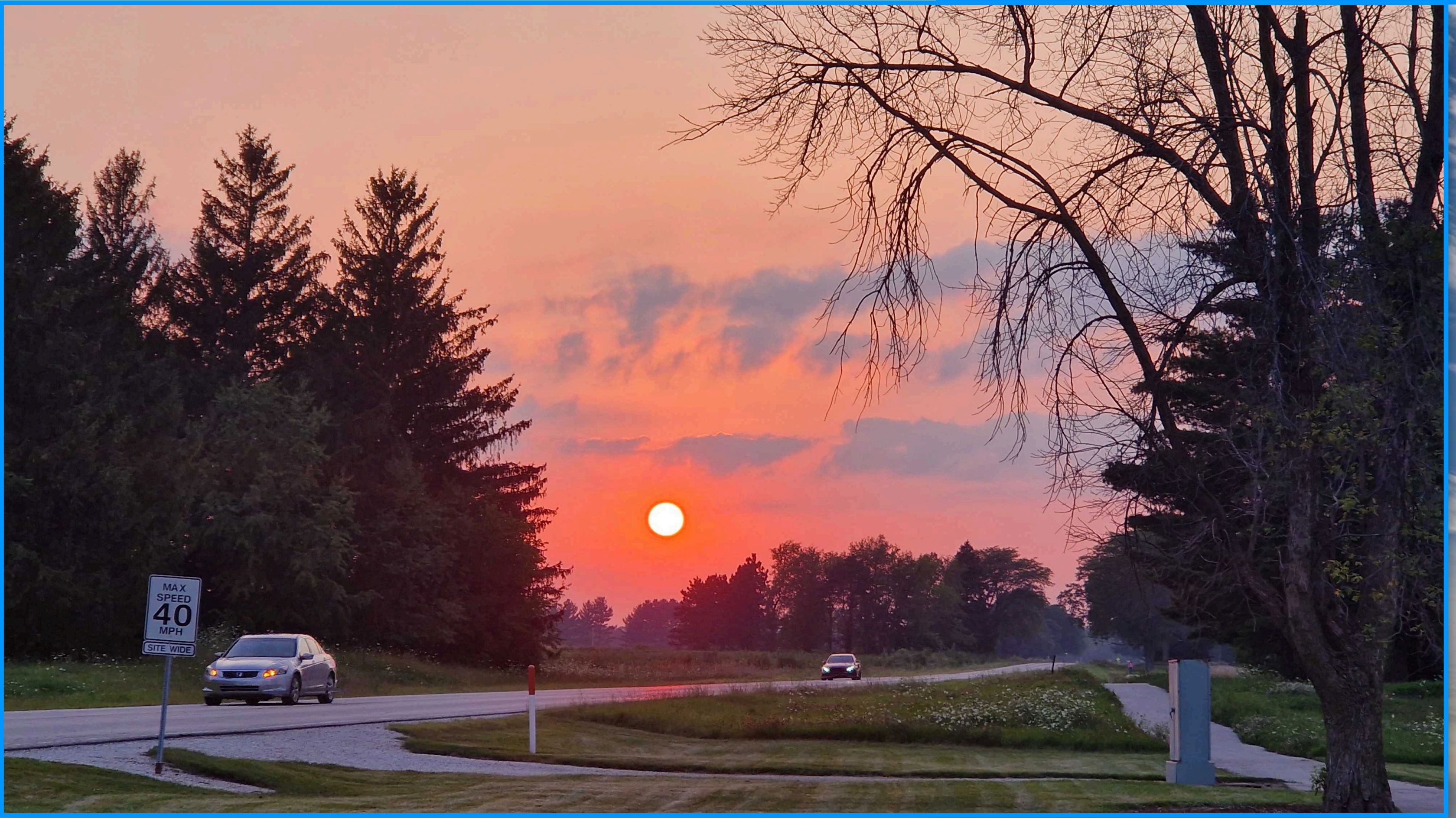
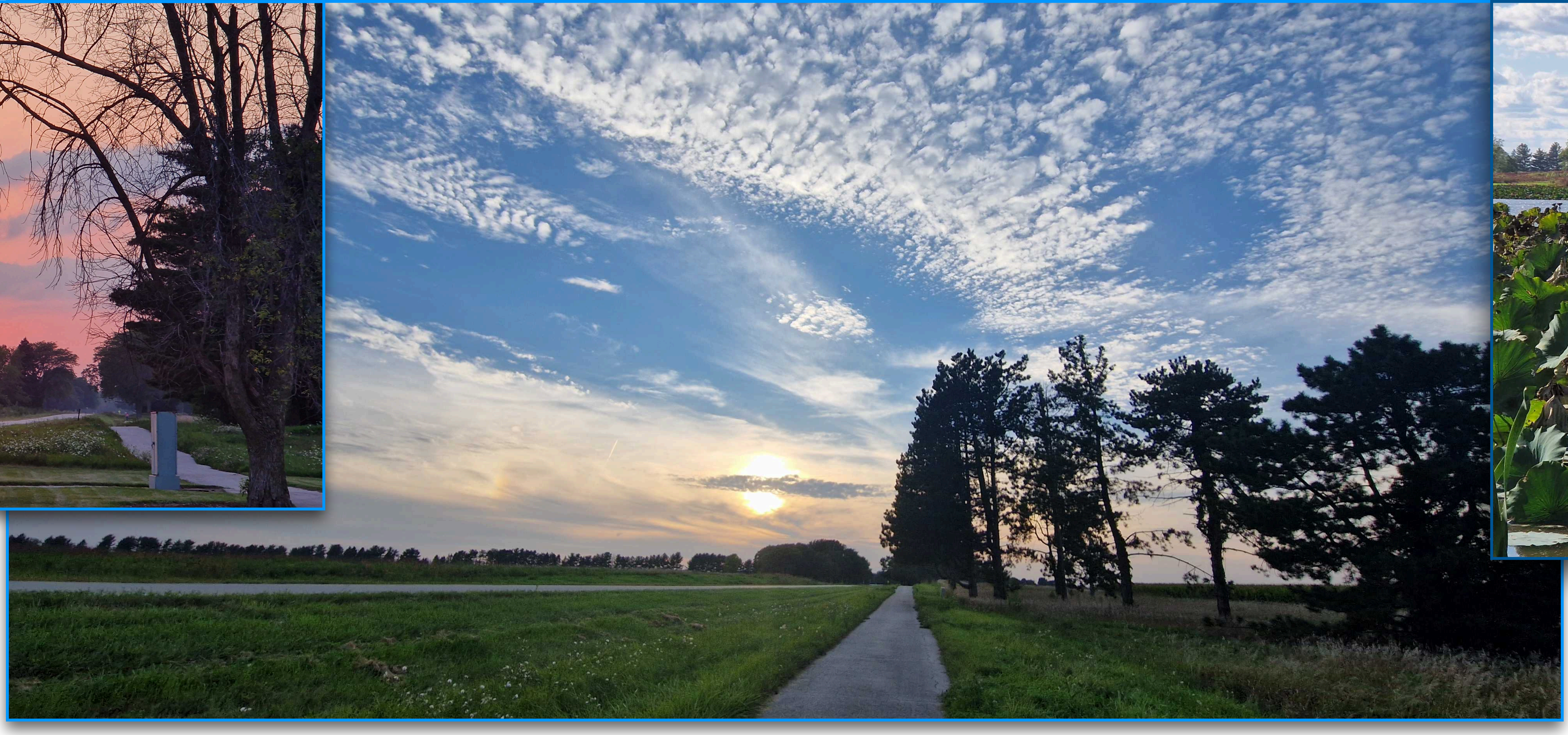
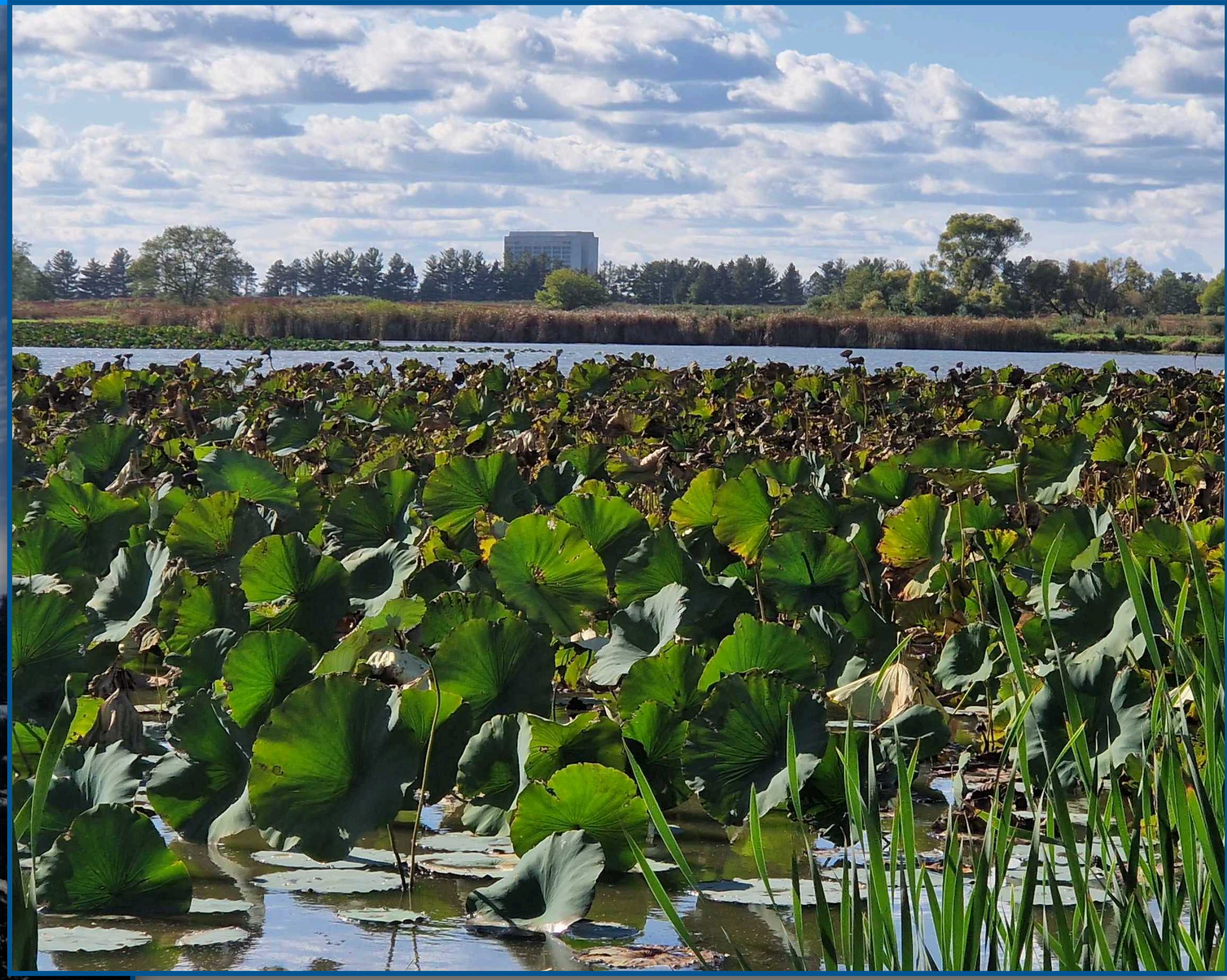






IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

The Short Baseline Neutrino (SBN) Program and the Icarus experiment at Fermilab

Alice Campani on behalf of the ICARUS collaboration

Università di Genova, INFN Sezione di Genova

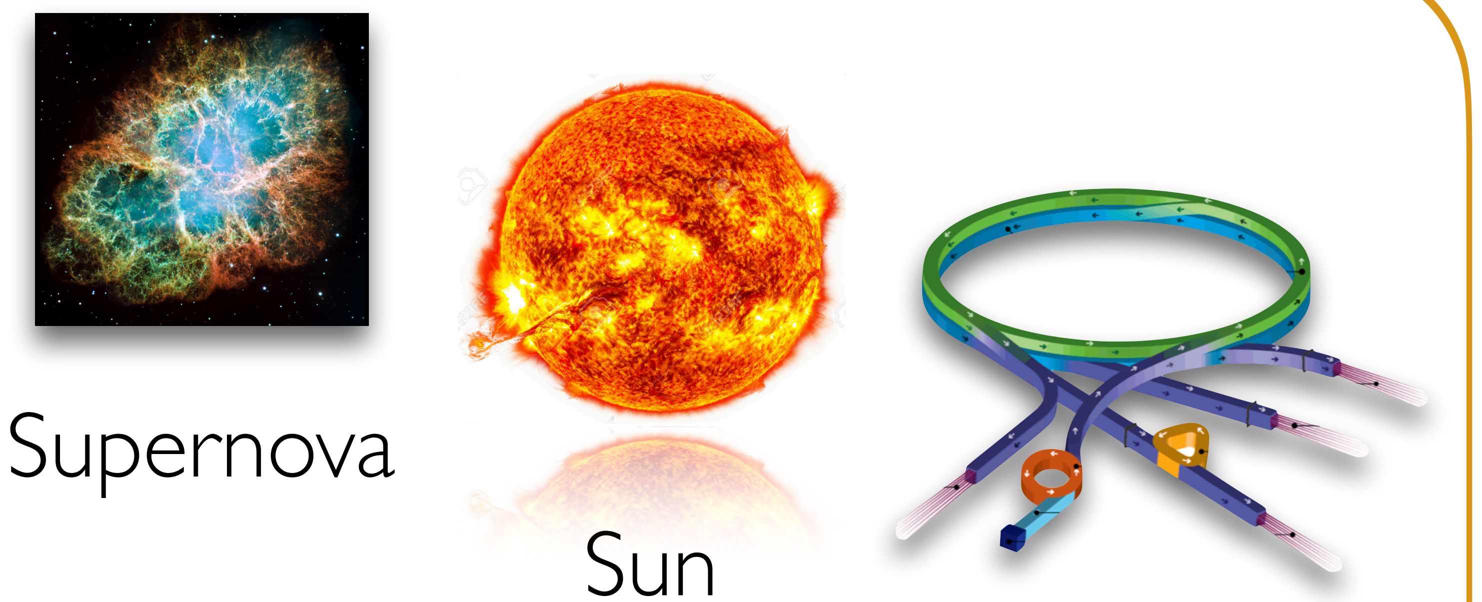
Università di Genova

INFN Istituto Nazionale di Fisica Nucleare

MidTerme review of SENSE

NEUTRINOS & THE STANDARD MODEL OF PARTICLE PHYSICS

- Experimental observations indicate the existence of **three neutrino families**: ν_e, ν_μ, ν_τ
  - Interacting only via *weak* interaction: small interaction probability → difficult to observe
  - In the Standard Model of particle physics they are described as mass-less particles
  - The phenomenon of **neutrino flavor oscillations** indicates they must have a mass



Supernova

Sun

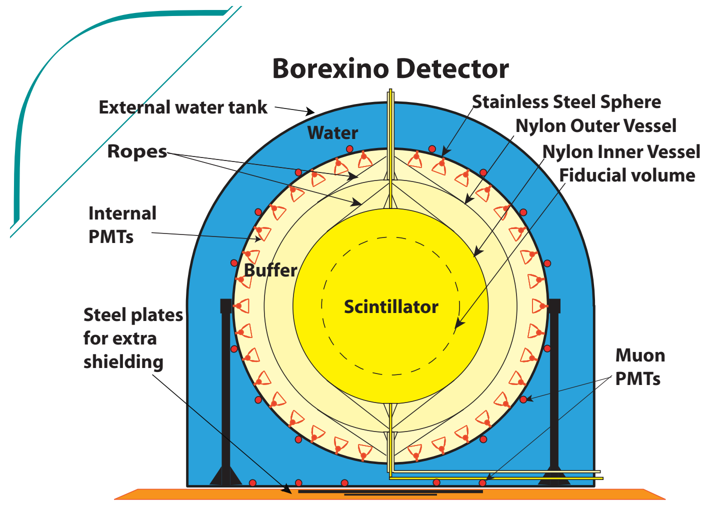
Beam

Neutrino source

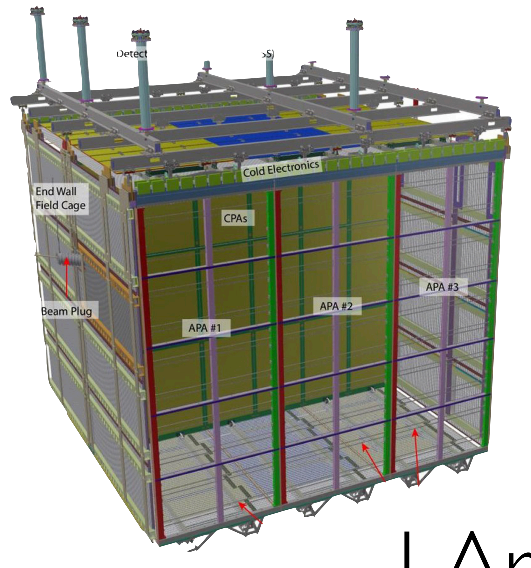
ν_α

Propagation over distance L

$\nu_\beta \neq \nu_\alpha$



Scintillator



LArTPC

Target (detector)

