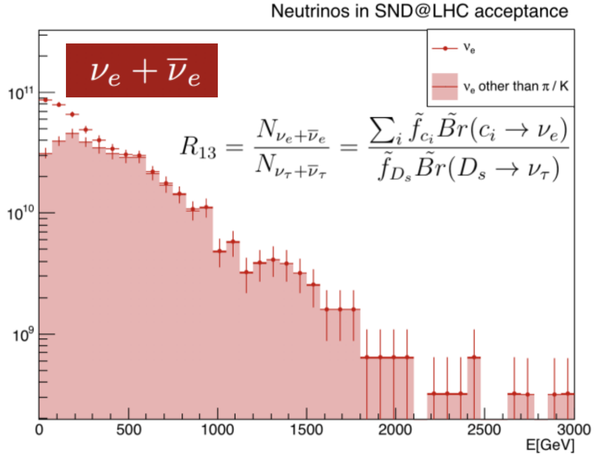
- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality.**
  - Charm parentage leads to partial cancelation of flux uncertainties

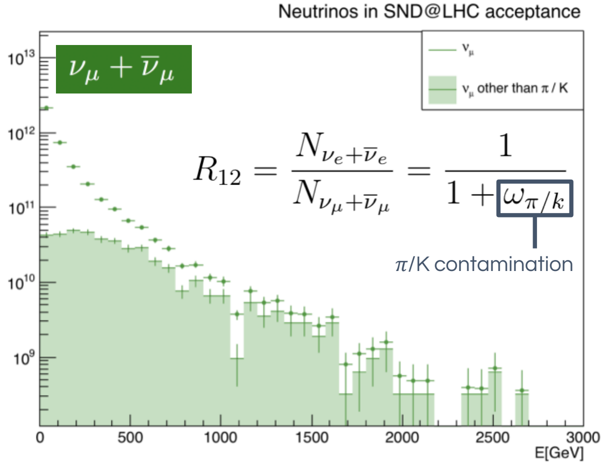
Neutrino interactions

- Measure **ν interactions** in unexplored ~TeV energy range.
- Large yield of ν_τ will likely double existing data.
  - About 20 events observed by DONuT and OPERA.

Beyond the Standard Model

- Search for **new**, feebly interacting, **particles decaying** within the detector or **scattering** off the target.

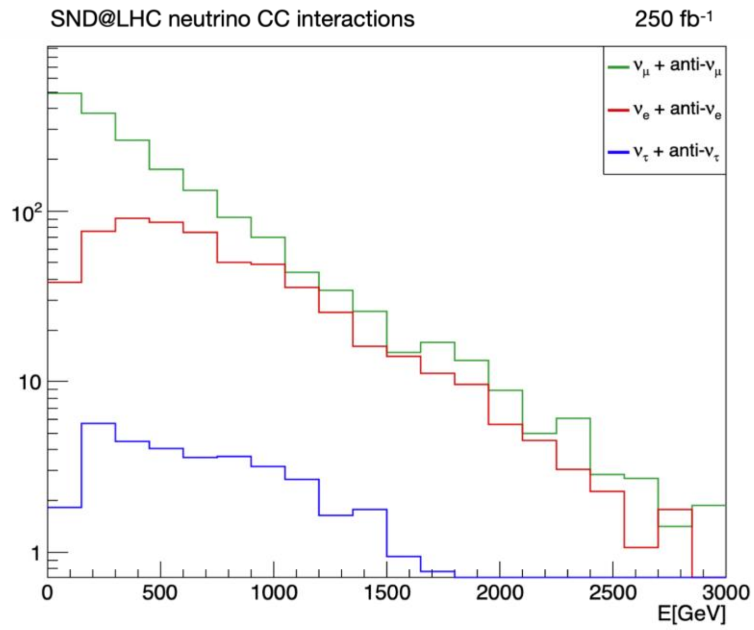




Expected neutrino event rates

- Model neutrino production in pp collisions with **DPMJET**.
- Propagation to SND@LHC with **FLUKA** model of the LHC.
- GENIE neutrino interaction model.
- Neutrino interactions in SND@LHC / 250 fb^{-1}:
  - $\nu_\mu + \bar{\nu}_\mu$ charged-current: 1270
  - $\nu_e + \bar{\nu}_e$ charged-current: 390
  - $\nu_\tau + \bar{\nu}_\tau$ charged-current: 30

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	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

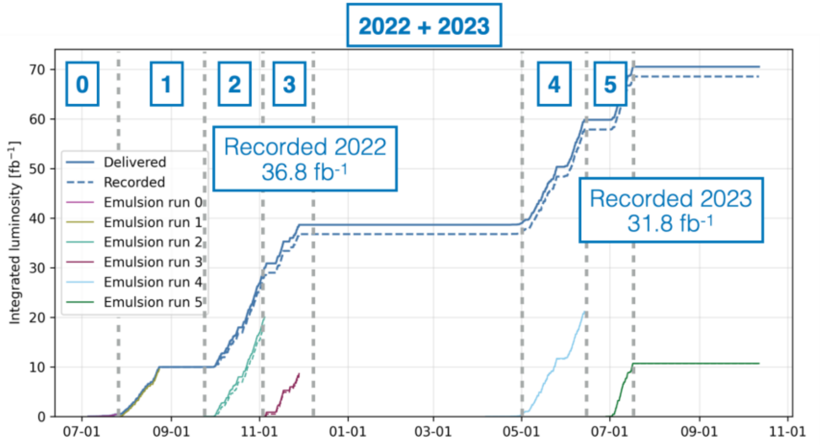


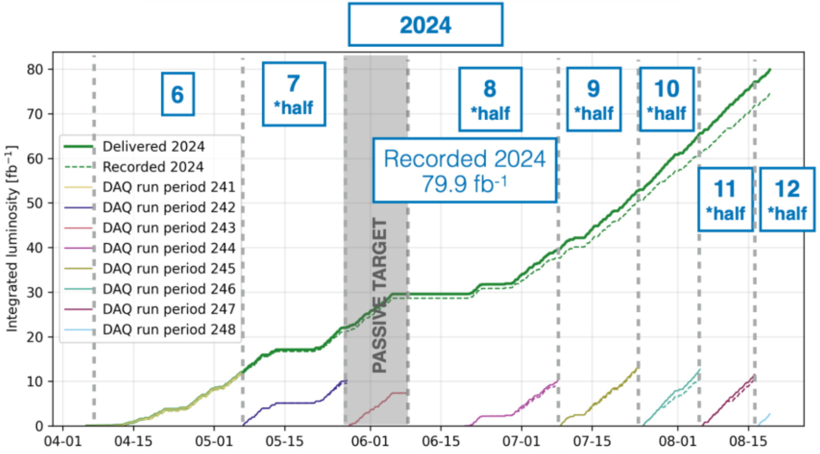
pp collision data

- **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 < 4x10^5 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

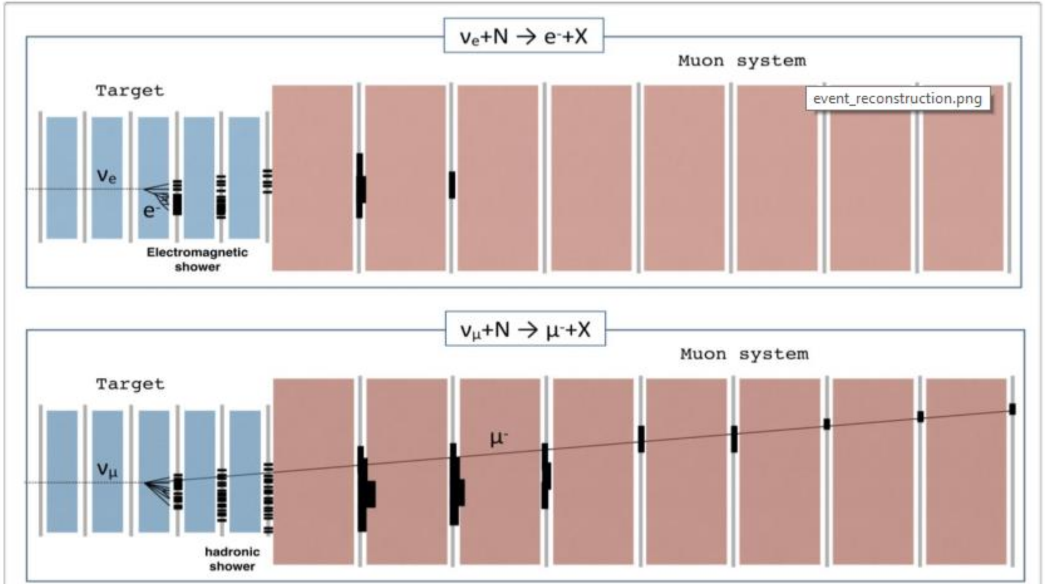
  79.9 fb^{-1} of proton-proton collisions recorded by the electronic detectors up to now
  - Seven emulsion target replacements performed, nine expected



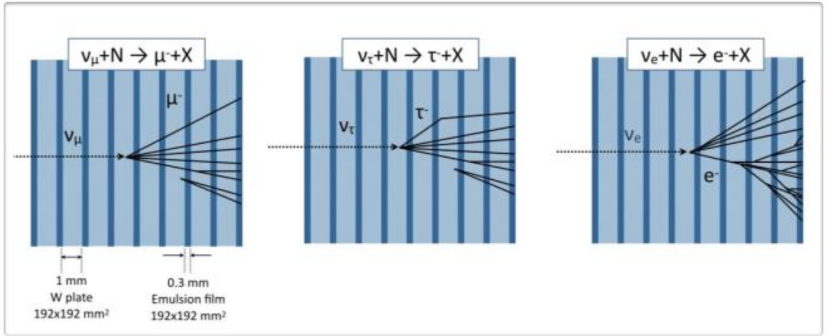


EVENT RECONSTRUCTION

- **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)

