NEW FRONTIERS IN NEUTRINO PHYSICS AT CERN

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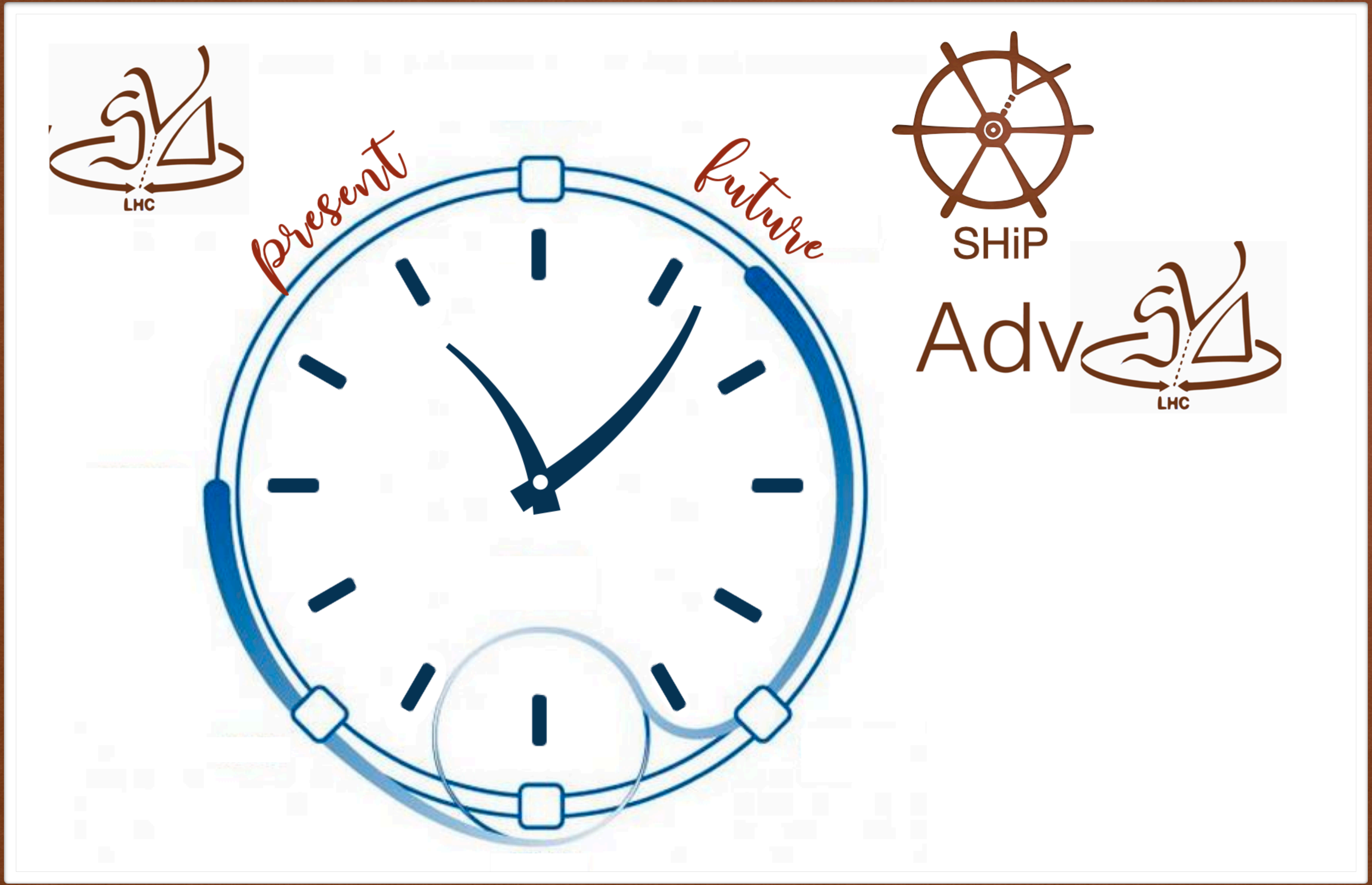
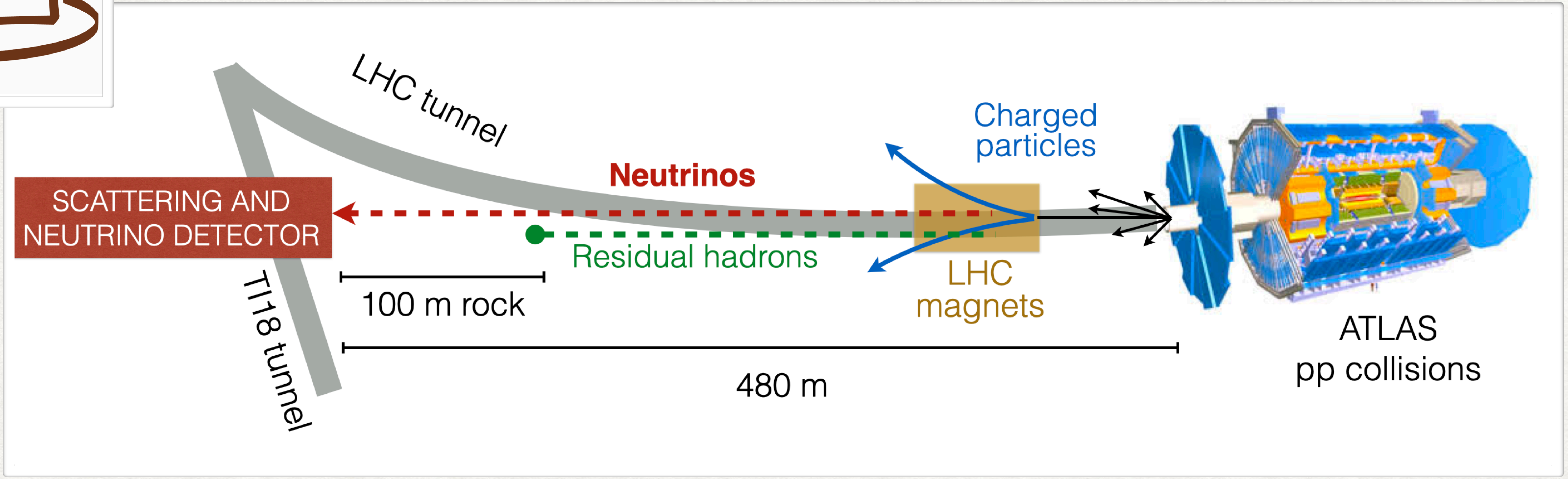
Naples-Chile Scientific Cooperation Meeting
7 October 2024

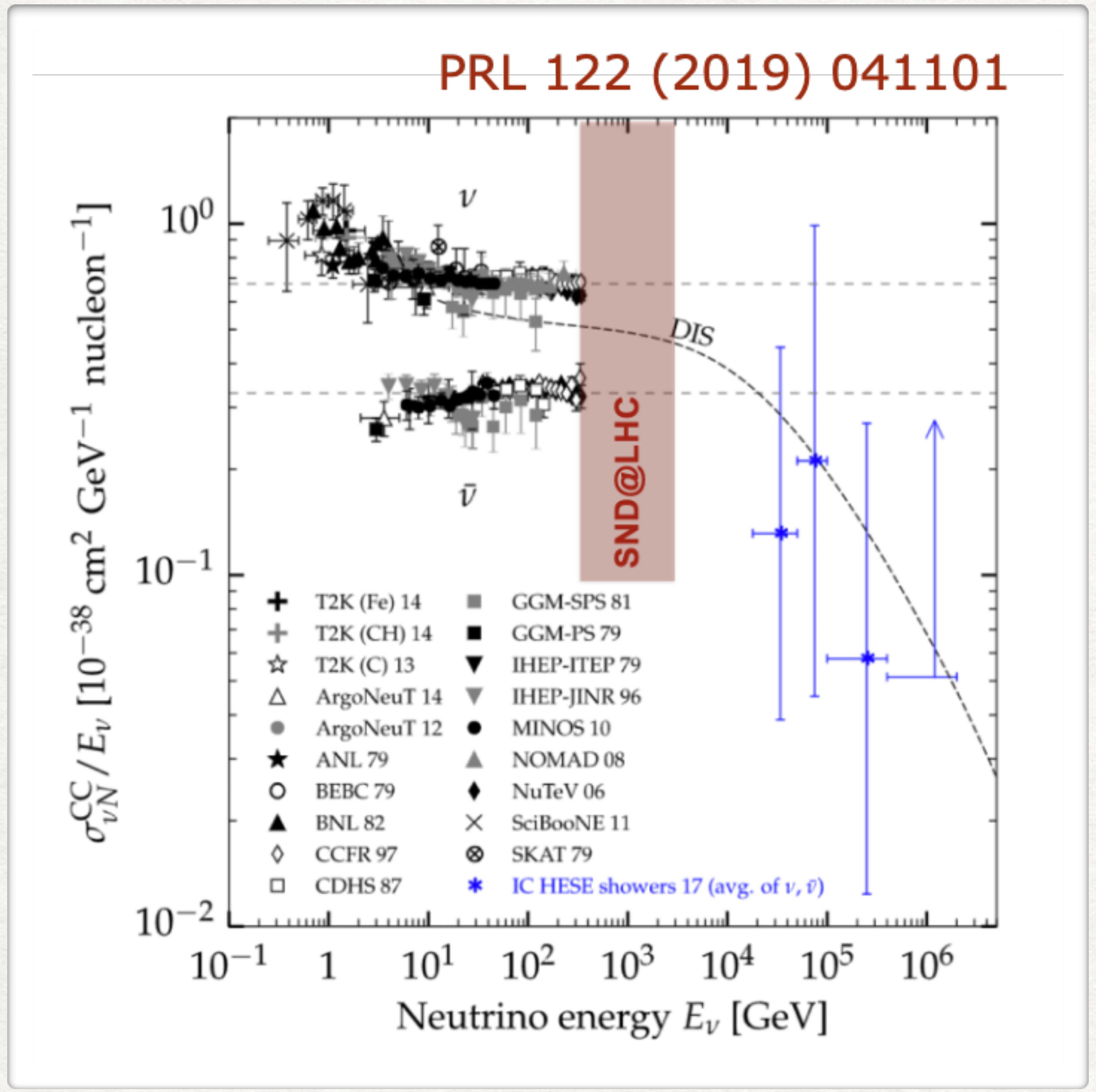
NEW FRONTIERS IN NEUTRINO PHYSICS AT CERN



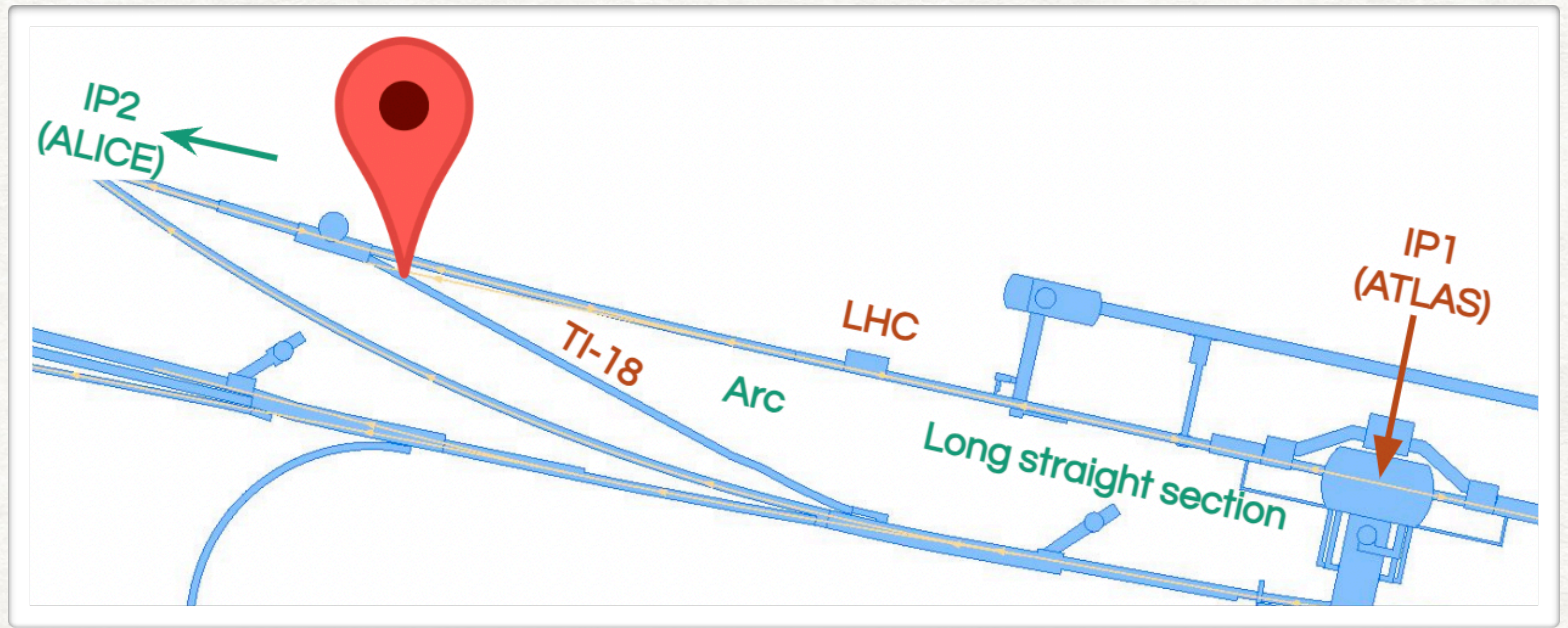
NEUTRINO PHYSICS AT CERN: THE **SND@LHC** EXPERIMENT



THE SND@LHC DETECTOR



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

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)

Operation in Run 3 (2022-2026) to collect ~290 fb^{-1}

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

THE SND@LHC CONCEPT

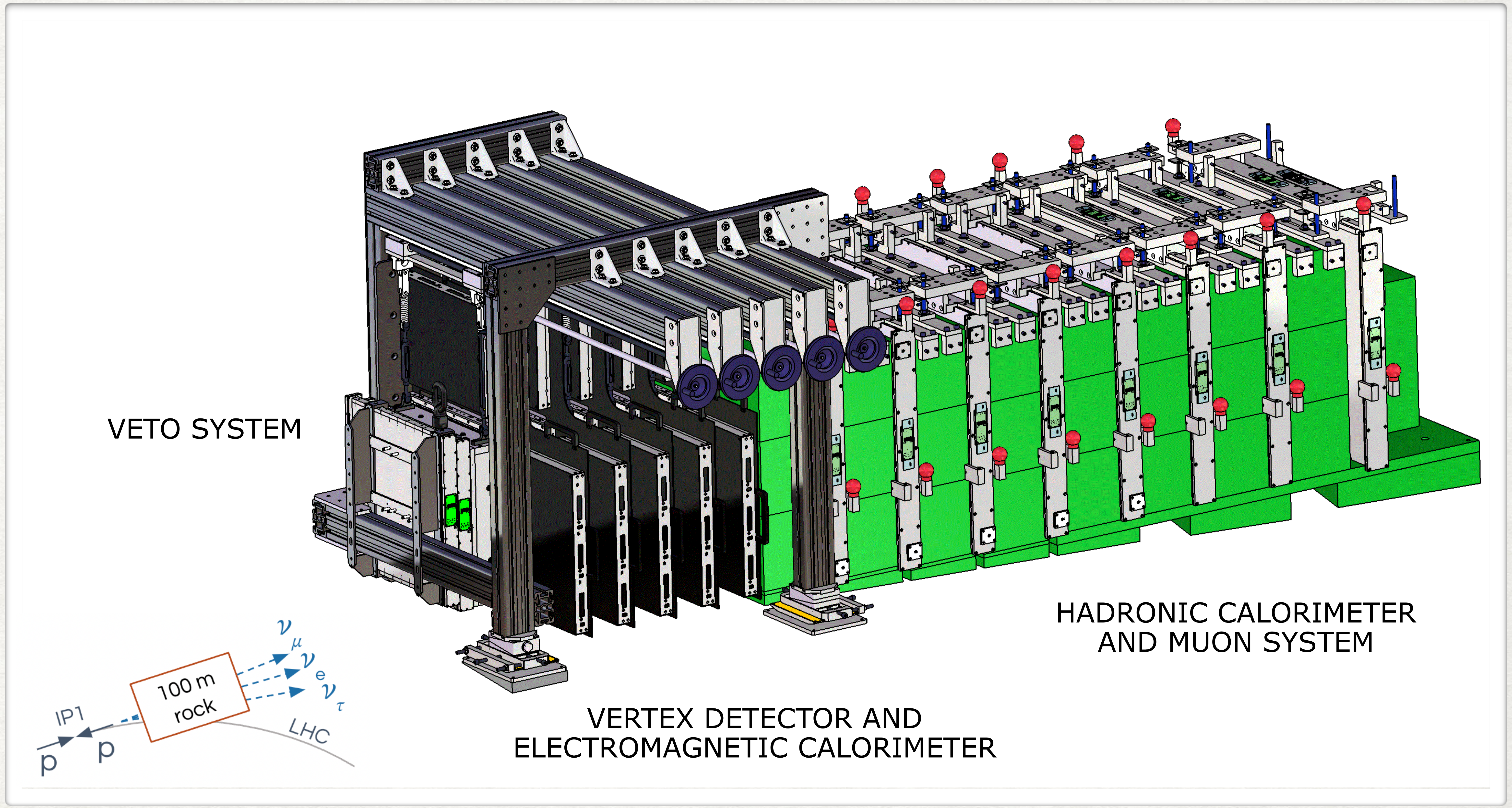
Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles

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

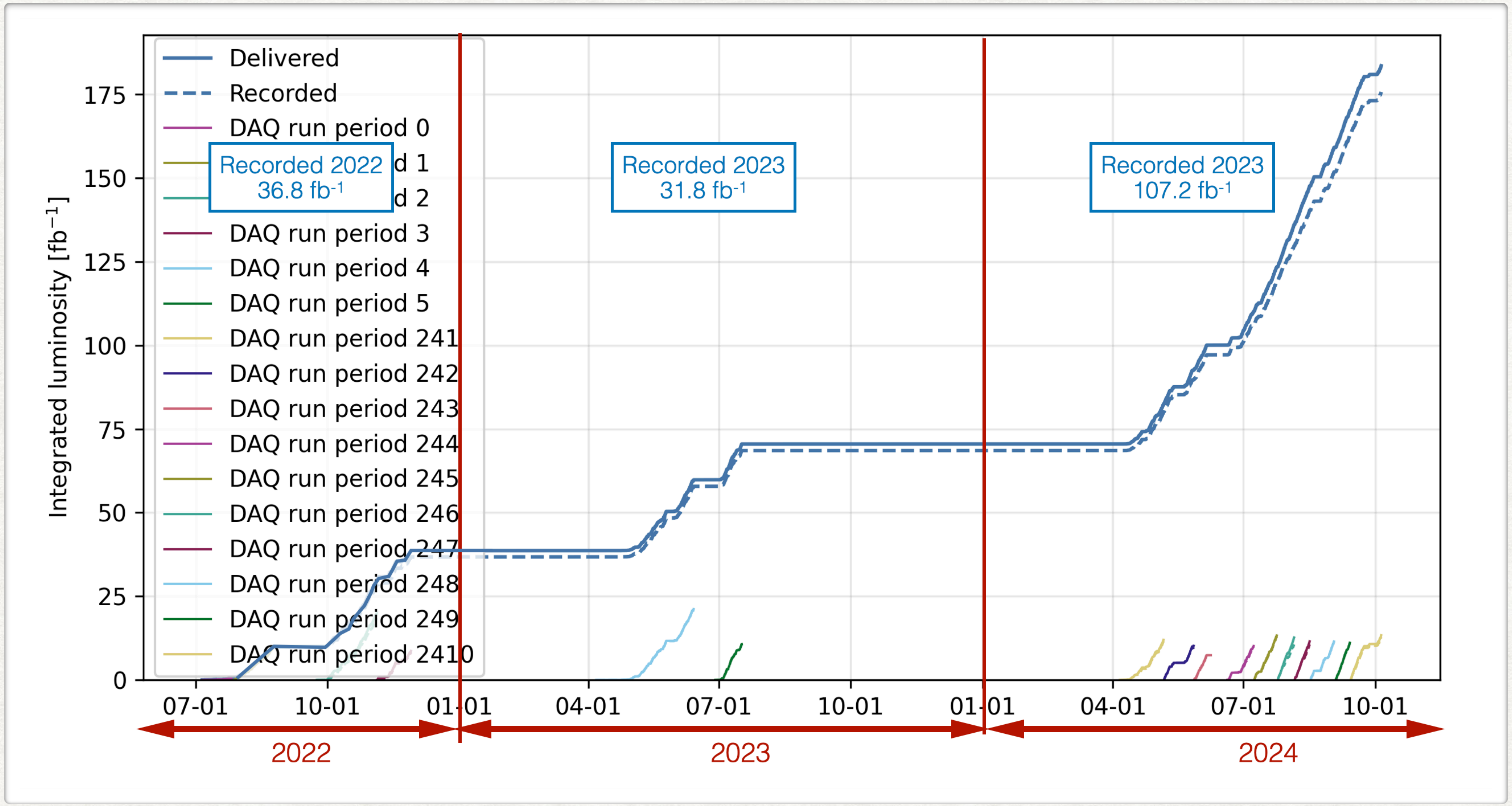
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

September 2021

December 2021

March 2022

DATA TAKING IN RUN3



- Delivered luminosity in 2022-2024: 186.6 fb^{-1}
- Integrated luminosity in 2022-2024: 175.8 fb^{-1}

