SHiP/SND@LHC

Approved 2024 *Approved 2021, 1st physics results 2023*

Hidden-Sector Particles & High-Energy Neutrinos

SHiP
Search for Hidden Particles

LHC
Scattering and Neutrino Detector
at the LHC

Fundação
para a Ciência
e a Tecnologia

CERN/FIS-INS/0028/2021

The LIP SHiP/SND@LHC Group

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LIP Advisory Committee

Lisbon, April 23rd 2025

(contact: nuno@cern.ch)

SND@LHC timeline

CERN approves new LHC experiment

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

March 2021

TECHNICAL PROPOSAL

SND@LHC

January 2021

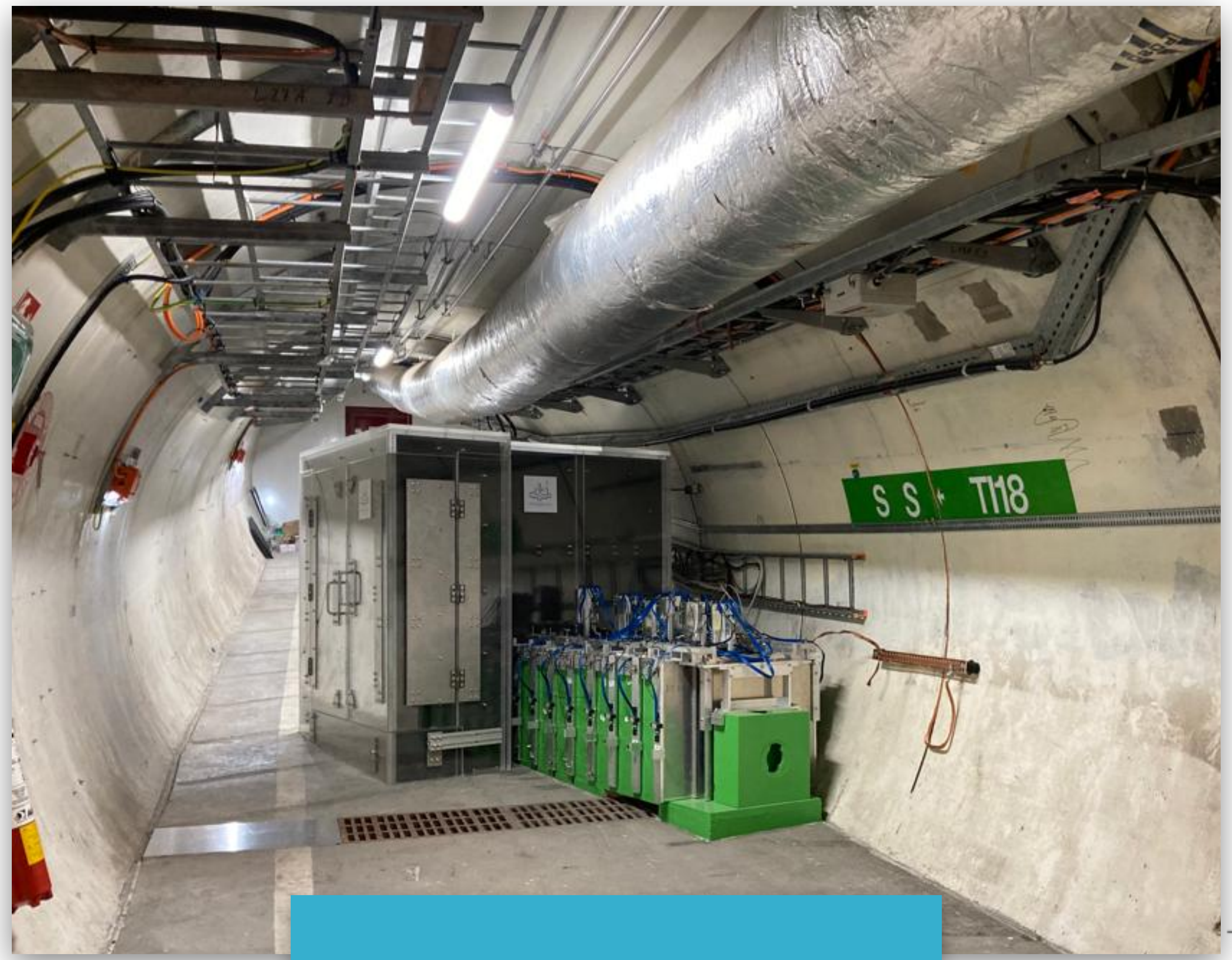
Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

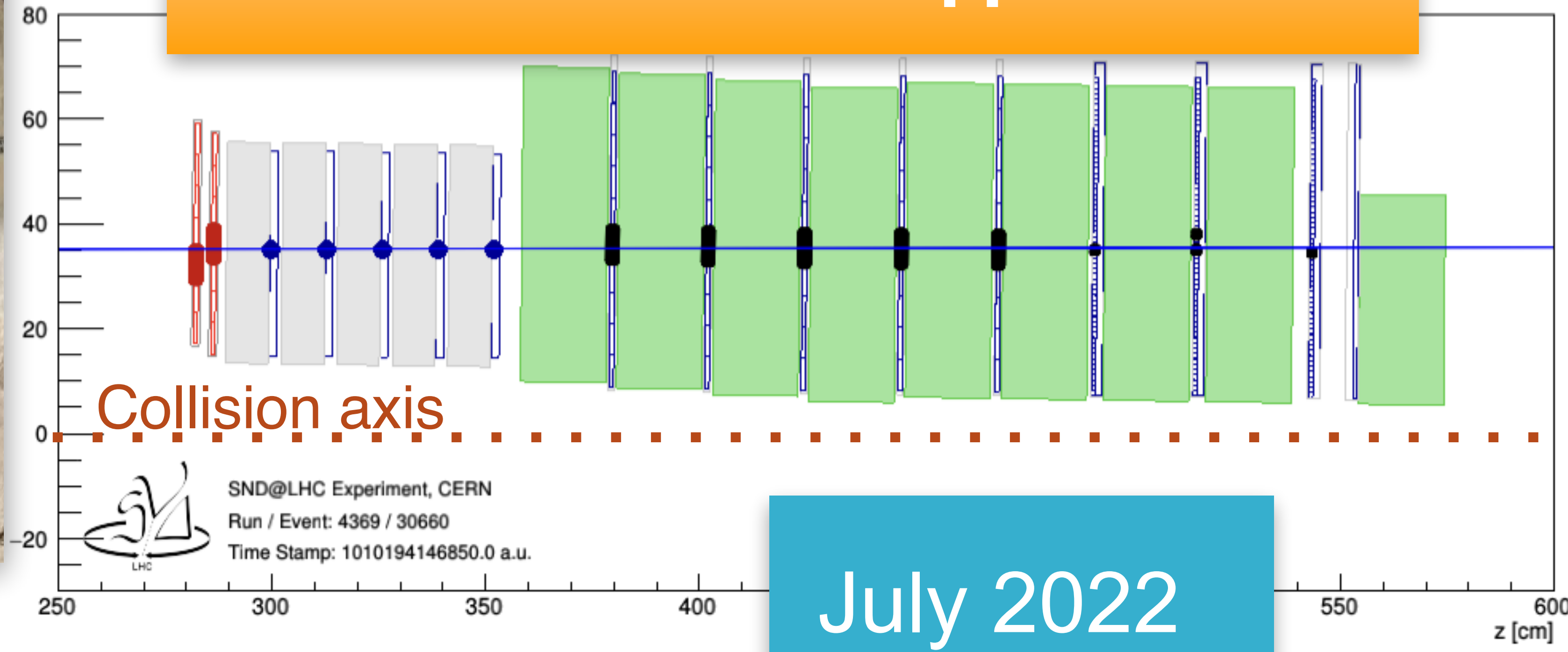
September 2021

December 2021



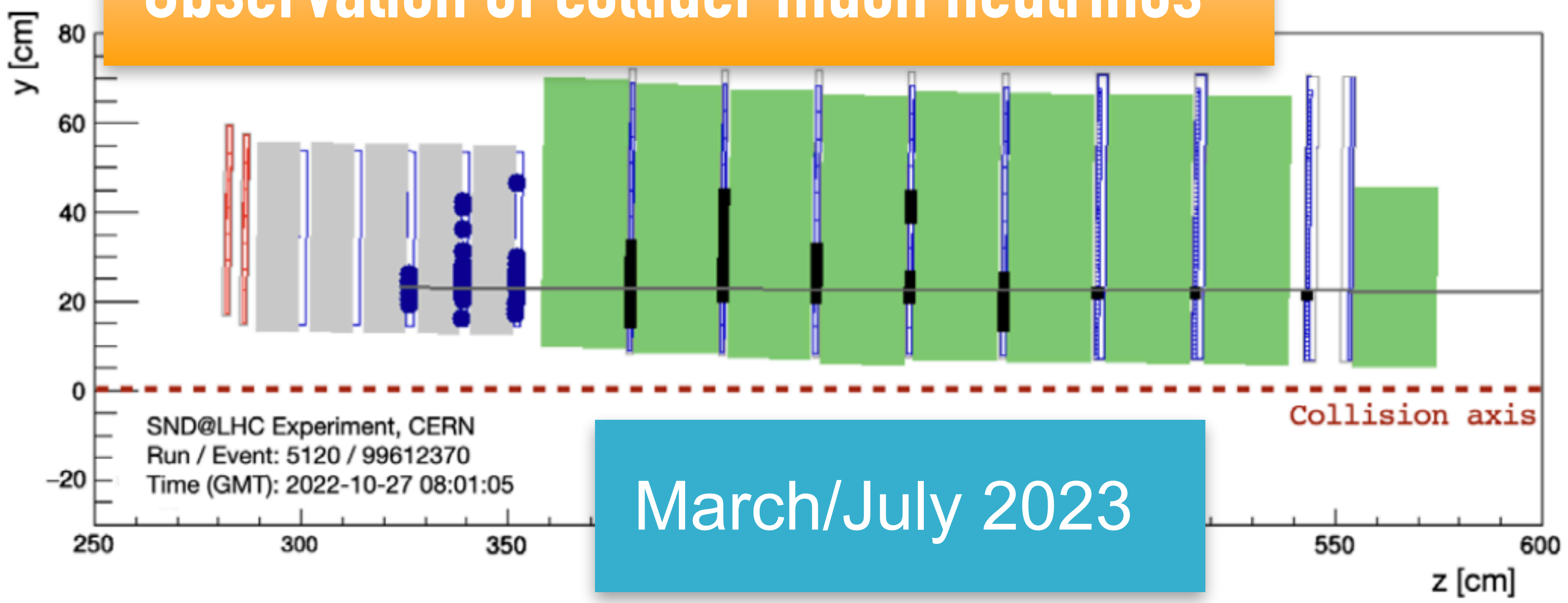
March 2022

Muons from 13.6 TeV pp collision



July 2022

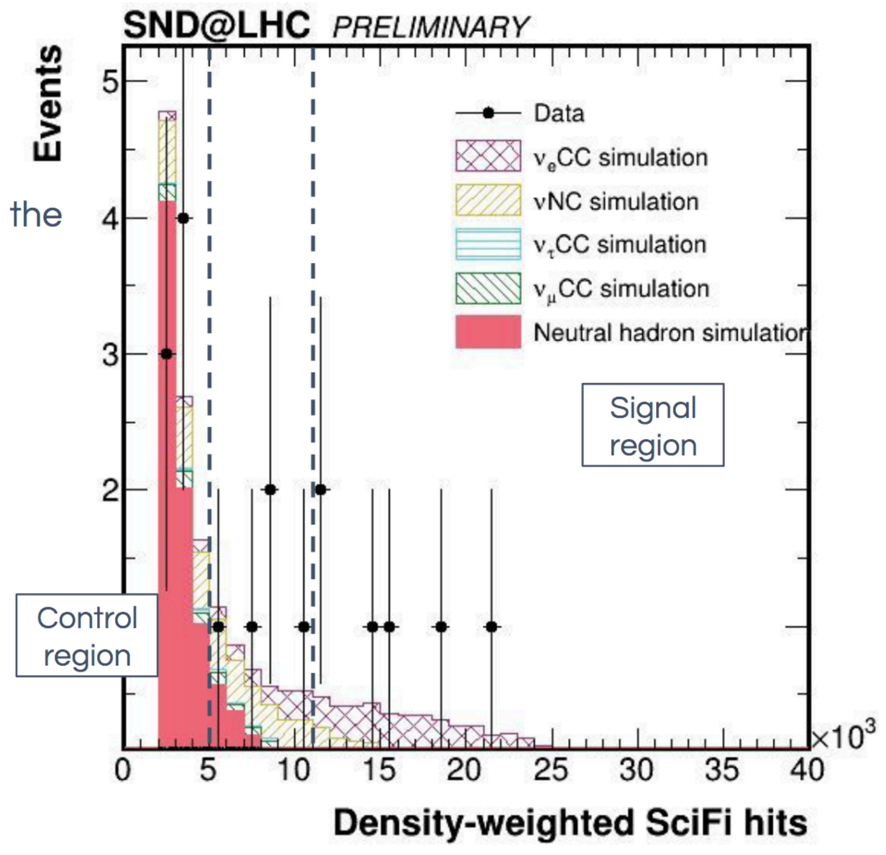
Observation of collider muon neutrinos



March/July 2023

Physics highlights

Observation of ν0μ interactions



- 2022 + 2023 data
- search for shower-like ν events
- signal = ν_e CC + NC

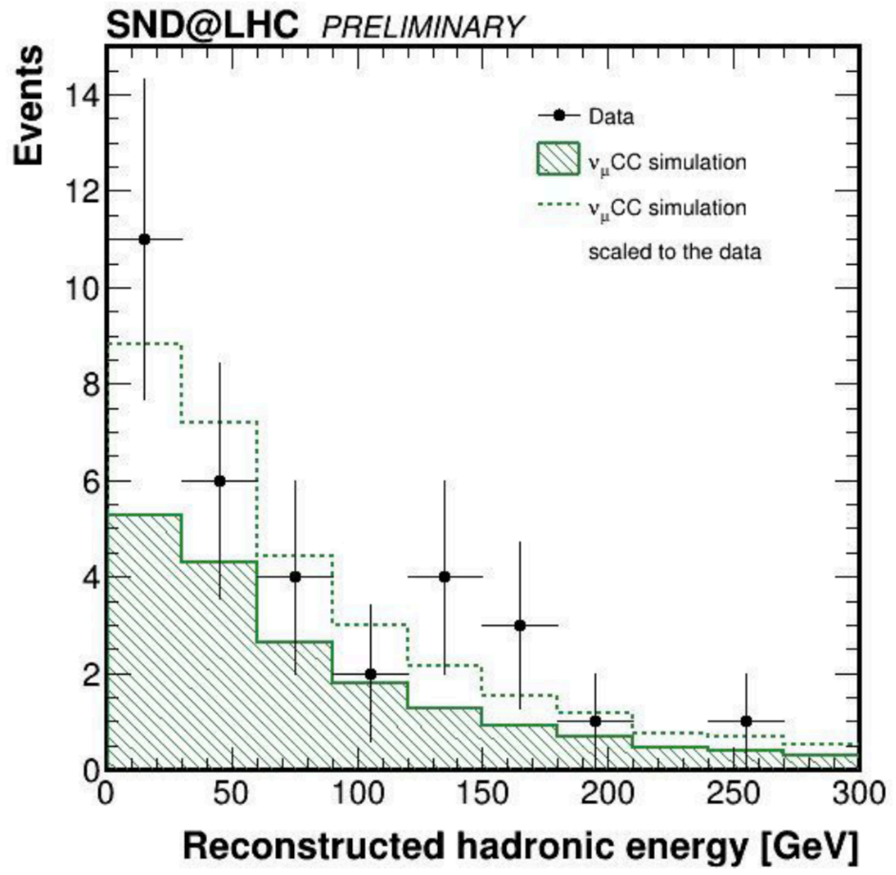
Observation of collider neutrinos without final state muons with the SND@LHC experiment

(Dated: December 2, 2024)

We report the observation of neutrino interactions without final state muons at the LHC, with a significance of 6.4 σ. A data set of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 and 2023 is used, corresponding to an integrated luminosity of 68.6 fb^{-1}. Neutrino interactions without a reconstructed muon are selected, resulting in an event sample consisting mainly of neutral-current and electron neutrino charged-current interactions in the detector. After selection cuts, 9 neutrino interaction candidate events are observed with an estimated background of 0.32 events.