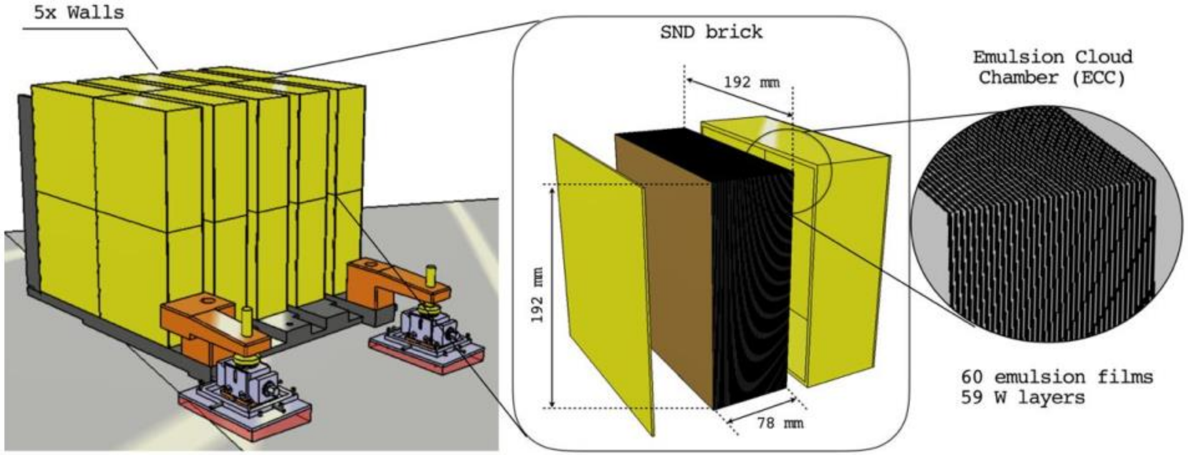


- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement



Flavor identification by ECC

ECC target



Number of bricks : 20

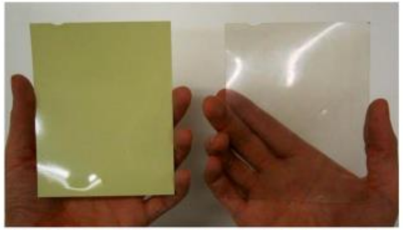
- walls: 5
- Bricks per wall : 4

Brick surface: 192x192 mm^2

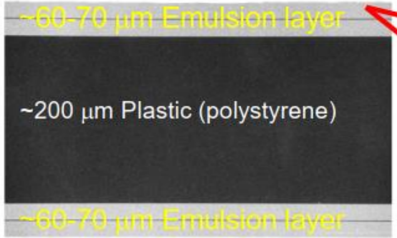
- Brick thickness: 78 mm
- 60 films + 59 W plate

Passive material : Tungsten

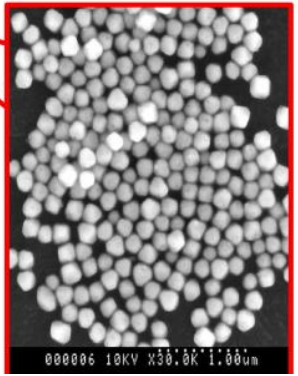
- Total mass : 830 kg
- Total emulsion surface : 44 m^2



Before and after development

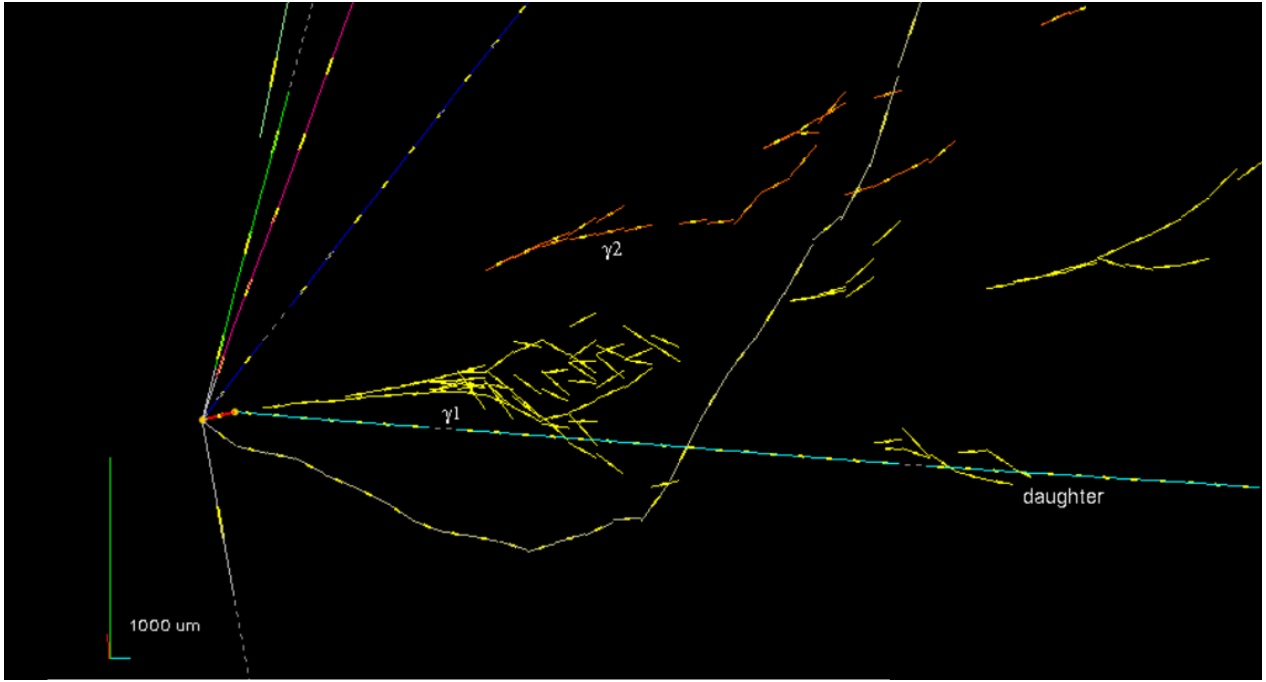


film cross section



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

Tau neutrino detection in OPERA ECC



Physics Letters B691 (2010) 138

OPERA conditions:
Low track density (10/mm^2)
Low momentum 1-20 Gev

Scanning System:
Position resolution 2-3 µm
Angular resolution 3 mrad

Enough for OPERA!

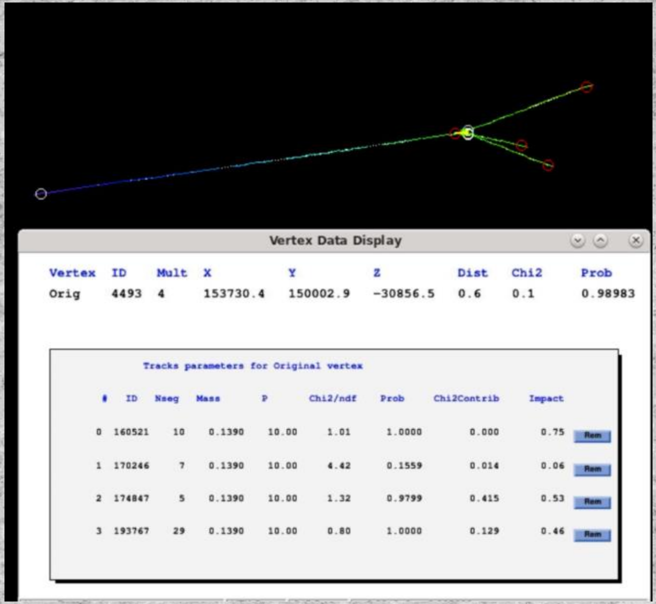
SND@LHC:
Track density 4000/mm^2
Momentum O(100) GeV
Tracks mainly parallel (beam)

Scanning System resolution become a problem!

Performance of the emulsion detector

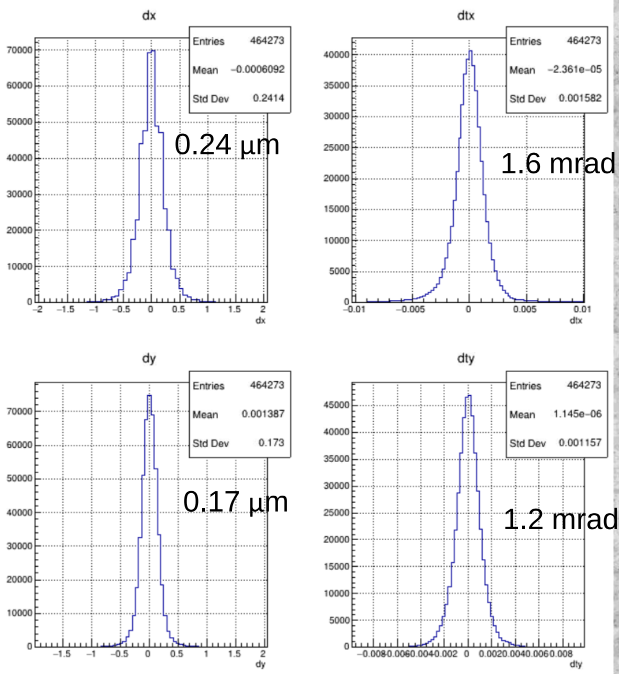
complete revision of the calibration and analysis chain in 2024

Reached values for high momentum tracks:
Position resolution 0.2 µm (track)
Angular resolution 1.5 mrad (segment)