96% efficiency

NEUTRINO OBSERVATION

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

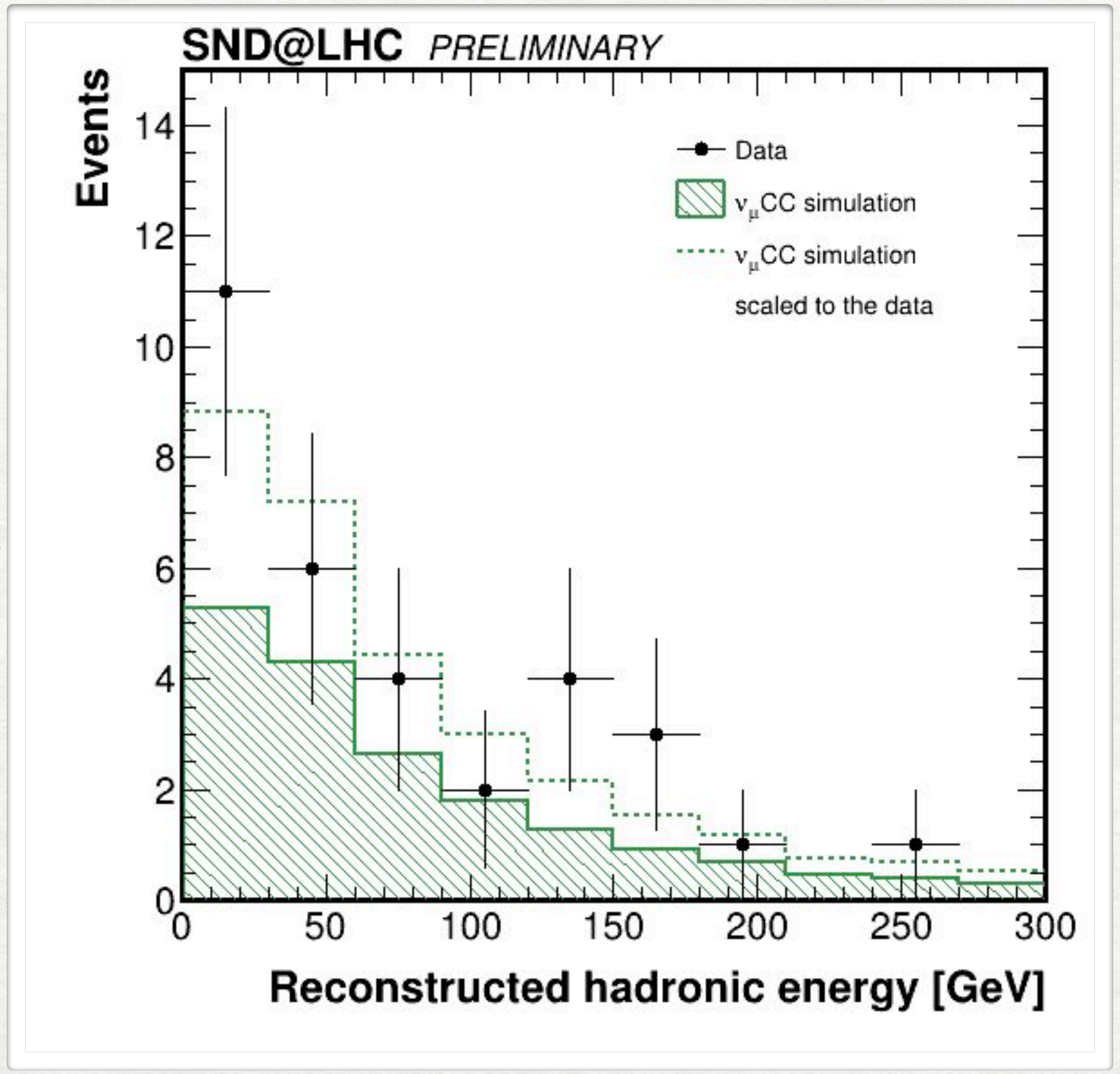
PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

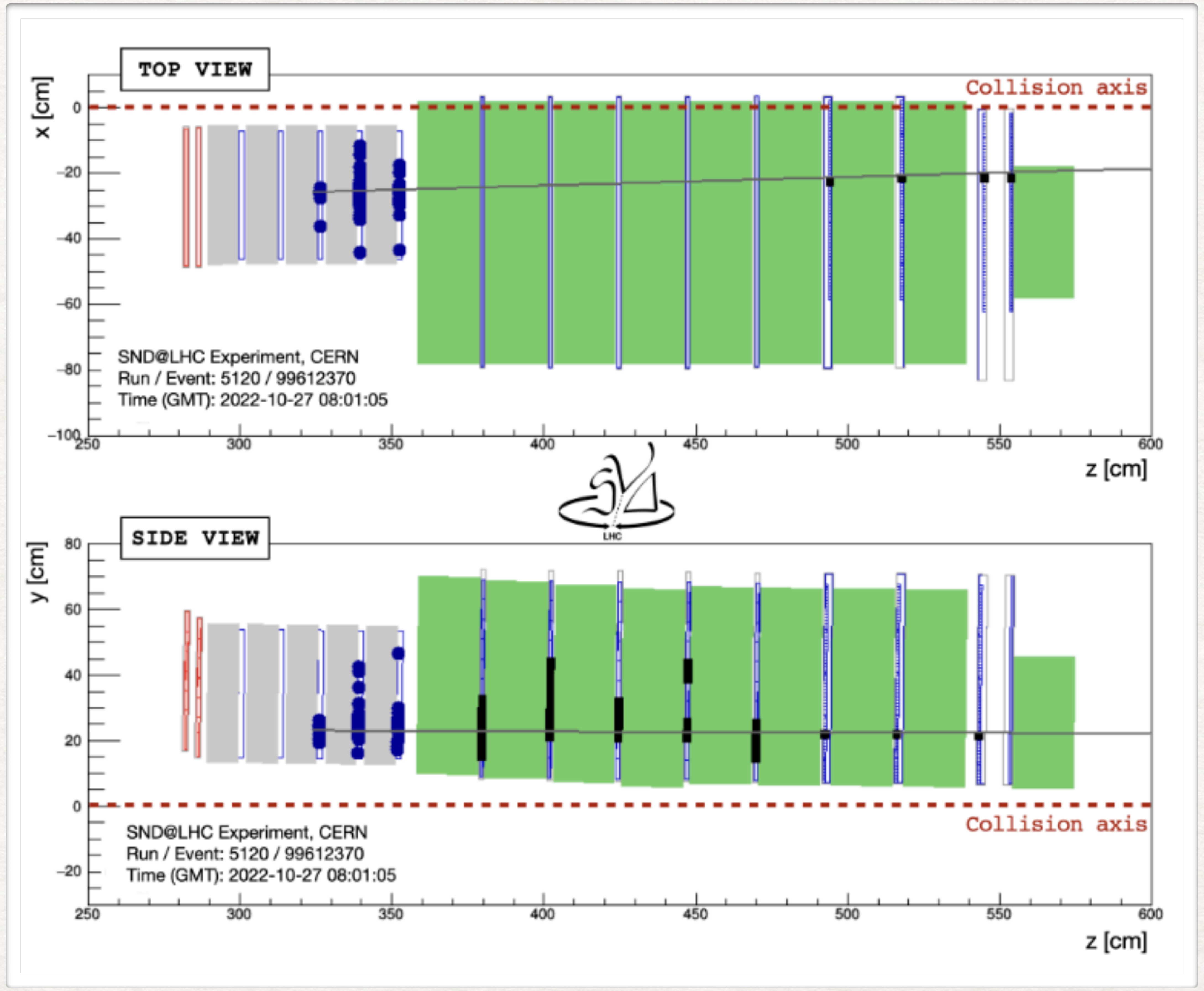
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

PRL 131 (2023) 031802

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

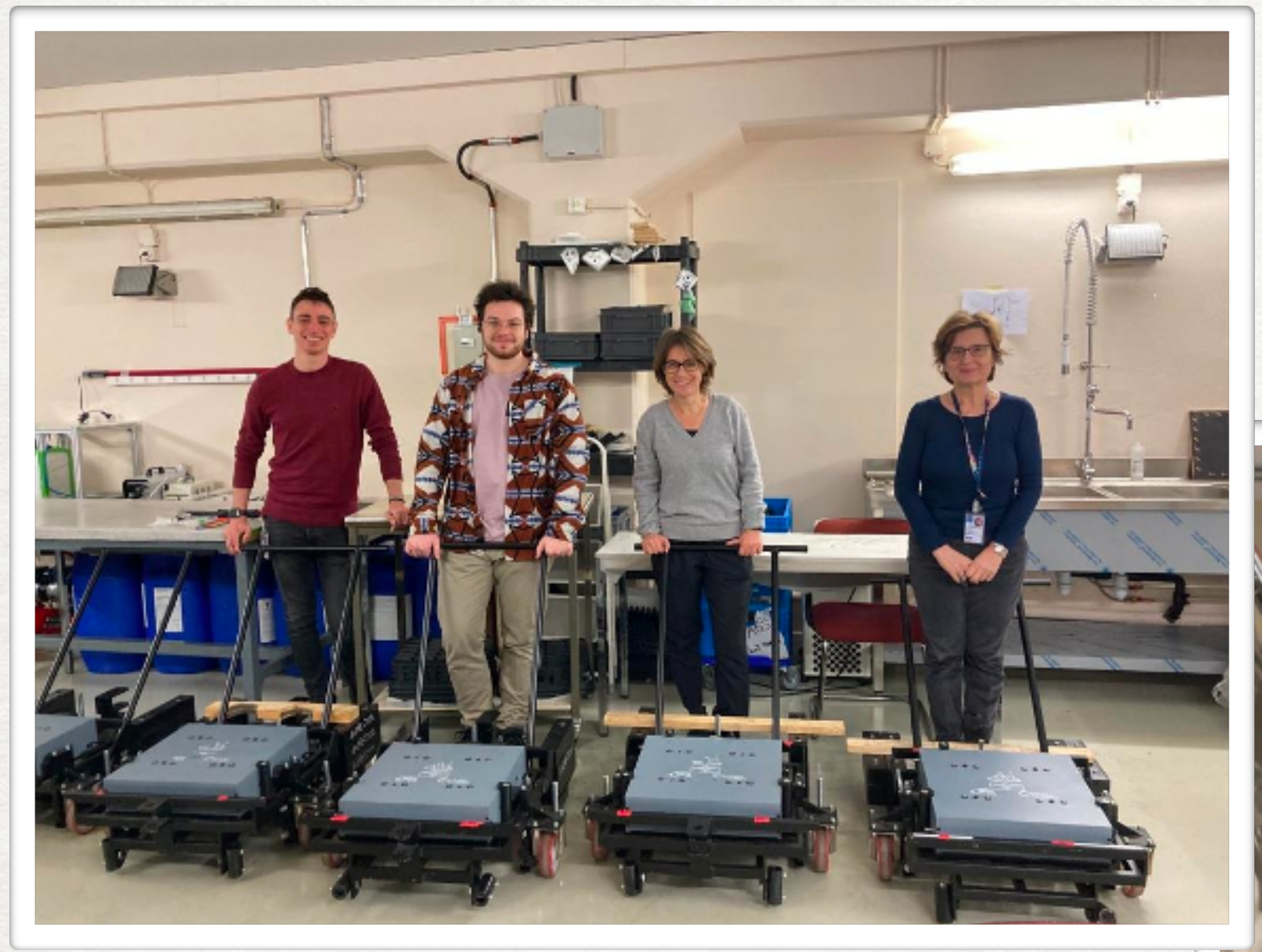


- Display of a ν_μ CC candidate event



EMULSION HANDLING AND SCANNING

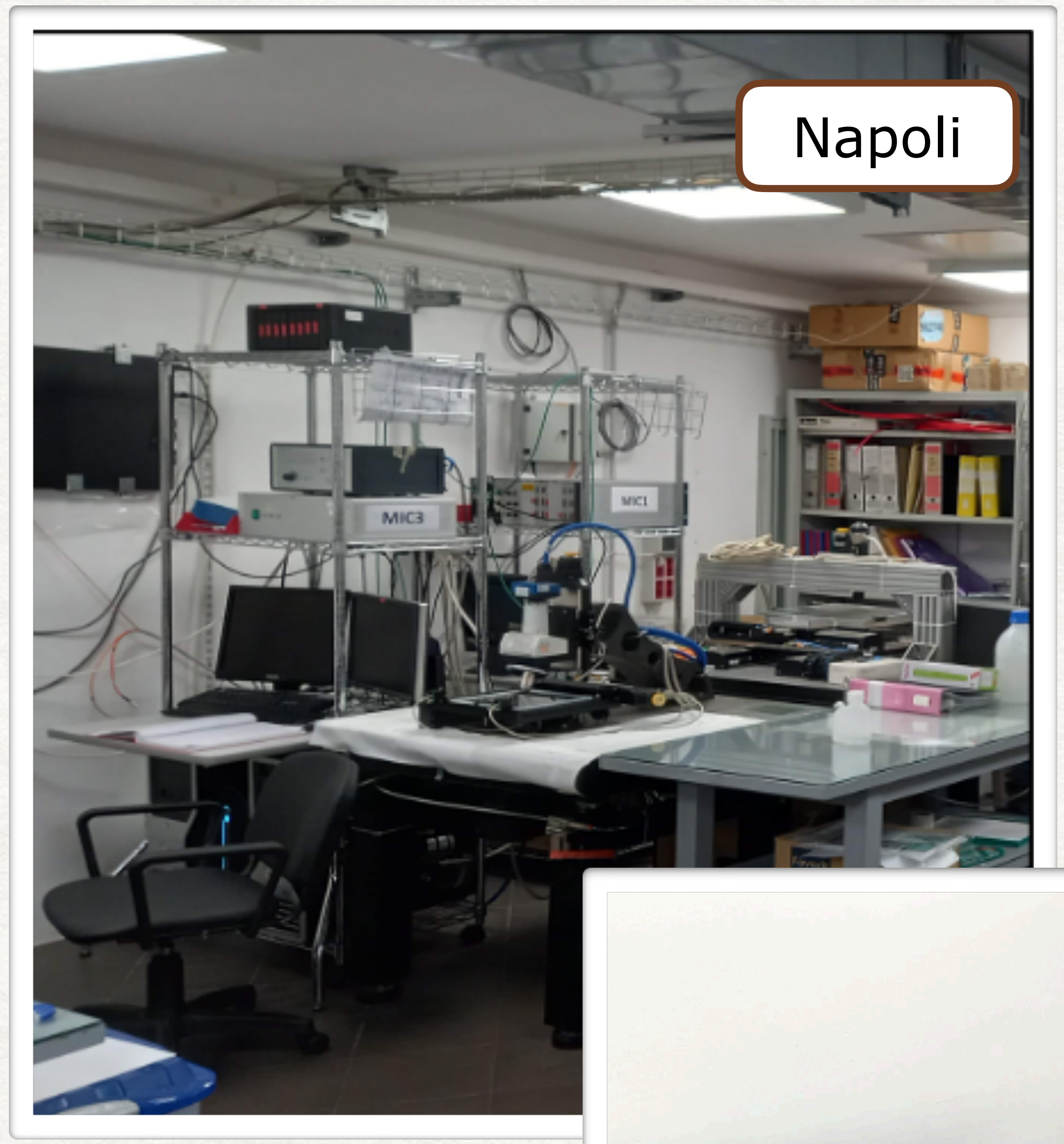
Emulsion handling and chemical development performed at the CERN emulsion facility and dark room



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

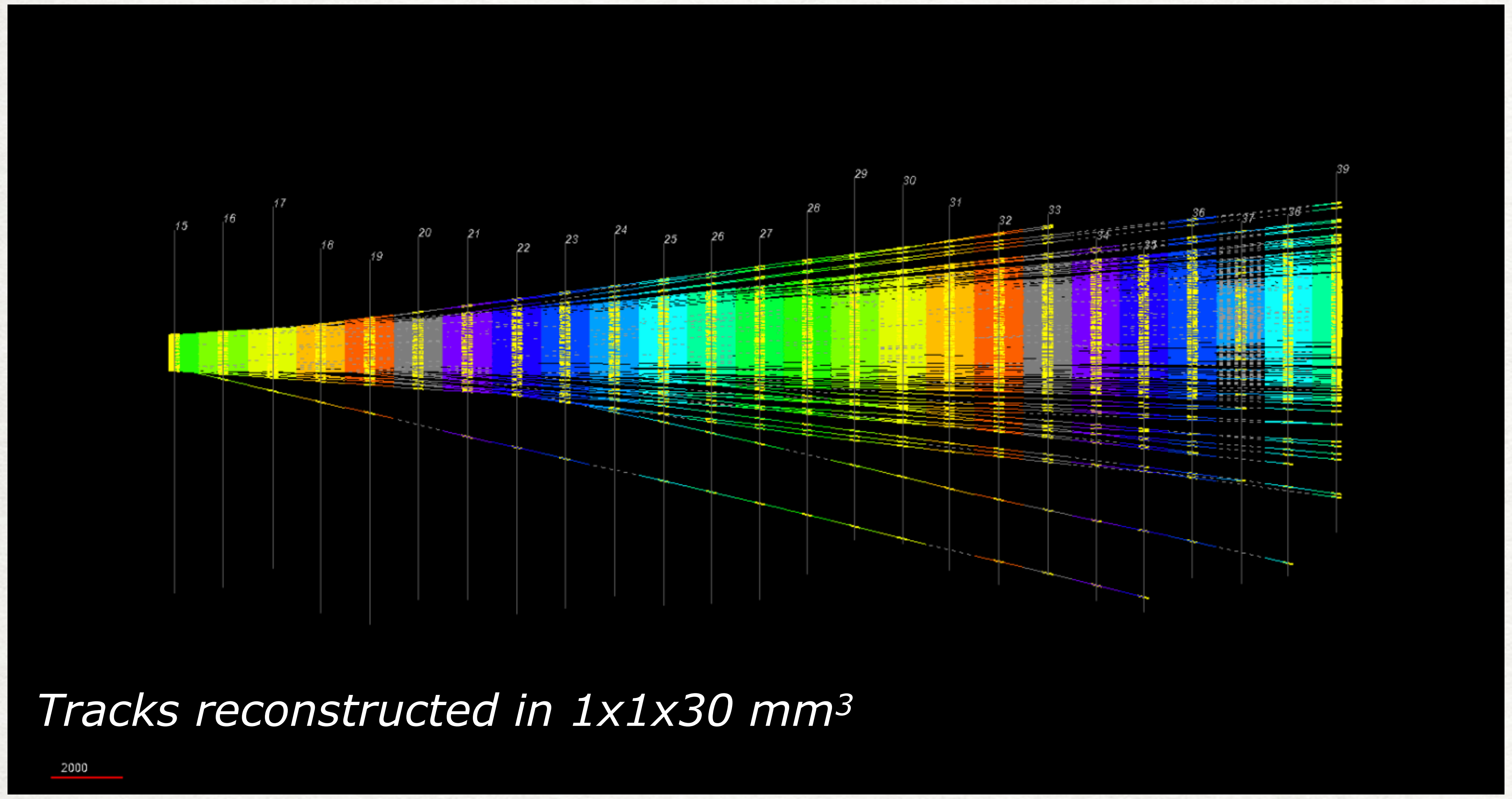
Emulsion scanning performed in different laboratories

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

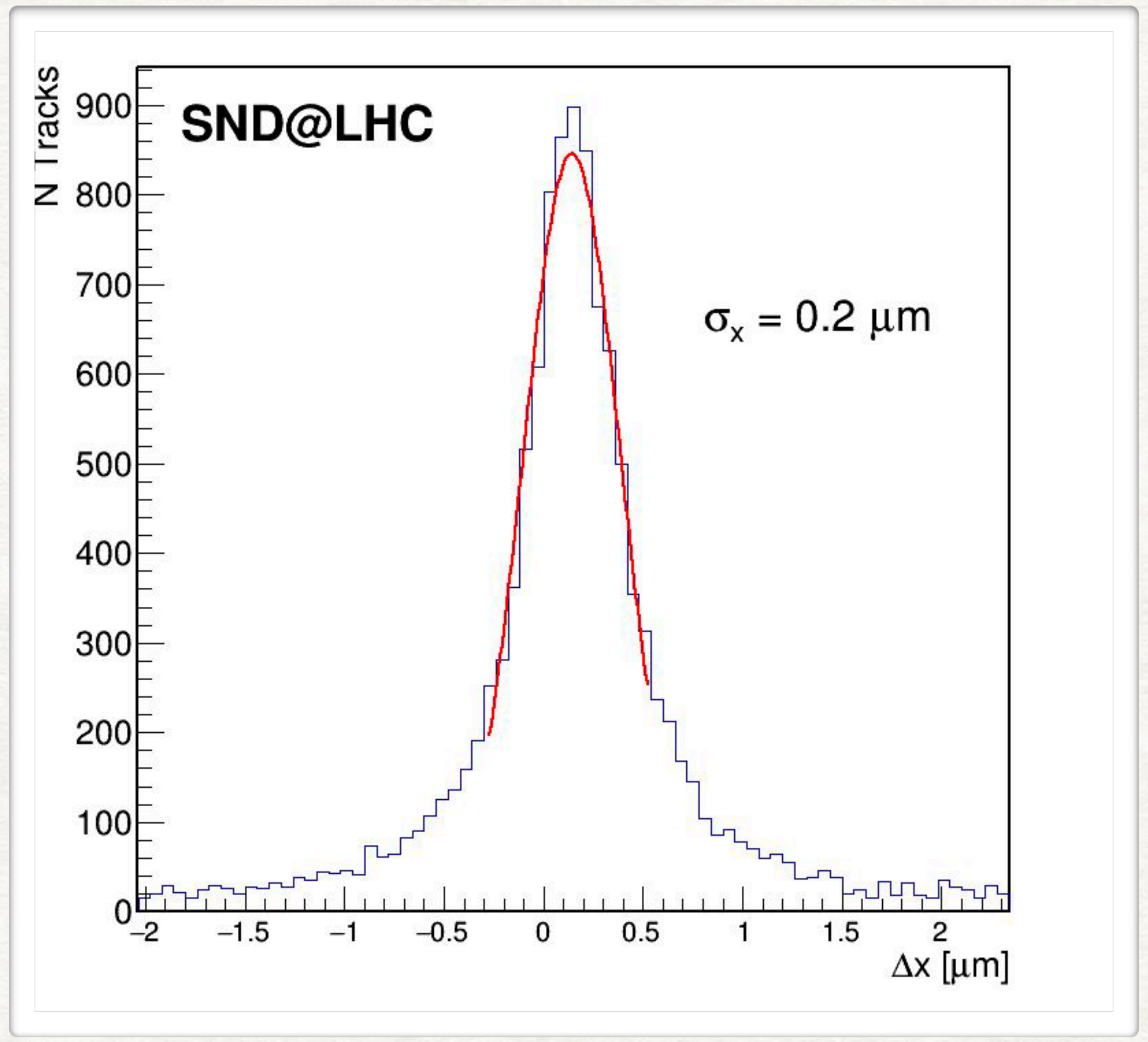


EMULSION DATA ANALYSIS AND RECONSTRUCTION

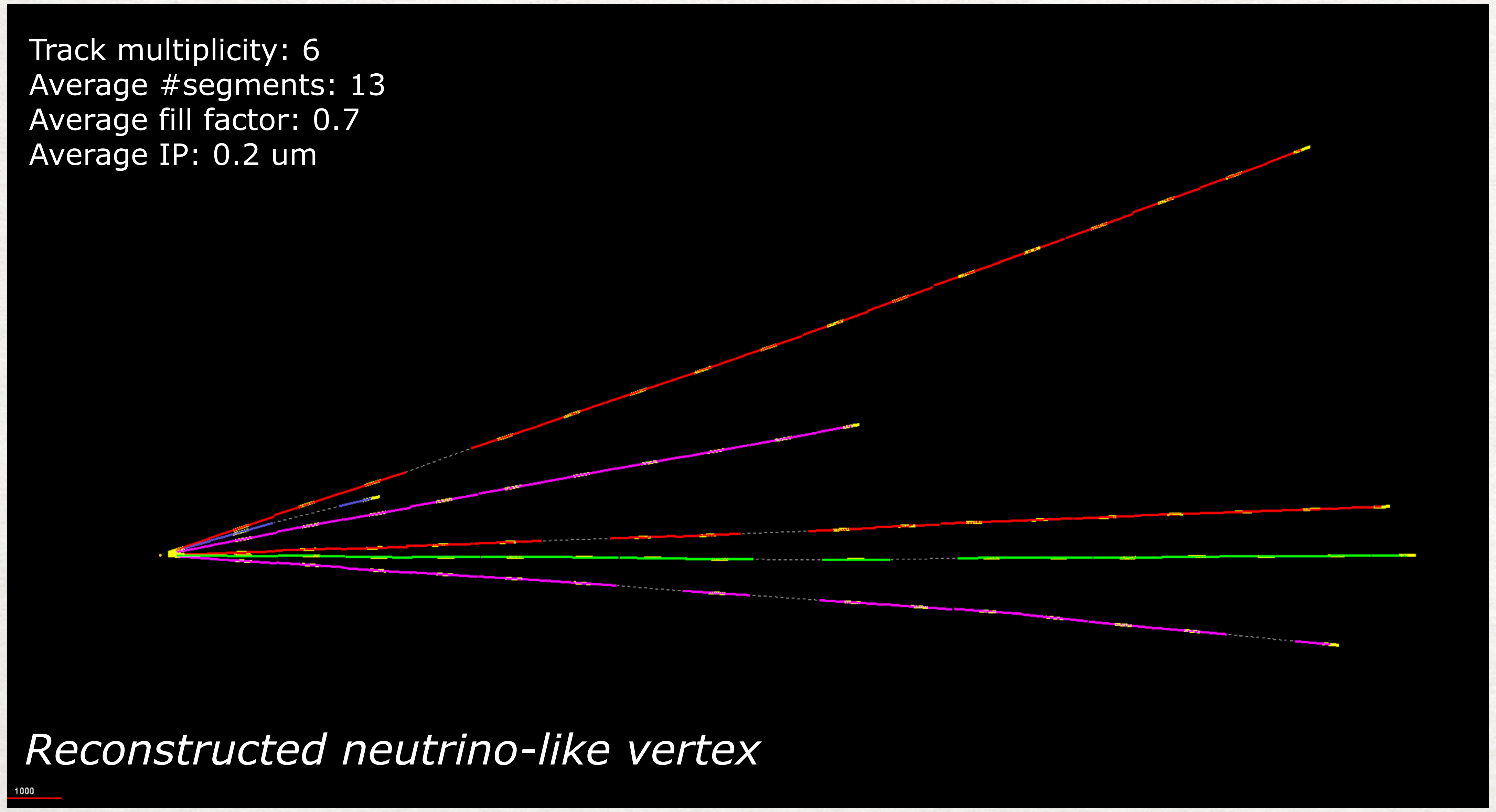
- High density environment: up to $4x10^5$ tracks/cm^2



