NEW FRONTIERS IN NEUTRINO PHYSICS AT CERN

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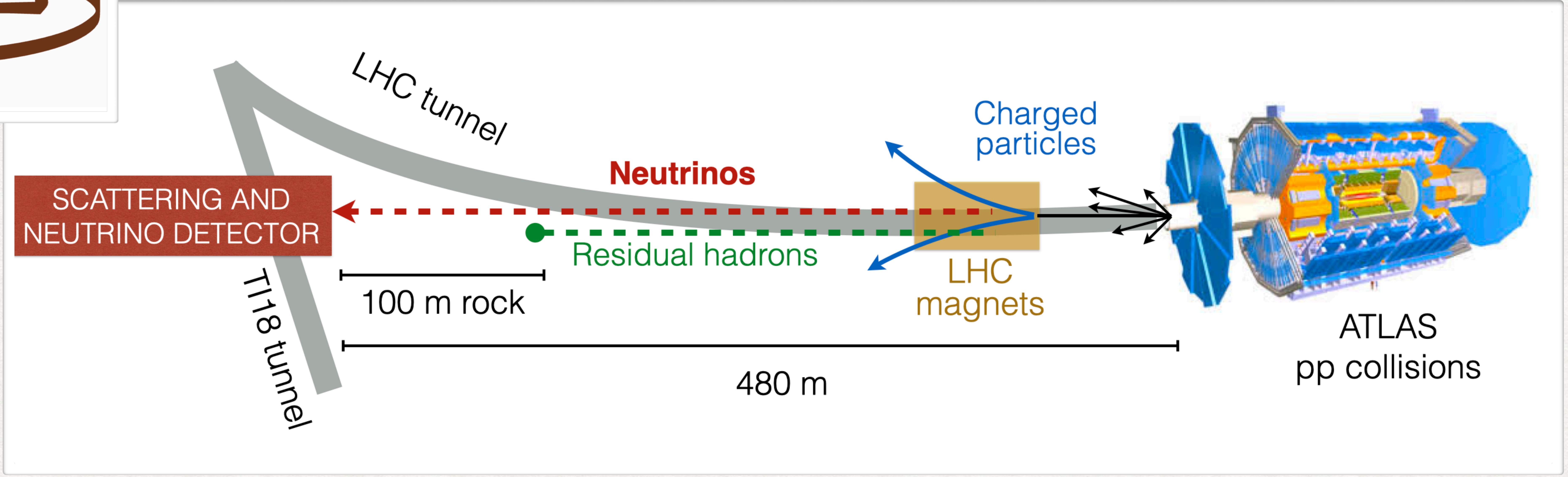
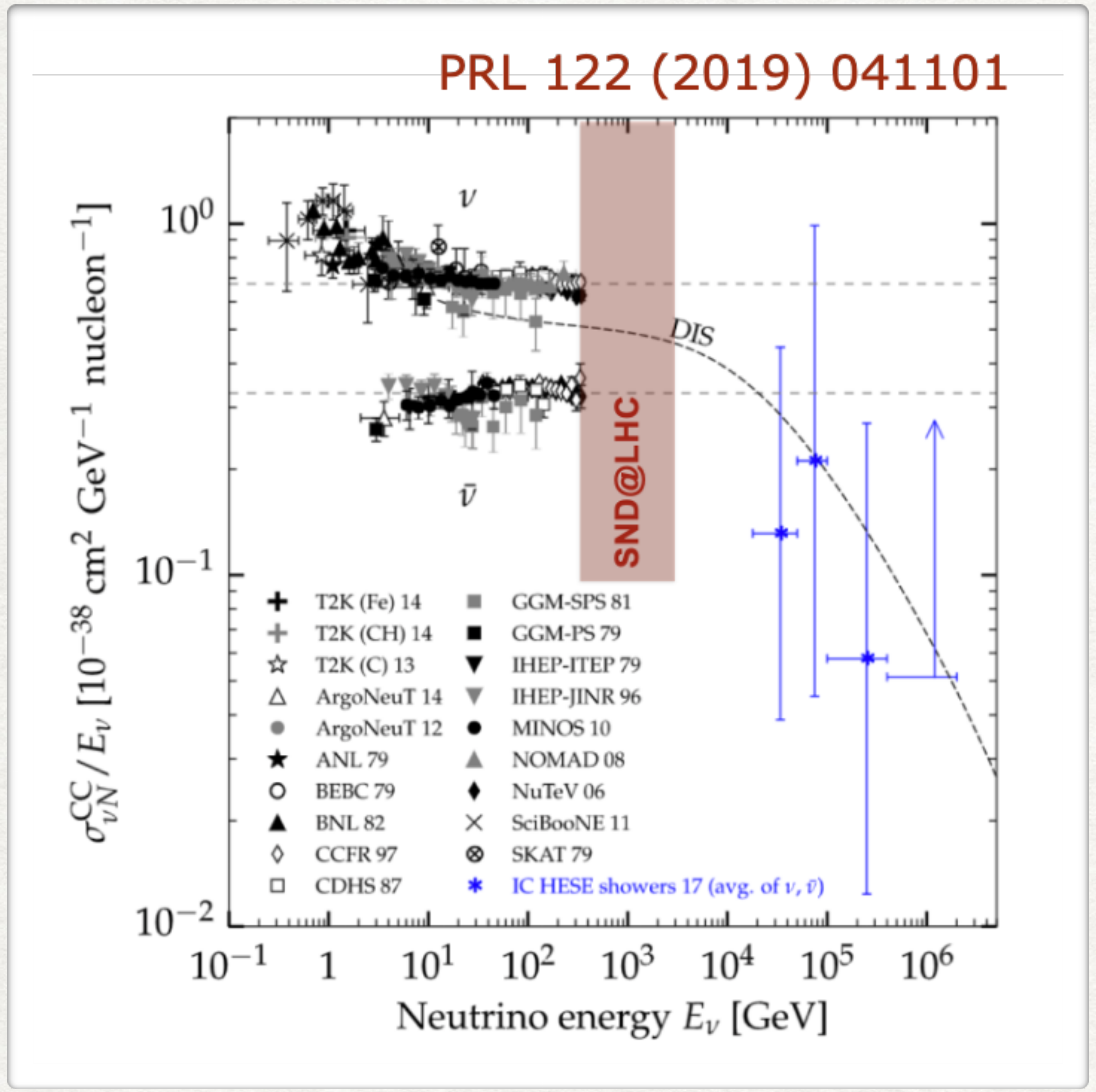
on behalf of the SND@LHC Napoli Group

INFN Napoli Gr1 Meeting - 16 January 2025

NEUTRINO PHYSICS AT CERN:
THE **SND@LHC** EXPERIMENT

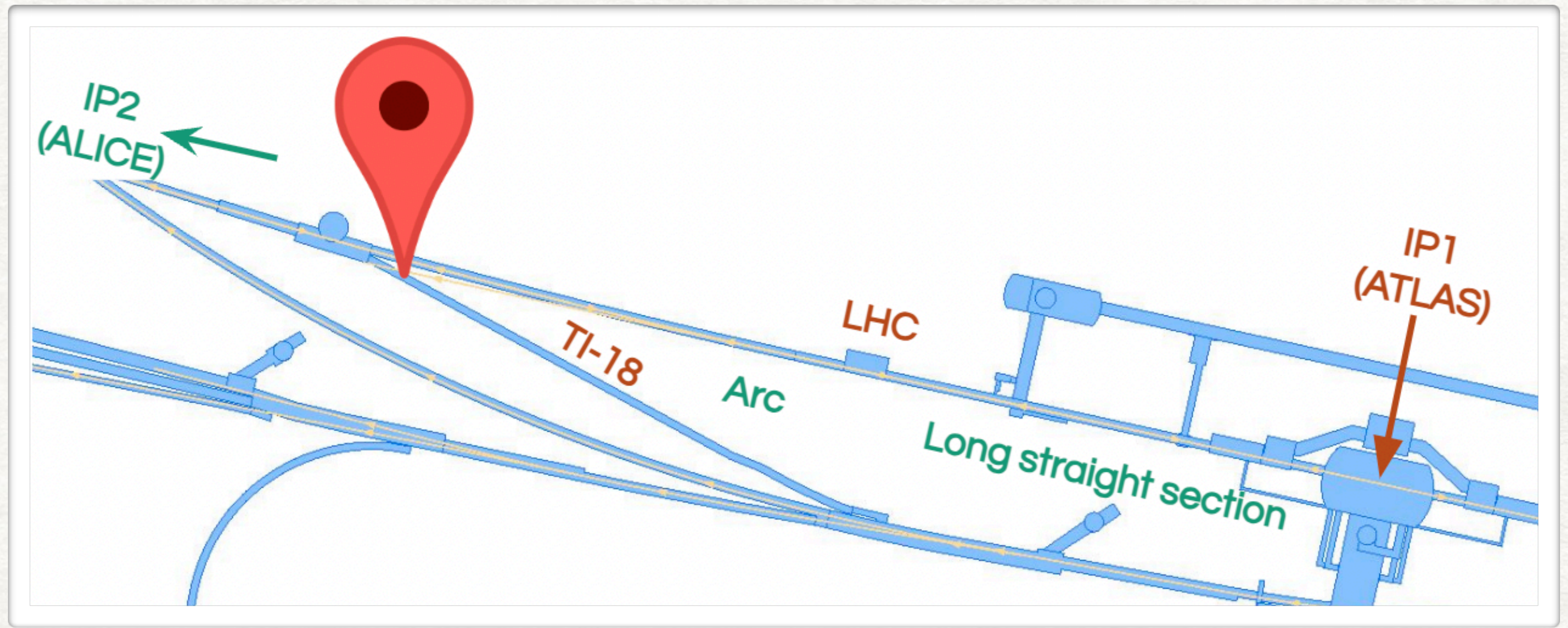


THE SND@LHC DETECTOR



OFF-AXIS LOCATION
- Rapidity range: $7.2 < \eta < 8$
- Enhances ν flux from **charm** parents
- Complementarity with FASERν, located **on-axis** in symmetric tunnel (TI-12)

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



TI-18 LOCATION
- Charged Old LEP positron transfer line tunnel
- 480 m away from IP1
- 100 m of rock between detector and IP1

Operation in Run 3 (2022-2026) to collect ~300 fb^{-1}

https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf

PHYSICS GOALS

QCD

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

Flavour

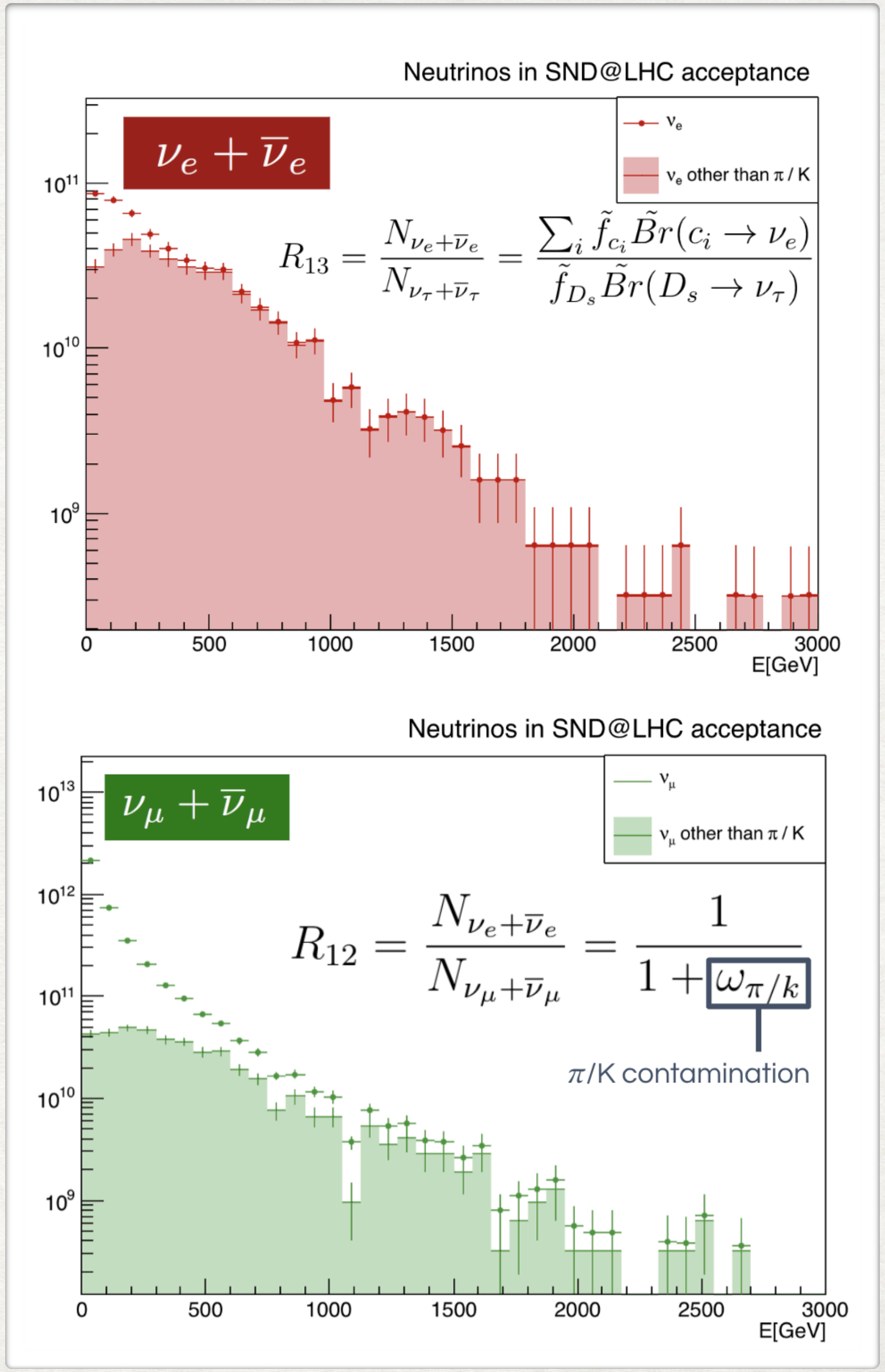
- Detection of all three types of neutrinos allows for tests of lepton flavour universality
  - Charm parentage leads to partial cancelation of flux uncertainties

Neutrino interactions

- Detection of all three types of neutrinos allows for tests of lepton flavour universality
  - Measure **neutrino interactions** in unexplored ~TeV energy range
  - Large yield of neutrinos 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



THE SND@LHC CONCEPT

Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles

JINST 19 (2024) P05067

VETO PLANE:

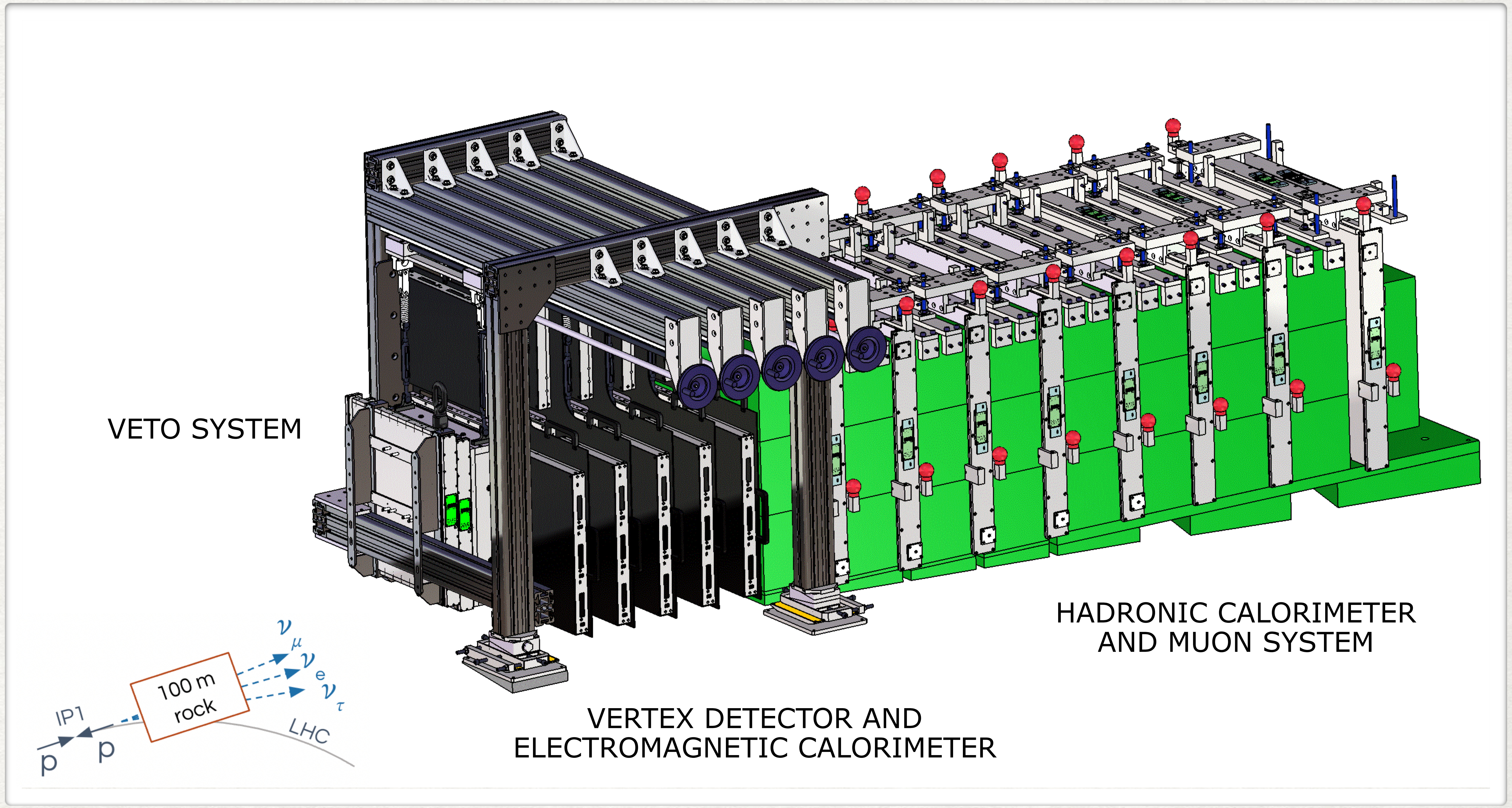
- two (2022–2023) / three (2024-)
1 cm-thick scintillator planes

TARGET, VERTEX DETECTOR AND ECAL:

- 830 kg tungsten target
- Five walls x 59 emulsion layers +
  five scintillating fibre stations 84 X_0, 3 λ_{int}

HCAL AND MUON SYSTEM:

- Eight 20 cm-thick Fe blocks + scintillator planes
- Last 3 planes have finer granularity to track muons
- 9.5 λ_{int}



EXPERIMENT TIMELINE

August 2020

Scattering and Neutrino Detector at the LHC

Letter of Intent

January 2021

TECHNICAL PROPOSAL

SND@LHC

March 2021

CERN approves new LHC experiment

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

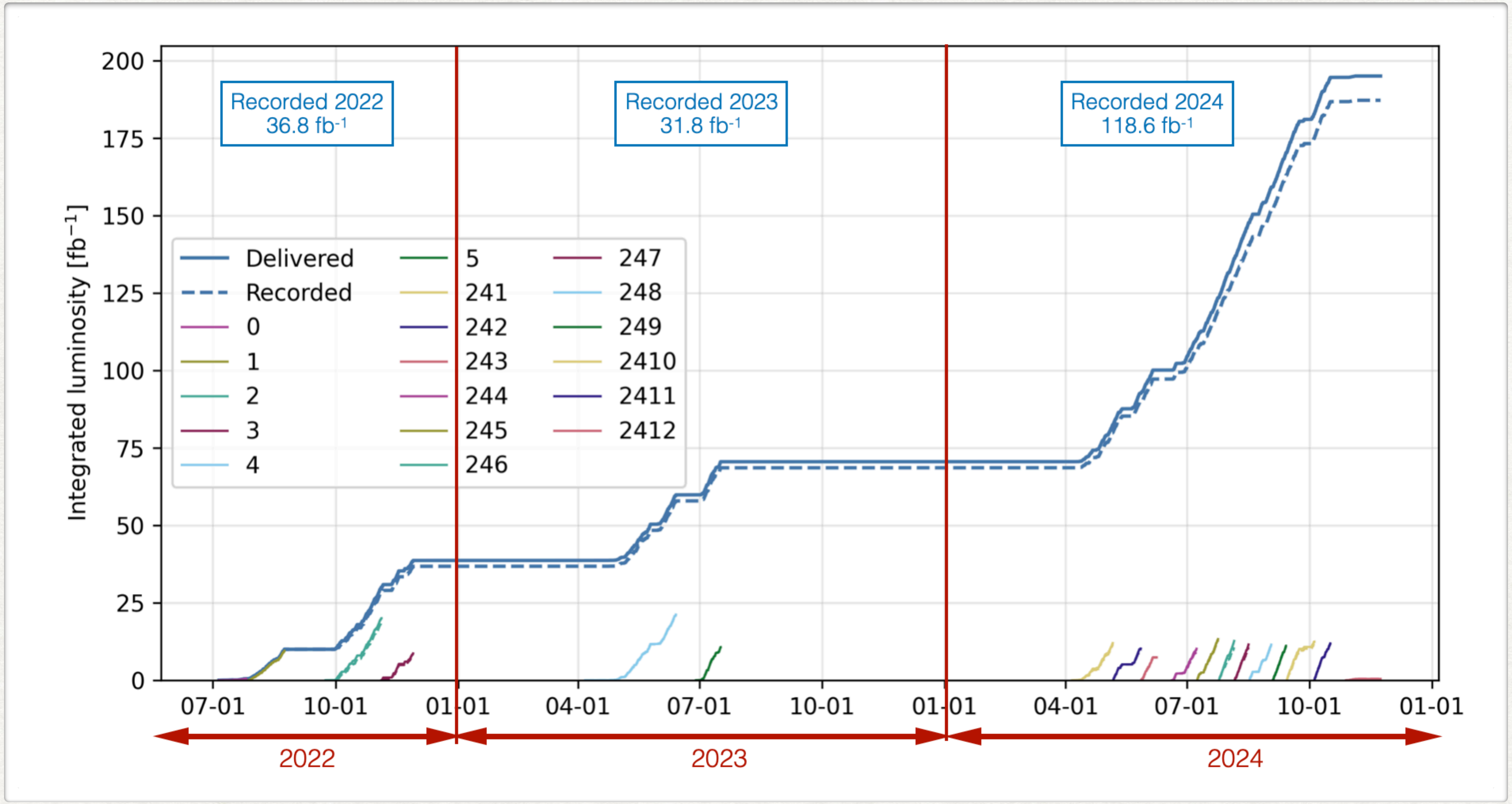
September 2021

December 2021

March 2022


LHC

DATA TAKING IN RUN3



- Delivered luminosity in 2022-2024: 195.0 fb^{-1}
- Integrated luminosity in 2022-2024: 187.1 fb^{-1}

96% efficiency

MUON NEUTRINO OBSERVATION

[PRL 131 (2023) 031802]