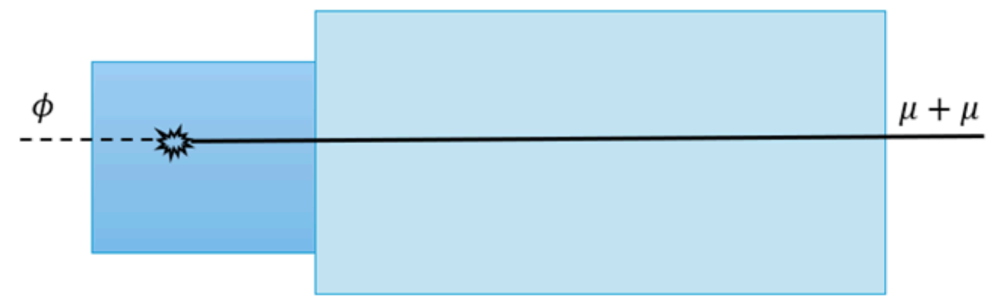
https://arxiv.org/abs/2411.18787

Measurement of ν_μ hadronic energy

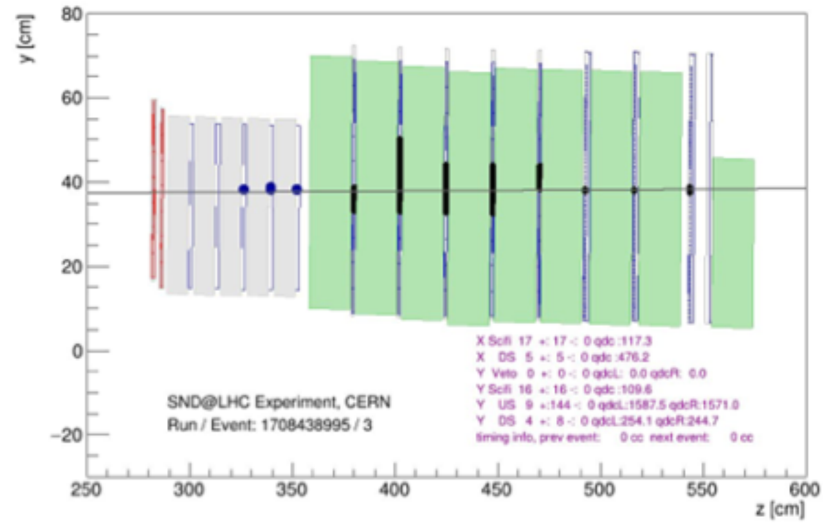


- extended ν_μ CC analysis
- 2022 + 2023 data
- increased fiducial region
- hadronic energy measurement
- paper under preparation

Search for new particles (dark Higgs)



- benchmark FIP model: dark scalar
- signature: collimated dimuons



Searching for Beyond the Standard Model particles decaying to muon pairs with SND@LHC

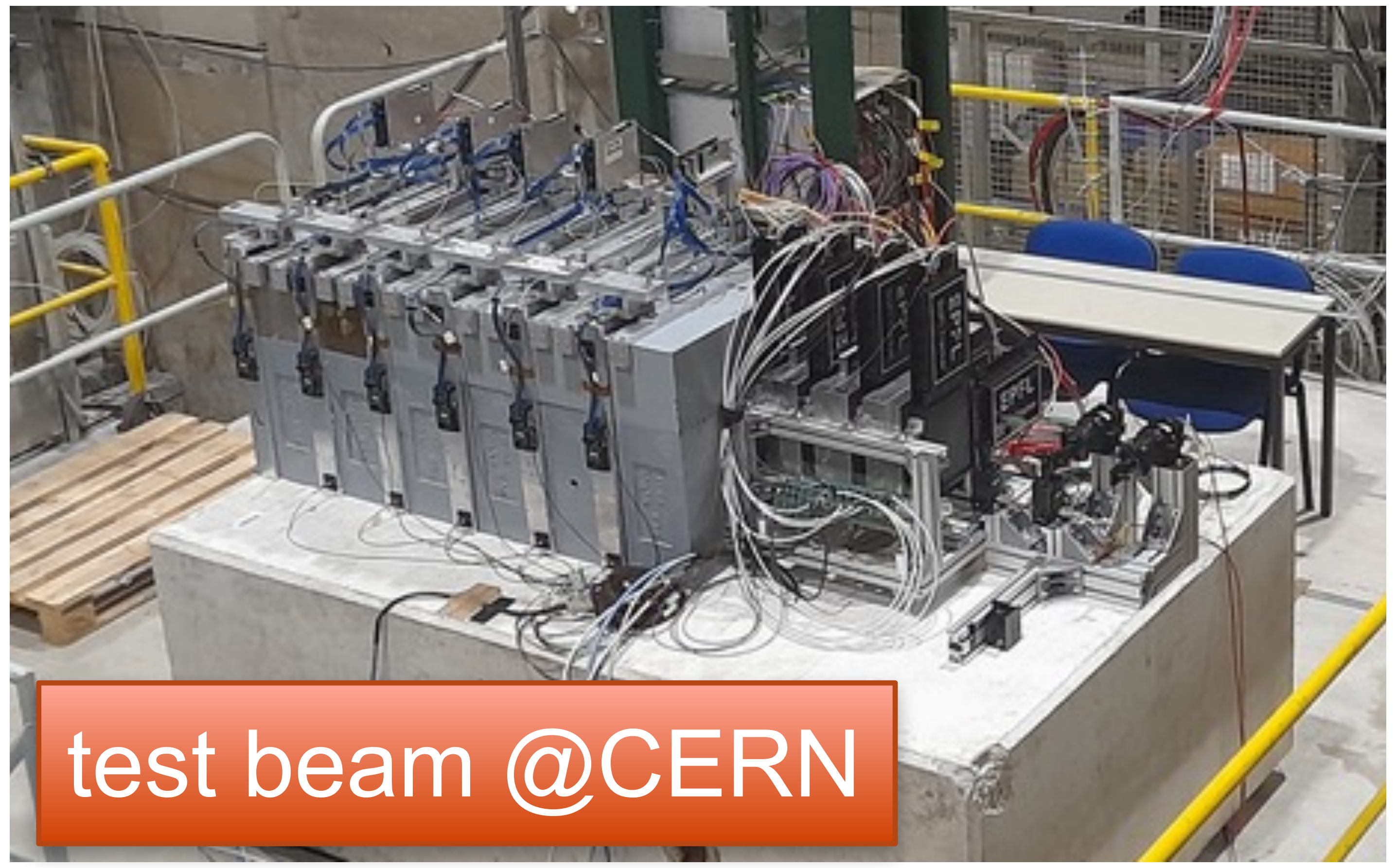
CERN-THESIS-2024-307
28/11/2024

Henrique de Sousa Santos

Thesis to obtain the Master of Science Degree in

Engineering Physics

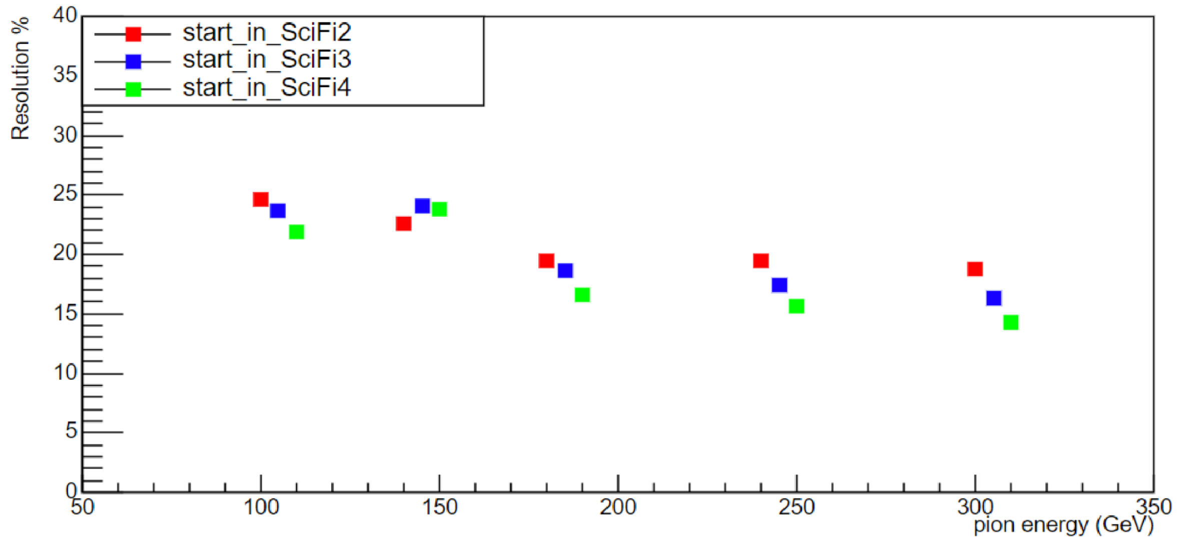
Operations highlights



A replica of SND@LHC detector for test-beam

HCAL mechanics built fully at LIP

Energy calibration of the hadronic calorimeter



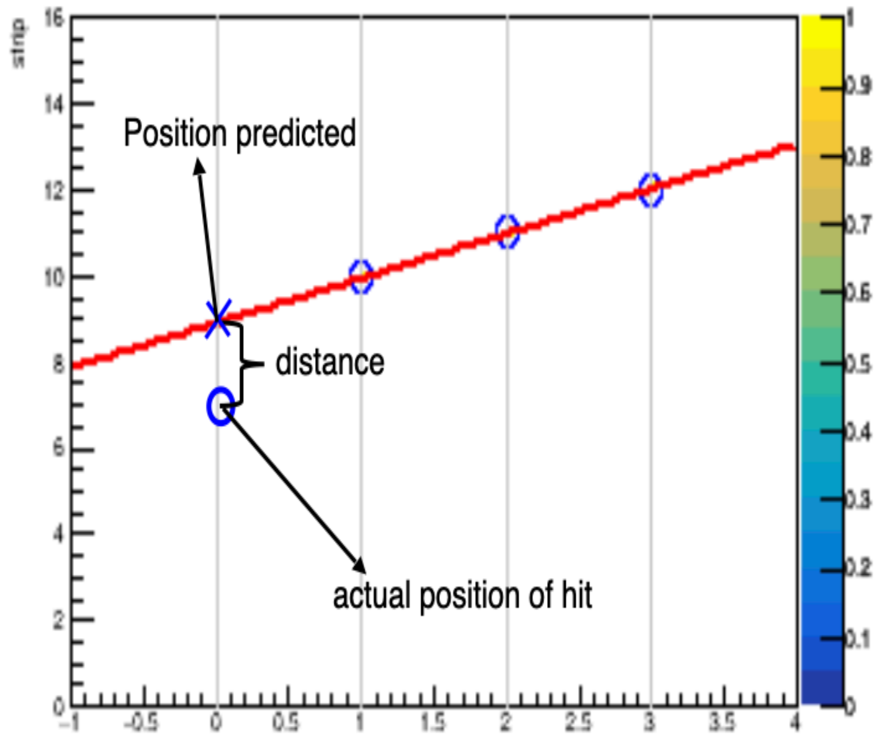
Prepared for submission to JINST

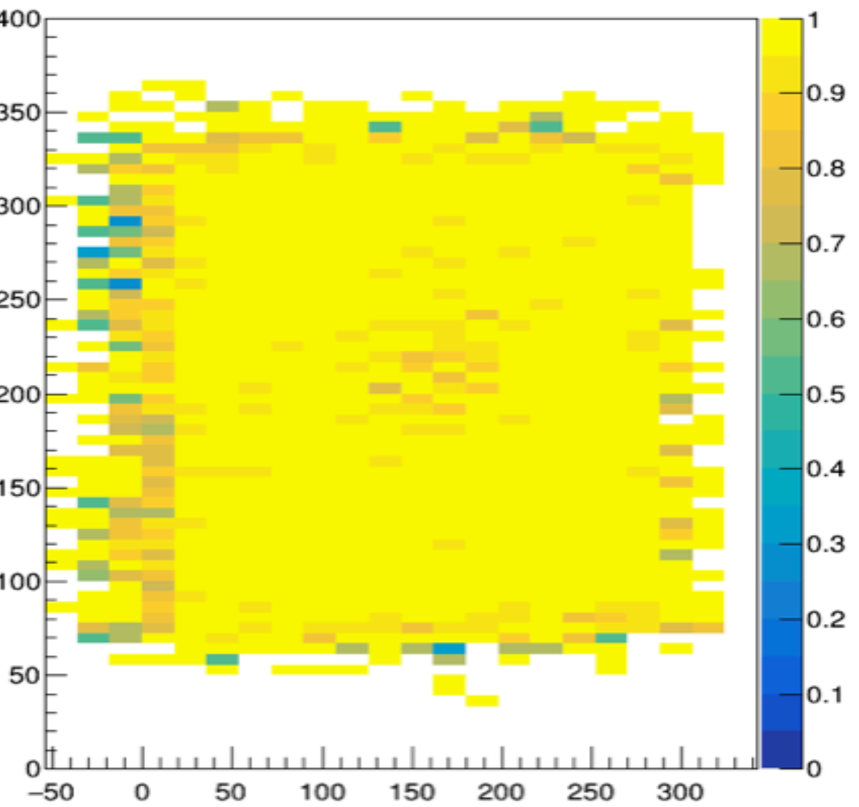
Studies of Hadronic Showers in SND@LHC

The SND@LHC Collaboration

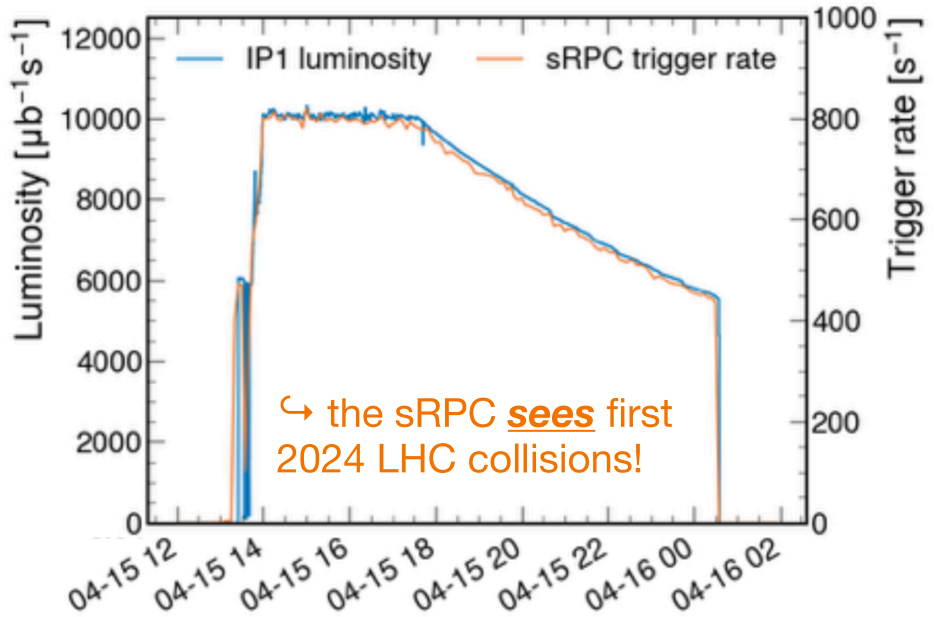
Abstract: The SND@LHC experiment was built for observing neutrinos arising from LHC pp collisions. The detector consists of two sections: a target instrumented with SciFi modules and a hadronic calorimeter/muon detector. Energetic νN collisions in the target produce hadronic showers. Reconstruction of the shower total energy requires an estimate of the fractions deposited in both the target and the calorimeter. In order to calibrate the SND@LHC response, a replica of the detector was exposed to hadron beams with 100 to 300 GeV in the CERN SPS H8 test beam line in Summer 2023. This report describes the methods developed to tag the presence of a shower, to locate the shower origin in the target, and to combine the target SciFi and the calorimeter signals so to measure the shower total energy.

