Status and perspectives of ICARUS at the Fermilab Short Baseline Neutrino program

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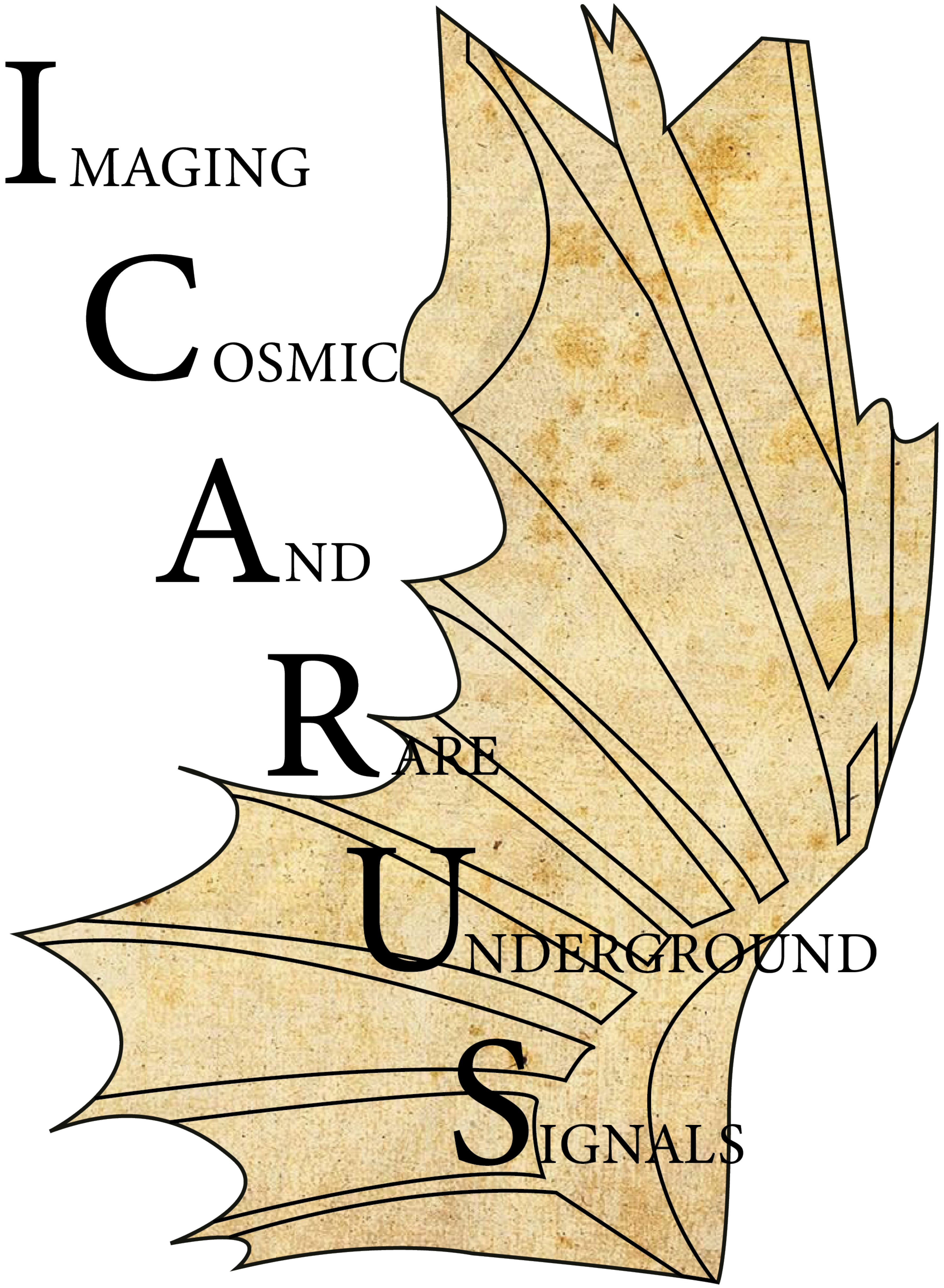
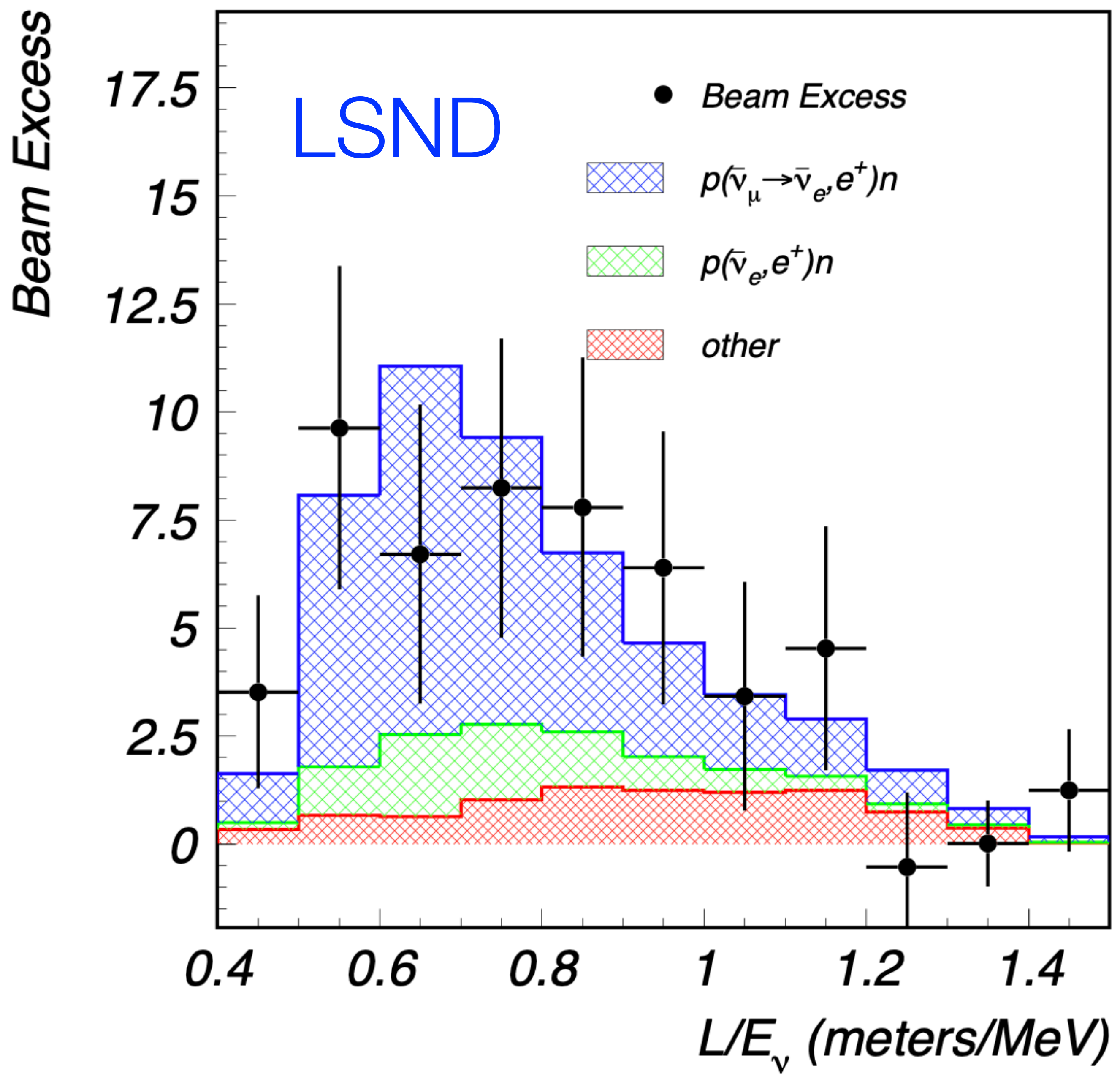
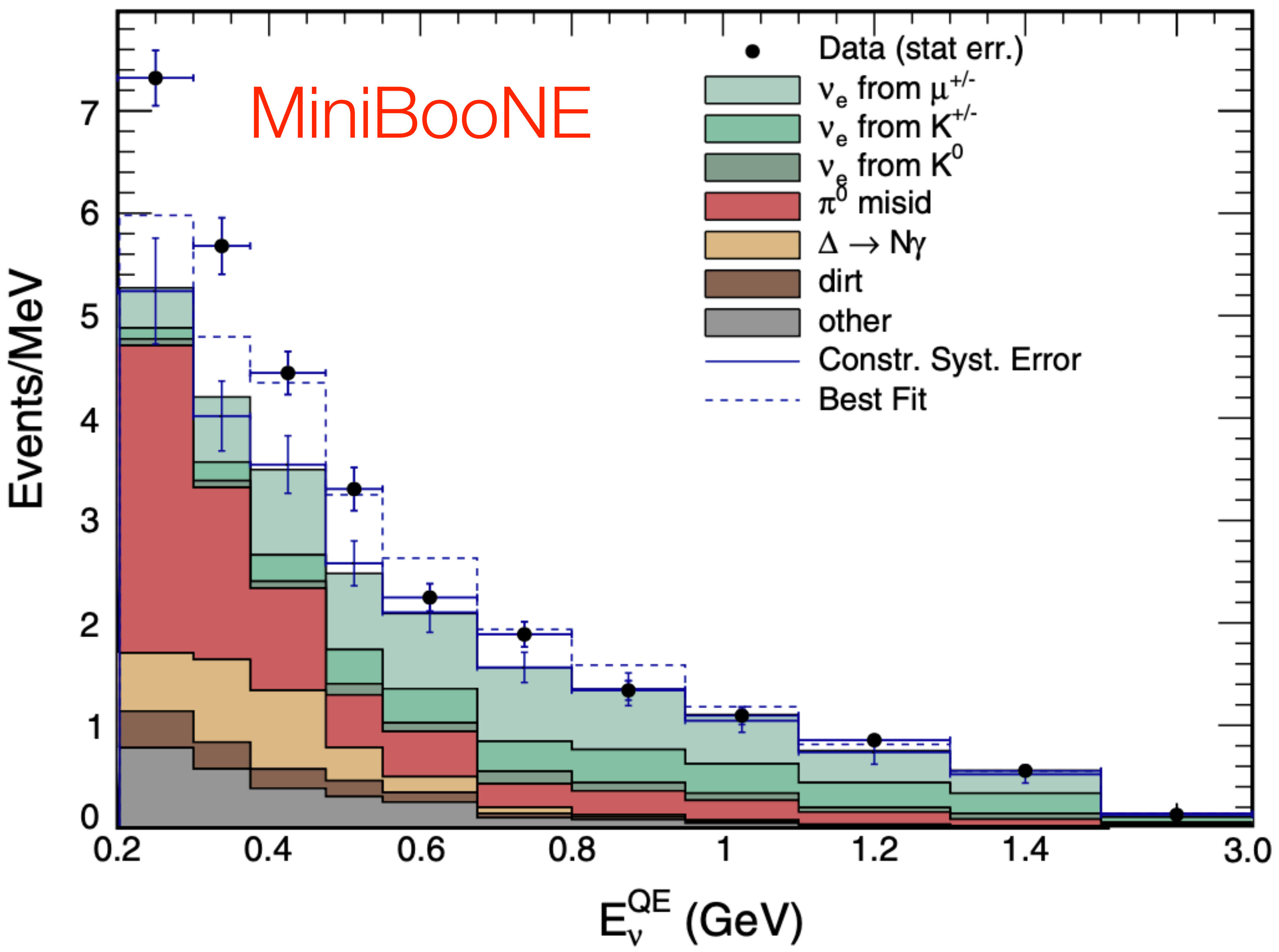
Istituto Nazionale di Fisica Nucleare



Neutrino physics: oscillations and the sterile neutrino puzzle

- **LSND** and **MiniBooNE** reported anomalous signals of ν_e excess at low E: this could imply an additional term $\Delta m^2_{new} \sim 1.0 \text{ eV}^2$ driving $\nu_\mu \rightarrow \nu_e$ oscillations at small distances and pointing towards the possible existence of non-standard heavier sterile neutrino(s)

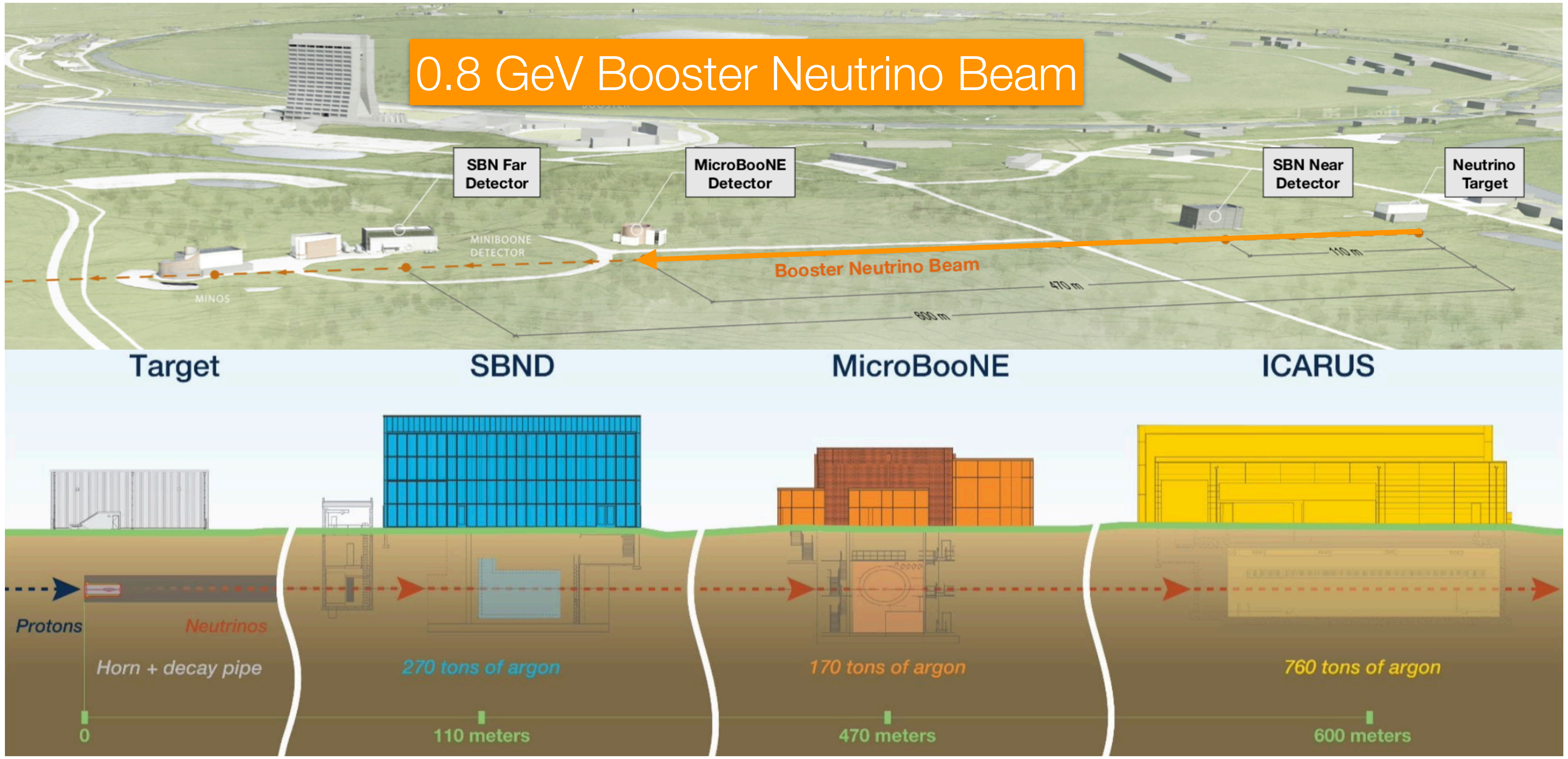




- A clear tension between **appearance** and **disappearance** results is also observed so the possibility to measure both channels with the same experiment is extremely helpful to understand the current physics scenario

Phys. Rev. D 64, 112007 (2001)   Phys. Rev. D 103, 052002 (2021)

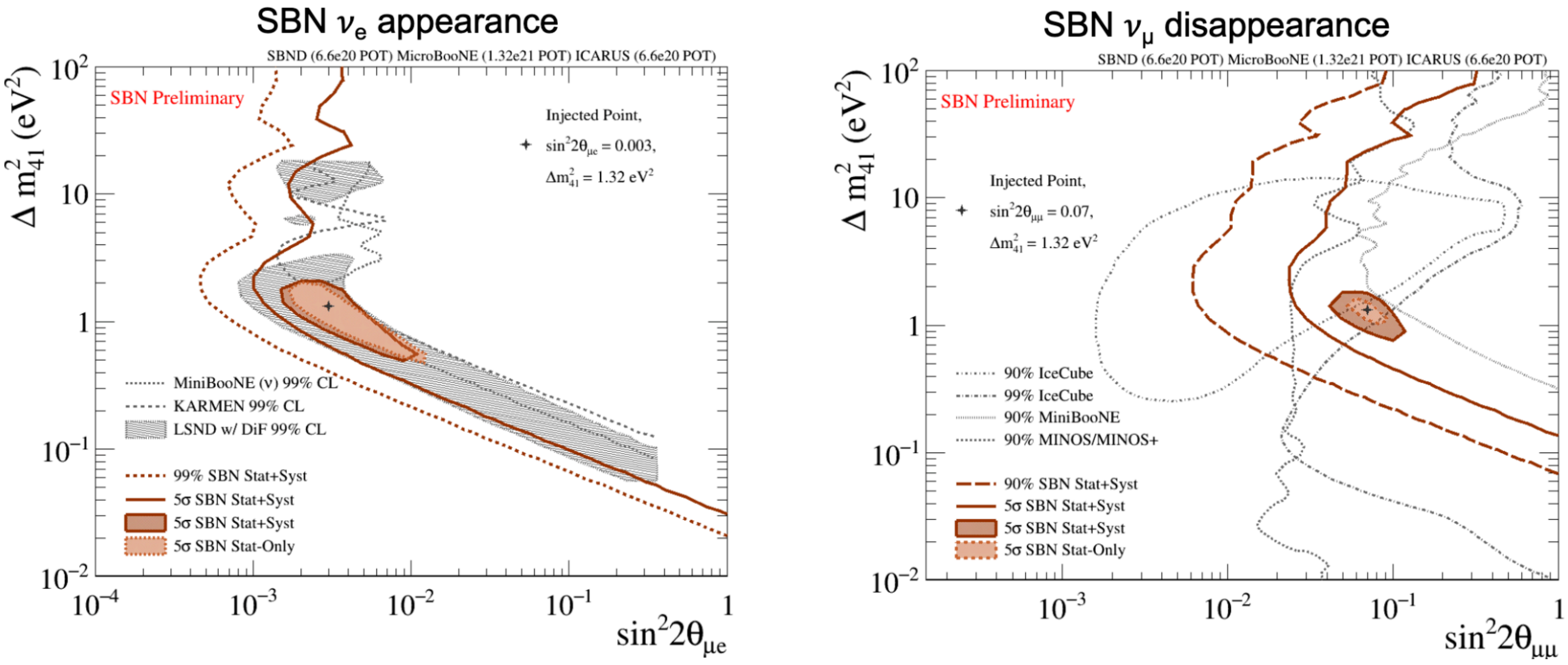
The Short Baseline Neutrino (SBN) physics program