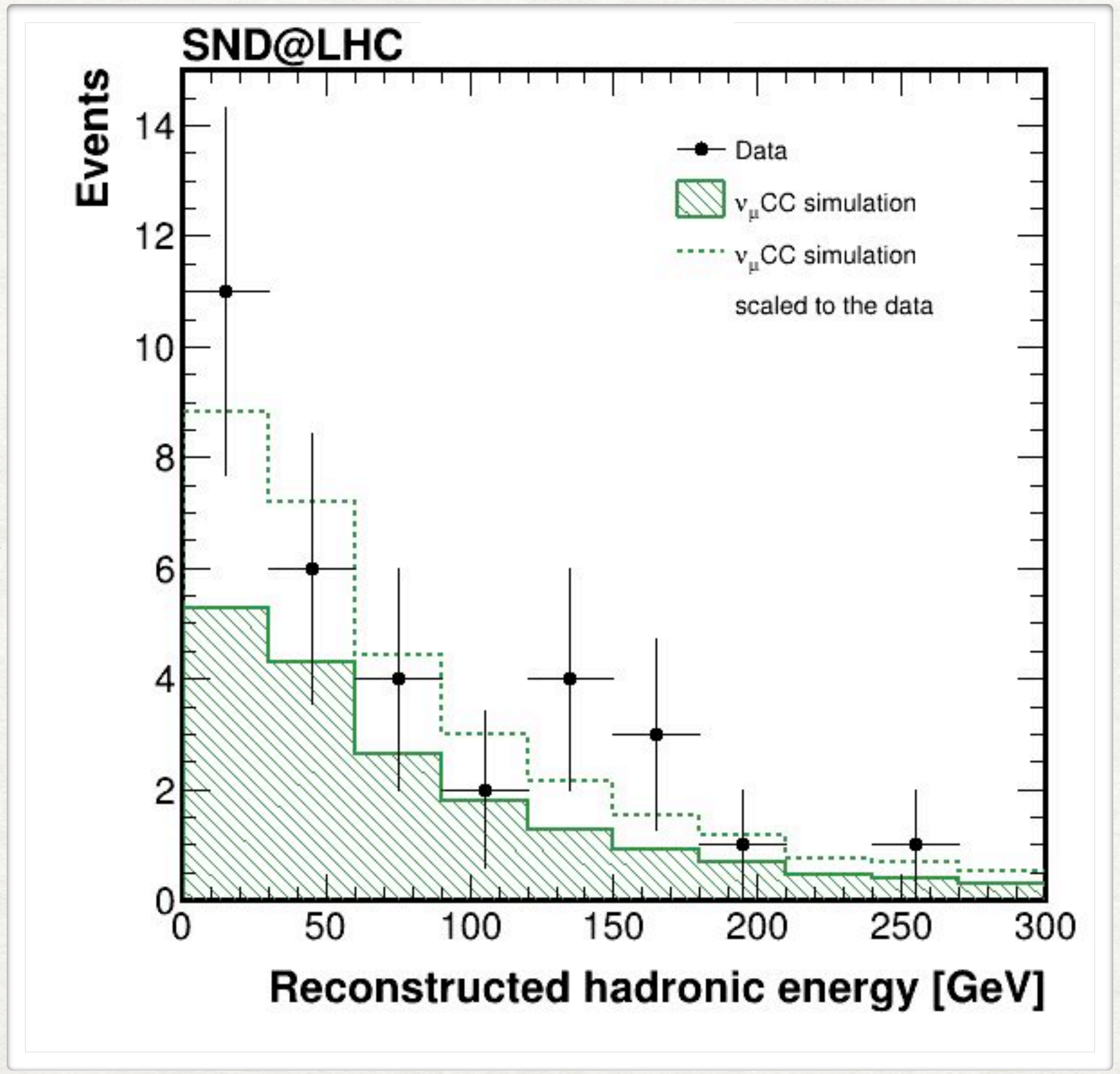
- First observation of muon neutrinos produced at colliders based on **2022** data published last year
- **8** observed **ν_μ candidates**
- Observation significance **7σ**

PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

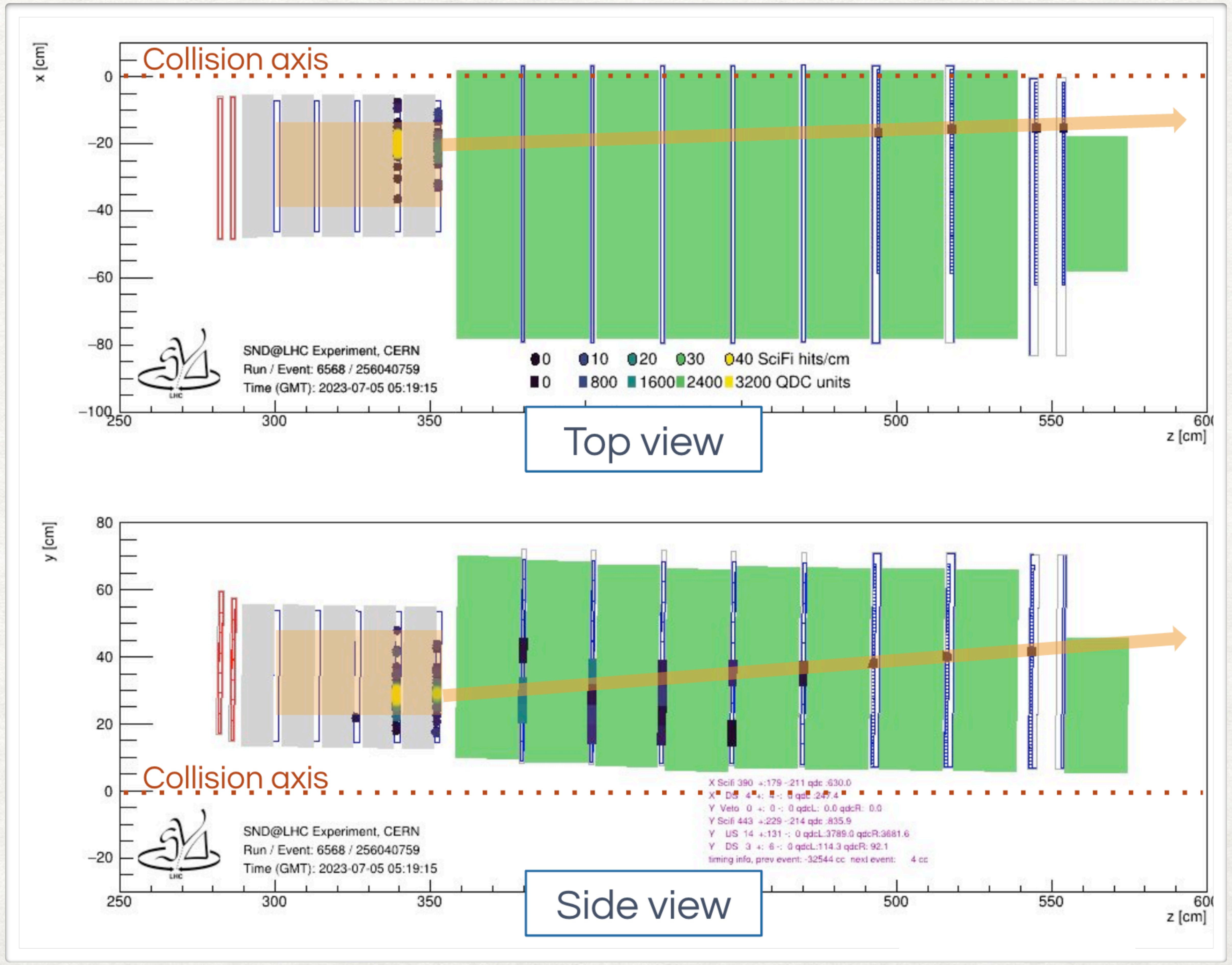
Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

- Updated results using **2022+2023** data:
- **32** observed **ν_μ candidates**
- Measurement of the hadronic energy



- Display of a ν_μ CC candidate event



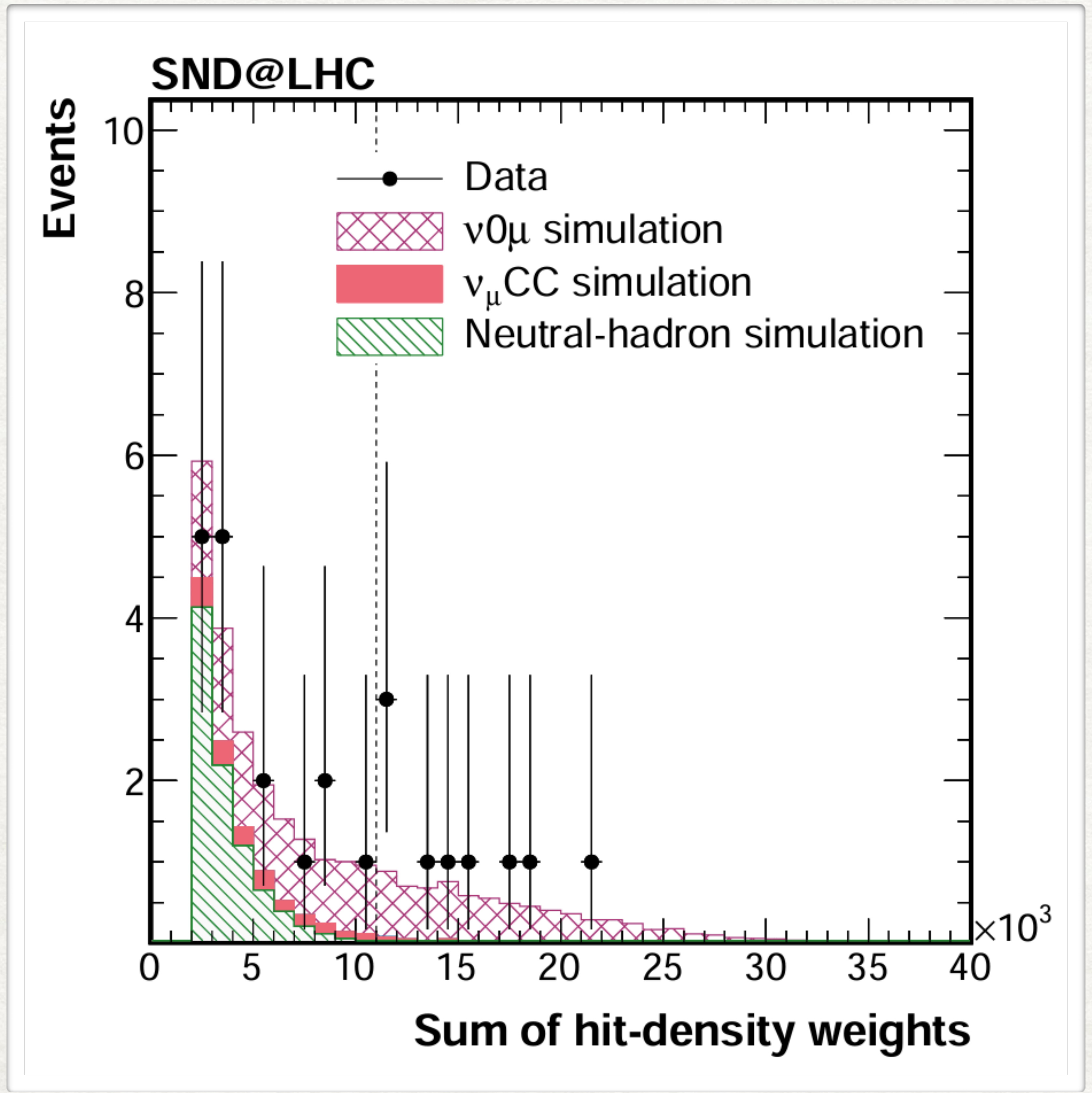
0μ NEUTRINO OBSERVATION

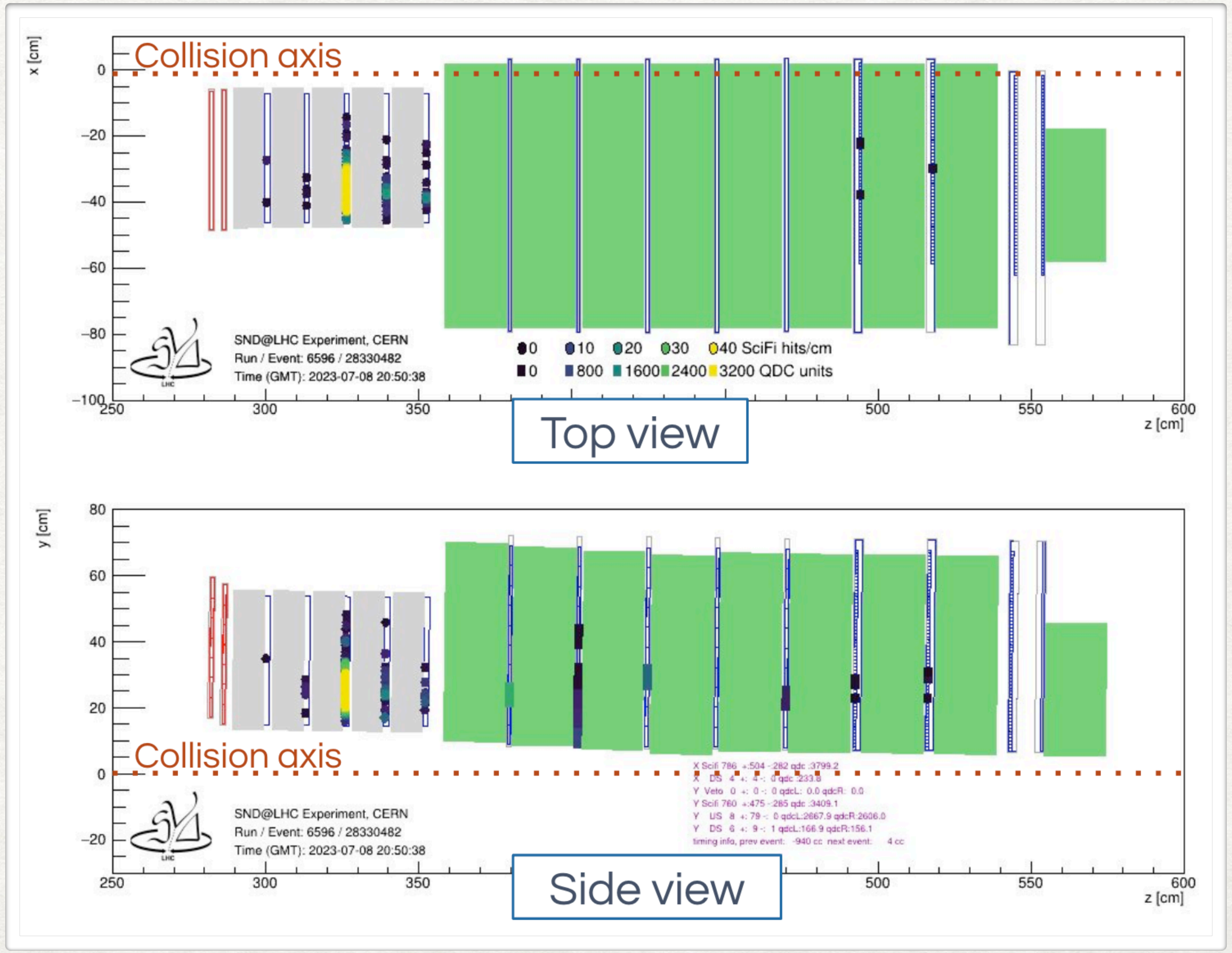
Submitted to PRL
arXiv:2411.18787

- First observation of neutrino interactions without a muon in the final state based on **2022-2023** data
- **9** observed **0μ ν-candidates**
- Observation significance **6.4σ**
- Evidence for **ν_e interactions** at 6.4σ

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

- Display of a 0μ ν-candidate event

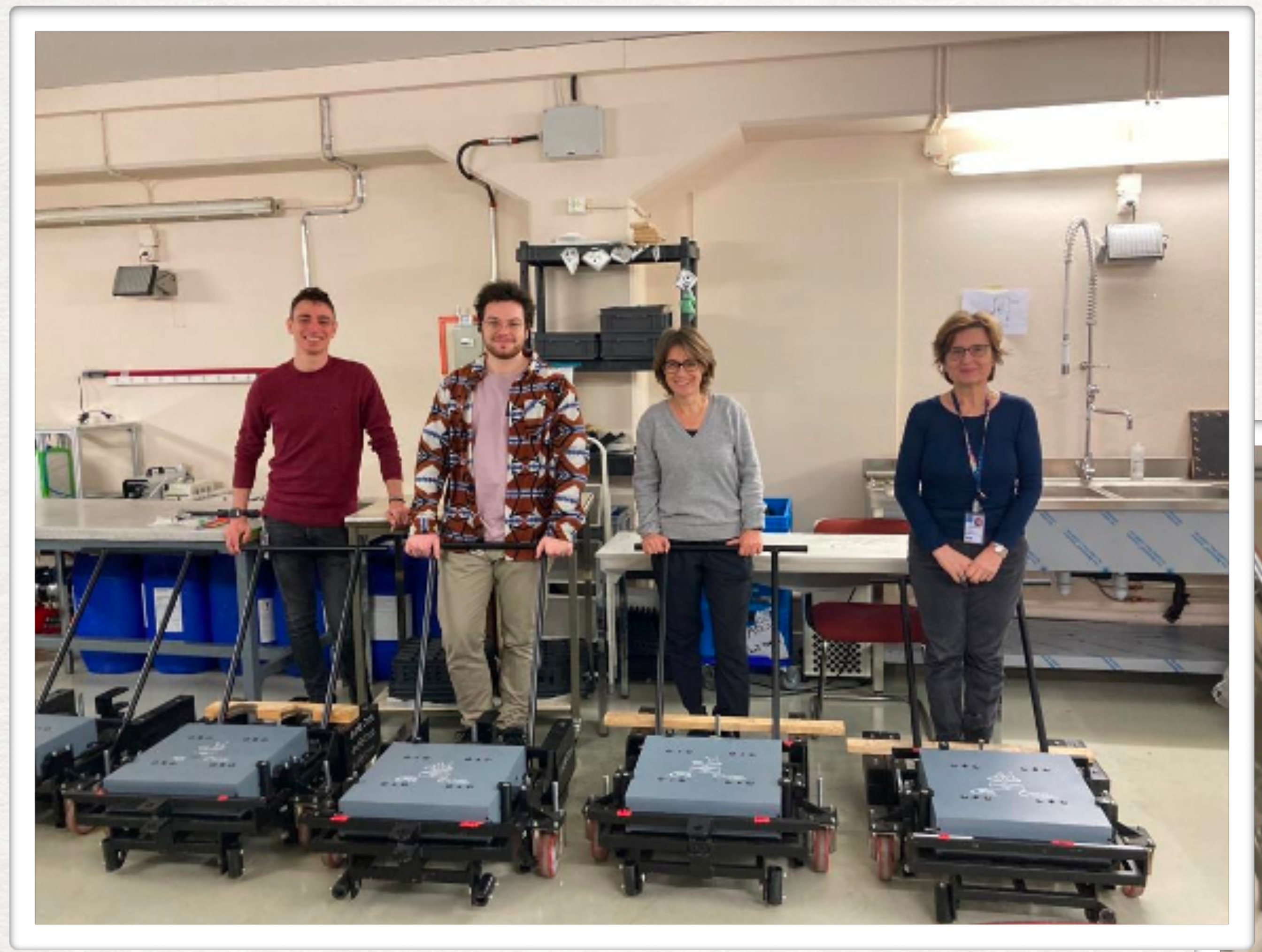




EMULSION HANDLING AND SCANNING

Microscopy expert:
Andrey Alexandrov

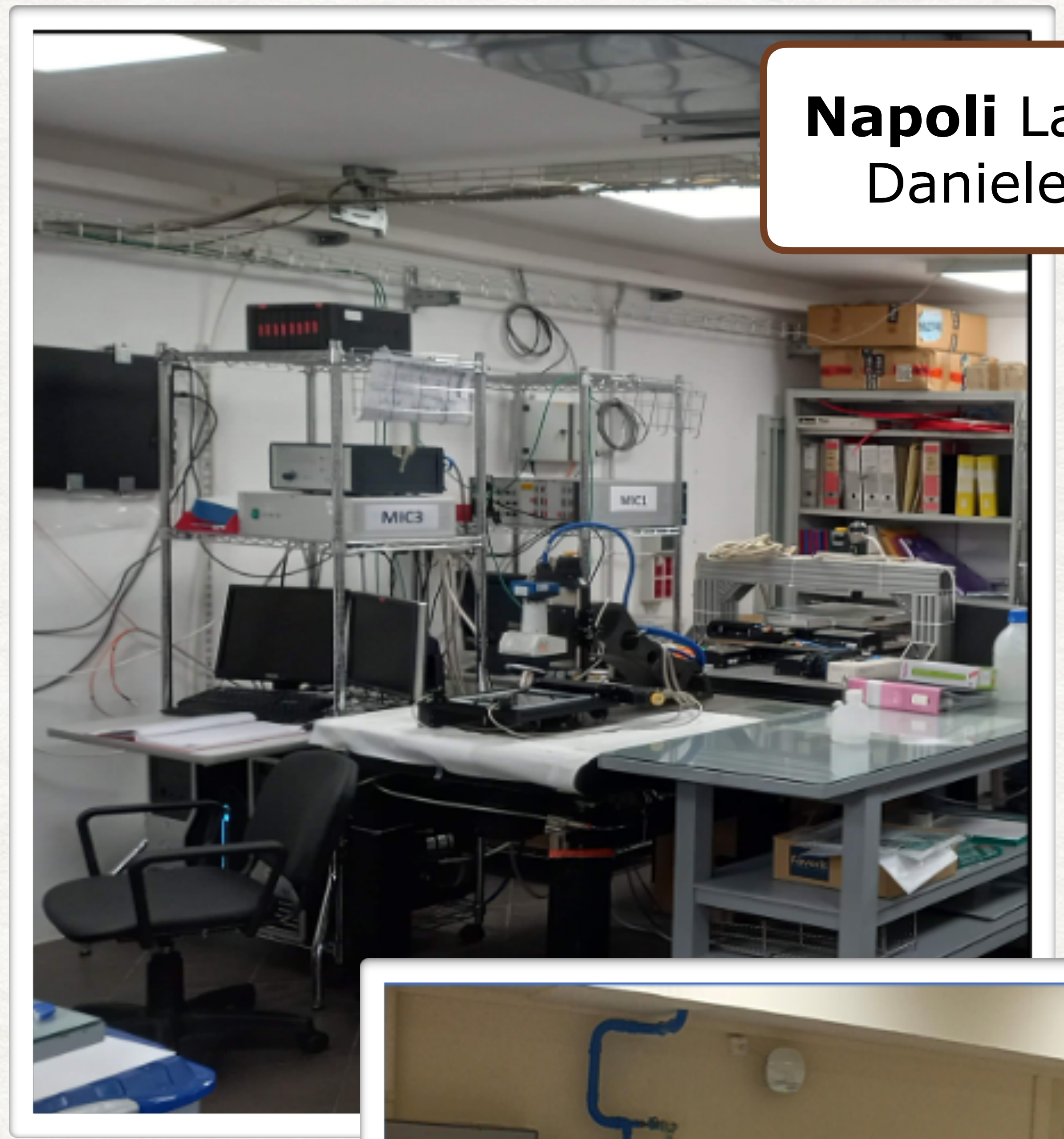
Emulsion handling and chemical development performed at the CERN emulsion facility and dark room



11500 emulsion films (415 m^2) exposed and developed in 2022-2024

Emulsion scanning performed in different laboratories

1) **Bologna:** 2 microscopes
2) **CERN:** 4 microscopes
3) **Napoli:** 3 microscopes
4) **Santiago:** 1 microscope installed in 2024