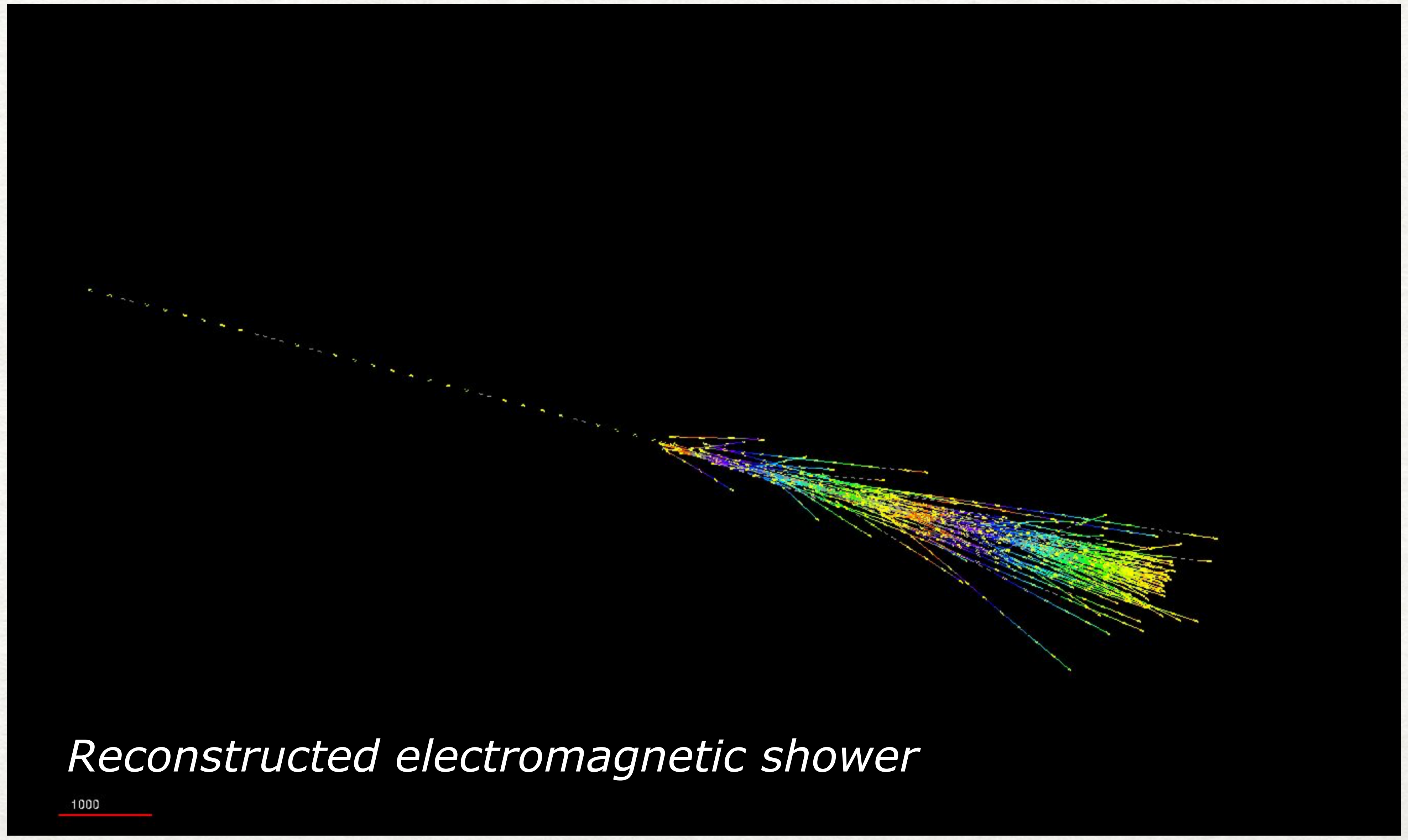
Tracks reconstructed in 1x1x30 mm^3



Position resolution 0.2 μm

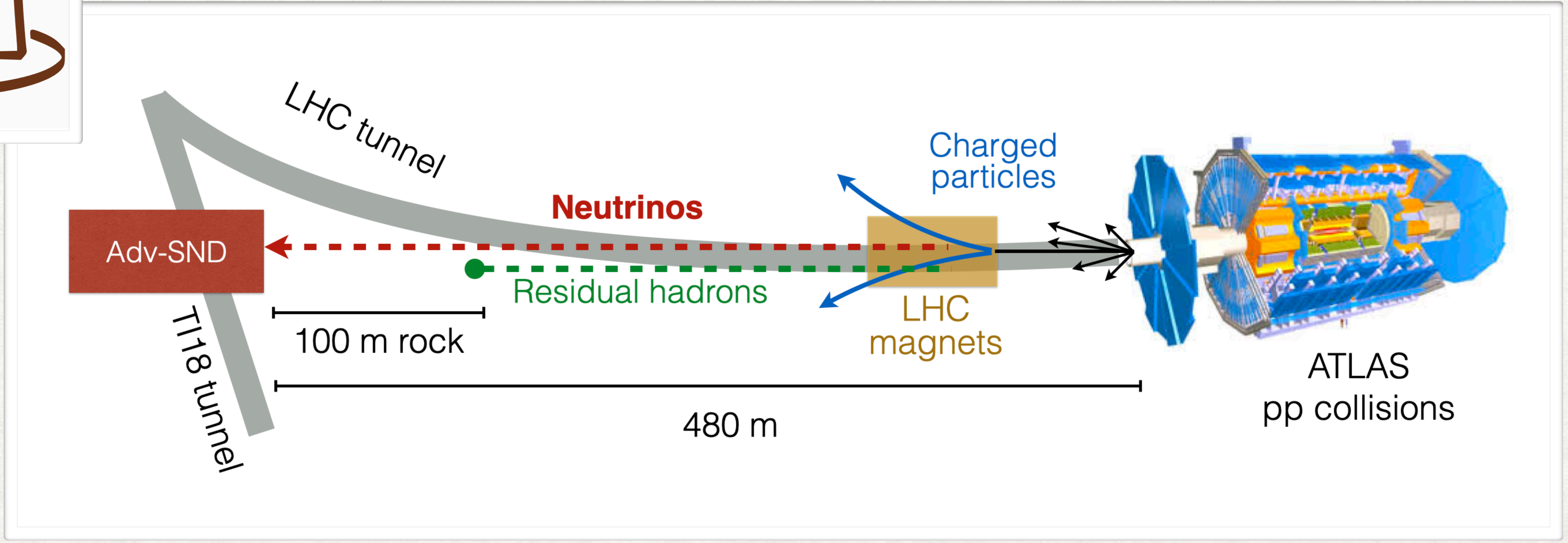


Reconstructed neutrino-like vertex



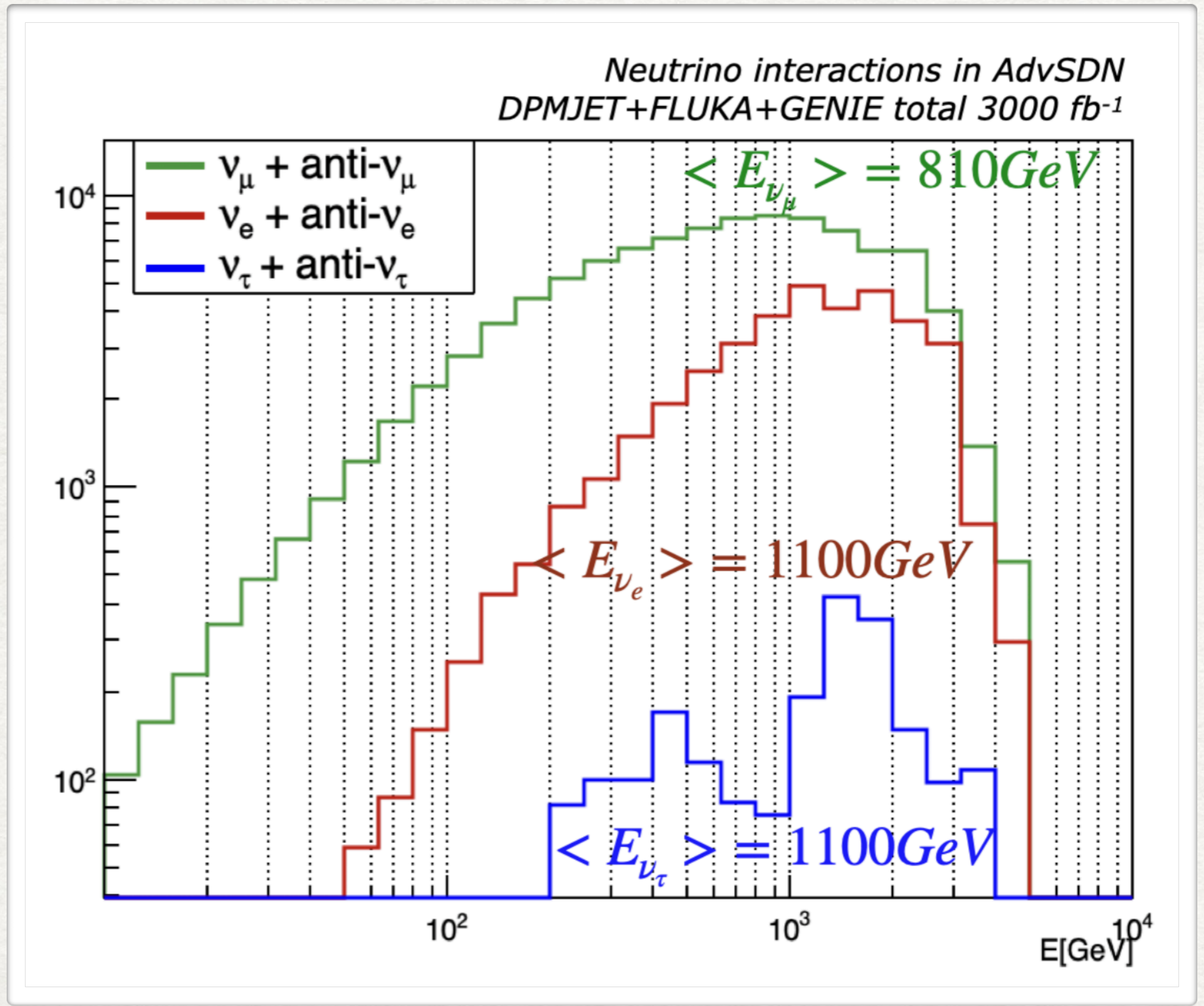
Reconstructed electromagnetic shower

NEUTRINO PHYSICS AT THE **ENERGY** FRONTIER:
THE **ADV-SND** EXPERIMENT



ADV-SND: 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
- Optimise angular acceptance to improve statistics and reduce systematic uncertainties



LHC Run3 SND@LHC — **HL-LHC AdvSND**

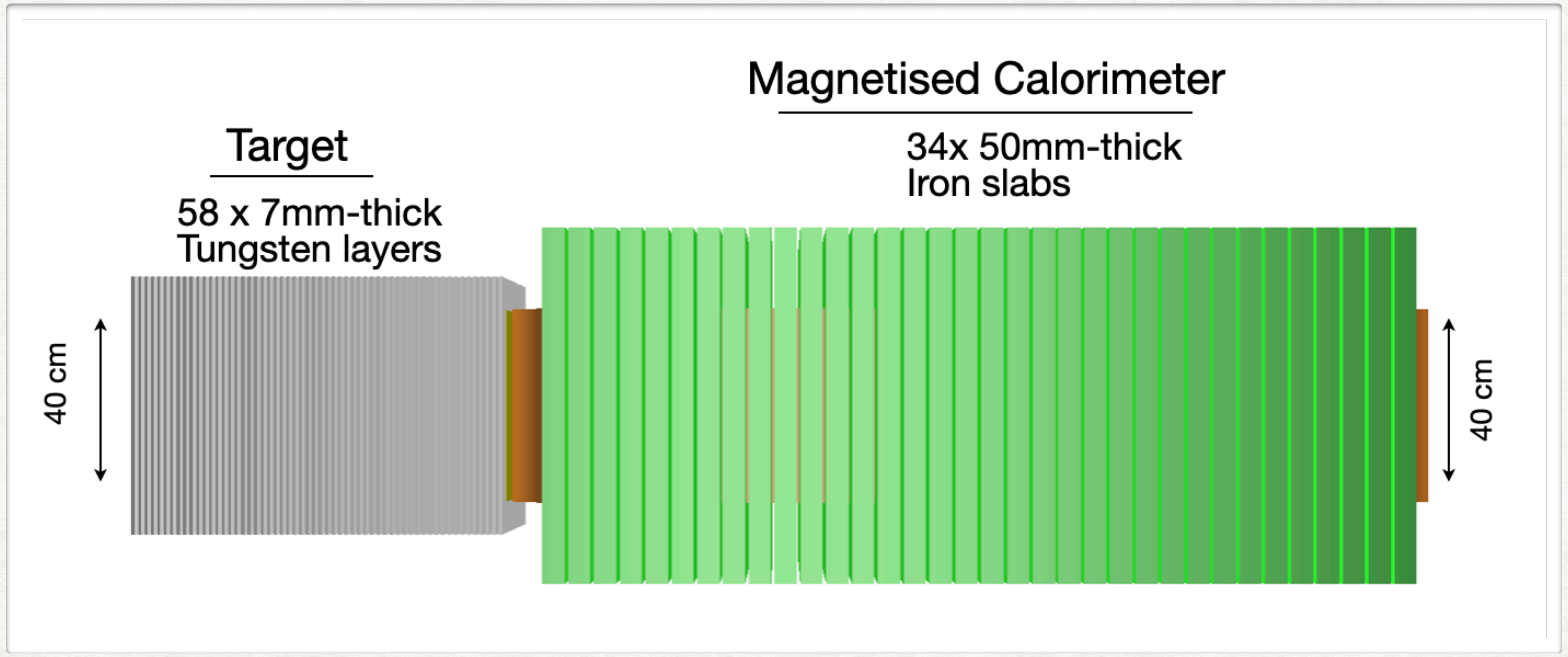
Flavour	Target	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	1.2×10^3	1.3×10^5
$\nu_e+\bar{\nu}_e$	3.9×10^2	4.5×10^4
$\nu_\tau+\bar{\nu}_\tau$	3.0×10^1	2.2×10^3
Tot	1.6×10^3	1.8×10^5

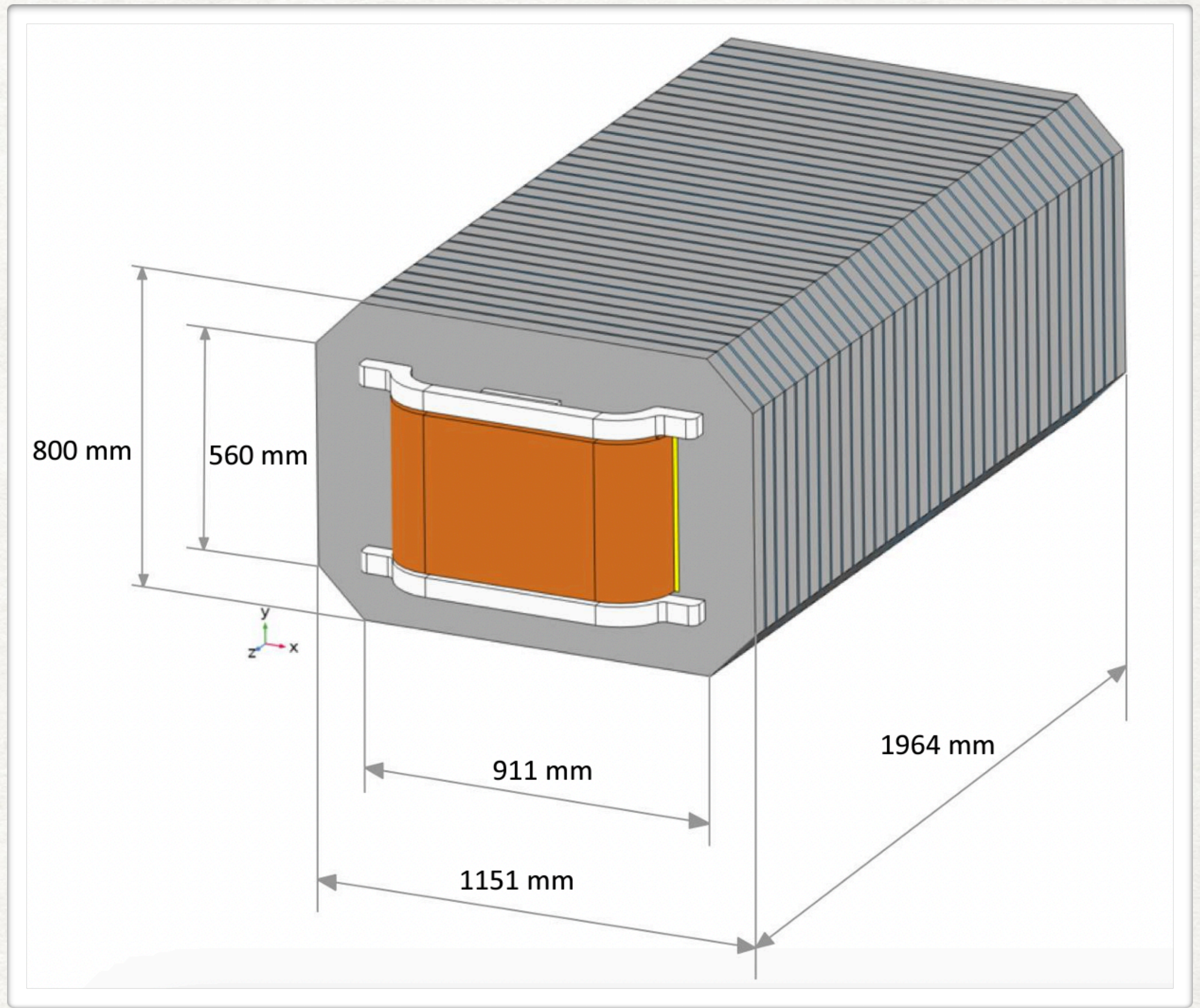
100 time more statistics

LHC Run3 SND@LHC — **HL-LHC AdvSND**

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%

ADV-SND DETECTOR LAYOUT





TARGET

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

MAGNETIZED HCAL

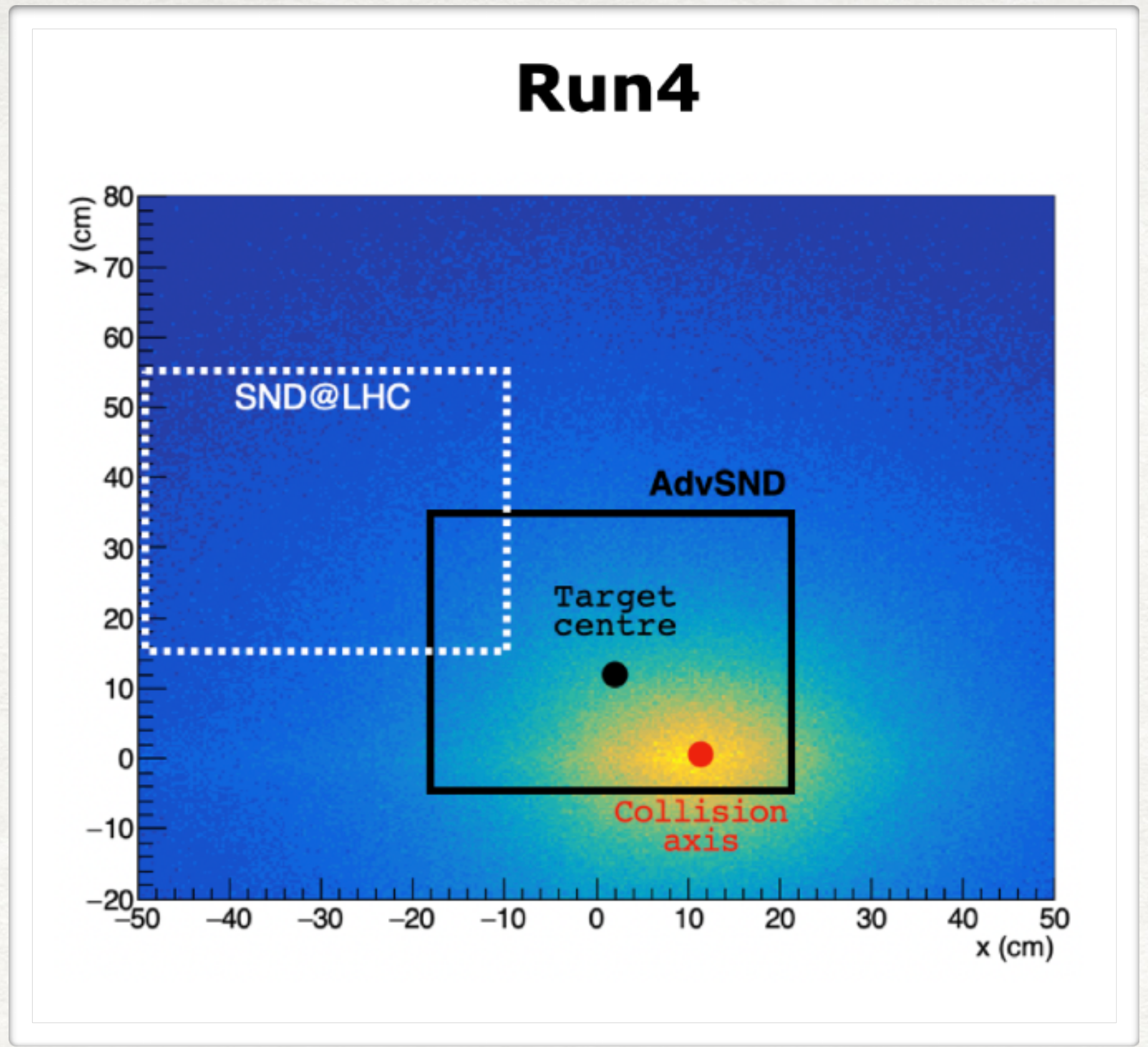
- Active surface: 40x40 cm^2
- Material: Fe
- Sensitive volume mass: 2.1 tons
- Sensitive layers: Silicon strips