- **SBND** is the **near detector**, whereas **ICARUS** is the **far** detector: using the same detector technology will greatly reduce systematics - **BNB** beam, ICARUS is also exposed to **NuMI** beam (6 degrees off-axis)

- The main goal is a precision search for **1 eV mass scale sterile ν** to confirm/rule out previous anomalies from past experiments
- Sensitive searches for ν_μ **disappearance** and ν_e **appearance** channels
- High statistics measurements of **ν-Argon cross sections** relevant for DUNE
- Search for Beyond Standard Model (**BSM**) **physics**

The Short Baseline Neutrino (SBN) physics program

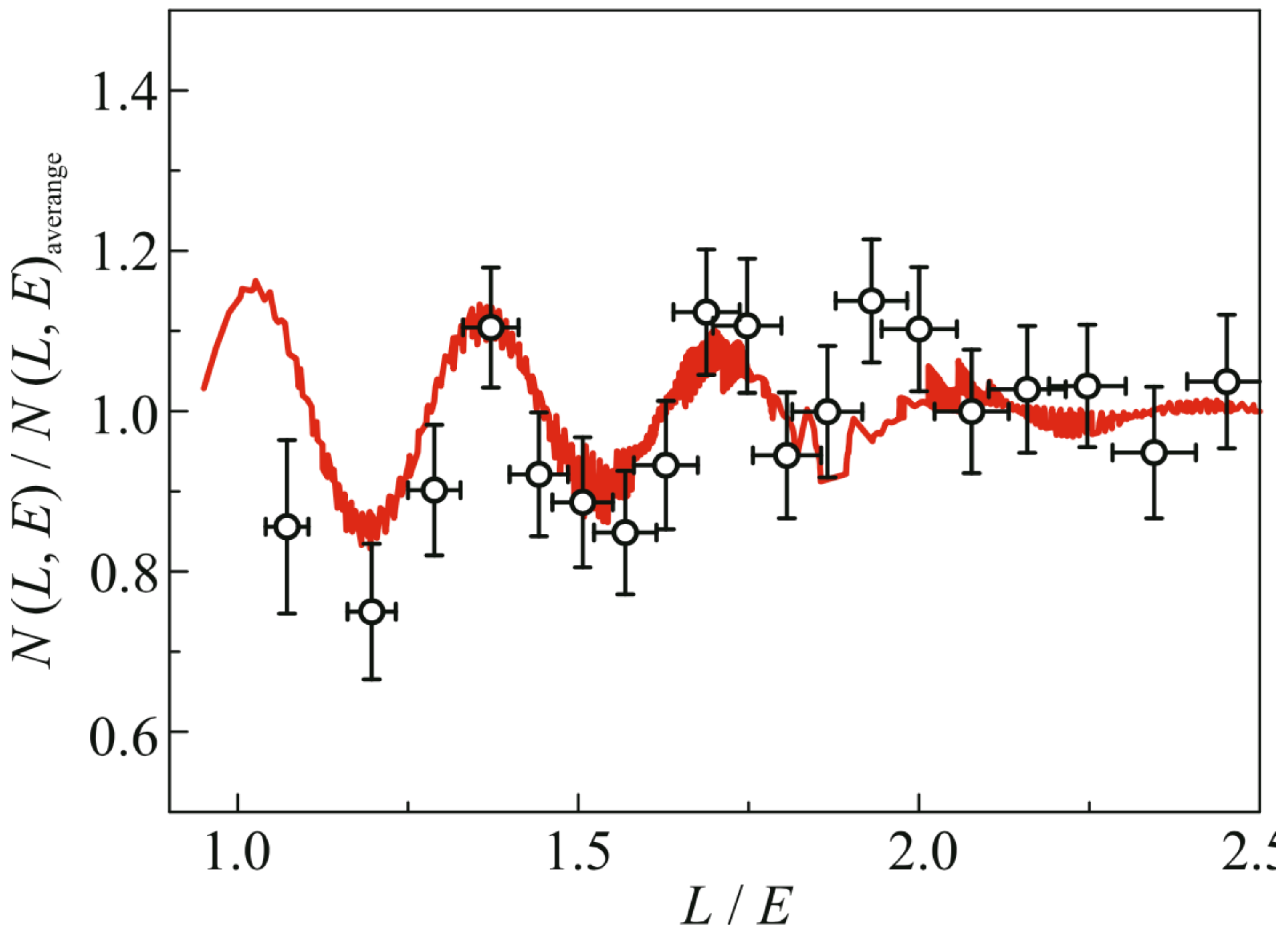


The combined analysis of near and far detector will allow a sensitive search with 5σ sensitivity in both appearance and disappearance channels in 3 years of data taking

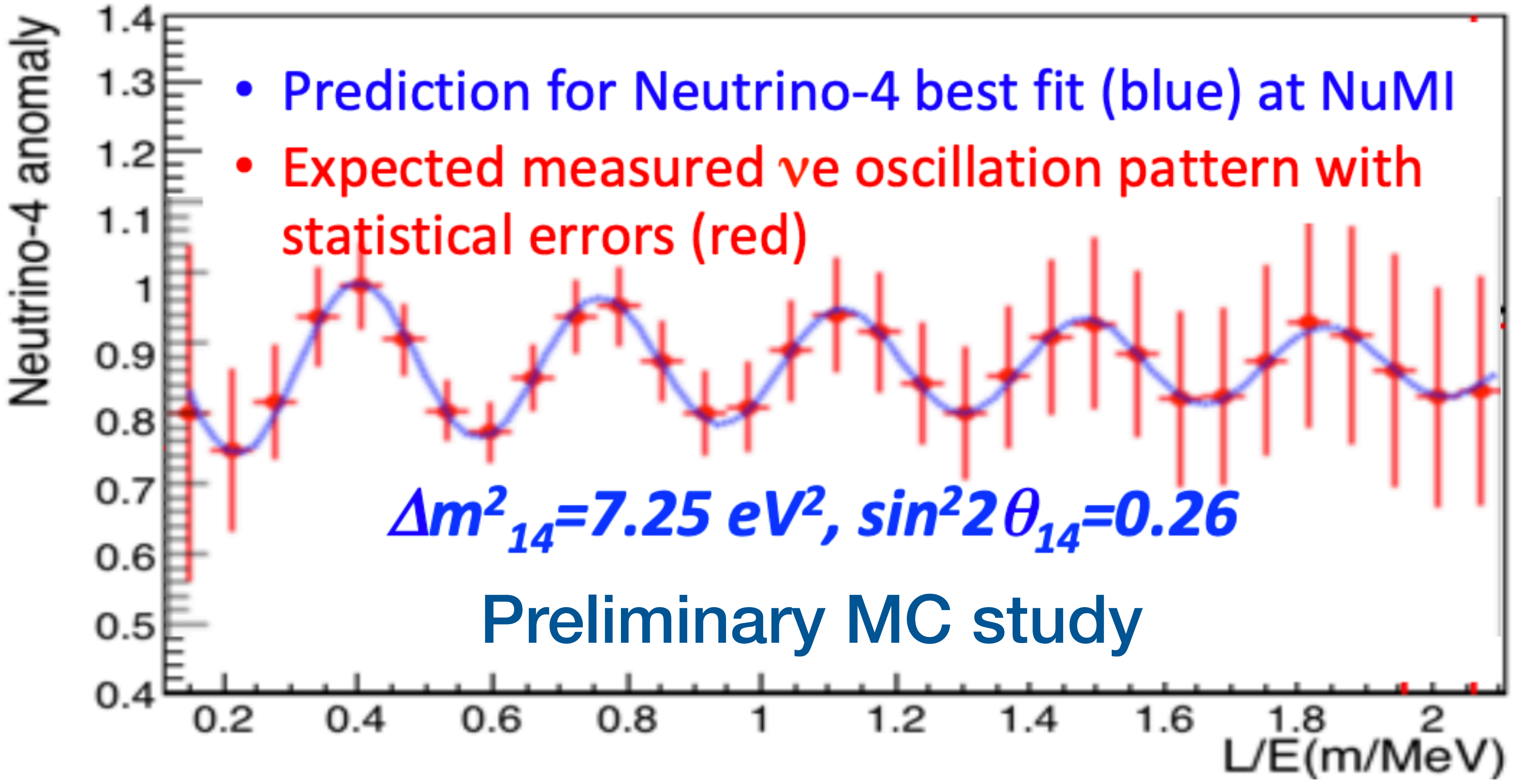
Ann.Rev.Nucl.Part.Sci. 69 363-387 (2019)

Testing Neutrino-4 claim with ICARUS

- **Neutrino-4** collaboration recently reported a possible hint of an oscillatory signature with parameters $\Delta m^2 \sim 7.3\ \mathrm{eV}^2$ and $\sin^2(2\theta) \sim 0.36$ Jetp Lett. 116, 669–682 (2022)



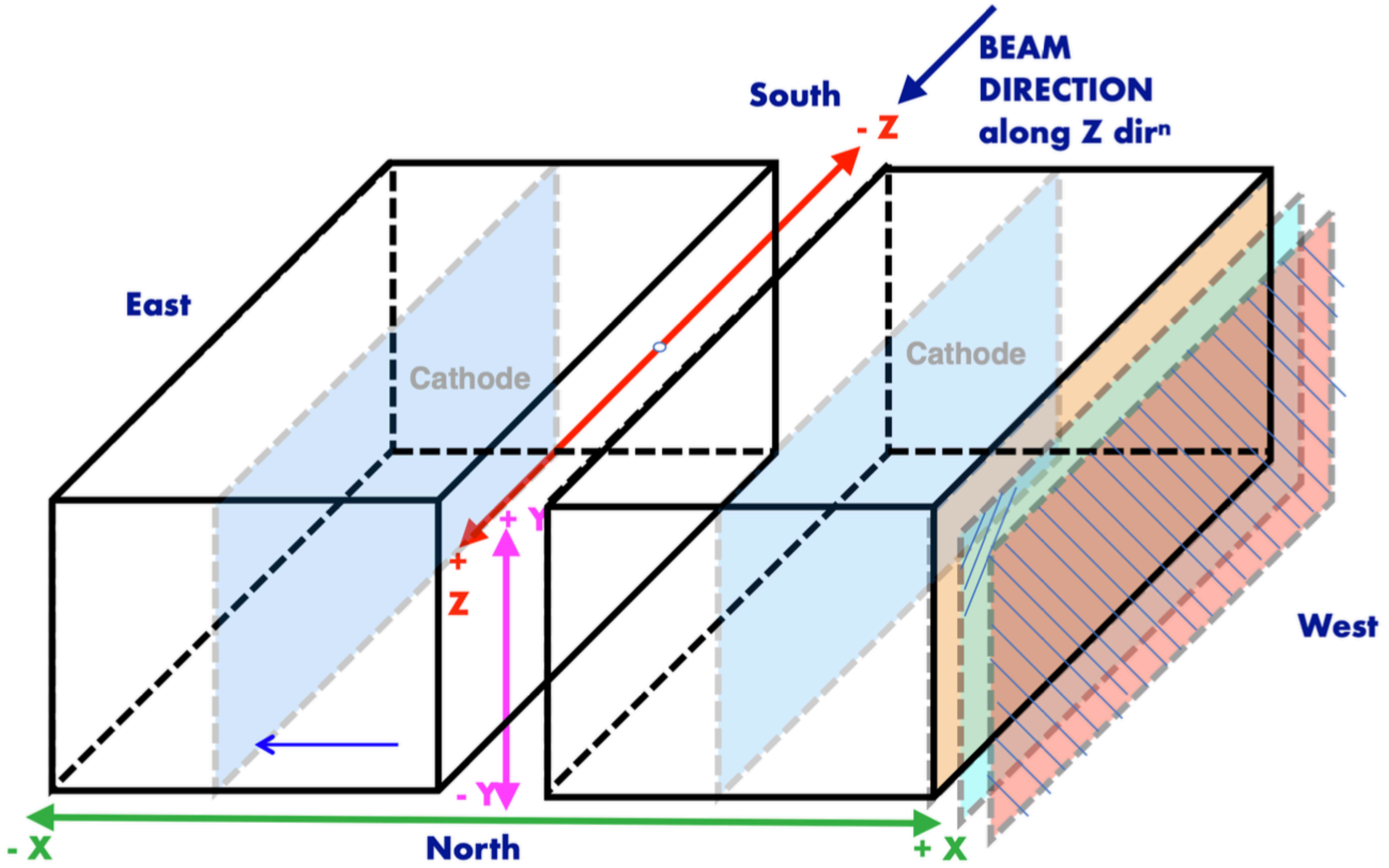
- **NuMI ν_e disappearance** is a relevant channel where **ICARUS** could test this claim since it works in the same L/E range of 1-3 m/MeV with 100 times higher E but L large and constant



- We expect to have **~5200 QE events** with an electromagnetic shower contained in **1 year of data taking** ($6 \cdot 10^{20}$ POT) from Monte Carlo simulations

ICARUS detector in a nutshell

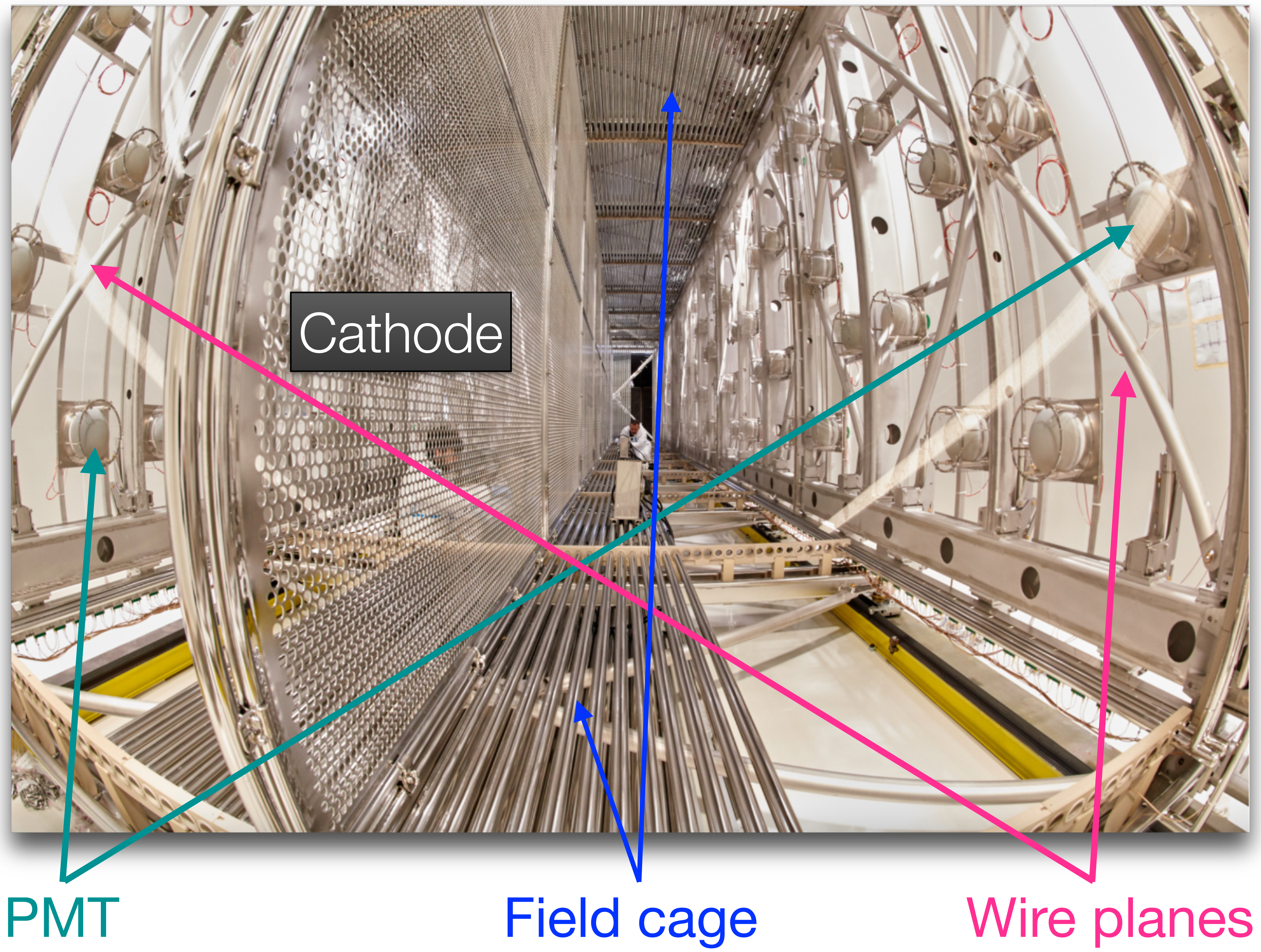
- Liquid Argon Time Projection Chambers (**LAr-TPCs**) proposed by C. Rubbia in 1977 are high granularity, continuously sensitive, self-triggering detectors with 3D imaging and calorimetric reconstruction capabilities, ideal for ν interaction studies in a wide energy range
- ICARUS T600 is **the first large scale LAr-TPC**: two identical cryostats (3.6 x 3.9 x 19.6 m^3) housing two TPC each, 760 tons of ultra pure liquid argon for a total active mass of 470 tons