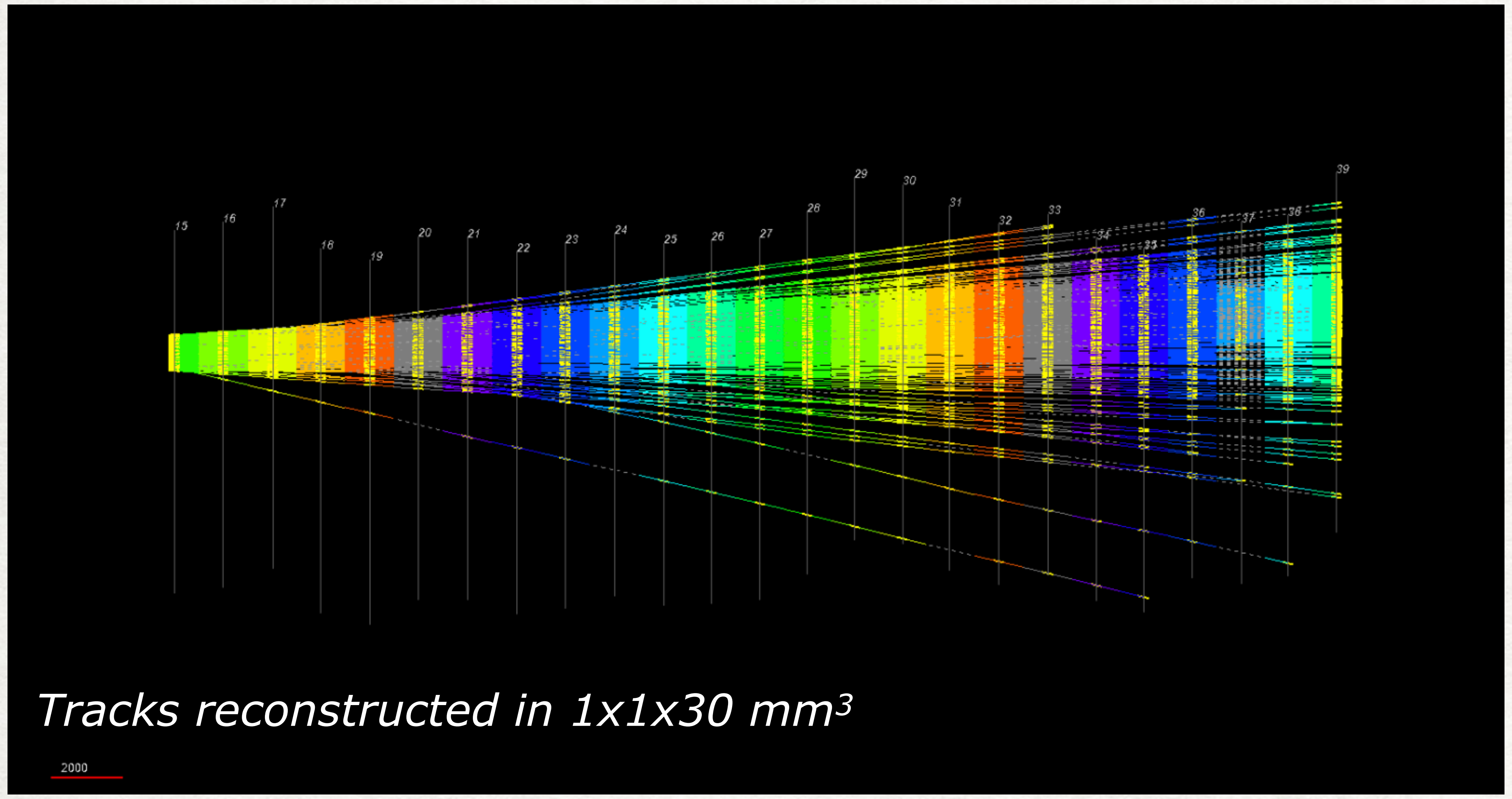


Napoli Lab Manager:
Daniele Centanni

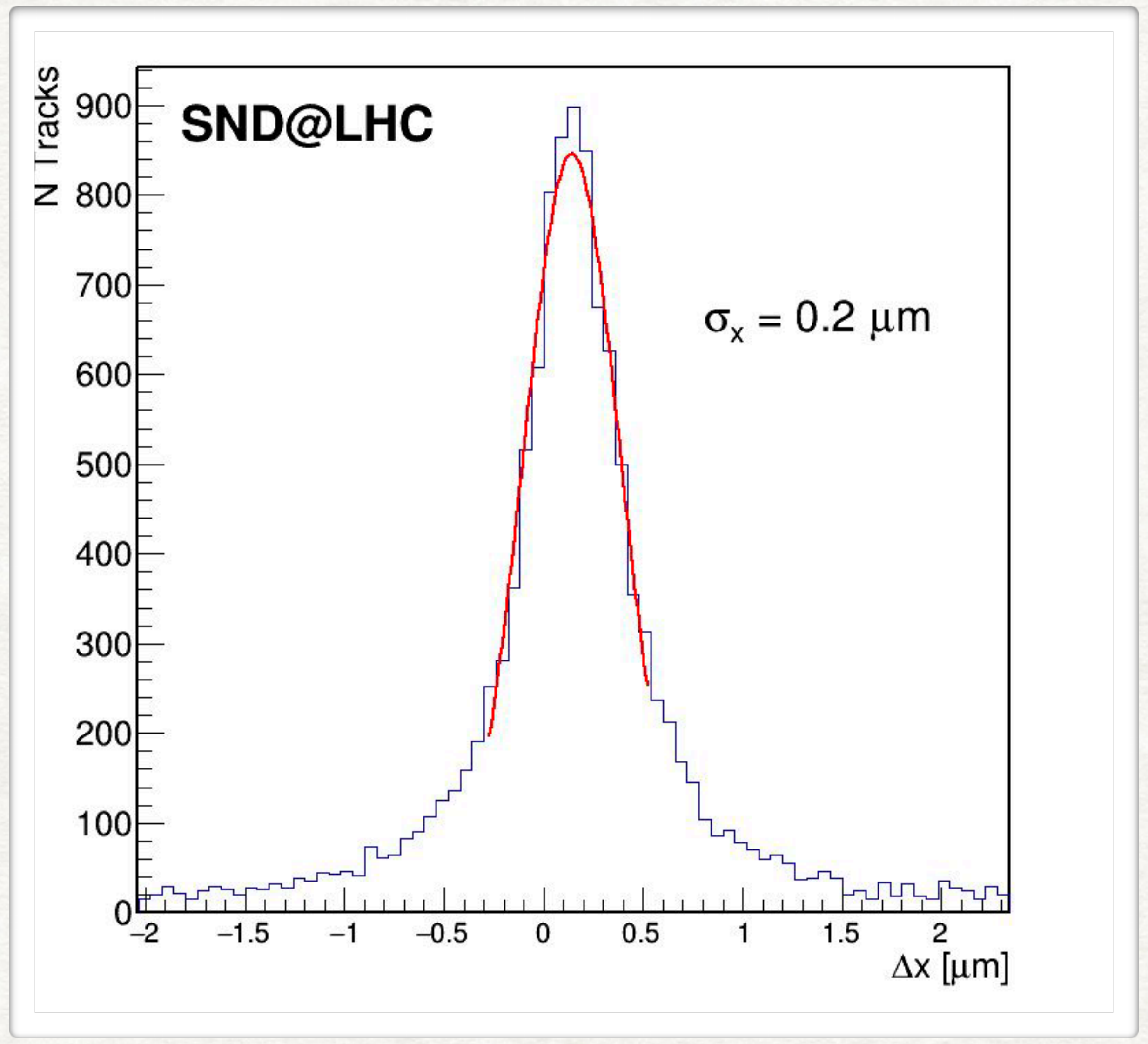
CERN Lab Manager:
Fabio Alicante

EMULSION DATA ANALYSIS AND RECONSTRUCTION

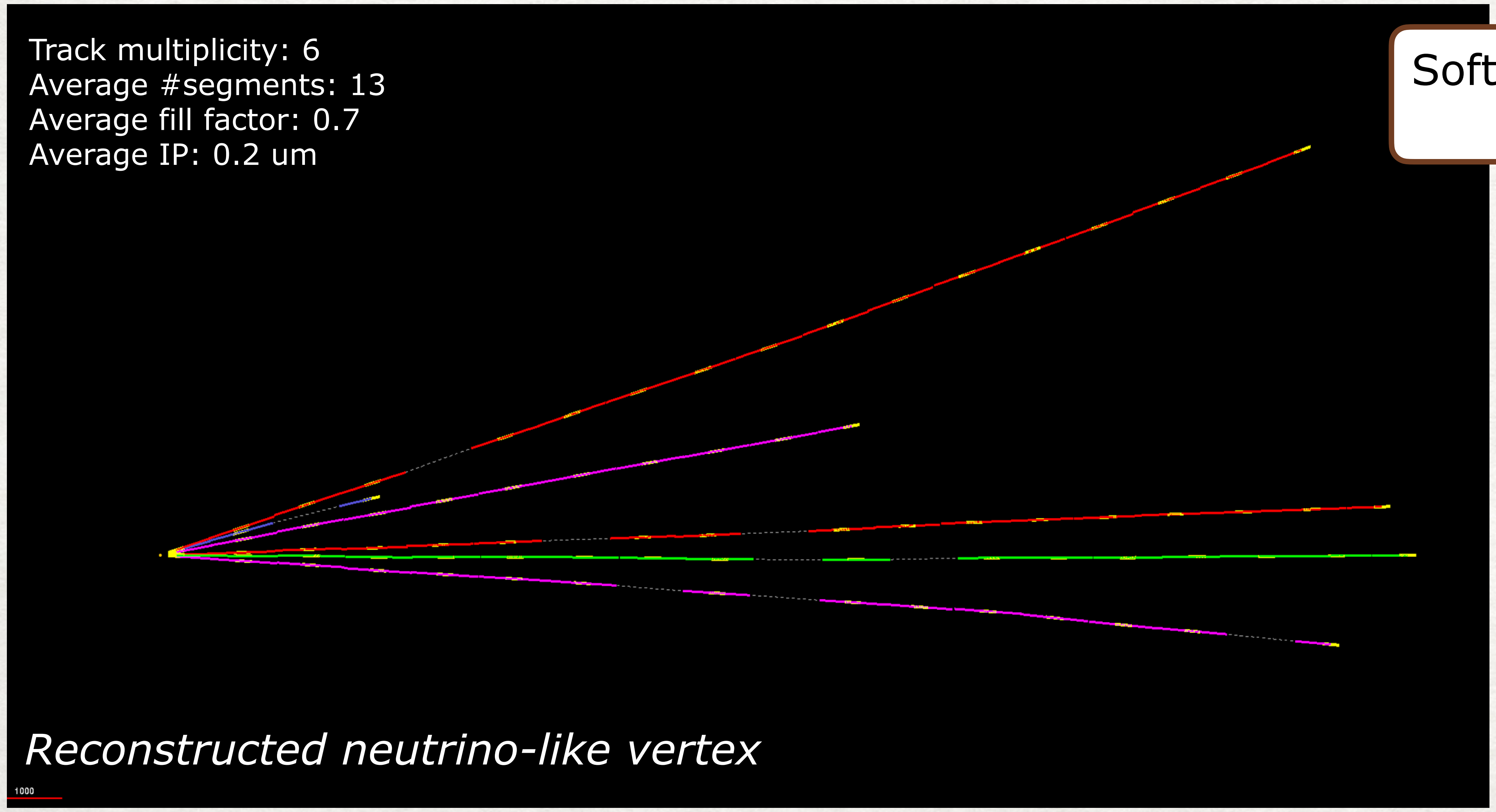
- High density environment: up to 4×10^5 tracks/cm^2



Tracks reconstructed in 1x1x30 mm³

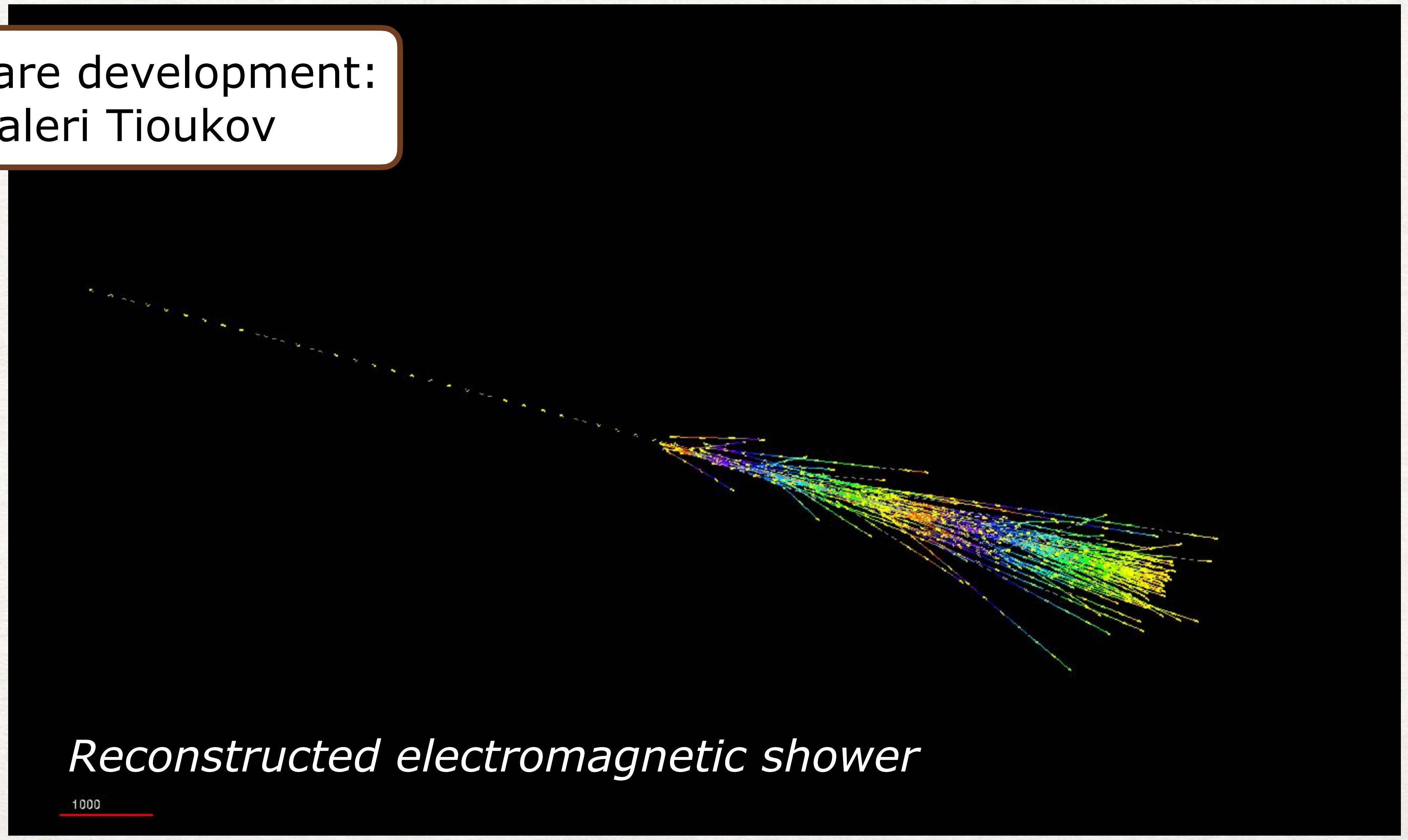


More details in Fabio Alicante's talk



Reconstructed neutrino-like vertex

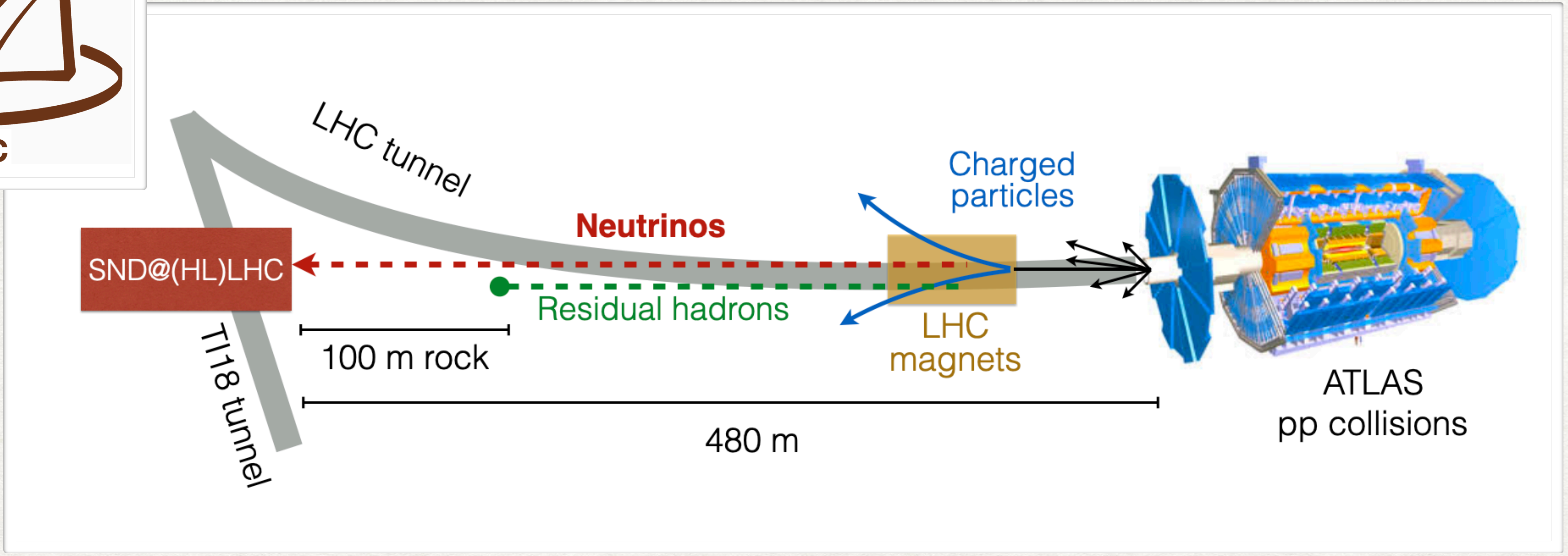
Software development: Valeri Tioukov



Reconstructed electromagnetic shower

NEUTRINO PHYSICS AT THE **ENERGY** FRONTIER: **SND@LHC** IN HI-LUMI ERA

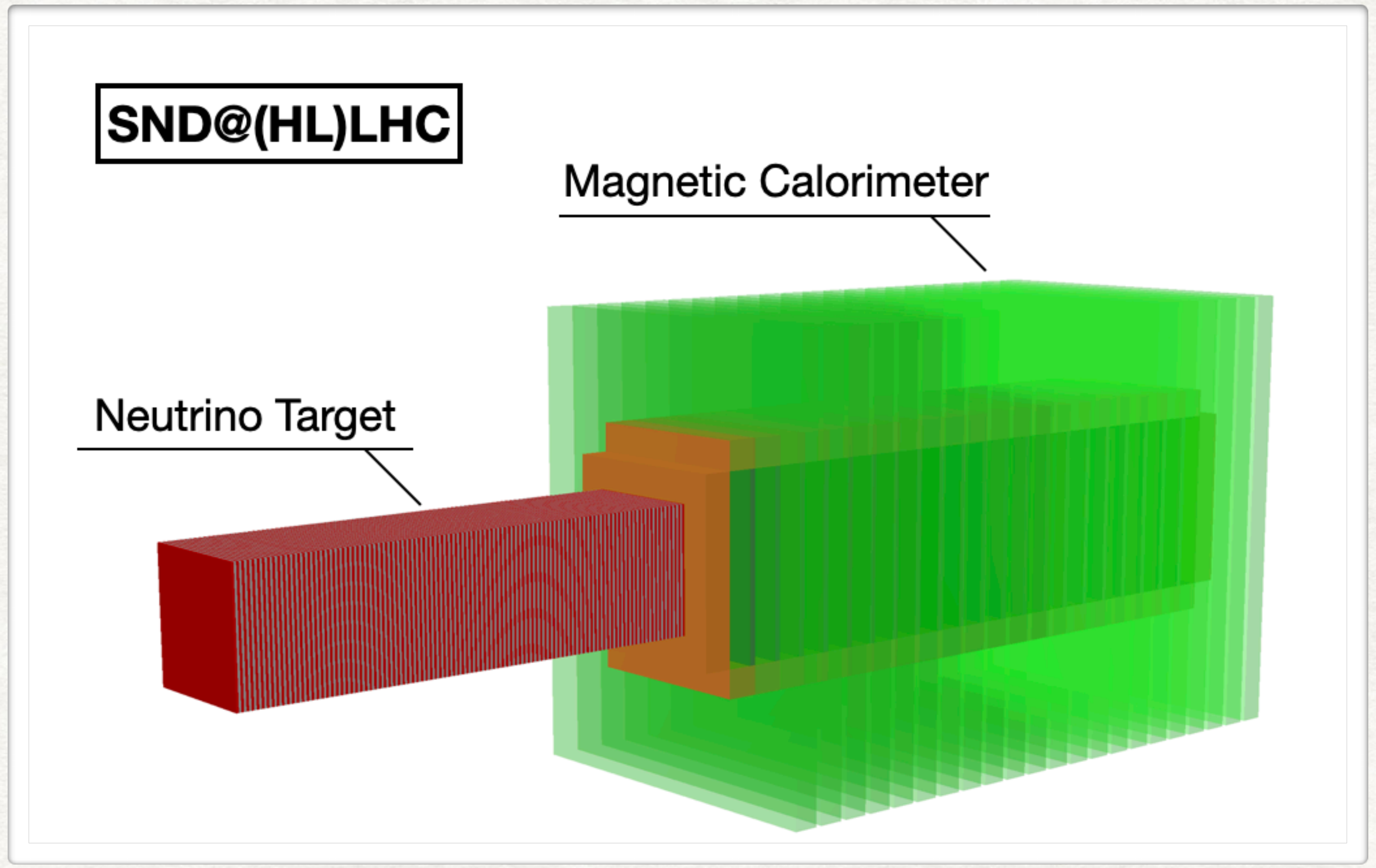
HL-LHC



SND IN THE HI-LUMI ERA

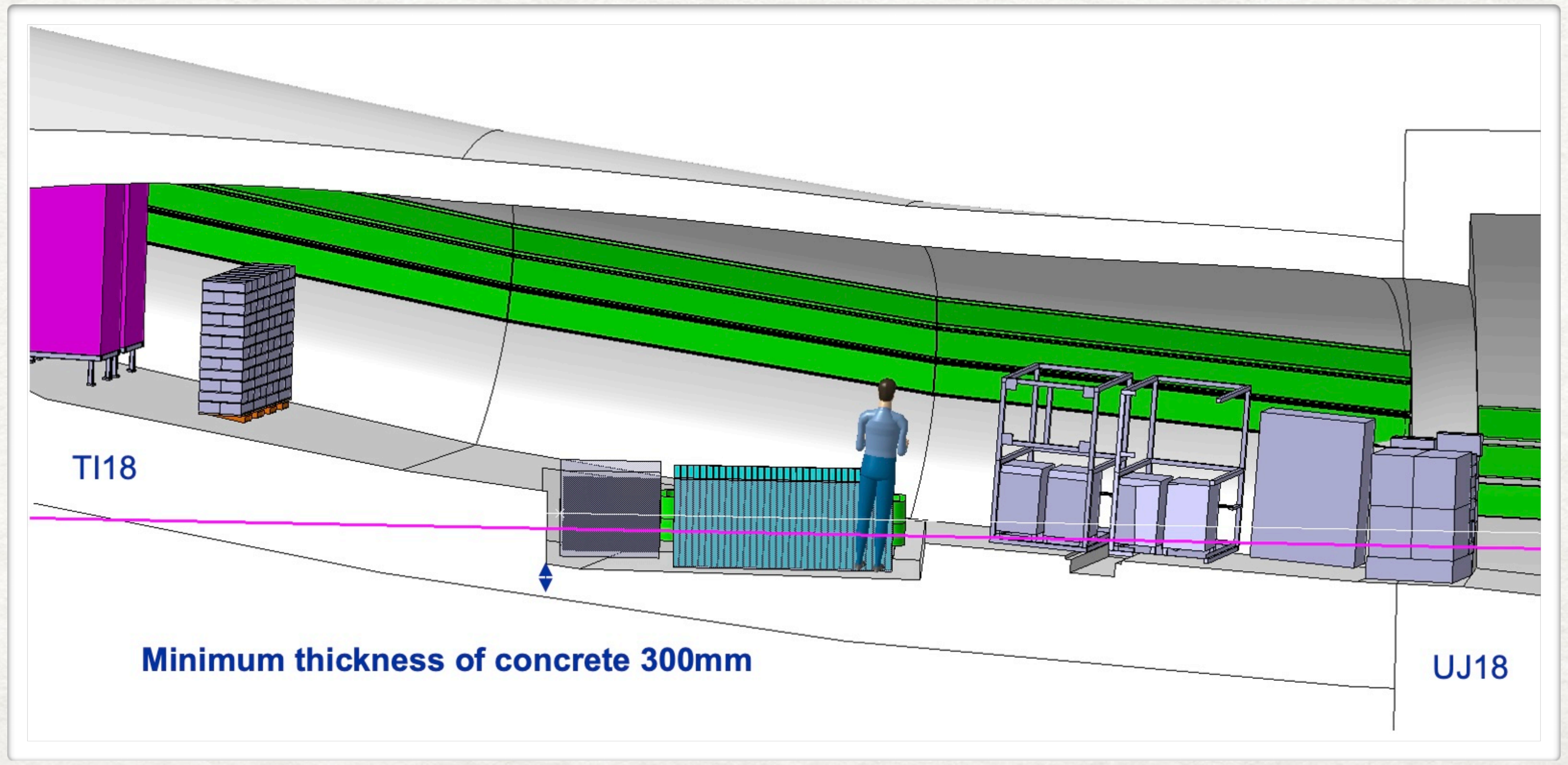
Motivation

- Exploit the High-Lumi LHC to perform neutrino physics measurements in the TeV energy range with unprecedented statistics
- Upgrade the SND@LHC detector to cope with high background rates
- Improve detector performances in energy measurement and charge separation



Main features of the detector

- Electronic vertex detector
- Silicon tracker as vertex detector
- Iron-core muon spectrometer
- Improved hadron calorimeter and timing detectors.