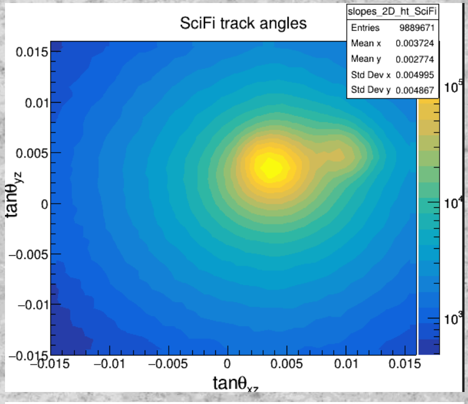


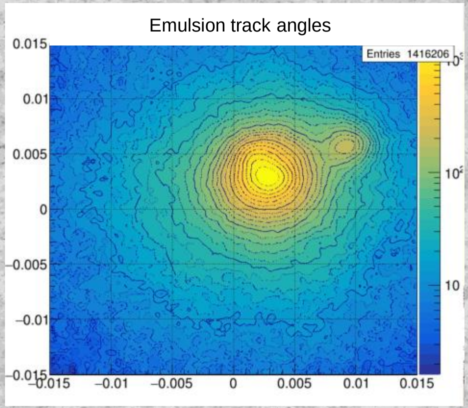
Scanning and reconstruction is ongoing

We use pass-through muons for precise local calibration of emulsion data



"one out of five" method used for residuals estimation





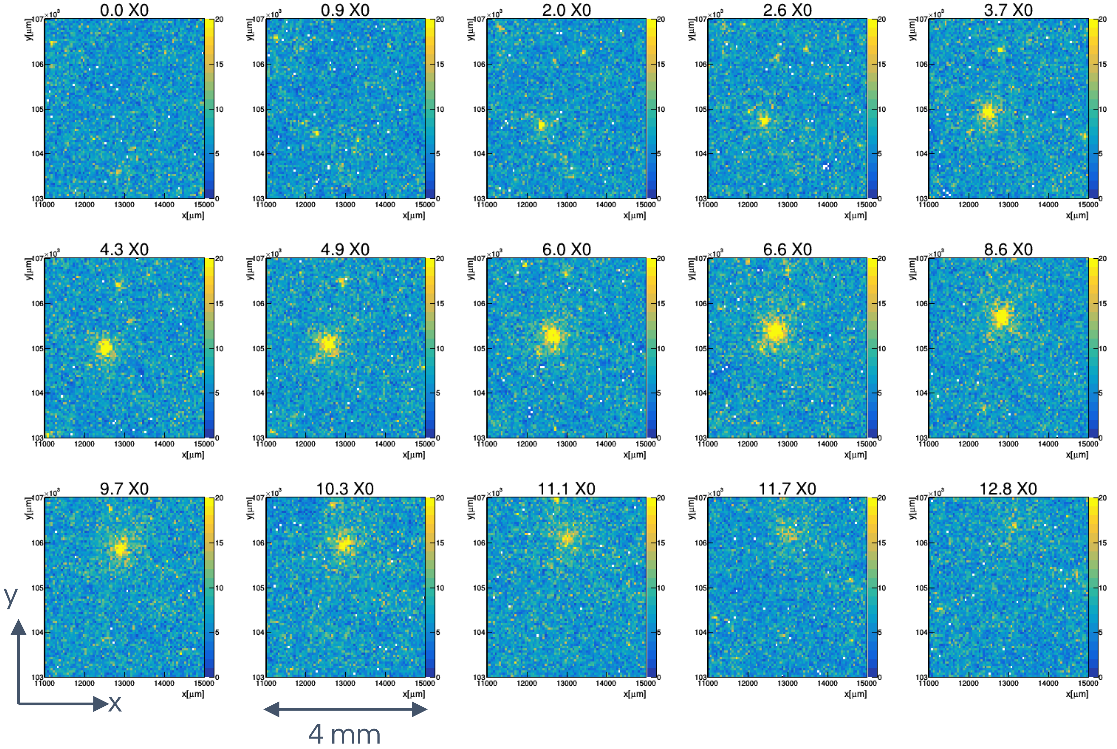
Search for ν_eCC interactions in the emulsion data

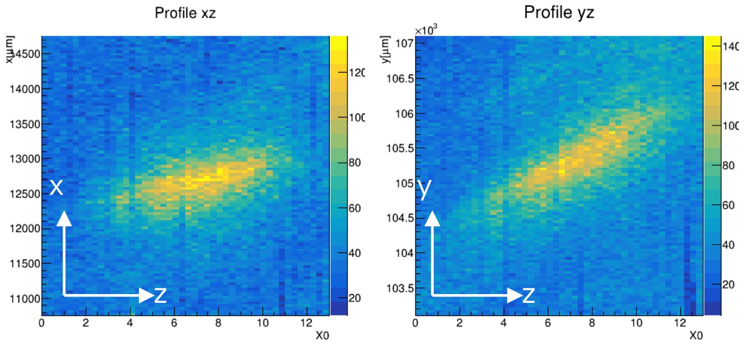
Strategy

- 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.

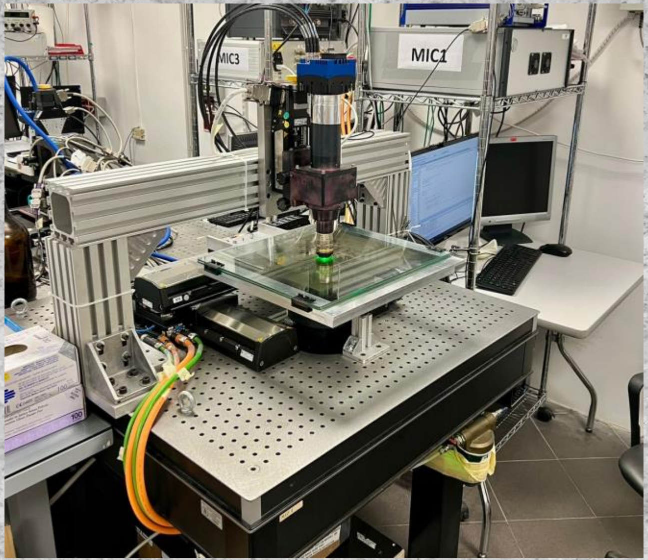


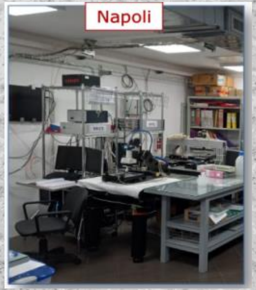


Emulsion scanning systems upgrades

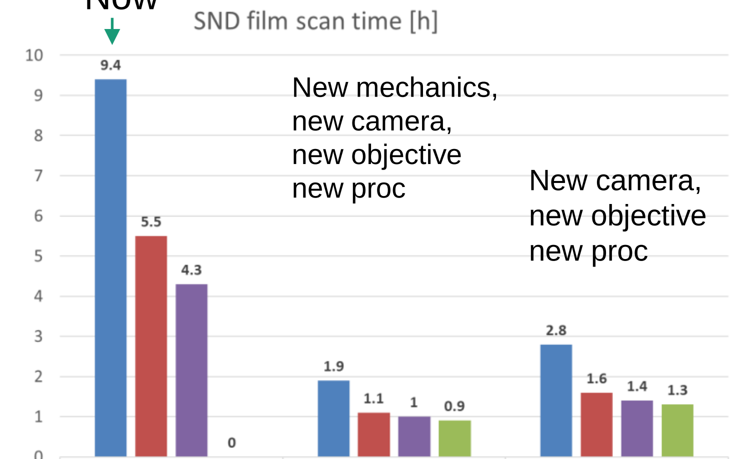
Upgraded prototype with
new mechanics&control
new camera, new objective

9 SS
Dedicated to
SND@LHC
+1(Chile)





Now



New mechanics,
new camera,
new objective
new proc

New camera,
new objective
new proc

Now →

	Standard mic	Na-mic1	Na-mic4
Stop&Go	9.4	1.9	2.8
Continuous Motion	5.5	1.1	1.6
Cont. Mot. Piezo Z	4.3	1	1.4
Inclined Motion	0	0.9	1.3

Muon neutrino analysis update

- Last year at Moriond, we reported the observation of 8 muon neutrino candidates in the 2022 data, with a significance of 6.8 σ.

Phys. Rev. Lett. 131, 031802

New this year

Updated analysis with 2023 data and extended fiducial volume.

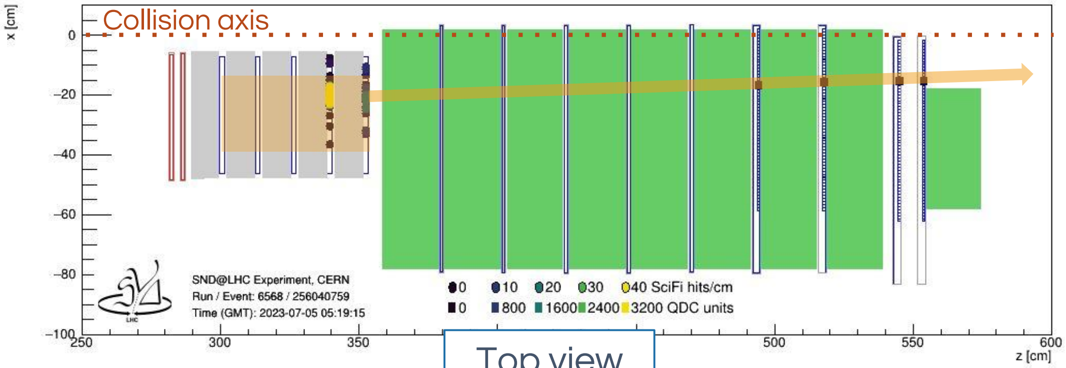
Event selection

Fiducial volume

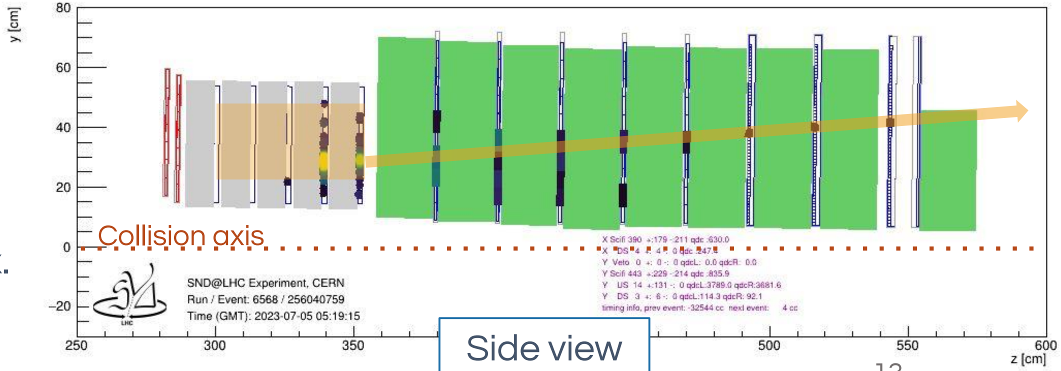
- Reject events in first wall.
  - Previously used only walls 3 and 4.
- Reject side-entering backgrounds.
- Signal acceptance: 18%
  - Up from 7.5%.