- $E_{drift} = 500$ V/cm gives $t_{drift} \sim$1 ms, $v_{drift} \sim$1.6 mm/μs
- Ionization charge is read by **3 wire planes** with different orientation: Induction1 (0°), Induction 2 (+60°) and Collection (-60°), 53248 wires in total
- **360 PMTs** coated with TPB located behind the wires to collect scintillation light and provide t_0 timing and detector trigger

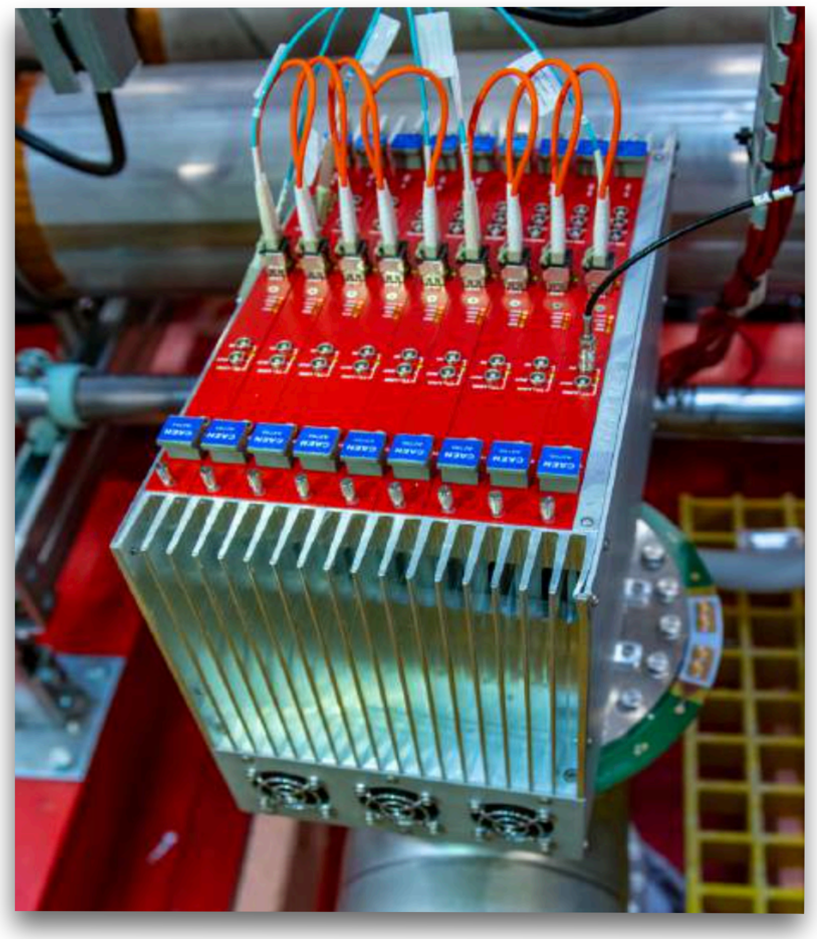
ICARUS detector from LNGS to FNAL

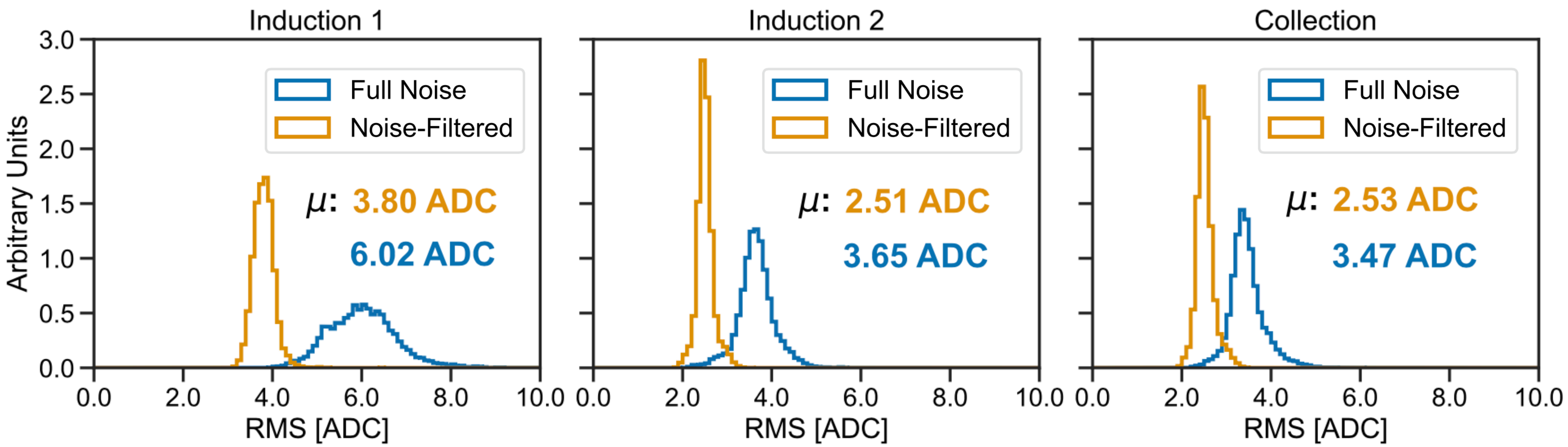
- After the first operations at LNGS an **intensive overhauling at CERN** was made before shipping the detector to Fermilab to upgrade
  - the cryogenics,
  - the LAr purification system,
  - the TPC readout electronics,
  - the light collection system.

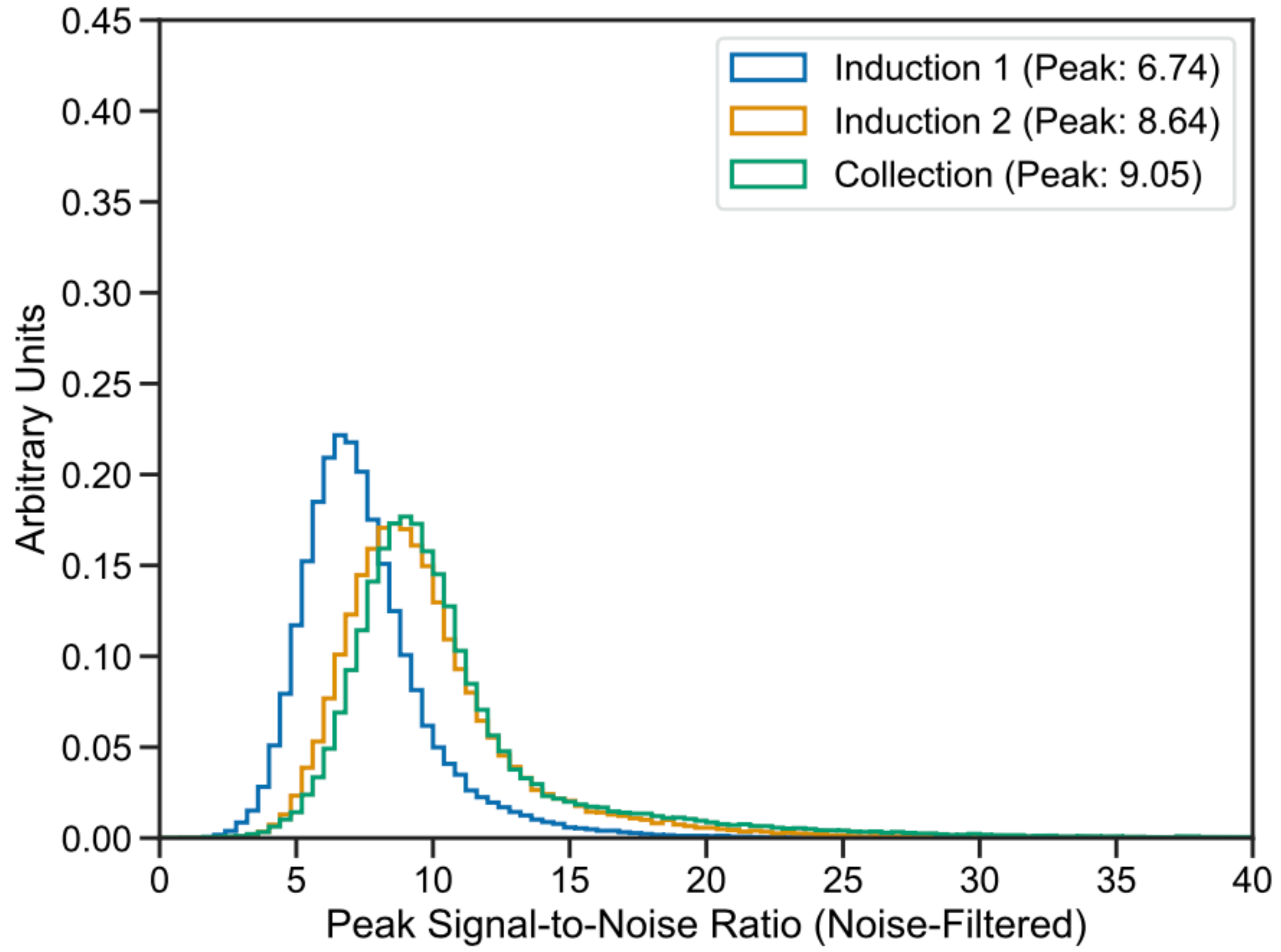


The TPC and upgrades of the electronics readout

- New, higher performance TPC readout electronics compliant with **higher data rates** at shallow depths at FNAL compared to LNGS
- Same modularity/architecture, but integration on a special custom crate: more **compact layout** with analog & digital components in the same board
- Anomalous coherent **noise** inside the 64 channels board found upon detector activation attributed to the ancillary cryogenics instrumentation reduced after several interventions   Eur. Phys. J. C 83:467 (2023)

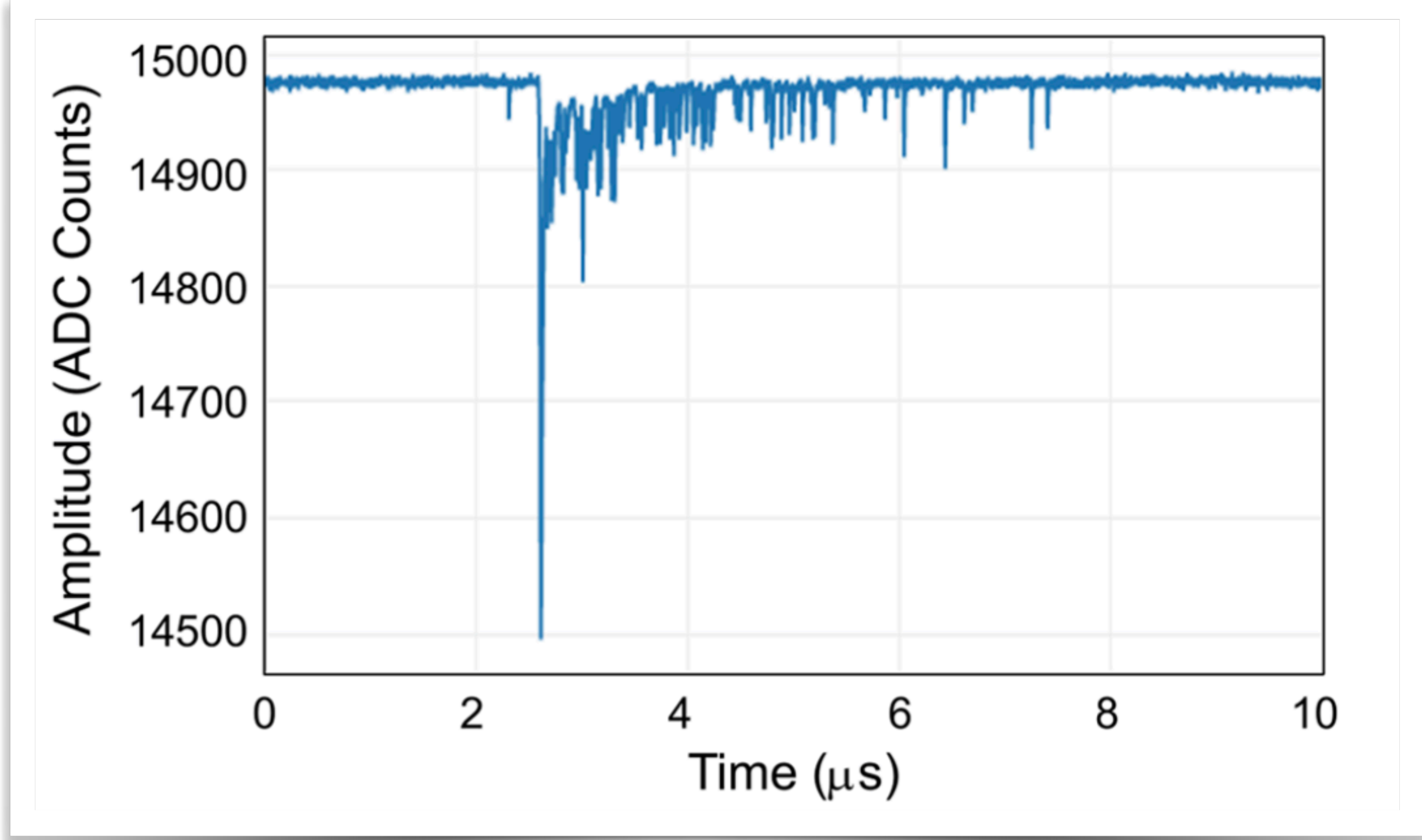






The light collection system

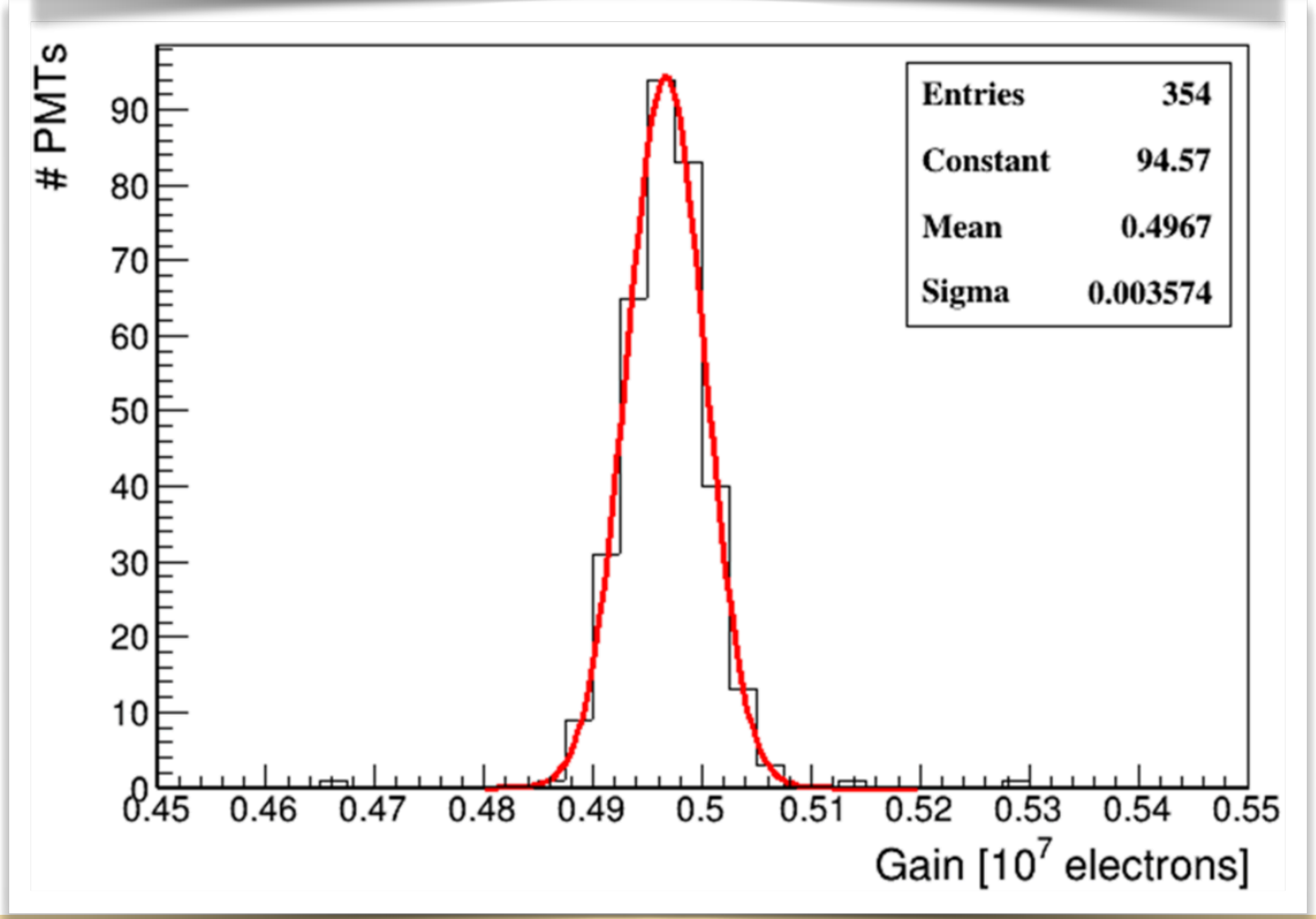
- Fundamental contribution to **cosmic rays background rejection** since ICARUS is currently operated at shallow depths
- It consists of 360 8” Hammamatsu **PMTs** coated with TPB, 90 per plane installed behind the TPC wire planes



- **PMT gains** calibrated with laser ($\lambda \sim 405$ nm) and equalized to $G = 5 \cdot 10^6$ with spread <1%
- **Trigger logic** based on PMTs signal in a limited TPC region