Letter of Intent: https://cds.cern.ch/record/2895224
Addendum: https://cds.cern.ch/record/2909524/

SND IN THE HI-LUMI ERA

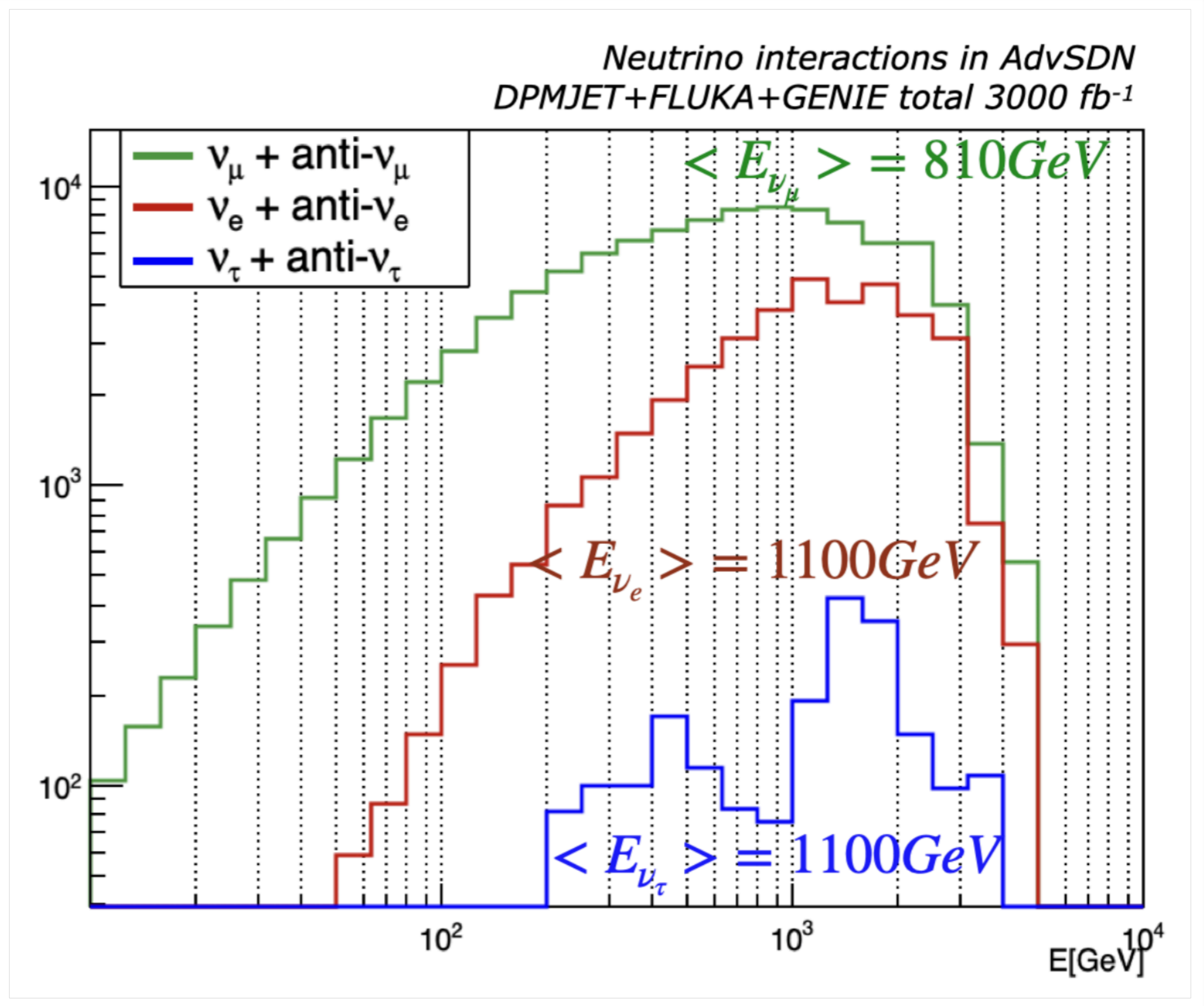
Physics performances

- Measurement of **charm production** with neutrinos
- Constrain **gluon PDF** at very **small x**
- **(Tau) neutrino** physics with high statistics
- Beyond Standard Model searches

LHC Run3 **HL-LHC**

Flavour	Target	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	1.2×10^3	1.3×10^5
$\nu_e+\bar{\nu}_e$	3.9×10^2	4.5×10^4
$\nu_\tau+\bar{\nu}_\tau$	3.0×10^1	2.2×10^3
Tot	1.6×10^3	1.8×10^5

100 time more statistics

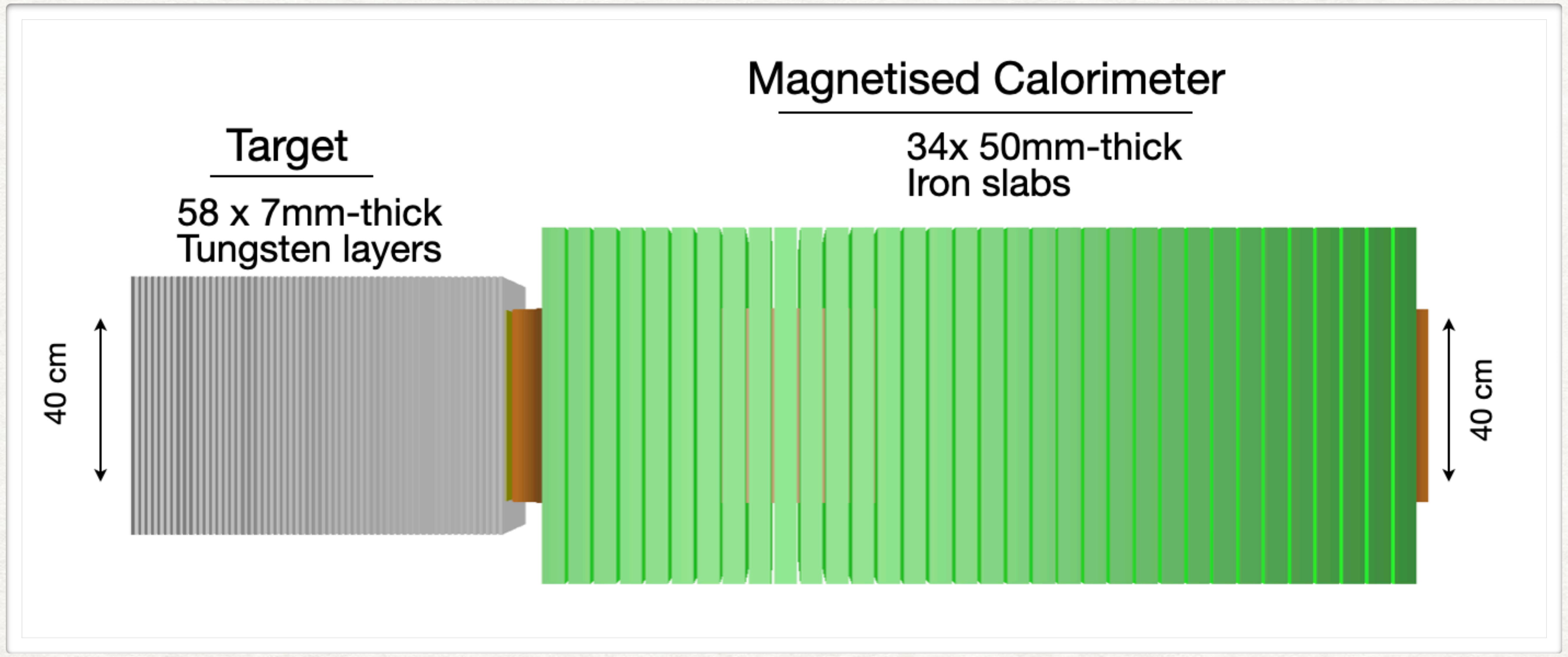


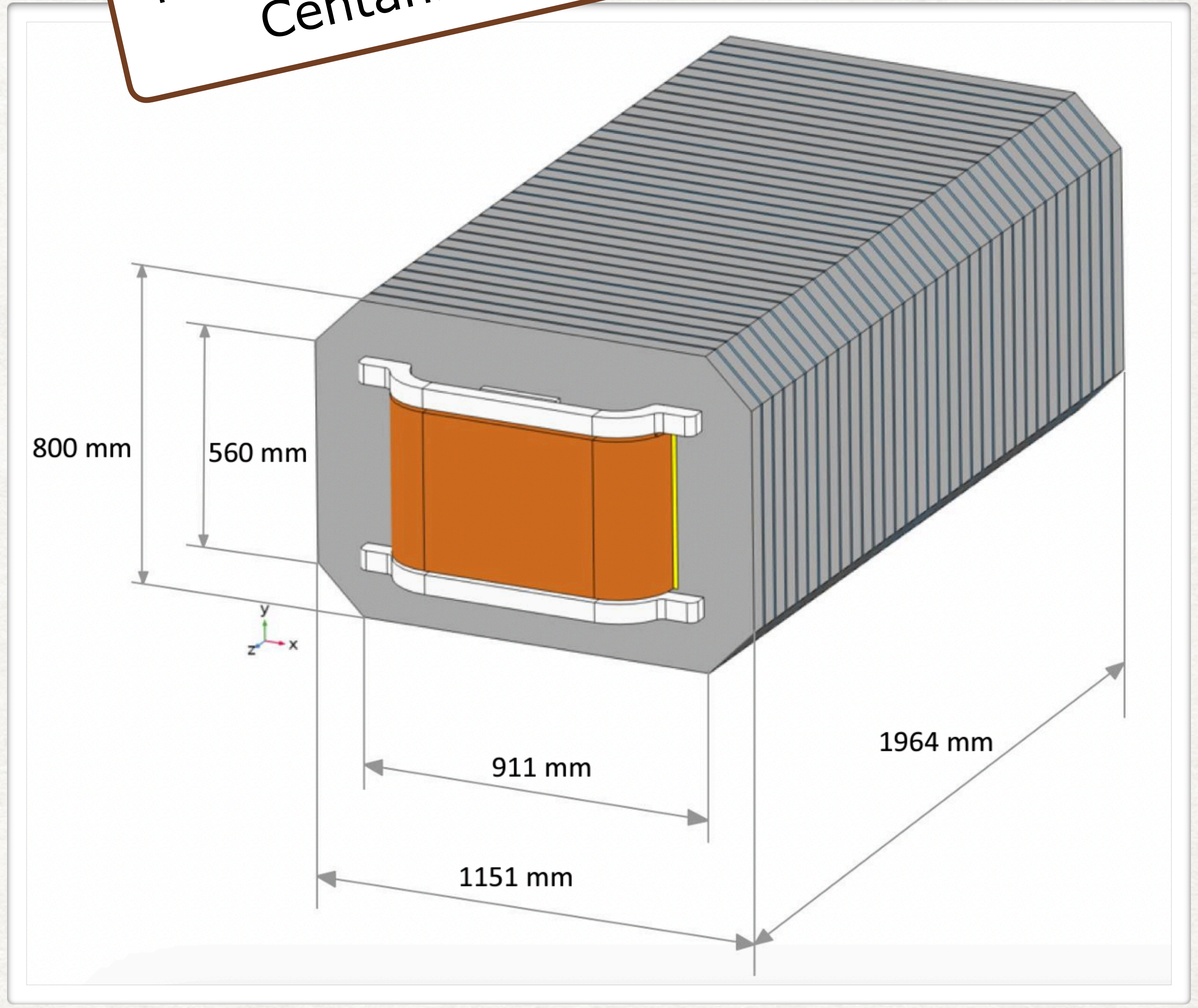
LHC Run3 **HL-LHC**

Measurement	Uncertainty Stat.	Uncertainty Sys.	Uncertainty Stat.	Uncertainty Sys.
Charmed hadron yield	5%	35%	1%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	5%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	1%	5%
ν_μ and $\bar{\nu}_\mu$ cross-section	-	-	1%	5%

SND UPGRADE: DETECTOR LAYOUT

More details in Daniele Centanni's talk





TARGET

- Active surface: 40x40 cm^2
- Material: W
- Total mass: 1.3 tons
- Sensitive layers: Silicon strips

MAGNETIZED HCAL

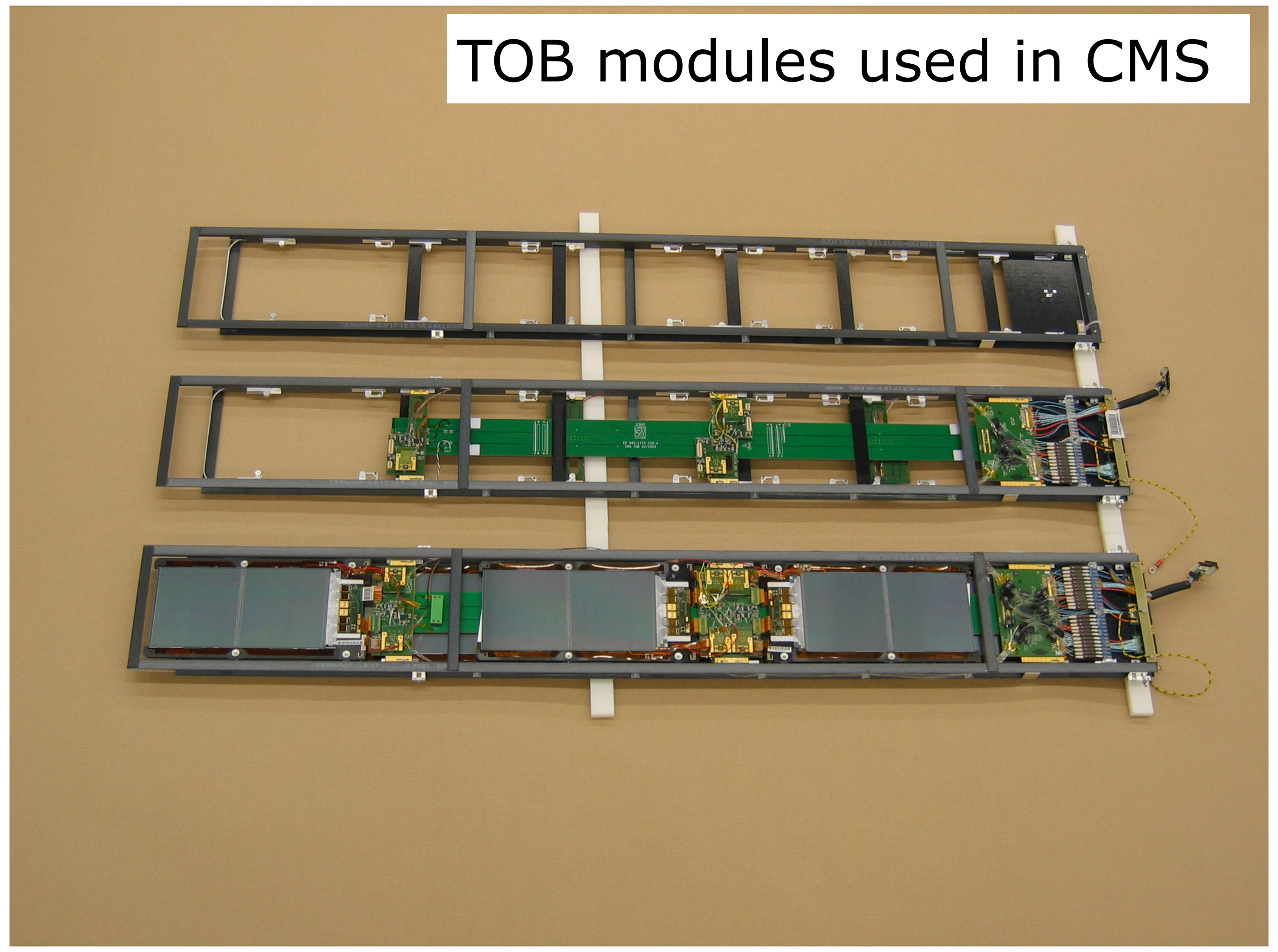
- Active surface: 40x40 cm^2
- Material: Fe
- Sensitive volume mass: 2.1 tons
- Sensitive layers: Silicon strips

IRON CORE MAGNET

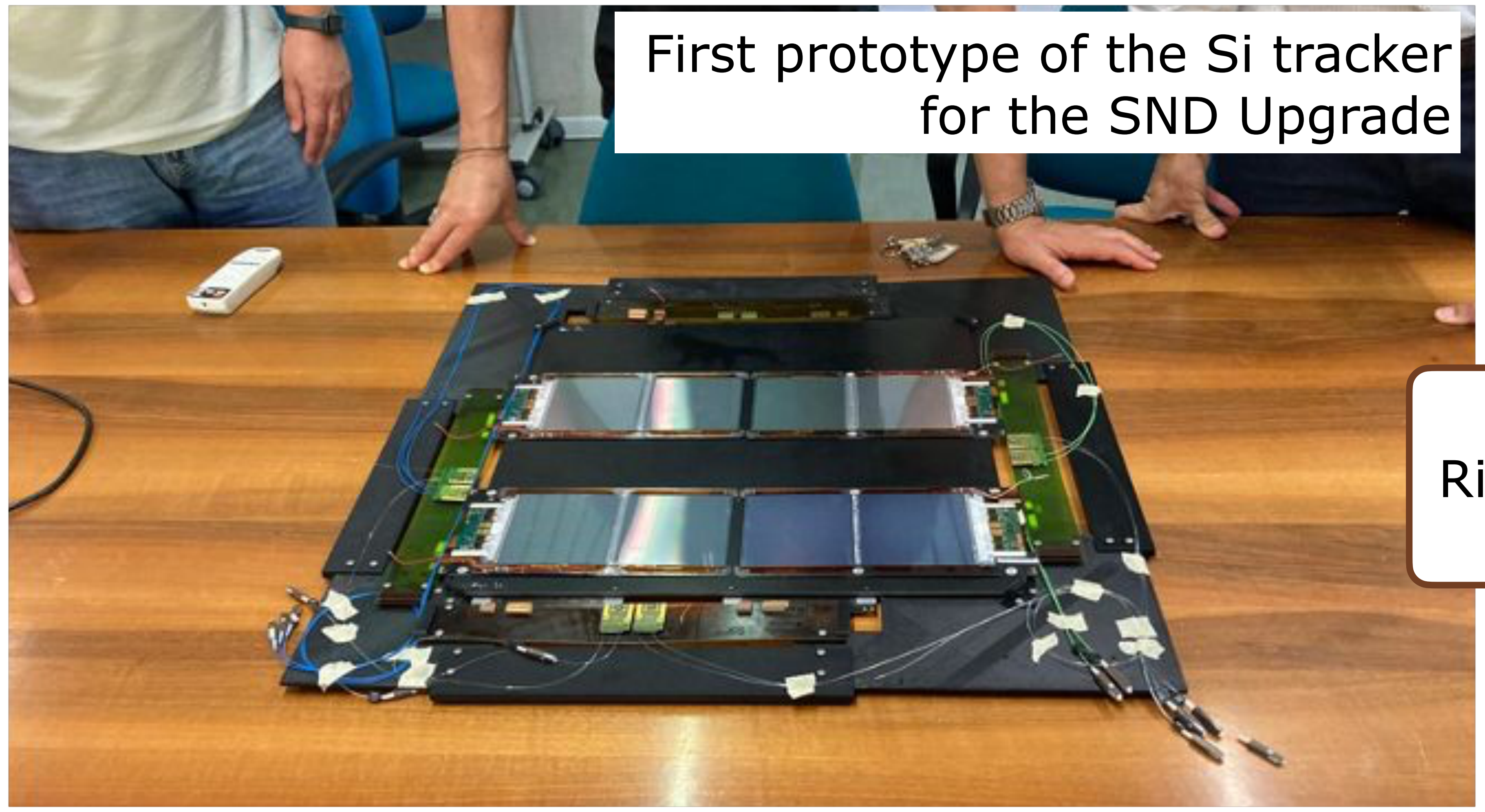
- Horizontal magnetic field 1.75 T
- Coil mass (copper): 0.86 tons
- Overall mass: 12 tons

SND UPGRADE: TRACKING SYSTEM

- Re-use of CMS Tracker Outer Barrel (TOB) modules
- Design of new mechanics and electronics for the Tracker performed at INFN Napoli