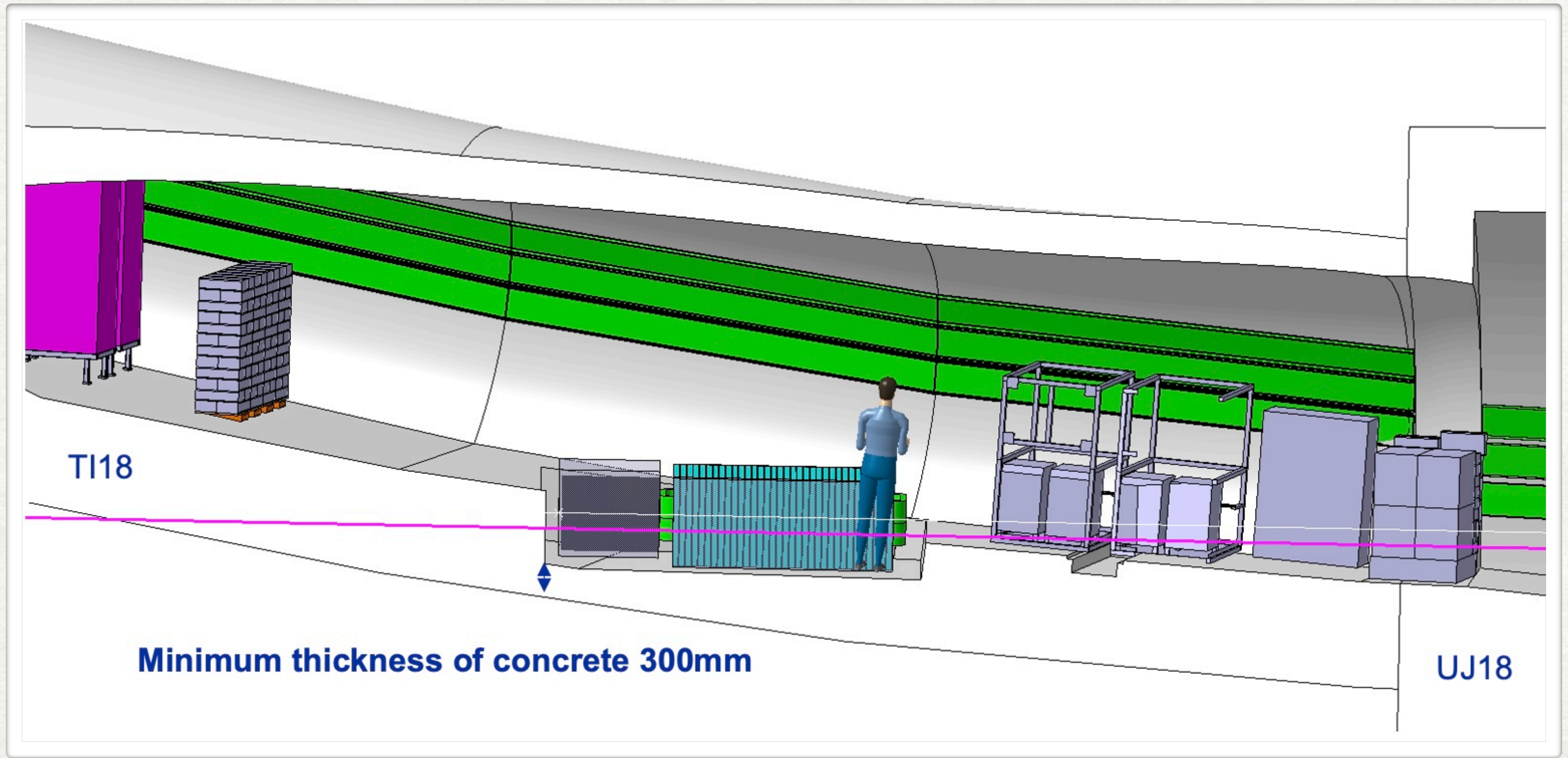
IRON CORE MAGNET

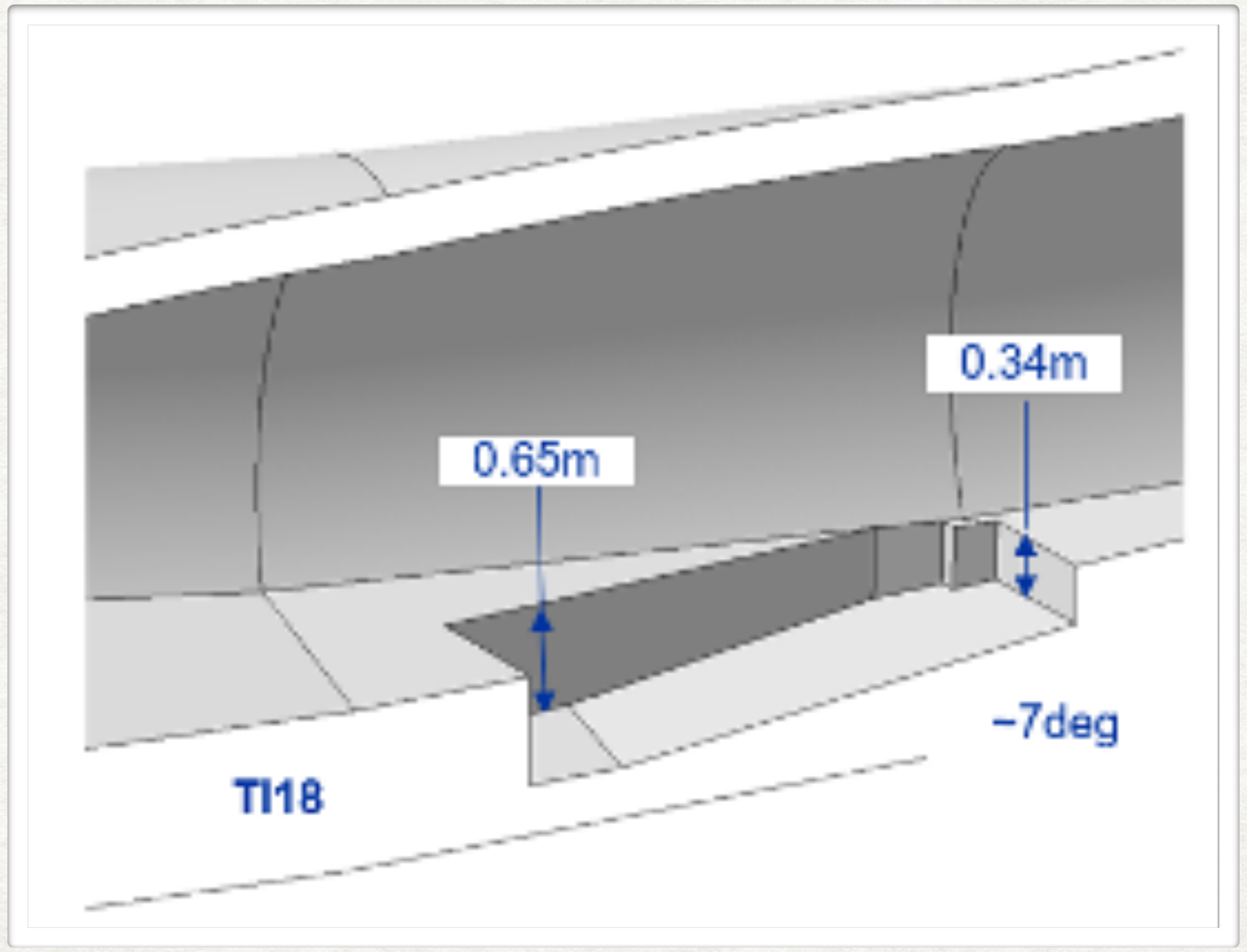
- Horizontal magnetic field 1.75 T
- Coil mass (copper): 0.86 tons
- Overall mass: 12 tons

DETECTOR LOCATION

- Detector located in the TI-18
- Optimization of detector position to increase the angular acceptance
- Civil engineering works required
- ~5 m^3 excavation in the floor to host the detector

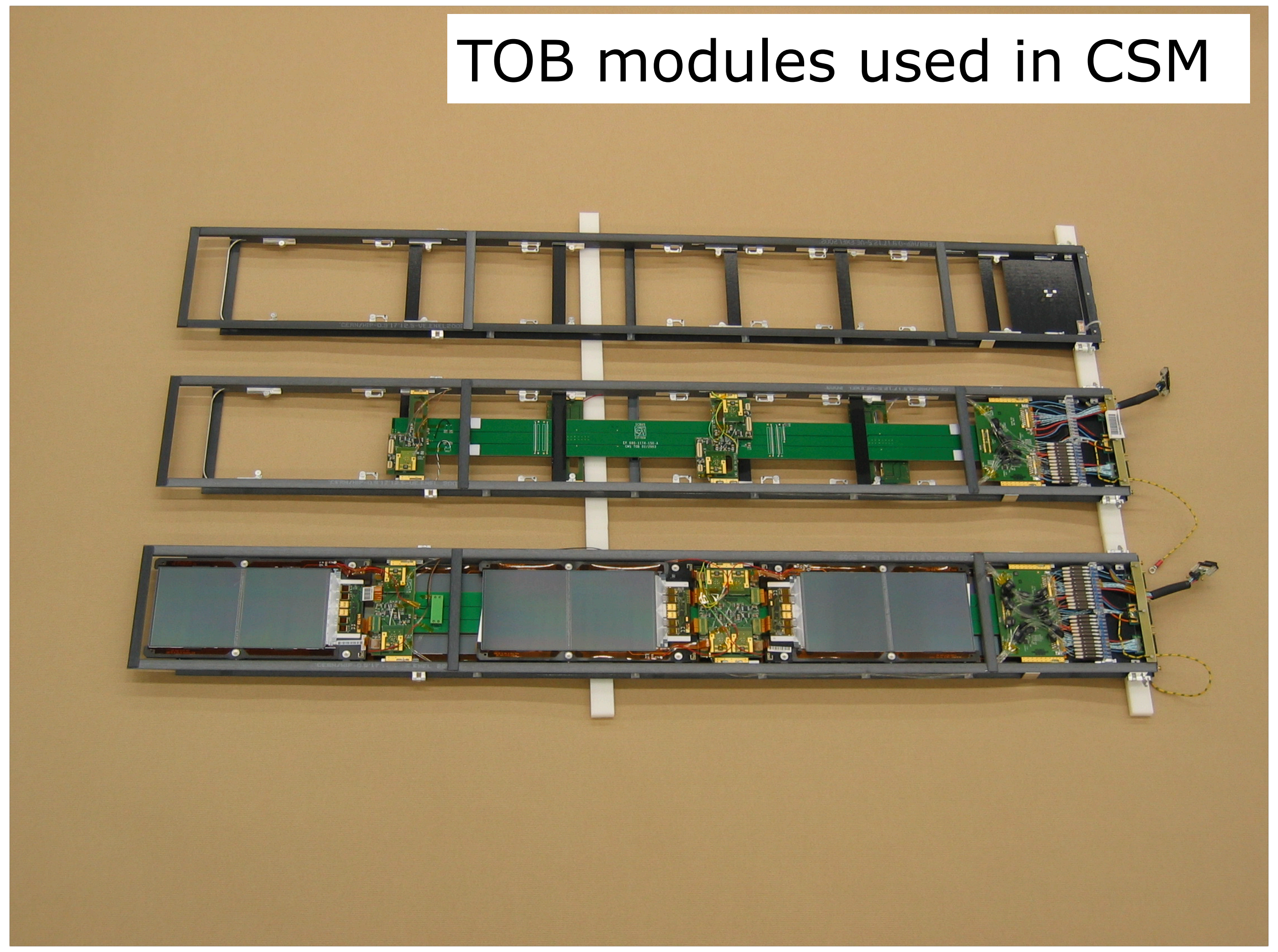


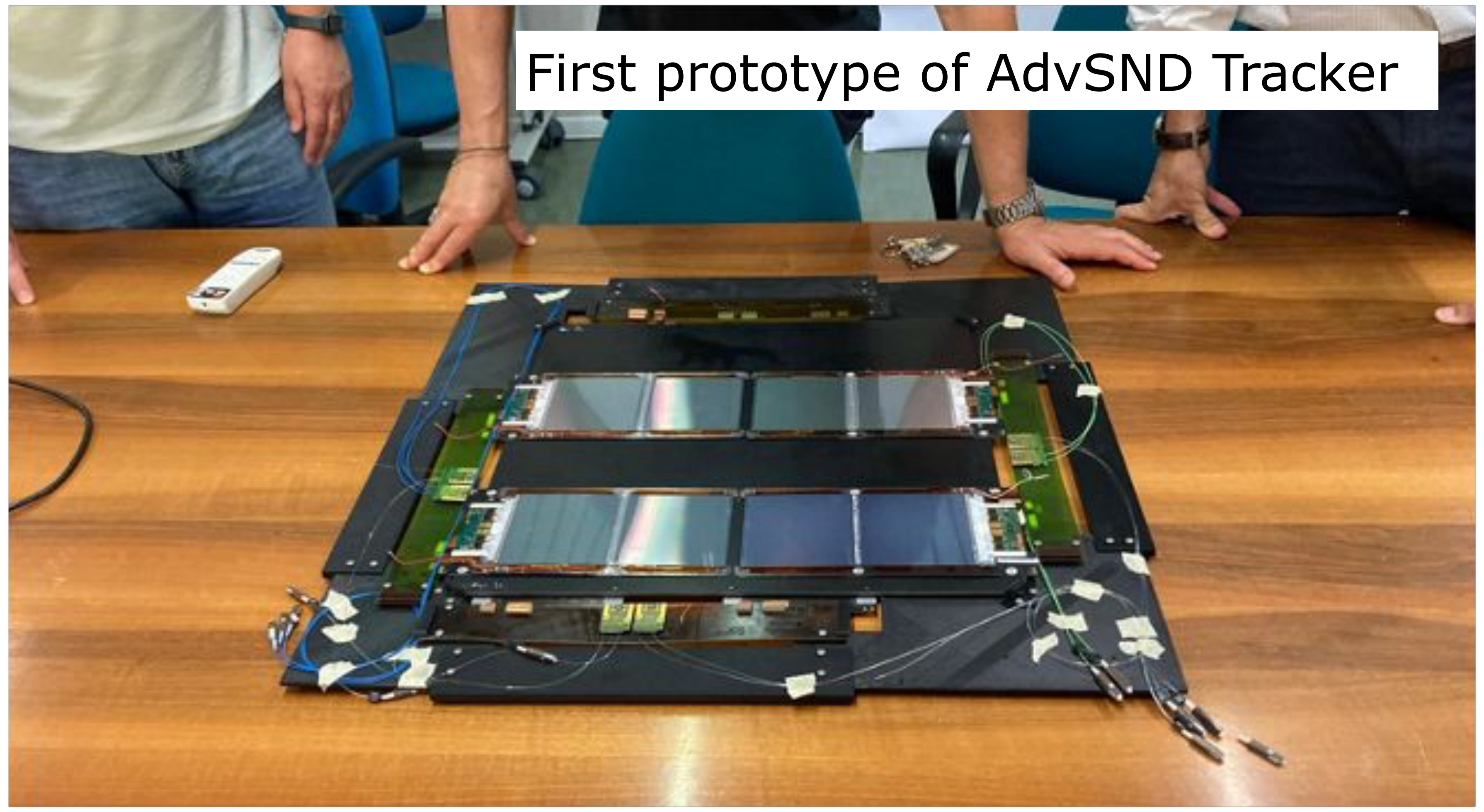


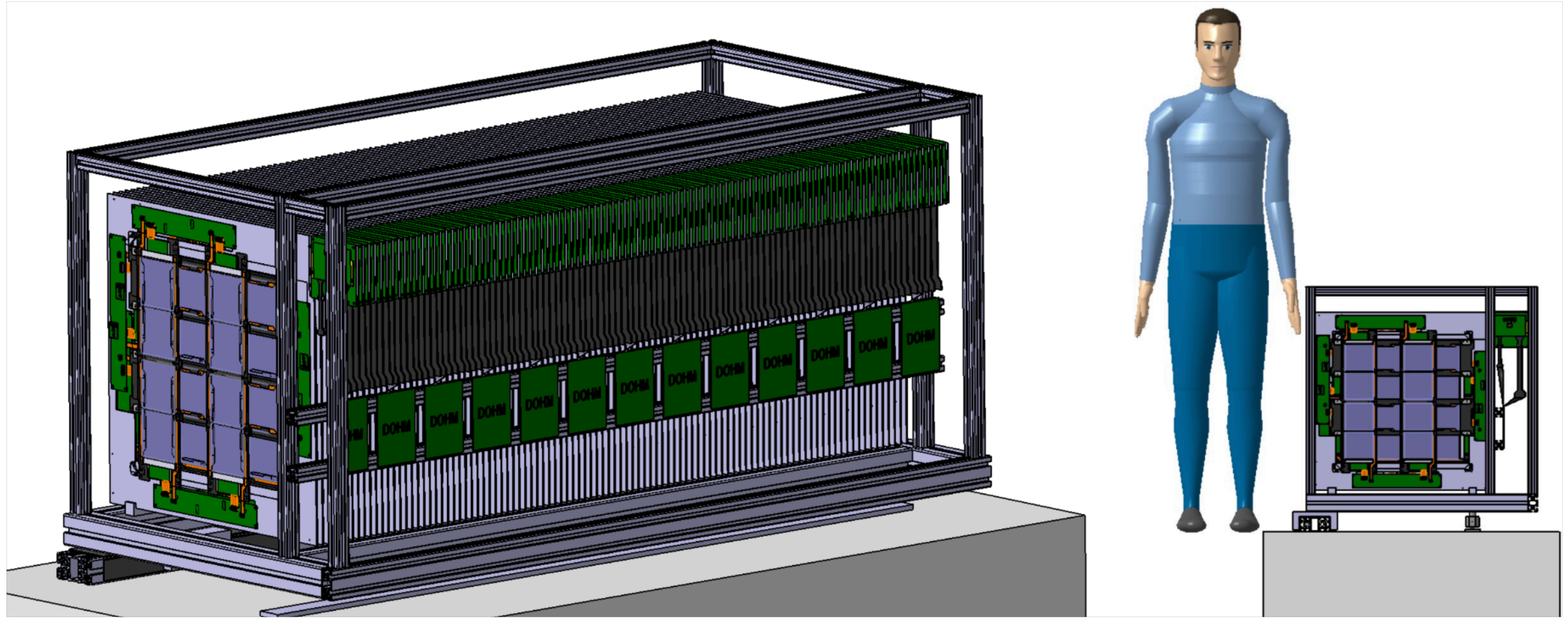


ADV-SND TRACKING SYSTEM

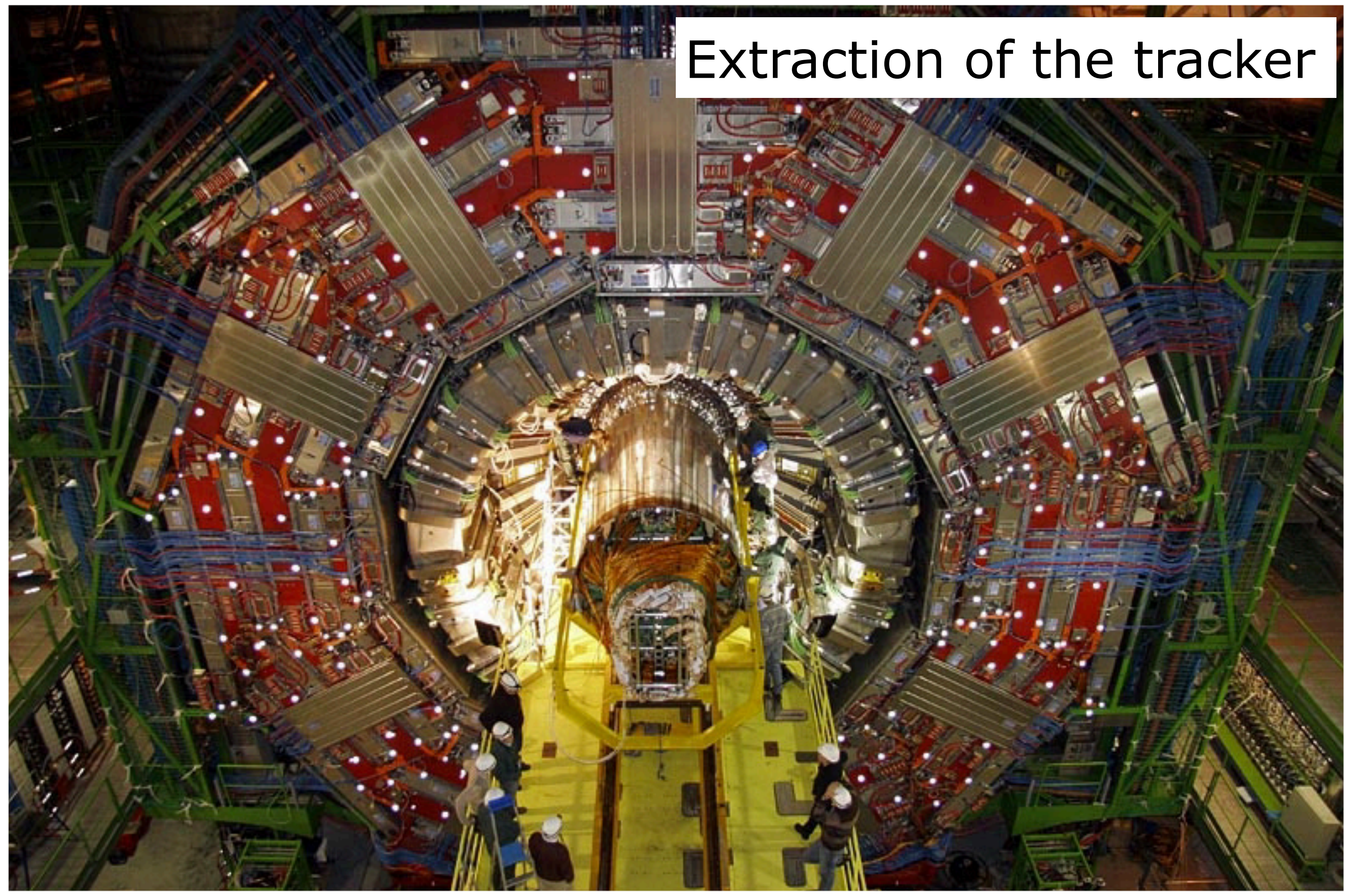
- Re-use of CMS Tracker Outer Barrel (TOB) modules
- Design of new mechanics and electronics for the AdvSND Tracker