https://arxiv.org/abs/2504.01716





Probing muon flux at the LHC with LIP's sealed-RPC



Tracking muons from ongoing LHC Collisions

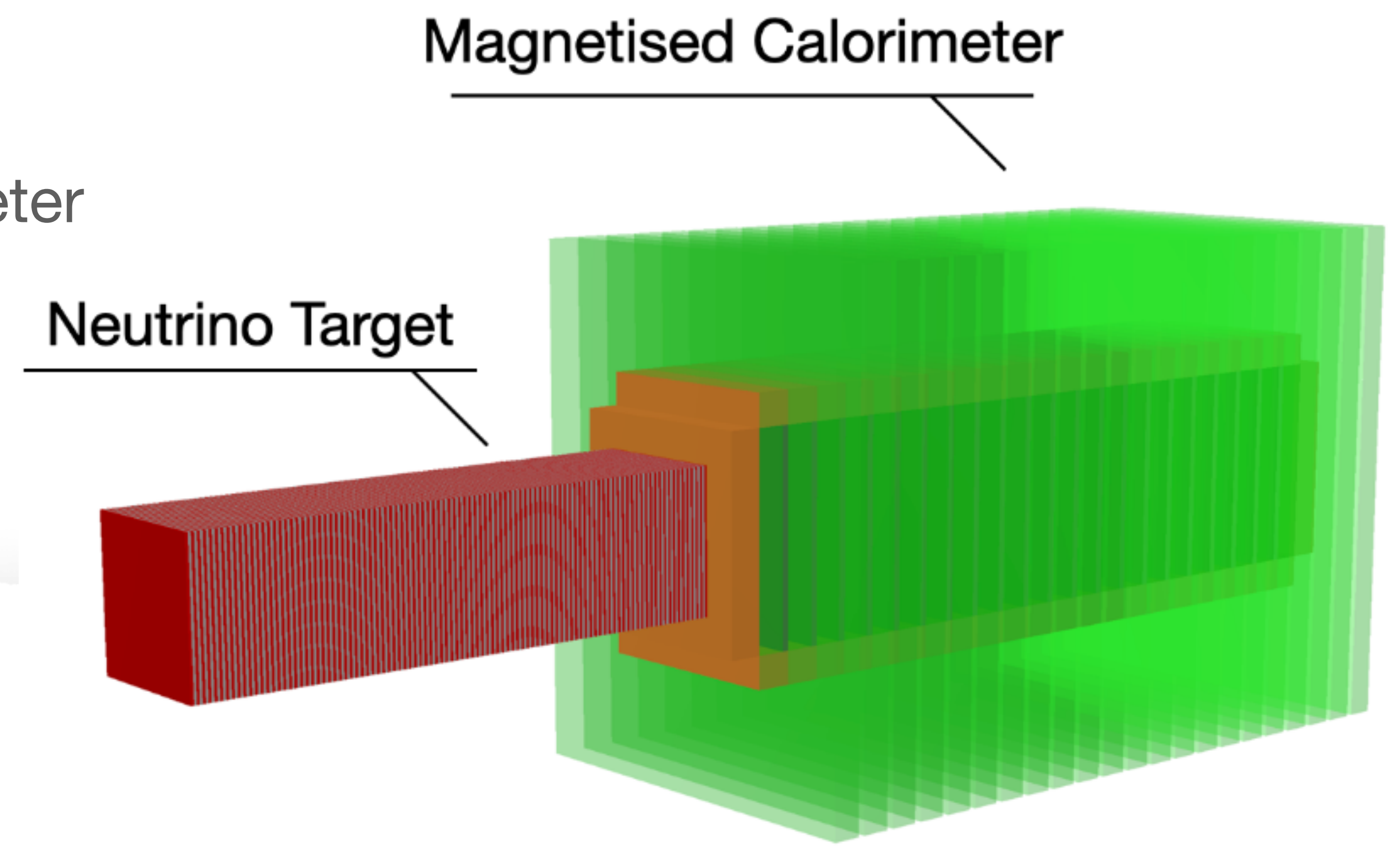
6th September 2024, LIP Summer Internship, Final Workshop

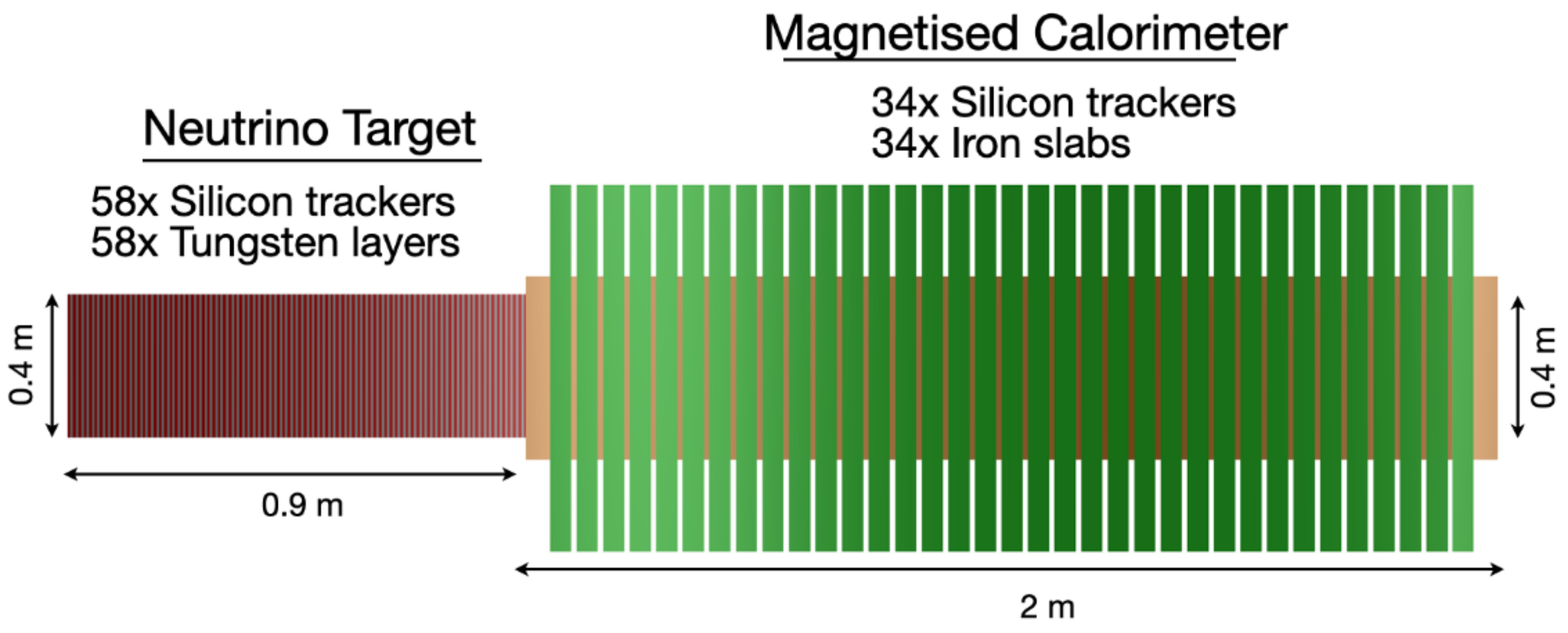
Alexandre Mendonça

Tristan Barlerin

Upgrades: SND@HL-LHC

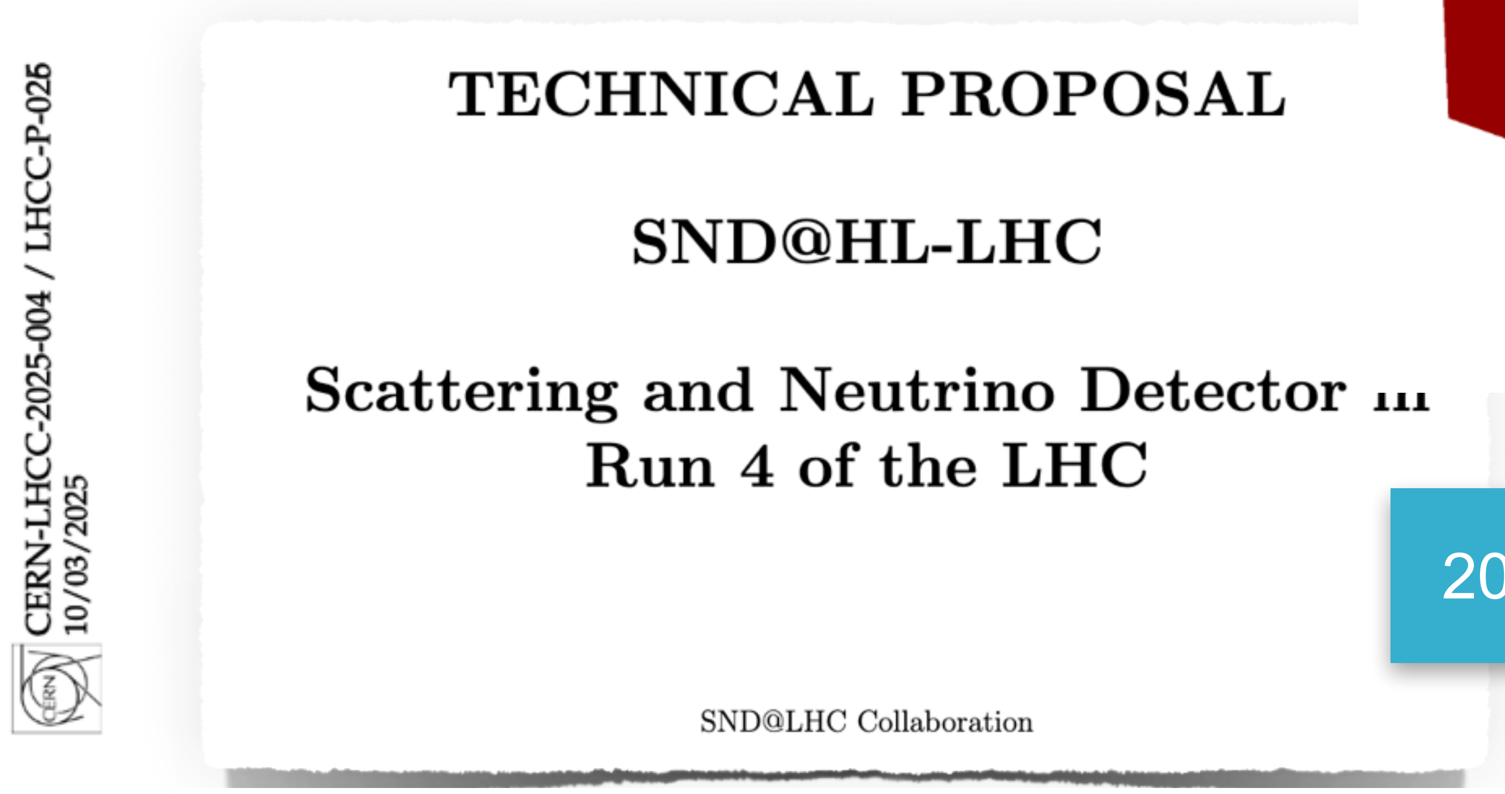
- detector for operating during Run 4
- adopted a **silicon**-based target + calorimeter (major excavation no longer considered)
- timing layers: scintillator or **RPC**





Silicon replaces emulsions (precise tracking at high-lumi)

Magnetised tracking calorimeter (fine shower sampling, μ p_T + charge)