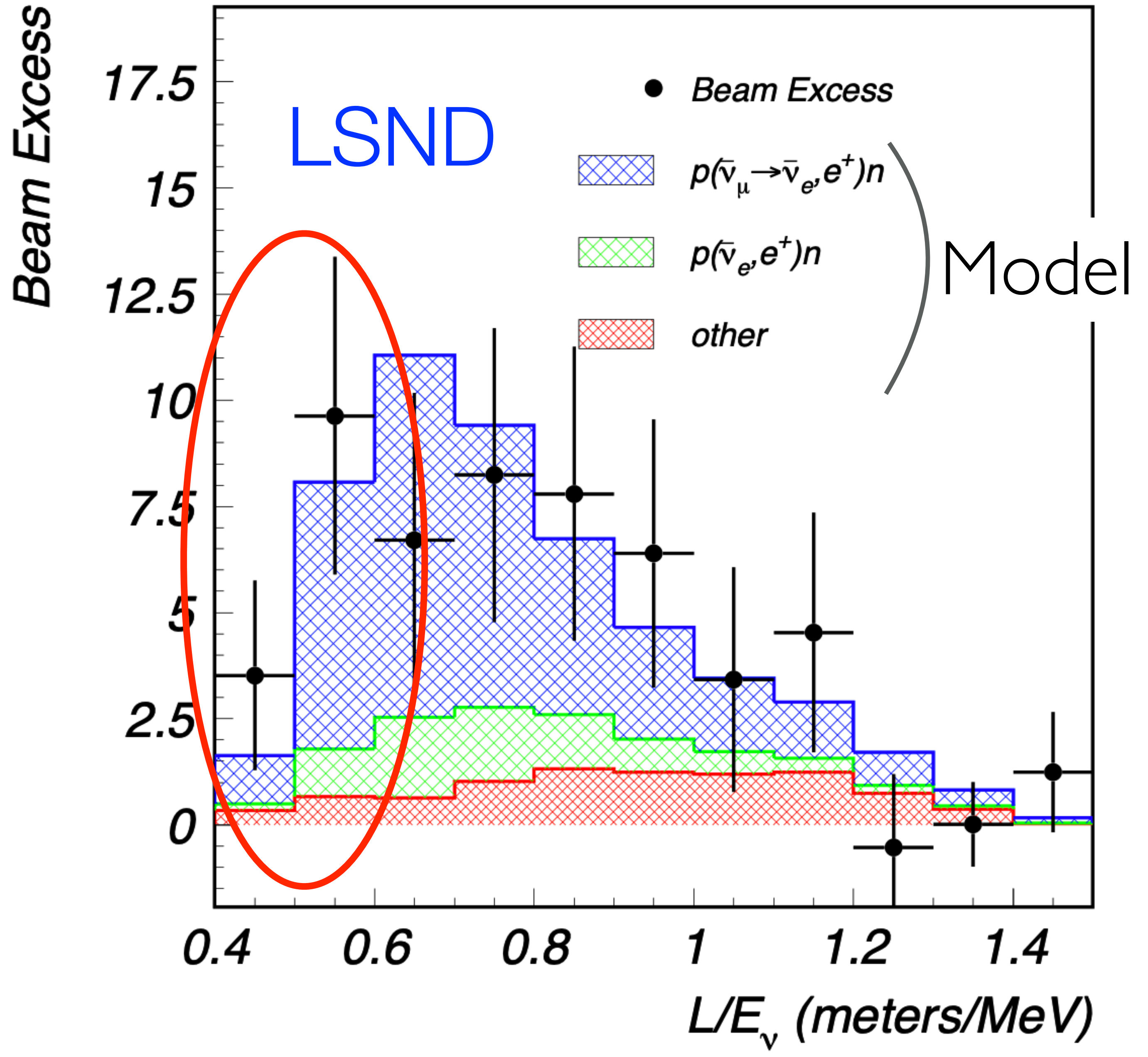
The **oscillation probability** depends on

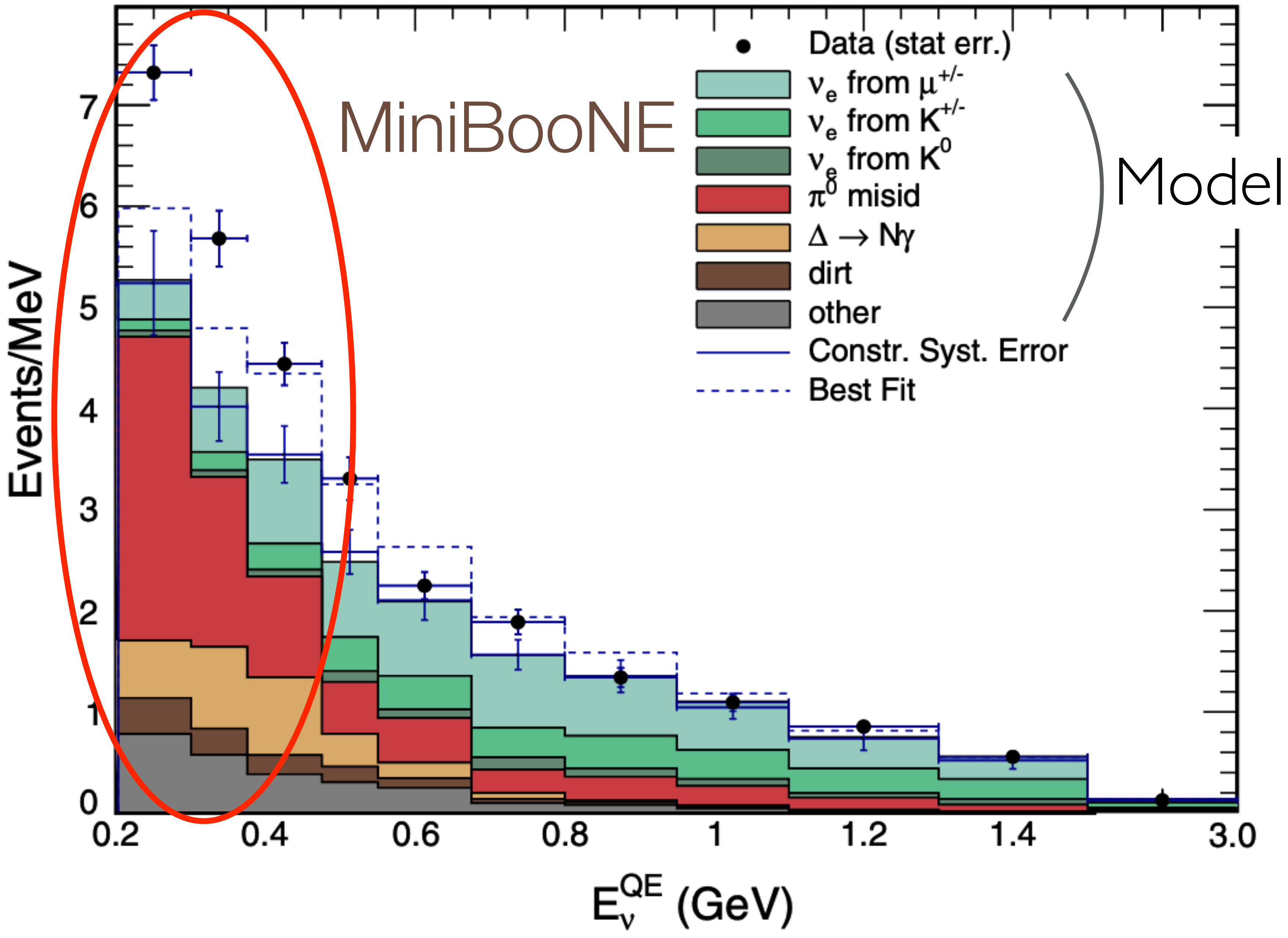
- square of the difference between neutrino masses Δm^2
- source-detector distance L
- neutrino energy E_ν and neutrino mixing angle θ

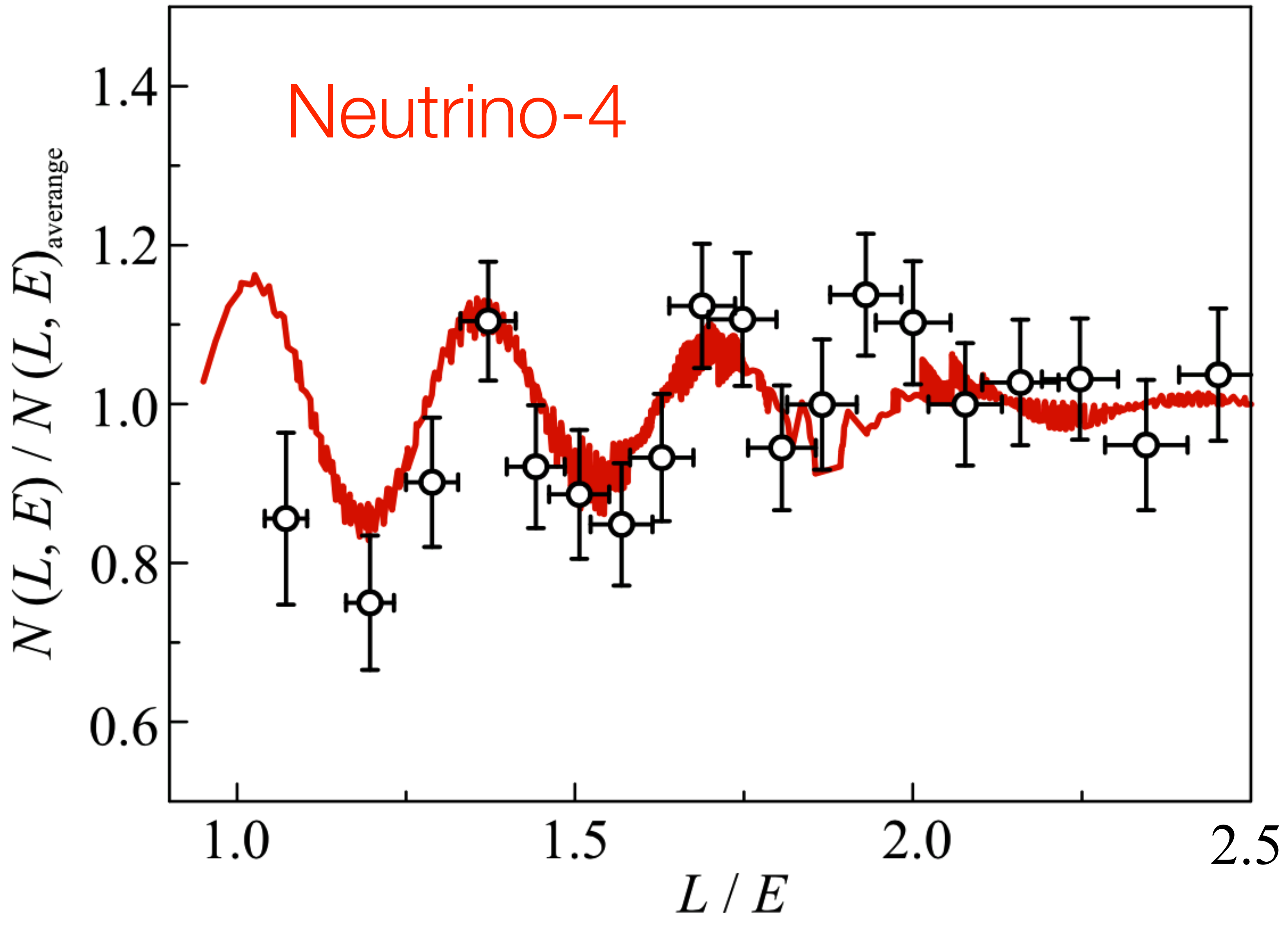
We study both channels: ***appearance*** of new flavors and the **disappearance** of the source ν flavor