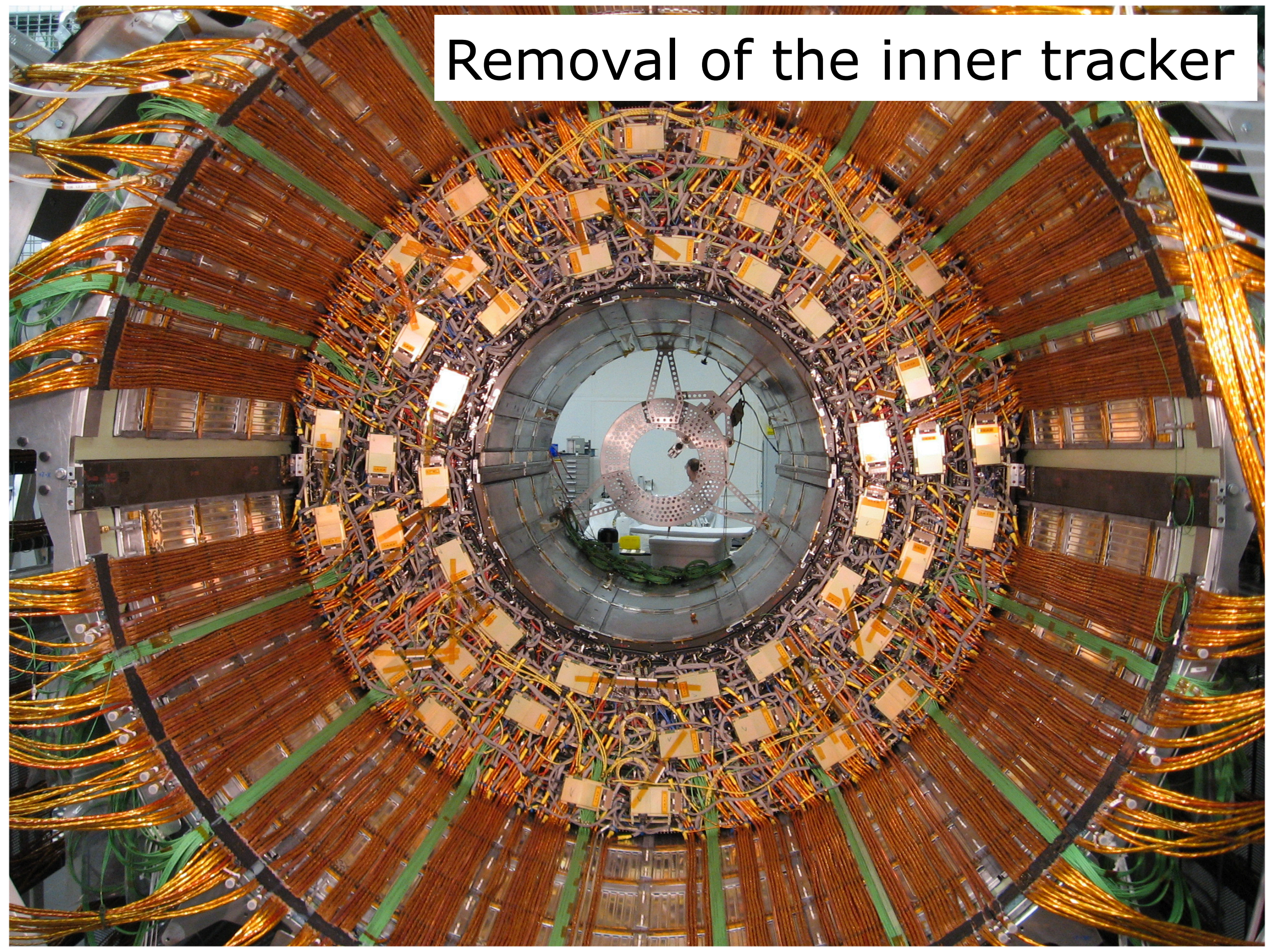

TOB modules used in CSM

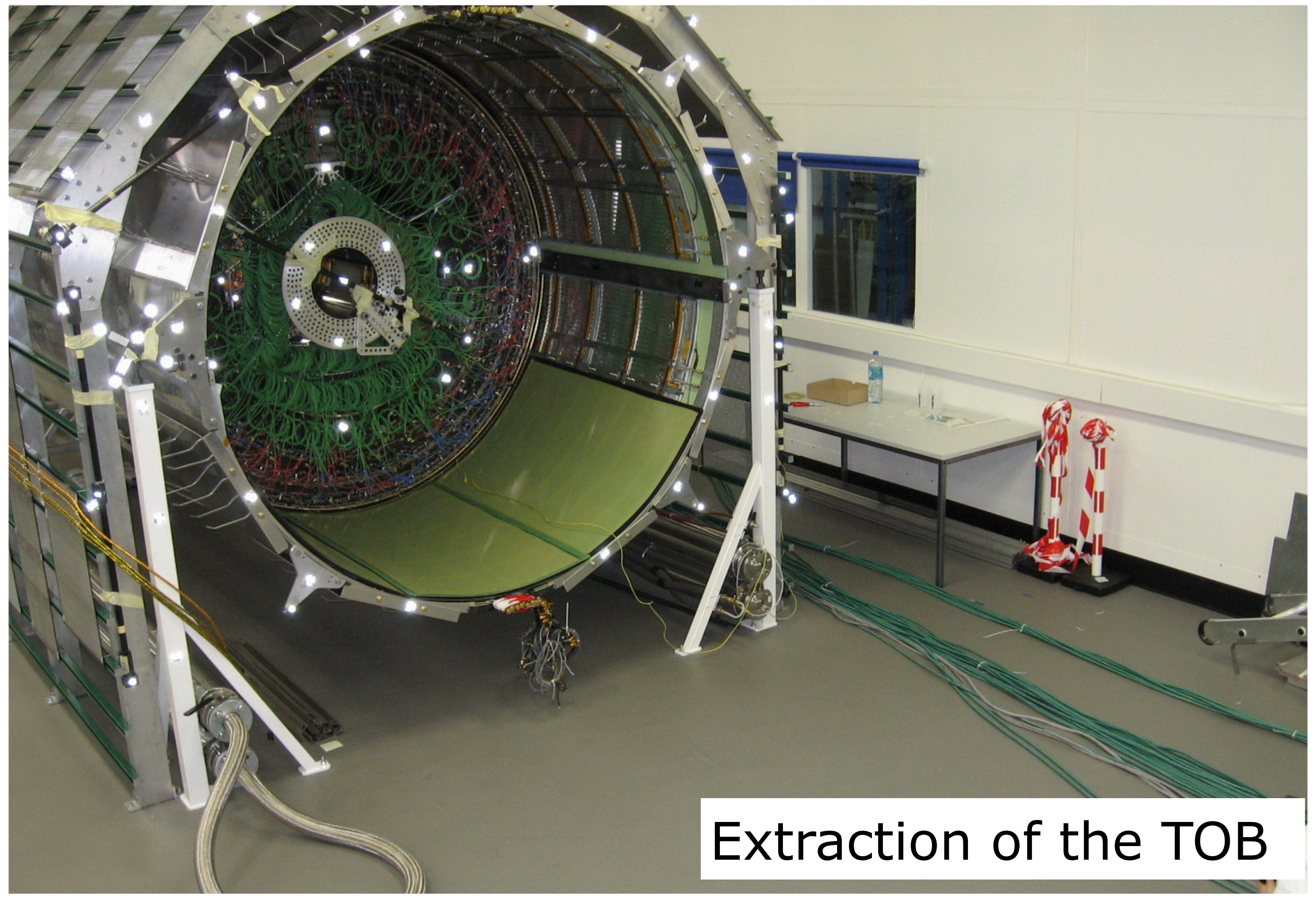

First prototype of AdvSND Tracker

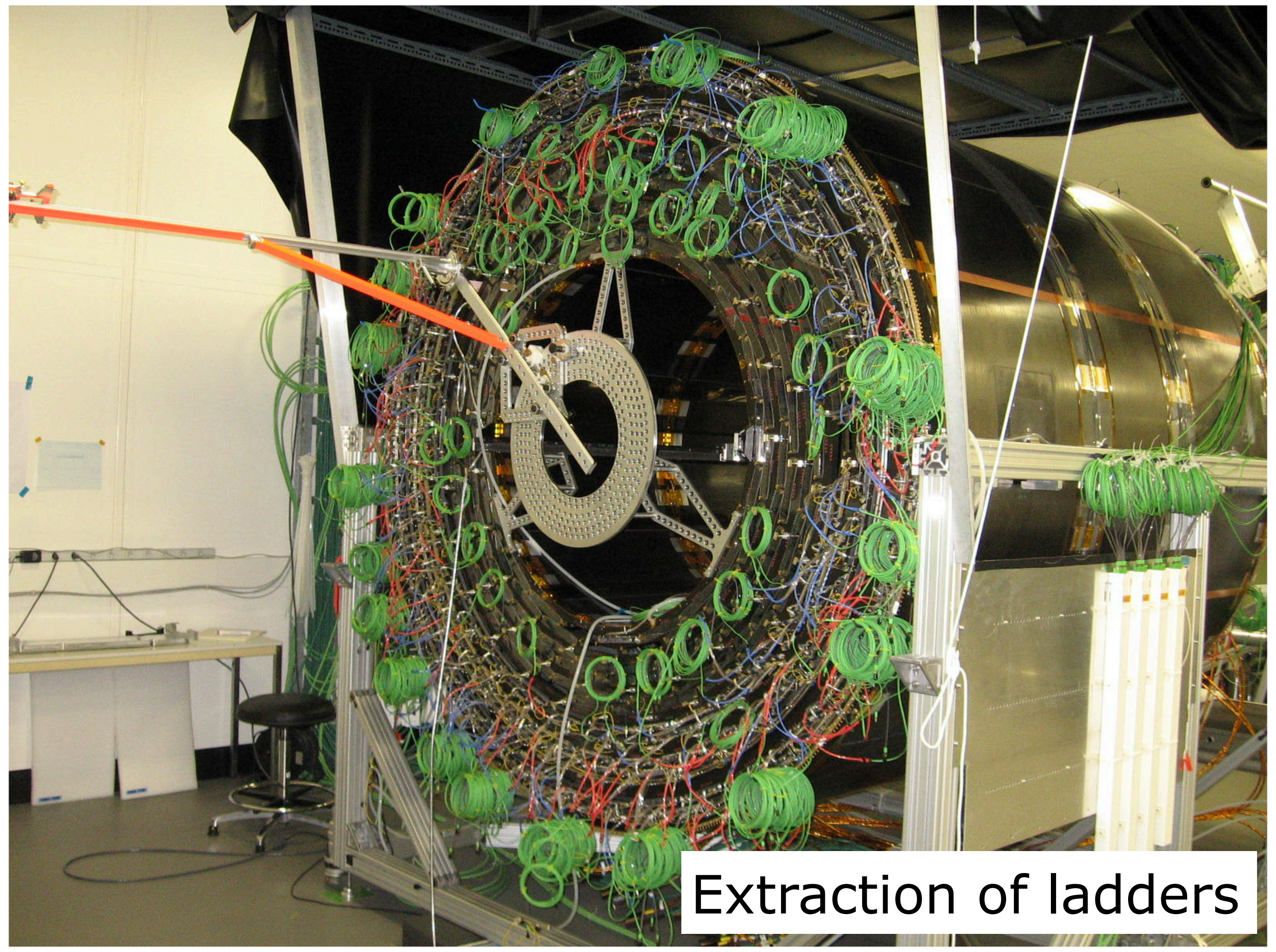


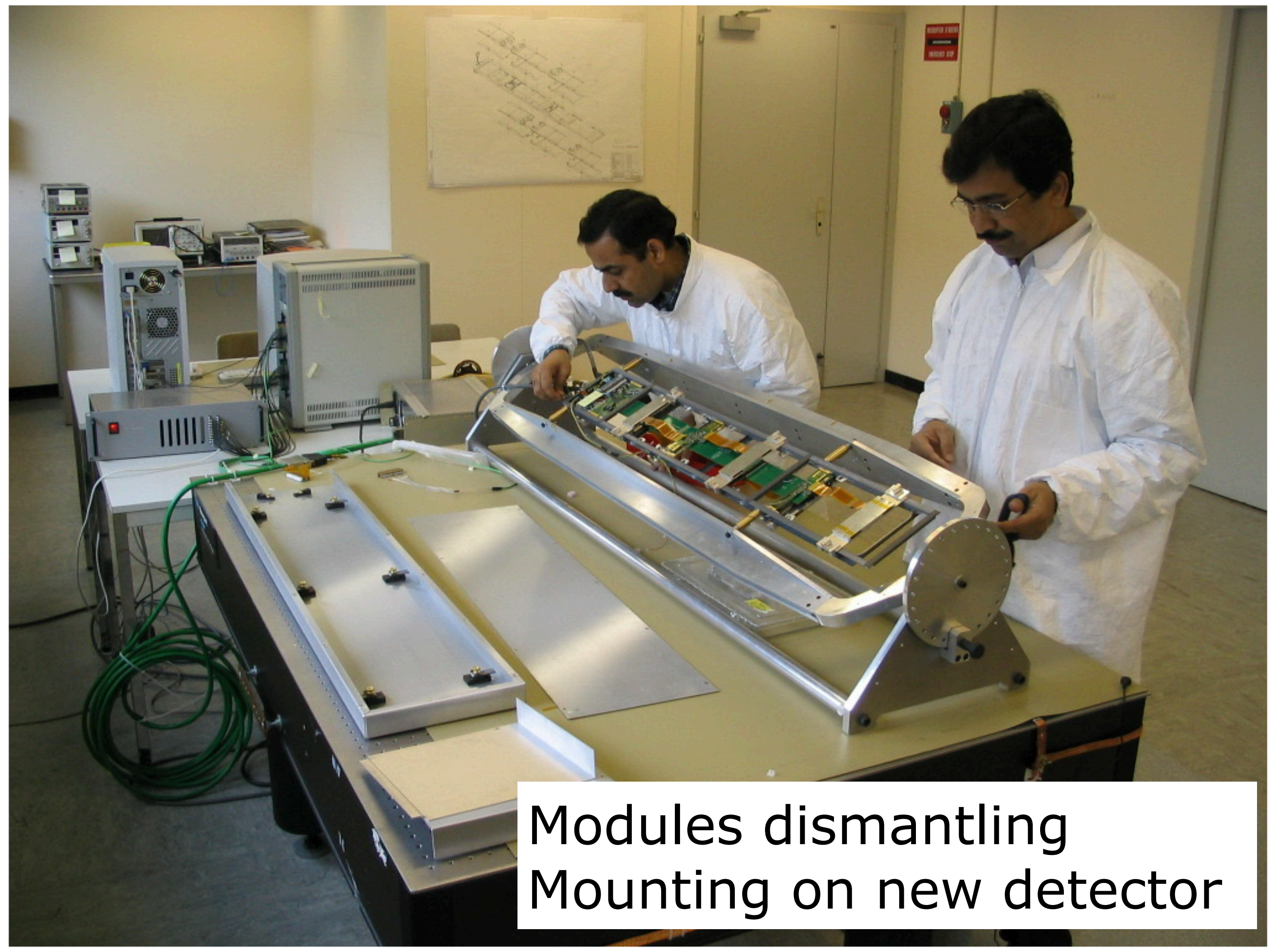
CMS TRACKER DECOMMISIONING AND RECOVERY OF TOB MODULES



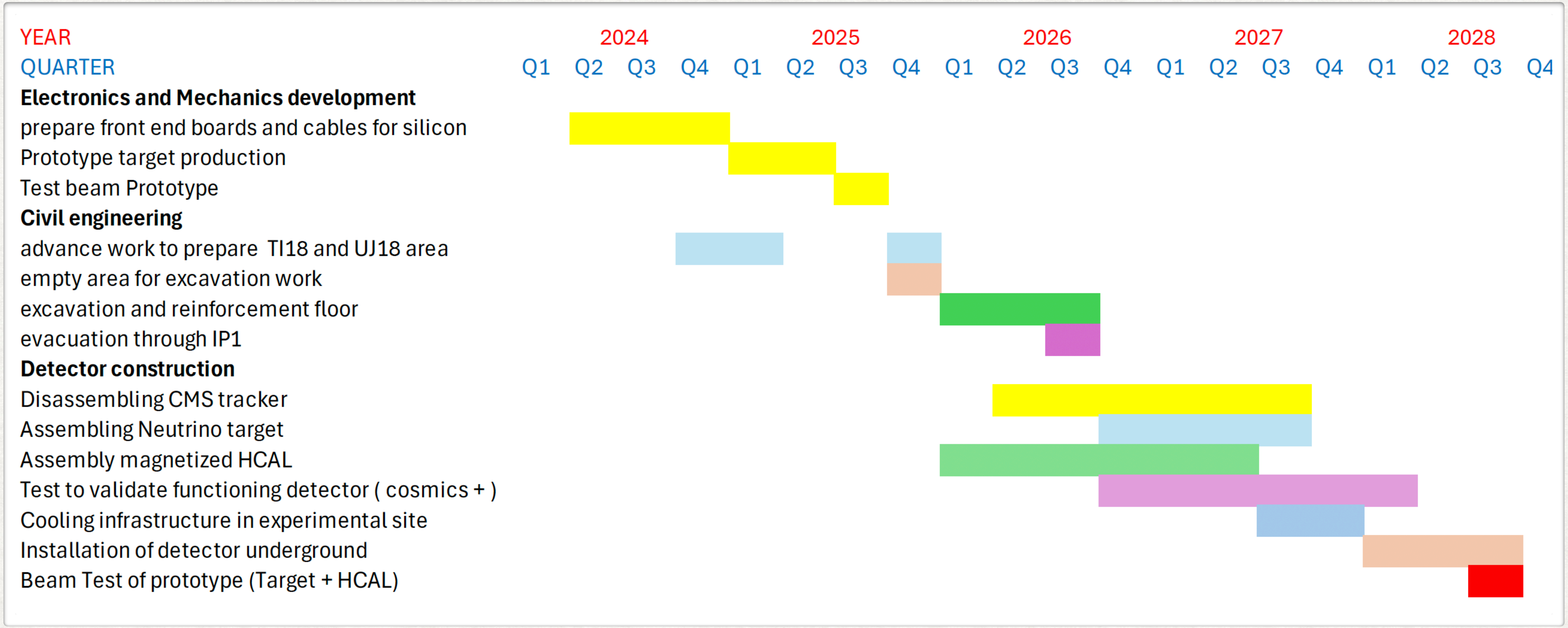








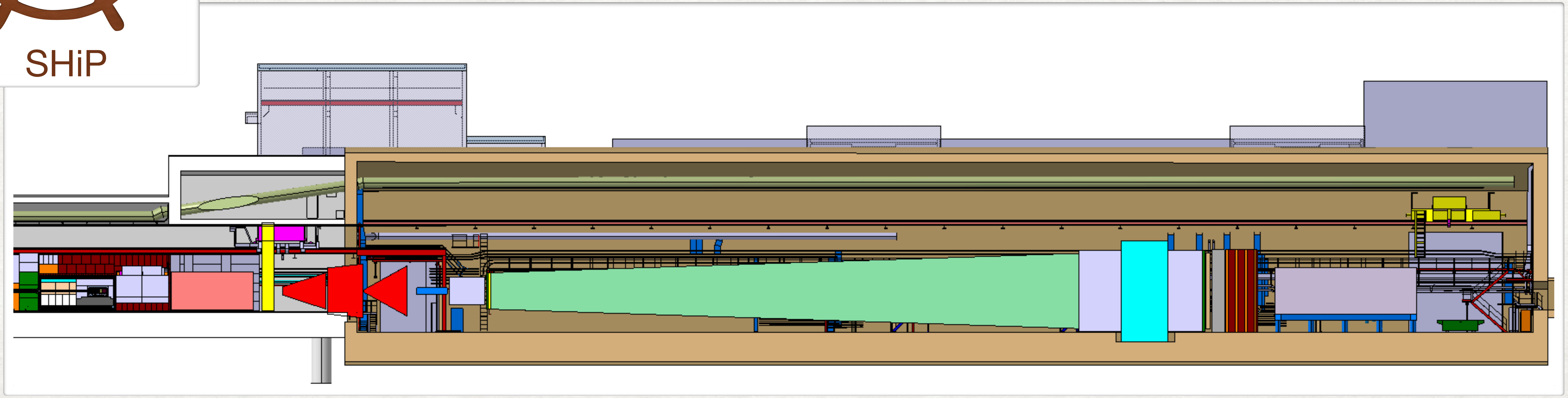
ADV-SND: TIMELINE



NEUTRINO PHYSICS AT THE **INTENSITY** FRONTIER

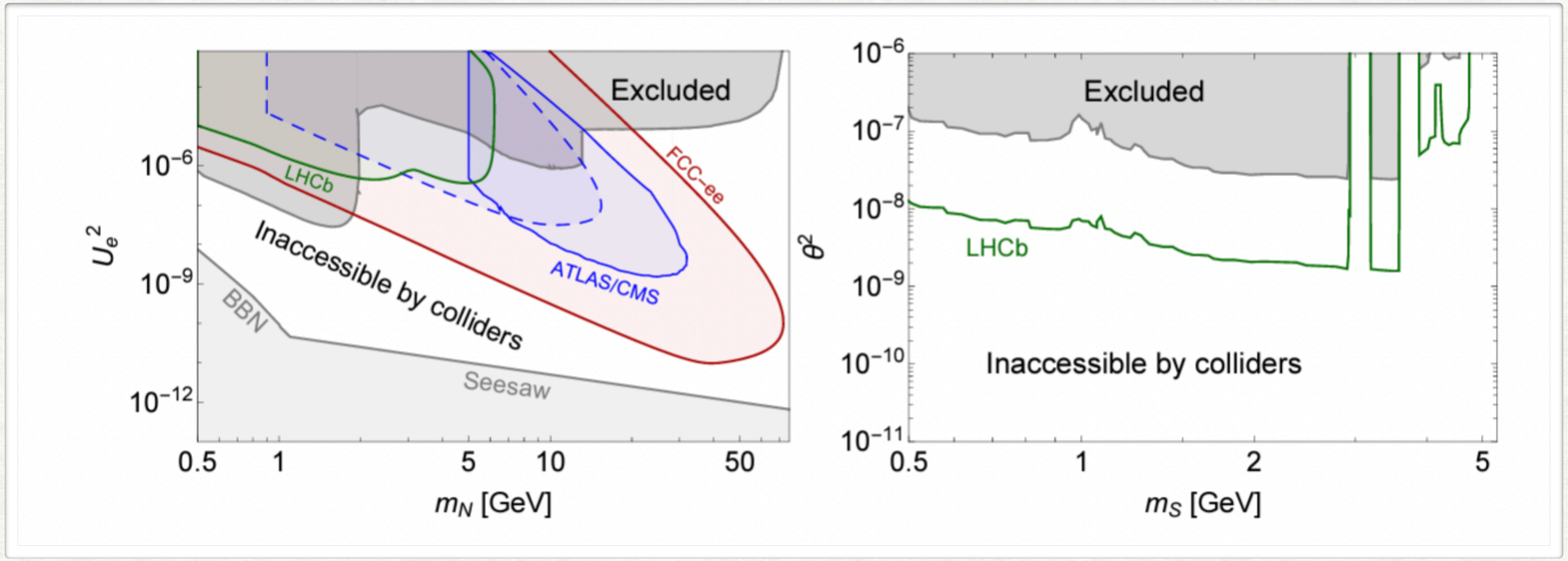
THE **SHIP** EXPERIMENT

SHiP



PHYSICS MOTIVATION

- Many mysteries beyond the Standard Model of Particle Physics remain, and at the GeV-scale there are plenty of areas, where New Physics could be hiding from collider experiments

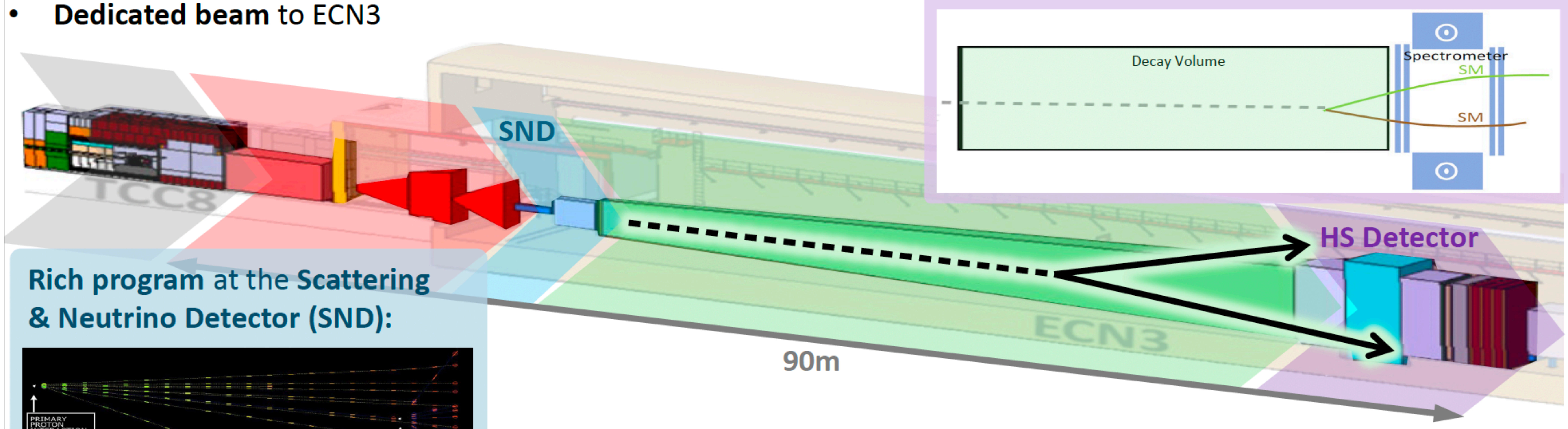


- SHiP is designed to explore these blank spots on the map!