CERN-LHCC-2025-004 / LHCC-P-026
10/03/2025

TECHNICAL PROPOSAL

SND@HL-LHC

Scattering and Neutrino Detector in Run 4 of the LHC

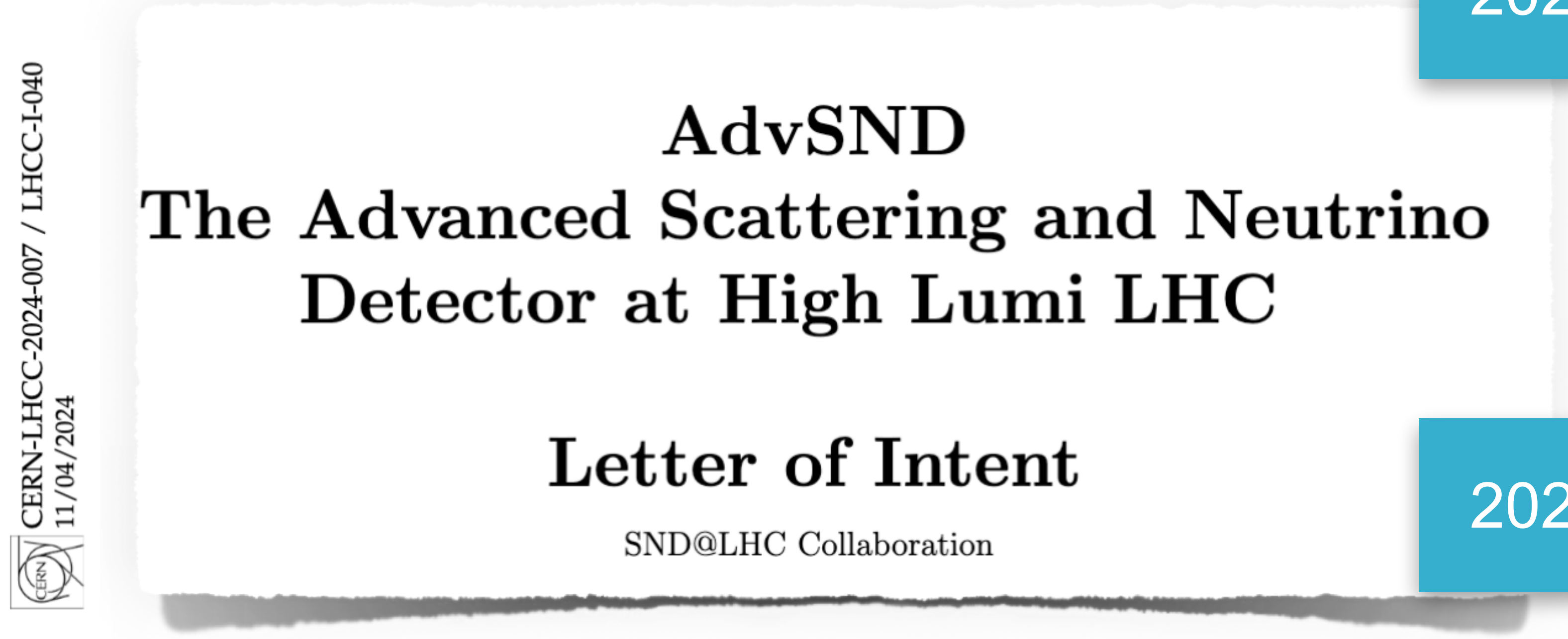
SND@LHC Collaboration

2025/3

Addendum to the AdvancedSND LoI

CERN-LHCC-2024-014 ; LHCC-I-040-ADD-1

2024/9

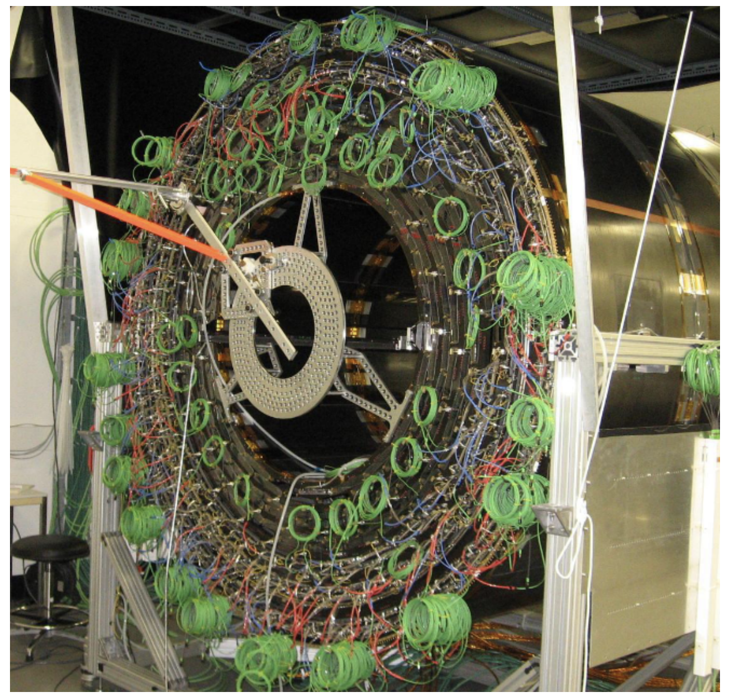

CERN-LHCC-2024-007 / LHCC-I-040
11/04/2024

AdvSND
The Advanced Scattering and Neutrino Detector at High Lumi LHC

Letter of Intent

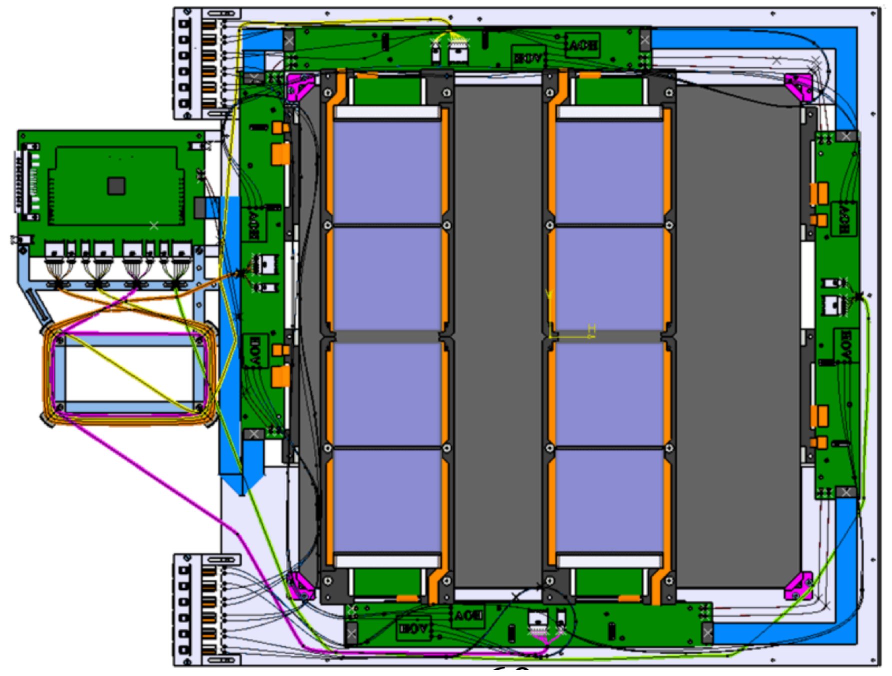
SND@LHC Collaboration

2024/4



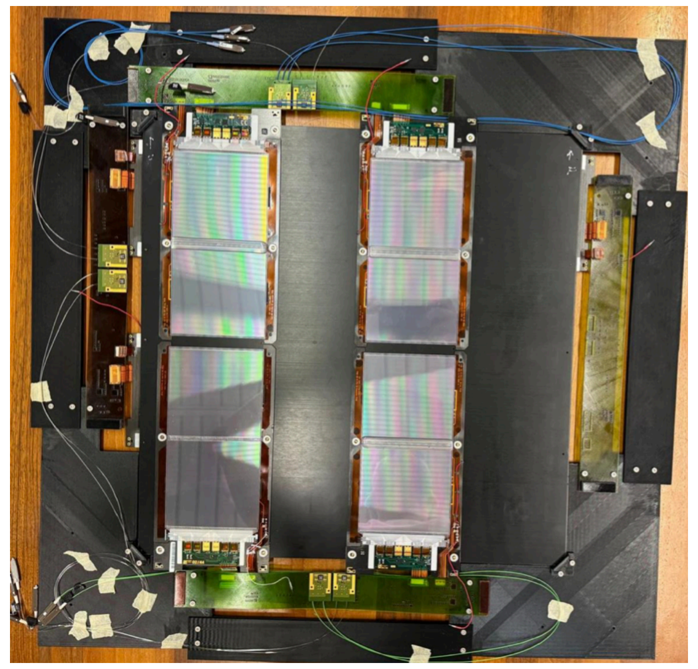
CMS tracker outer barrel

1680 modules available



Silicon station geometry layout

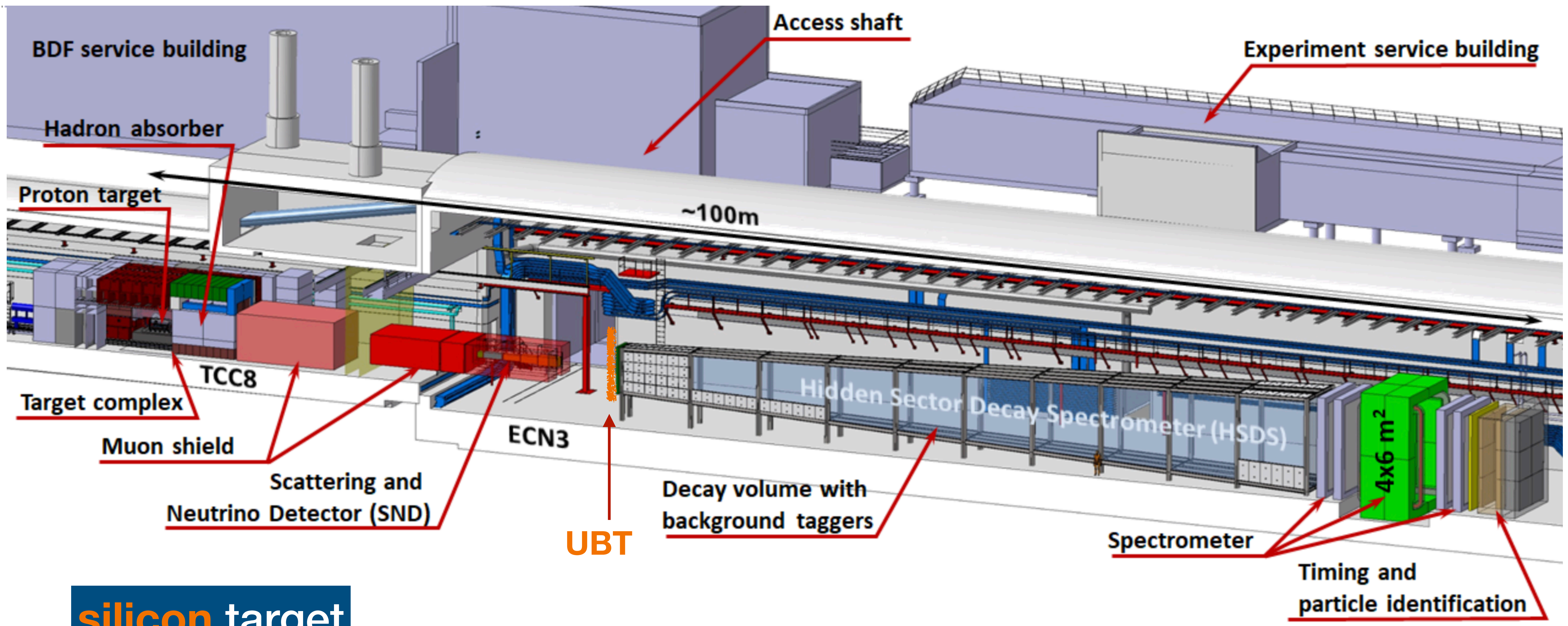
122μm strip pitch



Silicon station prototype

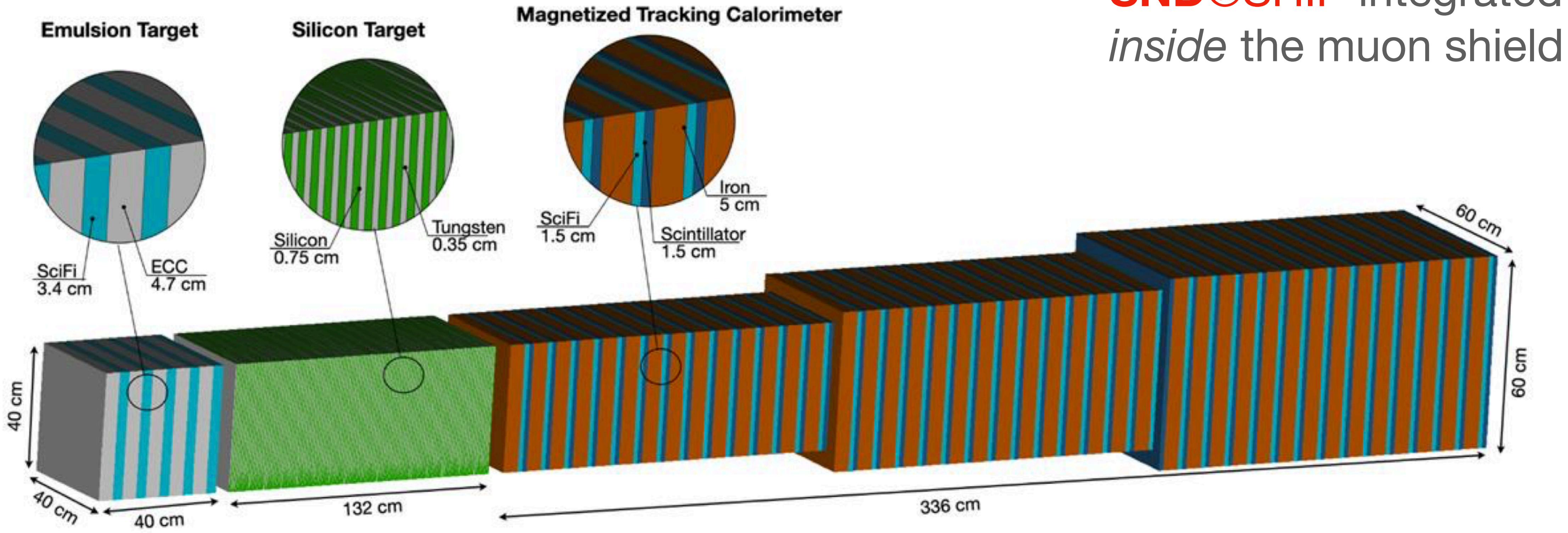
non-irradiated spares

Upgrades: SHiP@ECN3



SHiP approved: 2024

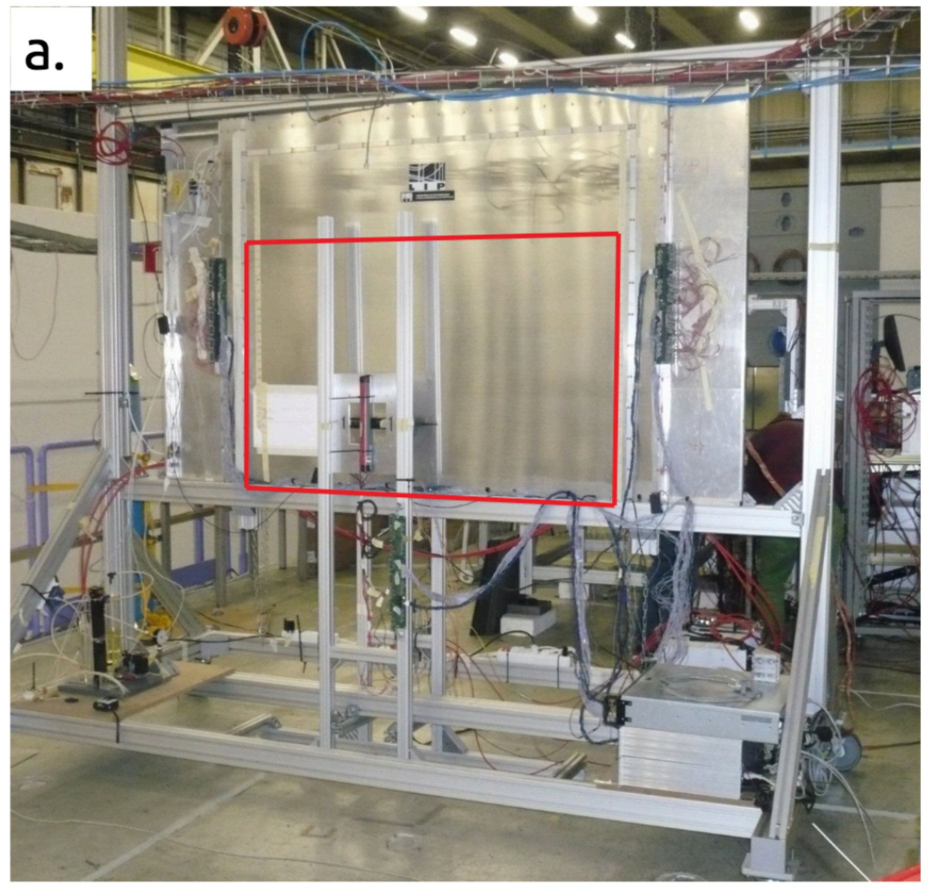
silicon target



SND@SHIP integrated *inside* the muon shield

UBT veto

- based on **RPC** technology
- specification reaccessed/reoptimisation
- a new prototype being advanced:
- reduced material budget
- gas-flow + sealed implementations
- optimize efficiency / timing / rate capabilities

