Recent Results from the SND@LHC experiment

42nd International Conference for High Energy Physics

(ICHEP 2024)

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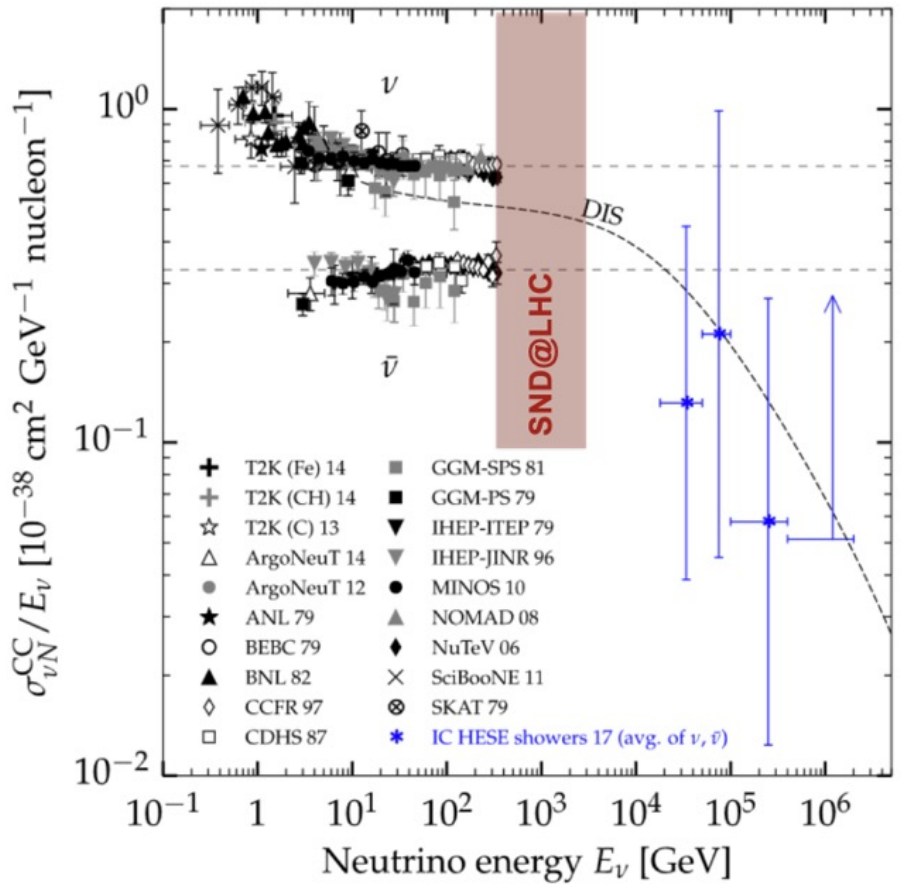
On behalf of the SND@LHC Collaboration

CERN

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Neutrinos at the LHC

PRL 122 (2019) 041101



Existing neutrino cross-section measurements

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **47** (2020) 125004 (18pp)
https://doi.org/10.1088/1361-6471/aba7ad

Further studies on the physics potential of an experiment using LHC neutrinos

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **46** (2019) 115008 (19pp)
https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

- Exploring a **neutrino physics program** at the LHC in discussion since 1980s
- LHC *pp* collisions (**pp** $\rightarrow \boldsymbol{\nu_X}$ **X**) $\rightarrow$ large neutrino flux
  - in the **forward region**
  - **unexplored energy range** $[10^2 - 10^3]$ ($\sigma_\upsilon \propto E_\upsilon$)
- **Small scale experiments** near the LHC IP in the forward region can observe these neutrinos
- In LHC Run 3 two experiments currently running: FASERν and **SND@LHC**

Scattering and Neutrino Detector at the LHC

March 2021

CERN approves new LHC experiment

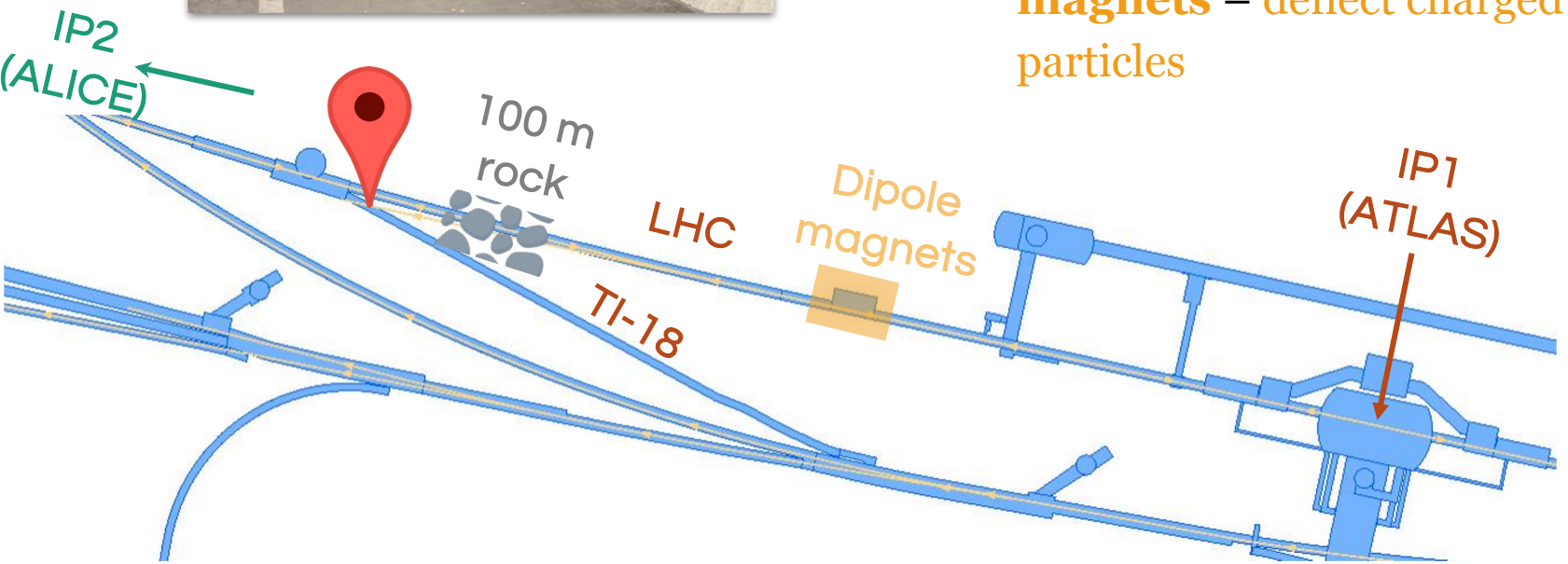
March 2022

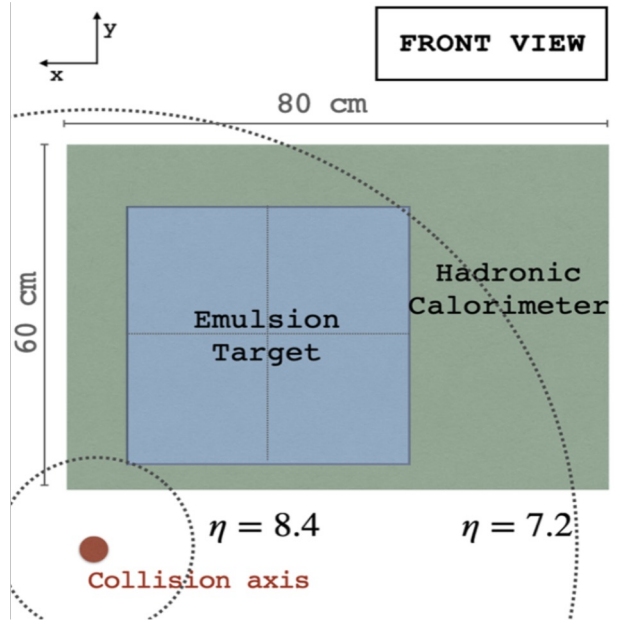
TI-18 location:

- Reusing old LEP transfer tunnel, **480 m away from IP1.**
- **100 m of rock** between detector and IP1 – shielding from collision debris
- Downstream of **dipole magnets** – deflect charged particles

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).





SND@LHC Physics Goals

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.

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

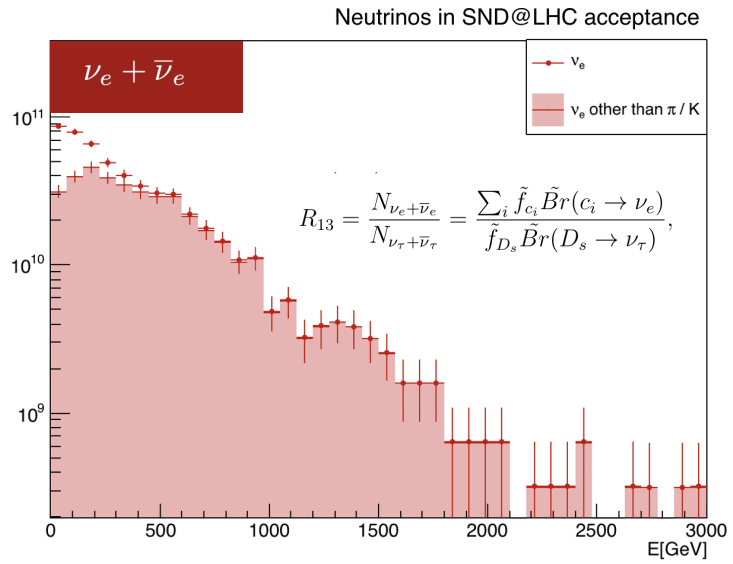
- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality**.

Beyond the Standard Model

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

250 fb^{-1}

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



Detector Layout

Veto system

2 (2022 – 2023) / 3 (2024 -) 1 cm thick scintillator planes. - **Tag penetrating muons**

Goal:
- identification of neutrino flavours
- detection of feebly interacting particles

Solution: Hybrid detector

Target, Vertex Detector & ECal

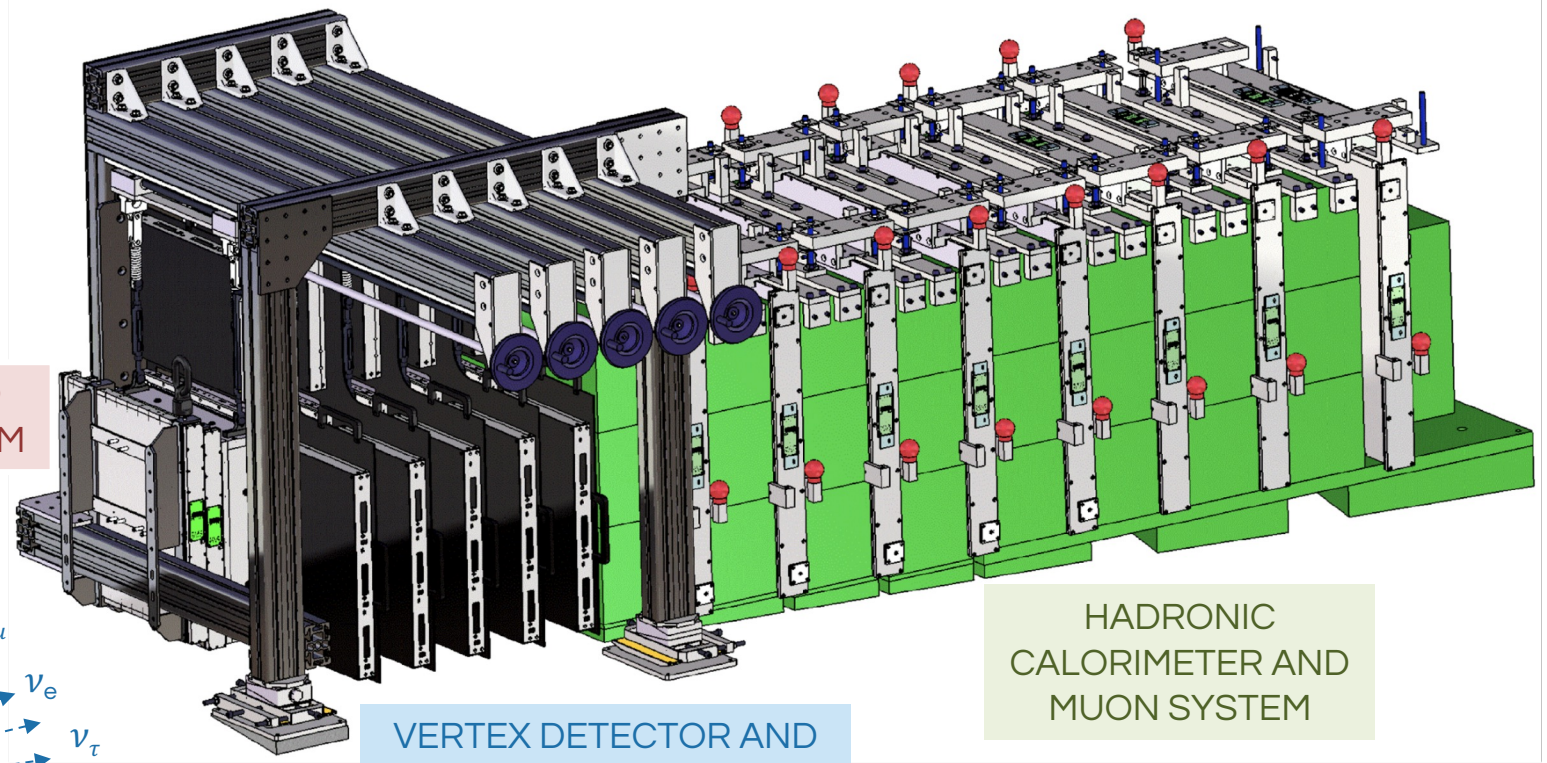
830 kg tungsten target.