EXPERIMENTAL ANOMALIES AND STERILE NEUTRINOS

- Despite the well-established 3-flavour neutrino oscillation picture, **several anomalies** have been measured in the last 20 years hinting to the existence of additional ***sterile*** (i.e. non standard) neutrino states







- LSND
  $\bar{\nu}_\mu$ accelerator experiment:
  excess of $\bar{\nu}_e$ at low energy
- MiniBooNE
  ν_μ accelerator experiment:
  excess of ν_e at low energy
- **Neutrino-4**
  reactor experiment:
  hint of oscillation signature
  at $\Delta m^2 \sim 7\ eV^2$

Results point towards a new sterile neutrino flavor at $\Delta m^2 \sim 1\ eV^2$ driving short-distance oscillations

EXPERIMENTAL ANOMALIES AND STERILE NEUTRINOS

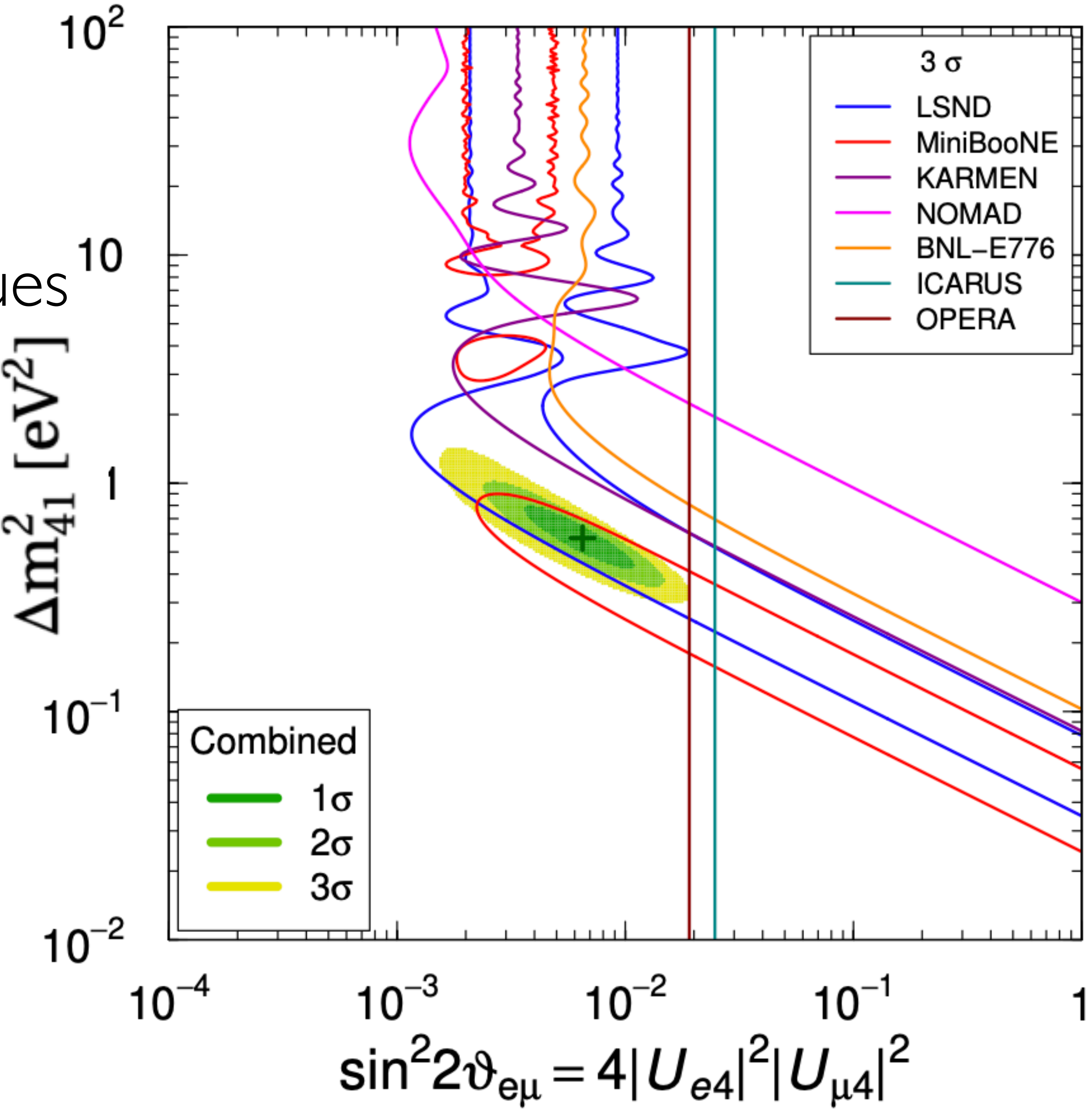
- The **global** analysis of oscillation data highlights a **tension** between **appearance** and **disappearance** results

Results from ≠ experiments:

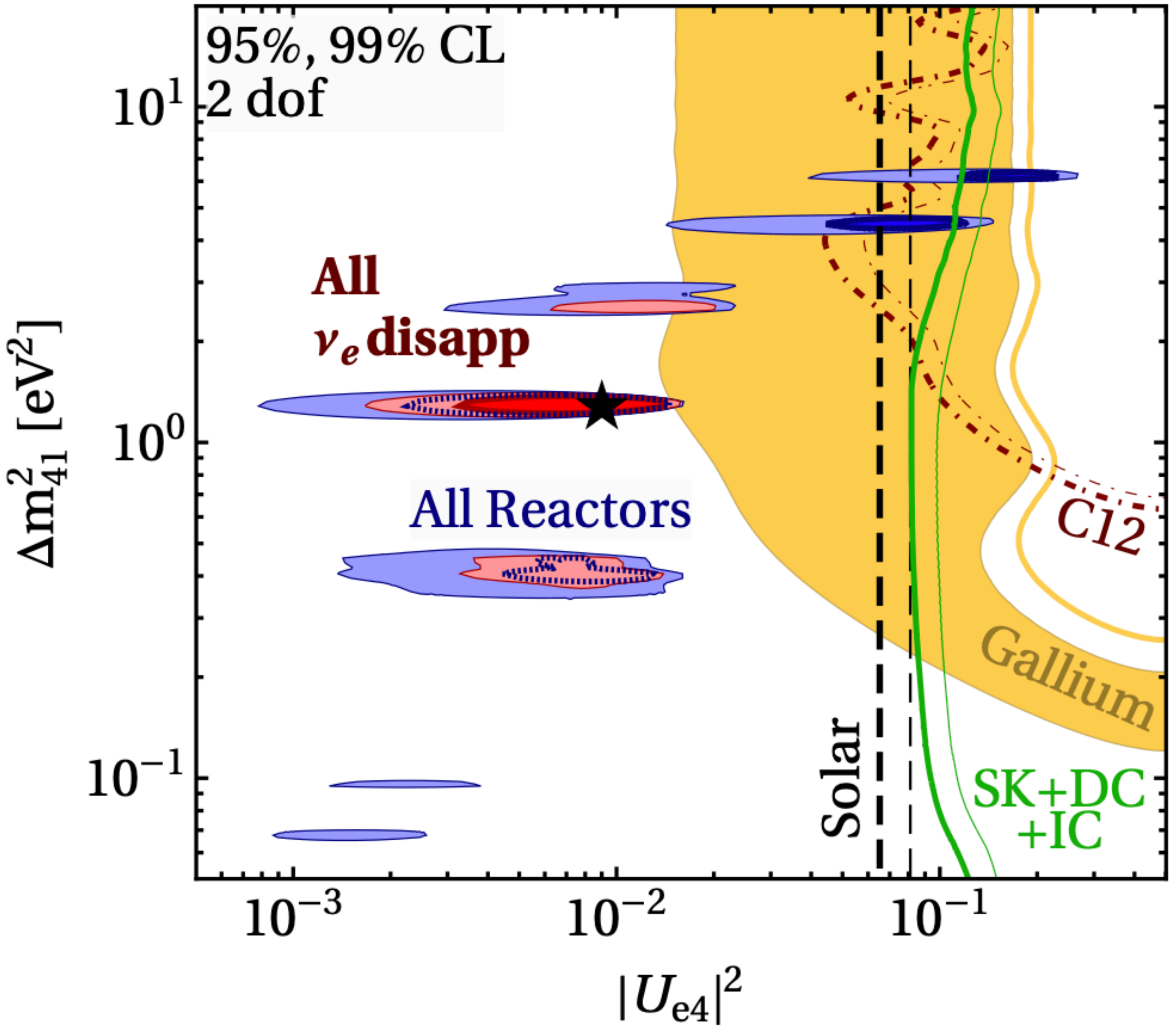
- different technologies
- different detection techniques
- different energy ranges

How to solve this?