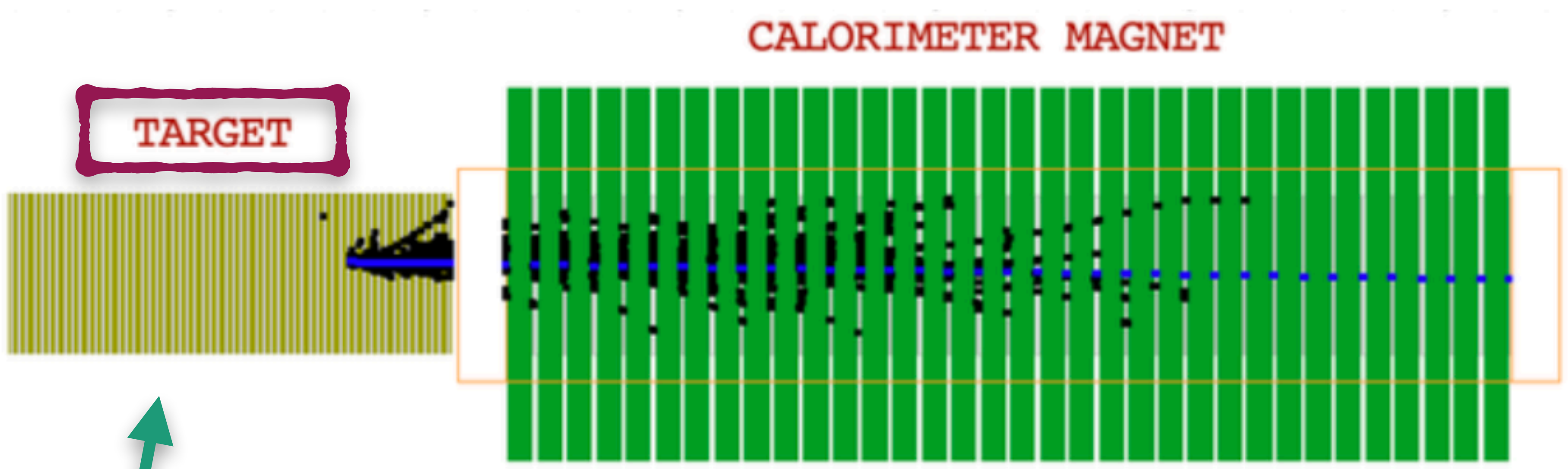


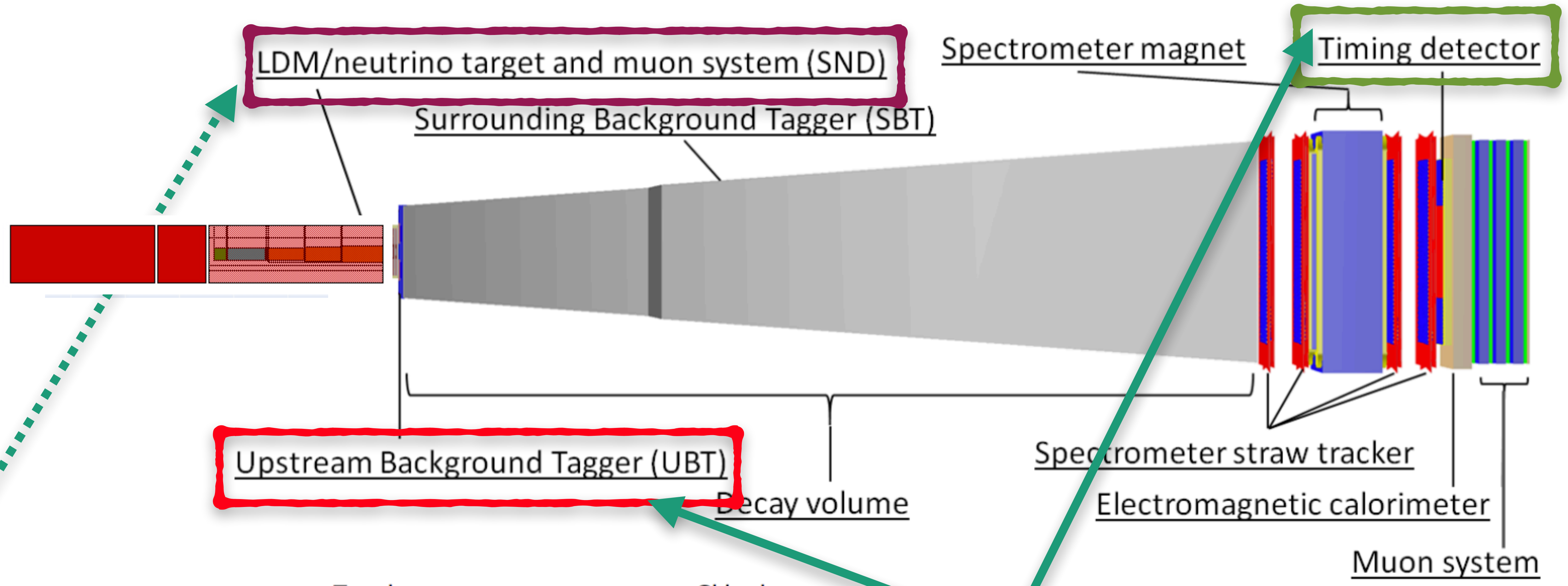
Original RPC prototype

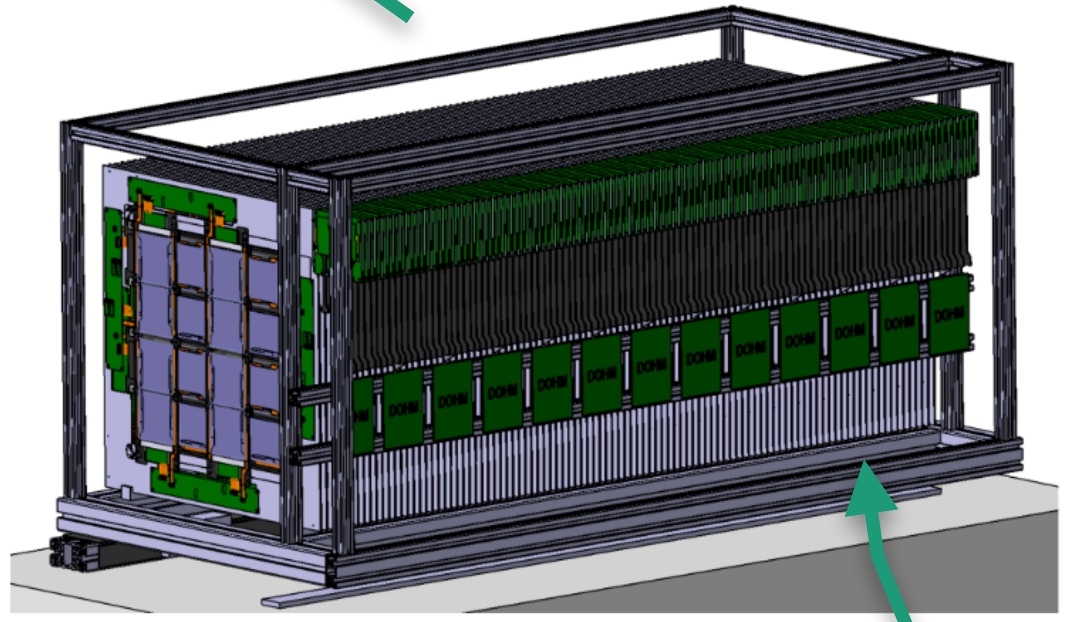
Towards the future detectors: HL-LHC/SHiP Synergy

AdvSND @HL-LHC

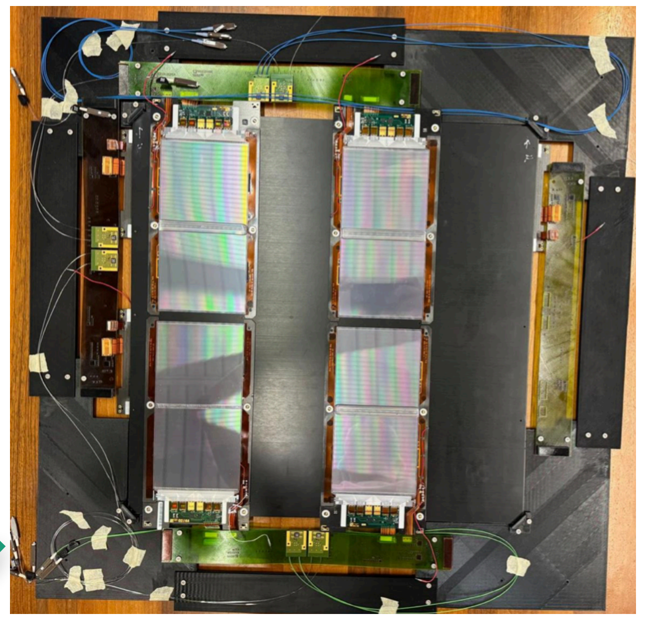
SHiP @ECN3



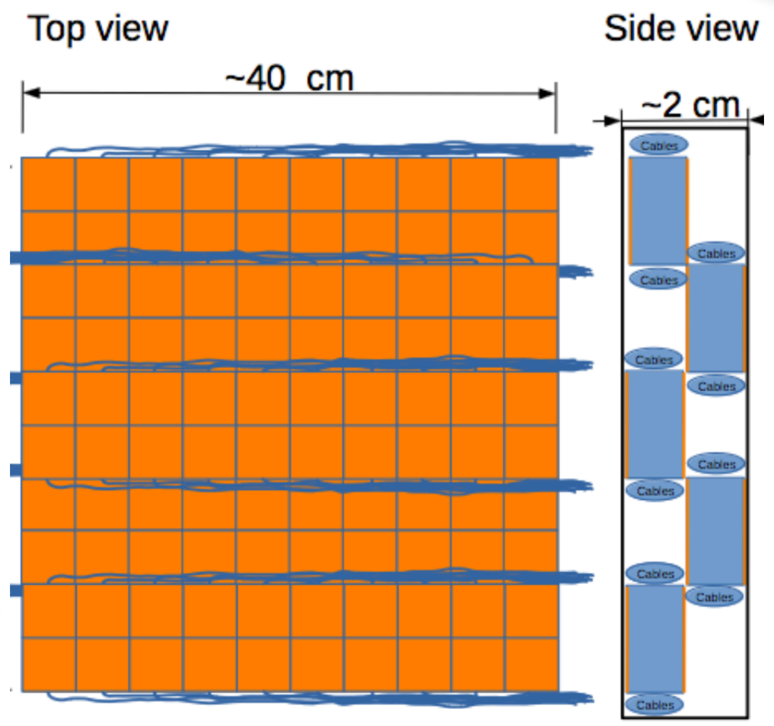




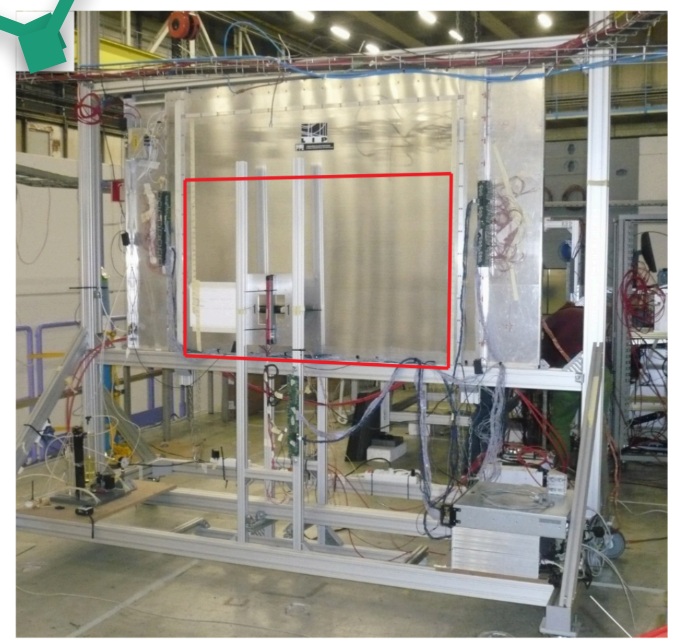
Silicon target model



Silicon station prototype



timing-RPC model



RPC prototype

Silicon-based target tracker

- **HL-LHC** experience directly benefits **SHiP**
- SND@**HL-LHC** as modulo-0 for SND@ **SHiP**

Precision-timing RPCs

- background vetoing (+ timing) core for **SHiP**
- also required for triggering Si in **SND@HL-LHC**

ν charm-tagging

- feed trigger to ATLAS
- requires fast timing

European strategy contributions

https://indico.lip.pt/event/1924/sessions/998/attachments/4939/8050/Collider_Neutrinos_SND-LHC.pdf

Exploring Hidden Sector | SHiP

The Search for Hidden Particles experiment (SHiP) is a proposed a general-purpose intensity-frontier experimental facility for operating in beam-dump mode at the CERN SPS accelerator to search for feebly interacting GeV-scale particles. The SHiP detector is sensitive both to decay and scattering signatures of models with heavy neutral leptons, dark photons, dark scalars, axion-like particles, light dark matter and other feebly intera…

https://indico.lip.pt/event/1924/sessions/998/attachments/4939/8051/Hidden_Particles_SHiP.pdf

Collider Neutrinos | SND@LHC

The recent first direct observation of neutrinos at the LHC, achieved by FASER and SND@LHC, opens the window for the exploration of Neutrino Physics at colliders. Portugal has a major involvement in the SND@LHC experiment, steering both physics analyses and detector upgrade. The exploitation of the potential of the HL-LHC with some key detector improvements will largely extend the physics reach of the experiment both in neutrino physics and in BSM searches. We strongly support the upgrade of the SND@LHC detector, that will allow the exploration of neutrino physics during the HL phase of the LHC.

https://arxiv.org/abs/2504.06692

arXiv:2504.06692v1 [hep-ex] 9 Apr 2025

SHiP experiment at the SPS Beam Dump Facility

[1]SHiP Collaboration & HI-ECN3 Project Team

Abstract

In 2024, the SHiP experiment, together with the associated Beam Dump Facility (BDF) under the auspices of the High Intensity ECN3 (HI-ECN3) project, was selected for the future physics exploitation of the ECN3 experimental facility at the SPS. The SHiP experiment is a general-purpose intensity-frontier setup designed to search for physics beyond the Standard Model in the domain of Feebly Interacting Particles at the GeV-scale. It comprises a multi-system apparatus that provides discovery sensitivity to both decay and scattering signatures of models with feebly interacting particles, such as dark-sector mediators, both elastic and inelastic light dark matter, as well as millicharged particles. The experiment will also be able to perform both Standard Model measurements and Beyond Standard Model searches with neutrino interactions. In particular, it will have access to unprecedented statistics of tau and anti-tau neutrinos. The construction plan foresees commissioning of the facility and detector, and start of operation in advance of Long Shutdown 4, with a programme of exploration for 15 years of data taking. By exploring unique regions of parameter space for feebly interacting particles in the GeV/c^2 mass range, the SHiP experiment will complement ongoing searches at the LHC and searches at future colliders.