Muon neutrino identification

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



Top view



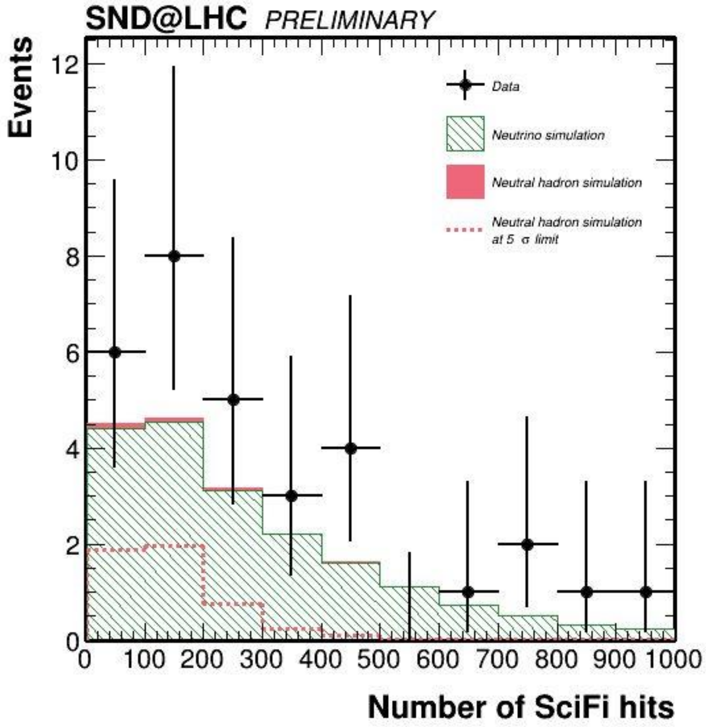
Side view

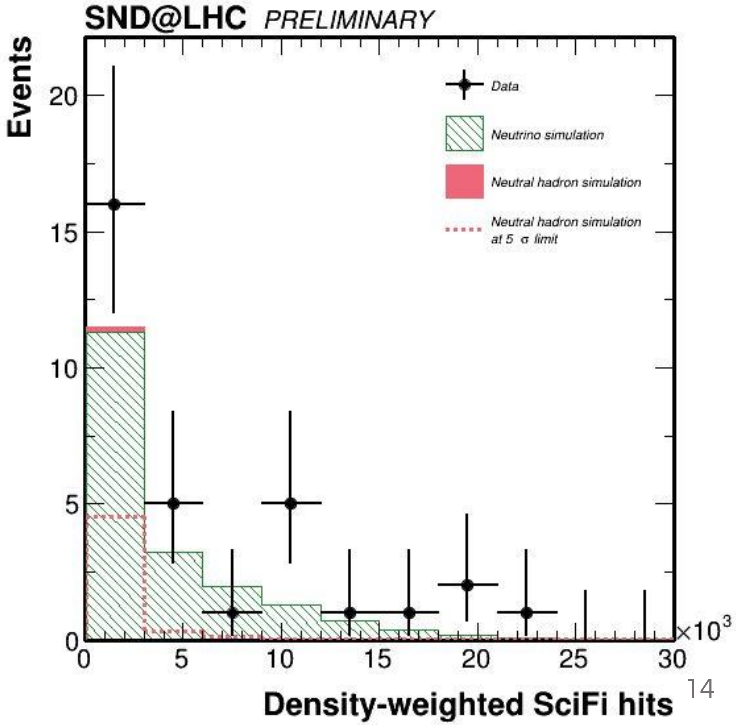
Updated muon neutrino results

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

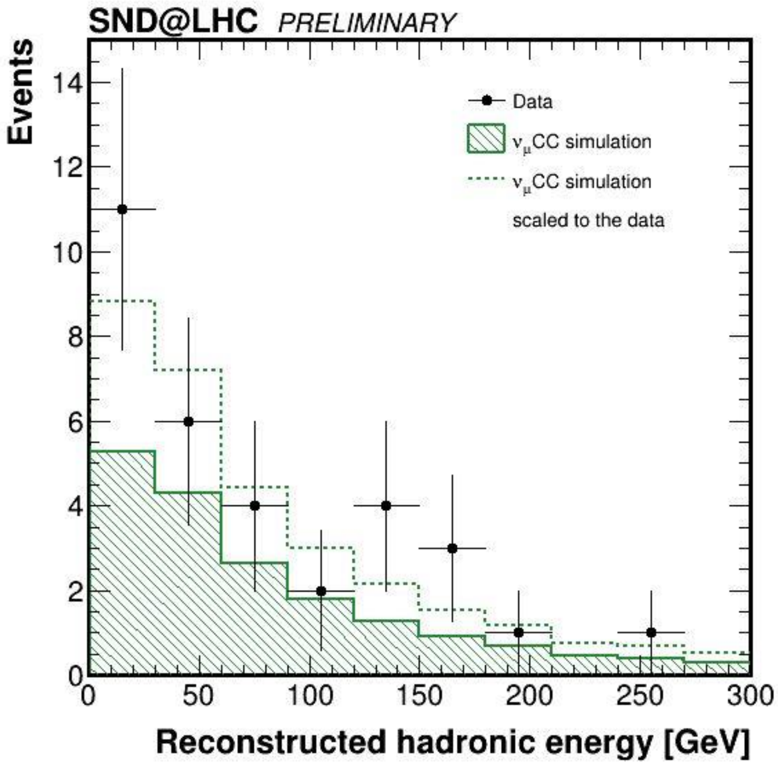
- Signal: 19.1± (4.1sist)
- Neutral hadrons: 0.25 ± 0.06