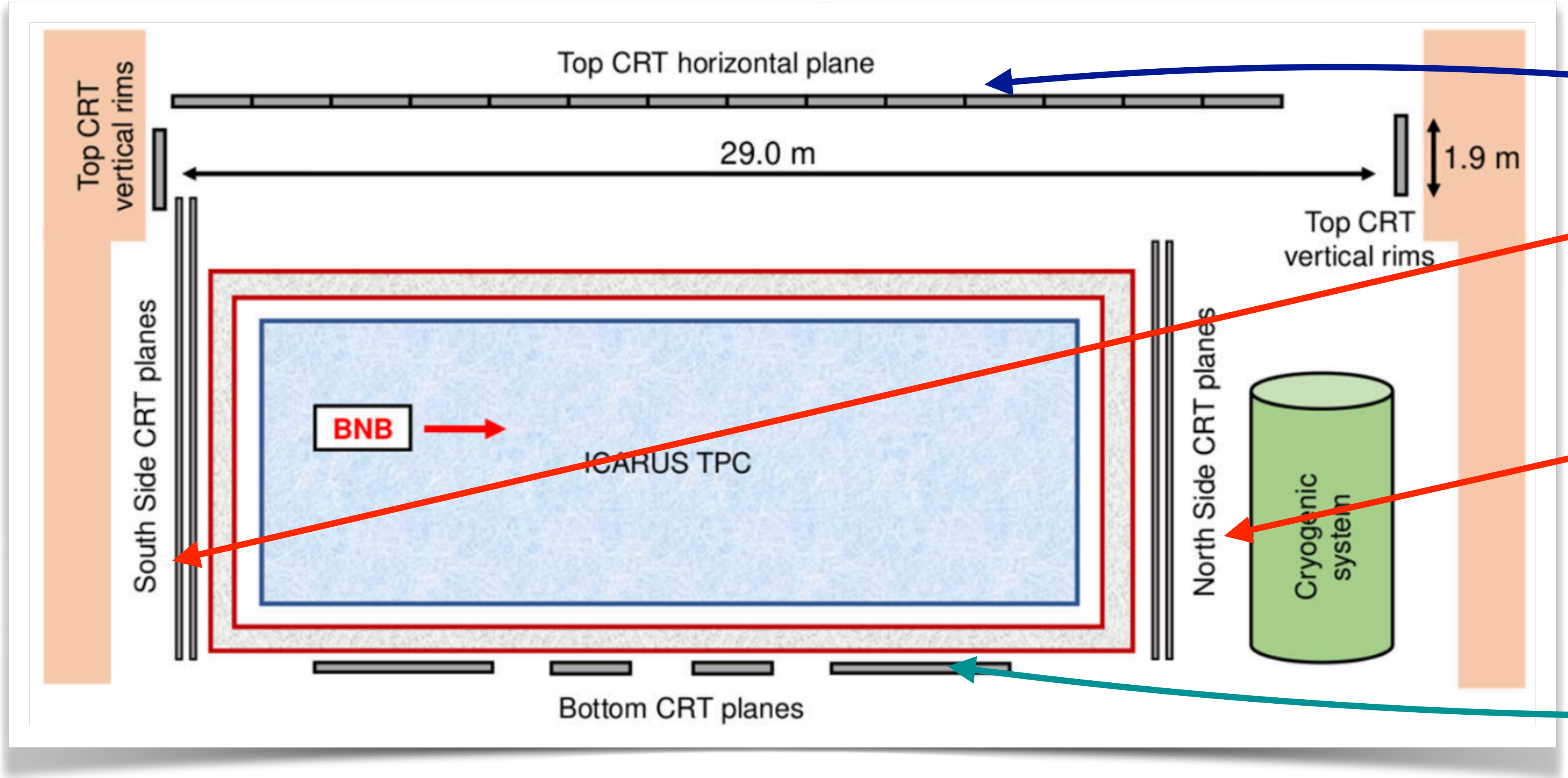
Further details in

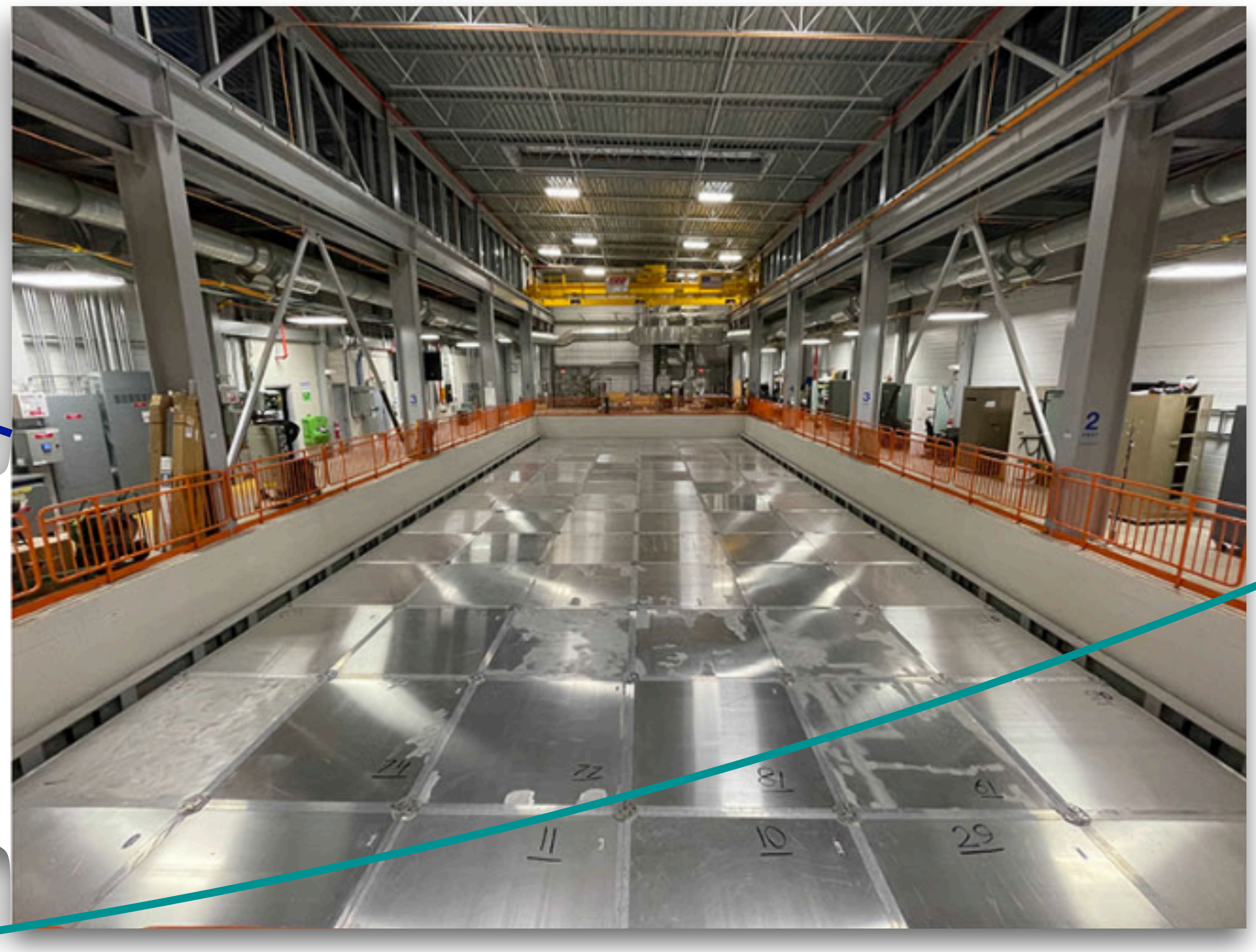
[Eur. Phys. J. C 83:467 (2023)]



The CRT for cosmic rays background mitigation

- More challenging experimental conditions compared to LNGS require countermeasures to identify ν interactions amongst **11 kHz of cosmic rays:**
  - 2.85 m (6 m w.e.) **concrete overburden** on top of CRT to remove charged hadrons and γs
  - We have **11 μ tracks** per triggering event in 1 ms TPC drift time, their γs are a background for ν_e since e^- from Compton/pair production can mimic ν_eCC events: an external 4π Cosmic Ray Tagger (CRT) to identify muons passing through cryostats helps us distinguishing externally originated interactions



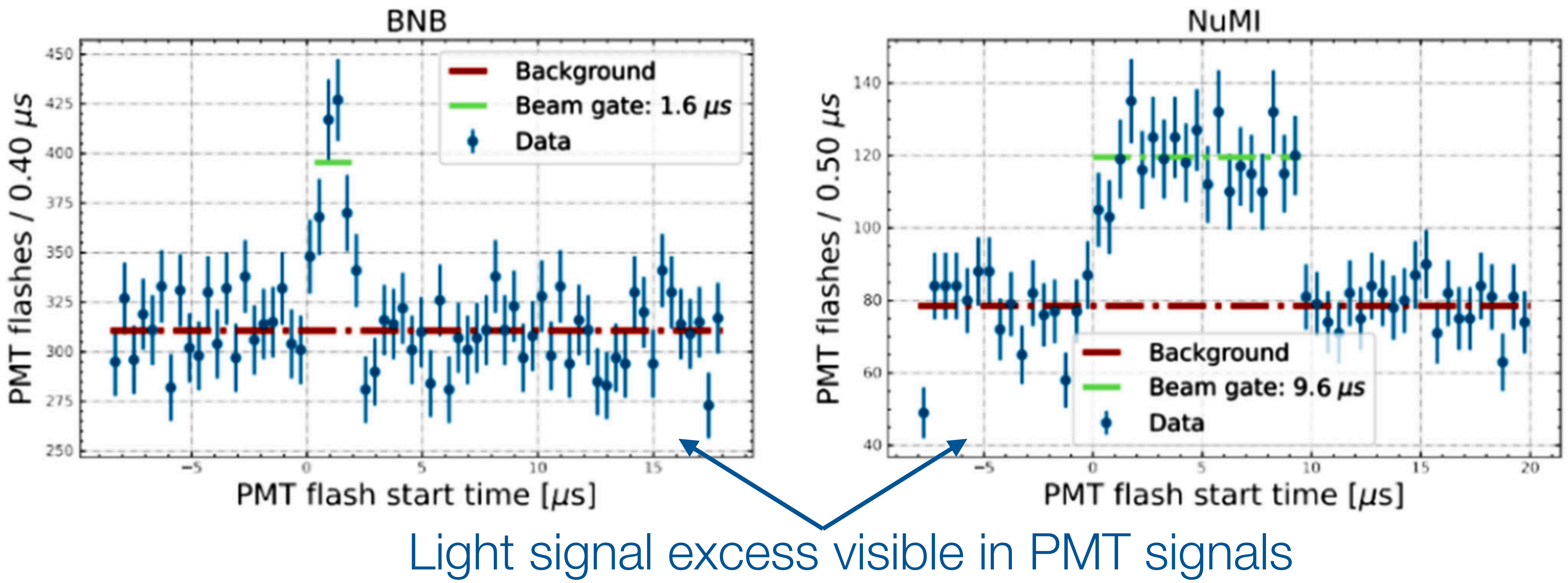


Additional Bottom CRT (modules from Double Chooz)

Side CRT (scintillation panels from MINOS) Top CRT

ICARUS trigger system

- Main trigger signal generated by the presence of light signals from PMT **in coincidence** with BNB (1.6 μs) and NuMI (9.5 μs) **beam spill gates**
- For every global trigger **light** and **CRT activity** within 2 ms are recorded to tag **cosmic rays** crossing ICARUS during the 1ms e^- drift time
- **Additional trigger signals** are generated in correspondance with beam spills w/o any request on the light and outside of the beam spills to the detect CR interactions for **calibration** and **background** studies for the ν oscillation searches



- 1.5 ms (30 μs) **acquistion window** for the TPC (PMT) signals
- **Trigger rate** is ~0.7 Hz (0.3, 0.15 and 0.25 Hz for BNB, NuMI and off beam respectively)
- **Trigger efficiency** is now under investigation on data

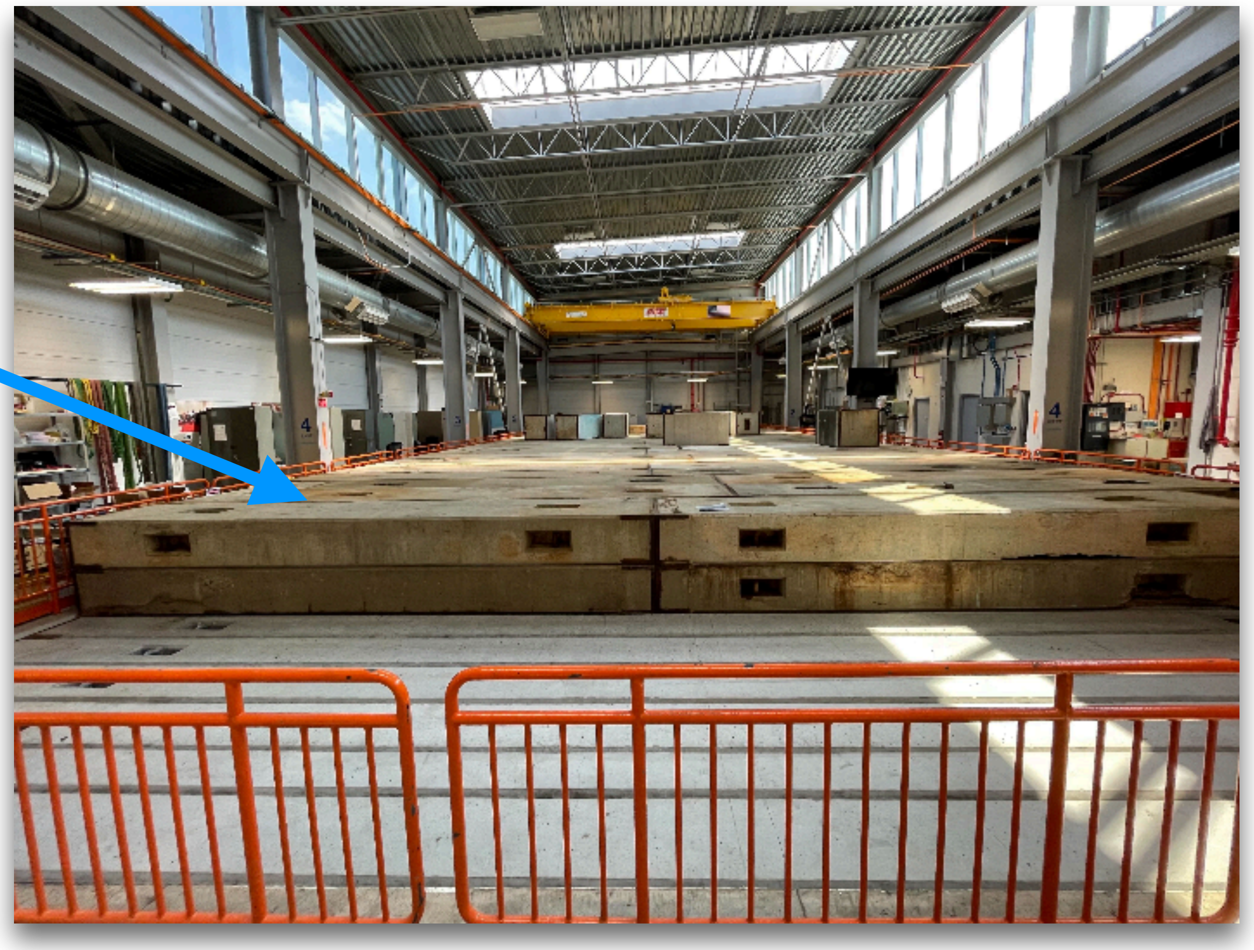
ICARUS detector evolution during commissioning