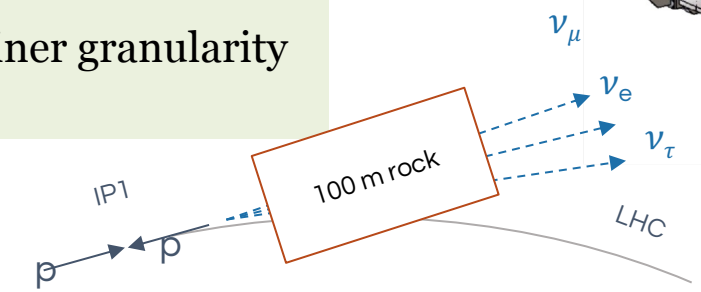
Five walls x 60 emulsion layers – **detecting neutrino interaction**
+ Five scintillating fibre stations - **timing information and energy measurement**

Muon system & HCal

Eight 20 cm Fe blocks + scintillator planes. - **fast time resolution and energy measurement**

Last 3 planes have finer granularity **- to track muons.**





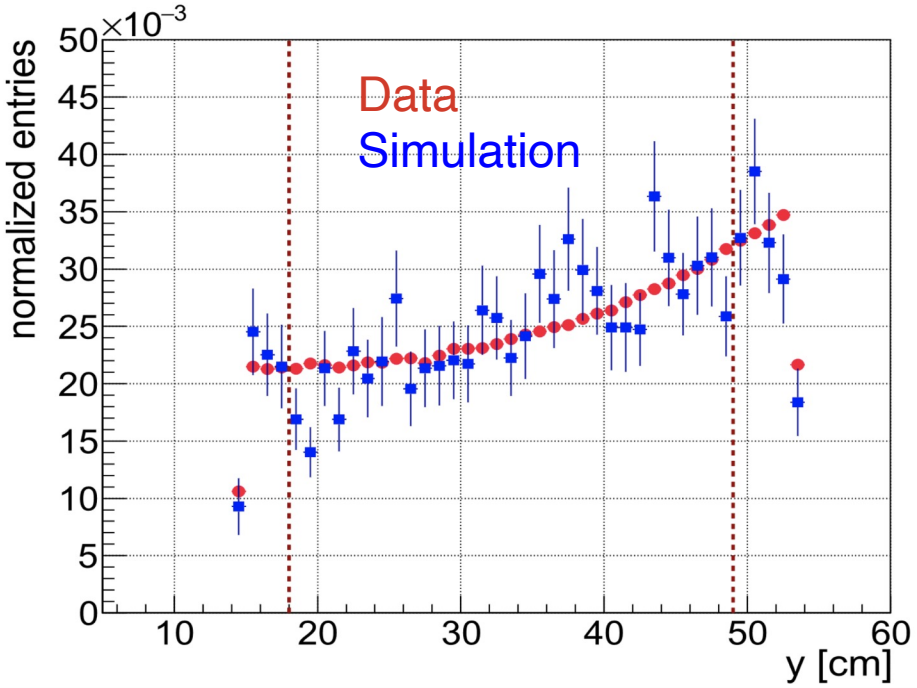
2024 JINST 19 P05067


DS 3H
←SND.IRON.S.H

Muon Flux Measurement

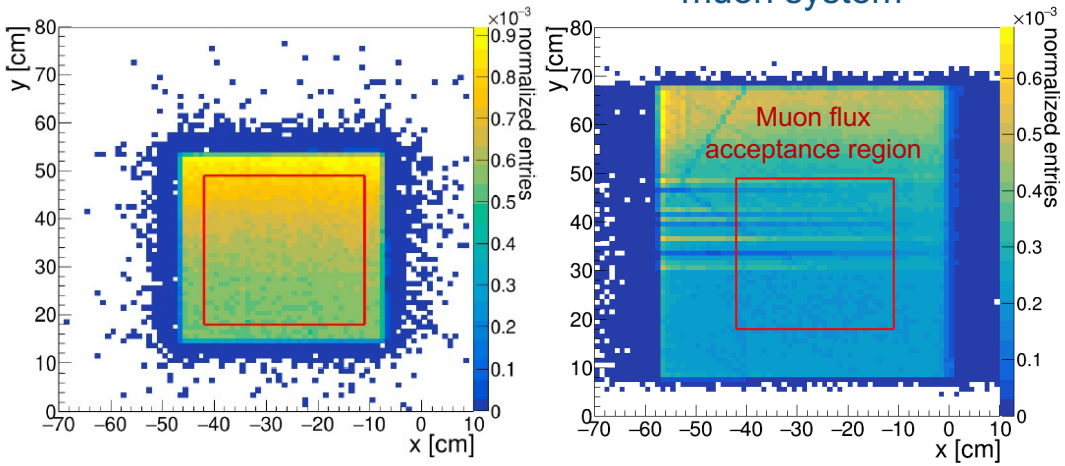
Published: Eur. Phys. J. C (2024) 84: 90

- **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.



Sci-Fi tracker

Downstream (DS) muon system



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**.
- Upgrade: Muon telescope

Muon Neutrino Analysis - Update

Phys. Rev. Lett. 131, 031802: 8 muon neutrino candidates in the 2022 data, with a significance of 6.8 σ.

New this year

Updated analysis with 2023 data and extended fiducial volume.