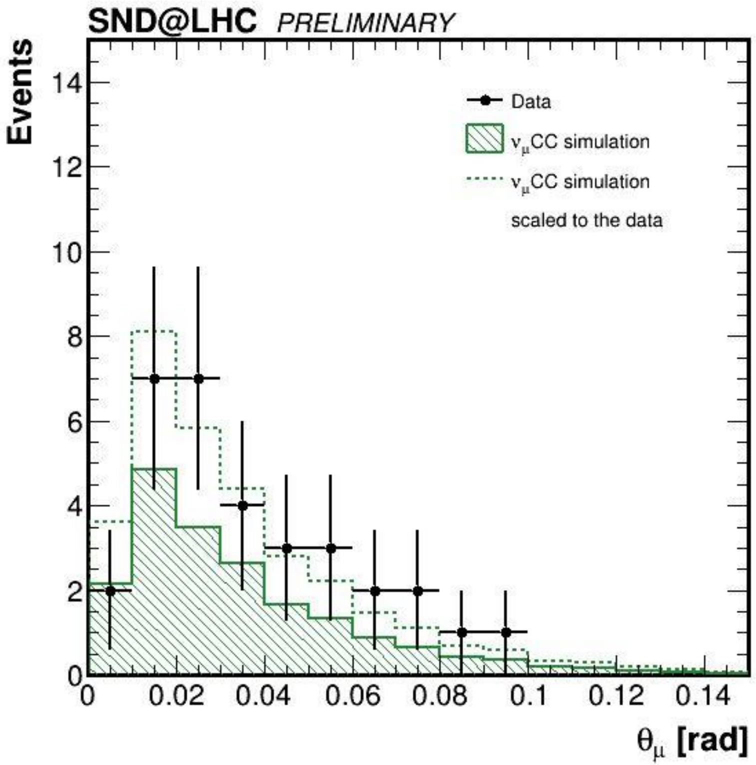
Number of events observed: 32





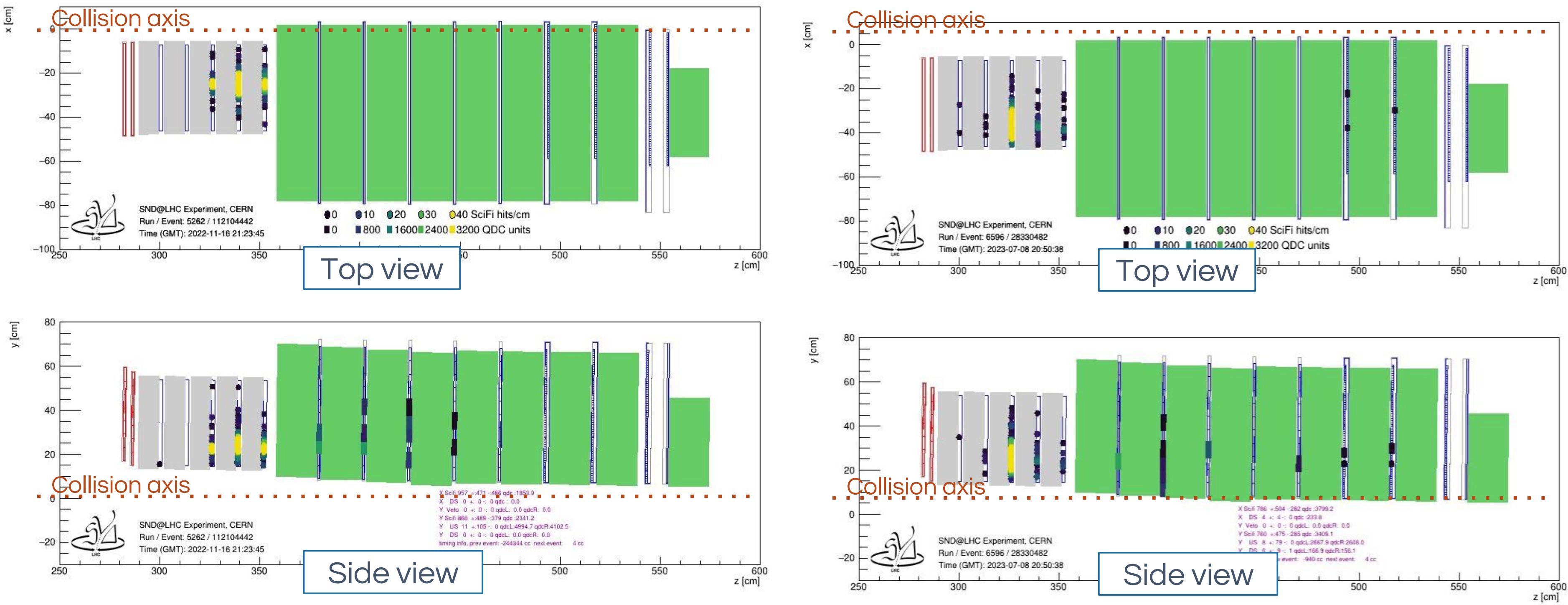
Muon neutrino event kinematics





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

0μ neutrino candidates



Search for shower-like (0μ) neutrino events

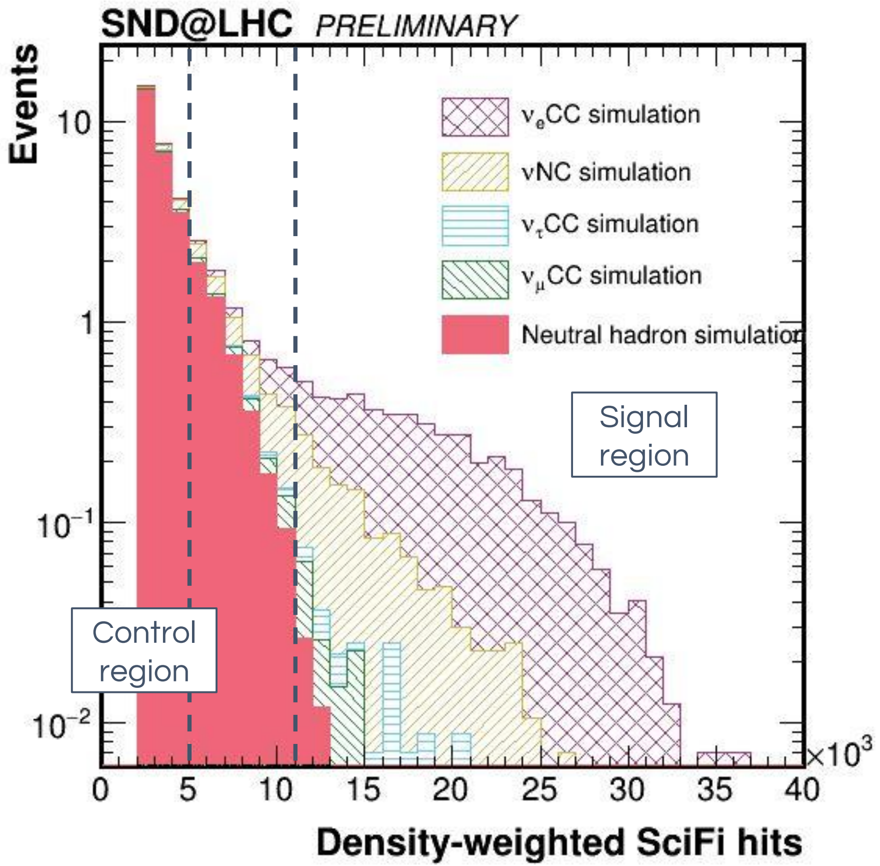
Signal: ν_eCC and NC interactions

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 > 11×10^3.
    - Optimized for maximum expected significance
- Signal selection efficiency: 42%



Observation of 0μ events in SND@LHC

Neutral hadron background

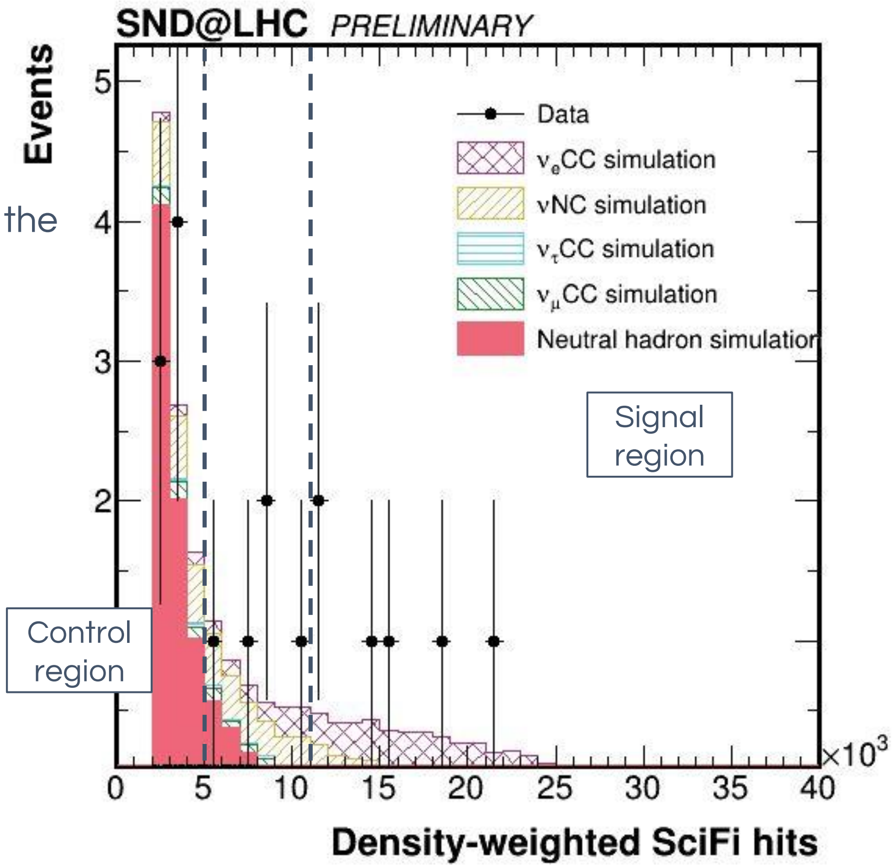
- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
  - Observed neutral hadron background is ⅓ of the predicted value.
- Events **expected in signal region: 0.01**

Neutrino background

- Muon neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC1μ 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**



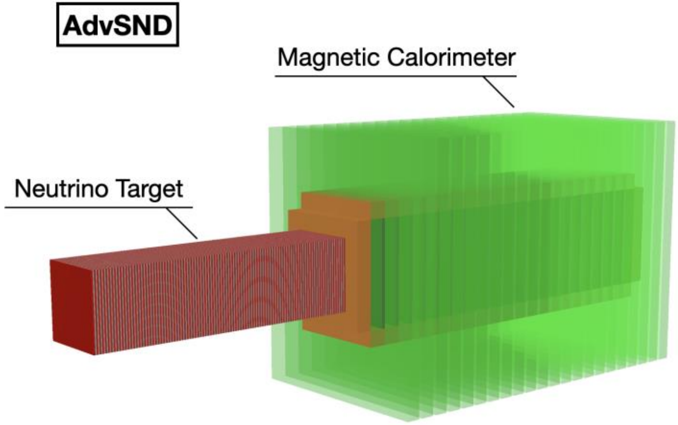
Number of events observed: 6
Observation significance: 5.8 σ

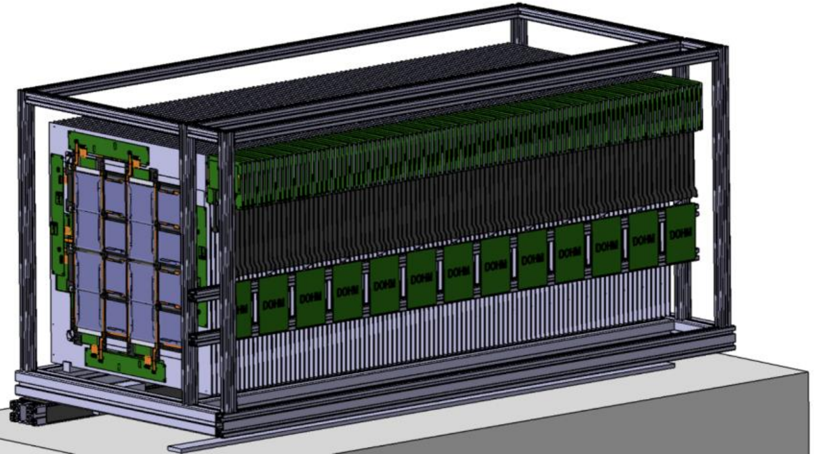
Paper in preparation

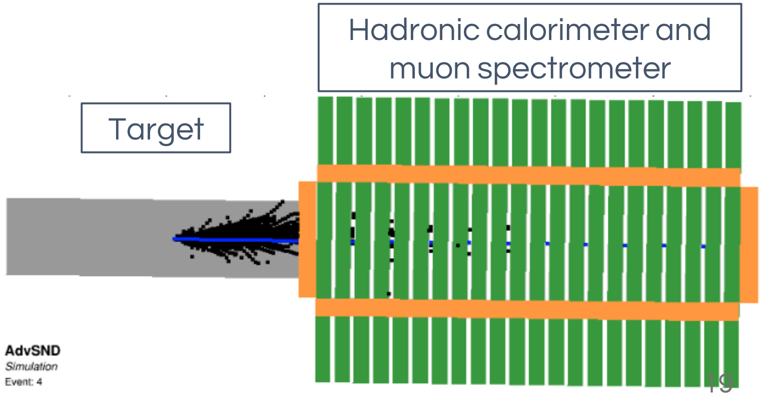
Upgrades beyond Run 3

HL-LHC

- Electronic **vertex detector.**
  - Si options under consideration.
- Iron-core **muon spectrometer (1.75 T)**
- Improved **hadron calorimeter** and **timing** detector.
- The expected statistics 3000 fb^{-1}







Conclusion

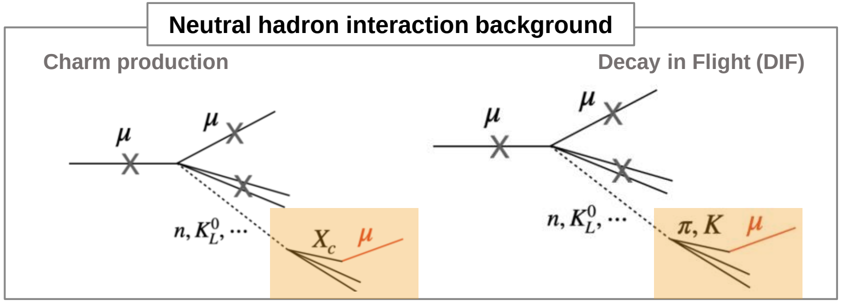
- SND@LHC measures neutrinos in the forward region of pp collisions
  - Forward charm production, lepton flavor universality, neutrino interactions, etc
- The muon flux reaching the detector was measured to validate the background model (Eur. Phys. J. C (2024) **84**: 90)
- The muon neutrino analysis 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)
- The detector performance is improved in 2024 thanks to HW and analysis upgrades
- 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

Backup

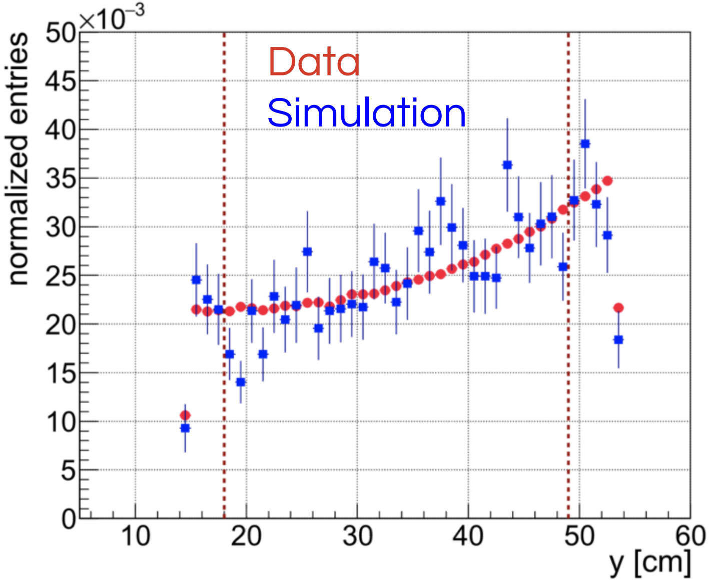
Muon flux measurement

Eur. Phys. J. C (2024) **84**: 90

- Backgrounds to neutrino signals in SND@LHC are mainly due to muon interactions in the tunnel walls.
- Precise measurements of the muon flux allow for validating and constraining our background model.