September 2020

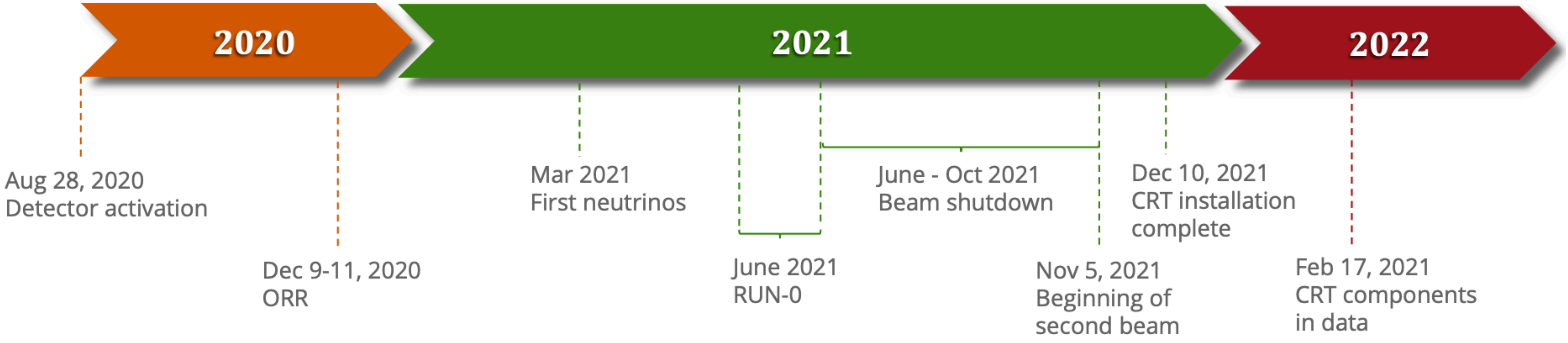
December 2021

Top CRT panels were mounted

May 2022

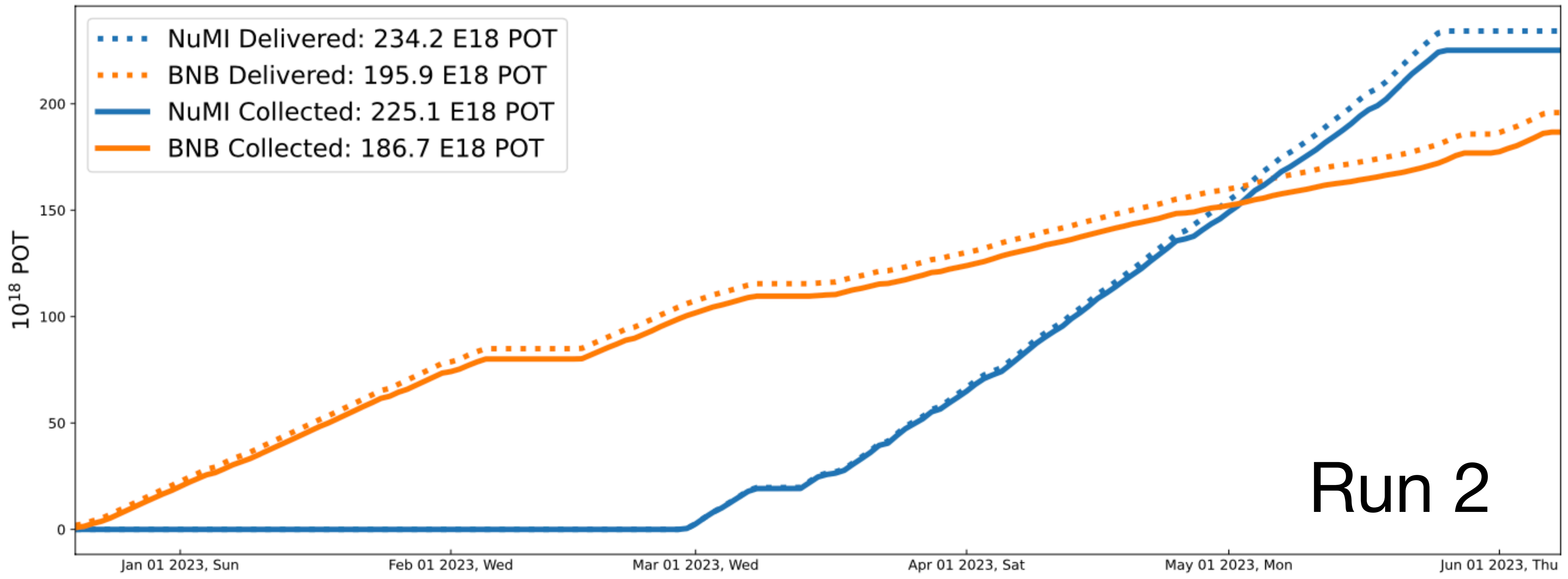


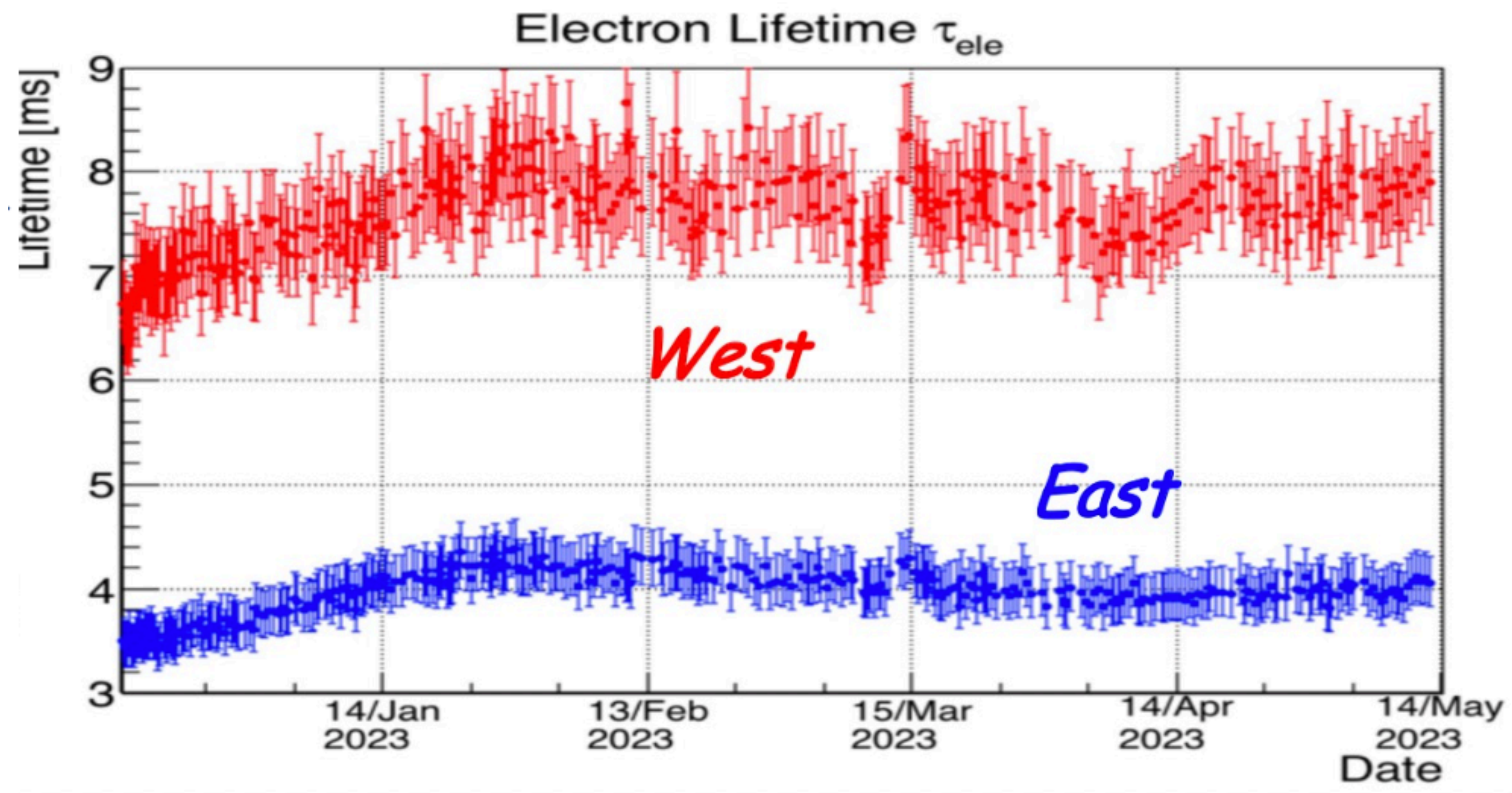
Overburden installation was completed



Data taking and overall detector performance

- First data set in parallel with commissioning activities: **data taking** started in **March 2021**, data collection devoted to **physics** started in **June 2022** - two physics runs since then
- **Run 1**: June 9 - July 10, 2022
  - $4.1 \cdot 10^{19}$ POT BNB
  - $6.8 \cdot 10^{19}$ POT NuMI
- **Run 2**: December 2022 - present
  - $1.9 \cdot 10^{20}$ POT BNB
  - $2.2 \cdot 10^{20}$ POT NuMI

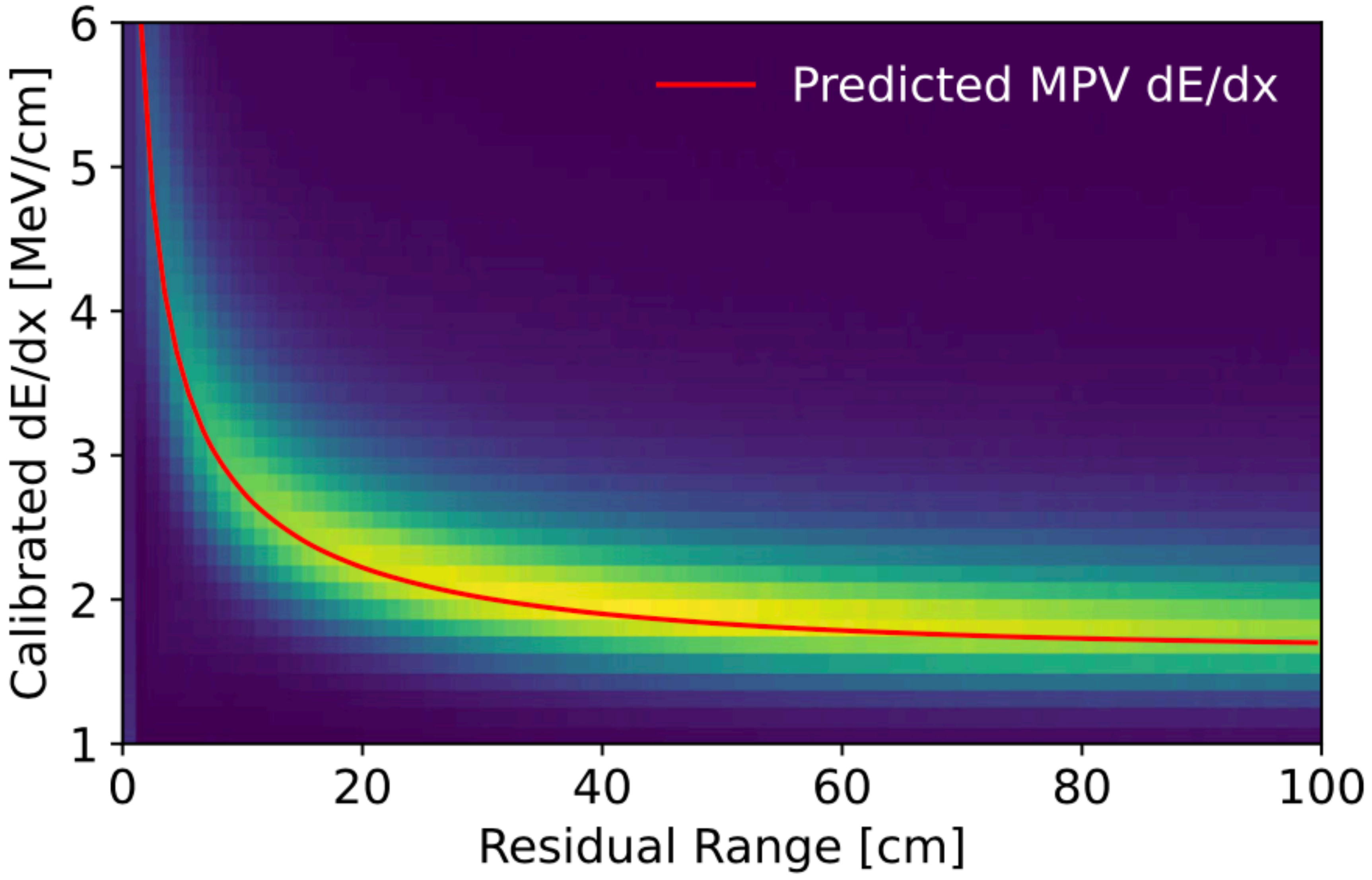




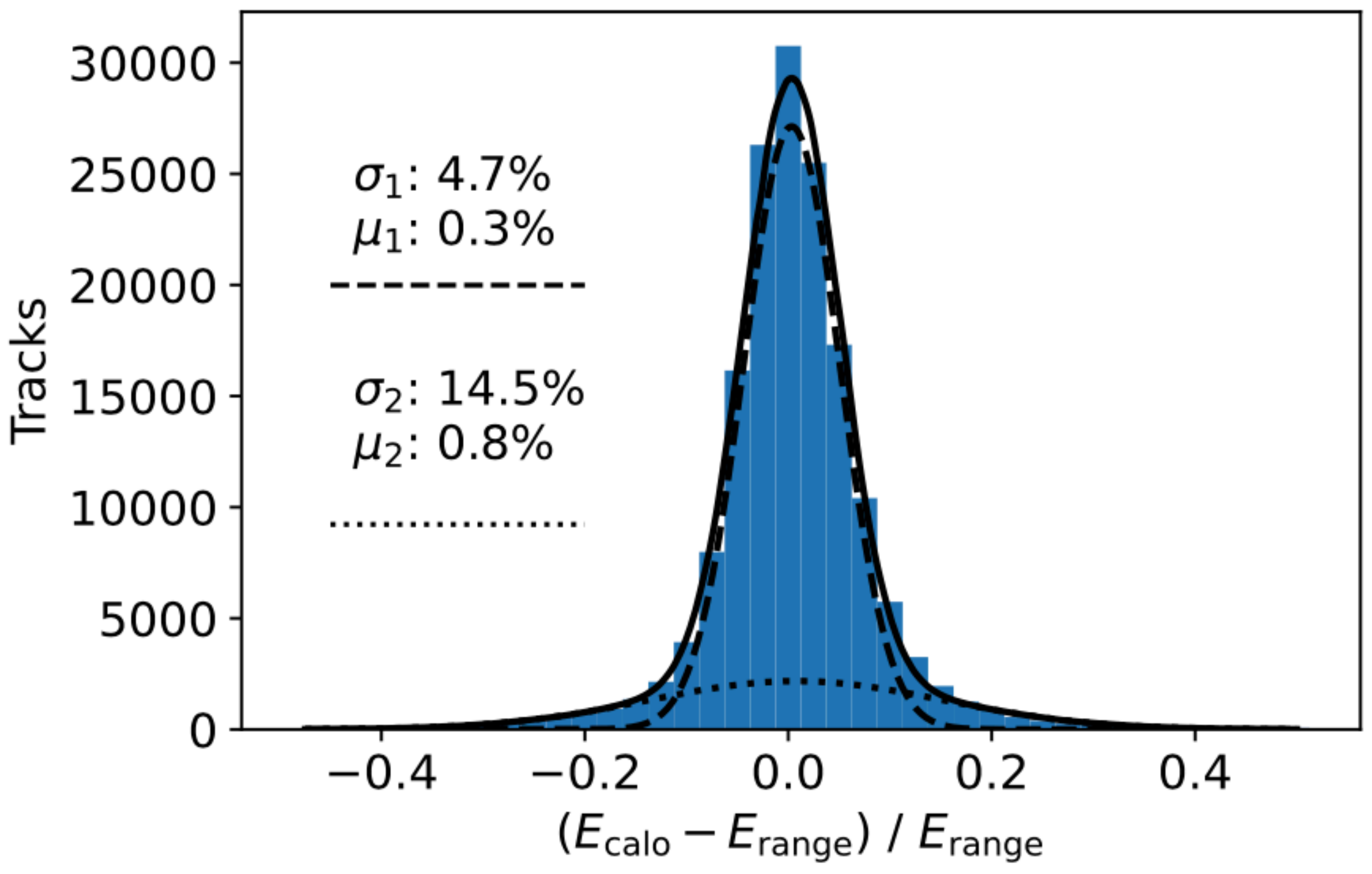
- **Steady data taking** with DAQ uptime ~93%, excellent stability on long runs at BNB rates > 4 Hz
- Liquid argon **purity level** continuously monitored measuring signal attenuation along drift direction of μ tracks: regeneration of the filters for the east cryostat to increase eletron lifetime τ_{ele} and improve uniformity

Detector calibration

- TPC calibration is based on the study of the ionization energy loss per unit length (dE/dx) versus residual range, i.e. distance from the end of the reconstructed TPC track, for cosmic muons (MIP) crossing the cathode and stopping/decaying in the active LAr volume
- Good agreement between calibrated data and predictions (<1% for dE/dx< 4 MeV/cm) for all TPCs



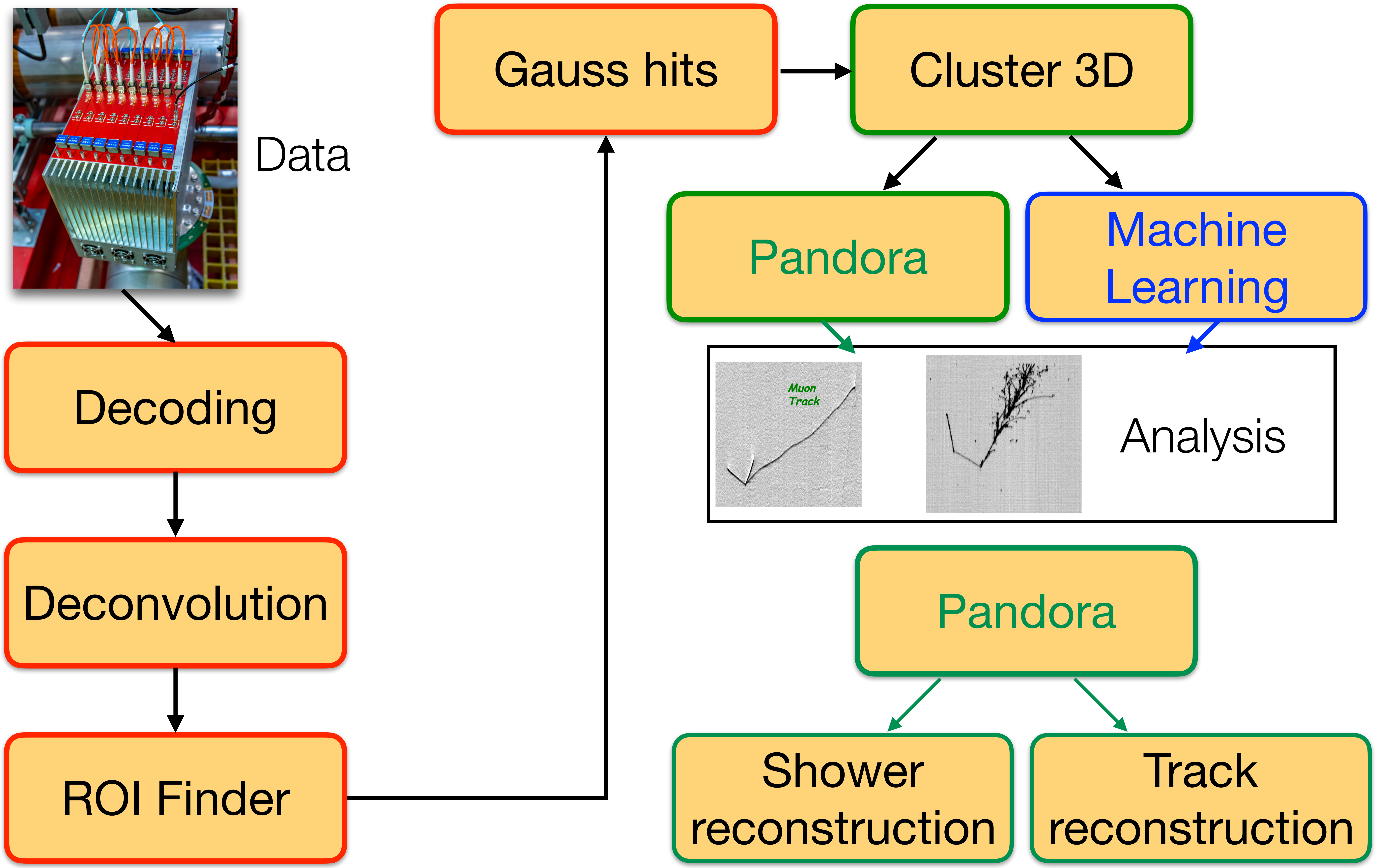
East TPC, West Cryostat - Collection Plane