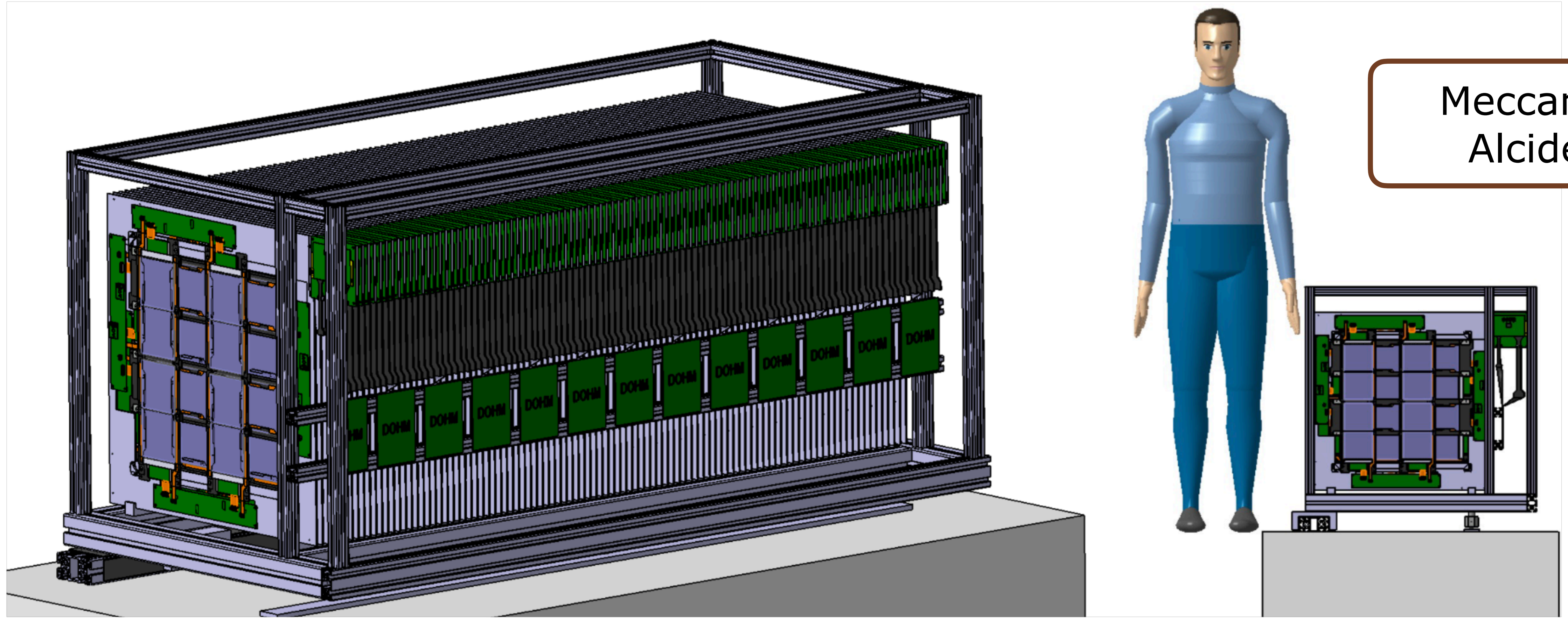


TOB modules used in CMS



First prototype of the Si tracker for the SND Upgrade

Electronics design: Riccardo De Asmundis, Paolo Di Meo

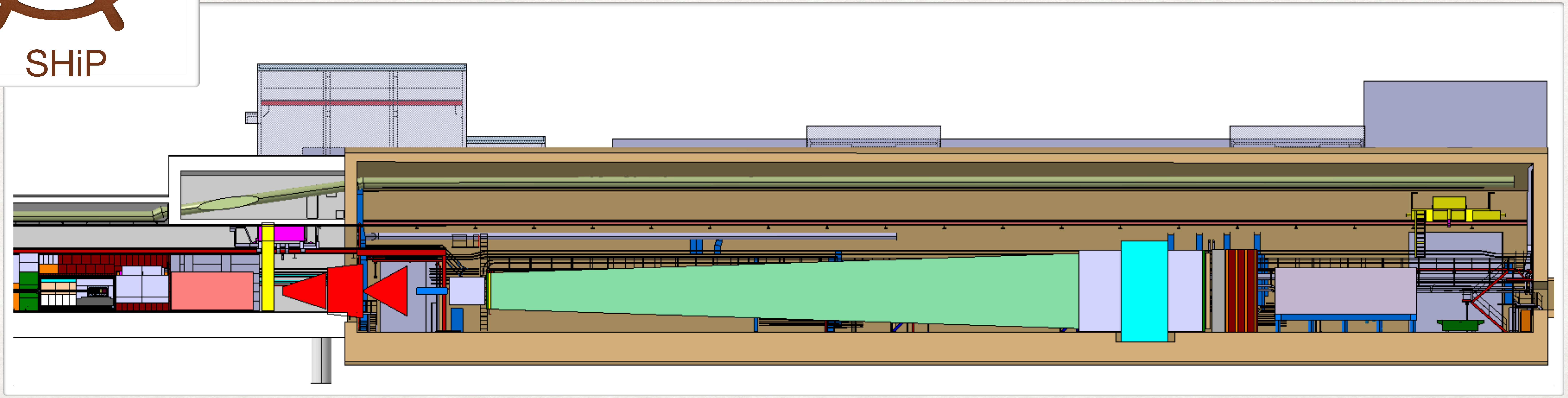


Meccanica design: Alcide Bertocco

NEUTRINO PHYSICS AT THE **INTENSITY** FRONTIER

THE **SHIP** EXPERIMENT

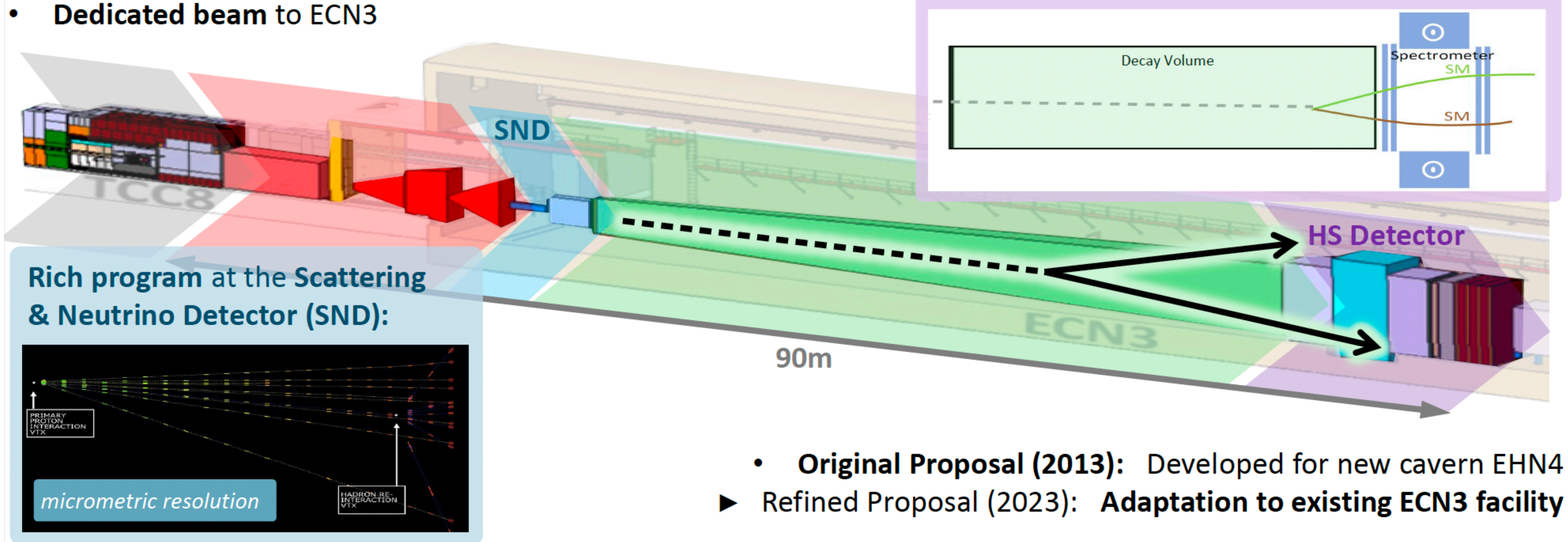
SHiP



SEARCH FOR HIDDEN PARTICLES (SHIP) AT A DEDICATED BEAM DUMP FACILITY (BDF)

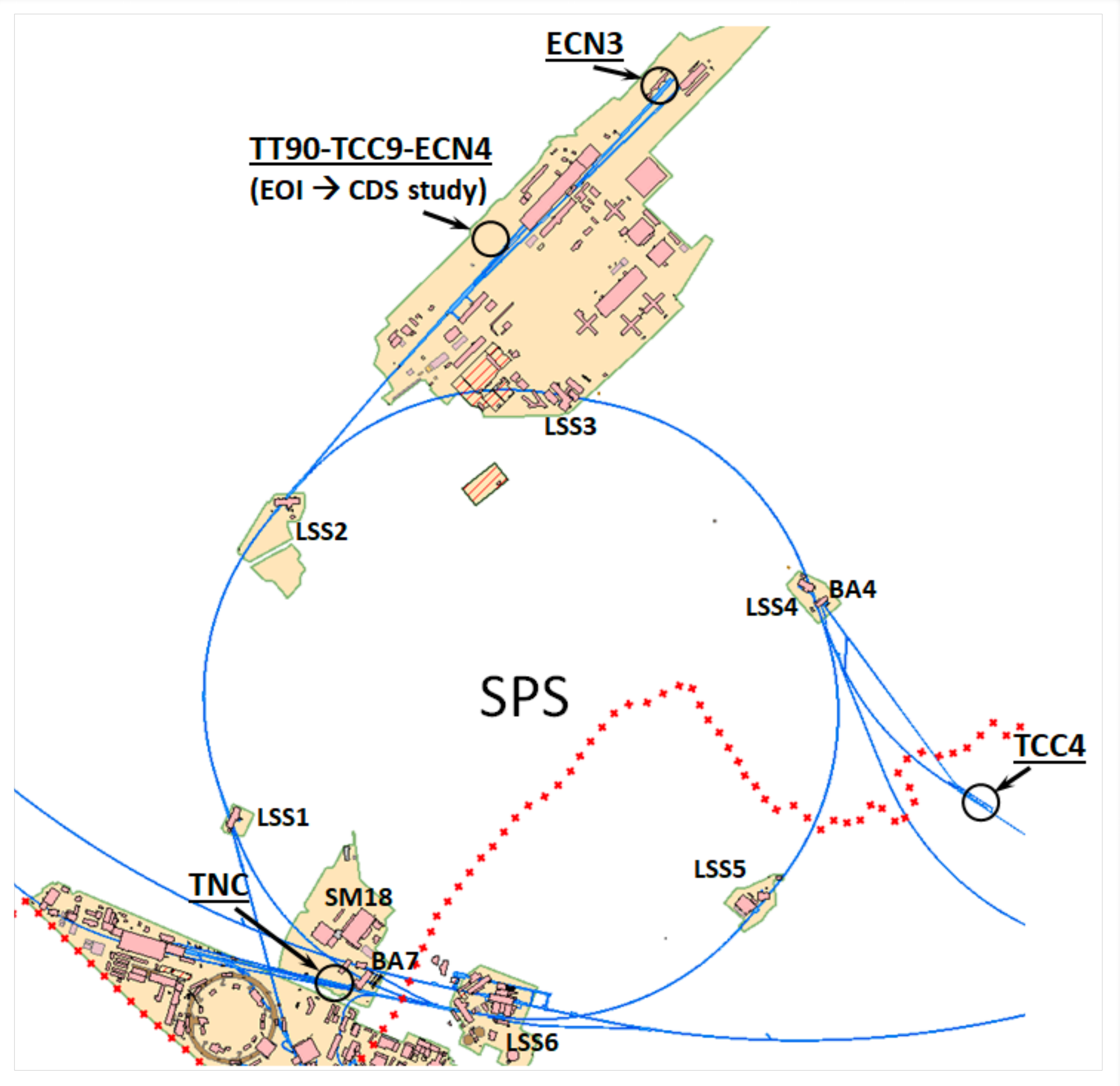
- High-Intensity (HI) upgrade of **CERN SPS 400GeV proton facility**
- General-purpose **beam dump facility**
- **Dedicated beam** to ECN3

Search for **Feebly-Interacting Particles** with the **Hidden Sector Decay Spectrometer (HSDS):**



- **Original Proposal (2013):** Developed for new cavern EHN4
- Refined Proposal (2023): **Adaptation to existing ECN3 facility**

[CERN-SPSC-2013-024, CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]



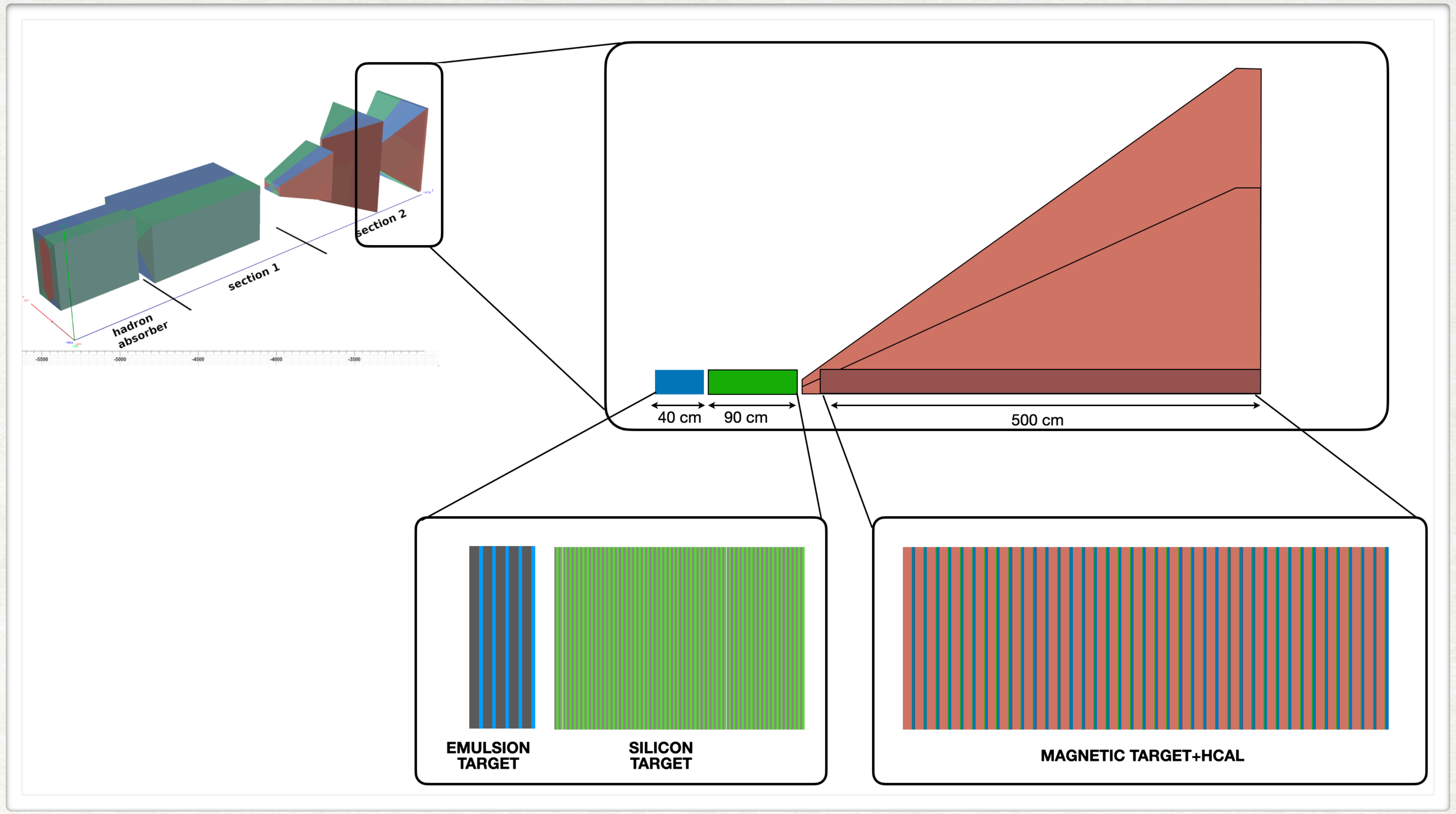
BDF/SHiP approved by the CERN Research Board in March 2024

http://cds.cern.ch/record/2007512/files/SPSC-P-350.pdf Technical Proposal in 2015
EPJC (2022) 82:486

SND@SHIP

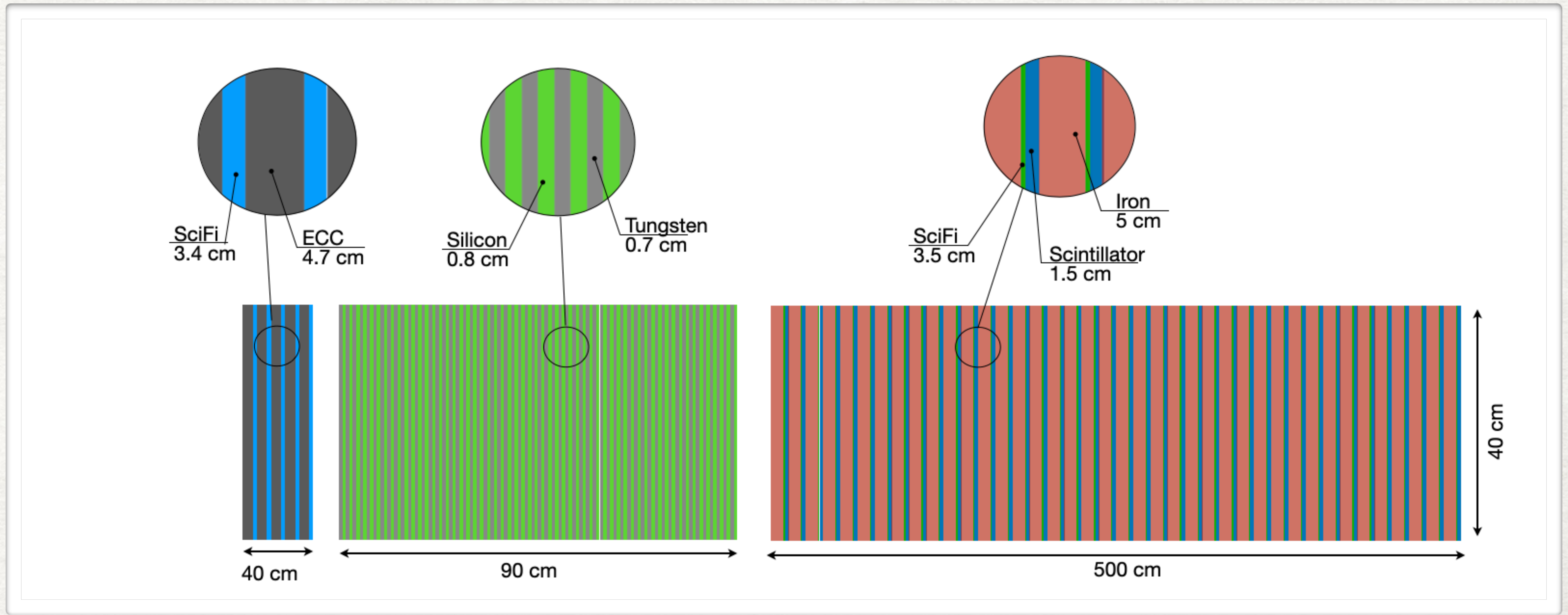
- **Neutrino physics** (10÷100 GeV) with unprecedented statistics, **complementary** to the LHC programme

  New concept for SND:
  - Detector embedded in the last section **muon shield**
  - Closer to the target, higher neutrino fluxes
  - Magnetized Iron interleaved with trackers and used as HCAL

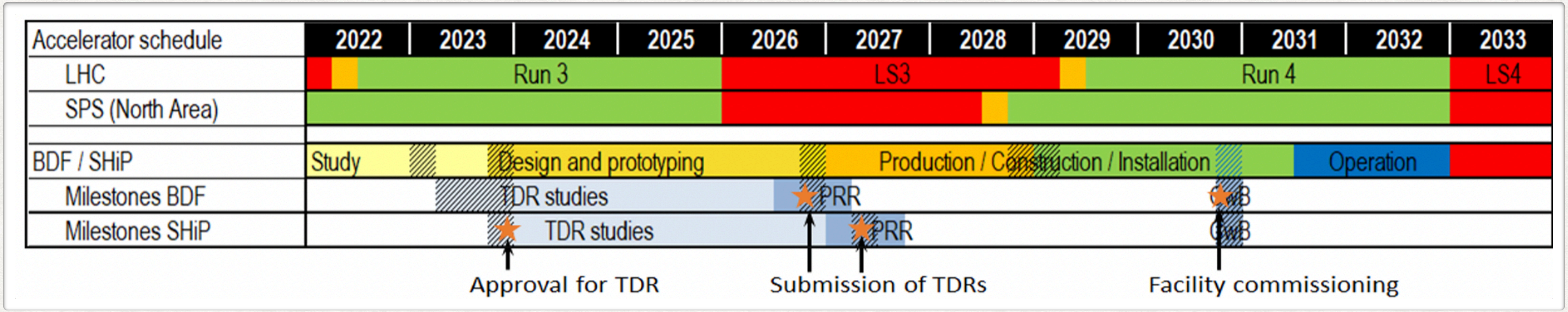


- **Emulsions** combined with **Silicon** trackers for the target
- Scintillators and SciFi as trackers in **Magnetized HCAL**

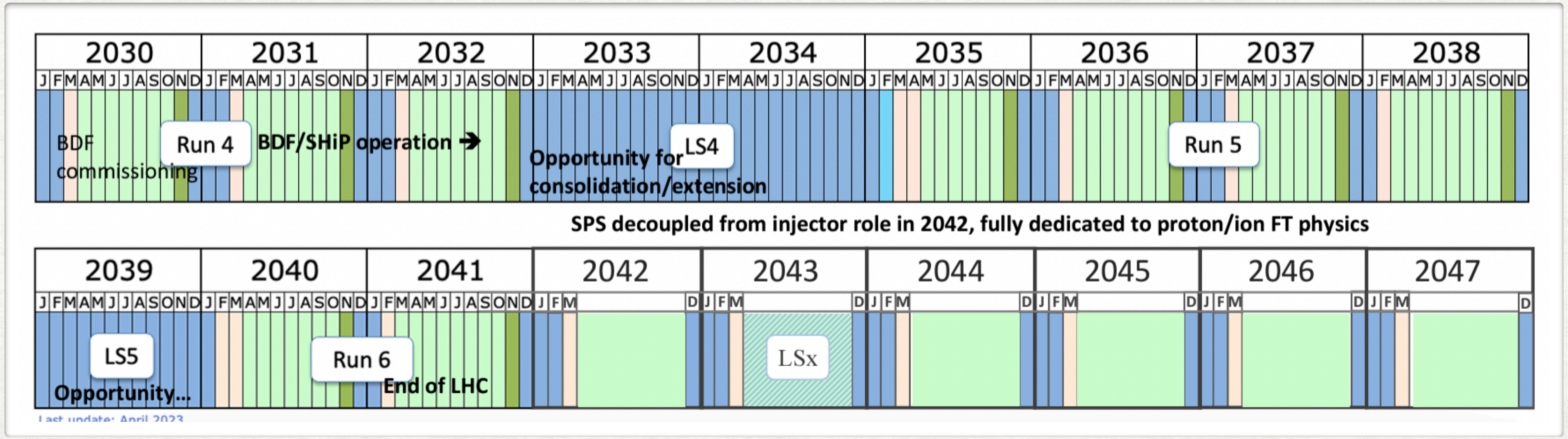
  - Profit of the experience gained in SND@LHC with **emulsions** in high-density environment
  - R&D and prototyping for **Silicon detectors** in common with the SND Upgrade for HL-LHC