- Measure **both channels** in the **same** experiment
- Build experiments with **same technology**, detection technique and exposed to the **same** neutrino **source** → SBN

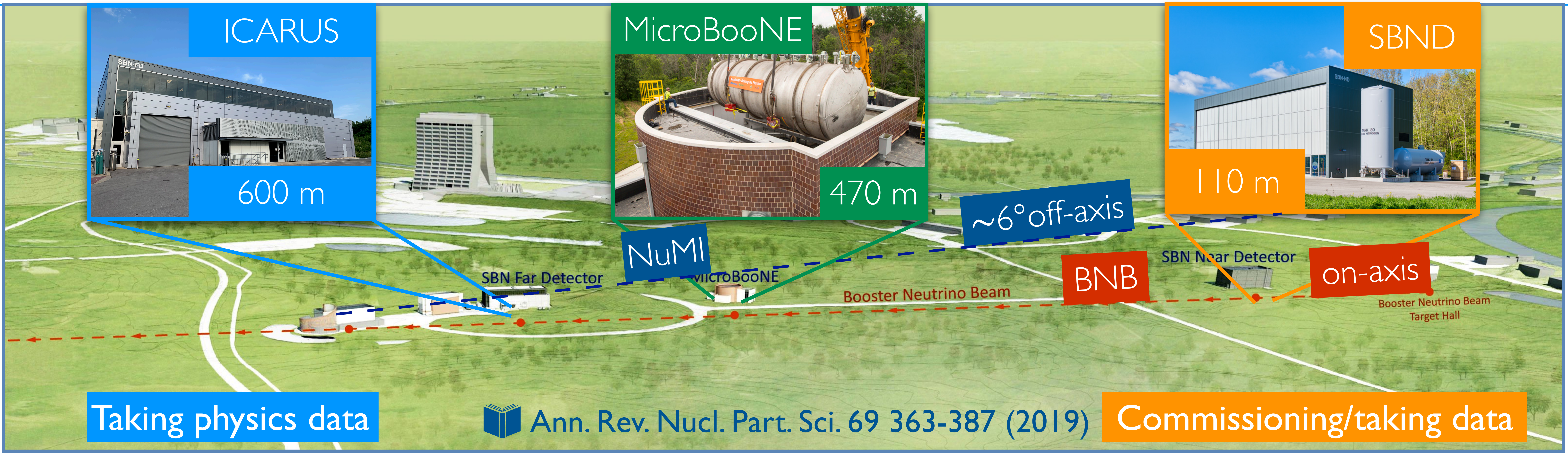


$\nu_e/\bar{\nu}_e$ appearance

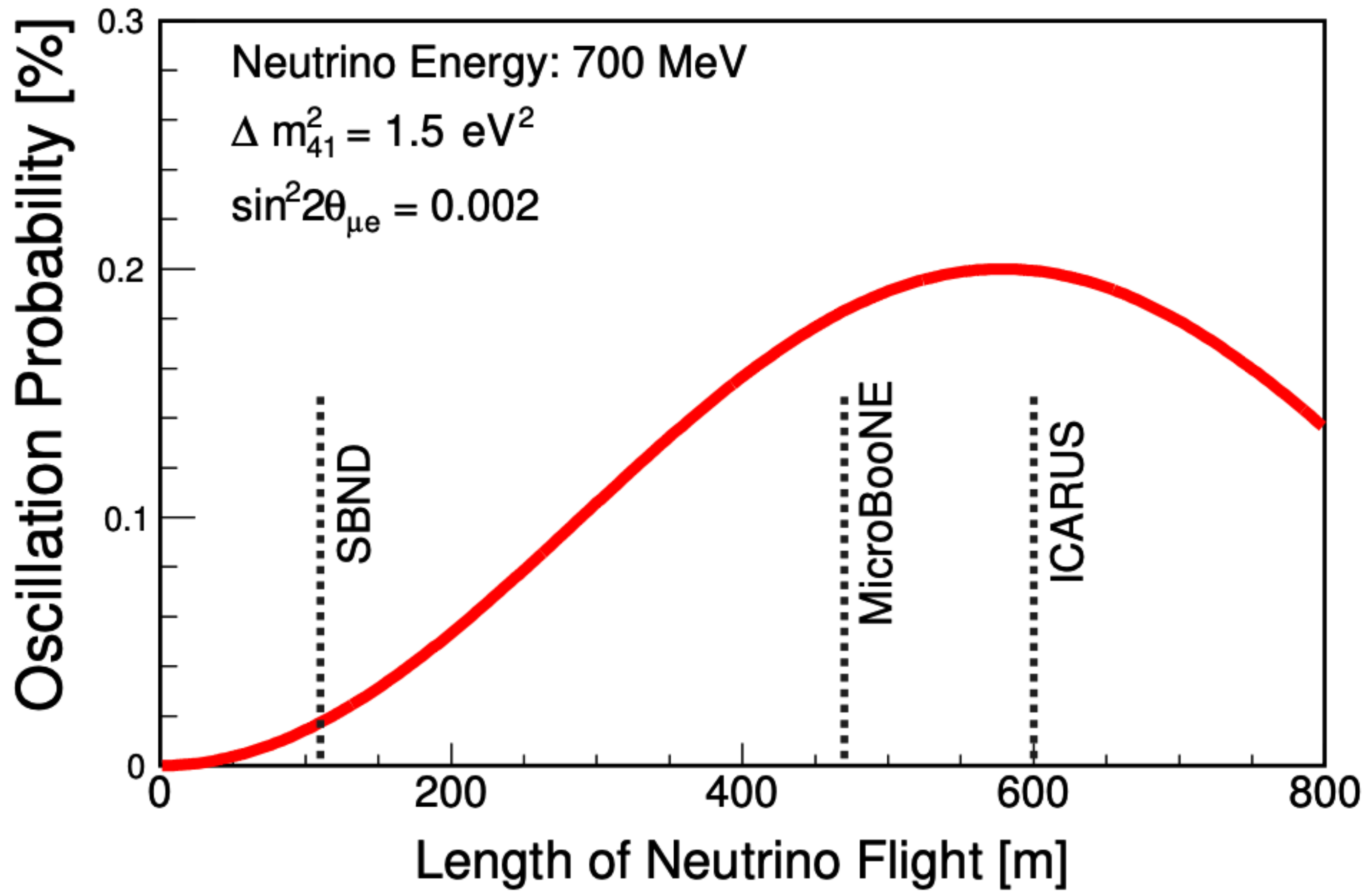


$\nu_e/\bar{\nu}_e$ disappearance

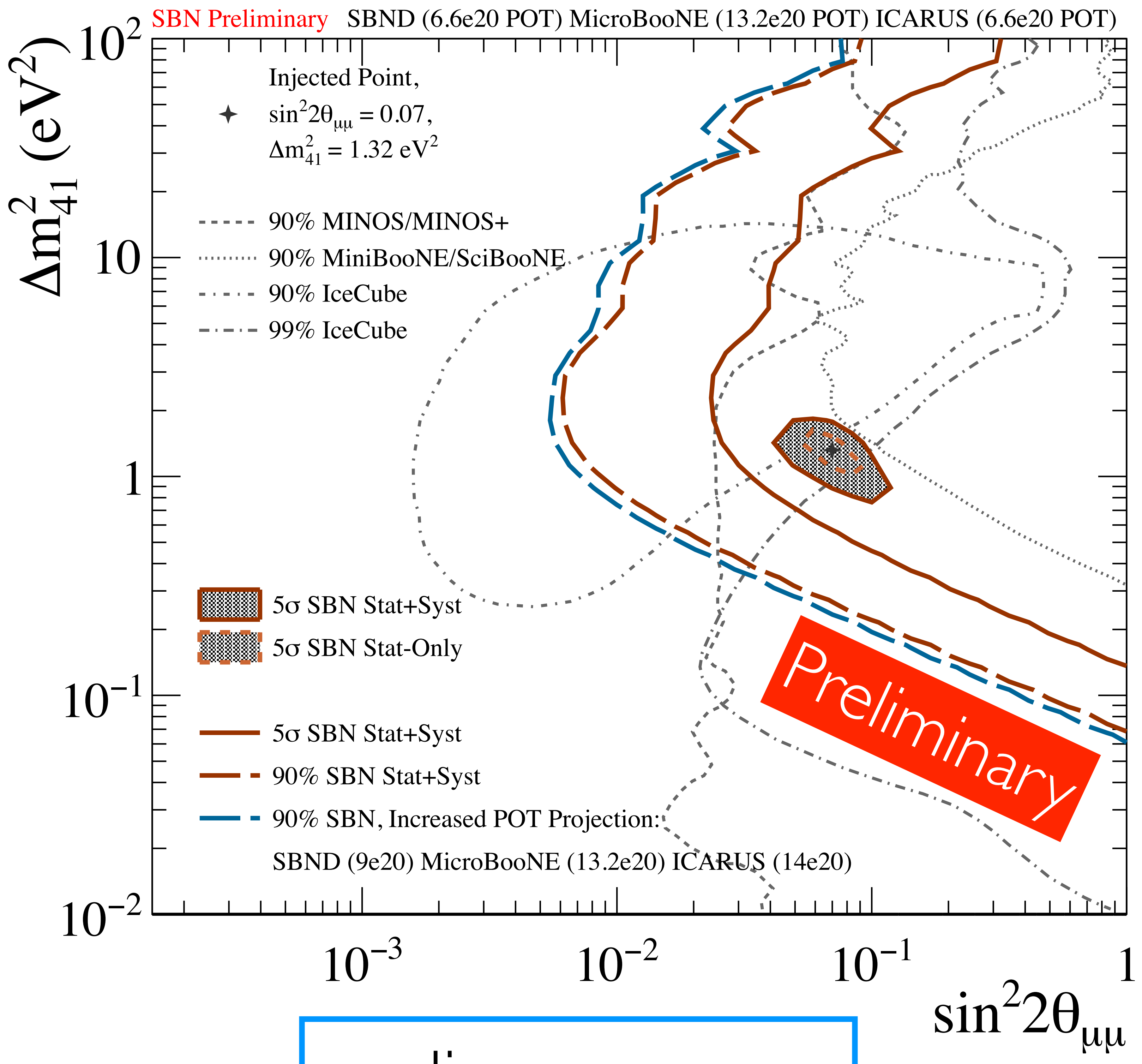
THE SHORT-BASELINE NEUTRINO PROGRAM AT FNAL



- **Same technology**: Liquid Argon Time Projection Chamber (**LArTPC**)
- **Same source:** Booster Neutrino Beam (**BNB**) sampled at ≠ **distances**
  - **Near detector** (**SBND**, 110 m) to measure neutrinos before they oscillate precise information on the initial composition and energy of the beam
  - **Far** (**ICARUS**, 600 m) to have non null oscillation probability
- **Main goal:** search for sterile neutrinos & solve the sterile neutrino puzzle