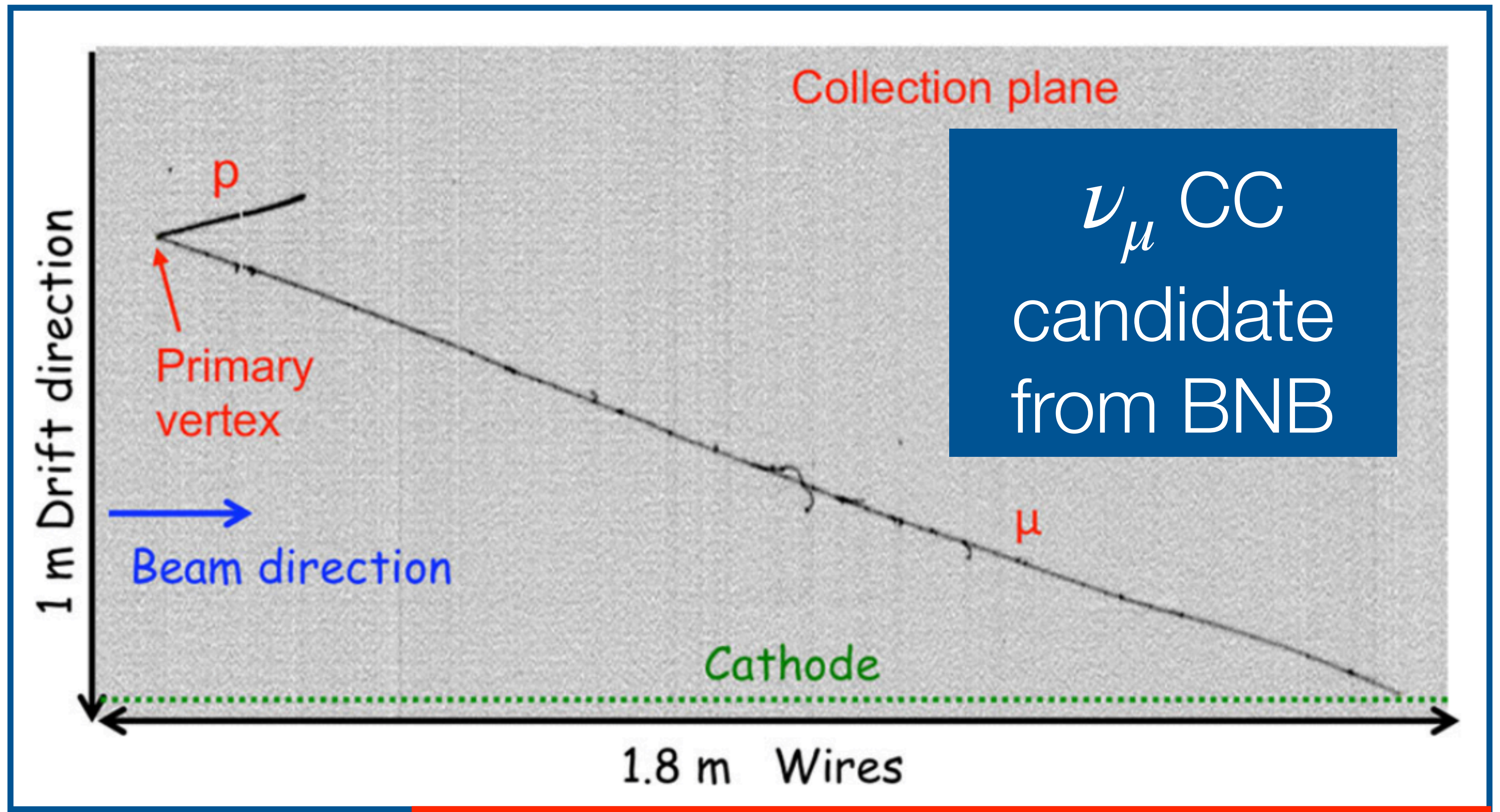
- Ongoing effort to tune TPC signal response to improve data/Monte Carlo agreement and to include the spatial variations observed in detector response to CR muons

Further details in Eur. Phys. J. C 83:467 (2023)

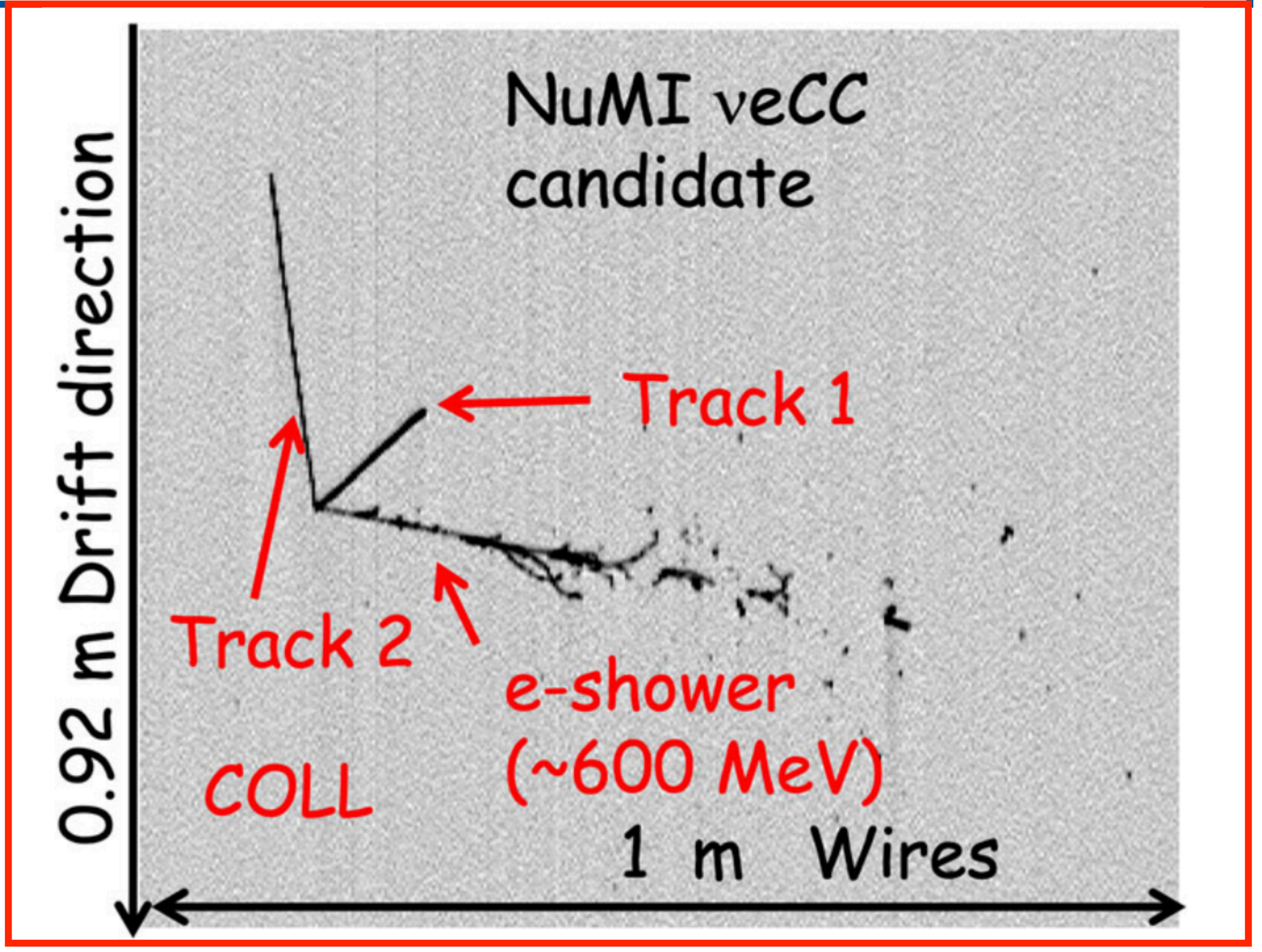
The ICARUS event reconstruction chain



Visual event study and TPC reconstruction performance

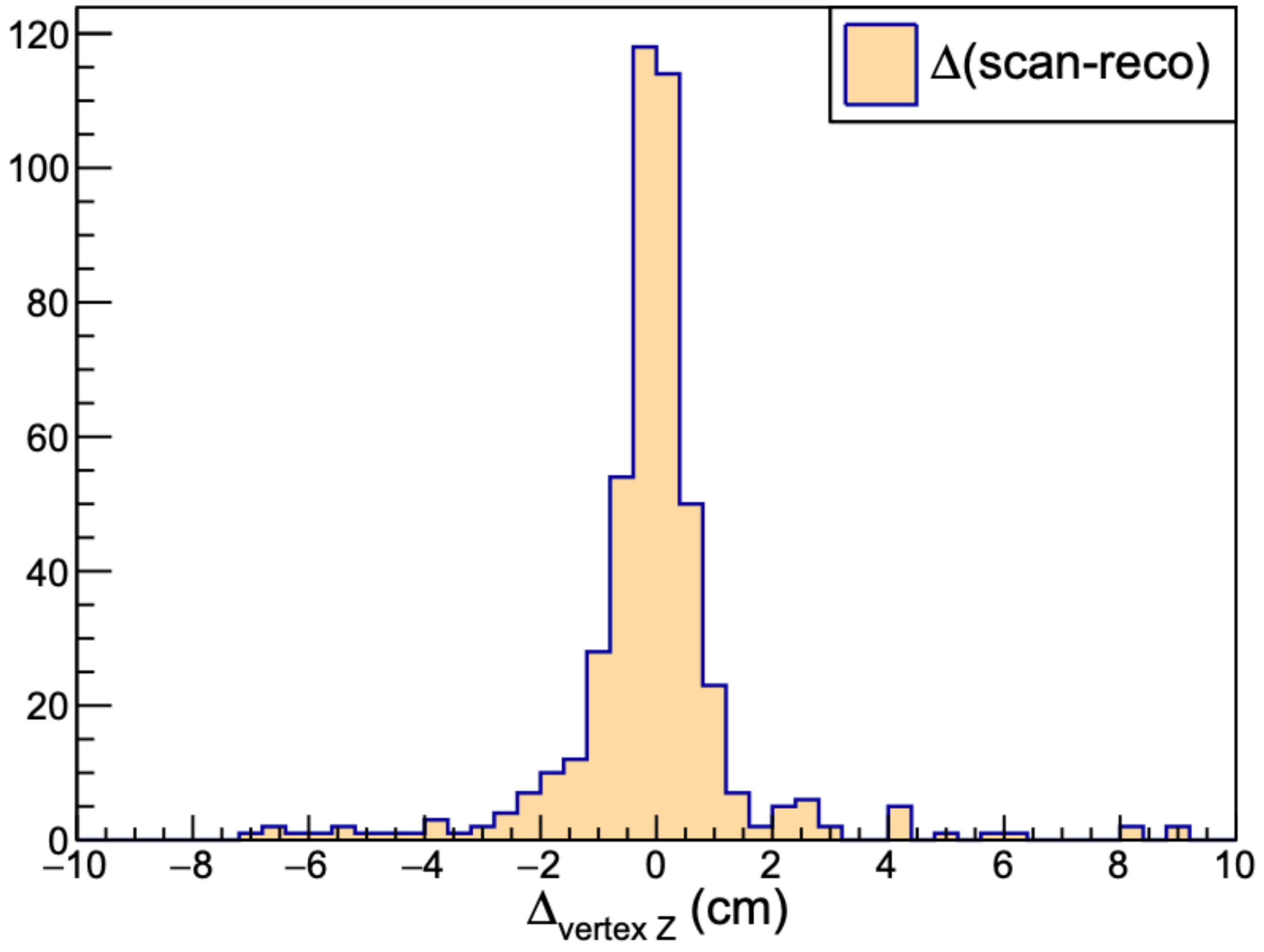


ν_e CC candidate from NuMI



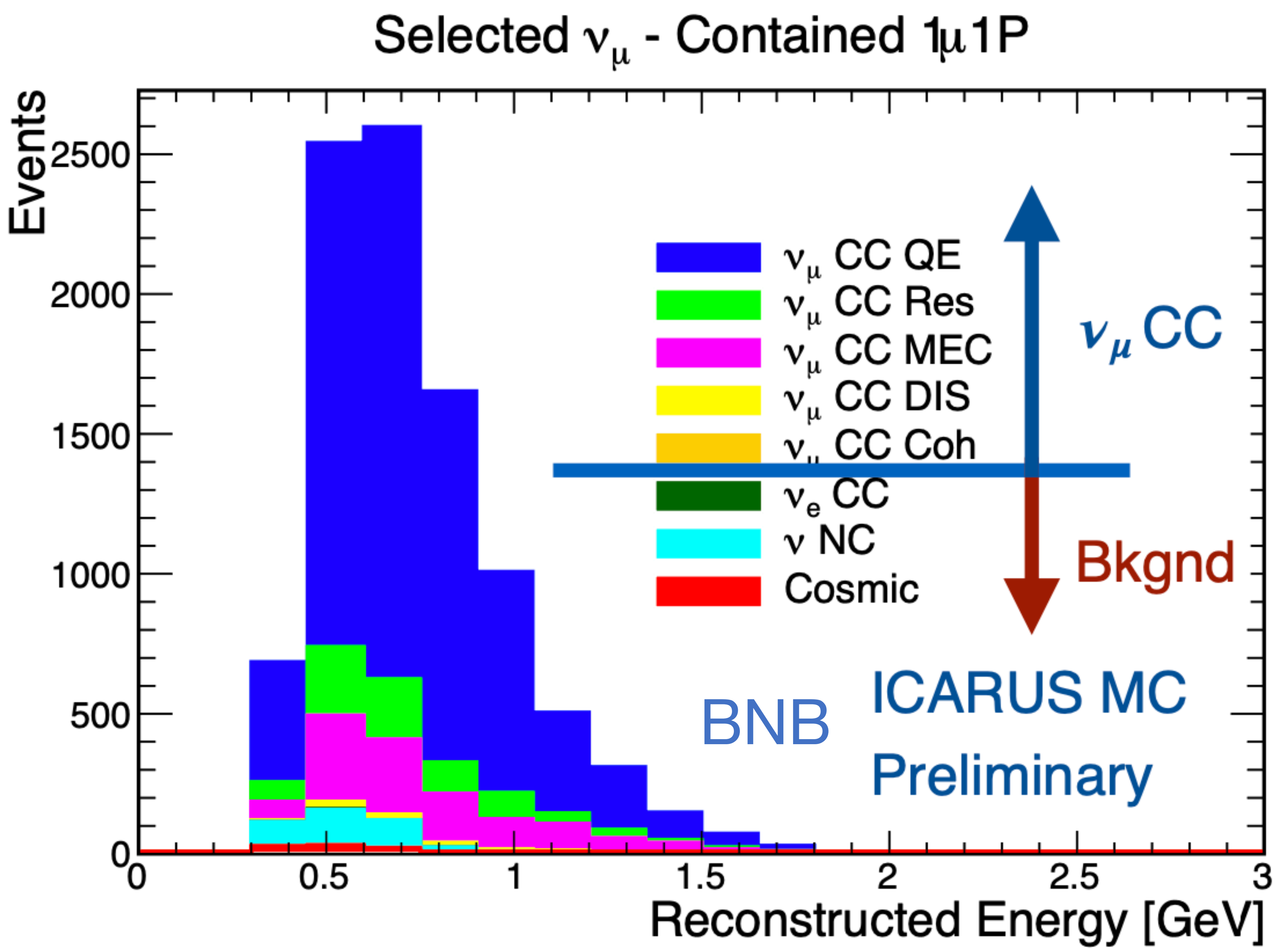
- Standard reconstruction uses **Pandora** (https://github.com/PandoraPFA), a pattern recognition software commonly used in LAr-based detectors
- We employ **visual scan event selection** and **Monte Carlo** simulations to identify pathologies, explore reconstruction improvements and tune our selection algorithms

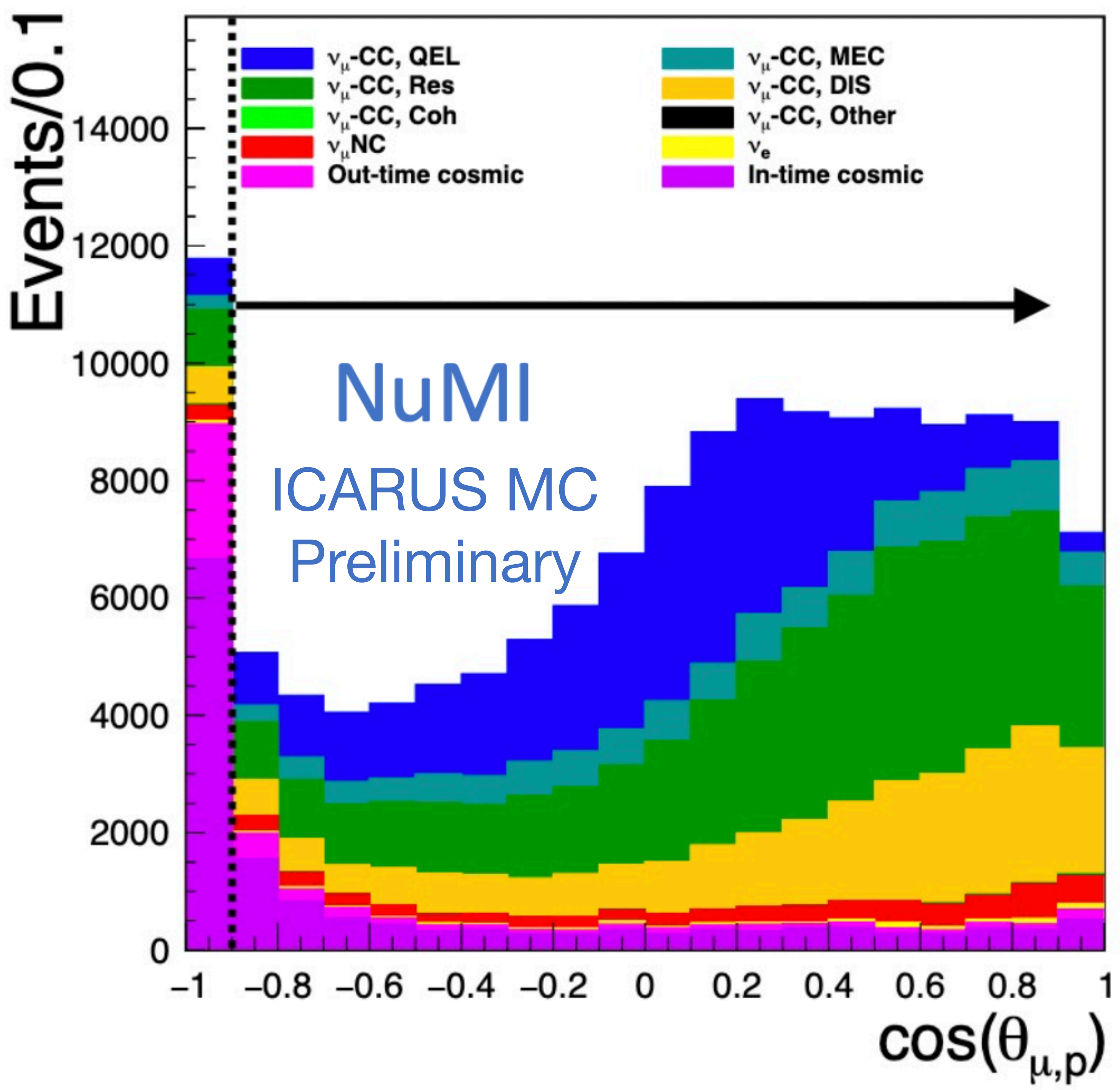
$\Delta(\mathrm{scan}-\mathrm{reco})\mathrm{vertex}_z$ in the beam direction for 476 ν_μ CC candidates from visual scan