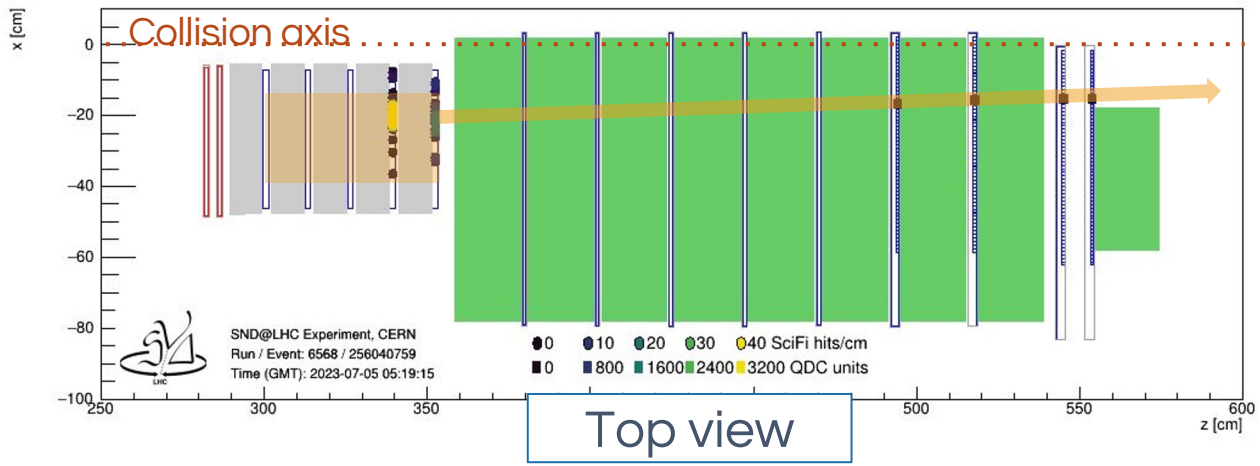
Event selection

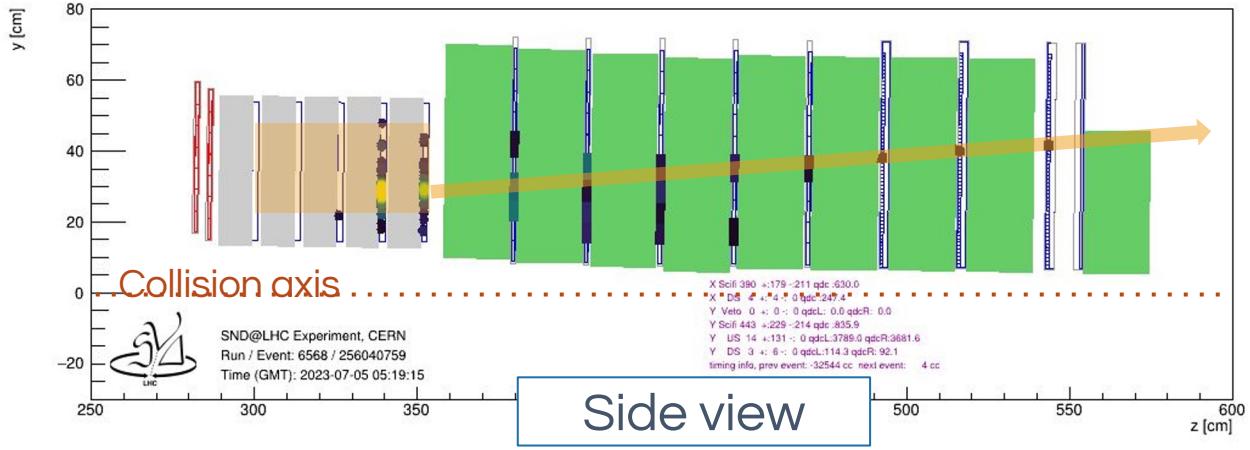
Fiducial volume

- **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%



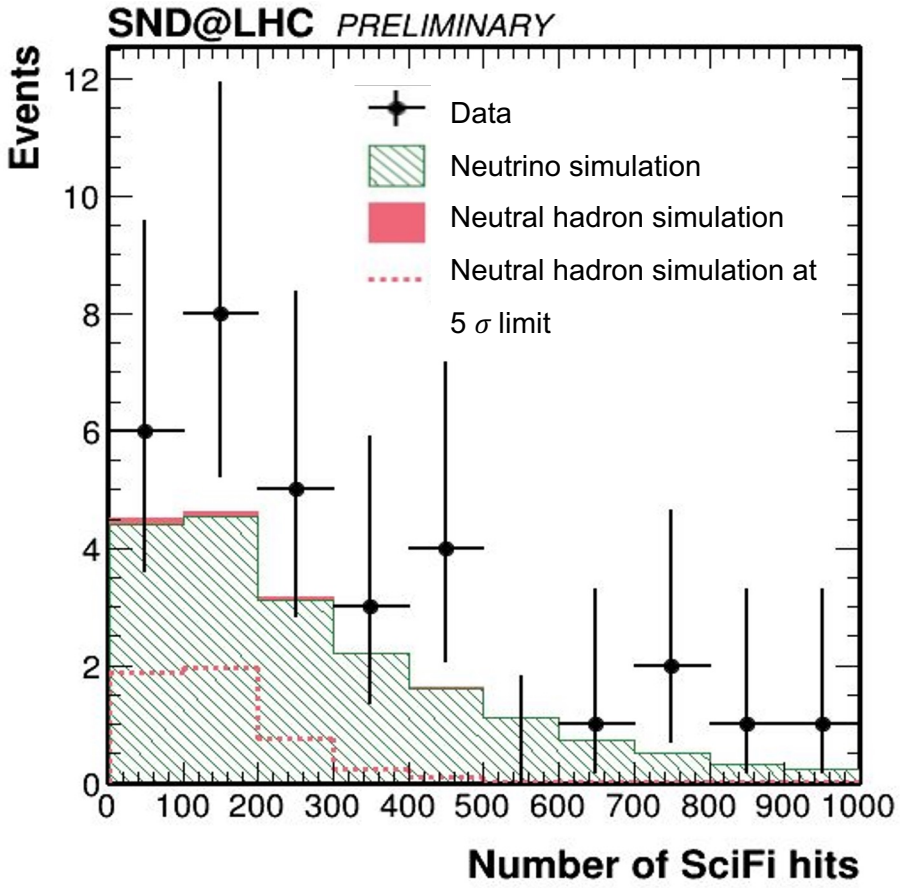


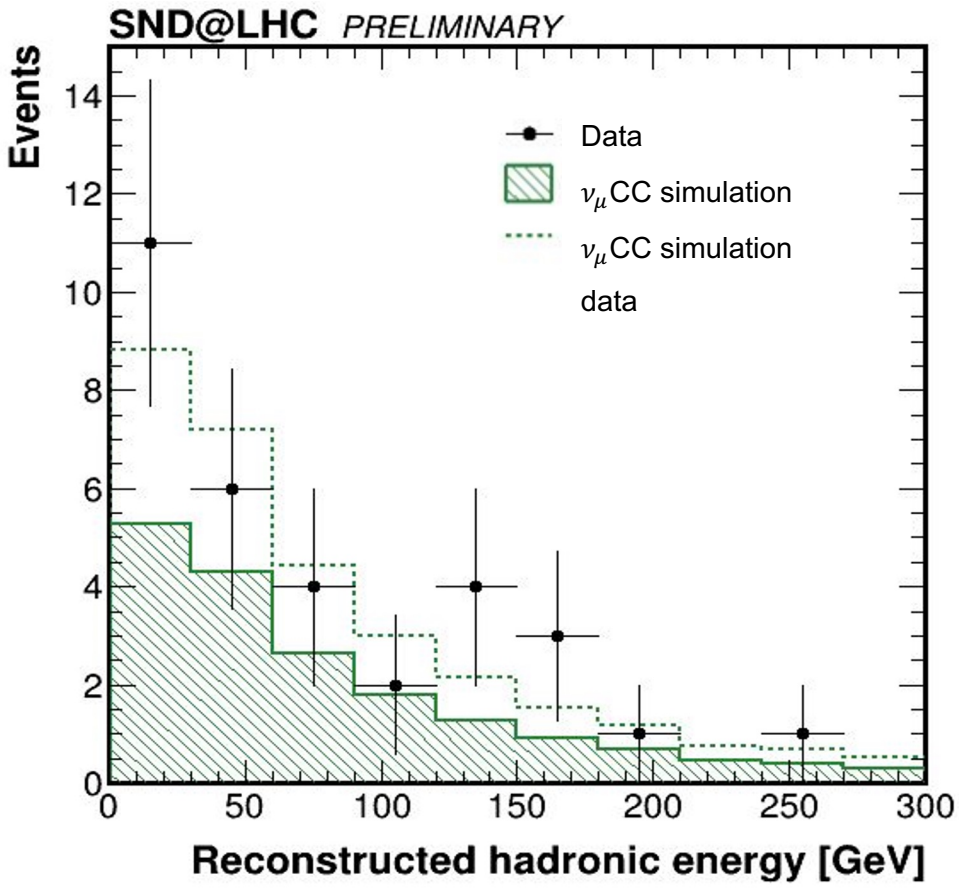
Updated Muon Neutrino Results

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

- Signal: 19 ± 4 (syst) ± 4 (stat)
- Neutral hadrons: 0.25 ± 0.06

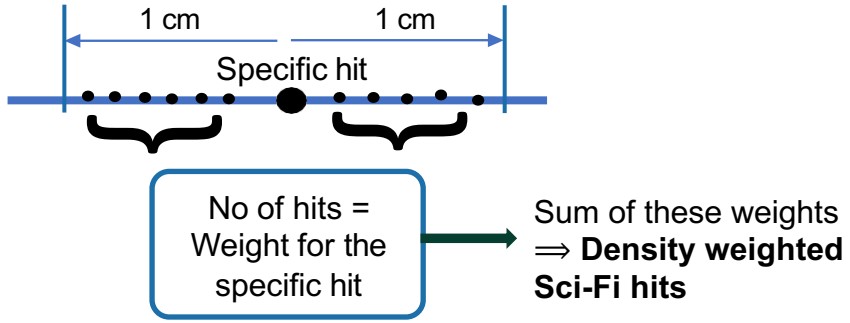
Number of events observed: 32

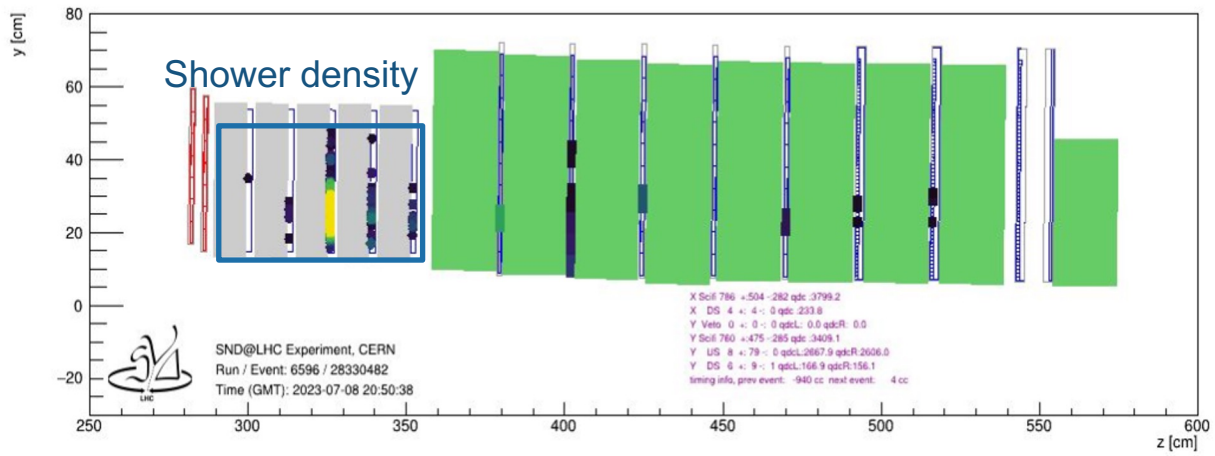




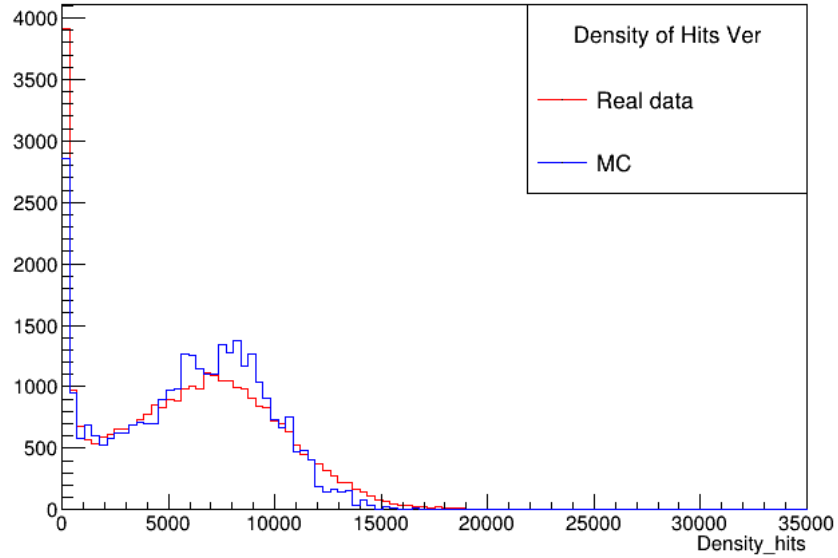
Shower Density

- Signal selection based on topological and calorimetric information
- **Density-weighted Sci-Fi hits** – promising variable to characterize showers
  - EM showers (for identifying ν_e CC) would be more dense than hadronic showers
- Defined as the summation of the weights of the hits.
  - Weight of a hit - consider the position of the hit and count the number of hits lying within 1cm distance from this hit
- Good agreement in data and MC in test-beam data





Data MC agreement in test beam data



Search for Shower-like (0μ) Neutrino Events

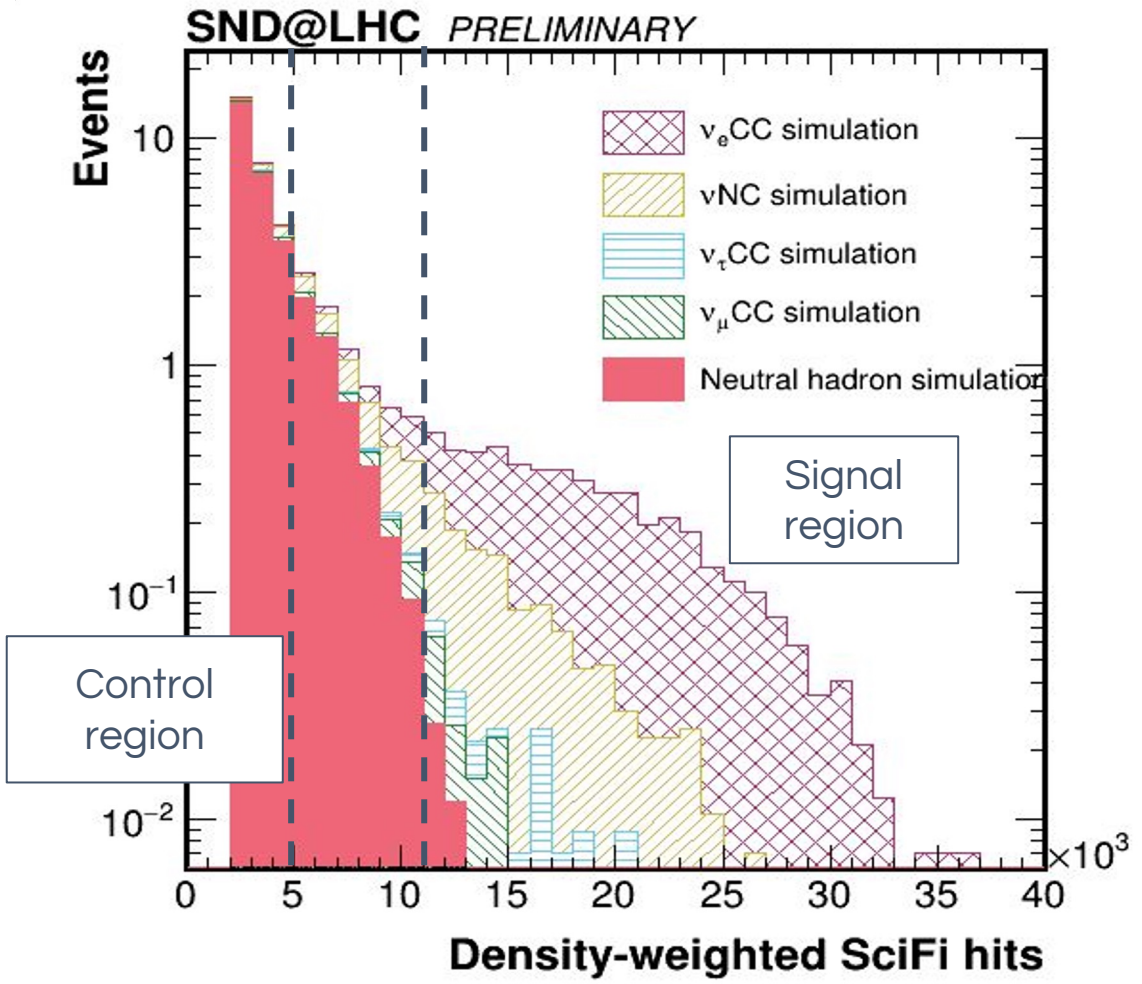
Signal: ν_eCC and NC interactions

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 > 11x10³.**
  - 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**