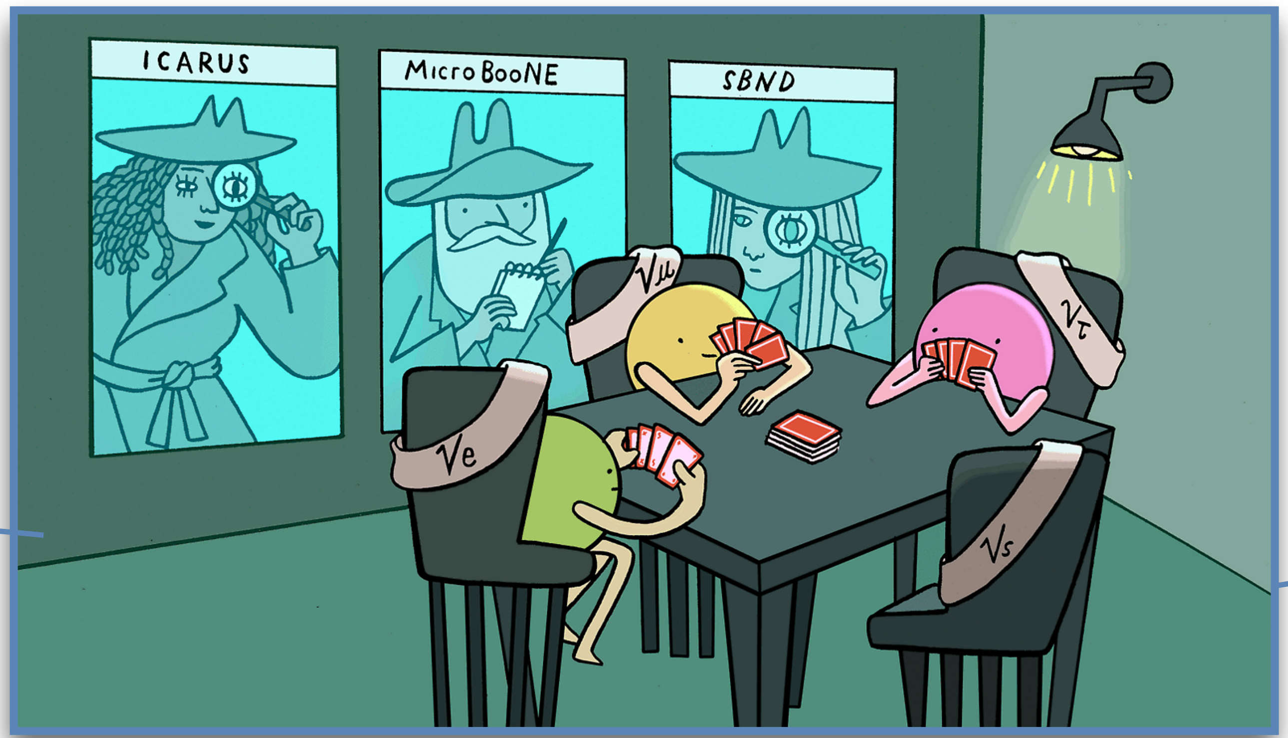


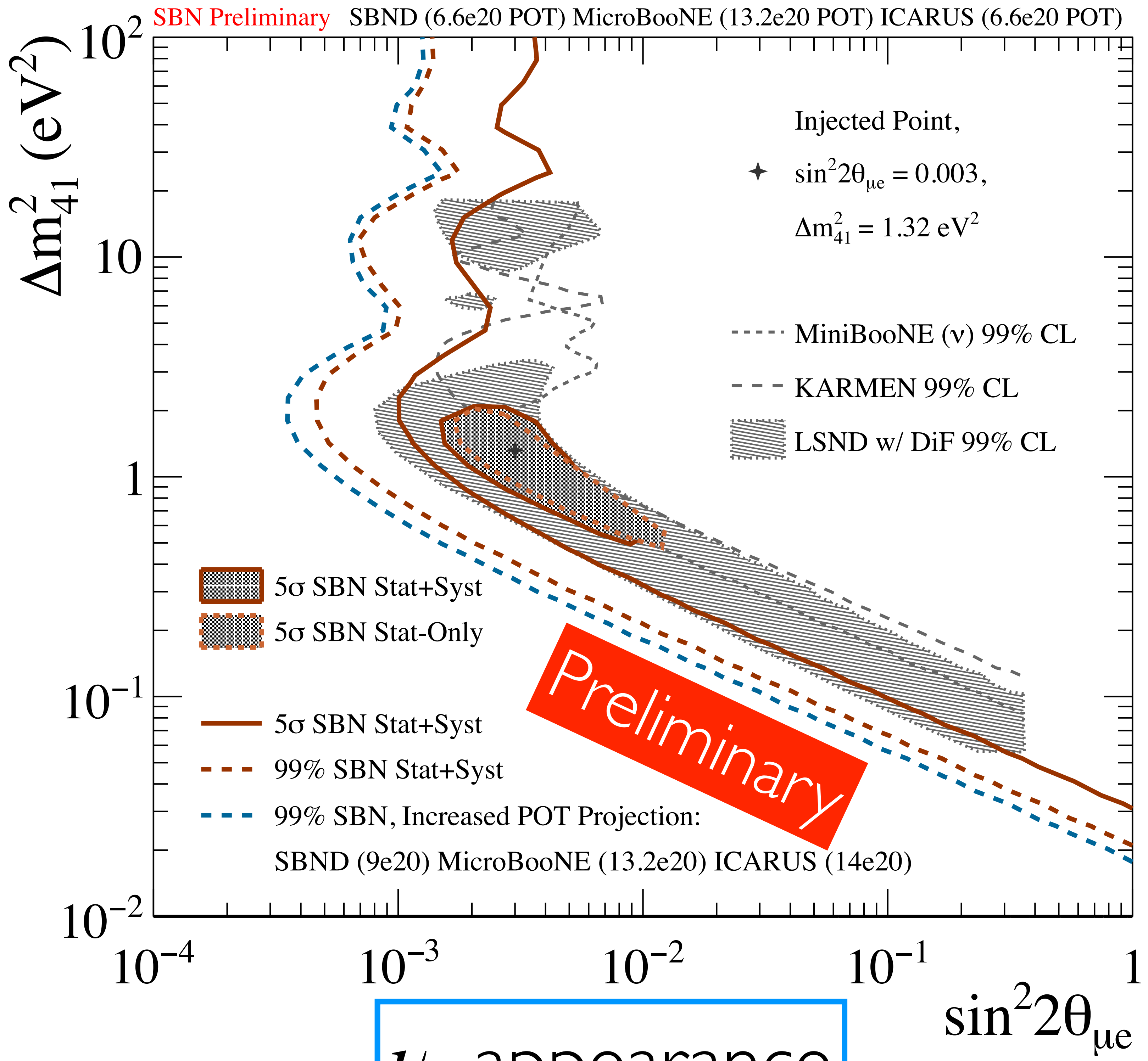
THE SHORT-BASELINE NEUTRINO PROGRAM



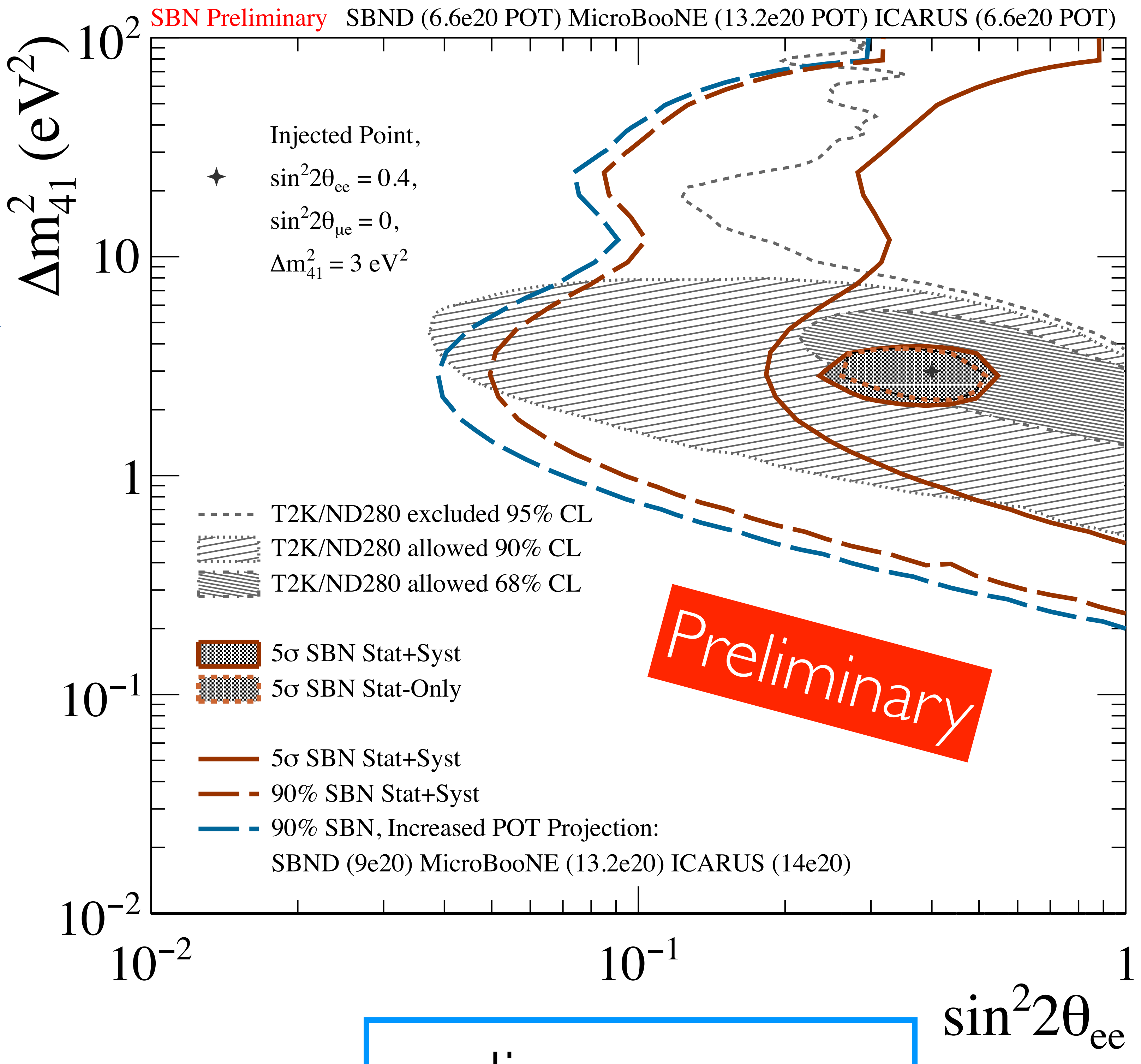
ν_μ disappearance

The combined analysis of near and far detector grants the unique capability to study