:= within SND@LHC acceptance



System	Muon flux [10^4 fb/cm^2] same fiducial area
SciFi	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$
DS	$2.02 \pm 0.01(\text{stat.}) \pm 0.08(\text{sys.})$

- Measurements with the SciFi tracker, downstream muon system and emulsion detectors give consistent results.

Detector upgrades in 2024

Veto detector upgrade

- Installed a 3rd plane veto plane in the detector.
    - Additional redundancy to mitigate the impact of detector inefficiency.
- Floor was excavated so that veto system could be lowered.
    - Better coverage of the target.
- This upgrade will allow for a significant increase of the fiducial volume used in neutrino data analyses.

New muon telescope

- Technology demonstrator: sealed resistive-plate chambers.
- Will allow for measuring the muon flux outside of the SND@LHC acceptance.
    - Further validation of the background model.

SND@LHC detector location

Strategy:

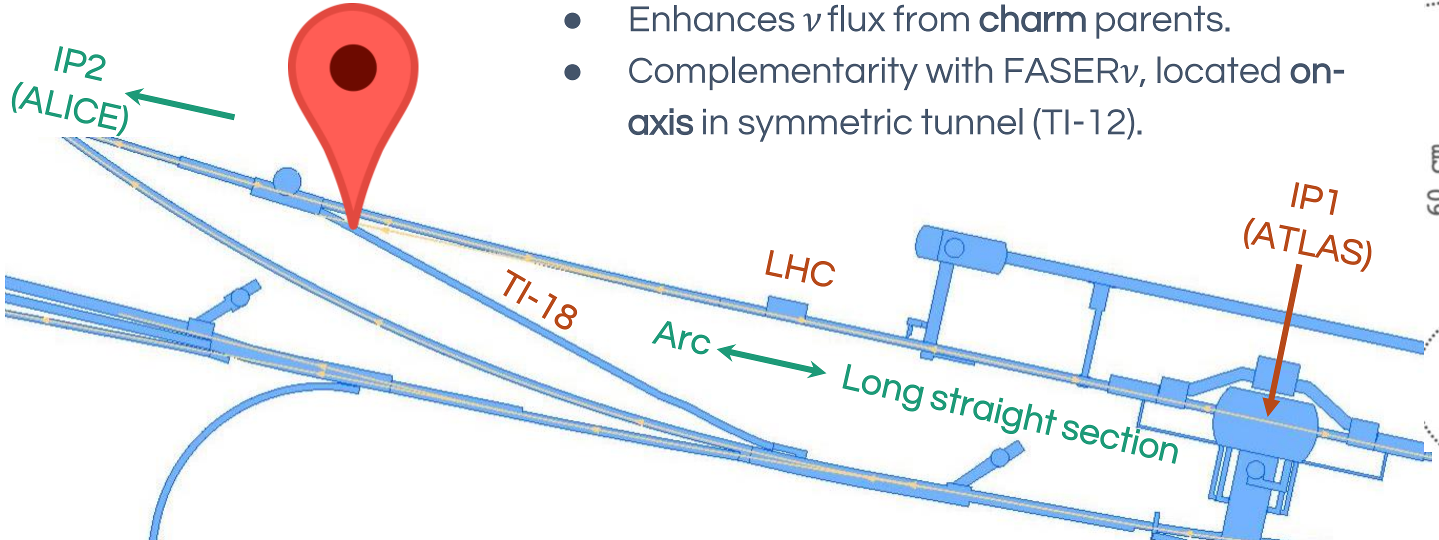
- Existing site (avoided major civil engineering).
- Enough material to shield against collision debris.
- Use LHC magnets to deflect charged particles.

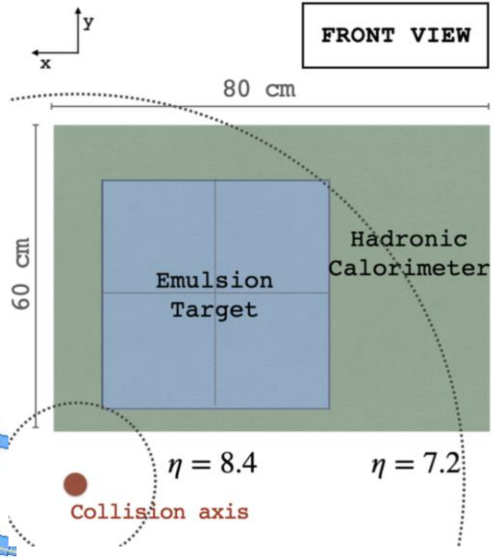
TI-18 location:

- Old LEP positron transfer line tunnel.
- 480 m away from IP1.
- 100 m of rock between detector and IP1.
- Downstream of dipole magnets.

Off-axis position:

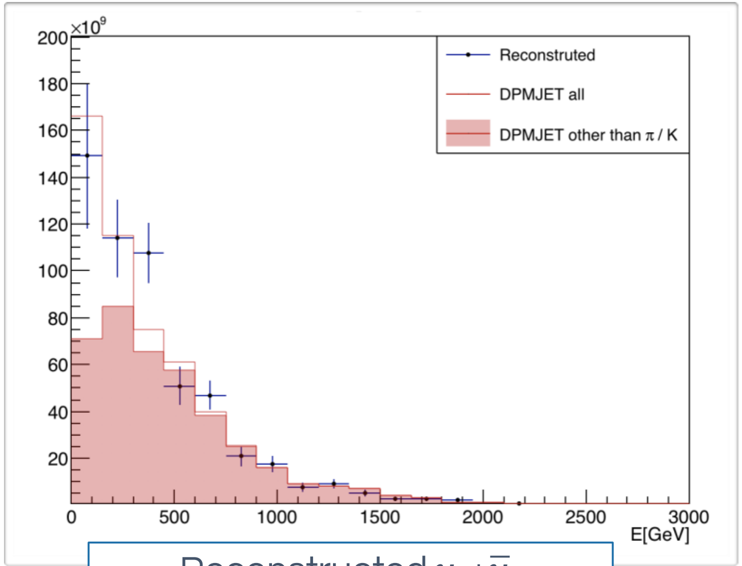
- Rapidity range: $7.2 < \eta < 8.4$
- Enhances ν flux from **charm** parents.
- Complementarity with FASERν, located **on-axis** in symmetric tunnel (TI-12).



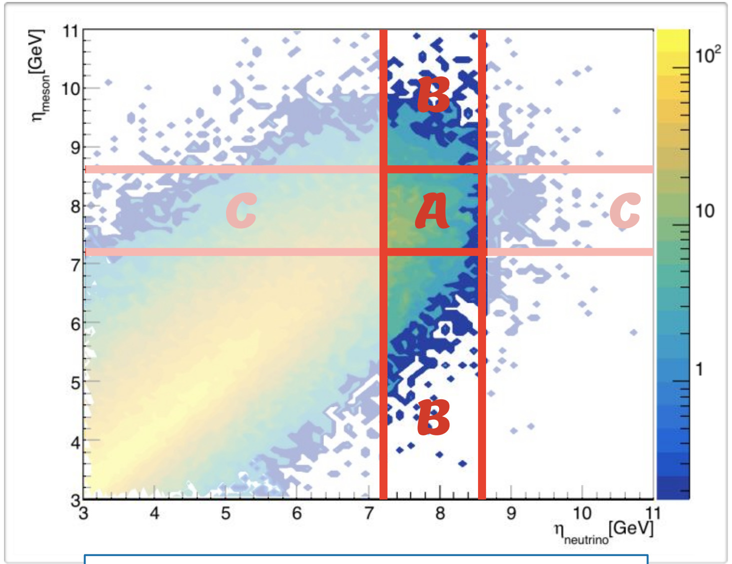


Neutrinos from charm production

- Expect 90% of $\nu_e+\overline{\nu}_e$ to originate from charm decays.
  - SND@LHC $\nu_e+\overline{\nu}_e$ are a probe of forward charm production.
  - Forward charm production measurement constrains gluon PDFs at very low x (10^{-6}).
- Impact on future higher energy hadron colliders and neutrino astrophysics.



Reconstructed $\nu_e+\overline{\nu}_e$ spectrum at SND@LHC.