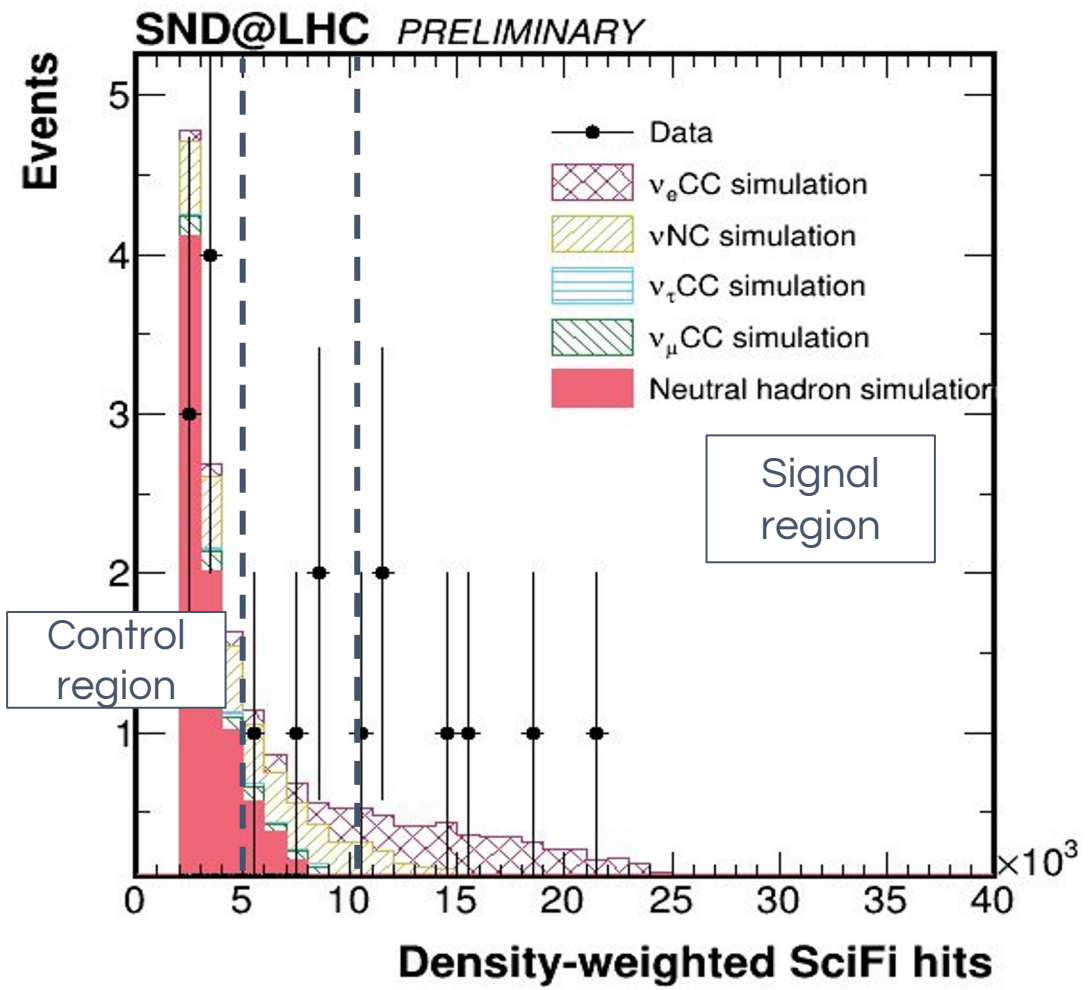
Neutrino background

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

0μ observation significance

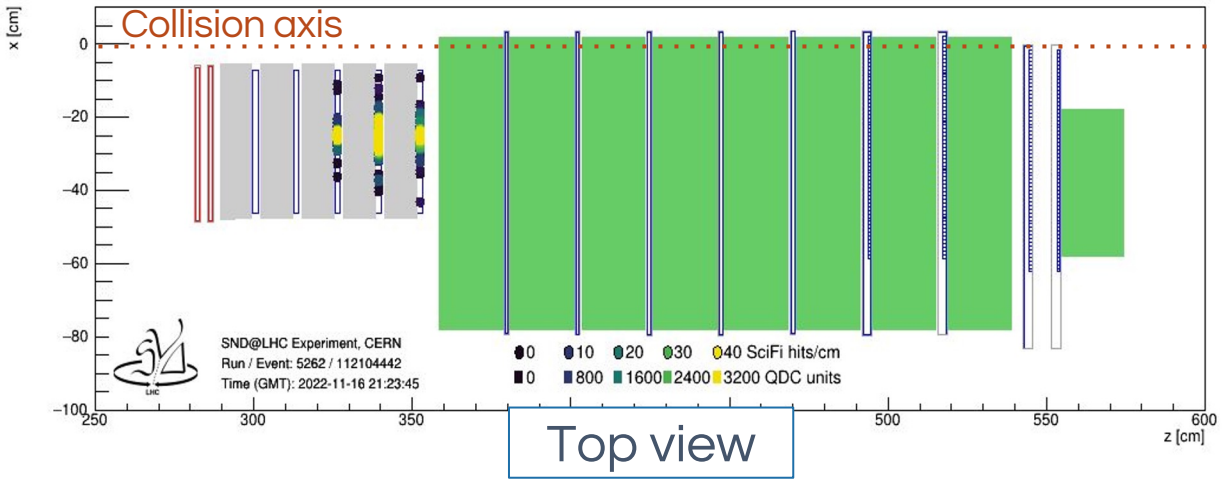
- **Total expected background: 0.13 ± 0.11 events**
- **Expected signal: 4.7 events**
- **Expected significance: 4.9 σ**

Number of events observed: 6
Observation significance: 5.8 σ

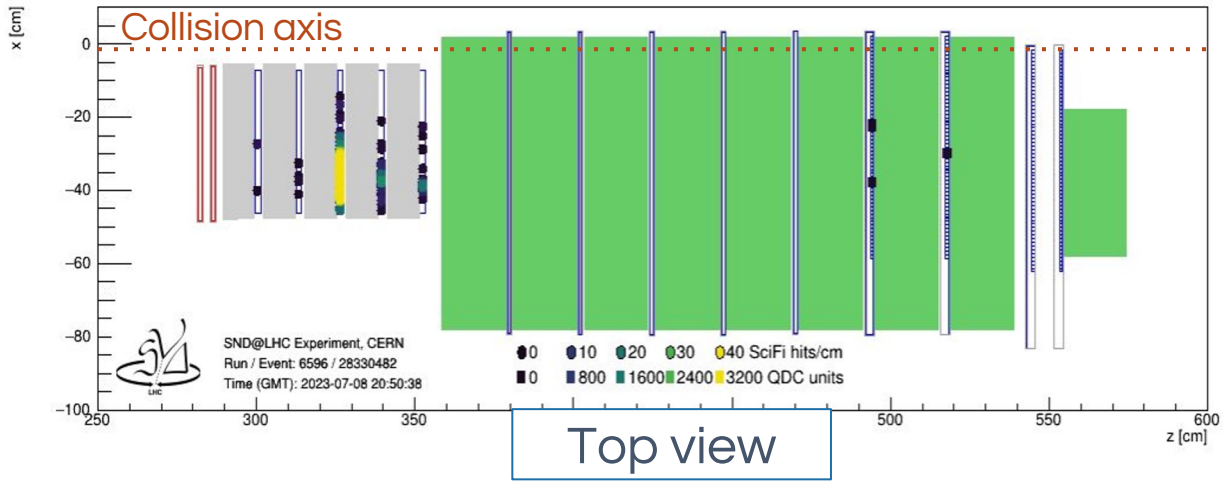


Paper in preparation

0μ Neutrino Candidates



Top view



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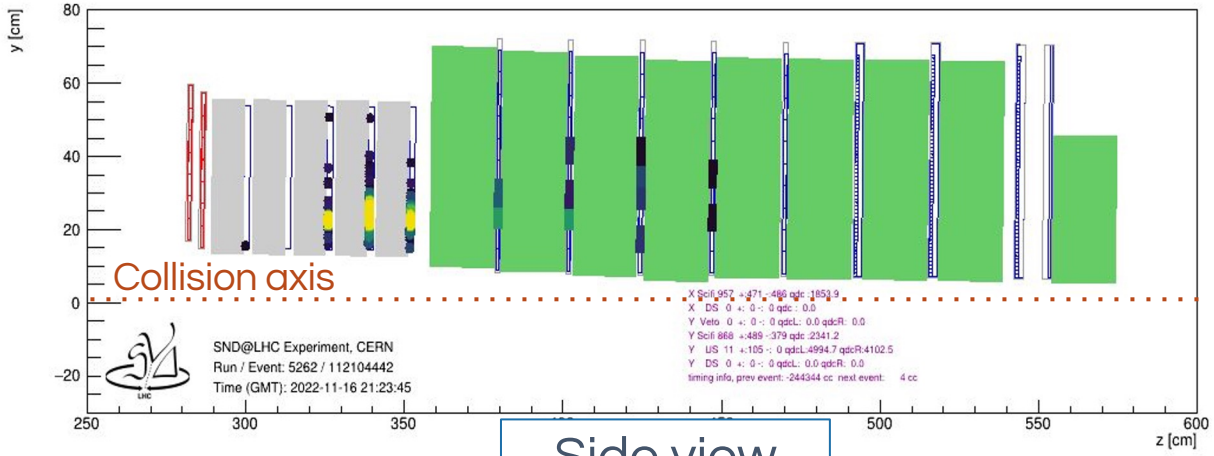
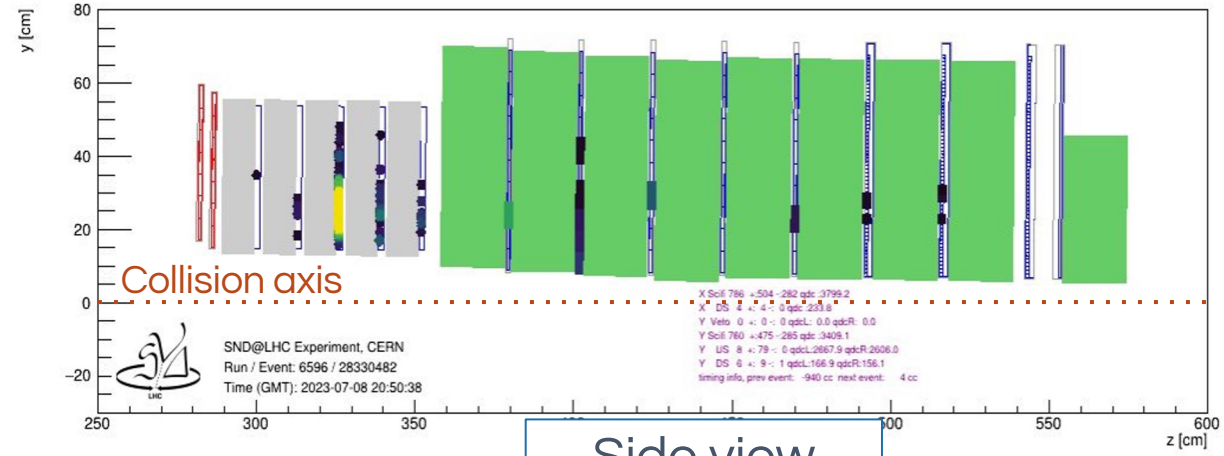


Side view



Side view

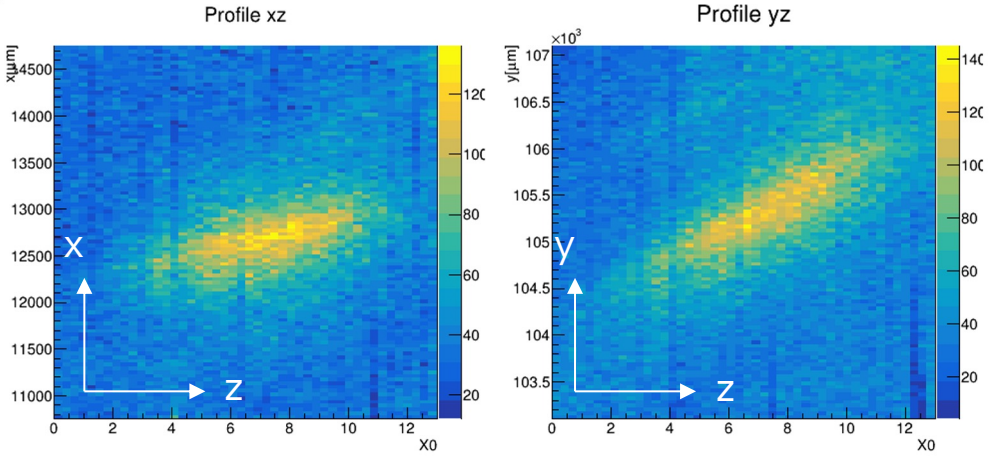
Search for ν_eCC interactions in the Emulsion data

Strategy

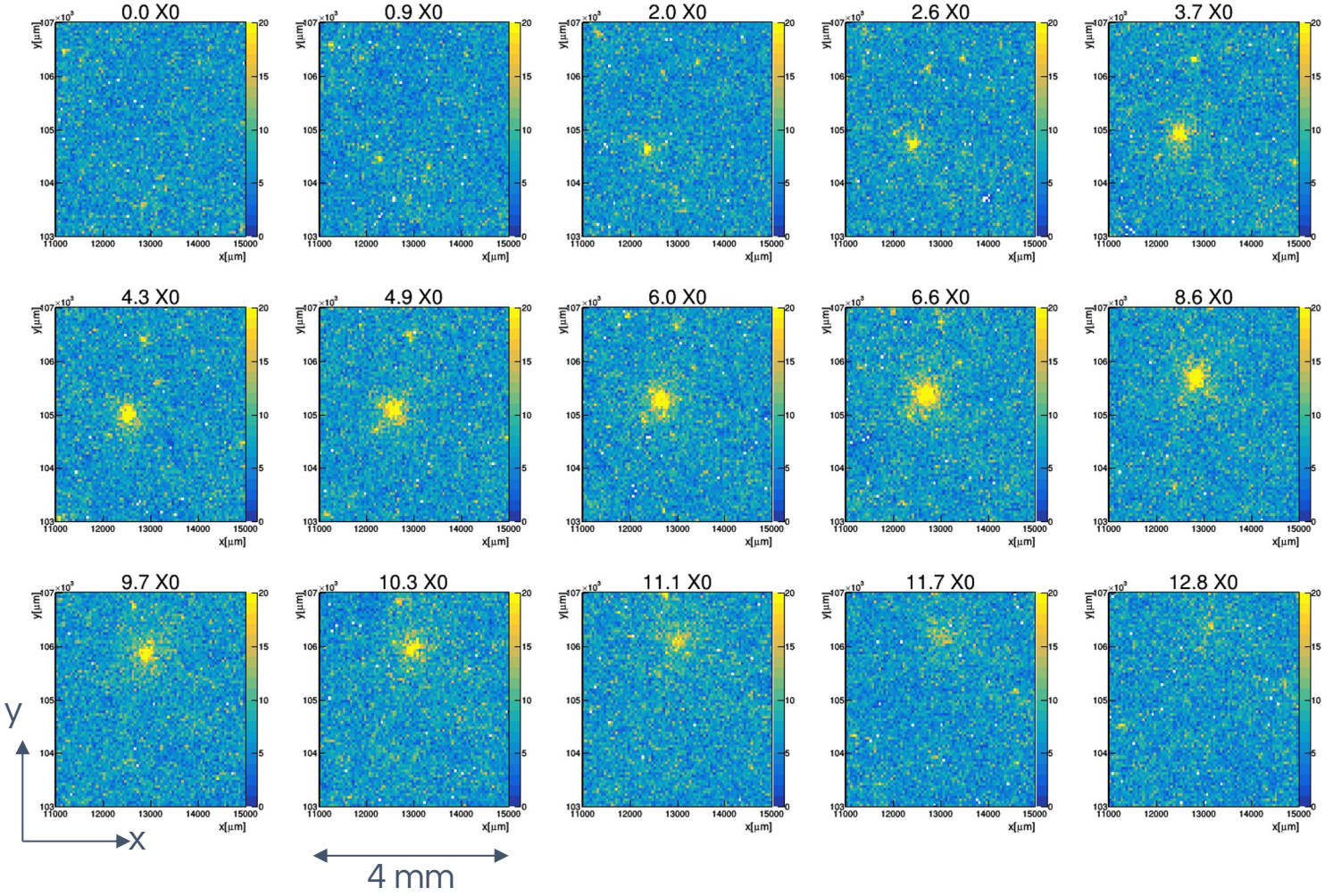
- Identify regions of high track density in the emulsions.
- Consistent with the expectation of electromagnetic shower development.
- Search for neutral vertices associated to identified showers.

Status

- Electromagnetic shower patterns identified.
- Vertex association ongoing.