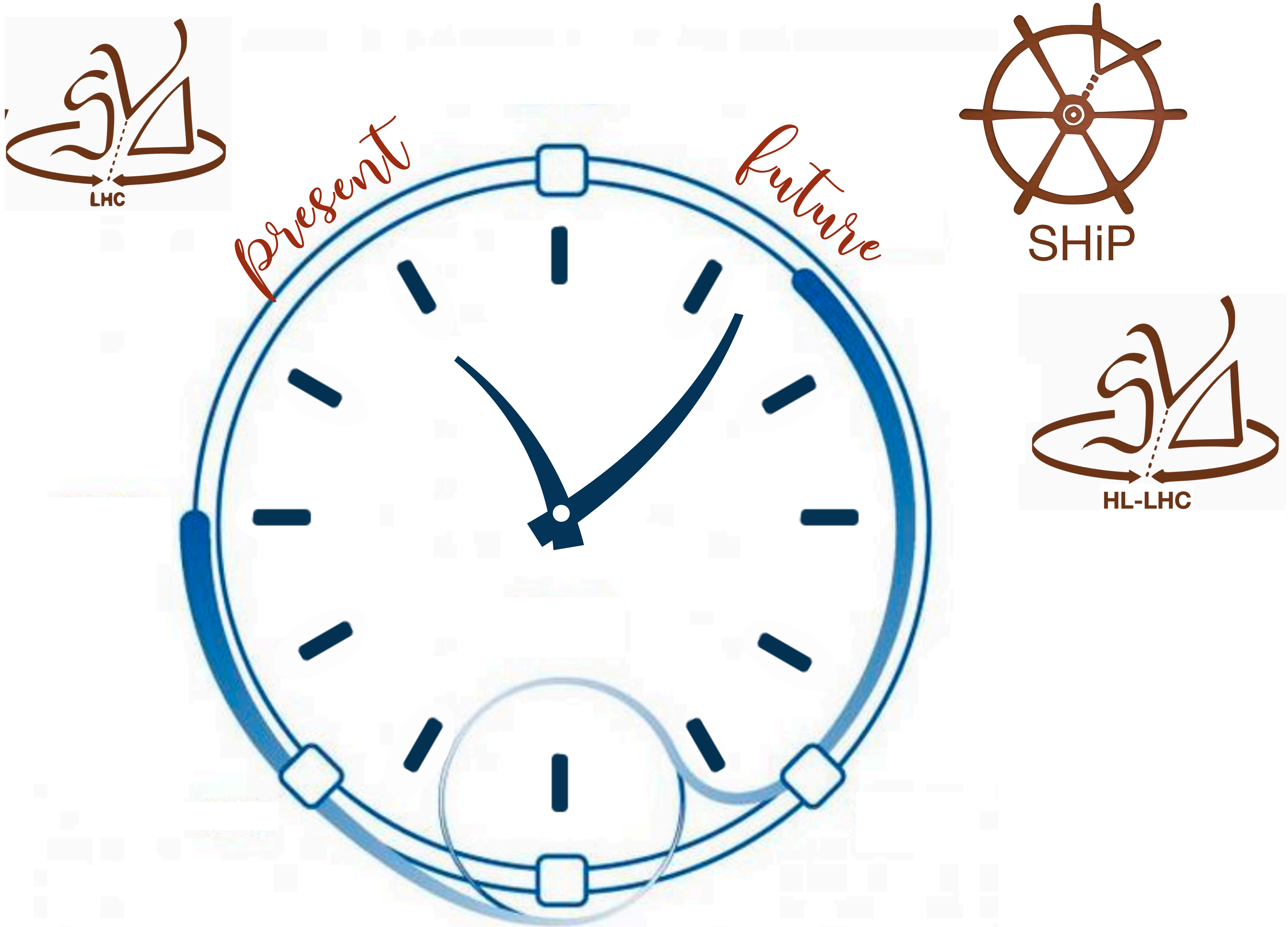
SHIP TIMELINE



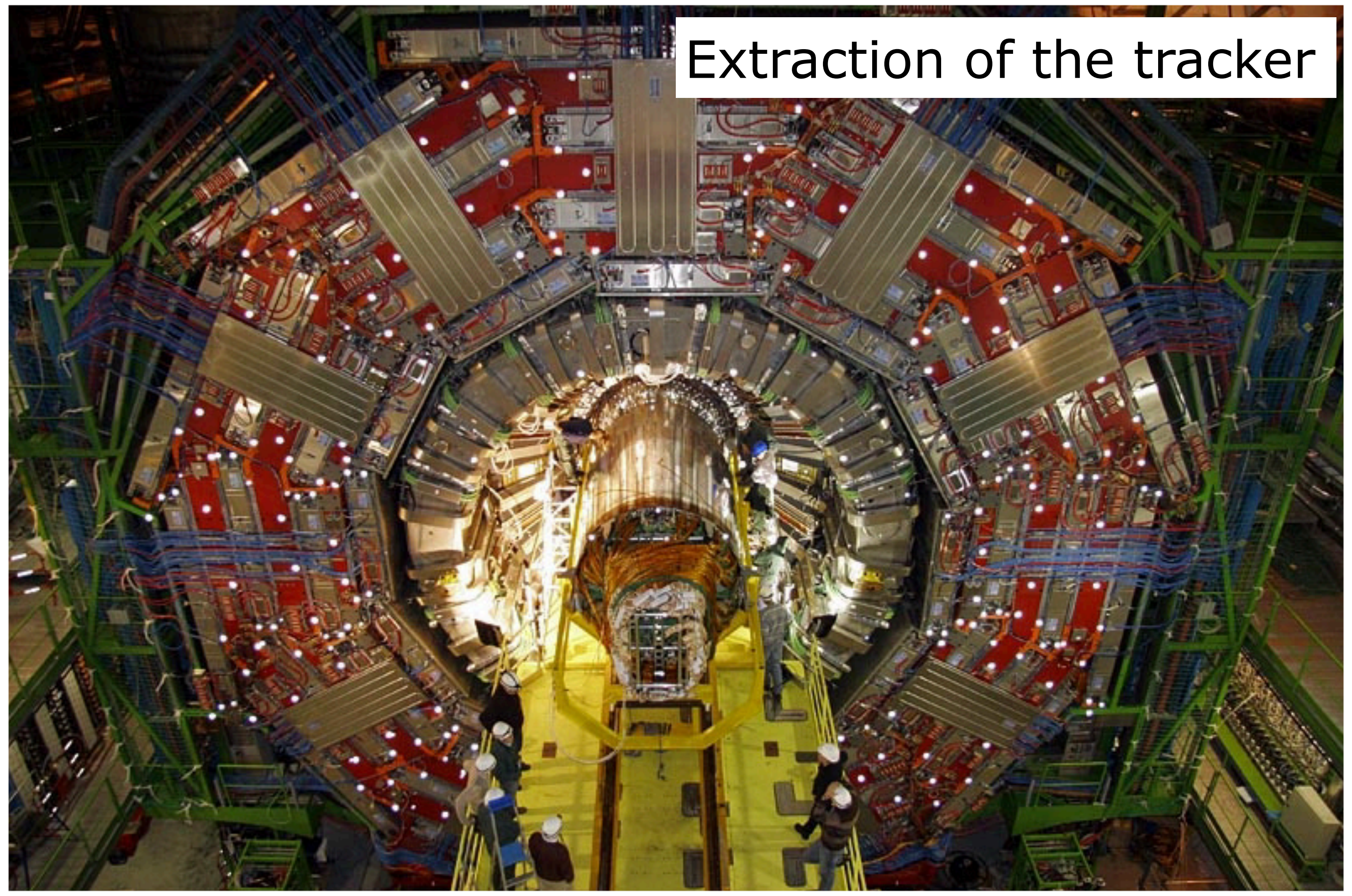
- ~2.5 years for Detector Technical Design Reports (TDRs)
- Start data taking in 2031

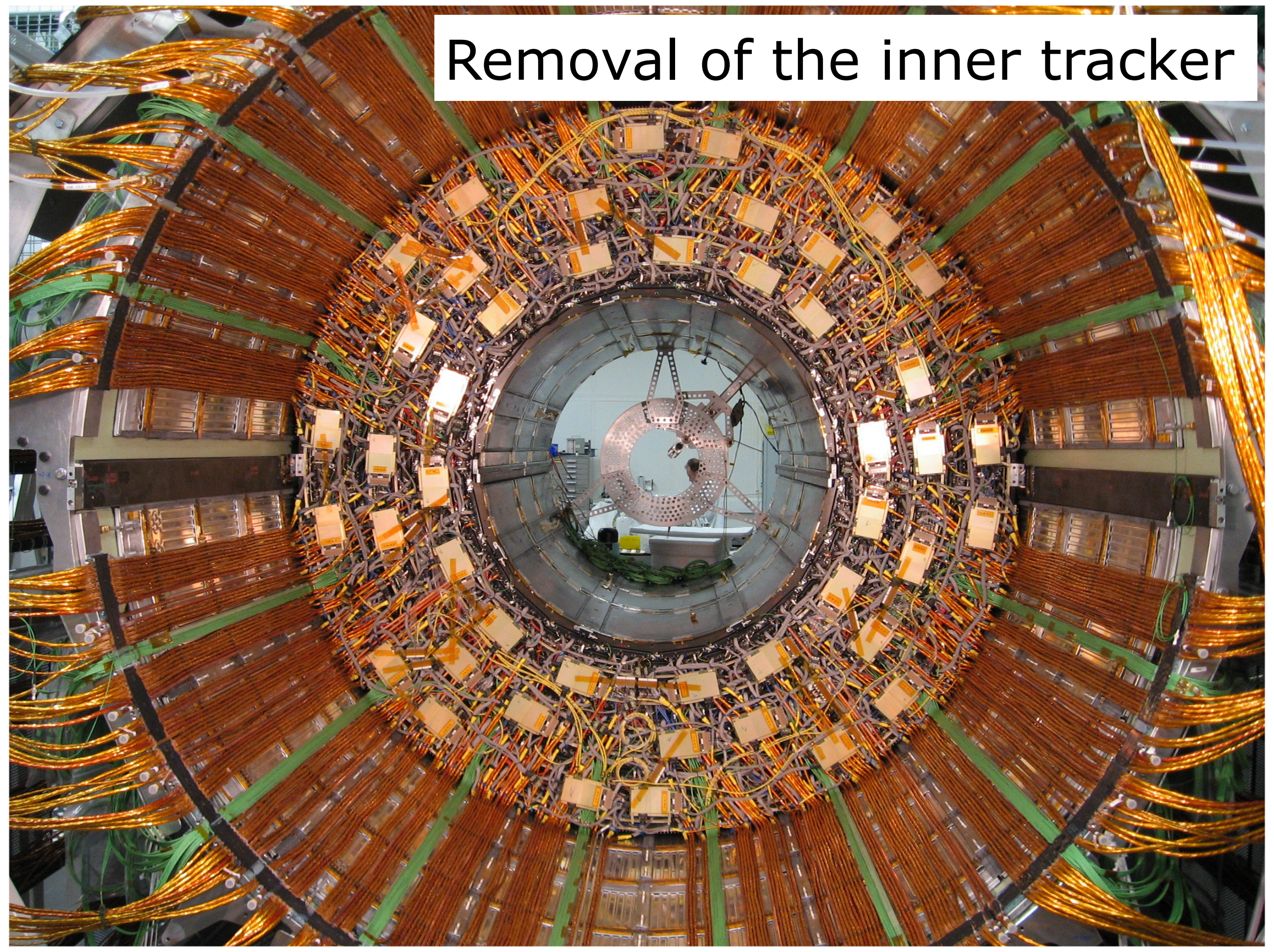


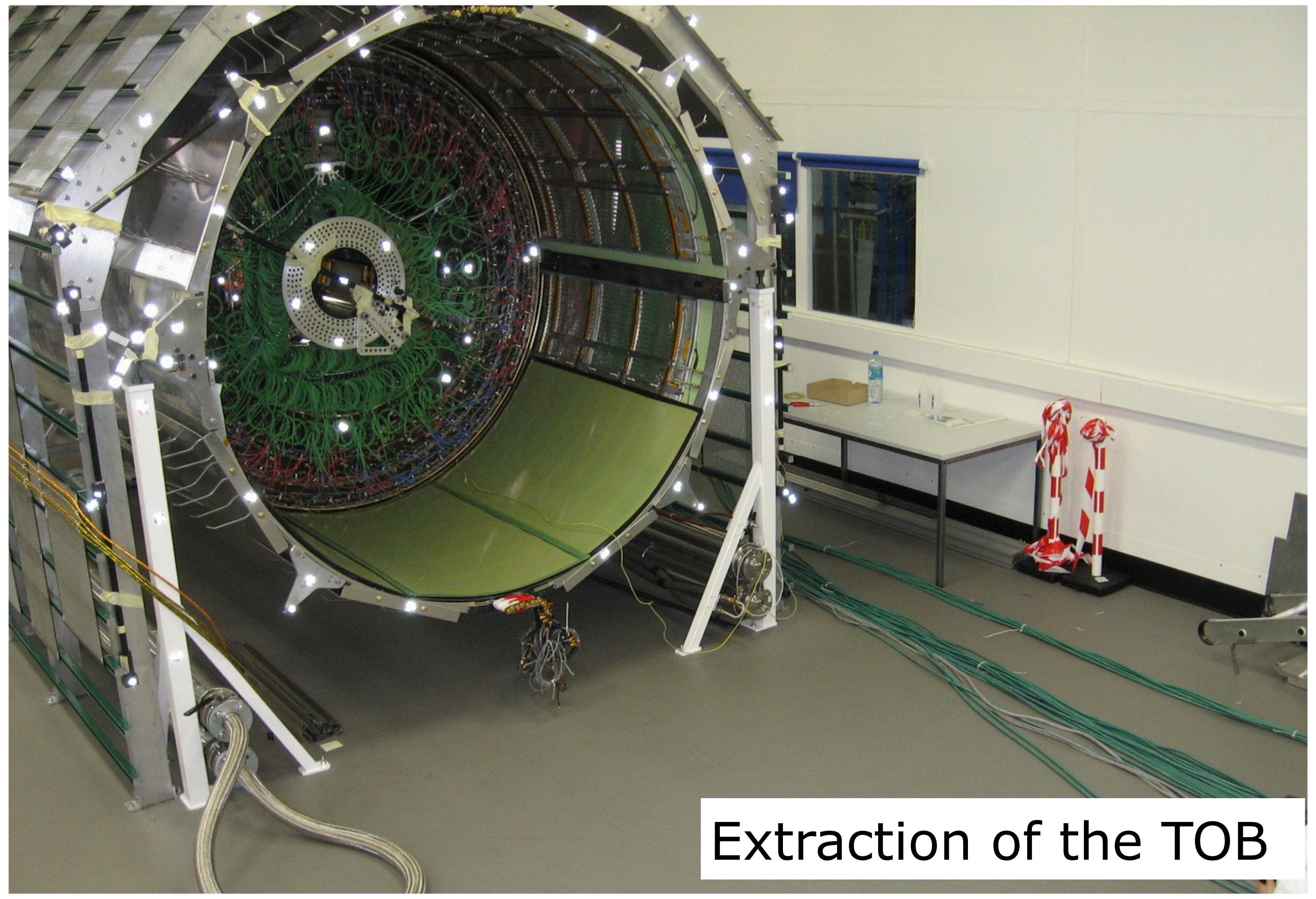
IT'S TIME FOR NEUTRINO PHYSICS AT CERN

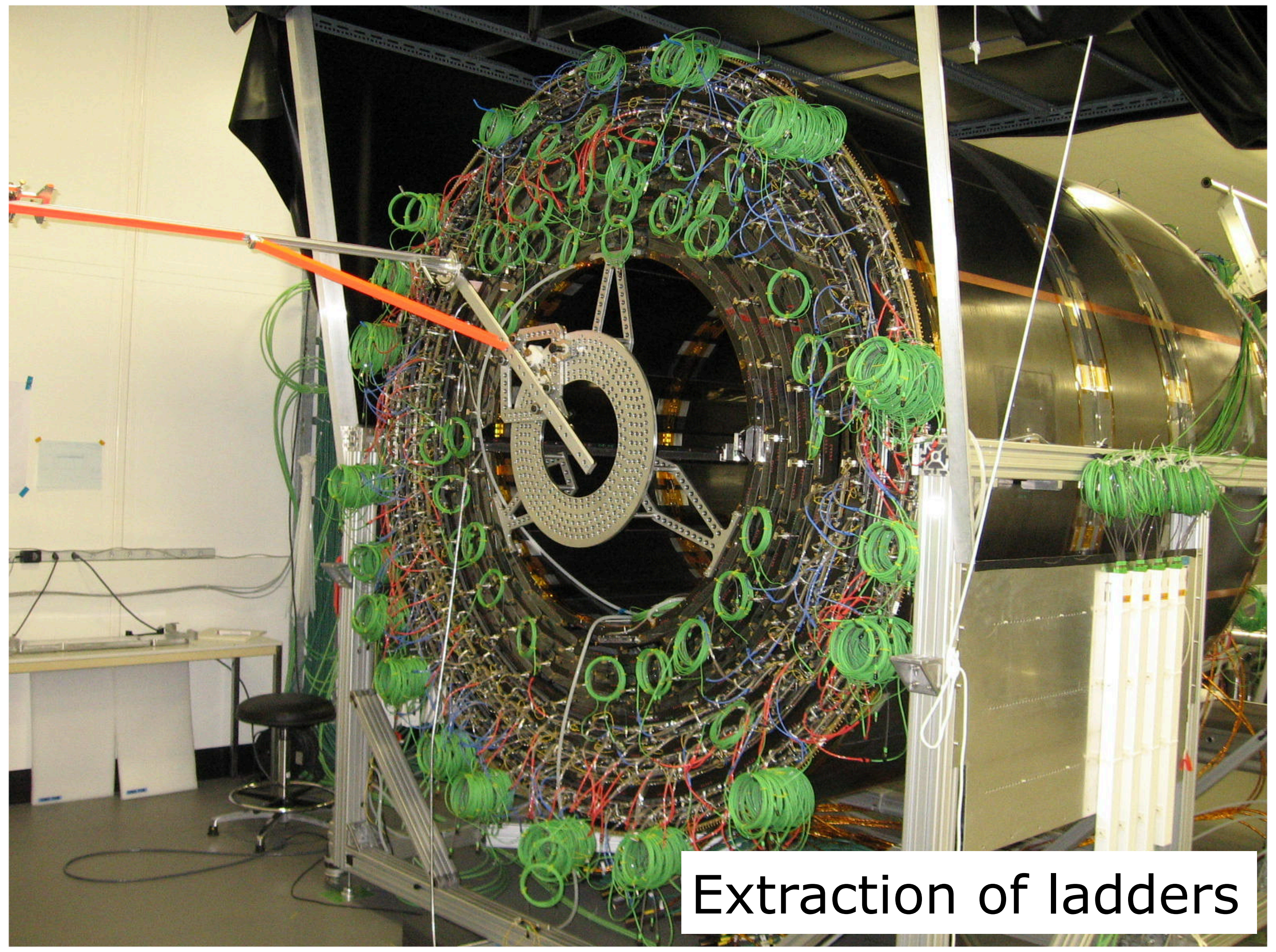


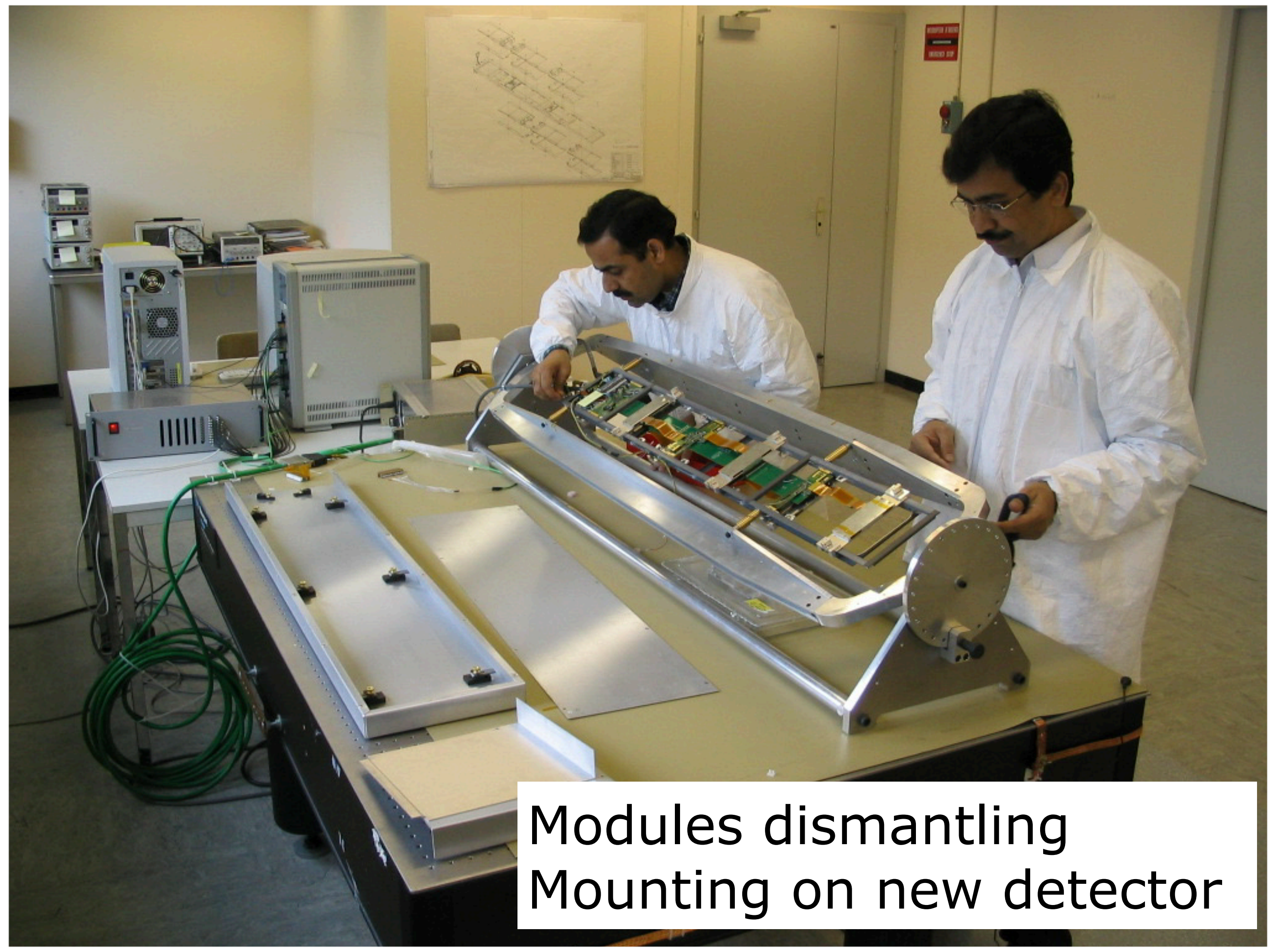
CMS TRACKER DECOMMISIONING AND RECOVERY OF TOB MODULES


Extraction of the tracker


Removal of the inner tracker

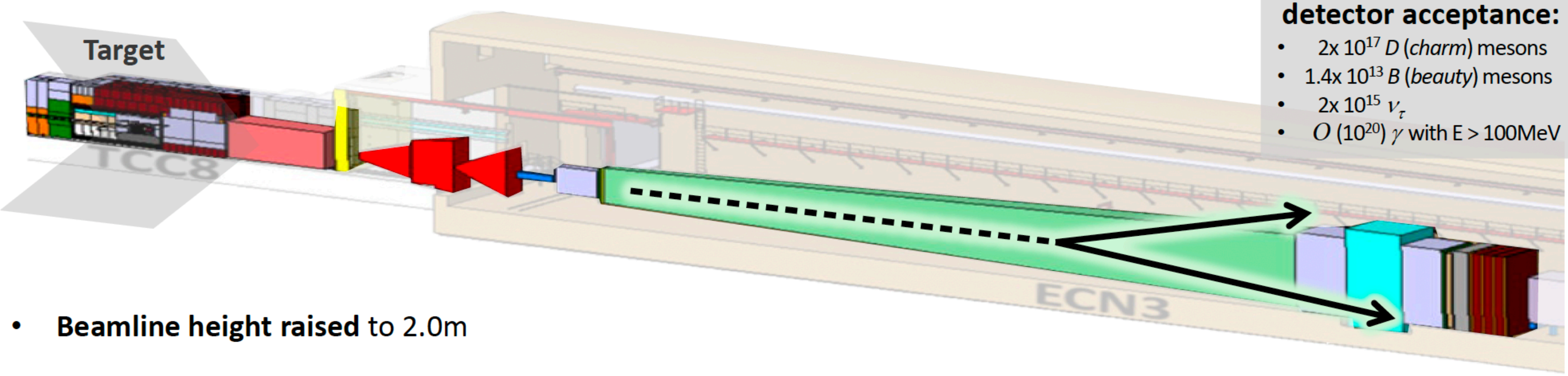

Extraction of the TOB


Extraction of ladders


Modules dismantling
Mounting on new detector

SHIP/BDF DETECTOR TECHNOLOGY

Target & Hadron Stopper

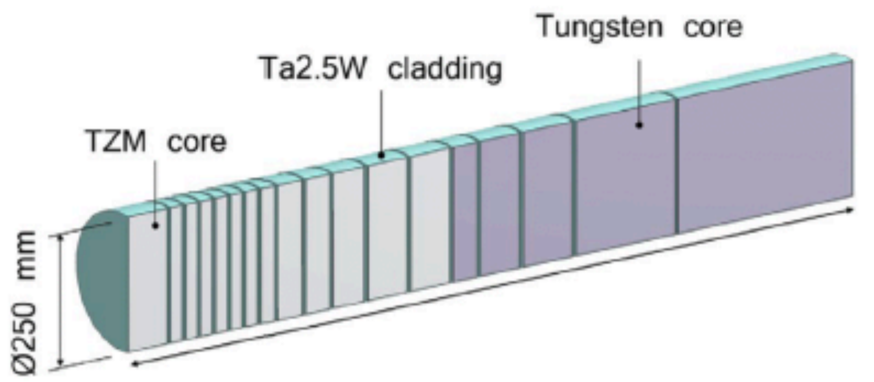


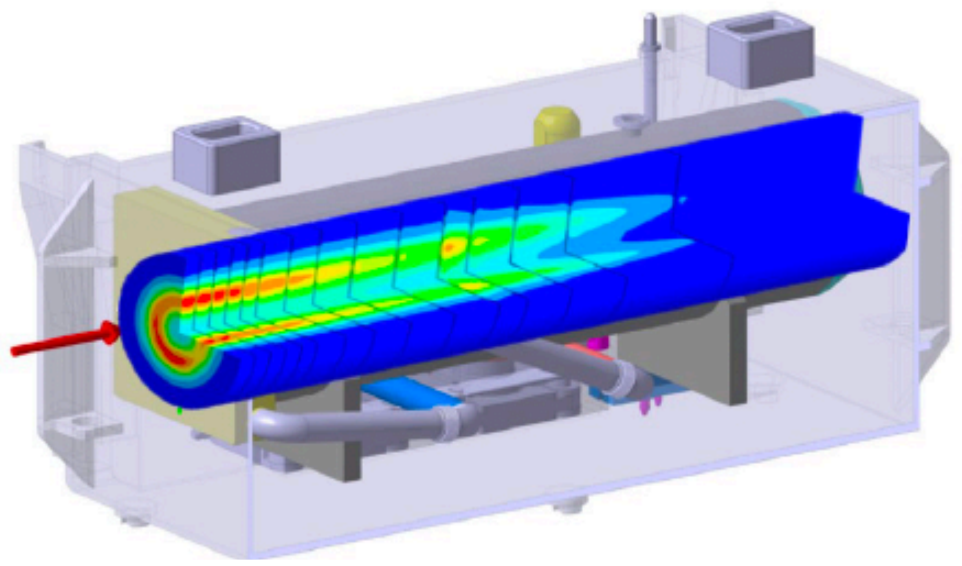
Annual yields within detector acceptance:

- $2x\ 10^{17}$ *D* (*charm*) mesons
- $1.4x\ 10^{13}$ *B* (*beauty*) mesons
- $2x\ 10^{15}\ \nu_\tau$
- $O\ (10^{20})\ \gamma$ with E > 100MeV

- **Beamline height raised** to 2.0m

[CERN-SPSC-2019-049 / SPSC-SR-263, CERN-PBC-Notes-2021-005, CERN-PBC-REPORT-2023-003, **CERN-SPSC-2023-033 / SPSC-P-369**]

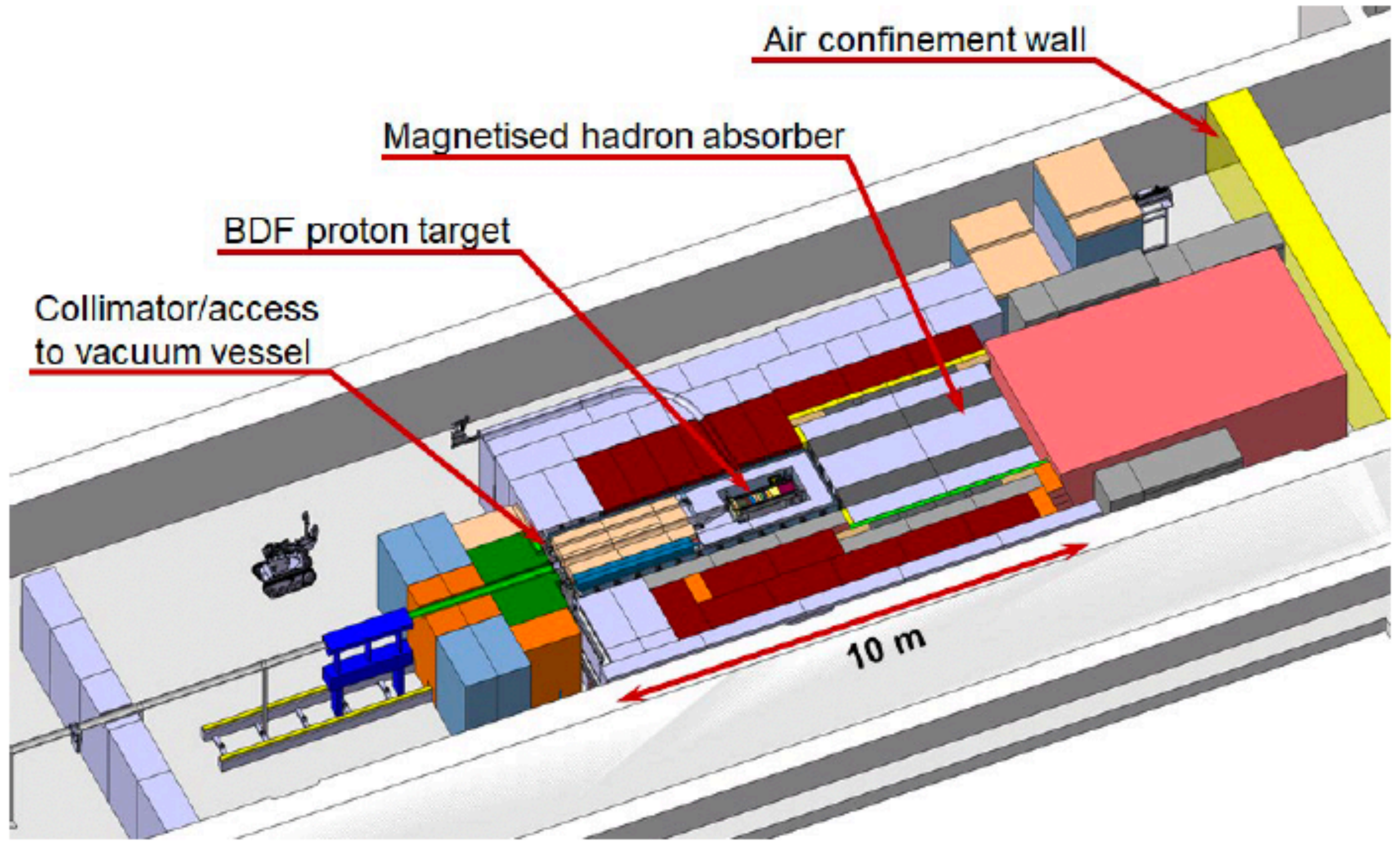




- **High-density proton target:** 12λ
  Ti-Zr-Mo (TZM) + **W blocks**, clad by **Ta**

► **Optimised for heavy meson production**

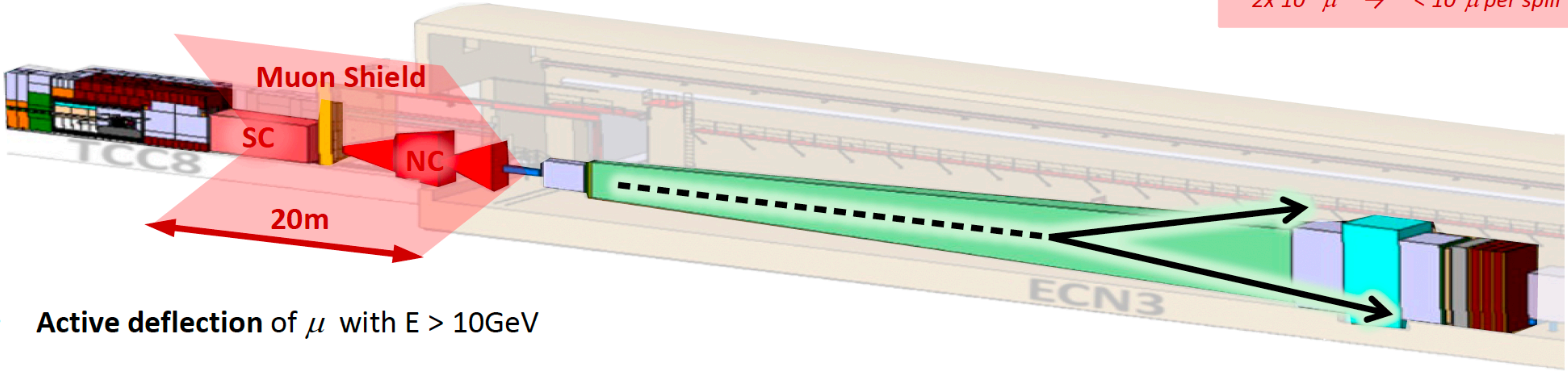
- **Shielding:** **Cast iron & concrete**, water-cooled & vacuum-confined
- 5m-long **magnetised hadron stoppper**



SHIP/BDF DETECTOR TECHNOLOGY

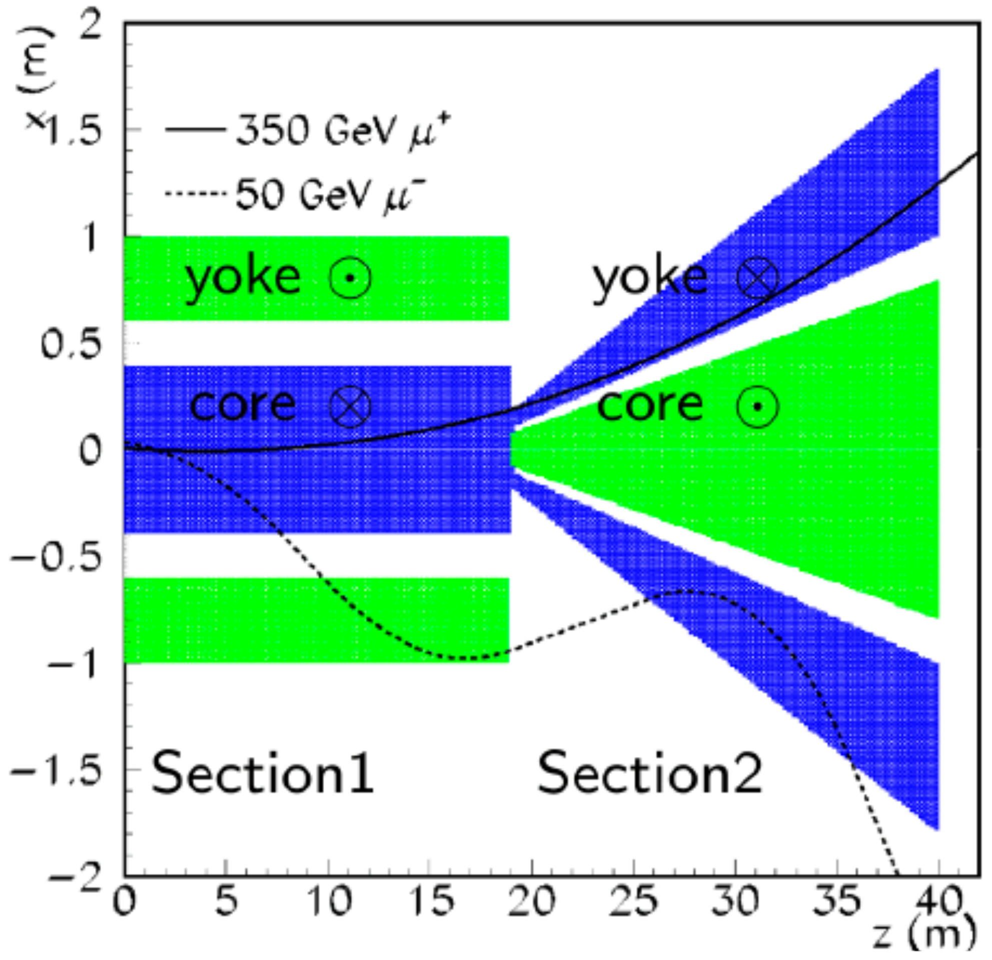
(Superconducting) Magnetic Muon Shield

Reduction of μ rate:
$2x\ 10^{10}\mu$ → $< 10^{5}\mu$ per spill



- **Active deflection** of μ with E > 10GeV

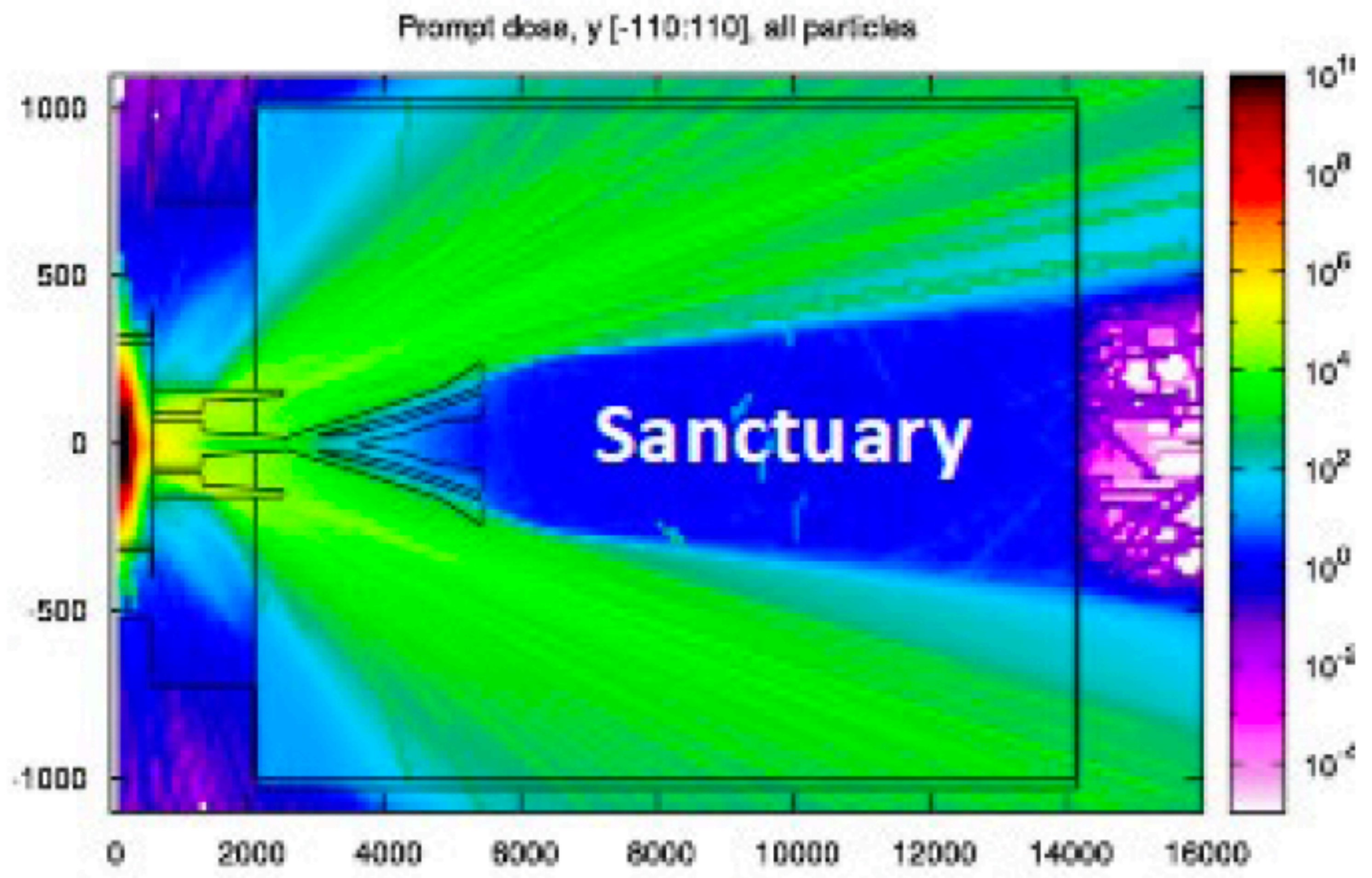
[CERN-SHiP-NOTE-2016-005, 2017 JINST-12-P05011, CERN-SPSC-2019-049 / SPSC-SR-263, **EPJC-80(2020)3-284**, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **Alternate-polarity scheme:**
  Split of **positive & negative μ** to **left & right** of decay volume

- **ECN3 optimisation (hybrid SC / NC):** 5.1T
  Shortened, preserving experiment sensitivity
- **Initial (& fallback) design (NC):** 1.7T

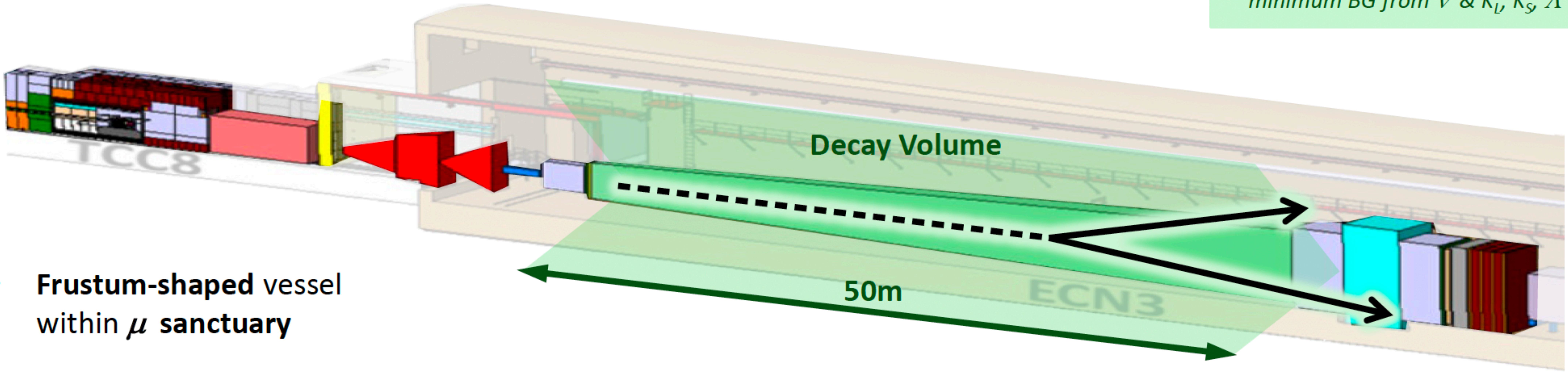
▶ Ongoing **ML-assisted optimisation campaign**



SHIP/BDF DETECTOR TECHNOLOGY

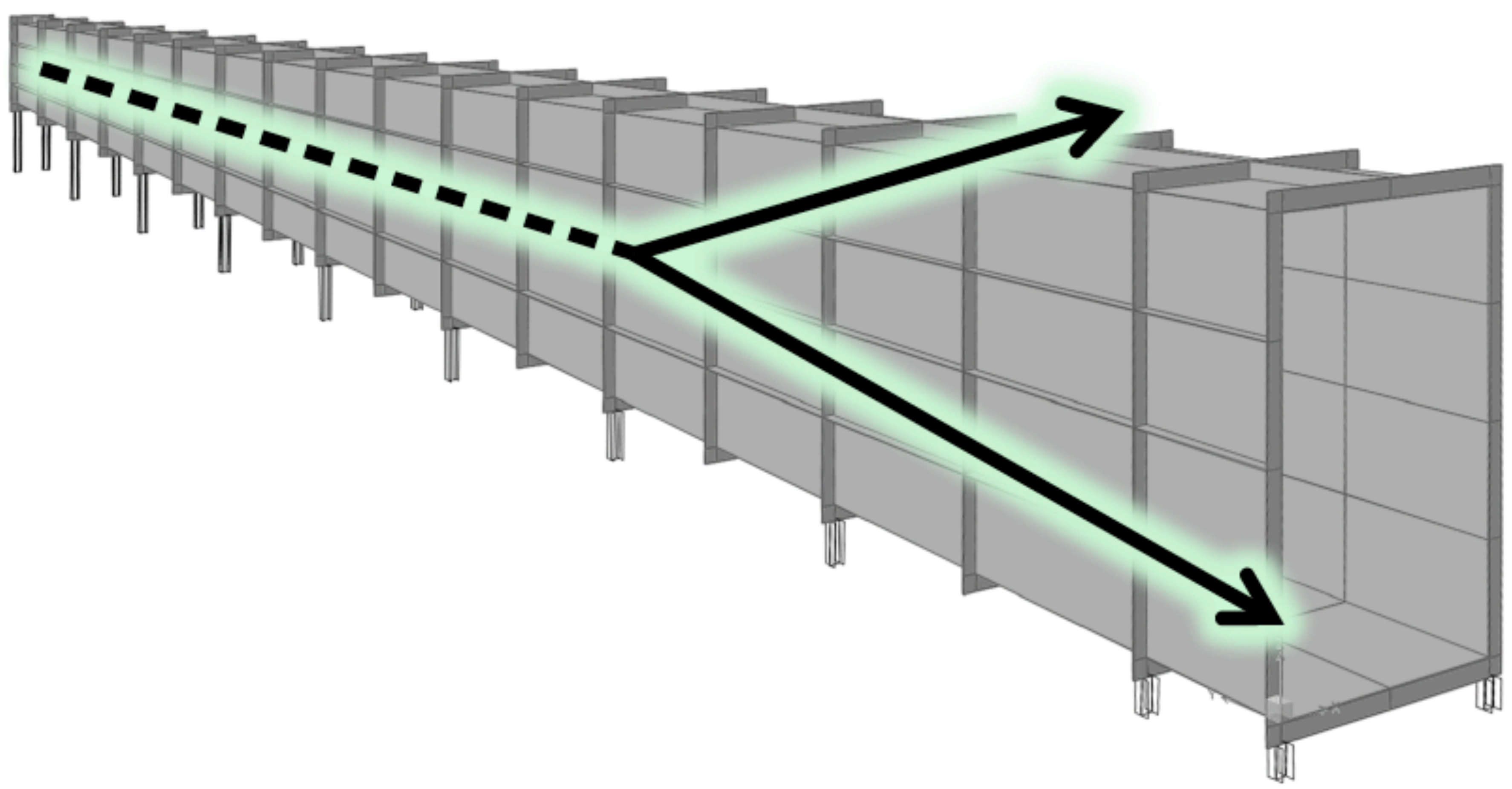
Hidden Sector (HS) Decay Volume

50m-long decay volume:
minimum BG from ν & K_L, K_S, Λ



- **Frustum-shaped** vessel within μ **sanctuary**

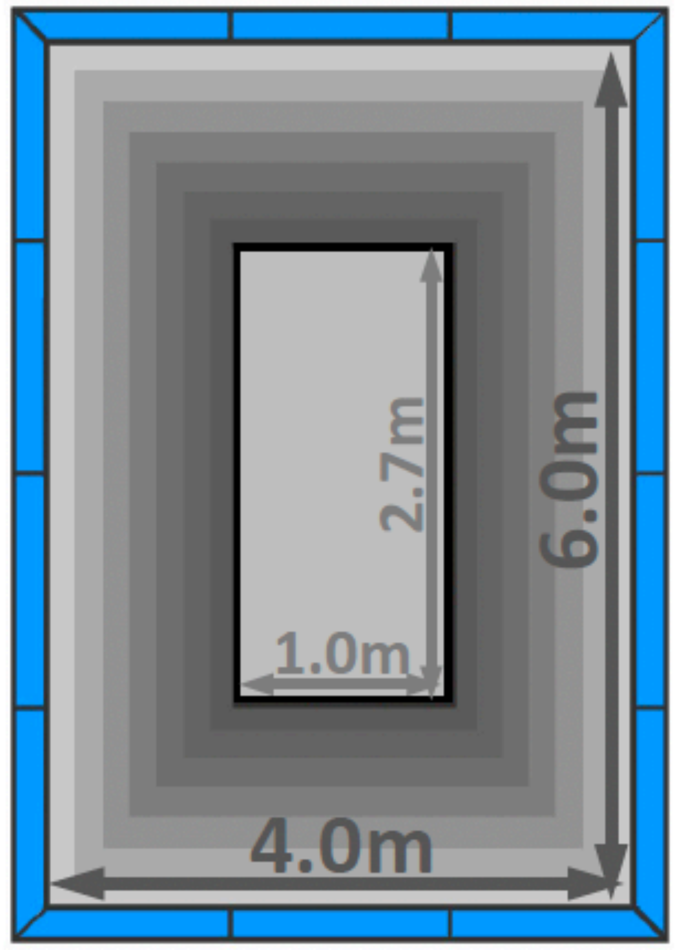
[CERN-SPSC-2019-049 / SPSC-SR-263, ACME (2021) 21:3, CERN-STUDENTS-Note-2023-122, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **He** at **atmospheric pressure**
  Initial design: Evacuated vessel at < 10^{-2} bar