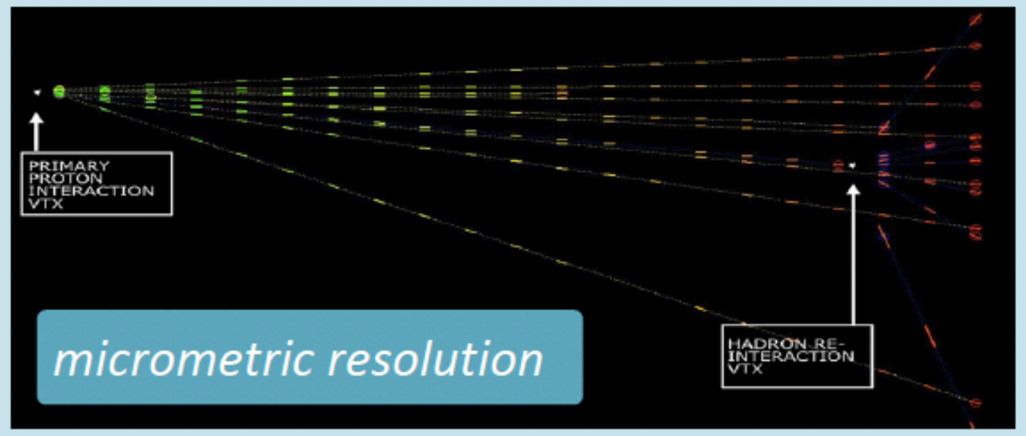
SEARCH FOR HIDDEN PARTICLES (SHIP) AT A DEDICATED BEAM DUMP FACILITY (BDF)

- 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):**

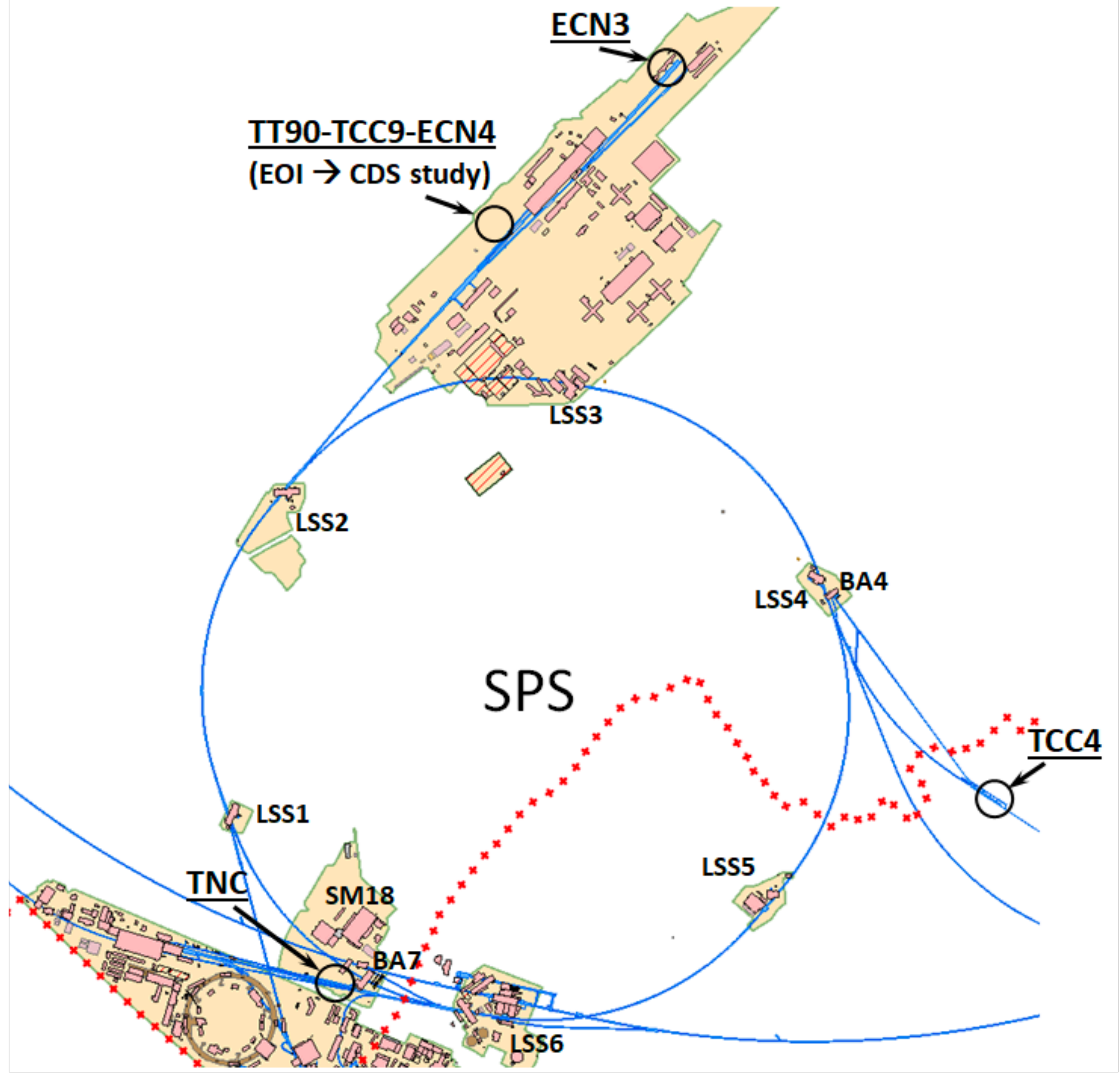


Rich program at the **Scattering & Neutrino Detector (SND):**



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

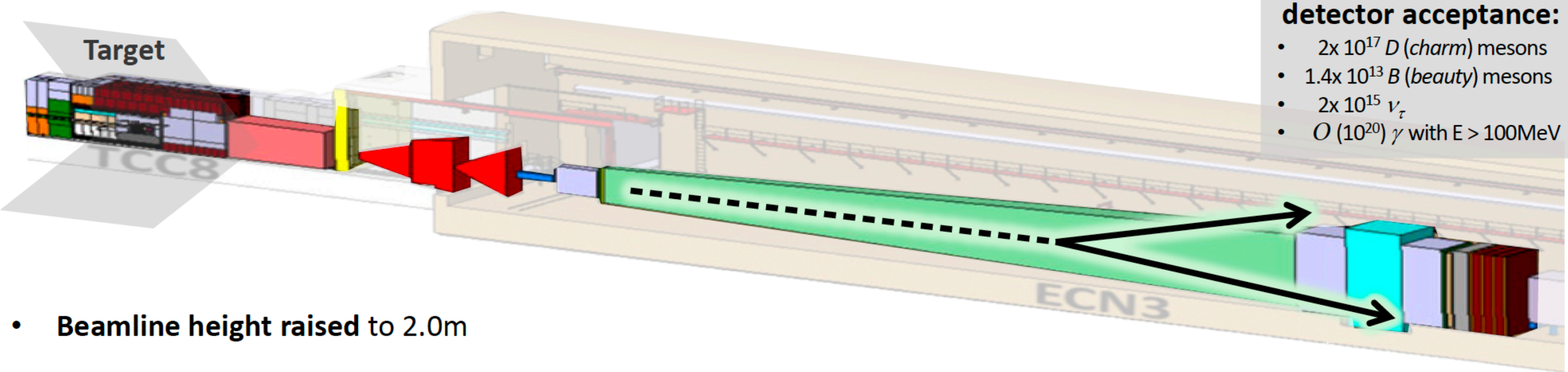
[CERN-SPSC-2013-024, CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]



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

SHIP/BDF DETECTOR TECHNOLOGY

Target & Hadron Stopper

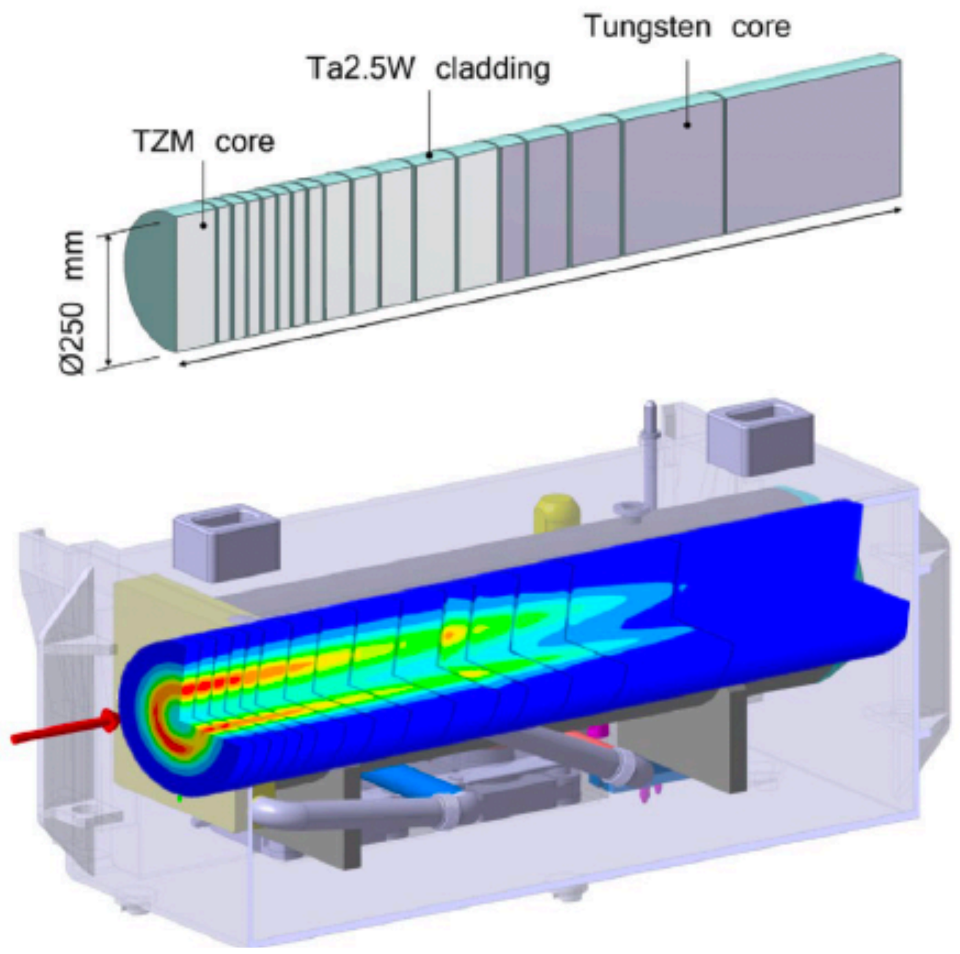


Annual yields within detector acceptance:

- $2x\ 10^{17}$ *D* (*charm*) mesons
- $1.4x\ 10^{13}$ *B* (*beauty*) mesons
- $2x\ 10^{15}$ ν_τ
- $O\ (10^{20})\ \gamma$ 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**]

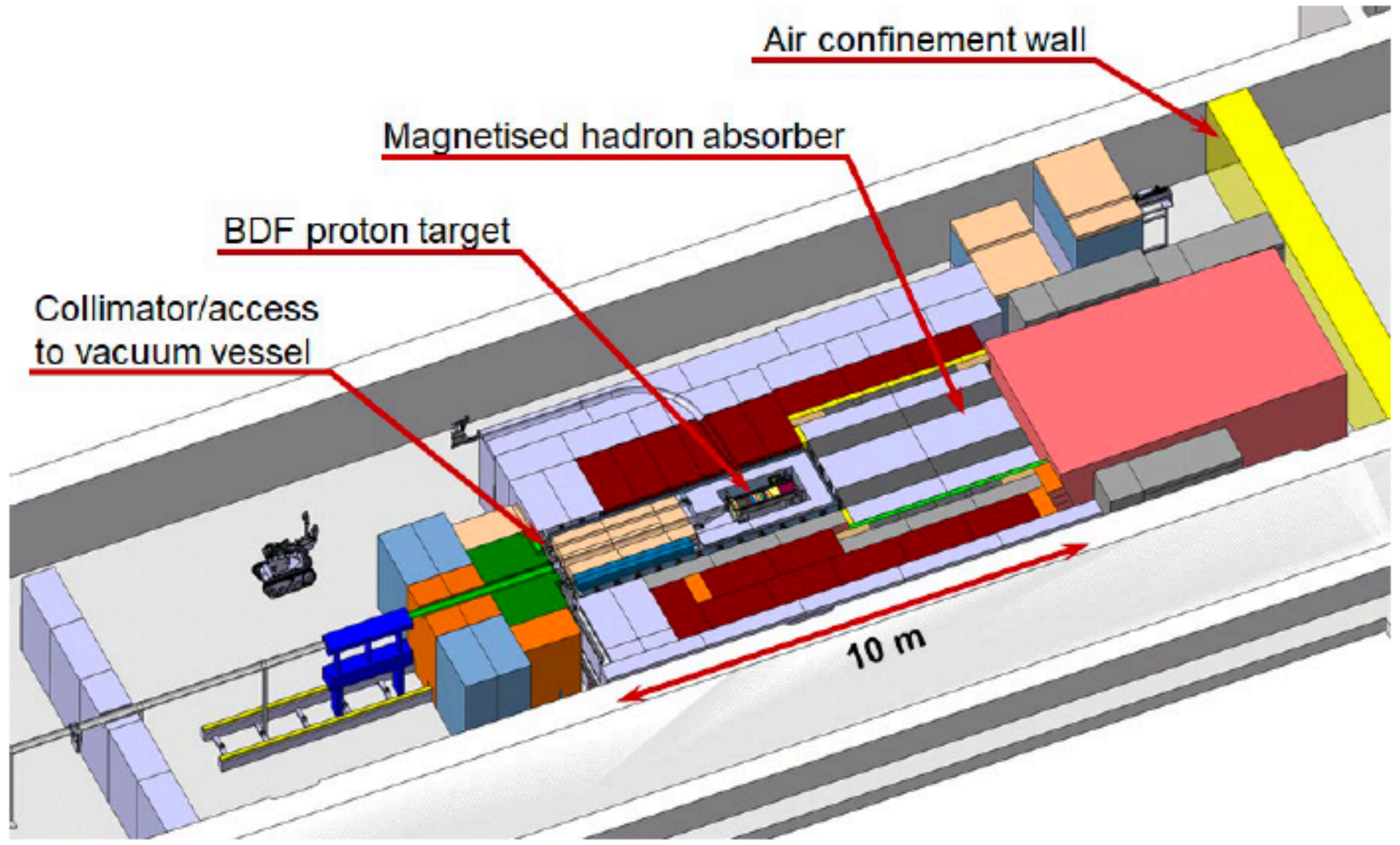


- **High-density proton target:** 12λ
  Ti-Zr-Mo (TZM) + **W blocks**, clad by **Ta**

▶ **Optimised for heavy meson production**

- **Shielding:** **Cast iron & concrete**,
  water-cooled & vacuum-confined

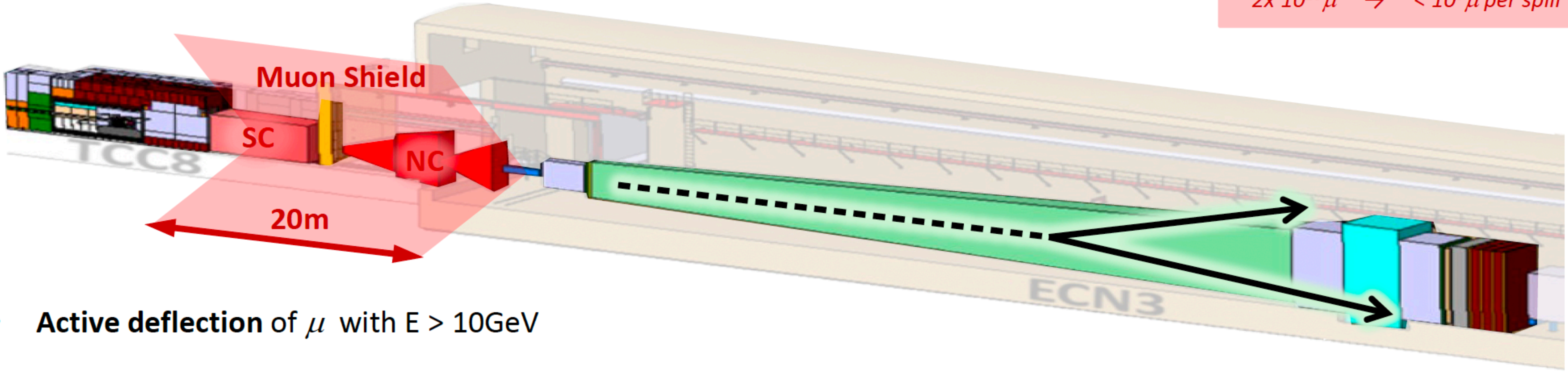
- 5m-long **magnetised hadron stoppper**



SHIP/BDF DETECTOR TECHNOLOGY

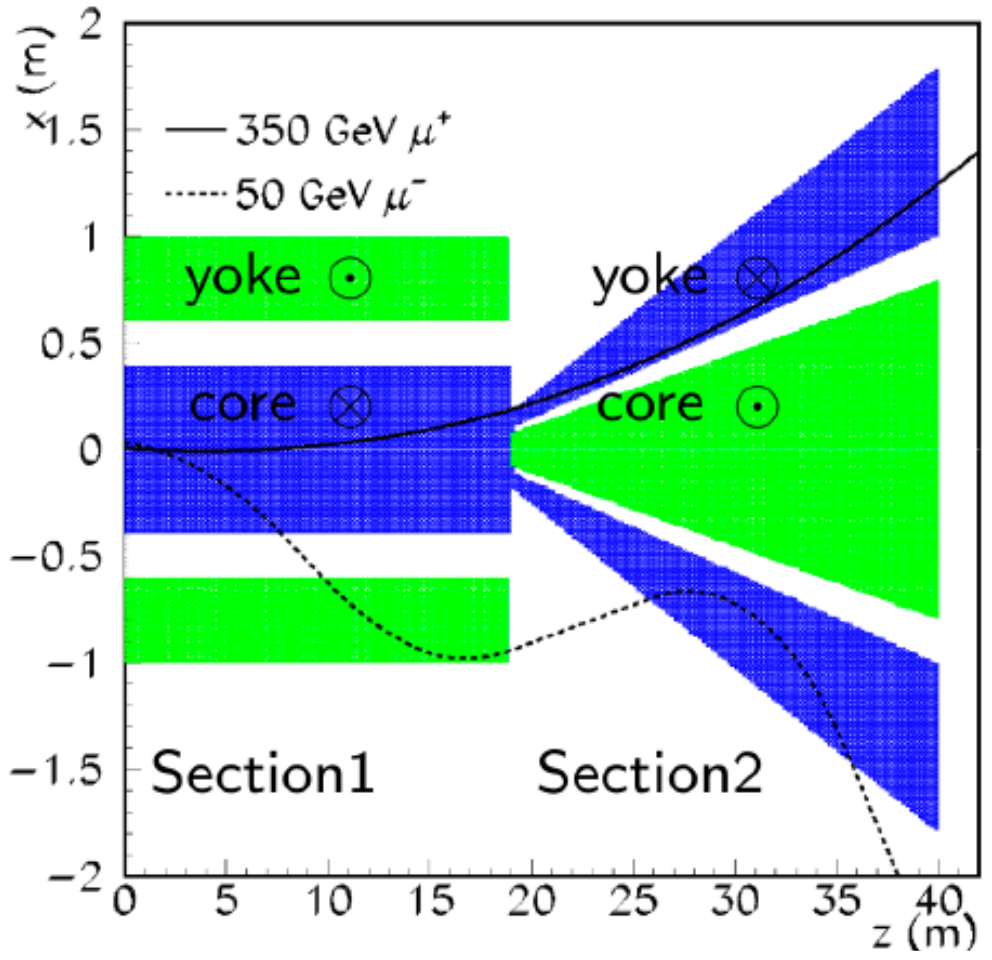
(Superconducting) Magnetic Muon Shield

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



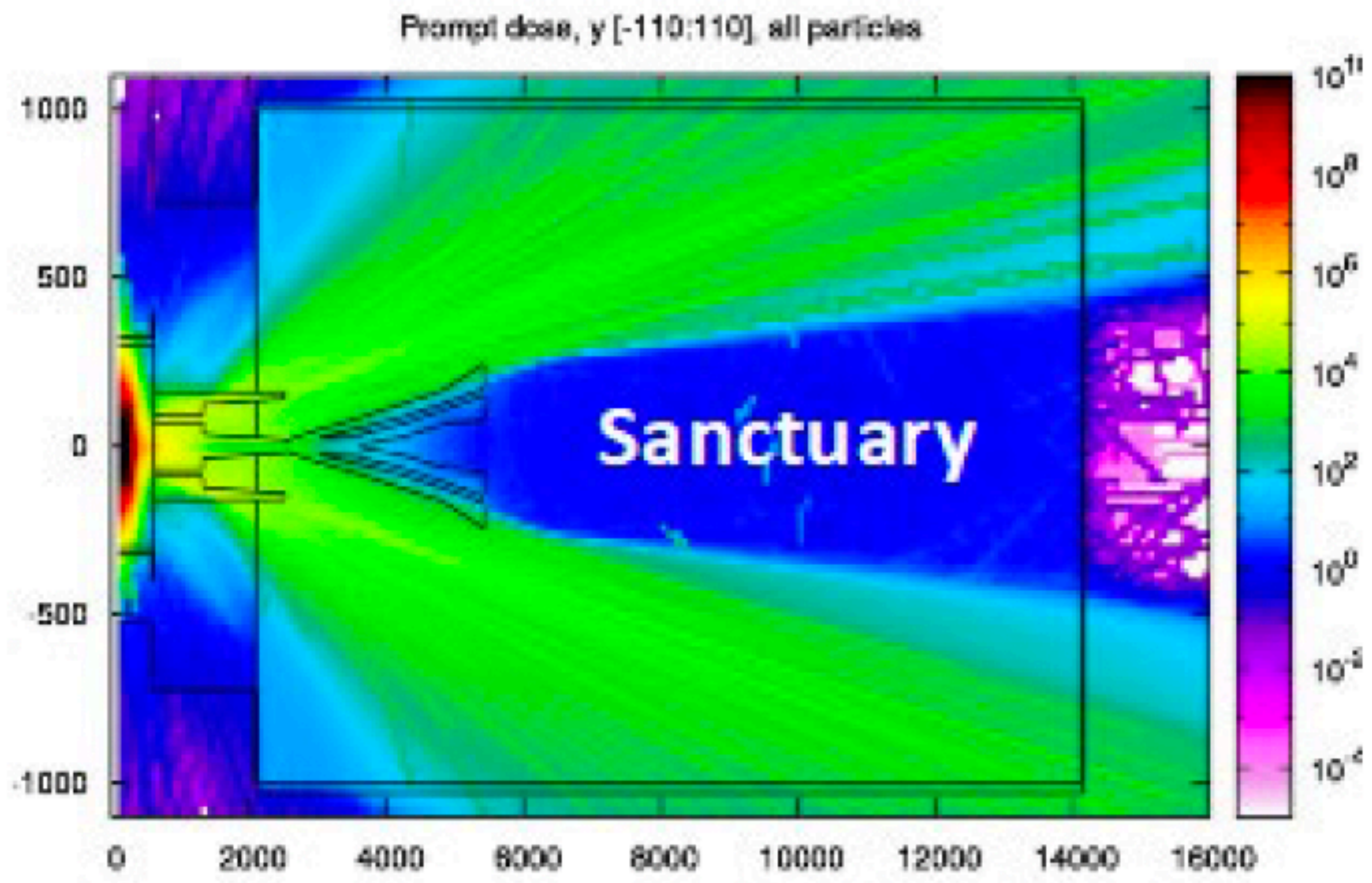
- **Active deflection** of μ with E > 10GeV