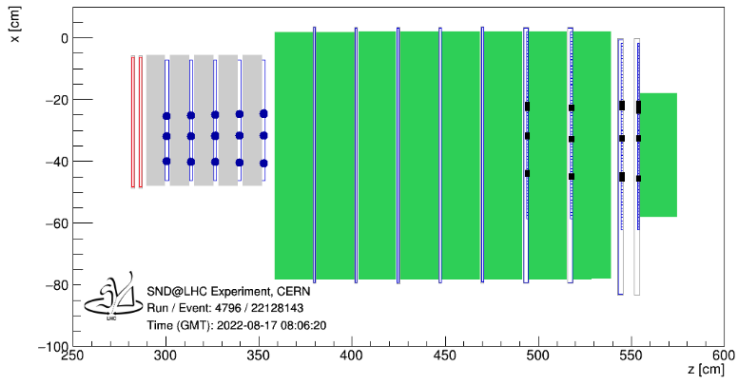
Z slices showing EM Shower development in the emulsion

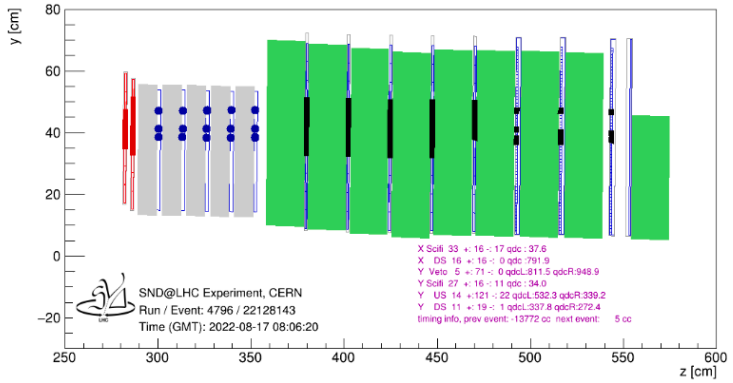


Search for Muon Trident Events

In Upstream rock

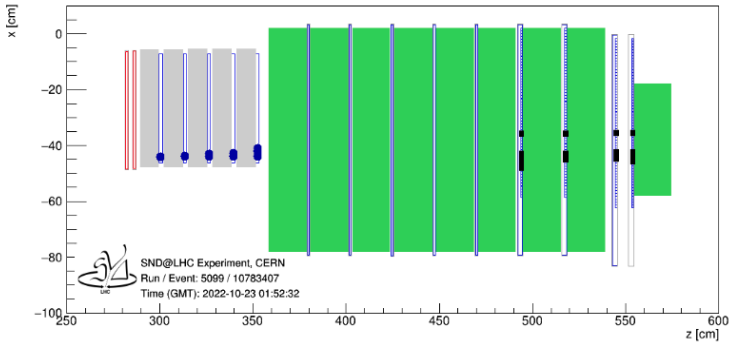
A

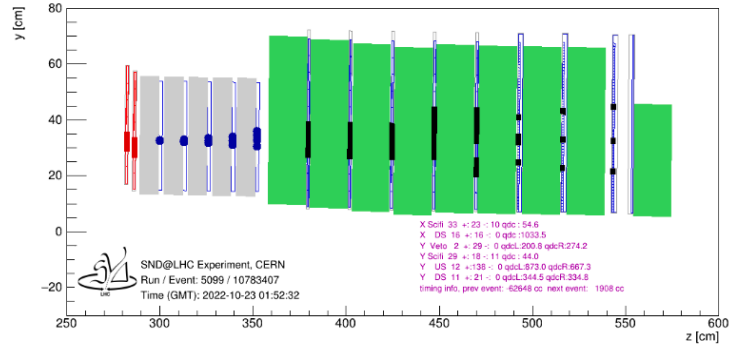




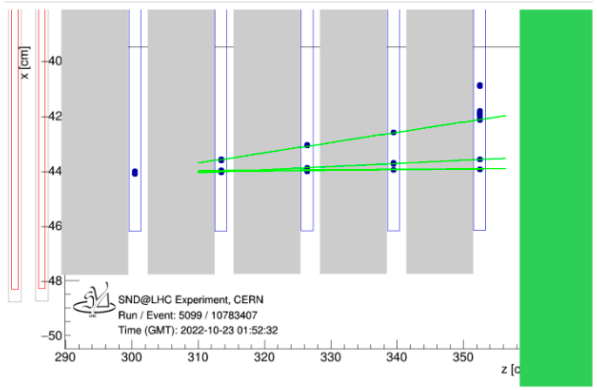
Interacting with the detector

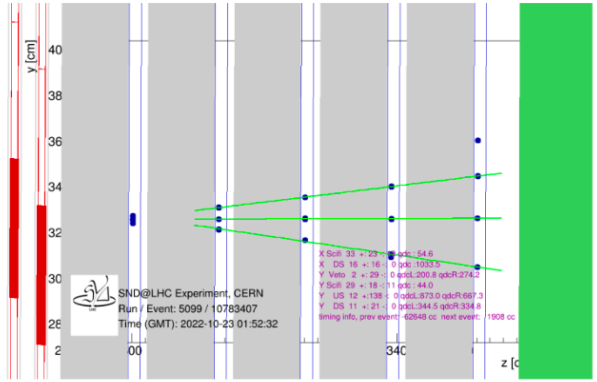
B





zoom into target:





We observe events with 3 tracks compatible with muon tridents

Analysis Ongoing

[Symmetry 2024, 16, 702]

Summary

Current Status:

- The **muon flux** reaching the detector was **measured** to validate the background model. (published)
- The **muon neutrino** analysis was **updated** with an extended fiducial volume and 2023 data.
  - The newly observed 32 events agreed to the signal predictions *(paper in preparation)*
- **Shower-like (0μ) neutrino events** were observed with a significance of 5.8 σ. *(paper in preparation)*
- The search for **electron neutrino** interactions in the **emulsion data** is in progress.
- Ongoing **searches** for exotic events like **muon tridents**.

Exciting times ahead!
Stay tuned...

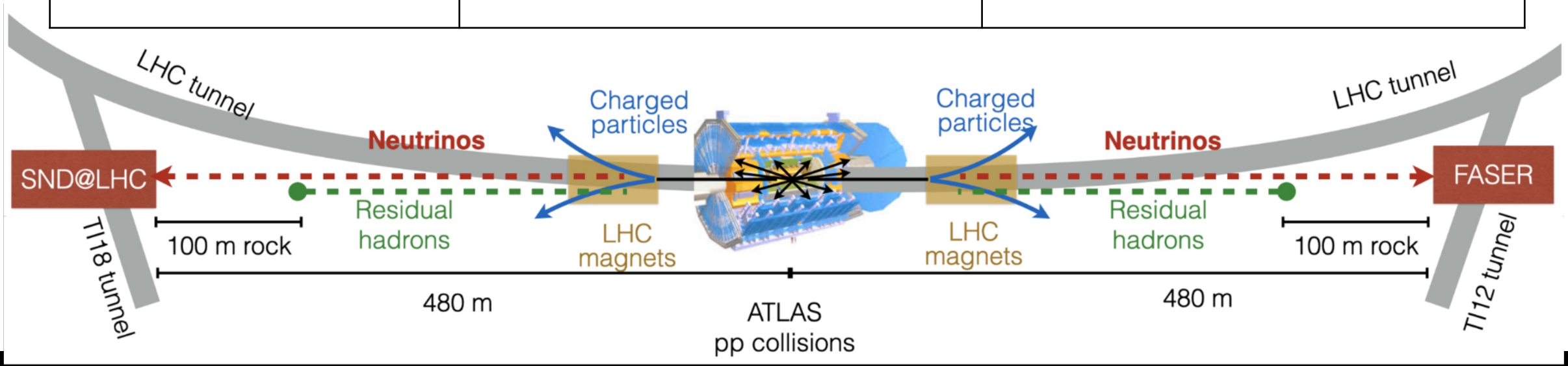
For detector performance and upgrades:
Check Giulia Paggi's talk (**Operation, Performance and Upgrade (incl. HL-LHC) of Present Detectors track, 20th July):**
https://indico.cern.ch/event/1291157/contributions/5876972/

Thank you

Back up slides

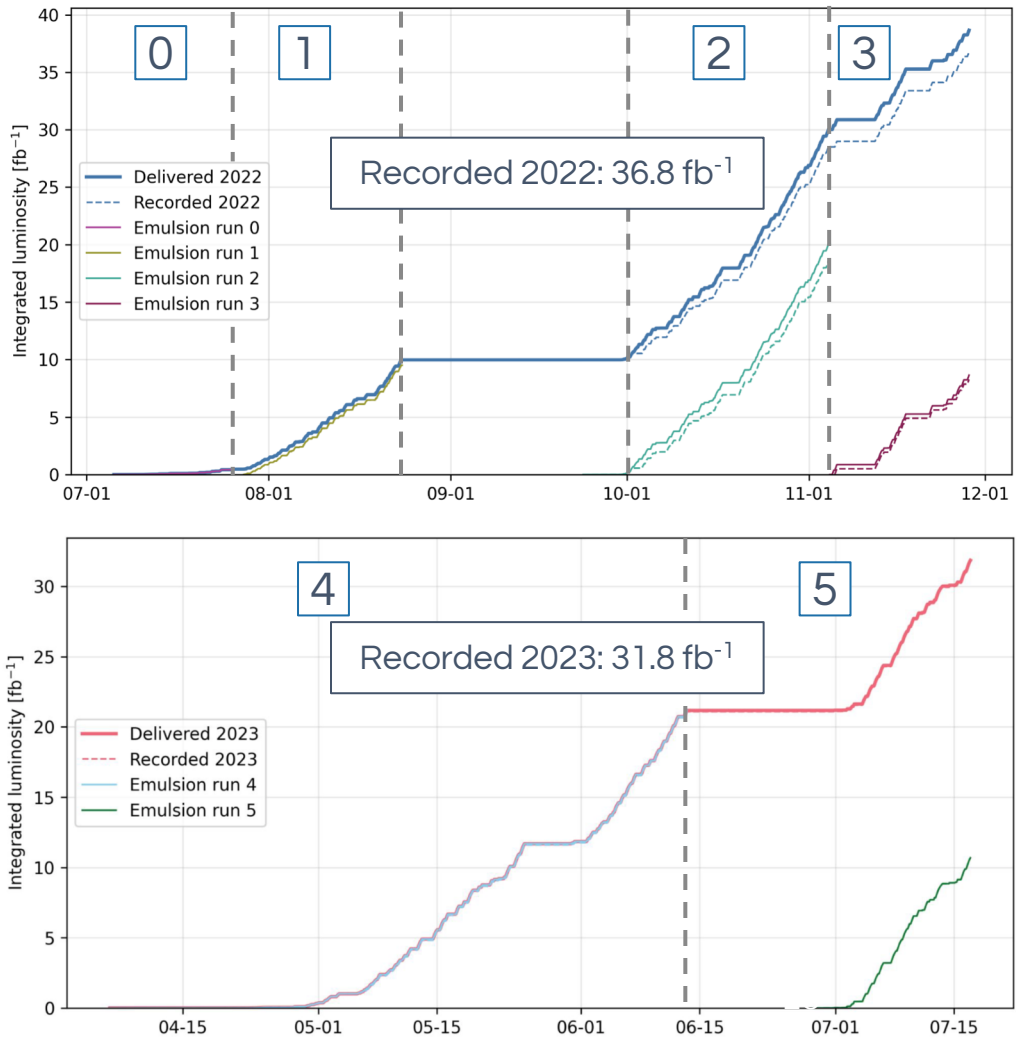
Two complementary LHC ν experiments

	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**



pp collision data

- **68.6 fb^{-1}** of proton-proton collisions **recorded** by the electronic detectors.
  - 97% detector uptime.
- **Six emulsion detector exchanges**.
  - Aim to limit each exposure to 20 fb^{-1}.
    - Keep the density of muon tracks at a reasonable level for the analysis.
      - < 4x10^5 tracks / cm^2