Document submitted to European Strategy for Particle Physics Update 2026

https://arxiv.org/abs/2503.24233

Input from the SND@LHC collaboration to the 2026 Update to the European Strategy for Particle Physics

SND@LHC Collaboration

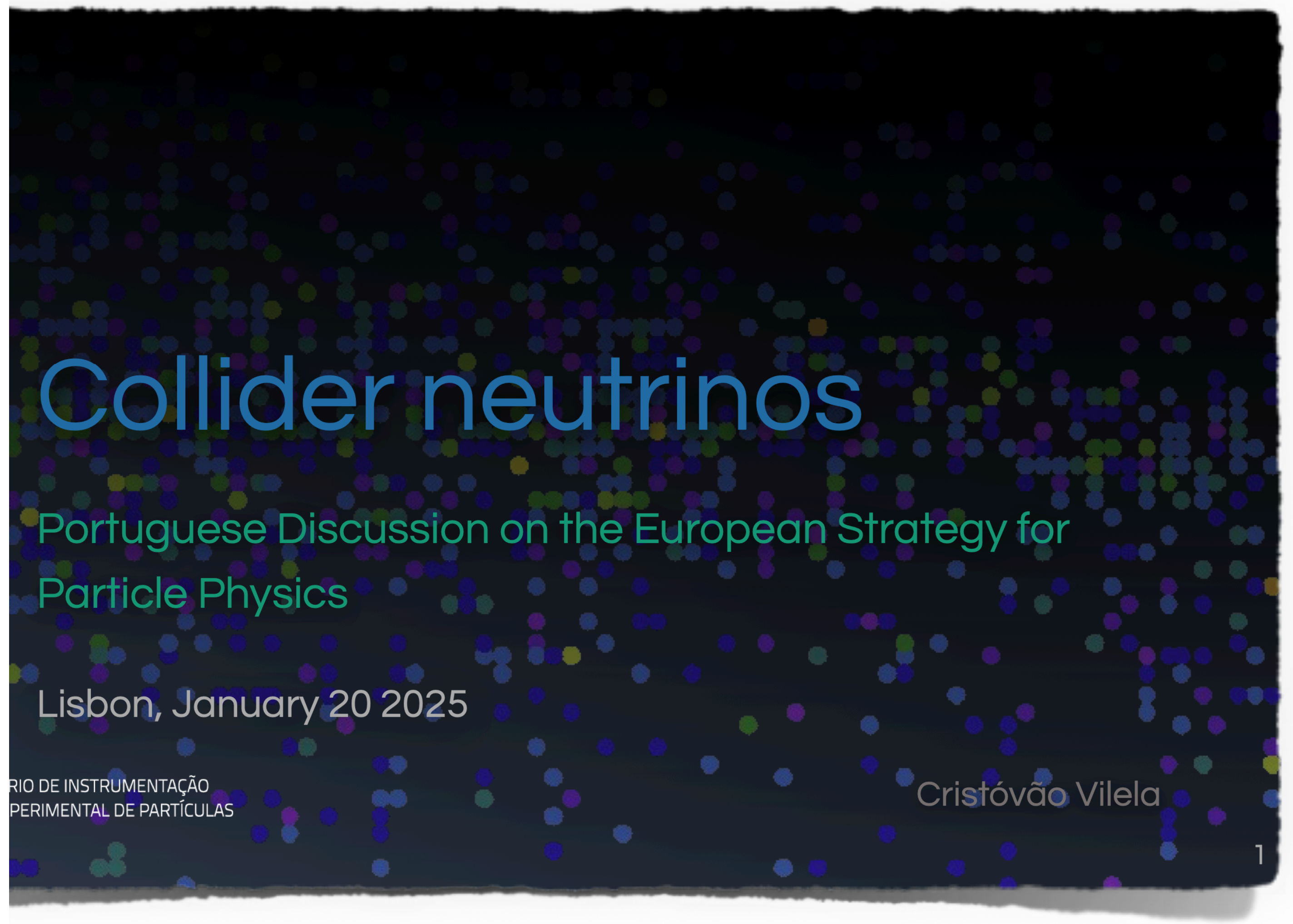
March 28, 2025

By observing collider neutrino interactions of different flavours, the SND@LHC and Faserν experiments have shown that the LHC can make interesting contributions to neutrino physics. This document summarizes why the SND@LHC Collaboration intends to continue taking data at the High Luminosity LHC (HL-LHC).

The upgraded detector[1] will instrument the regions of both the neutrino vertex and the magnetized calorimeter with silicon microstrips. The use of this technology will allow us to continue the physics program of the current SND@LHC detector with higher statistics. It will also offer new possibilities. For instance, the magnetization of the hadron calorimeter will enable the separation between neutrinos and antineutrinos. This could lead to the first direct observation of tau antineutrinos.

The use of ultrafast timing layers will enable triggers to be sent to ATLAS, potentially allowing the identification of the charm quark pair that produced the neutrino interacting in the detector. Such tagging of the neutrino source would fulfill Pontecorvo's original proposal of a tagged neutrino beam. The experiment will perform unique measurements with high energy neutrinos and will also provide a means to measure gluon parton distribution functions in a previously unexplored domain (Bjorken-$x < 10^{-5}$).

Furthermore, the technological advancements of the upgrade and the experience that will be gained in the areas of operation and data analysis will play a crucial role in the design of the neutrino detector for the SHiP experiment.



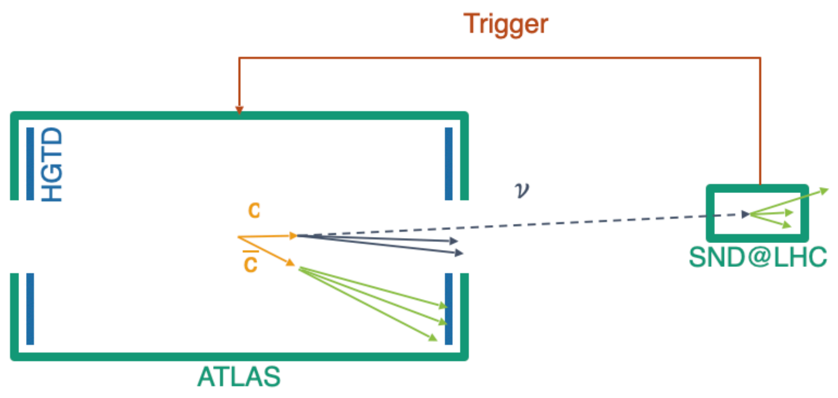
https://indico.lip.pt/event/1924/timetable/?view=standard

S.W.O.T.

Strengths

- team formed of **consolidated researchers**
- strongly integrated in the collaborations
- leadership roles in **Detector** *and* **Physics**

Physics Coordination (CV)
Upgrade Coordination (TC)
Editorial Board (NL)
Decay Vessel Task Force (AB)



Opportunties

- Collecting unique datasets, **extending LHC physics** reach
- **HL-LHC upgrade** offers exciting opportunities for LIP
- **SHiP's approval** by CERN (2024) is a major milestone, **beyond HL-LHC**
- SND + SHiP facilitate long-term **synergies** — in **detector** *and* **physics**
- **Novel windows** in the exploration of Neutrinos *and* New Particles (FIPs)

Weaknesses/Threats

- responsibilities undertaken by the group demand **sustainable funding:** pay collaboration dues; detector construction & operations & upgrade R&D; support researcher's missions; award **studentships**

Funding

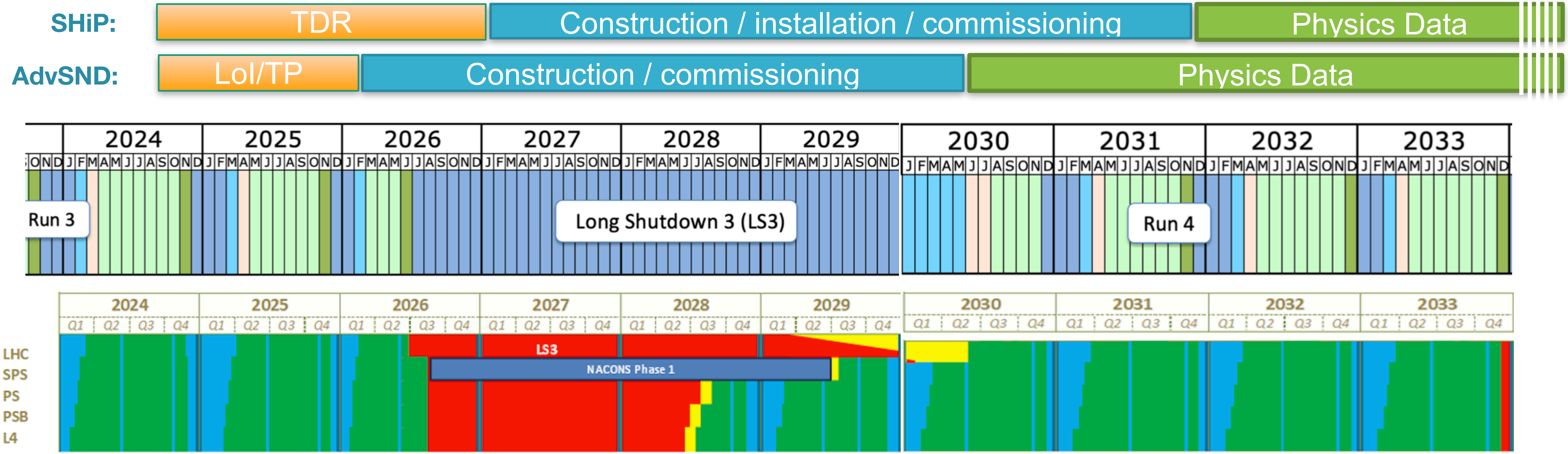
- the group's project submitted to most recent FCT fundo CERN call was **favourably evaluated**, and recommended for funding (x3 wrt previous budget)
- (issue in overall LIP's applications led to withdrawal; current working budget)
- applications have been also submitted to other FCT and European calls

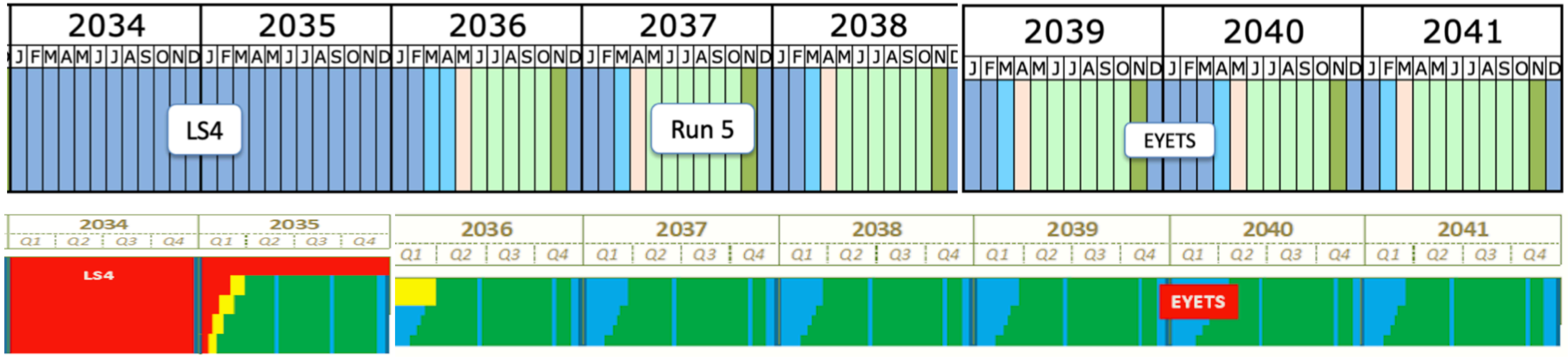
LIP hosted the 2024 SND@LHC Collaboration Week in June, 11-14, in Lisbon, LIP event page

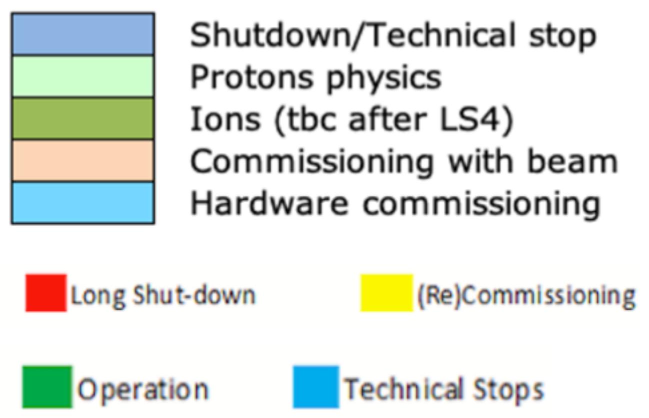
Extra

(extra) CERN long-term schedule

2022-2026 LHC Run3 ATLAS/CMS phase1, SND
2030-2041 HL-LHC ATLAS/CMS phase2, AdvSND
2032-2045 SHiP
2045-2060 (?) FCCee
2070-2095 (?) FCChh