Correlation between η_ν and η_c

Neutrinos from charm production

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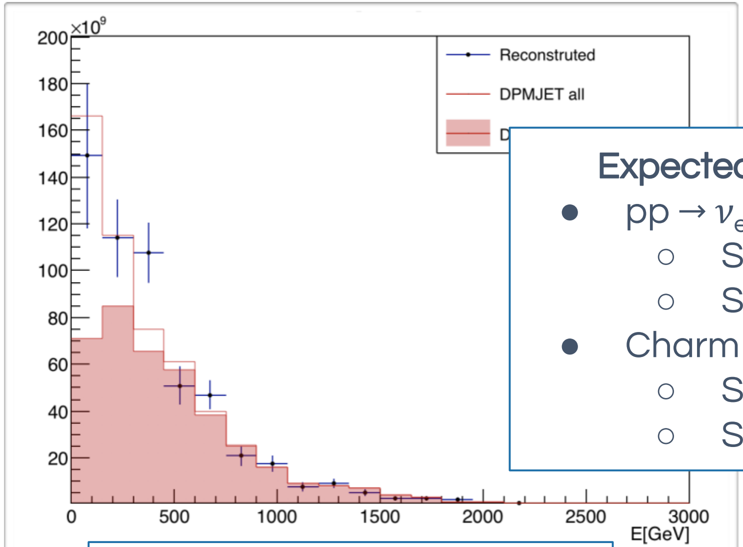
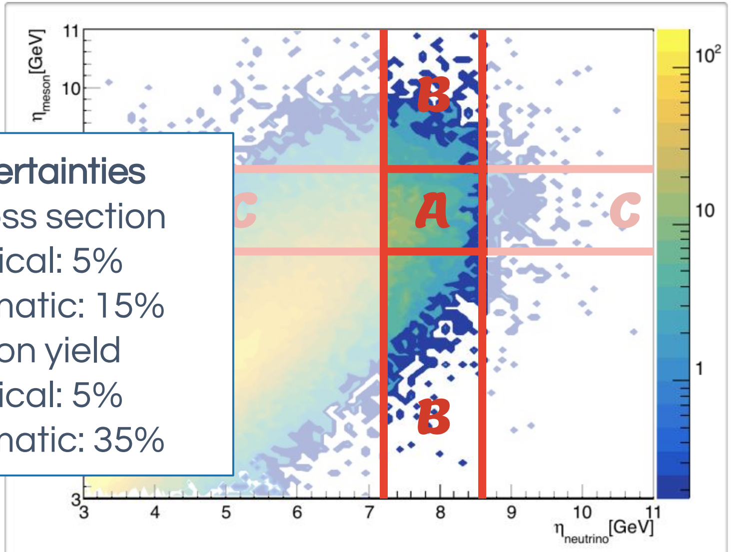


Reconstructed $\nu_e + \bar{\nu}_e$ spectrum at SND@LHC.

Expected uncertainties

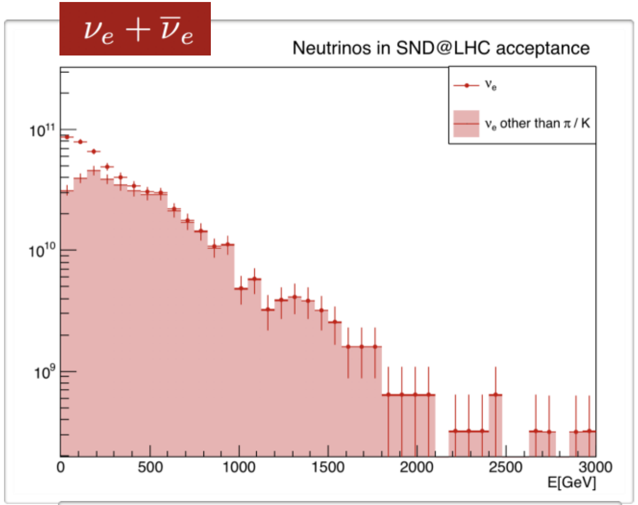
- pp → ν_eX cross section
  - Statistical: 5%
  - Systematic: 15%
- Charm hadron yield
  - Statistical: 5%
  - Systematic: 35%



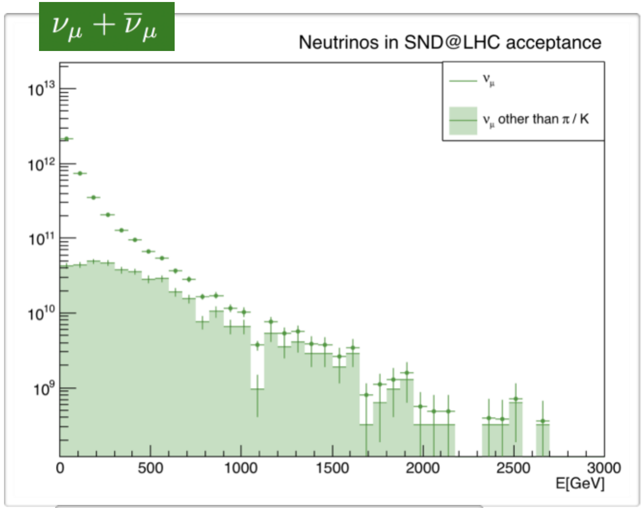
Correlation between η_ν and η_c

Lepton Flavour Universality tests

- Charm hadron decays contribute to the flux of all three types of neutrinos at SND@LHC.
- The detector has excellent flavour identification capabilities.
- Unique opportunity to test lepton flavour universality with neutrinos.
  - Take ratios of event rates: ν_e/ν_τ and ν_e/ν_μ.



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



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

π/K contamination

Lepton Flavour Universality tests

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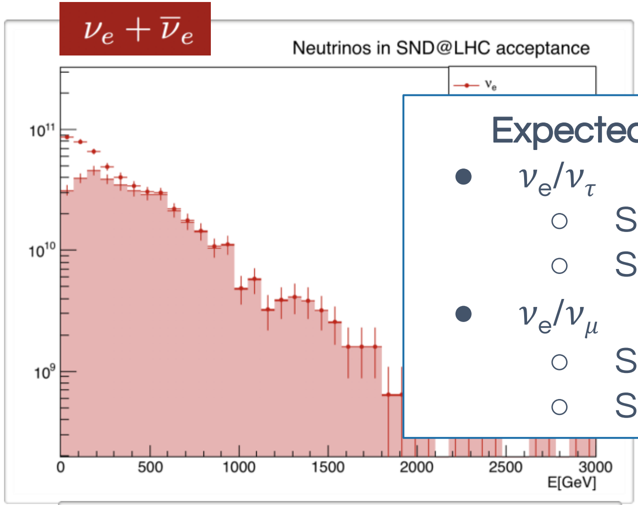
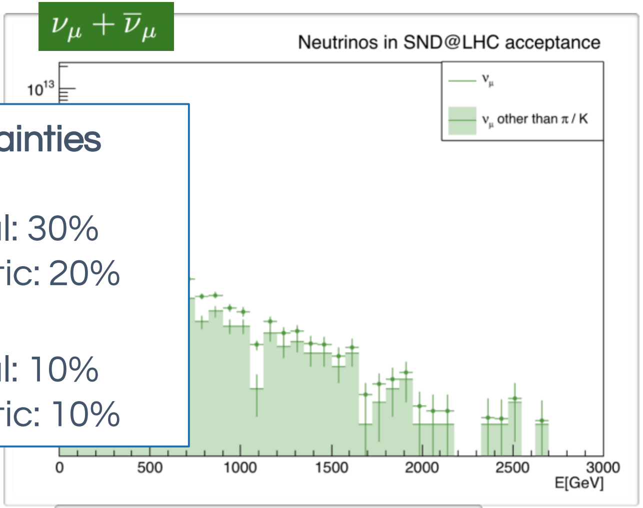


Expected uncertainties
- ν_e/ν_τ
  - Statistical: 30%
  - Systematic: 20%
- ν_e/ν_μ
  - Statistical: 10%
  - Systematic: 10%



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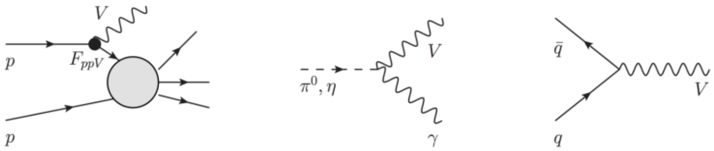
$\omega_{\pi/k}$: π/K contamination

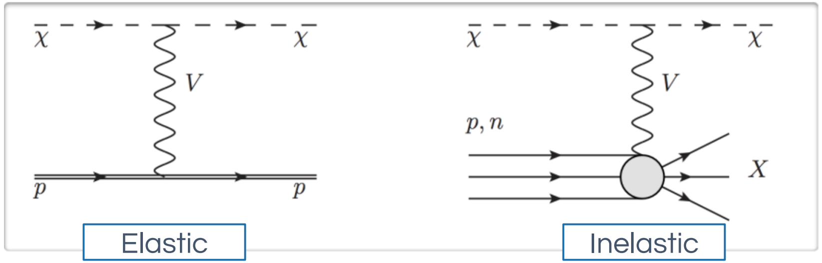
Feebly interacting particles

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

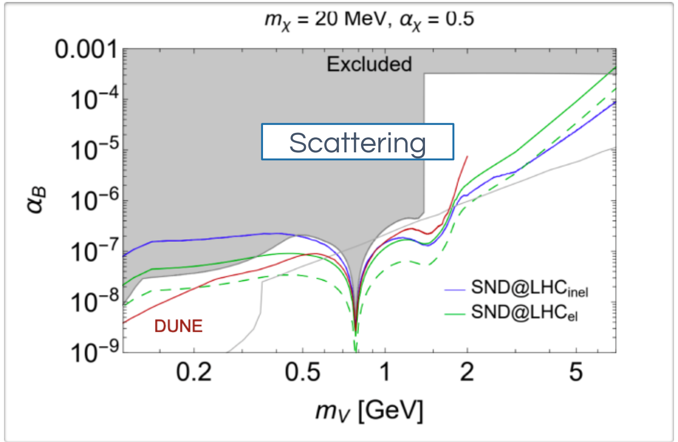


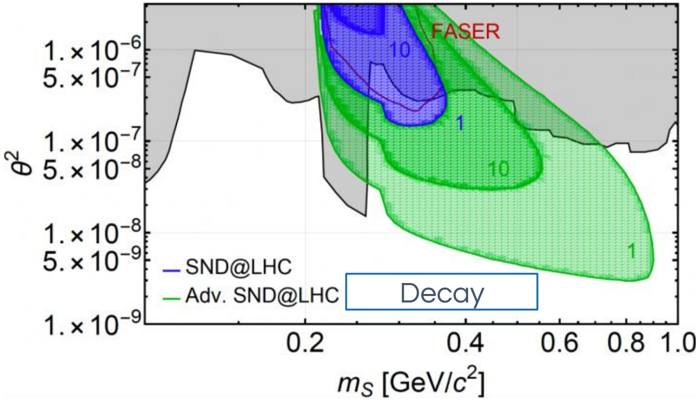
p bremmstrahlung | Meson decay | Drell-yan

  - **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.