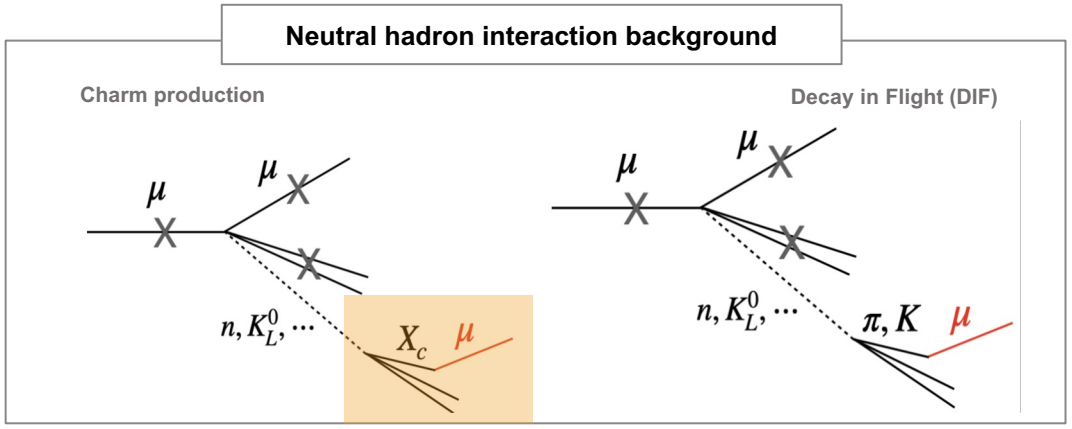


Backgrounds

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

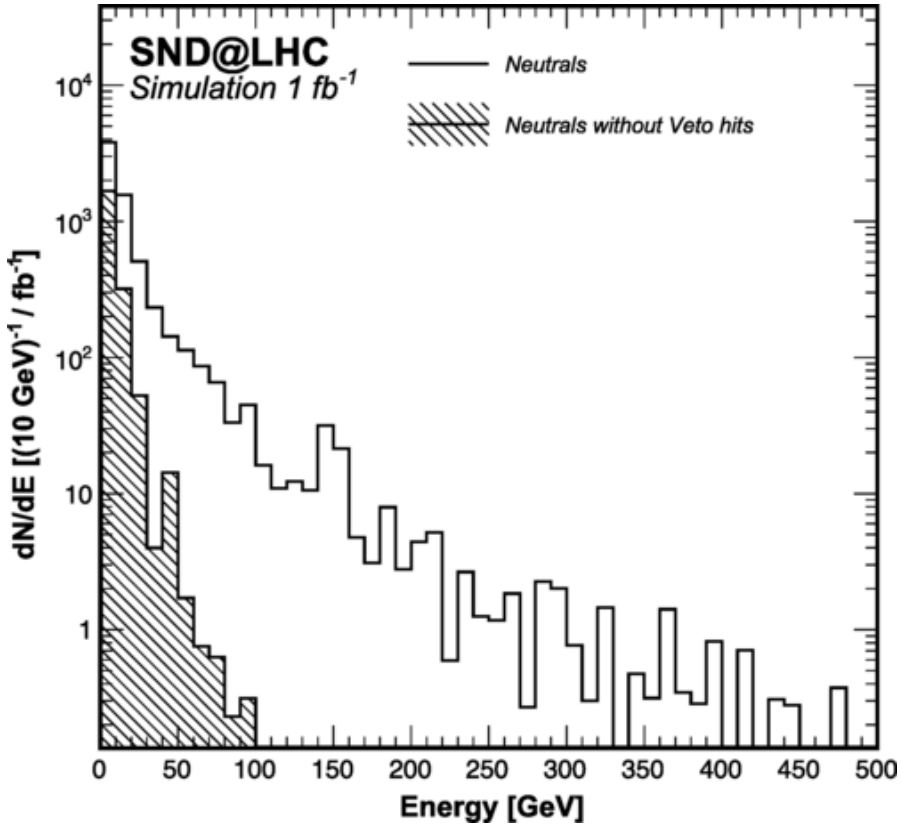
Major background for neutrino search – muons reaching the detector

- Muon bremsstrahlung & DIS
  - Muons not vetoed - enter the fiducial volume – generate showers
- Neutral Hadron Background
  - Muons interacting with surrounding material
  - Can mimic neutrino interactions



:= within SND@LHC acceptance

Neutral hadron Background energy confined to low energy (<100 GeV)



Energy distribution of the neutrals before and after rejecting events with the veto hits

Simulation

PRODUCTION

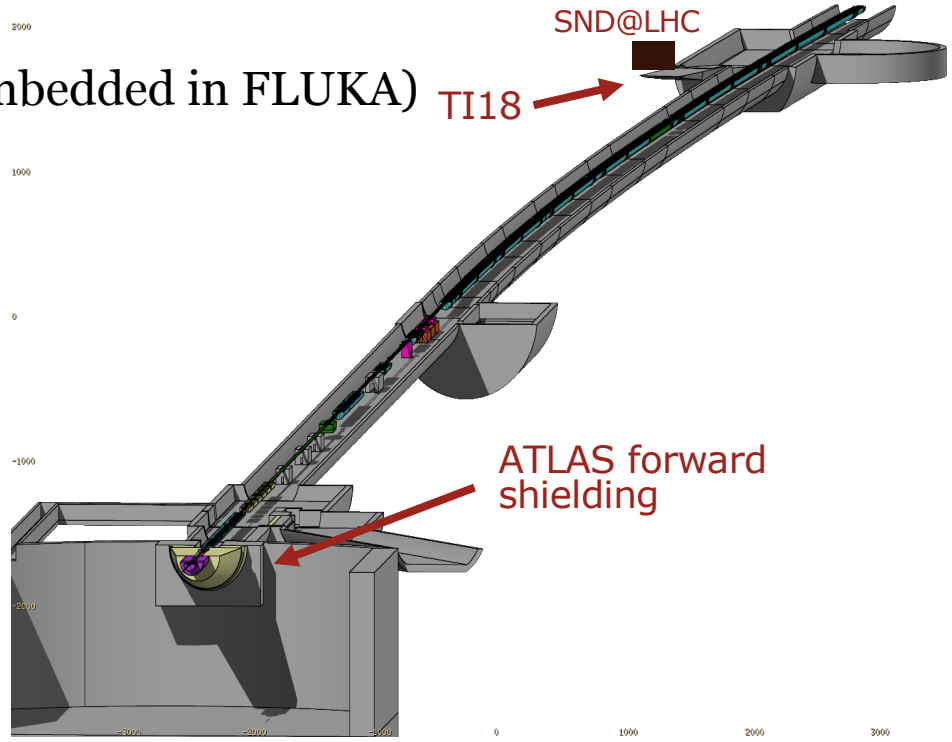
- pp collisions at LHC with **DPMJET III - v10** (embedded in FLUKA)
- $\sqrt{s}$ = 13 TeV

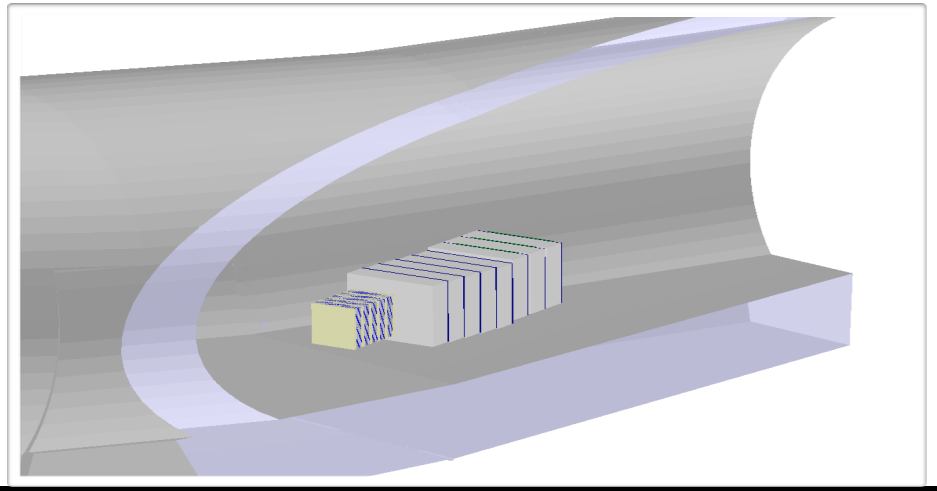
PROPAGATION

- Detailed simulation of LHC beam line with **FLUKA**
- Prediction of neutrino yields and spectra at SND@LHC location
- Prediction of muon population in the upstream rock, 75m from SND@LHC

DETECTOR

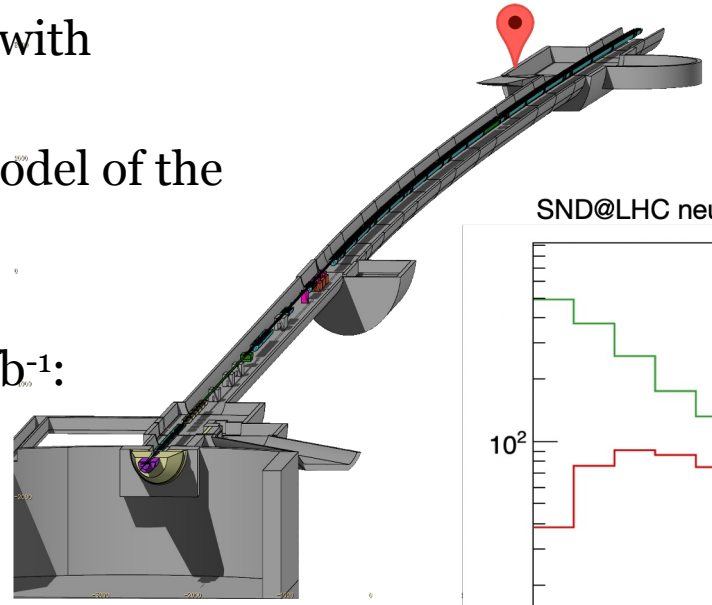
- Neutrino interactions in SND@LHC material simulated with **GENIE**
- Detector geometry and surrounding tunnel implemented in **GEANT4**

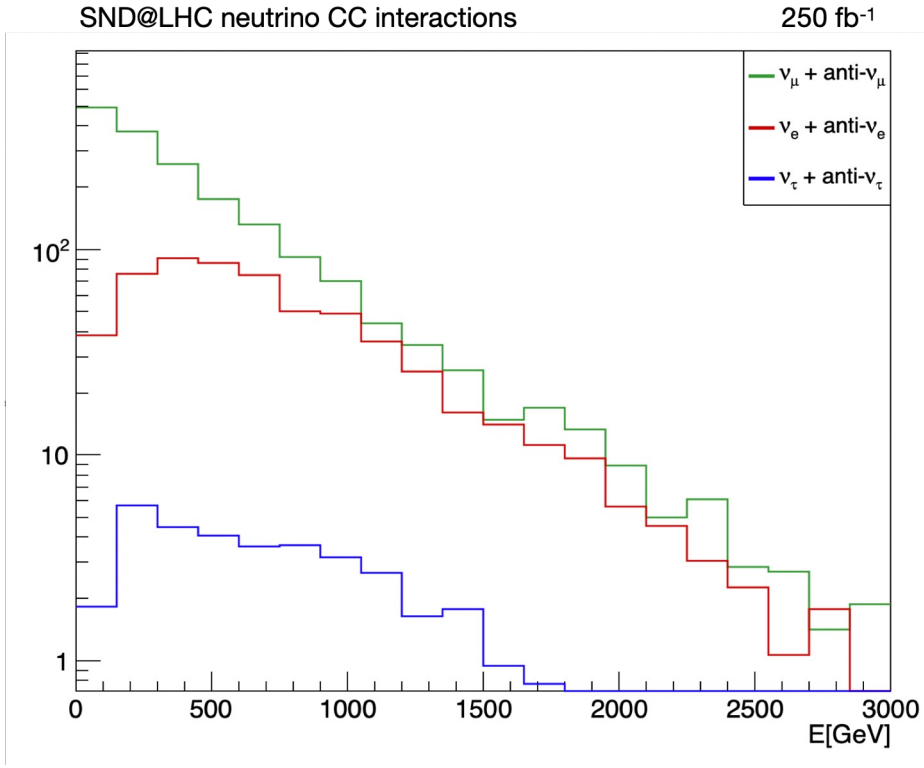




Expected neutrino event rates

- 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}:
  - ν_μ+$\bar{\nu}_\mu$ charged-current: 1270
  - ν_e+$\bar{\nu}_e$ charged-current: 390
  - ν_τ+$\bar{\nu}_\tau$ charged-current: 30