Status of event selection for oscillation analyses

- Initial studies focusing on a sample of events with **1 muon and 1 proton** in the final states to perform an **ICARUS-only ν_μ disappearance measurement** - similar selection in BNB and NuMI to discard clear cosmics events, include a FV + containment cut and the requirement to have two reconstructed tracks consistent with a muon and a proton (PID)





- The short term physics goals include also **cross section measurements** on argon in the few MeV to few GeV energy range significant for DUNE profiting of the off axis ν flux from NuMI and **BSM searches**

Conclusions and next steps

- The ICARUS experiment is steadily operating at Fermilab as part of the SBN program and is currently taking data for physics analyses after the completion of the commissioning stage
- Detector characterization has reached a good stage, some space of improvement remains
- We are currently devoting major efforts to tune our reconstruction and selection algorithms using Monte Carlo simulations and data profiting of the increasing statistics we gain
- Early ICARUS data represent an opportunity to perform a variety of physics analyses, including oscillation studies as well as searches for BSM physics
- The experience we are acquiring with ICARUS data/analysis will be extremely useful to accelerate SBN physics analyses

Thank you on behalf of the ICARUS collaboration

IMAGING
COSMIC
AND
RARE
UNDERGROUND
SIGNALS

Imaging
Cosmic
And
Rare
Underground
Signals

Backup slides

ICARUS collaboration members

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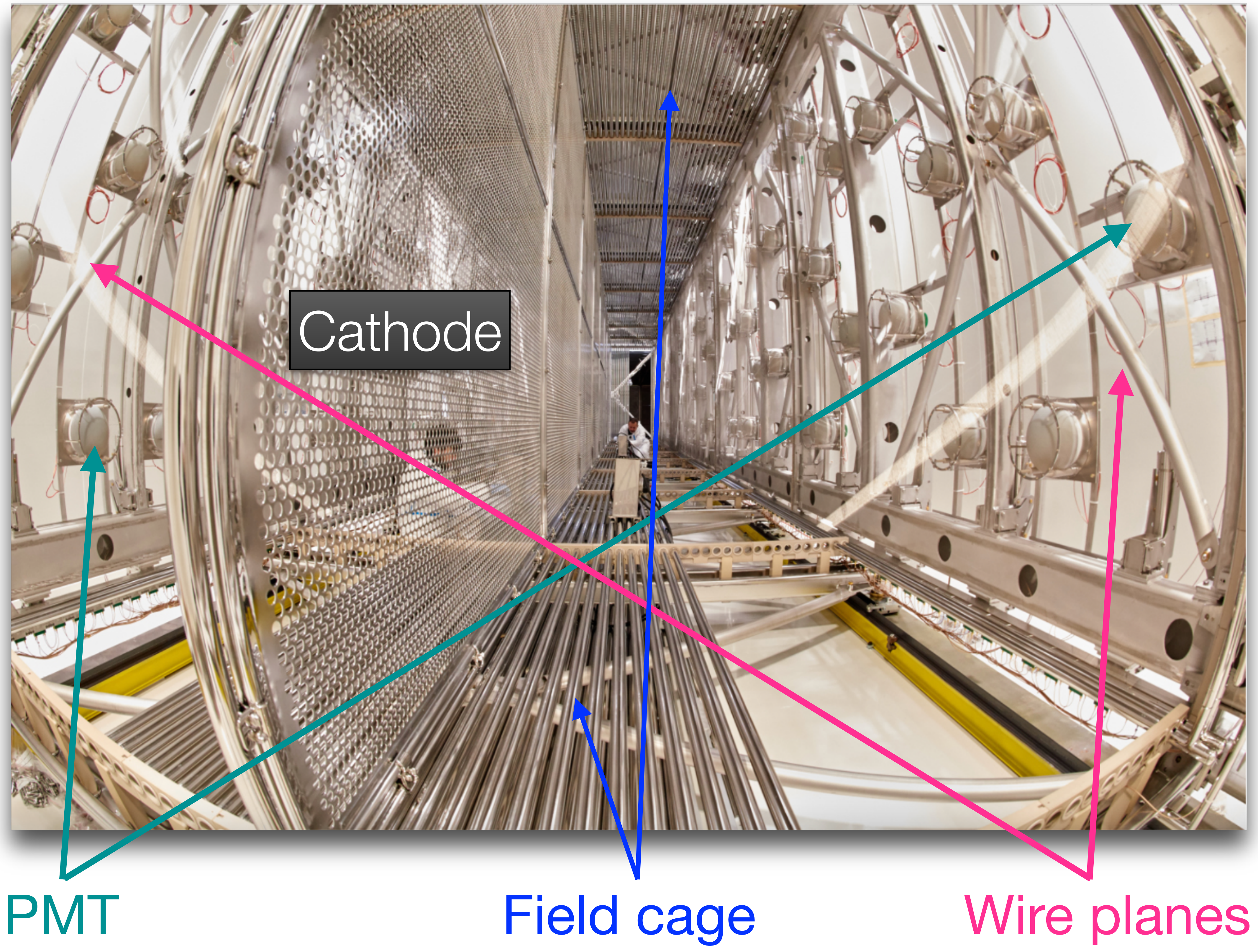
12 INFN groups, 12 US institutions, CERN, 1 Mexican institution, 1 Indian Institution

Spokesperson: C. Rubbia, GSSI

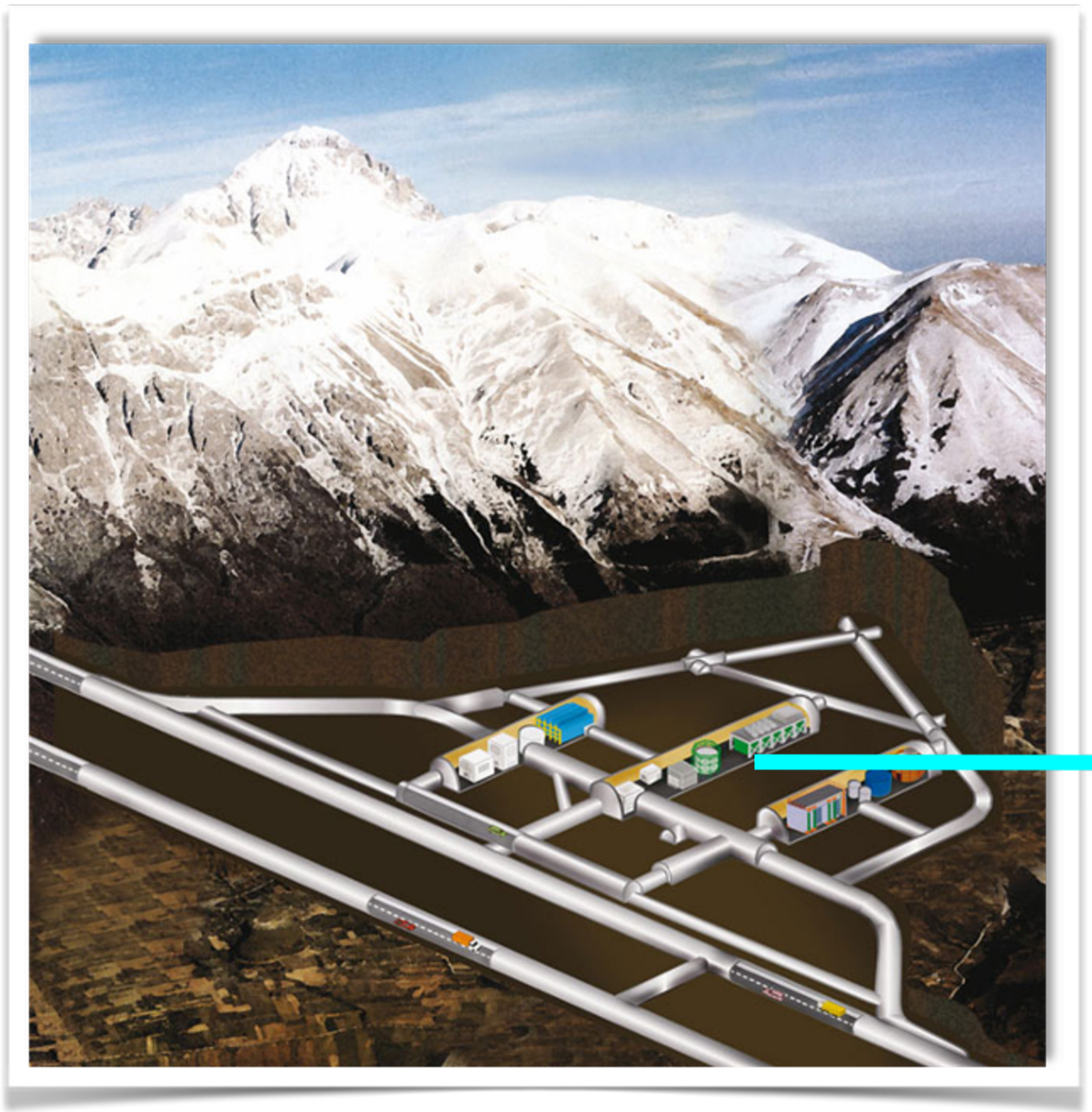
ICARUS detector from LNGS experience to FNAL

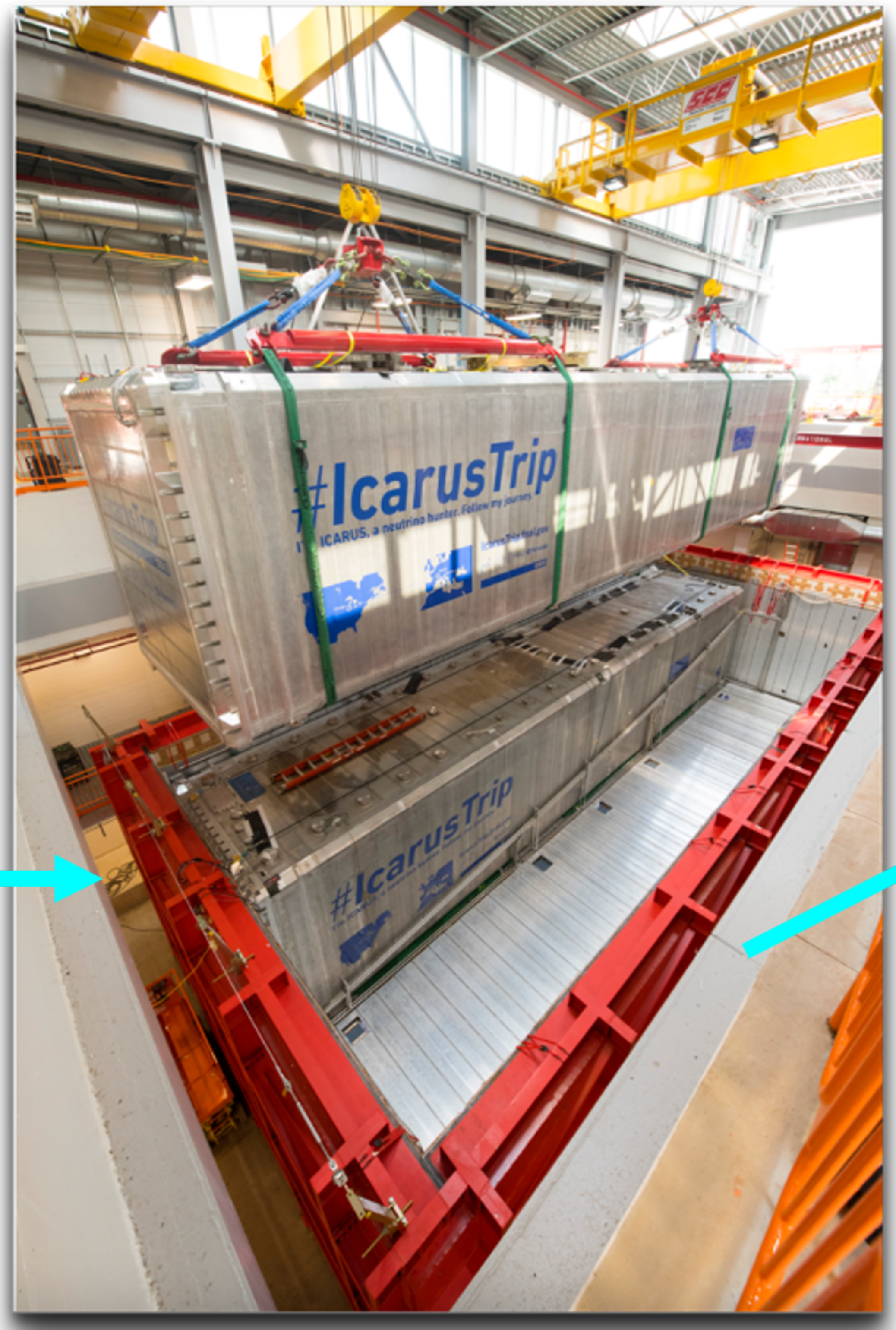
- Sensitive search for a ν_e **excess** made at LNGS with the **CERN to LNGS ν_μ beam** completed in 2013, with **remarkable e/γ separation** and **15%** momentum resolution in range **0.4-4 GeV/c**:
    - 7 electron-like events observed against the (8.5 ± 1.1) expected from standard 3-flavor oscillations: LSND signal constrained to $\sin^2(2\theta) \sim 0.005,\ \Delta m^2 < 1\ \text{eV}^2$



- **Intensive overhauling at CERN** before shipping to Fermilab in order to upgrade the cryogenics, LAr purification system, TPC readout electronics and light collection system

ICARUS detector trip from LNGS to FNAL





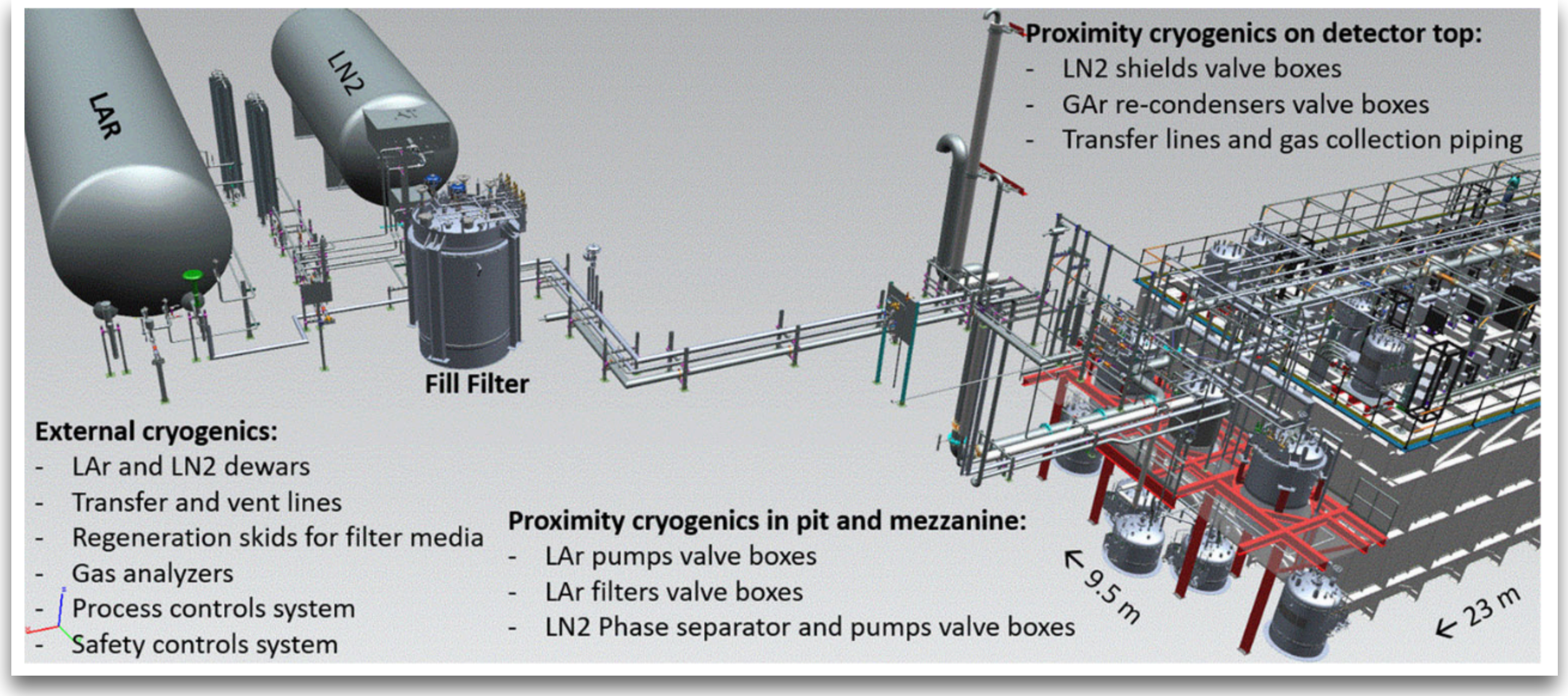
From Hall B of Laboratori Nazionali del Gran Sasso (Italy) to Fermilab (US)

The cryogenic system

- **New cryogenic/purification system** built according the LNGS design except for the choice of an open loop cooling circuit

- **Installation** completed in July 2019, **stabilization phase** ended in ∼May 2020: all of the subsystems running steadily since detector activation, with parameters meeting design values