[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

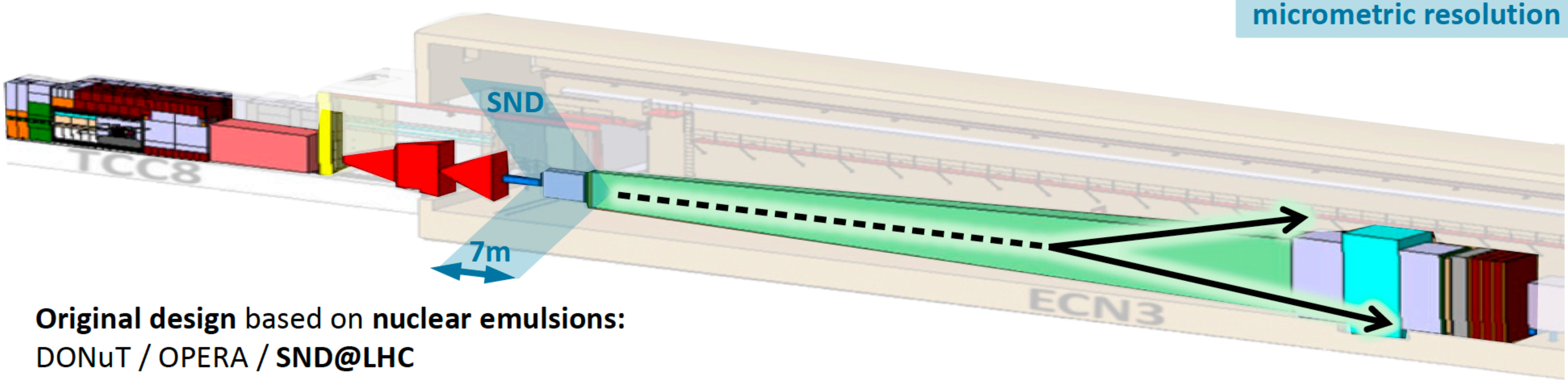
▶ Ongoing **ML-assisted optimisation campaign**



SHIP/BDF DETECTOR TECHNOLOGY

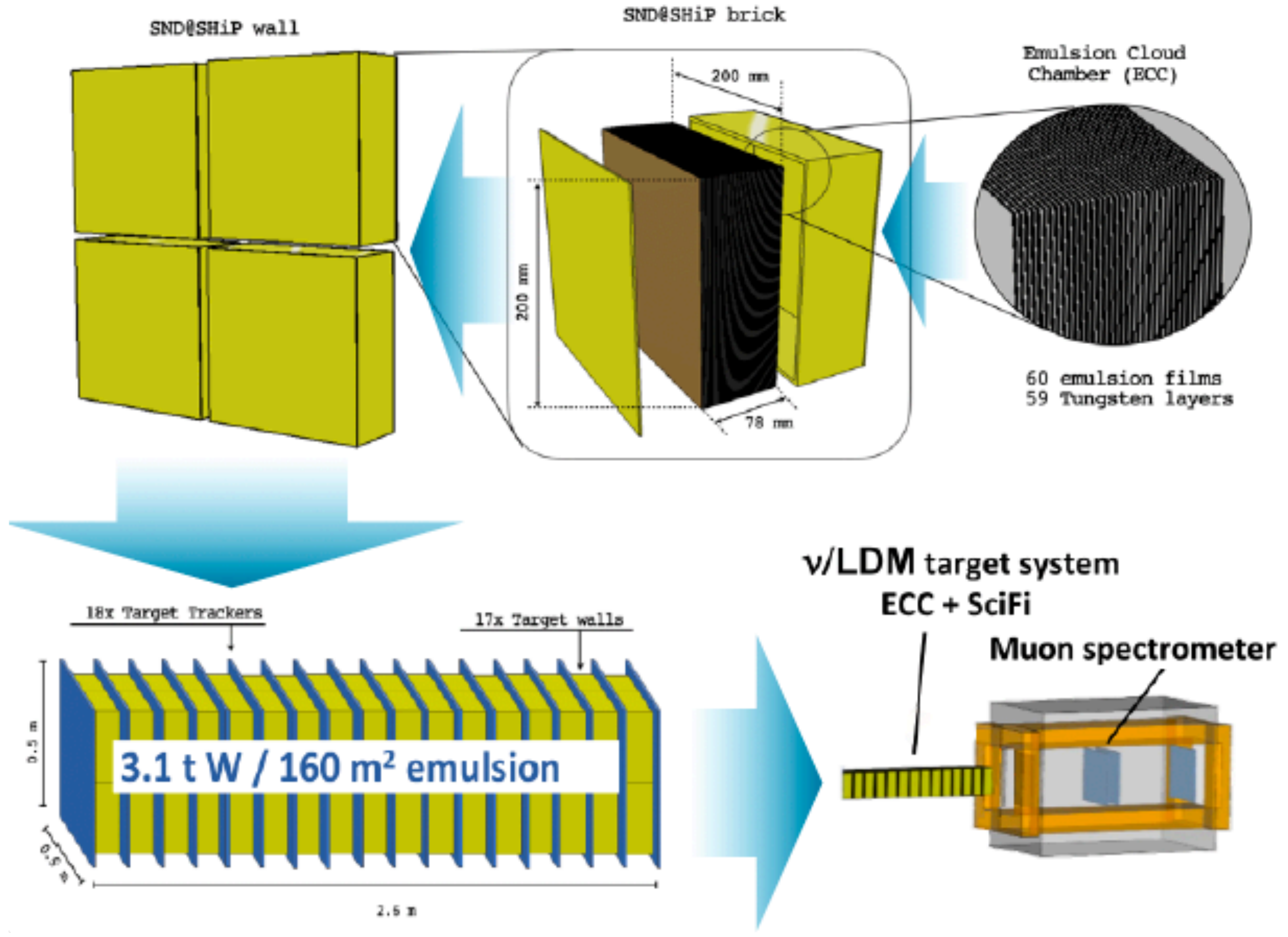
BDF/SHiP: Scattering & Neutrino Detector (SND)

Particle tracking with micrometric resolution



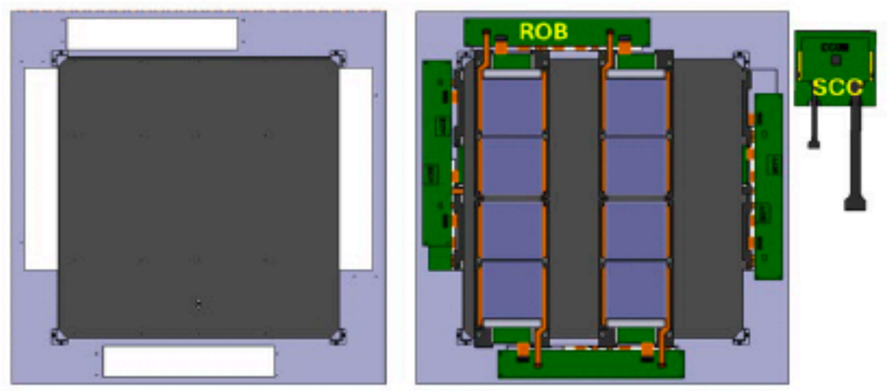
- **Original design** based on **nuclear emulsions:**
  DONuT / OPERA / **SND@LHC**

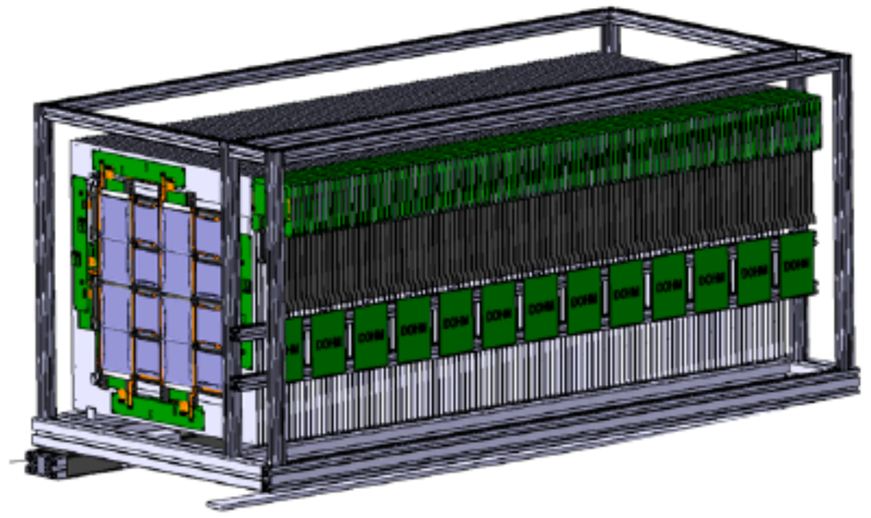
[CERN-SPSC-2019-049 / SPSC-SR-263, CERN-LHCC-2020-002, **CERN-SPSC-2023-033 / SPSC-P-369, EPJC(2024)84:562, CERN-LHCC-2024-007 / LHCC-I-040**]



- **Emulsion Cloud Chamber (ECC) bricks:**
  AgBr nuclear emulsions interleaved with **W**
- **Target Tracker (TT):** 18 layers of **SciFi**
- μ **spectrometer:** Drift tubes (4 stations)
- **Air core dipole magnet:** 1 T

▶ **Re-optimisation study** for **realtime readout** using **CMS TOB silicon modules (AdvSND)**

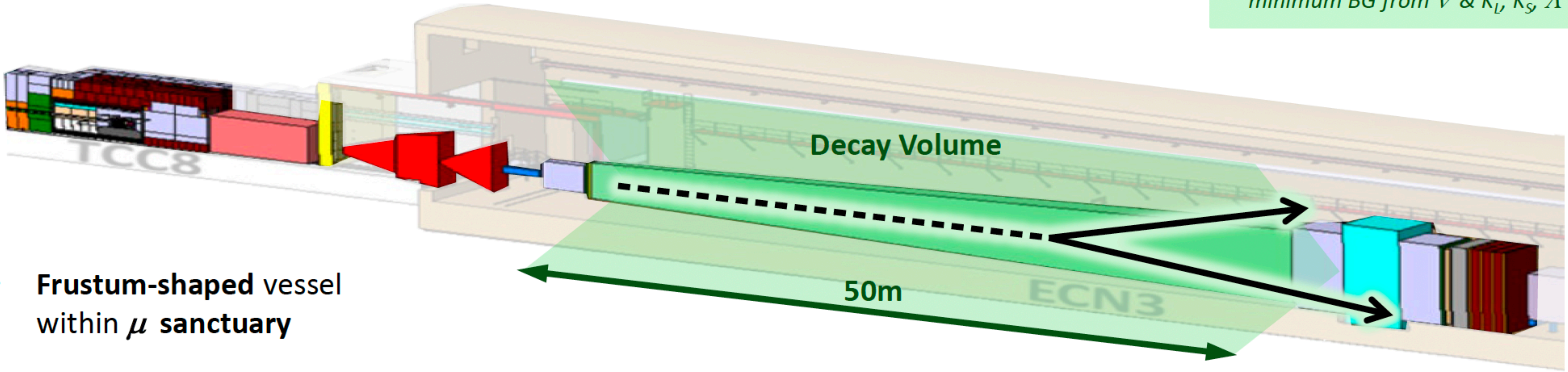




SHIP/BDF DETECTOR TECHNOLOGY

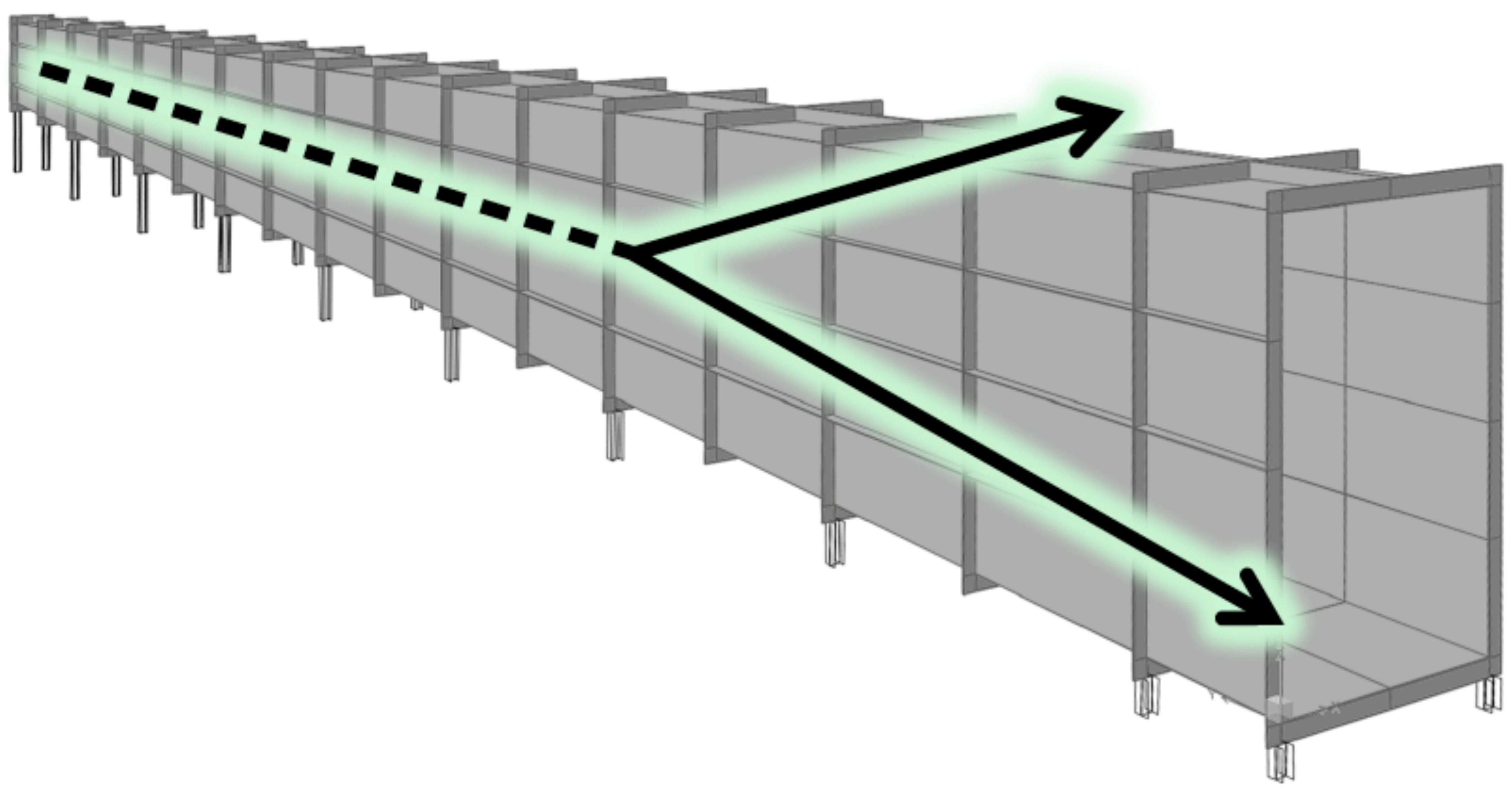
Hidden Sector (HS) Decay Volume

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



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

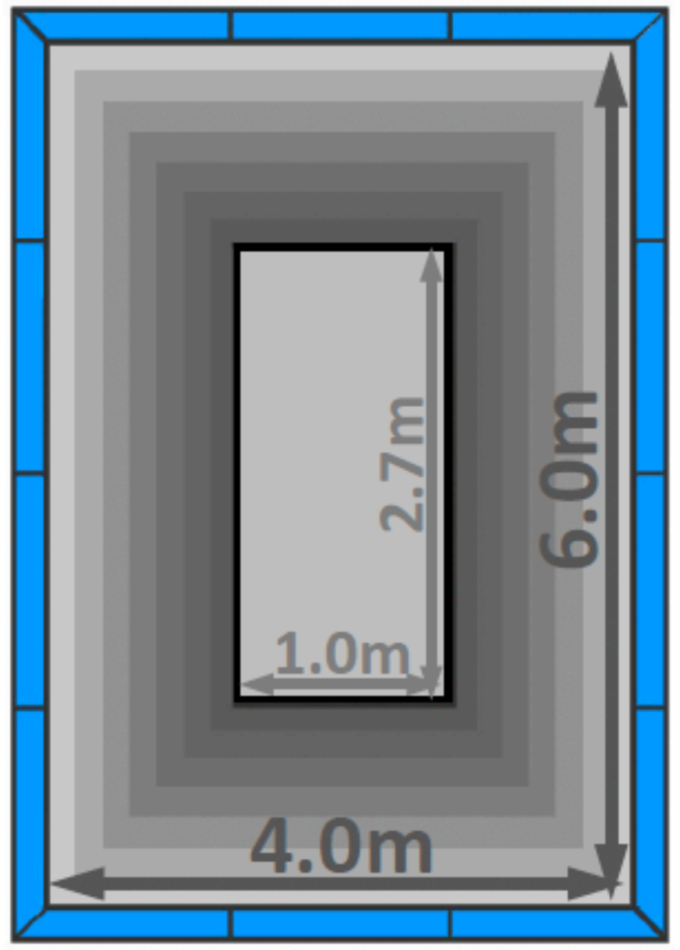
[CERN-SPSC-2019-049 / SPSC-SR-263, ACME (2021) 21:3, CERN-STUDENTS-Note-2023-122, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **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**

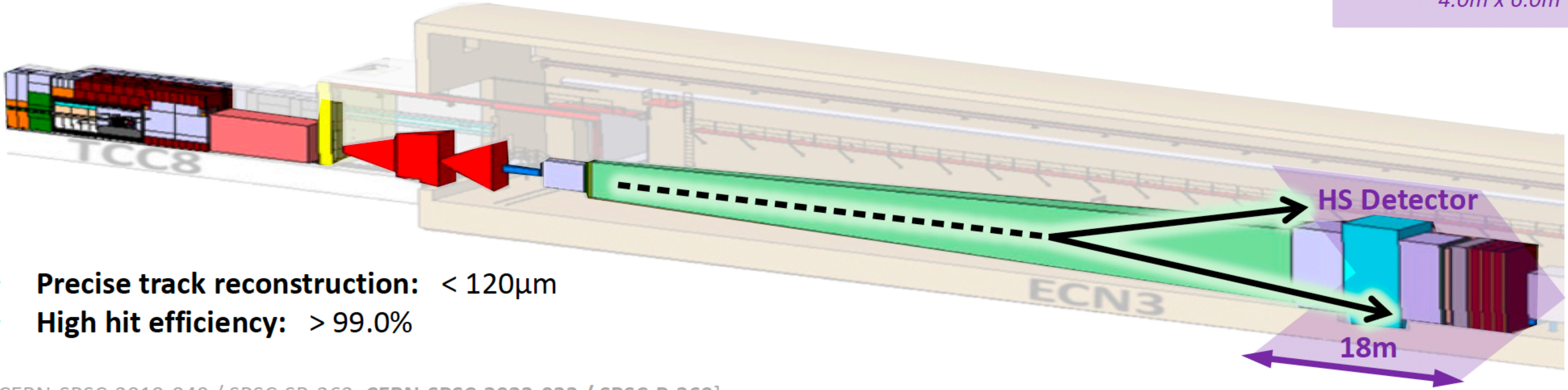
\+ **Support** for **LS-SBT** integration