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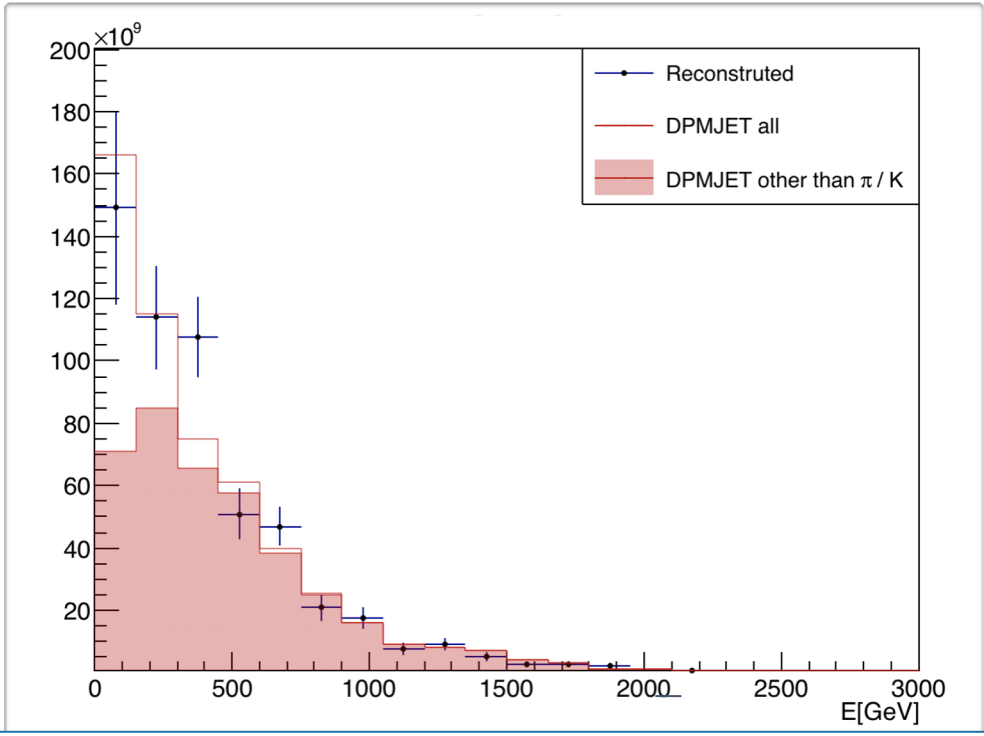
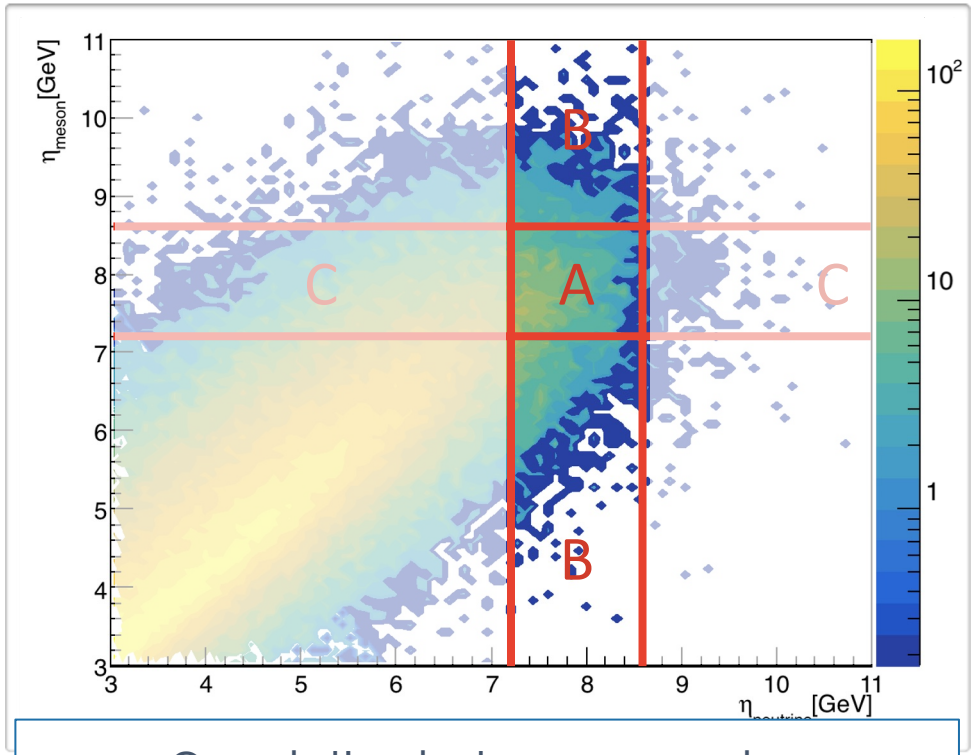
ν_τ	415	2.4×10^{10}	740	20	740	10
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10	740	5
TOT		4.0×10^{12}		1690		555

Neutrinos from charm production

- Expect 90% of ν_e+ν_e to originate from charm decays.
  - SND@LHC ν_e+ν_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 ν_e+ν_e spectrum at SND@LHC.



Correlation between η_ν and η_c

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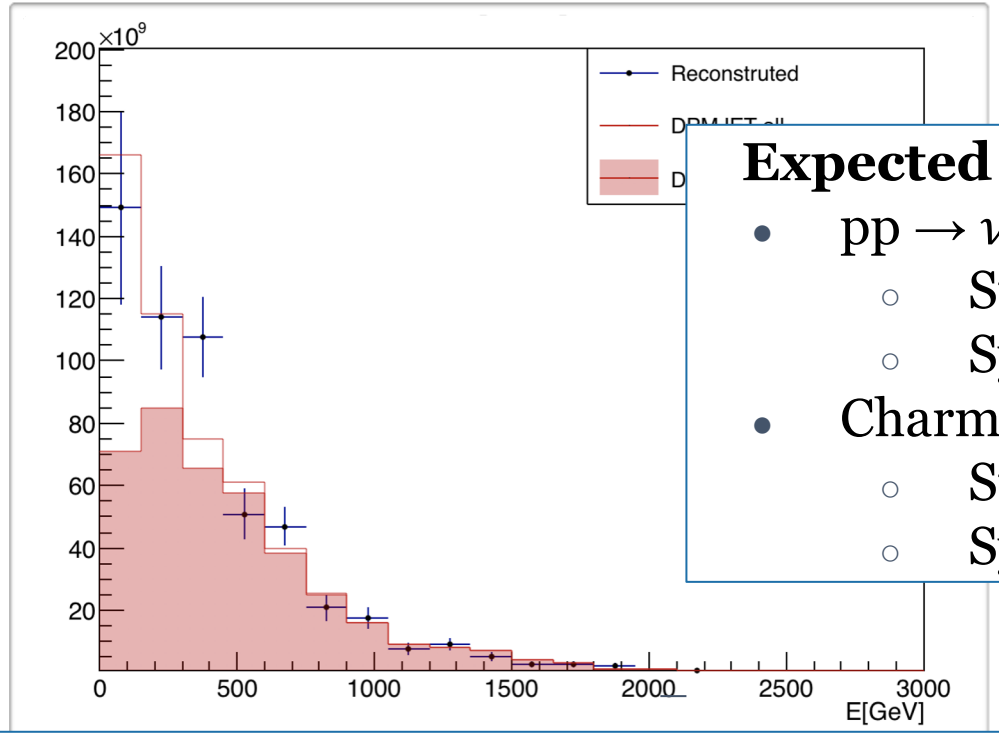
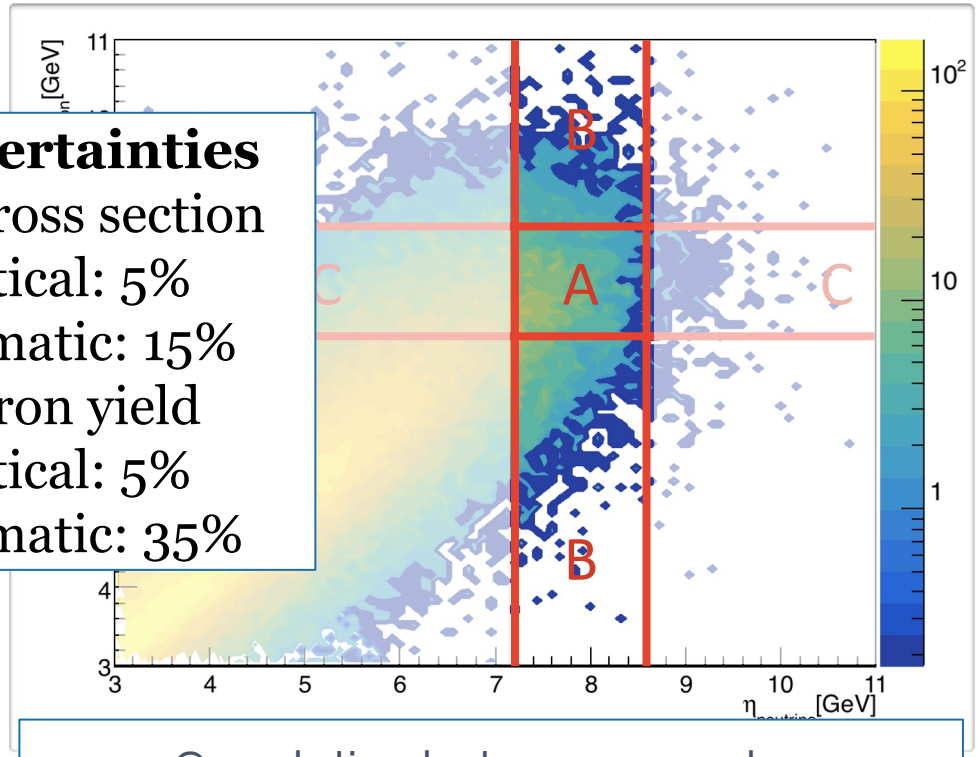


Reconstructed ν_e+ν_e spectrum at SND@LHC.

Expected uncertainties

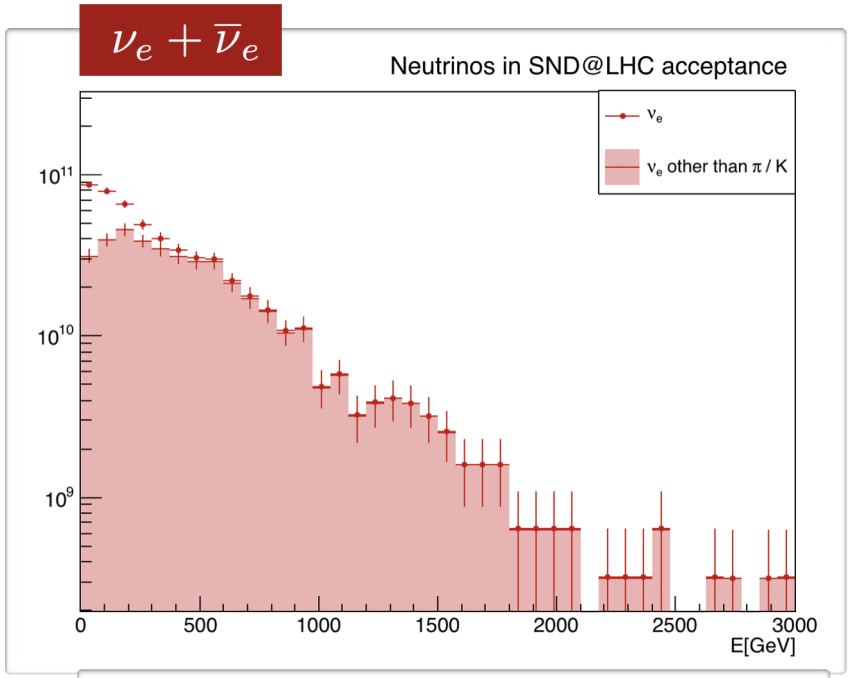
- pp → ν_eX cross section
  - Statistical: 5%
  - Systematic: 15%
- Charm hadron yield
  - Statistical: 5%
  - Systematic: 35%



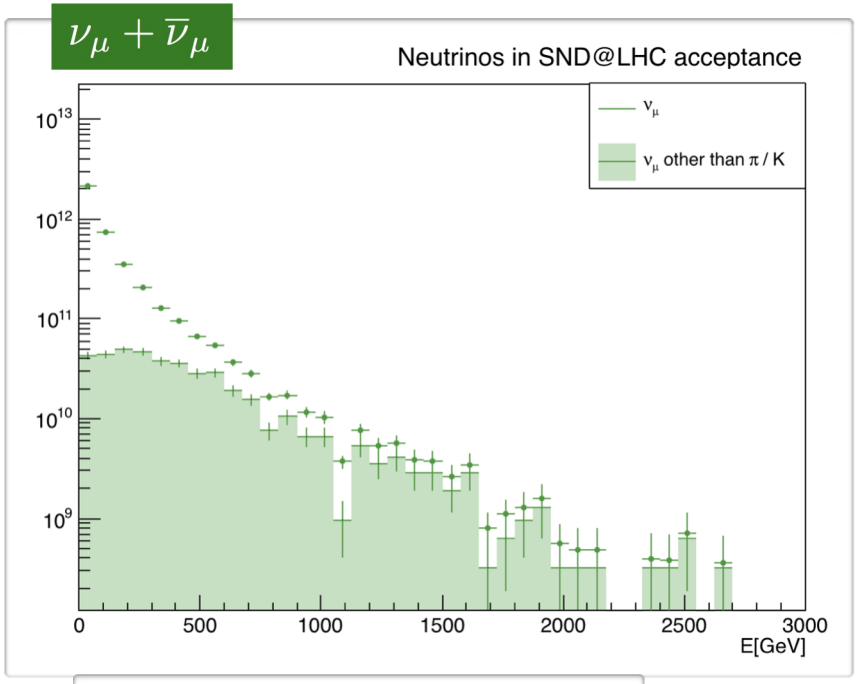
Correlation between η_ν and η_c

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.