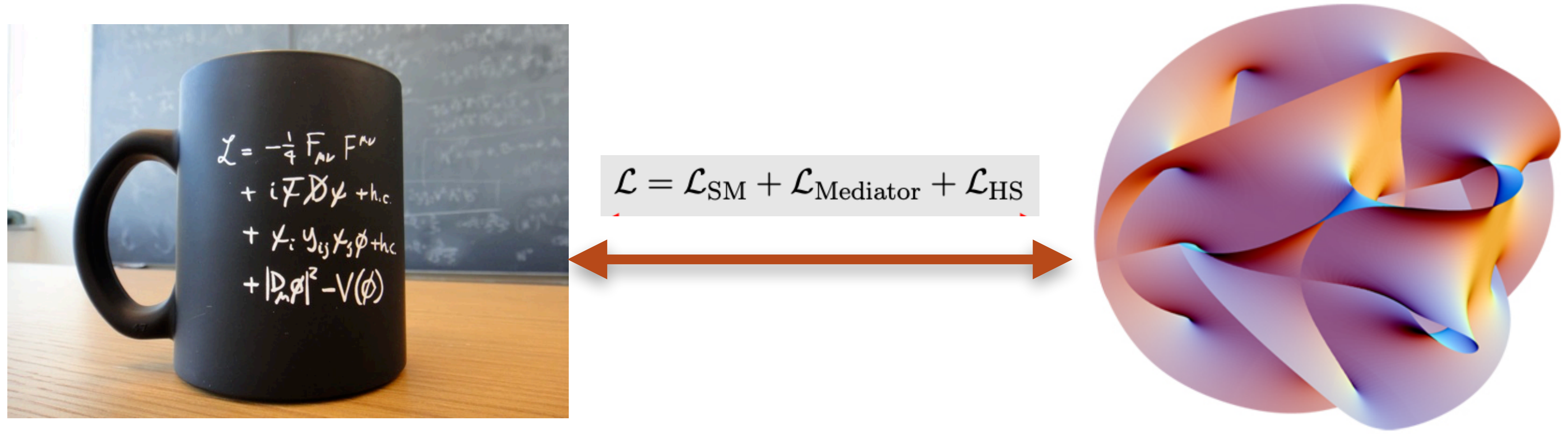




http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

https://home.cern/news/opinion/accelerators/updated-schedule-cerns-accelerators

SHiP: exploring the **hidden sector** of particle physics

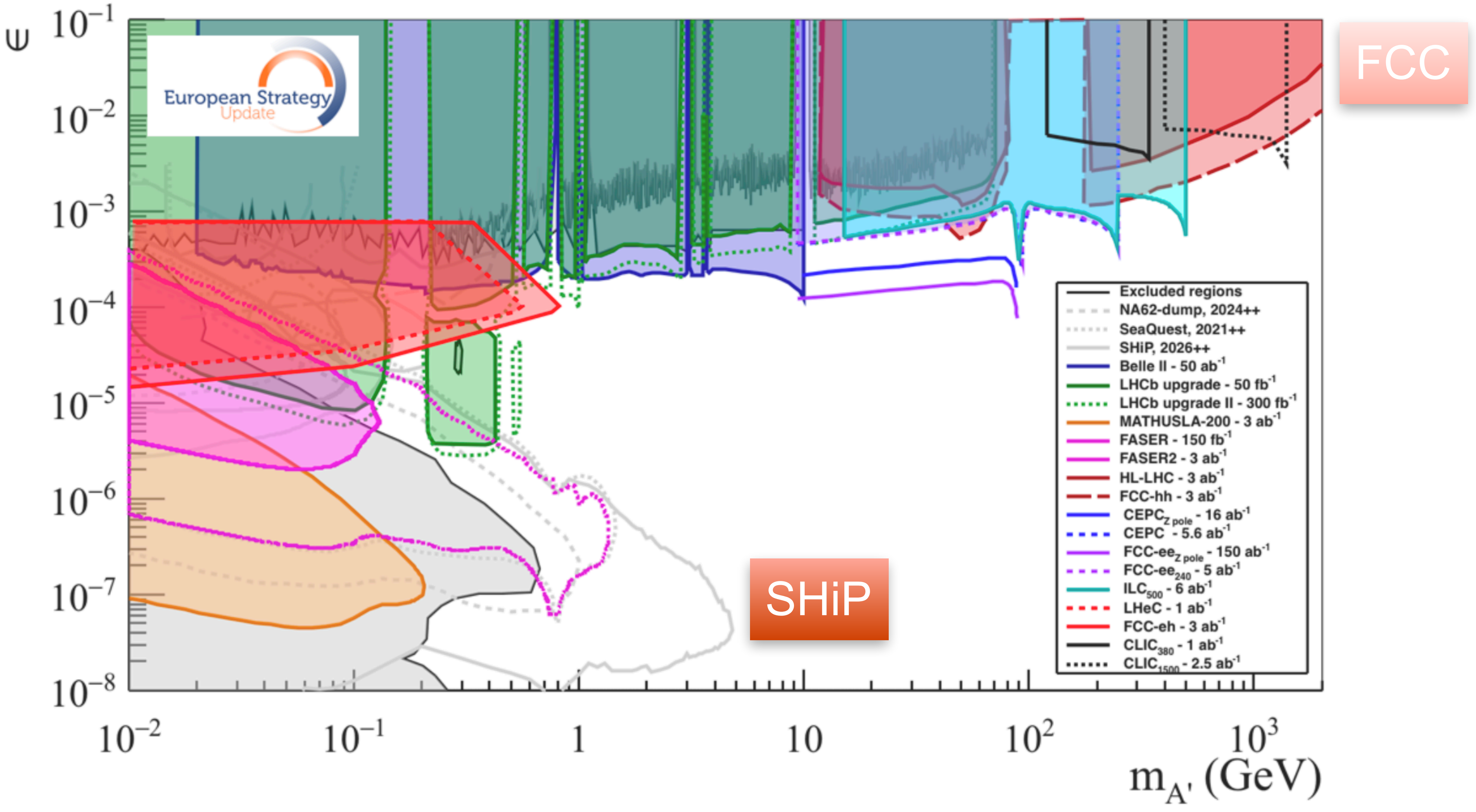


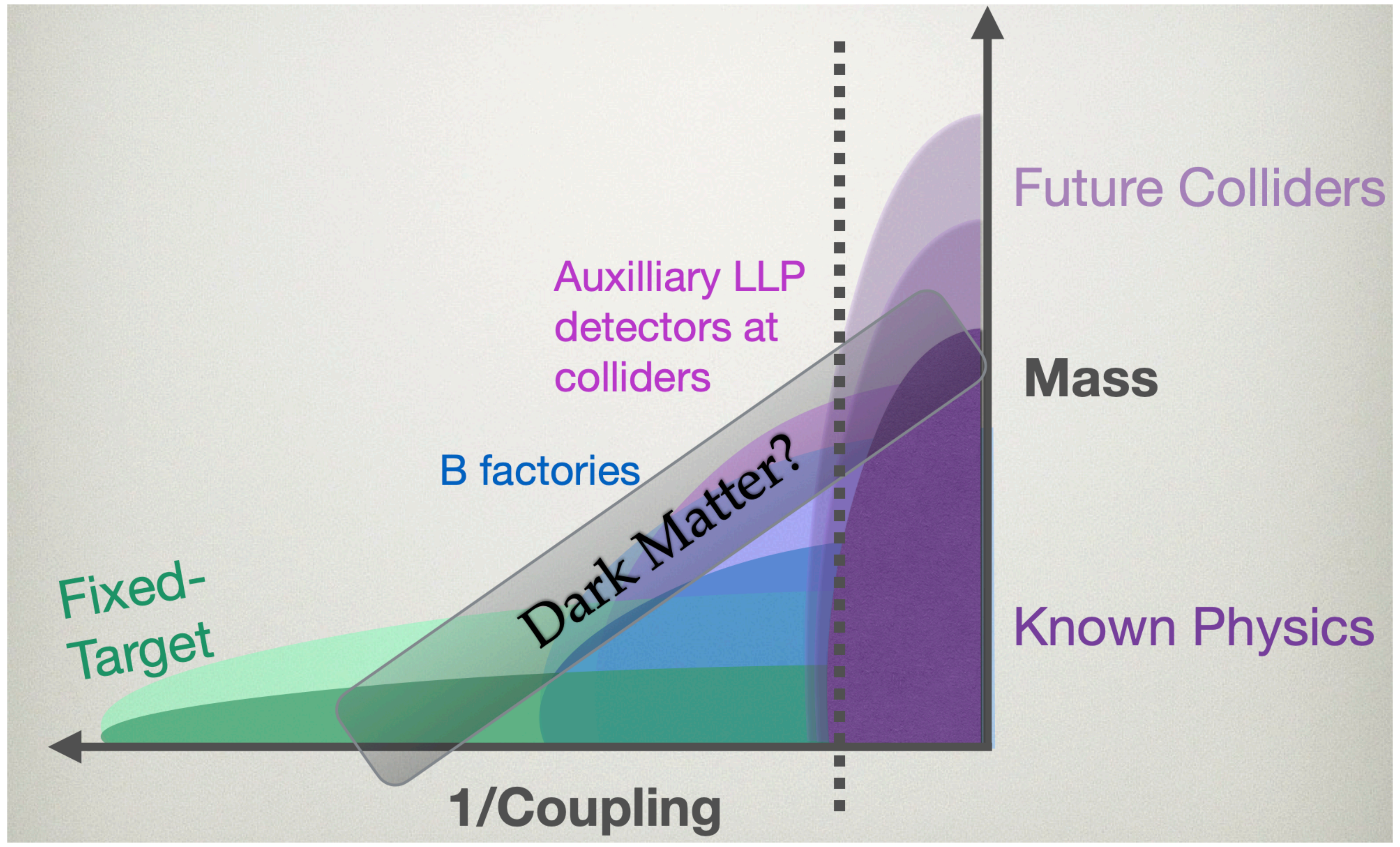
Standard Model → Connector → Hidden Sector

(model-independent) **phenomenology**:

- production through meson decays (π,K,D,B)
- production & decay to SM very suppressed
- feebly interacting / long-lived particles

Models	Final States
HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}$
DP, DS, ALP (fermion coupling), SUSY sgoldstino	$\ell^{+}\ell^{-}$
DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^{+}\pi^{-}$, $K^{+}K^{-}$
HNL, SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$





SND@LHC physics goals

Neutrino interactions

- Measure ν **interactions** in unexplored ~TeV energy range
- Large yield of **tau neutrinos** will likely double existing data

Flavour

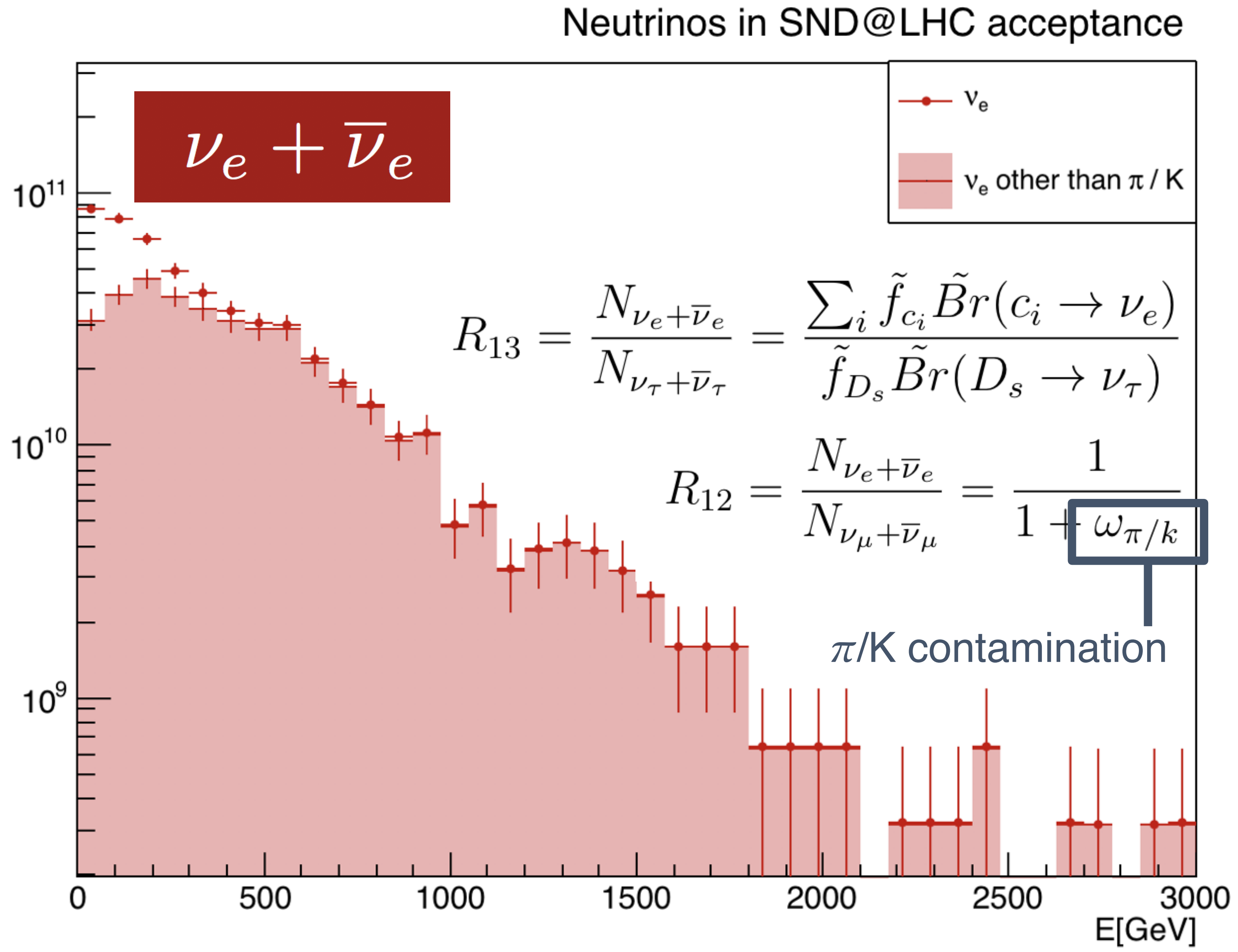
- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality (LFU)**
  - charm parentage reduces flux uncertainties

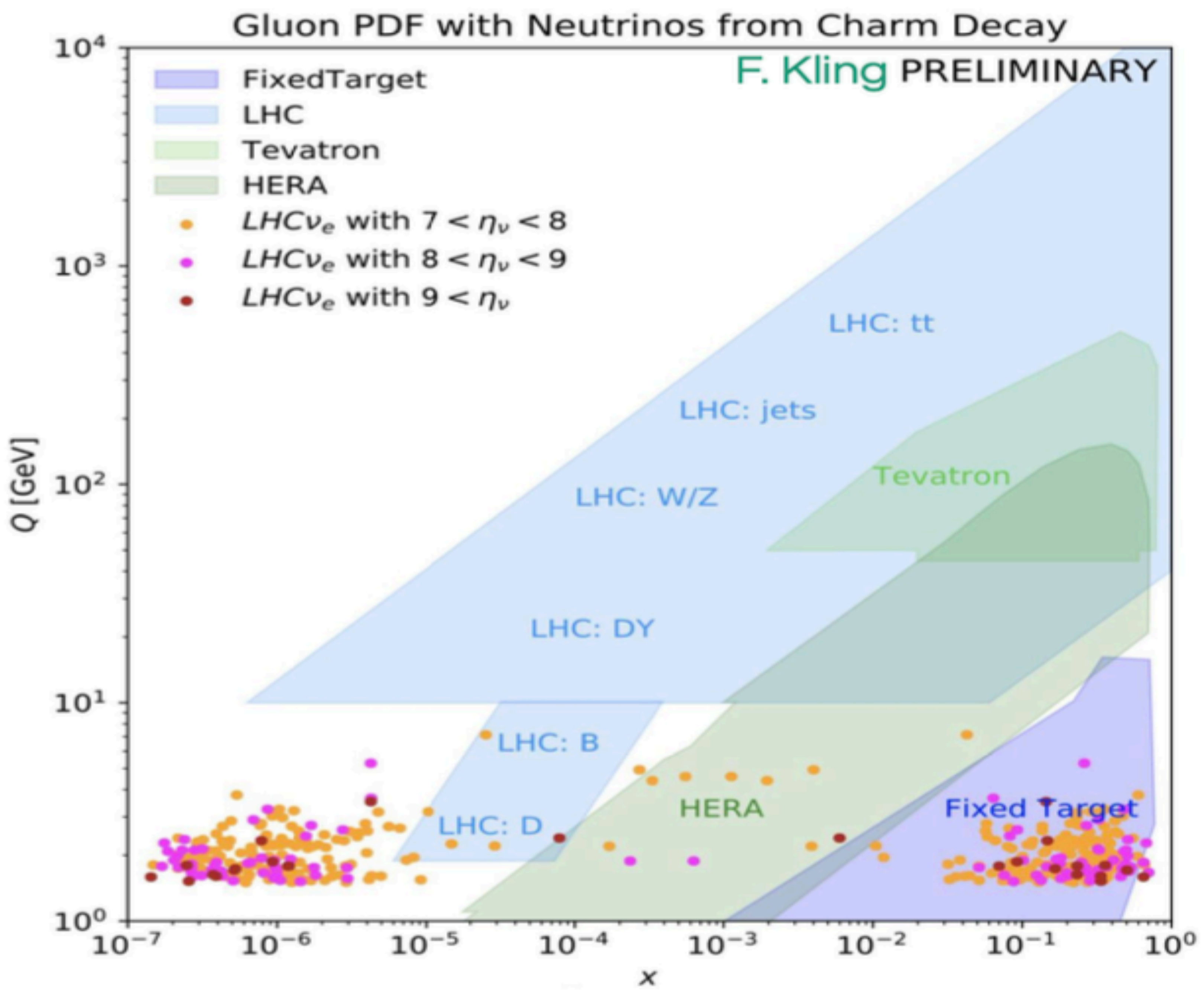
QCD

- Decays of **charm** hadrons contribute significantly to the neutrino flux in SND@LHC
  - measure **forward charm production** with ν_e
  - constrain **gluon PDF** at very **small x**