▶ **Lightweight structure** (**Al** / stainless steel)
▶ Low material budget to **minimise μ** and **ν interactions**

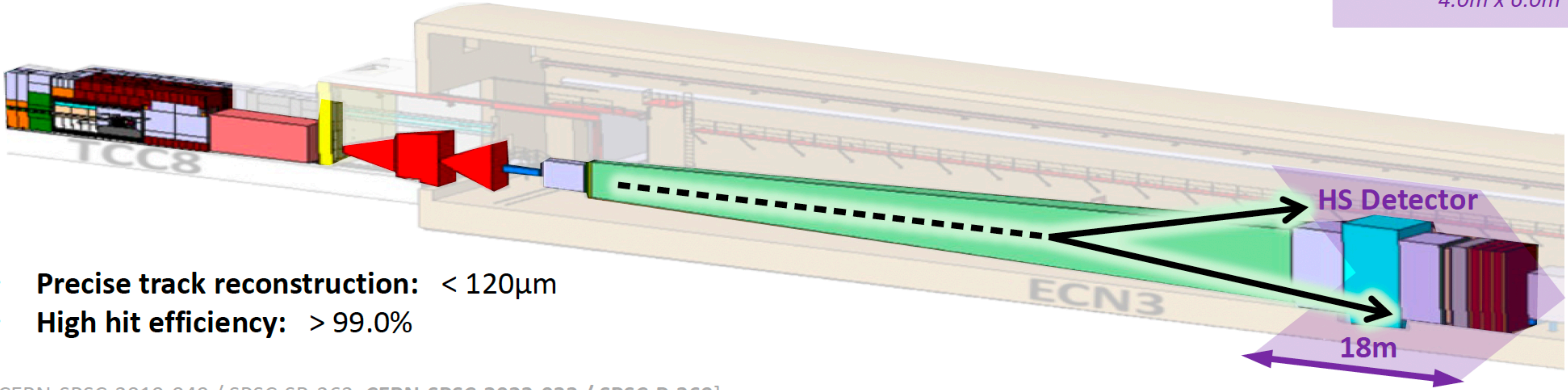
\+ **Support** for **LS-SBT** integration



SHIP/BDF DETECTOR TECHNOLOGY

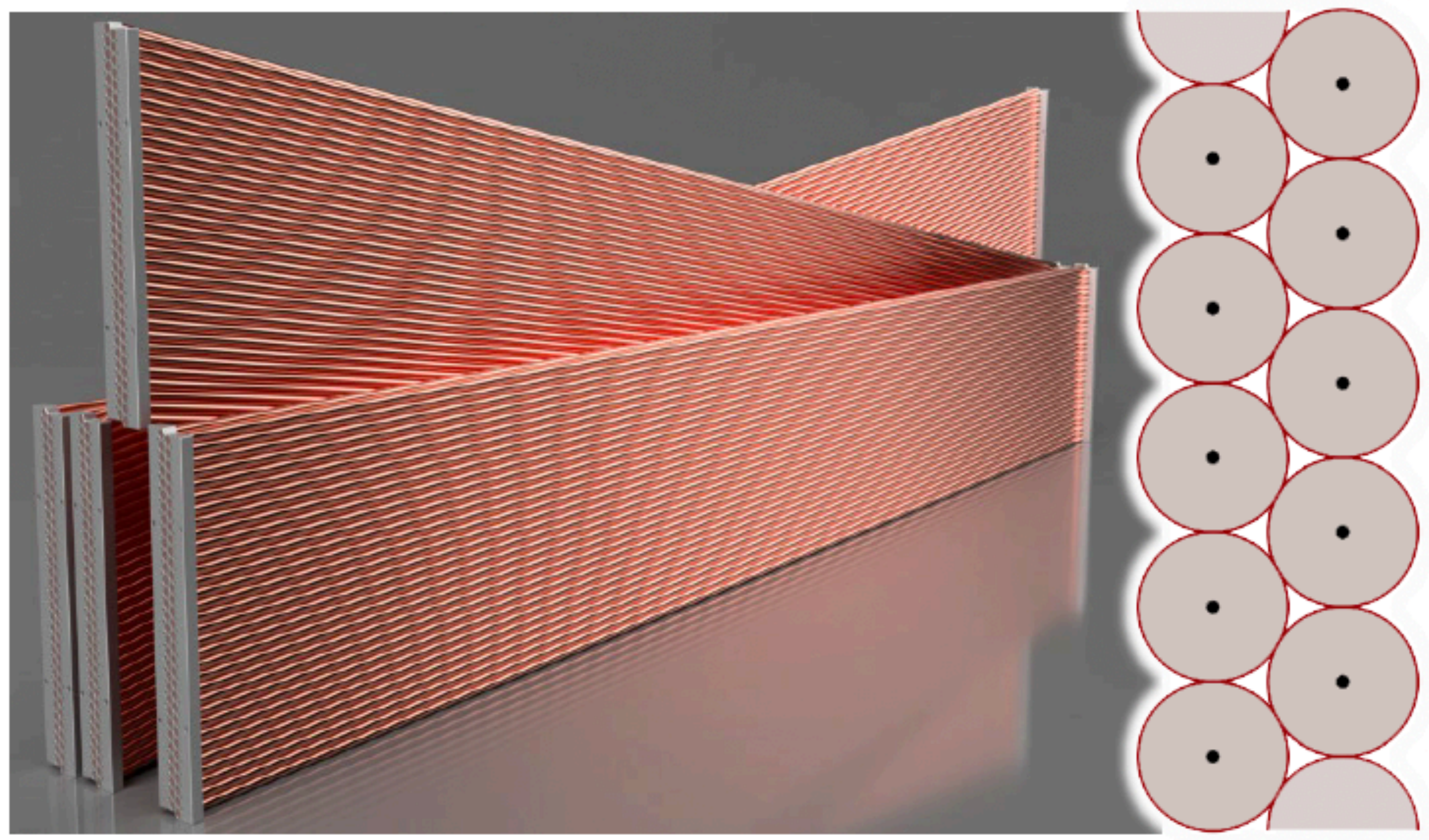
HS Detector: Spectrometer Straw Tracker (SST) & Magnet

Large aperture:
4.0m x 6.0m

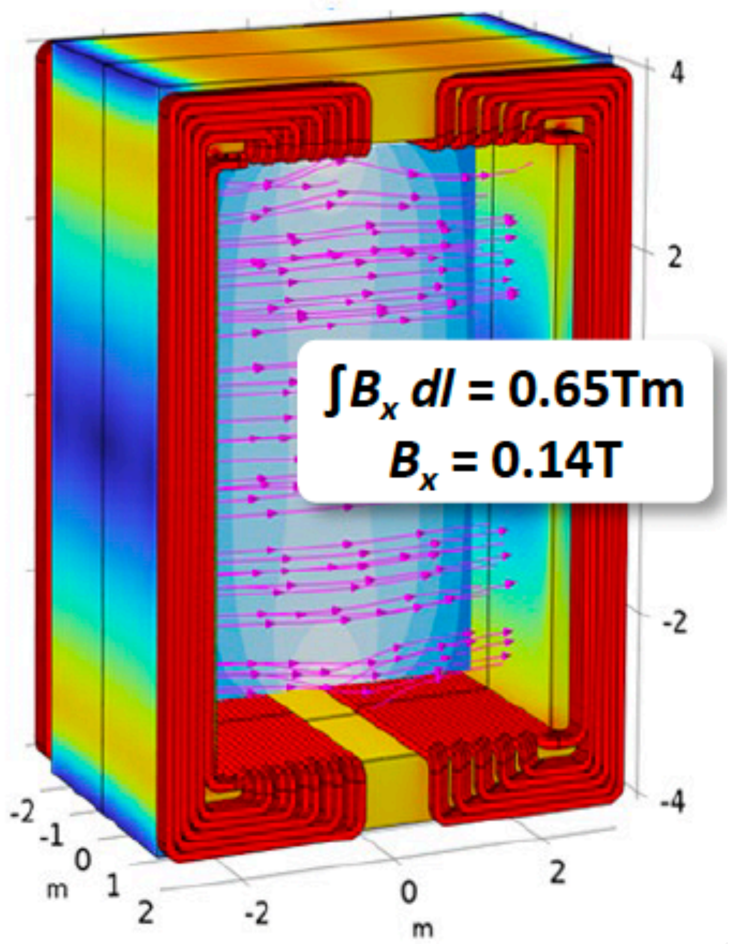


- **Precise track reconstruction:** < 120µm
- **High hit efficiency:** > 99.0%

[CERN-SPSC-2019-049 / SPSC-SR-263, **CERN-SPSC-2023-033 / SPSC-P-369**]



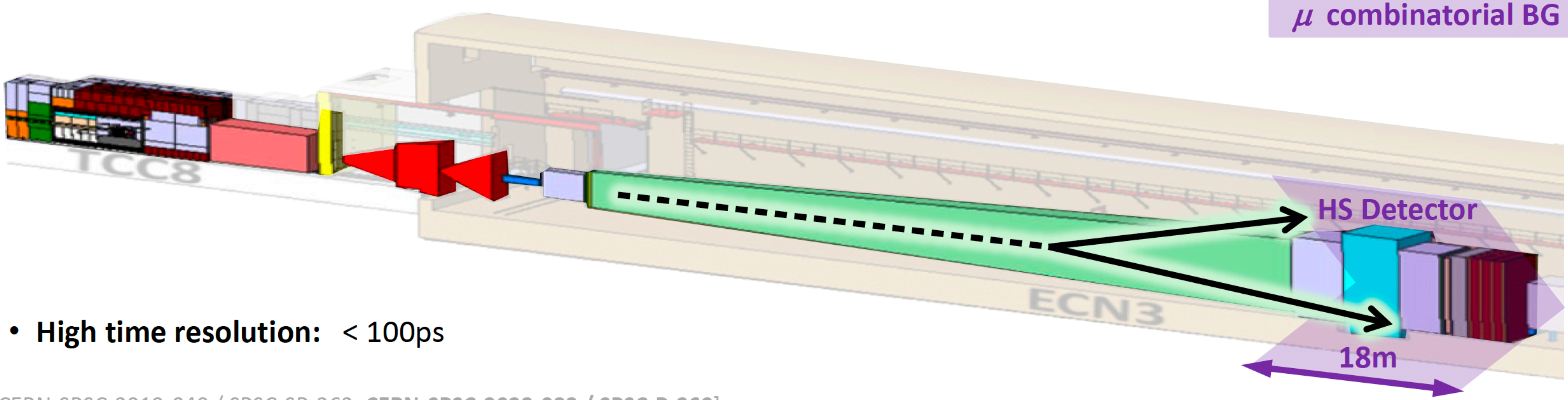
- **Cu/Au-coated Mylar drift tubes (NA62 design):** 4m length, 2cm diameter, 36µm wall thickness, Ar:CO_2 mixture (70:30)
  ▶ **Low material budget**
- 2x 2 stations of 4 double layers at 10° stereo angle, **10 000 channels altogether**
- **Magnet (NC baseline):** 0.65Tm / 0.15T
  SC options being studied (MgB_2)



SHIP/BDF DETECTOR TECHNOLOGY

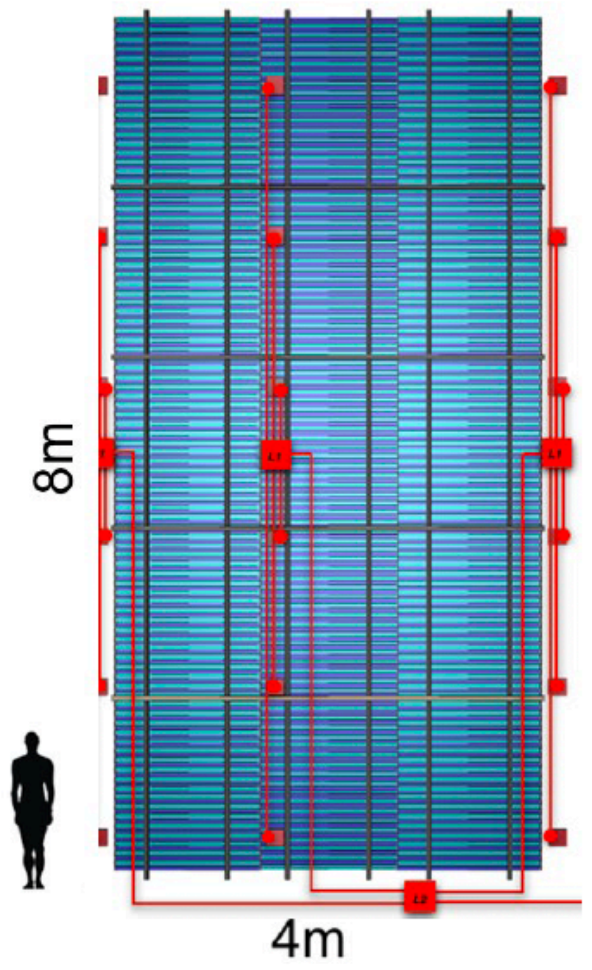
HS Detector: Timing Detector (TD)

Suppression of μ combinatorial BG



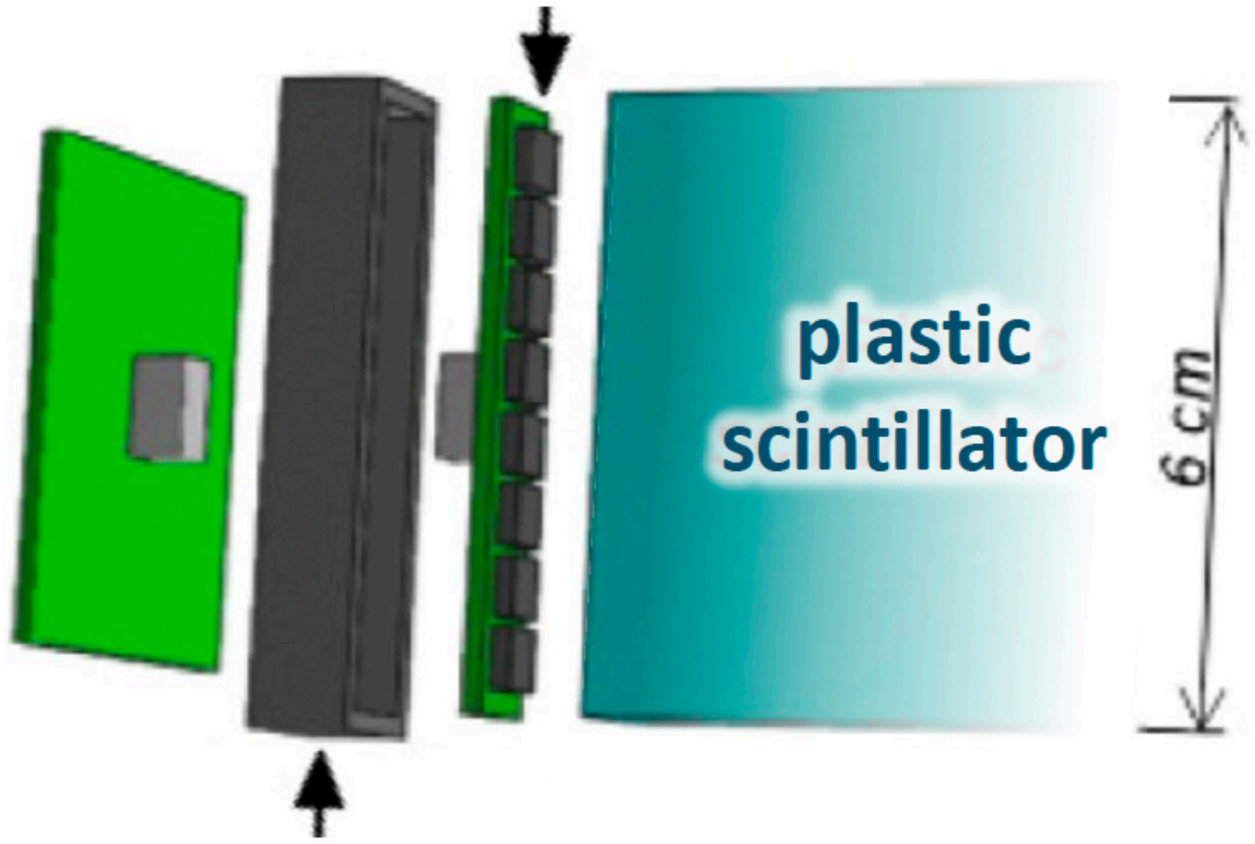
- **High time resolution:** < 100ps

[CERN-SPSC-2019-049 / SPSC-SR-263, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **EJ200 plastic scintillator bars:**
  135cm x 6cm x 1cm
- **Readout** at both ends by **SiPM arrays**
- 3 columns of 111 vertically staggered bars (5mm overlap),
  666 channels altogether

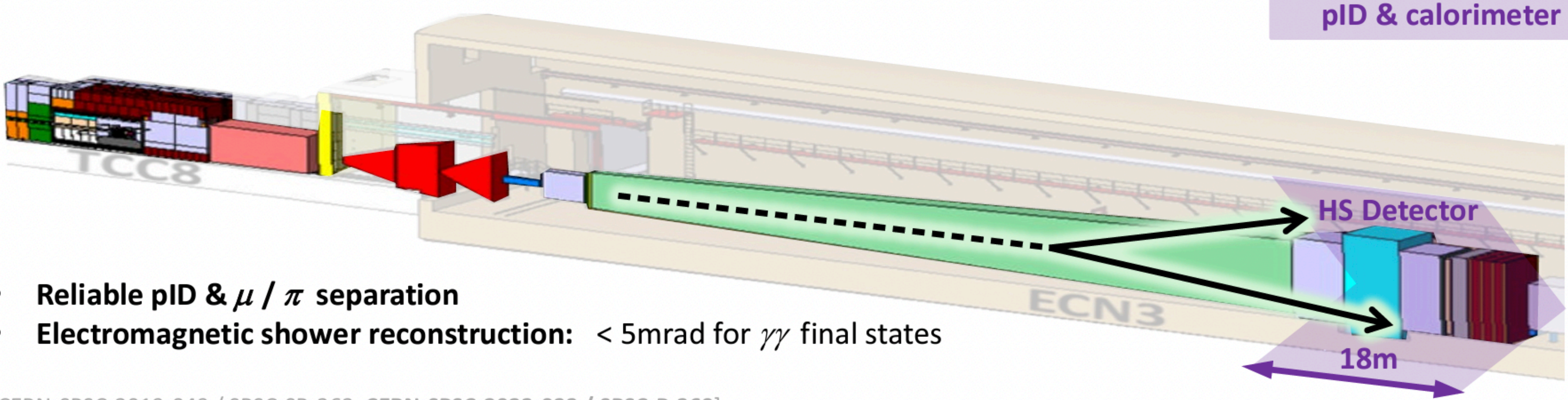
▶ **Timestamp** for SST
▶ **ToF identification** of particle decay products



SHIP/BDF DETECTOR TECHNOLOGY

HS Detector: Particle Identification (pID) & Calorimeter (ECal / HCal)

Integrated system of pID & calorimeter



- **Reliable pID & μ / π separation**
- **Electromagnetic shower reconstruction:** < 5mrad for $\gamma\gamma$ final states

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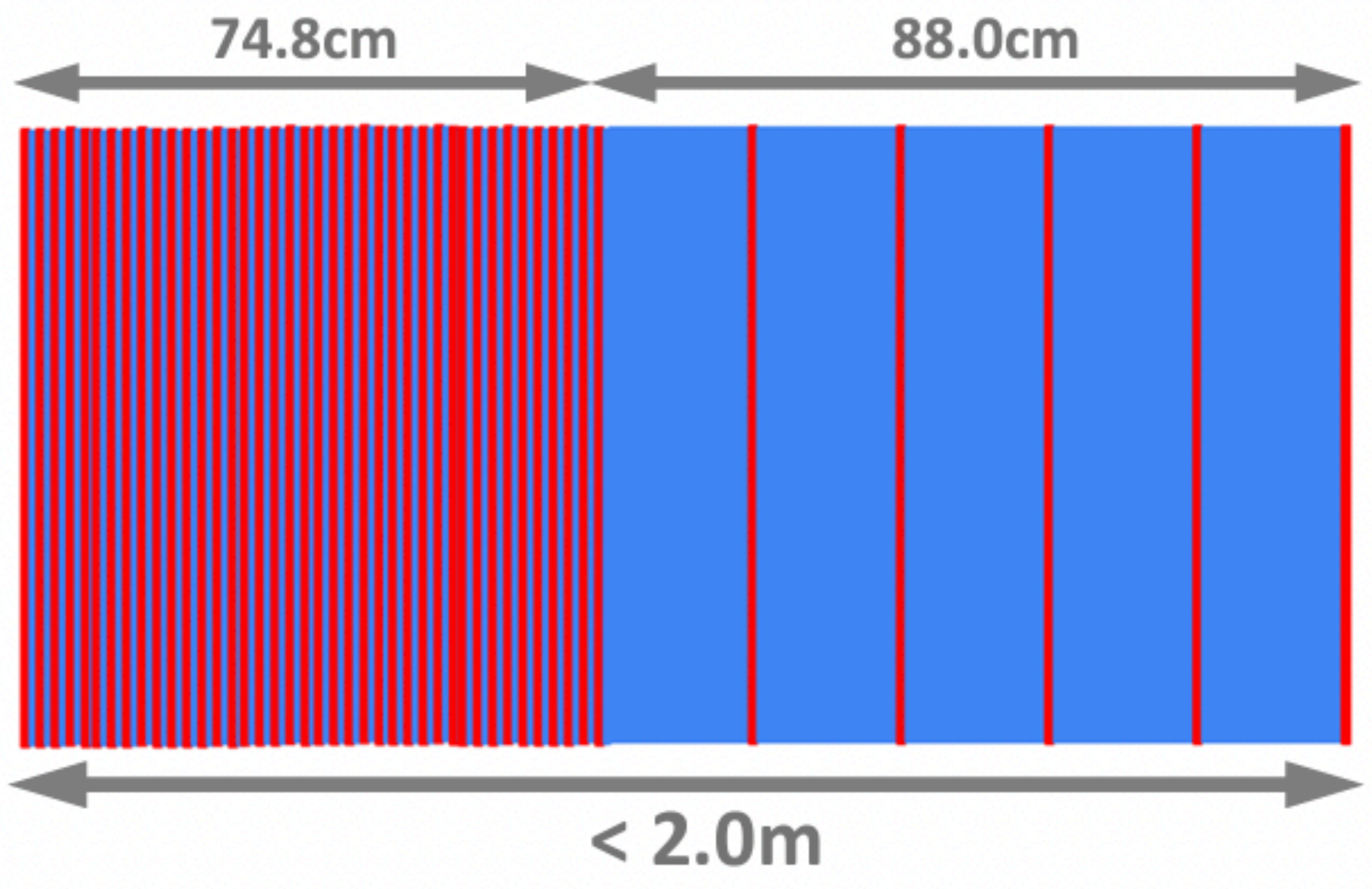

- **Electromagnetic sampling calorimeter (ECal):** 40 layers of **thin Fe absorbers** (1/20λ each) & **plastic scintillators**
- **Compact hadron sampling calorimeter (HCal):** 5 layers of **thick Fe absorbers** (1λ each) & **plastic scintillators**

▶ **Total length:** 7λ (> 99.5% π interaction probability)

\+ **1 – 3 MicroMeGaS high-precision layers**

\+ Possible 1m-air gap for **additional μ stations**