both **appearance** and **disappearance** channels





ν_e appearance



ν_e disappearance

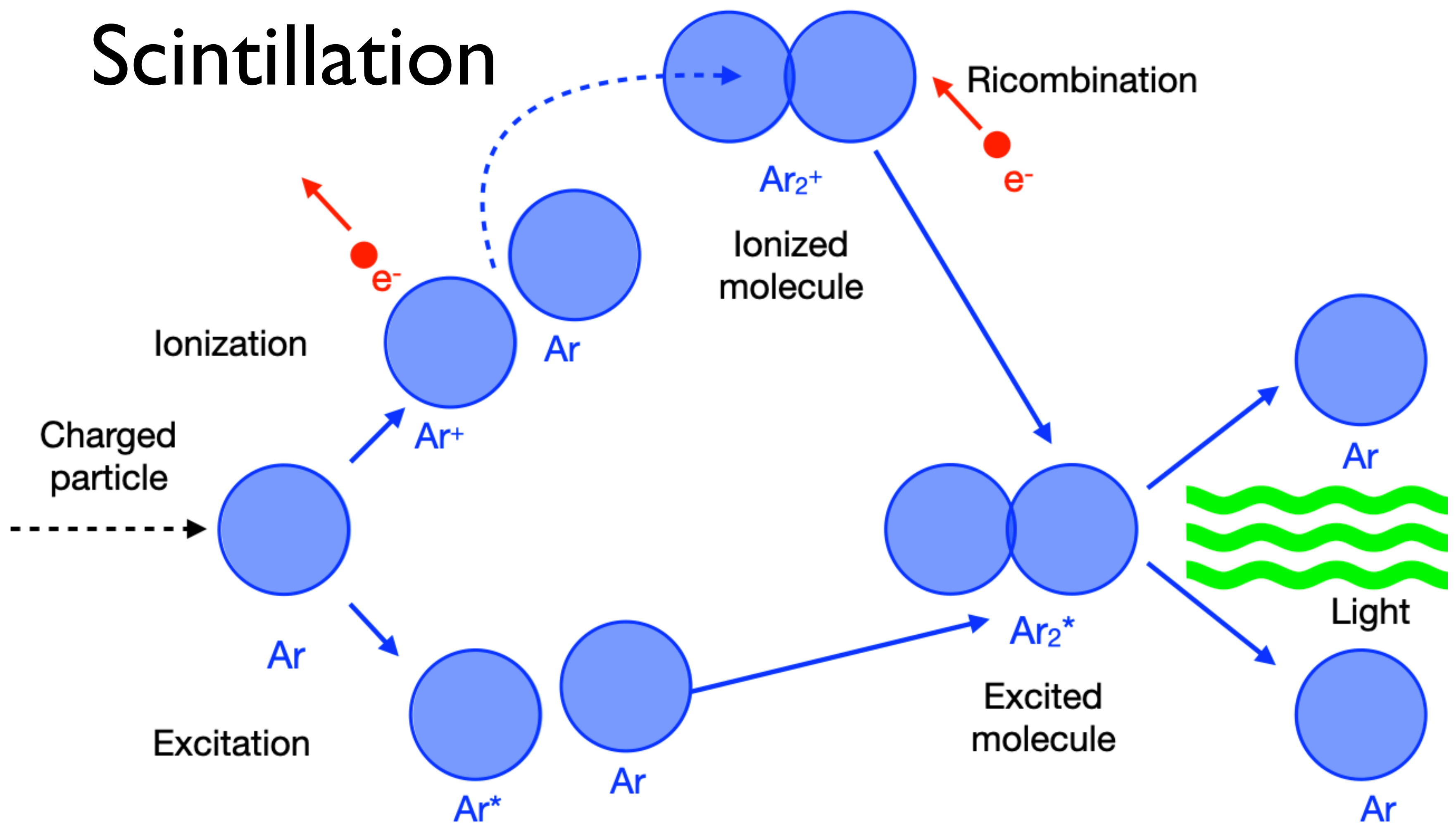
The combined analysis grants to reach a high (5σ) **sensitivity** to many of the observed anomalies (LSND in 3 years data taking)