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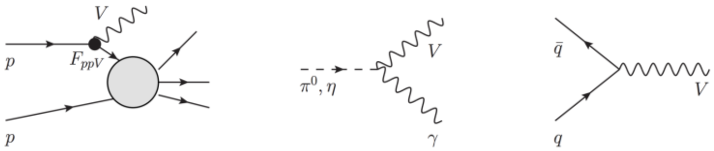
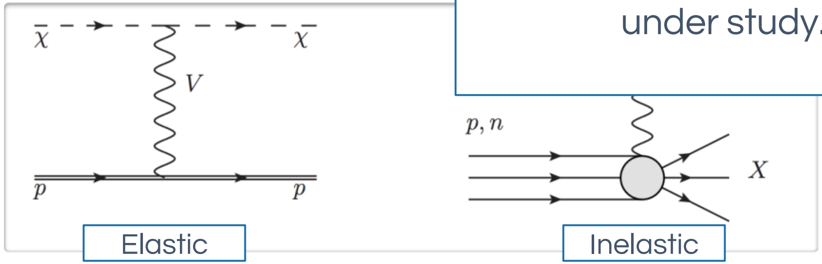


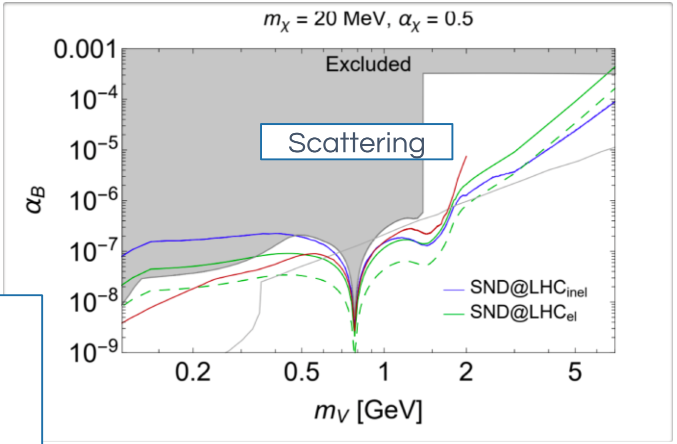
p bremmstrahlung | Meson decay | Drell-yan

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



Elastic | Inelastic

Signal efficiencies and backgrounds (neutrinos!) under study.



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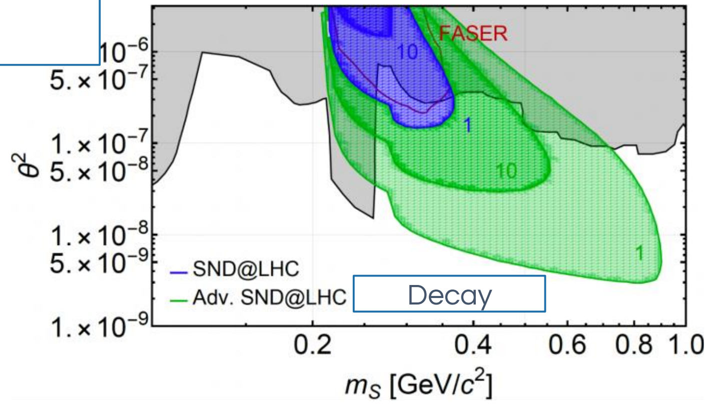

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Experiment timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

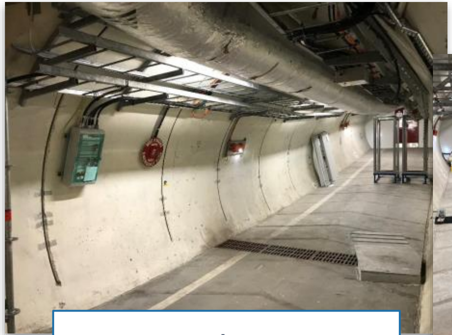
SND@LHC

January 2021

CERN approves new LHC experiment

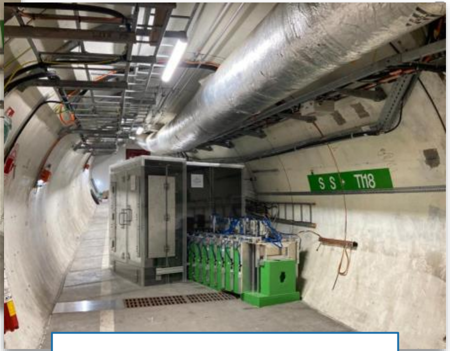
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

March 2021

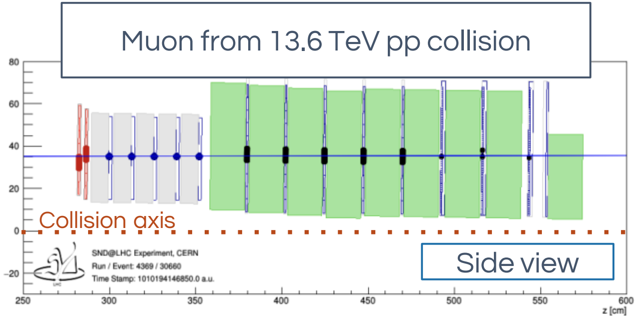


September 2021

December 2021

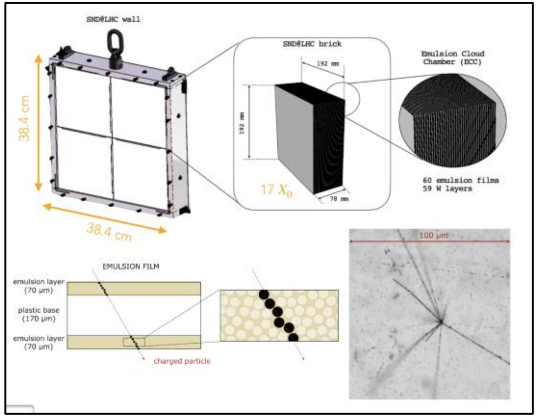


March 2022



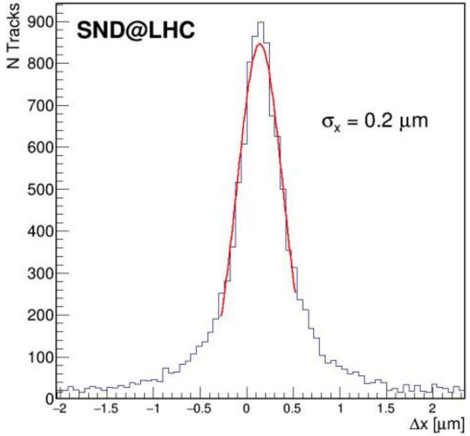
July 2022

Emulsion target



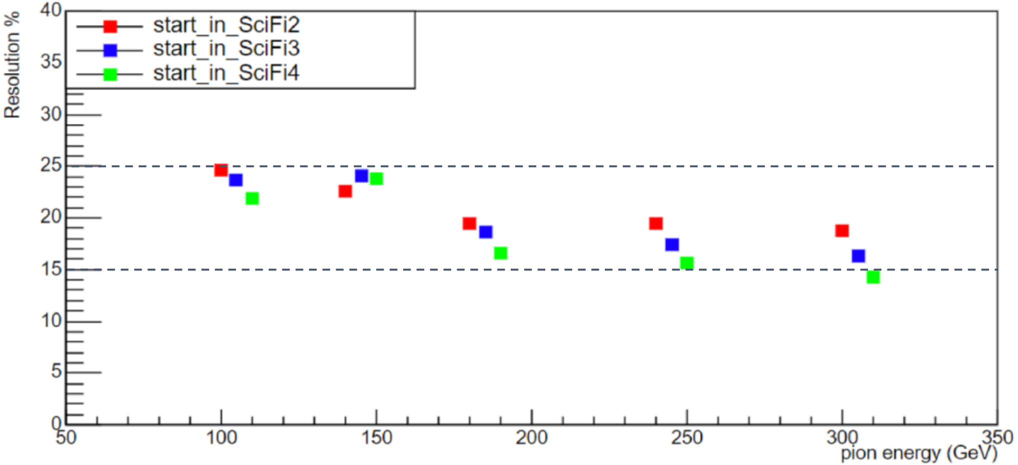
- Full target system equipped with 5 Tungsten/emulsion walls
- Total mass: 830 kg
- Number of emulsion films: 1200
- Limit to the integrated track density: 4×10^5 tracks corresponding to 20 (10) fb^{-1} in 2022-2023 (2024)
- Emulsion development in the CERN emulsion facility
- Emulsion scanning with automated optical microscopes in three scanning stations (CERN, Bologna, Napoli)

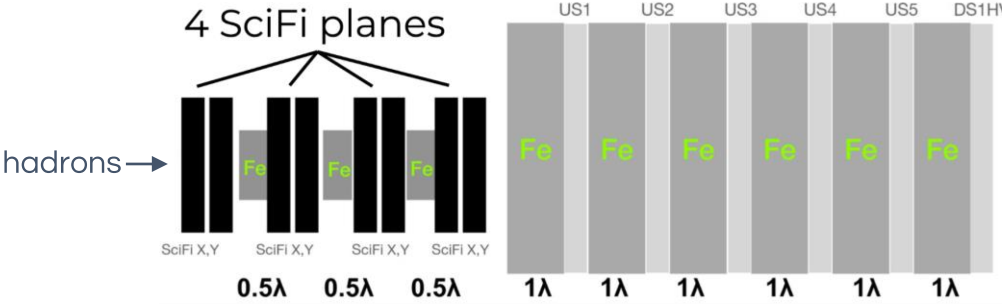
Position resolution
2 um



Hadron calorimeter test beam

- Very successful test beam data taking campaign in August 2023.
- Exact replica of the hadron calorimeter.
- Downsized mockup of the target.
    - Narrow beam spot.
- Calibrated calorimeter response.
    - Confirmed expected performance.





Two complementary LHC ν experiments

	SND@LHC	FASER
Location	**Off-axis:** $7.2 < \eta < 8.4$ Enhances **charm** parentage	**On-axis:** $\eta > 9.2$ Enhances **statistics**
Target	**800 kg** of tungsten	**1100 kg** of tungsten
Detector technology	**Emulsion vertex detector,** electromagnetic and hadronic **calorimeters**	**Emulsion vertex detector** and **spectrometer**