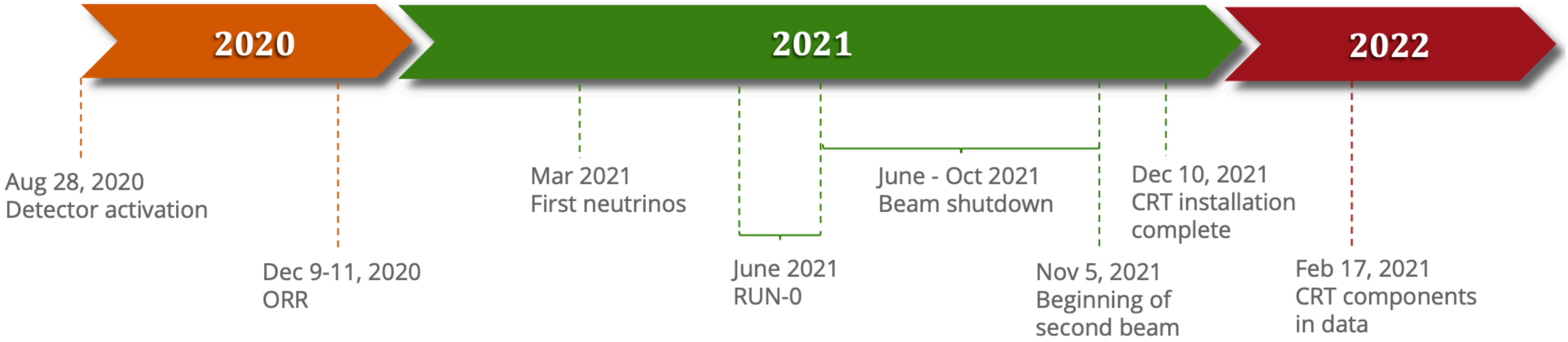
- Few **upgrades** during summer 2021 and 2022:
    - Installation of **warm filters** to improve the gas recirculation system
    - **Regeneration** of the **liquid recirculation filters** of the **west module**



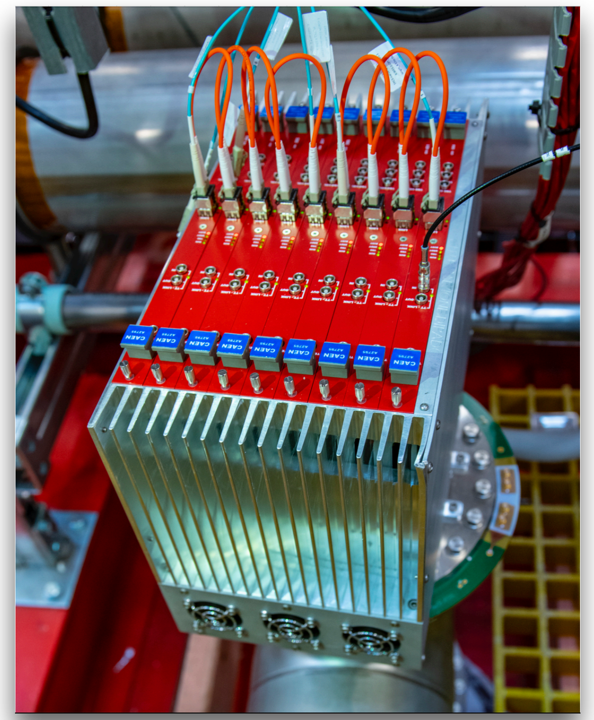
- **Free electrons lifetime** τ_{ele}**∼7 (4) ms** in **west (east) cryostat** (large improvement in west cryostat after filter regeneration), within design but lower than at LNGS and unequal between the two cryostats

ICARUS detector commissioning

- After the activities at CERN, ICARUS was **shipped to FNAL in July 2017**. The **cryostats** were deployed in **August 2018,** feedthrough flanges for TPC/PMT were installed by December 2018, PMTs rate and gain were characterized, TPC electronics/power supplies were installed and tested
- **Cryogenic plant installation** ended in **July 2019** and the cooldown/filling started in February 2020
- **Detector activation** took place in **August 2020**: TPC and cathode HV were set to -75 kV voltage
- **TPC commissioning ended in May 2022** and included characterization of noise levels, peak SNR for MIP μs, measurement of the drift velocity across the 4 TPCs and space charge effects
- **CRT installation** was completed in **December 2021** and the **overburden** installation in **June 2022**



The ICARUS event reconstruction chain

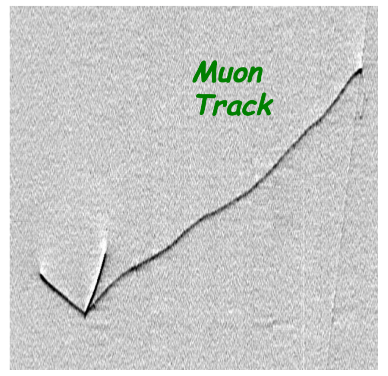


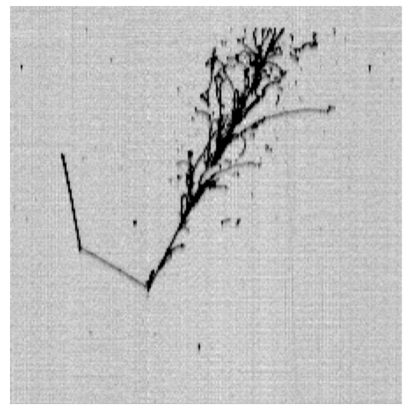
Data

Decoding → Deconvolution → ROI Finder

- **Decoding:** Unpack data and turn it into a raw waveform
- **Deconvolution:** 1D deconvolution to remove electric field distortions and electronic shaping effects
- **ROI Finder:** Threshold based algorithm to find the regions with *hits,* i.e. segments of waveforms corresponding to signal
- **Gauss hits:** Fit each signal hit with Gaussians: area is proportional to $n_{electrons}$ that generated it.
- **Cluster 3D:** Keep only the hits consistent with 3D points to reduce the noise contribution
- **Pandora:** reconstruction based on cluster, slice, i.e. interaction, and pattern recognition
- **Machine Learning:** reconstruction fully based on machine learning approach

Gauss hits → Cluster 3D → Pandora / Machine Learning → Analysis



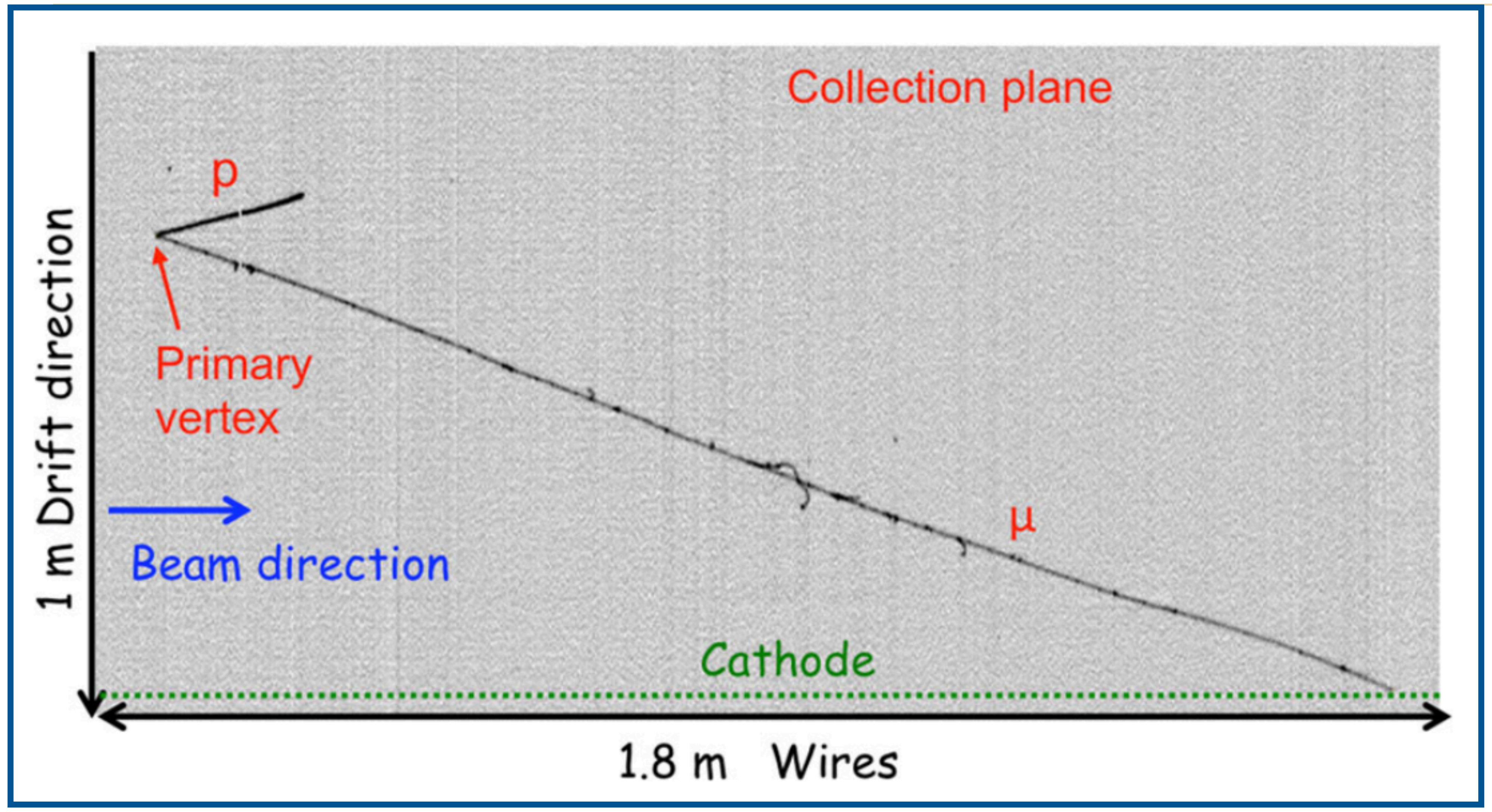


Analysis

TPC event reconstruction

- Standard reconstruction uses Pandora (https://github.com/PandoraPFA), a pattern recognition software commonly used in detectors based on LAr technology to:
  - **Cluster** the objects together into reconstructed particles in 3D by joining information (hits) from the TPC wire planes;
  - Reconstruct the **interaction vertex**, i.e. the common point where reconstructed particles originate and thus the point where the ν candidate interacted;
  - Reconstruct **particle hierarchy;**
  - Classifies particles as **track-like** (μ, p, $\pi^{\pm}$, …) or **shower-like** (e, γ…)
- We employ **visual scan event selection** and **Monte Carlo** simulations to identify pathologies, explore reconstruction improvements and tune our selection algorithms:
  - Primary effort so far focused on ν_{μ} CC events and track reconstruction (vertex, start/end points, length, PID), but other activities ongoing to improve track vs shower discrimination, shower reconstruction and to integrate TPC information with signals from PMT and CRT

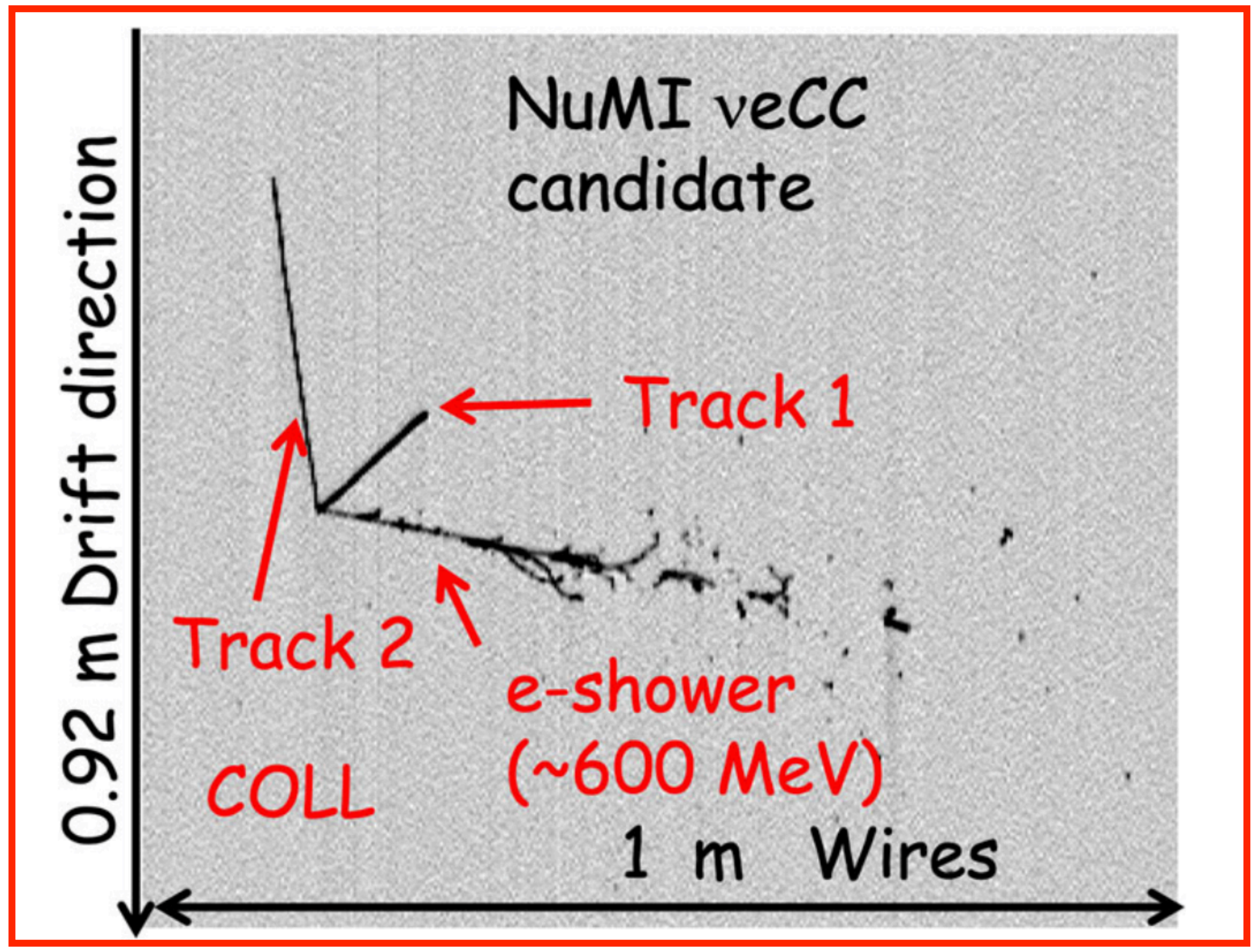
Visual event study and TPC reconstruction performance

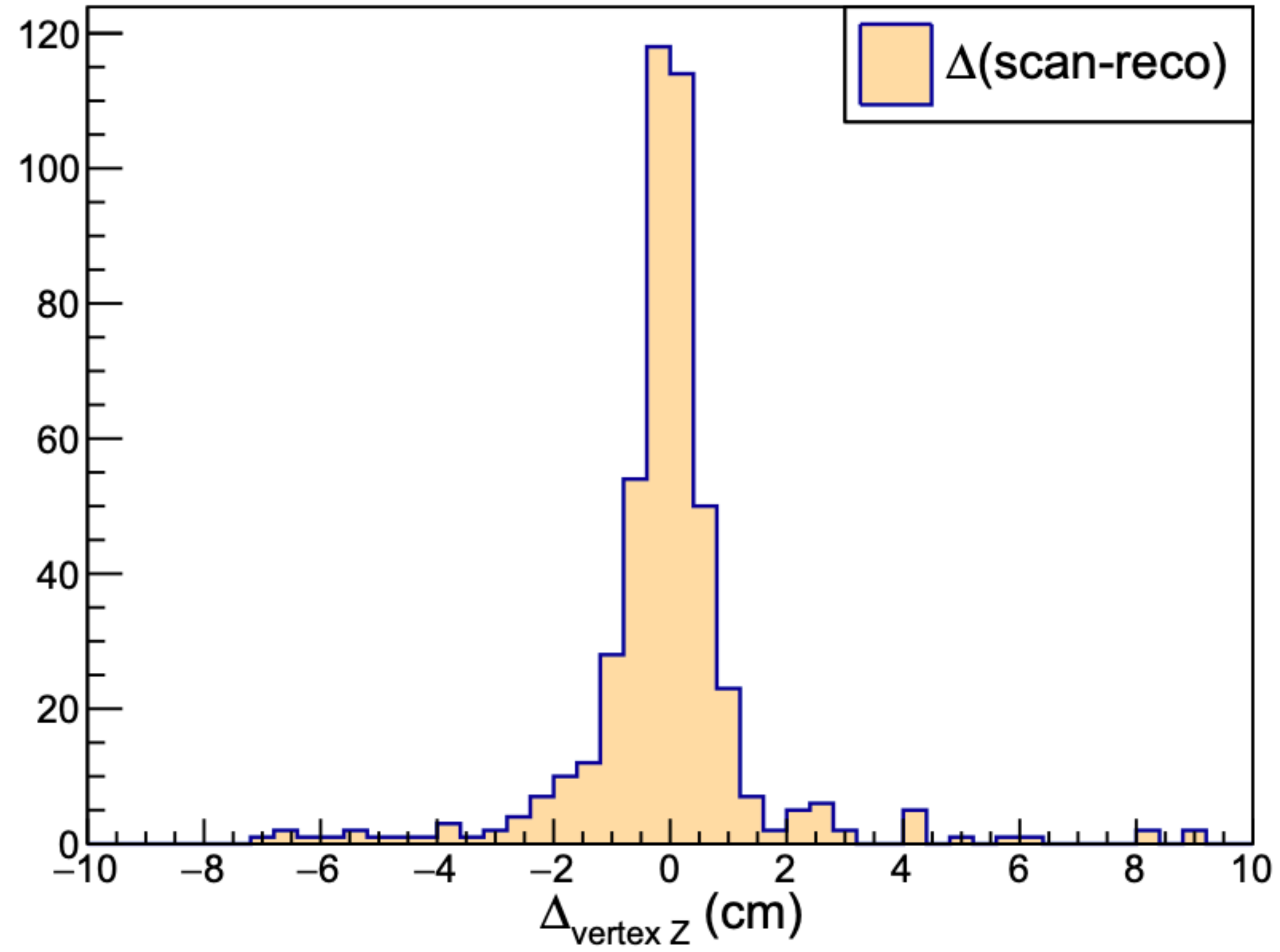


Comparison of the outcome of the visual scan event selection and the automatic reconstruction proved extremely useful to study event reconstruction

Visually selected ν_μ CC candidate from BNB beam

Visually selected ν_e CC candidate from NuMI beam





Difference in the beam direction Δz for 476 ν_μ CC candidates from visual scan