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



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

π/K contamination

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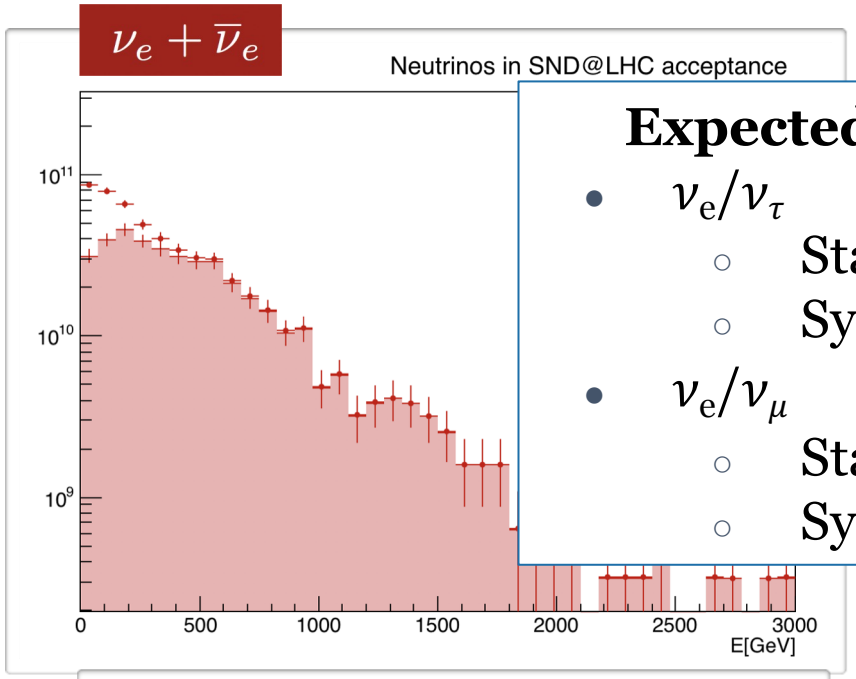

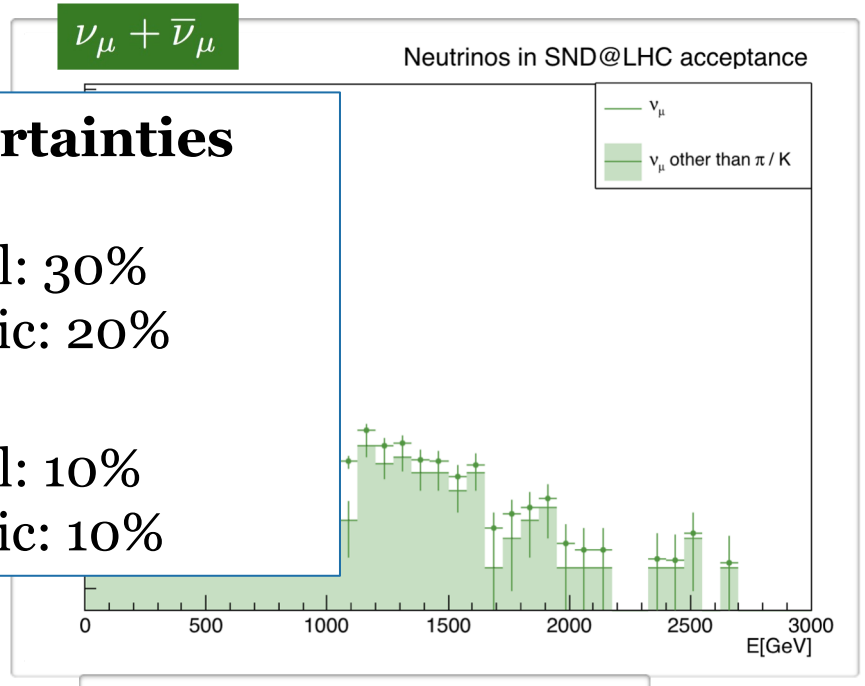

Expected uncertainties

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

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

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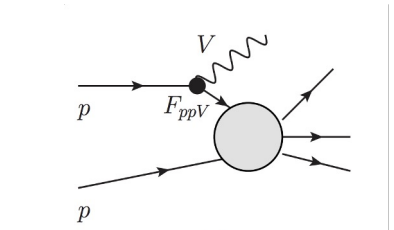
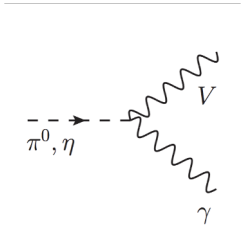
π/K contamination

Feebly interacting particles

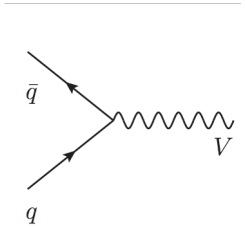
- SND@LHC is sensitive to new **dark sector** particles.



p bremmstrahlung

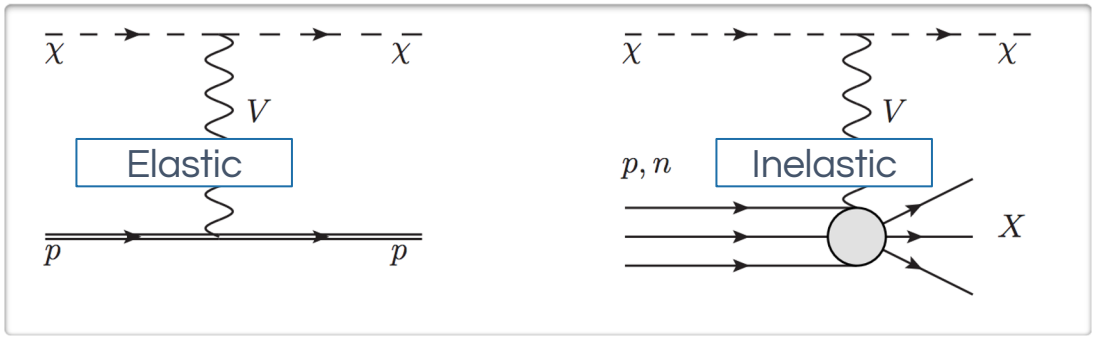


Meson decay

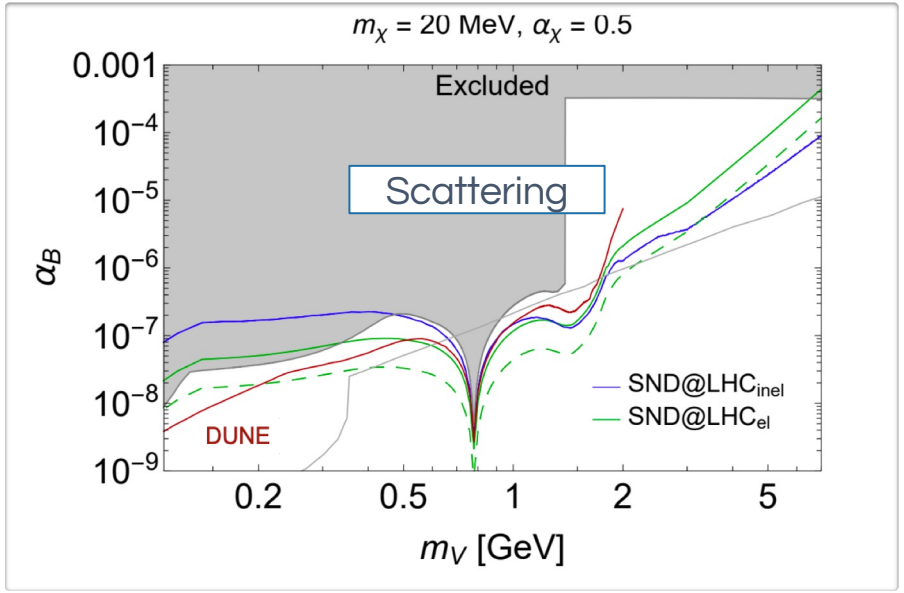


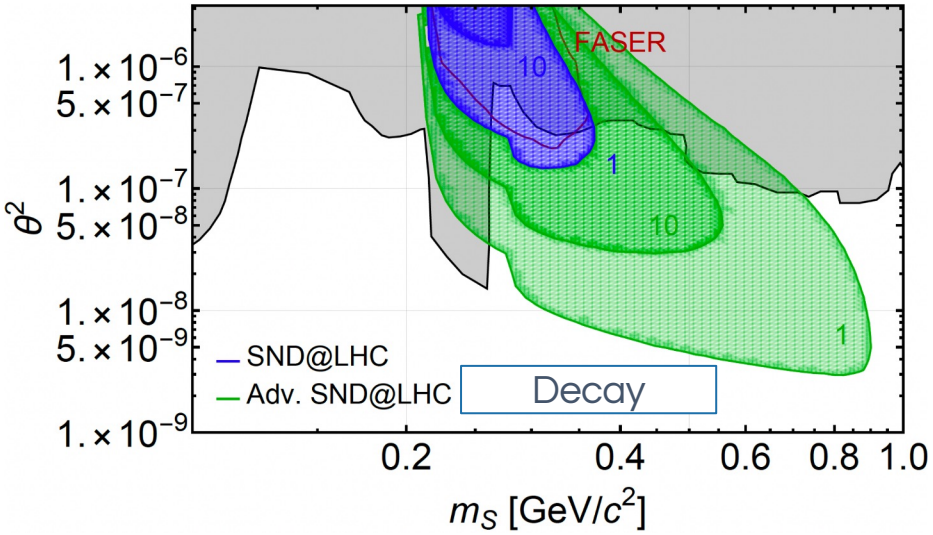
Drell-yan

  - **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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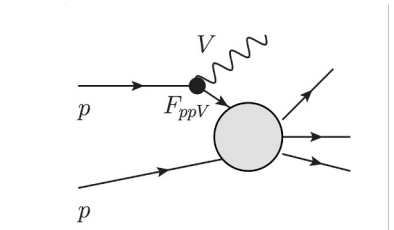

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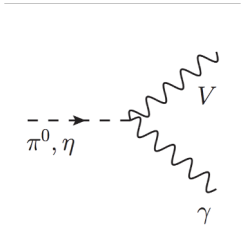

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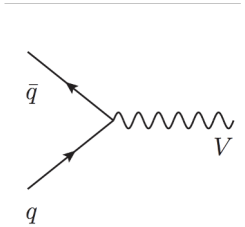
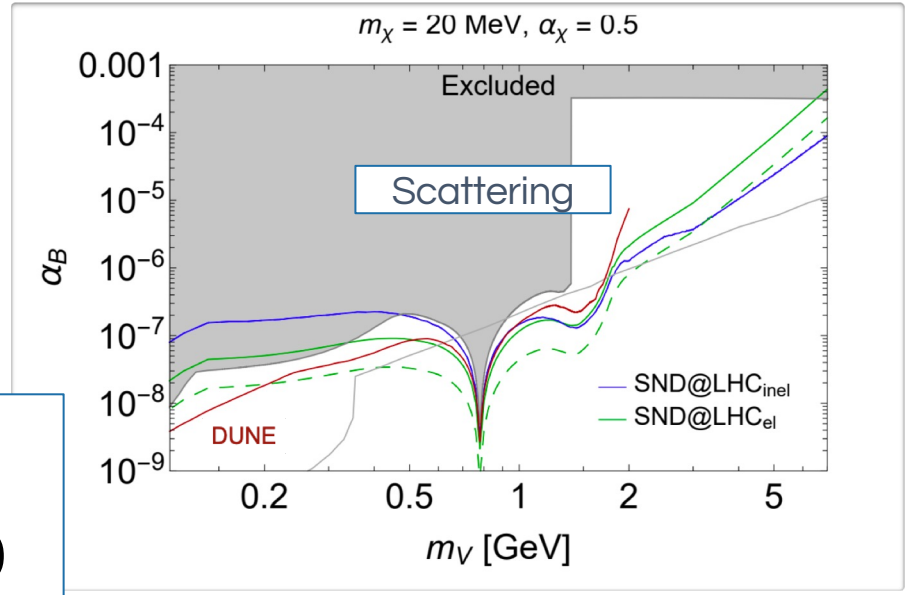


Drell-yan



- **Scattering** in the detector.
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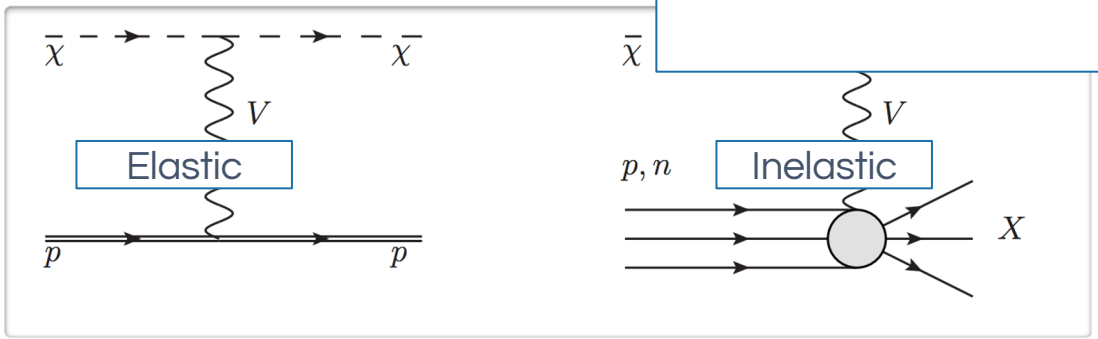
    leptophobic portal.

Signal efficiencies and backgrounds (neutrinos!) under study.



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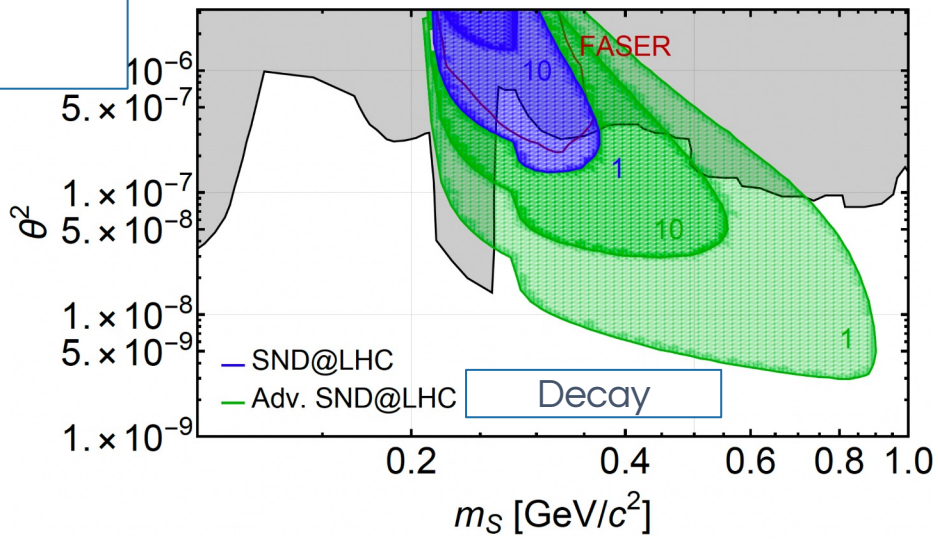

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