Beyond the Standard Model

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





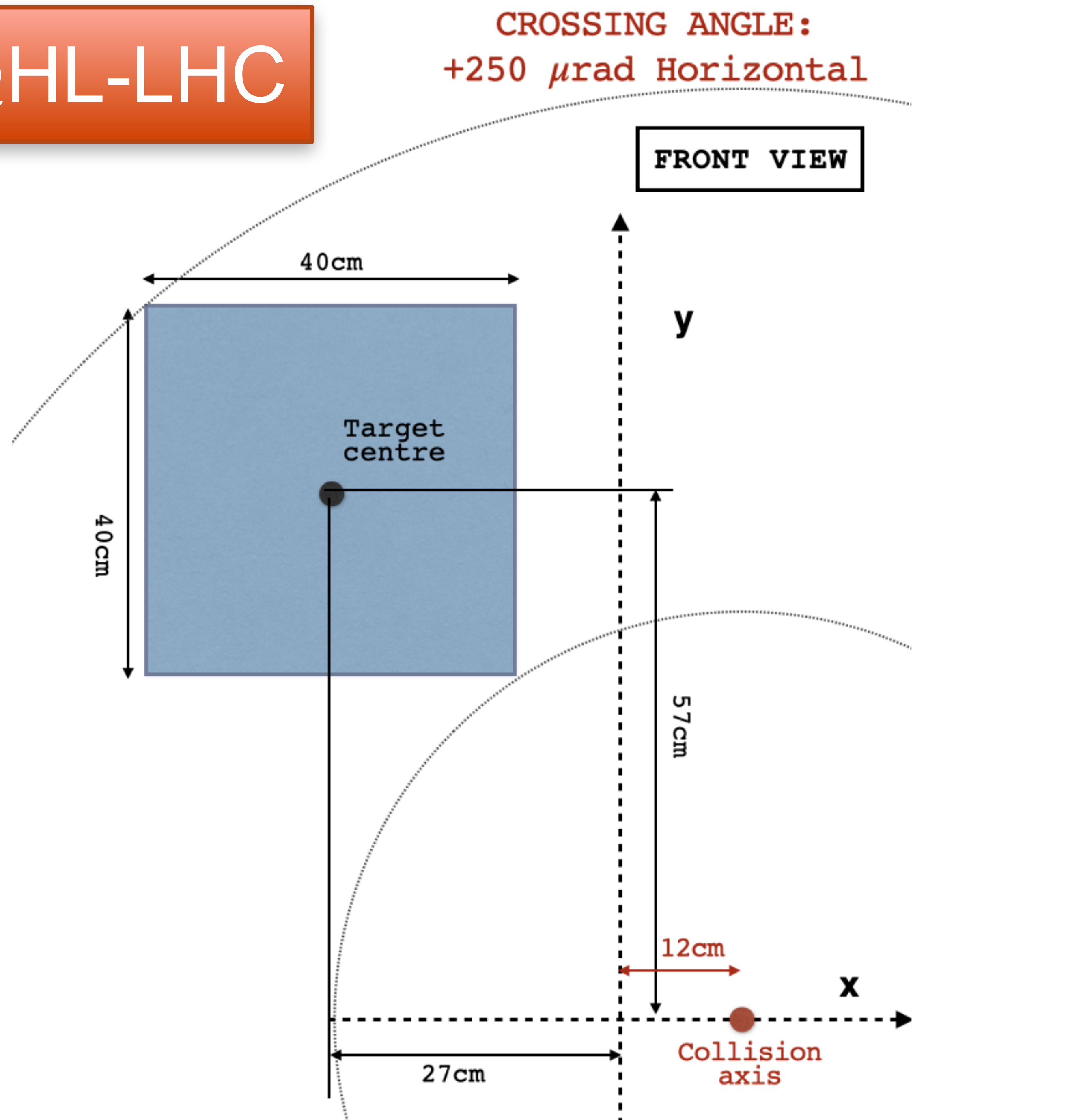
Expected neutrino event rates

SND@LHC

- 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

SND@HL-LHC



$6.9 < \eta < 7.7$ $\phi = 0.066$

Flavour	CC DIS Interactions (3k fb^{-1}, 1.3 ton) total (DPMJET)	cc-bar (DPMJET)
$\nu_\mu+\bar{\nu}_\mu$	1.5x10^4	2.4x10^3
$\nu_e+\bar{\nu}_e$	3.4x10^3	2.7x10^3
$\nu_\tau+\bar{\nu}_\tau$	2.8x10^2	2.8x10^2
Total	**1.9x10^4**	**5.4x10^3**

Muon neutrino analysis

- Observation of collider muon neutrinos achieved with one year of data.
  - Phys. Rev. Lett. 131, 031802
- Updated result in 2024 with more data and improved analysis.

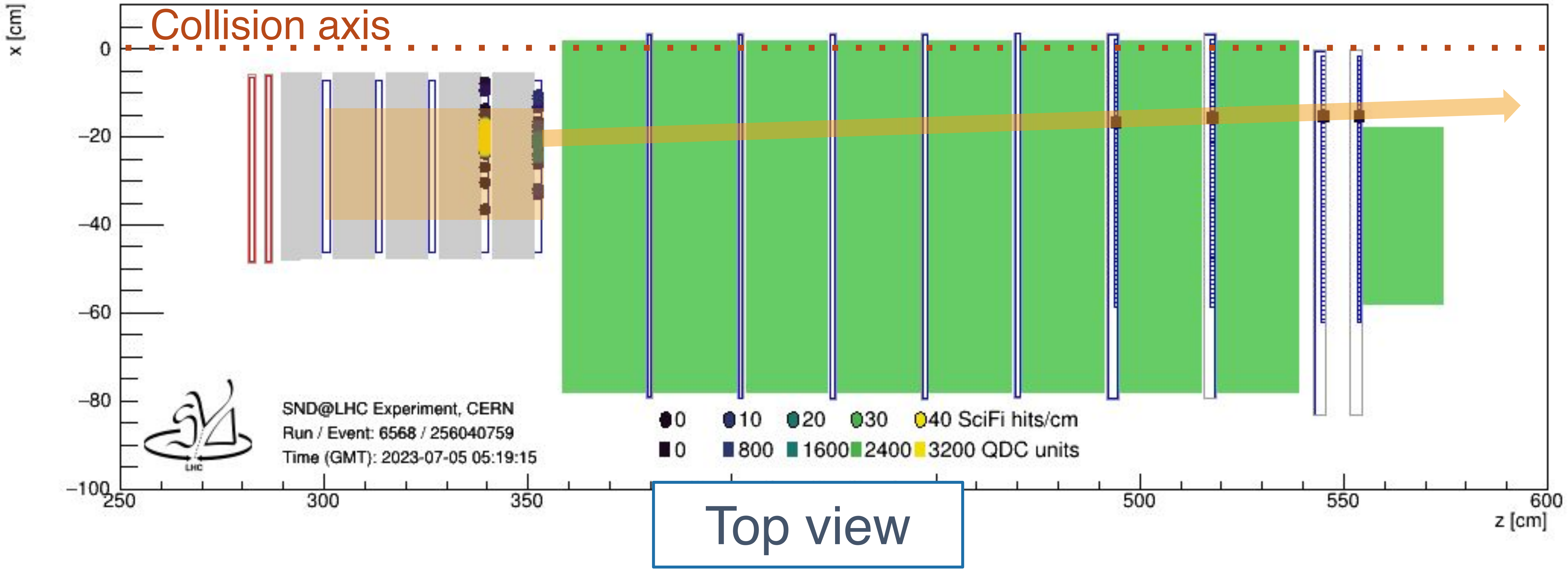
Event selection

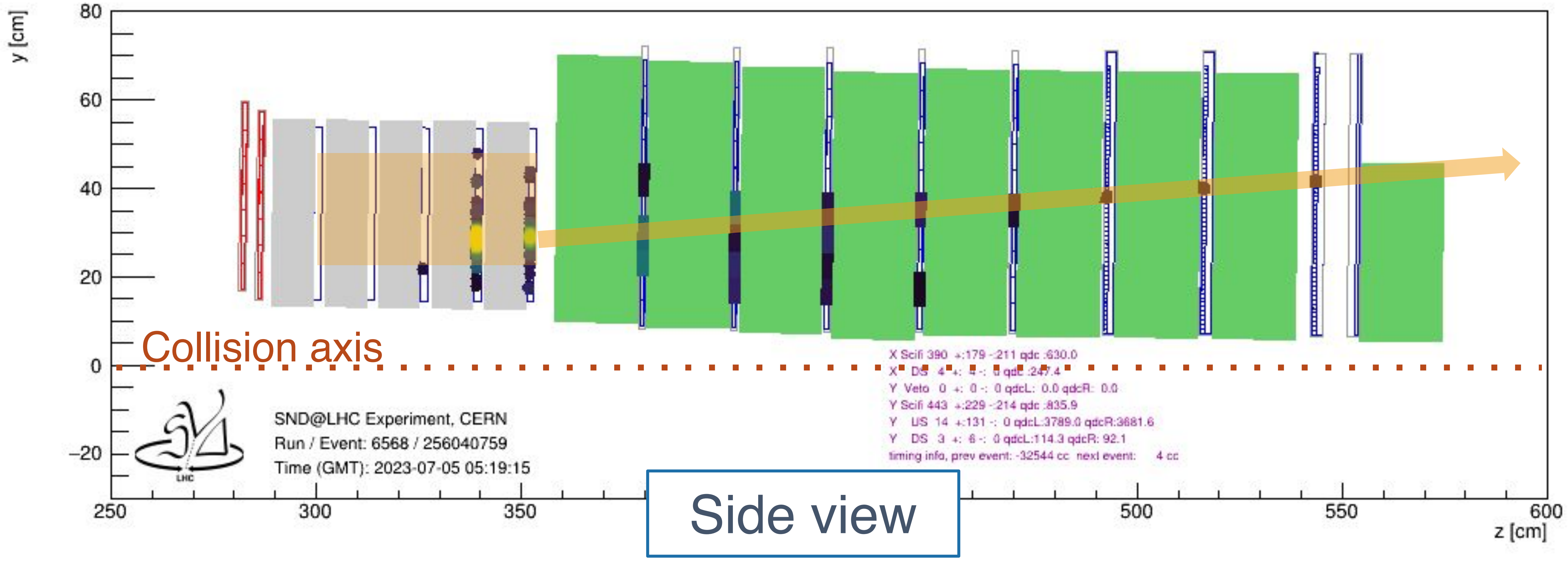
Fiducial volume

- 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 0μ events in SND@LHC

arXiv 2411.18787

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**

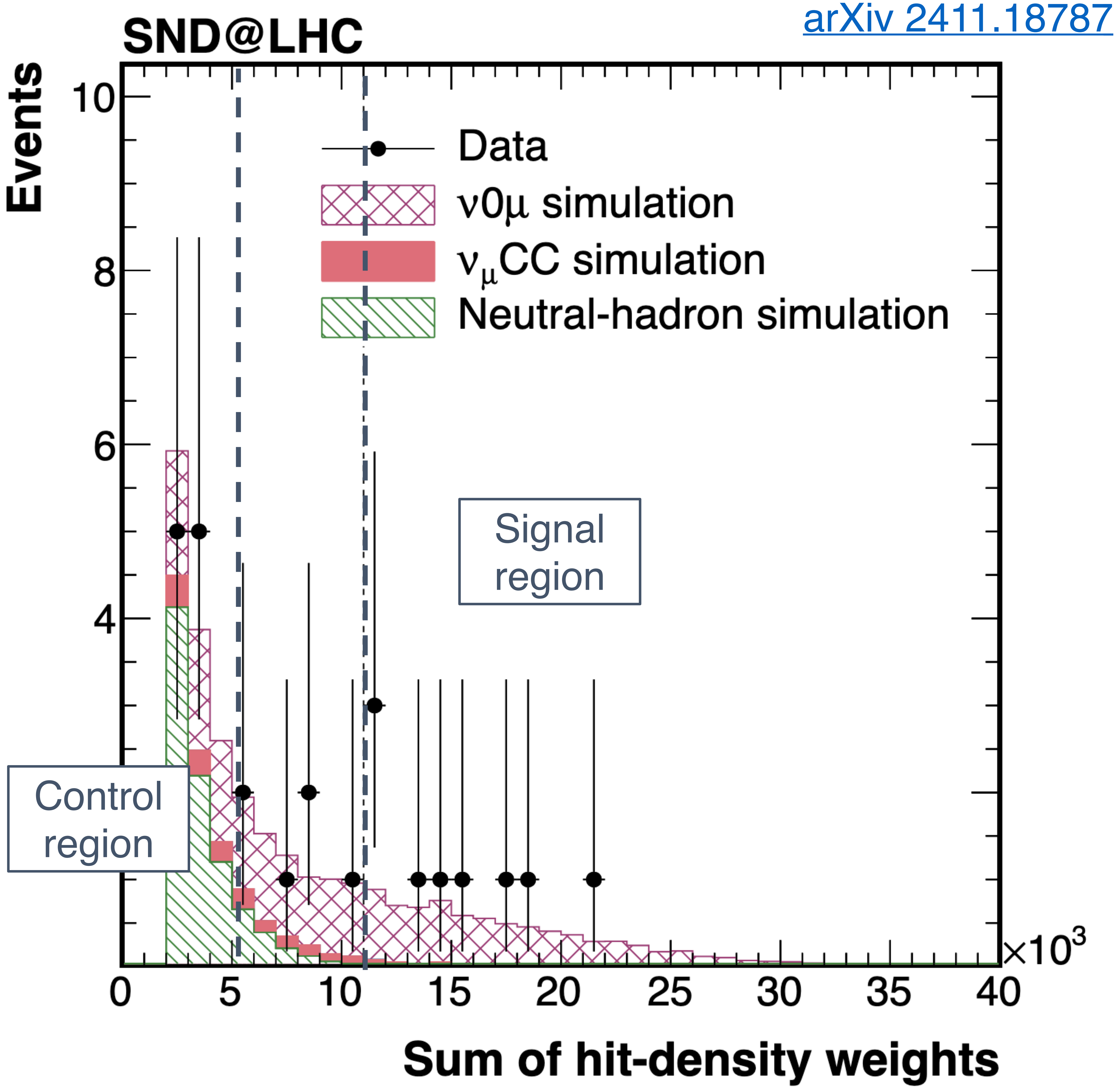
Neutrino background

- Muon neutrino CC interactions are the dominant background, with **0.30** expected events.
- Tau neutrino CC1μ interactions expected: 0.002

0μ observation significance

- **Total expected background: 0.32 ± 0.06 events**
- **Expected signal: 7.2 events**
  - 4.9 ν_eCC, 2.2 NC, 0.1 ν_τCC
- **Expected significance: 5.5 σ**

Number of events observed: 9
Observation significance: 6.4 σ



Prospects for charm-tagged neutrinos

- A sizeable fraction of the interacting neutrinos originate in open charm production.
- In around 10% of these events, the associated charm quark is emitted within the acceptance of ATLAS: over 500 events expected.
- A charm-tagged neutrino sample would allow for clean flavour ratio measurements.
- Requires fast timing detectors to resolve the pile-up, and sending a trigger signal to ATLAS.