SHIP/BDF DETECTOR TECHNOLOGY

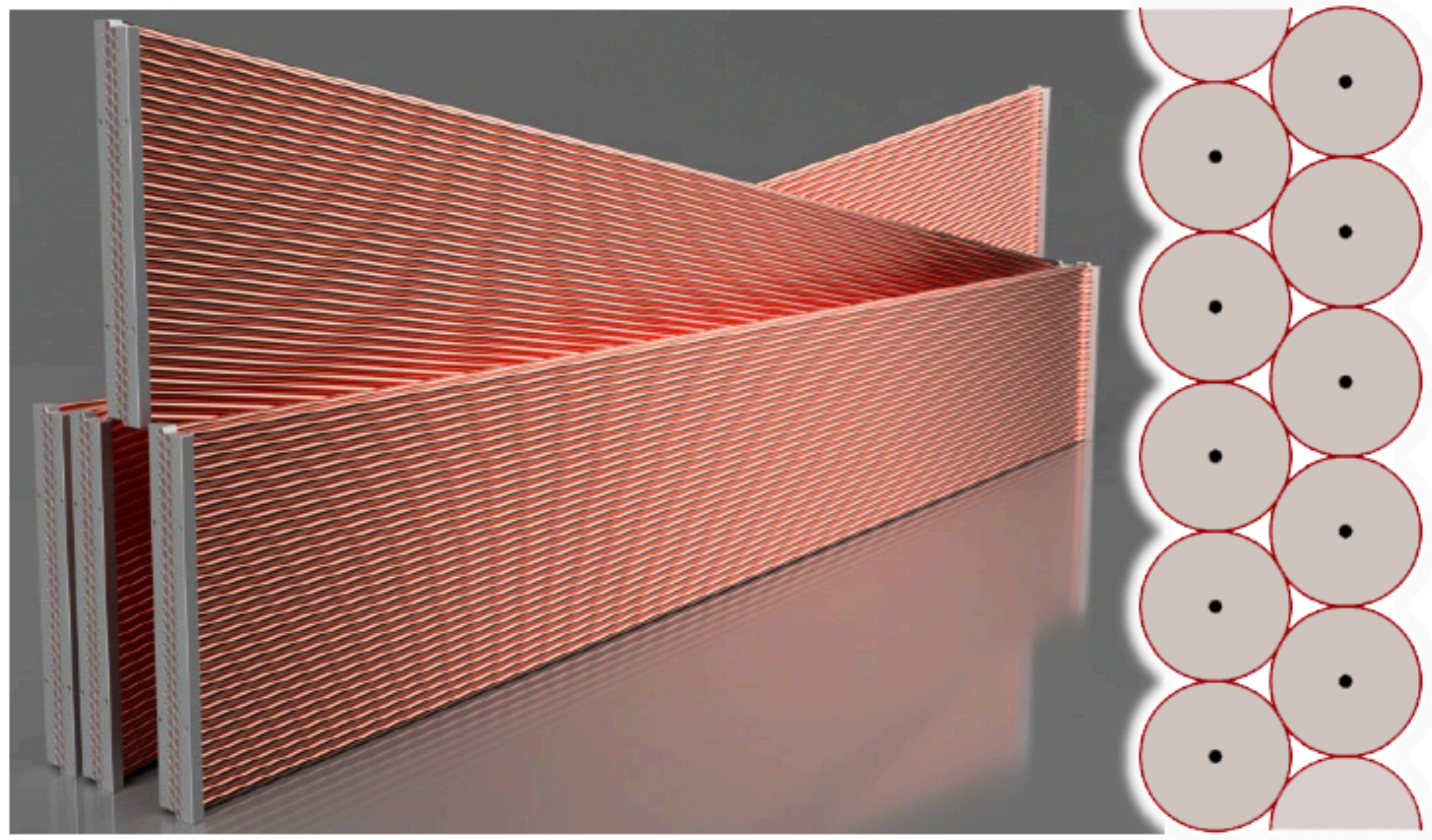
HS Detector: Spectrometer Straw Tracker (SST) & Magnet

Large aperture:
4.0m x 6.0m

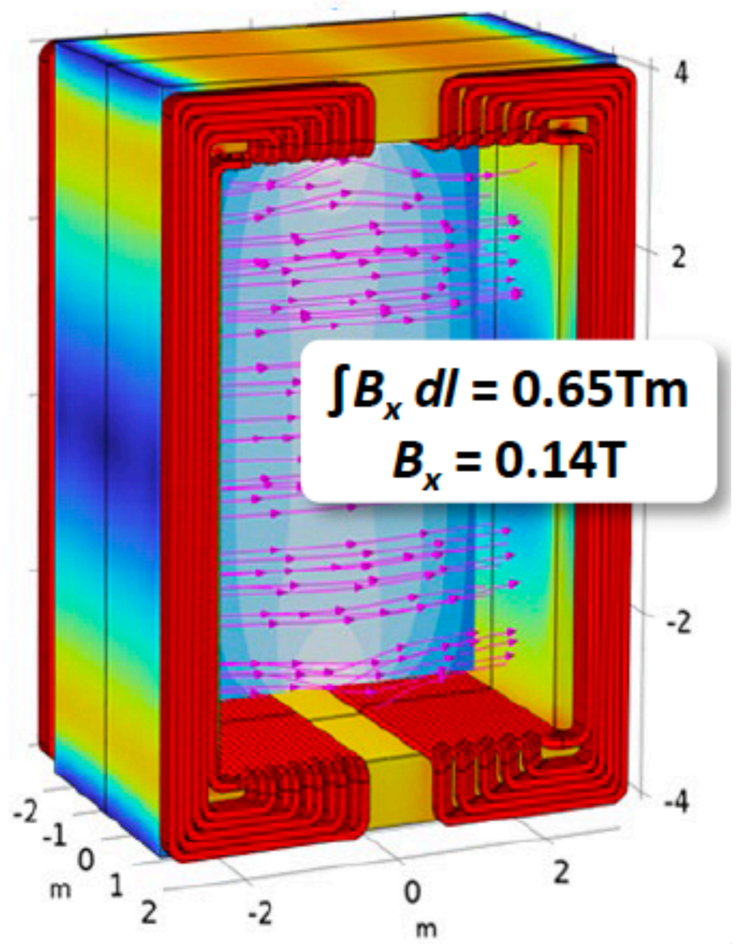


- **Precise track reconstruction:** < 120µm
- **High hit efficiency:** > 99.0%

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

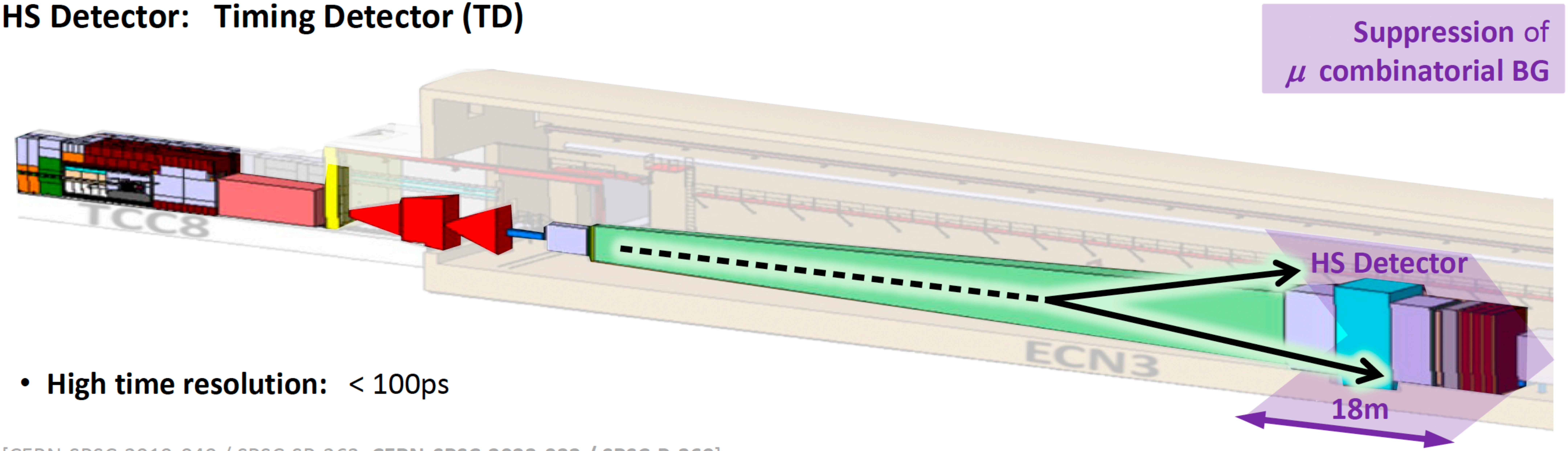


- **Cu/Au-coated Mylar drift tubes (NA62 design):** 4m length, 2cm diameter, 36µm wall thickness, Ar:CO_2 mixture (70:30)
- ▶ **Low material budget**
- 2x 2 stations of 4 double layers at 10° stereo angle, **10 000 channels altogether**
- **Magnet (NC baseline):** 0.65Tm / 0.15T
  SC options being studied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



SHIP/BDF DETECTOR TECHNOLOGY

HS Detector: Timing Detector (TD)



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

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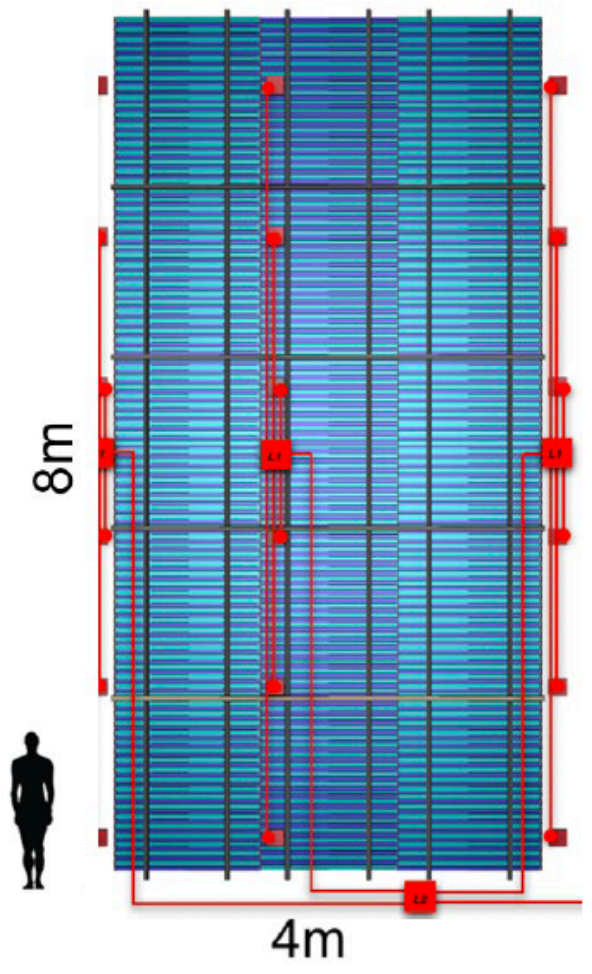
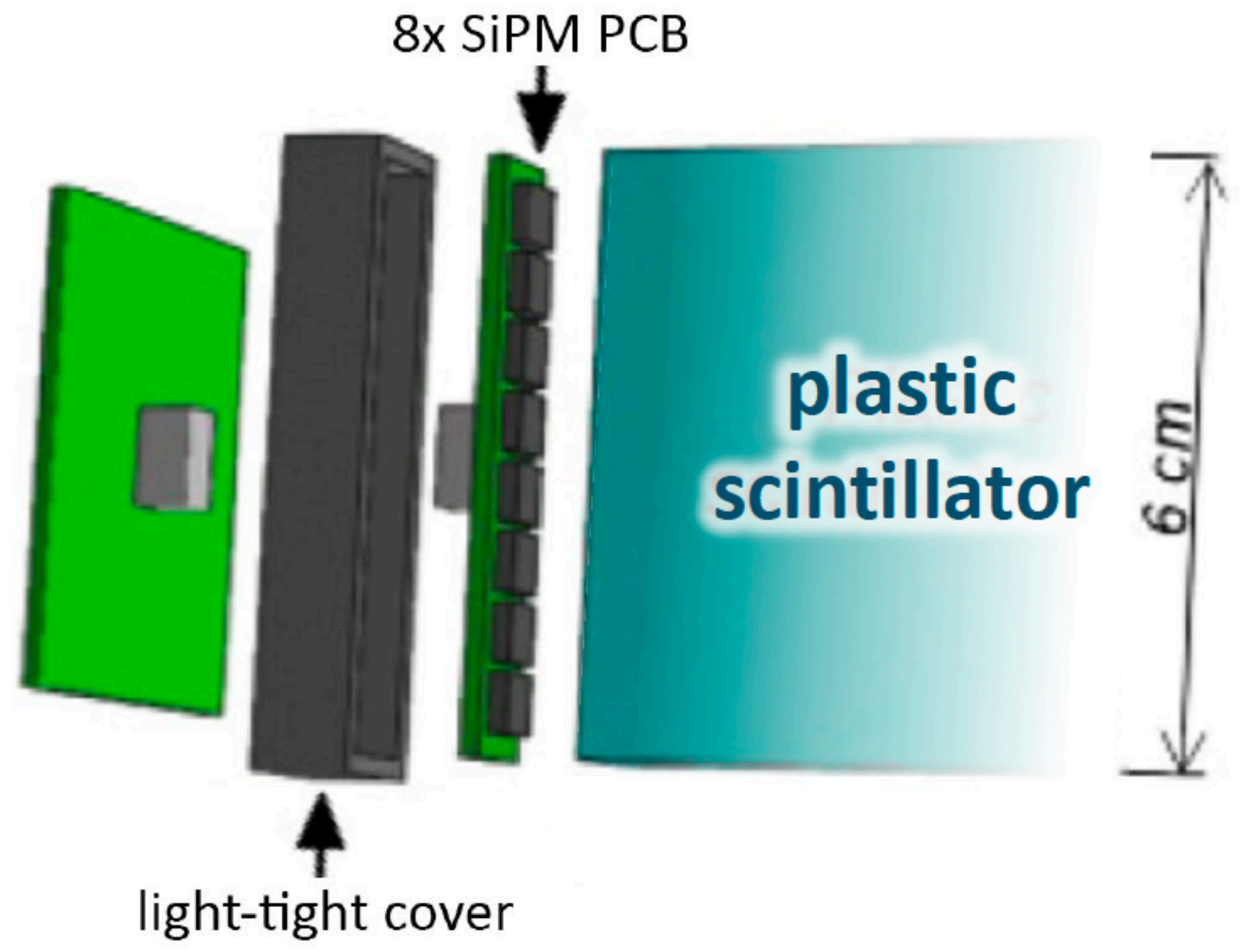


- **EJ200 plastic scintillator bars:** 135cm x 6cm x 1cm
- **Readout** at both ends by **SiPM arrays**
- 3 columns of 111 vertically staggered bars (5mm overlap), **666 channels altogether**

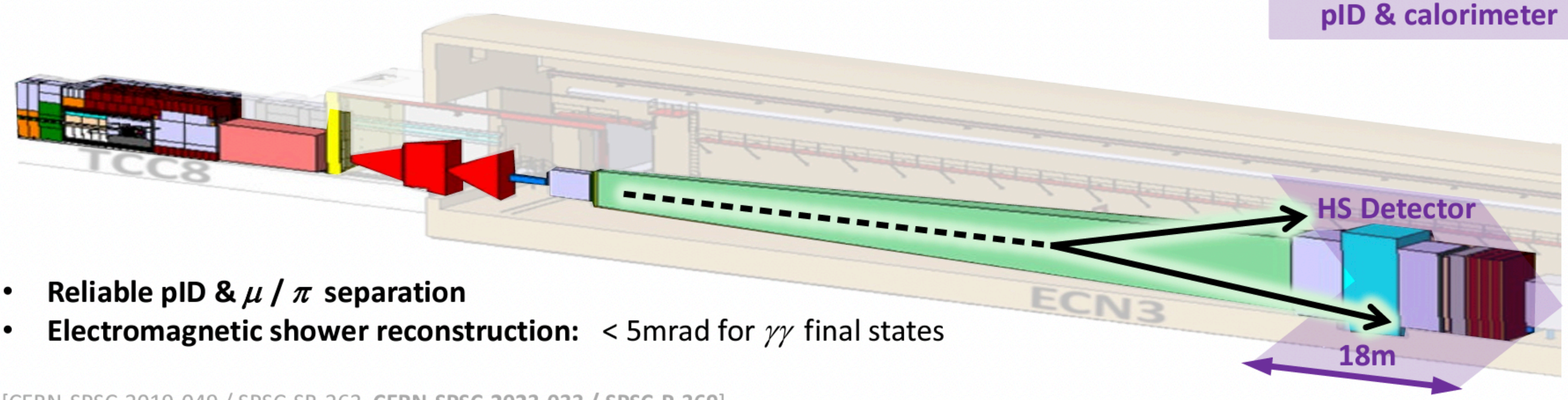
▶ **Timestamp** for SST
▶ **ToF identification** of particle decay products



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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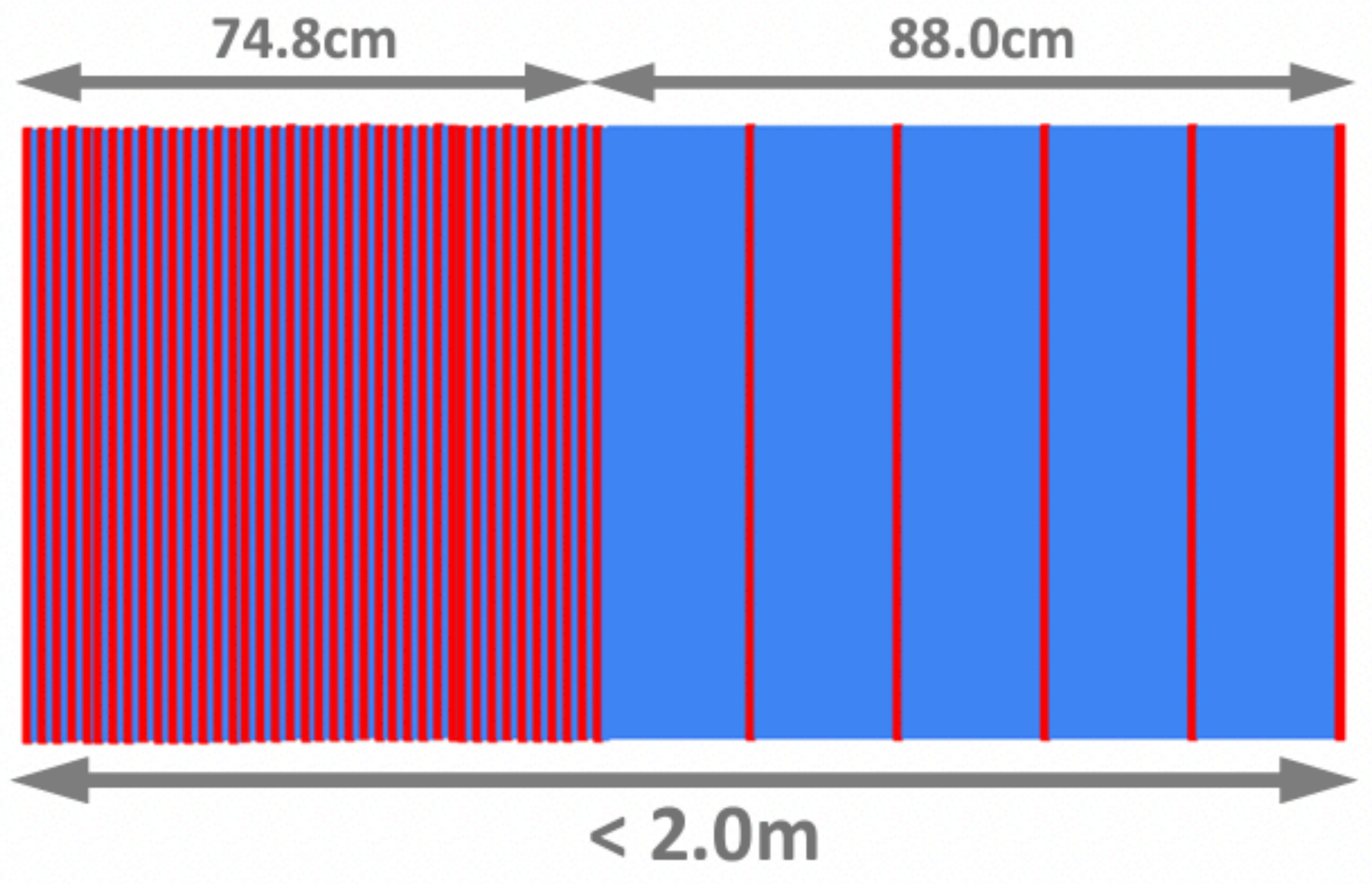


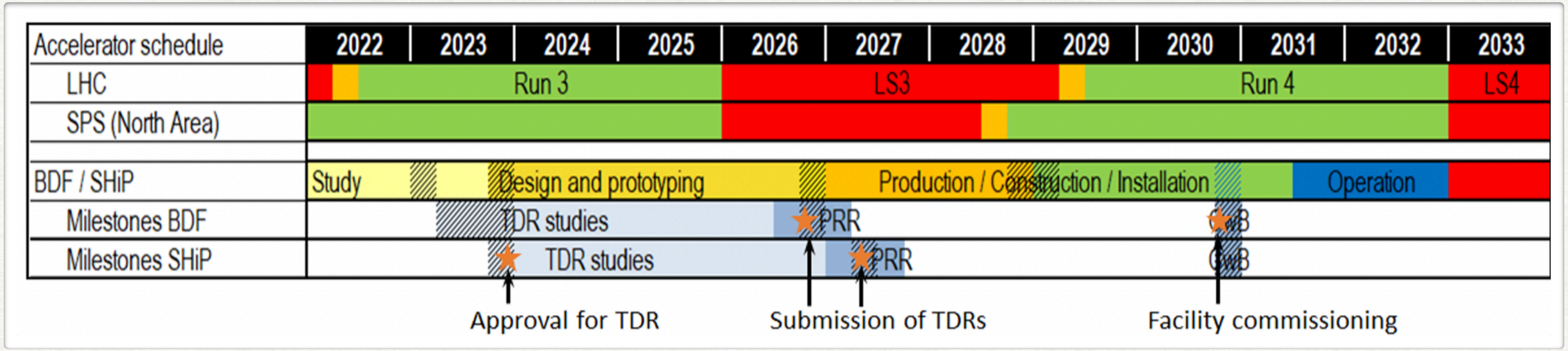
- **Electromagnetic sampling calorimeter (ECal):**
  40 layers of **thin Fe absorbers** (1/20λ each) & **plastic scintillators**
- **Compact hadron sampling calorimeter (HCal):**
  5 layers of **thick Fe absorbers** (1λ each) & **plastic scintillators**

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

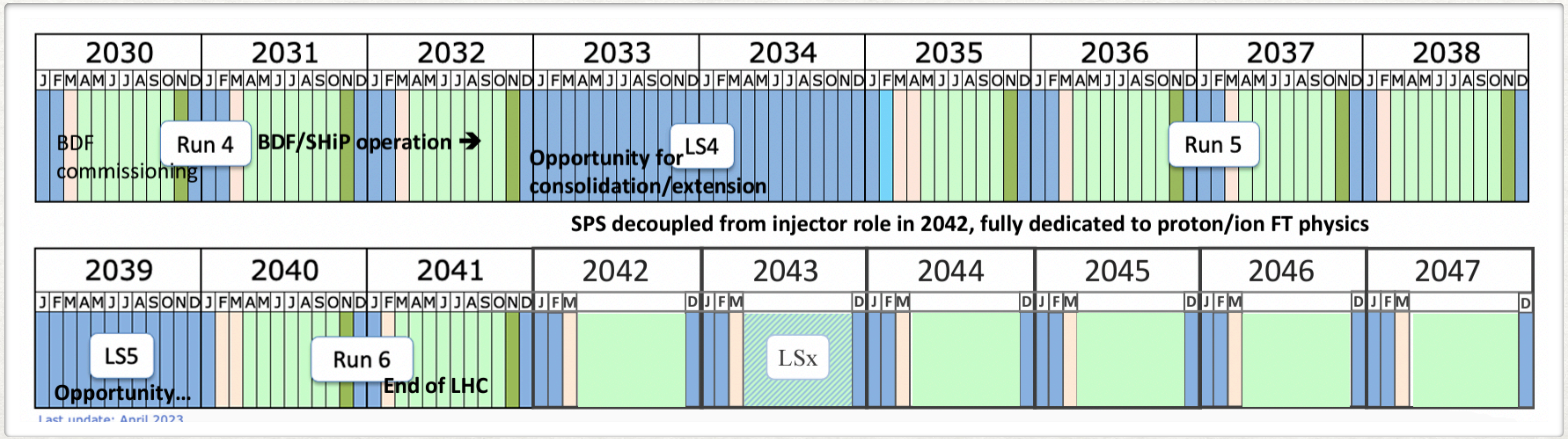
\+ **1 – 3 MicroMeGaS high-precision layers**

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

SHIP TIMELINE



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



IT'S TIME FOR NEUTRINO PHYSICS AT CERN