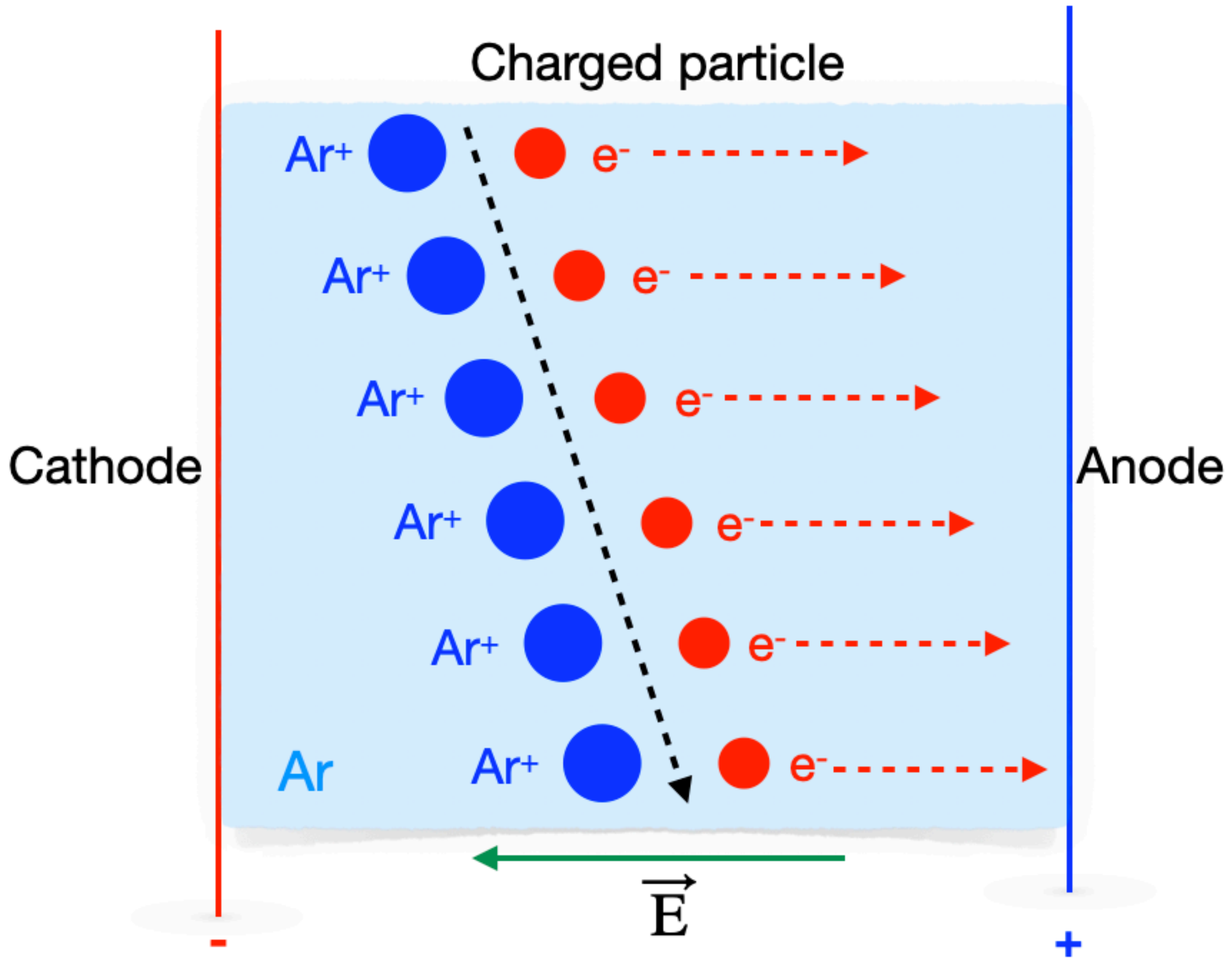
LIQUID ARGON TIME PROJECTION CHAMBERS

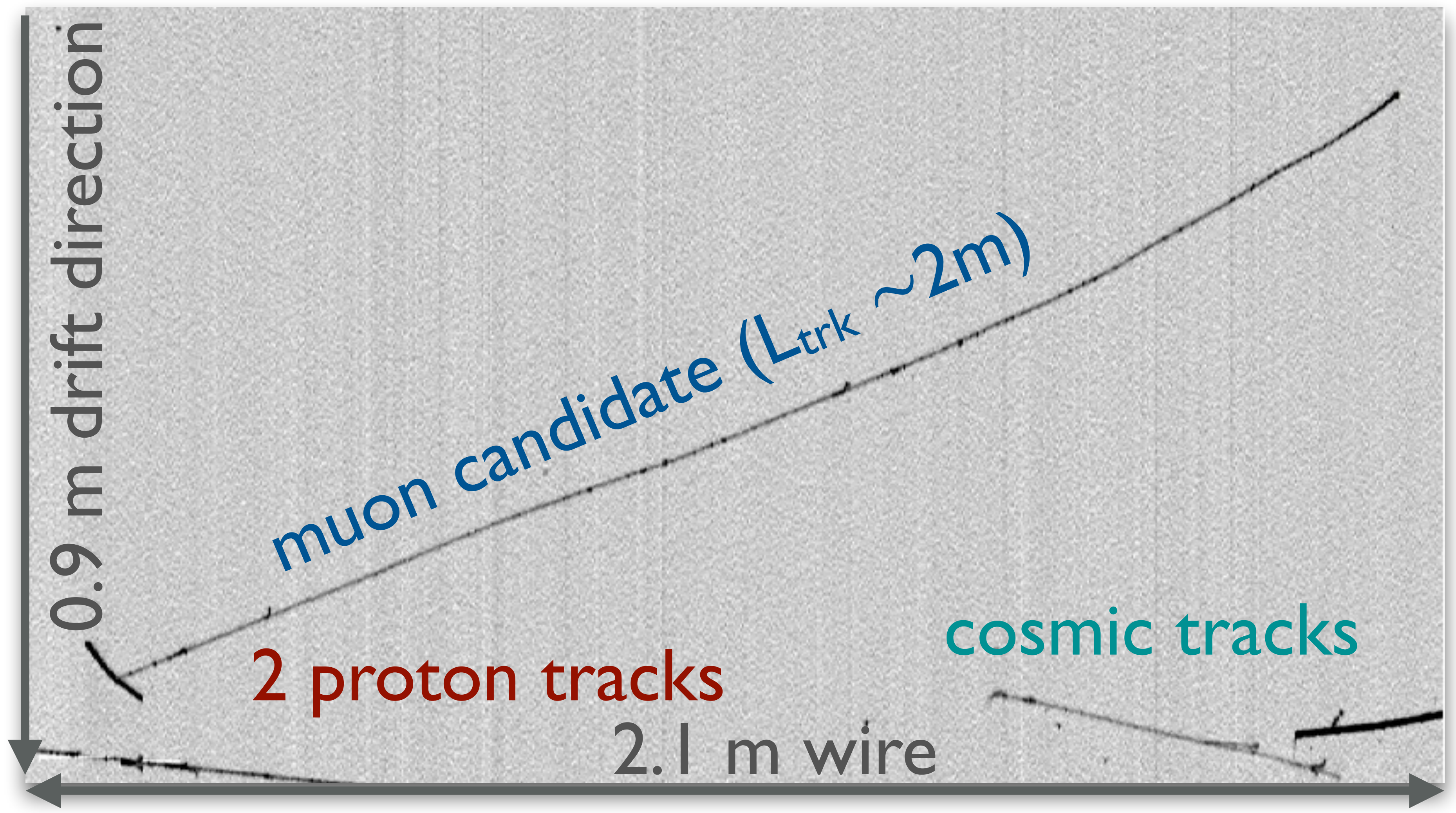
- From an idea of Carlo Rubbia (1977), LArTPCs are ideal detectors for neutrino physics: they allow to have simultaneously an **energetic** reconstruction of the events and a **3D image** of neutrino interactions

Why liquid Argon?

Ionization



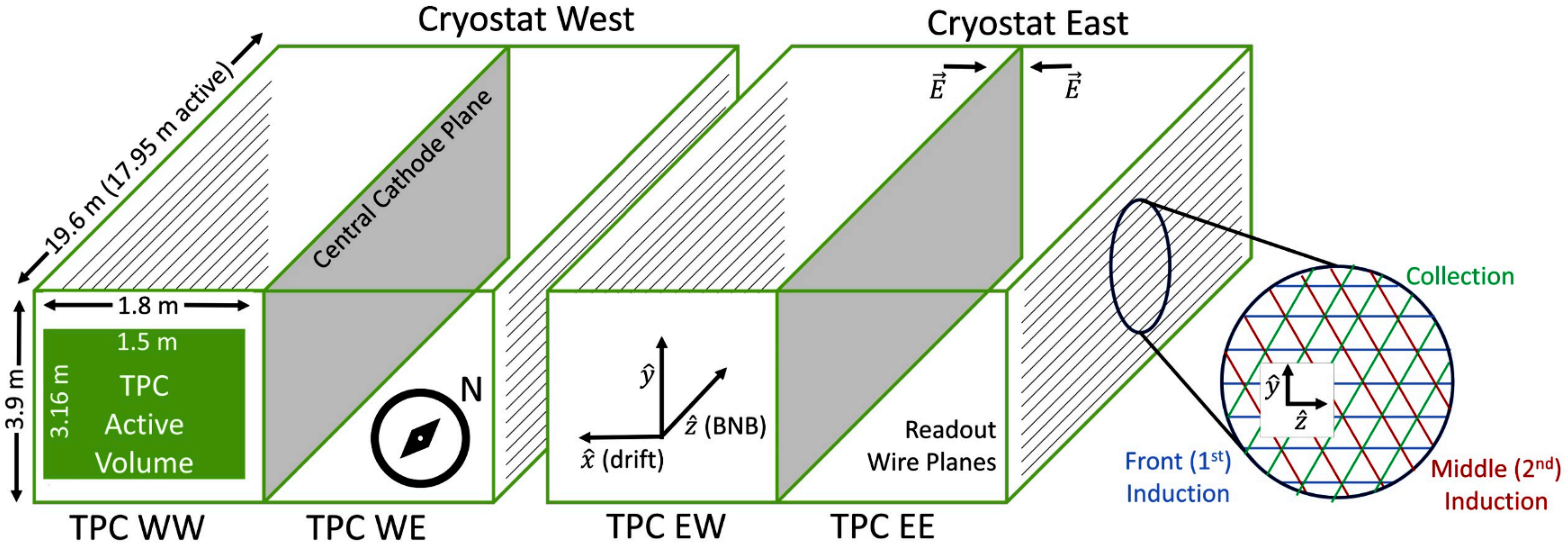


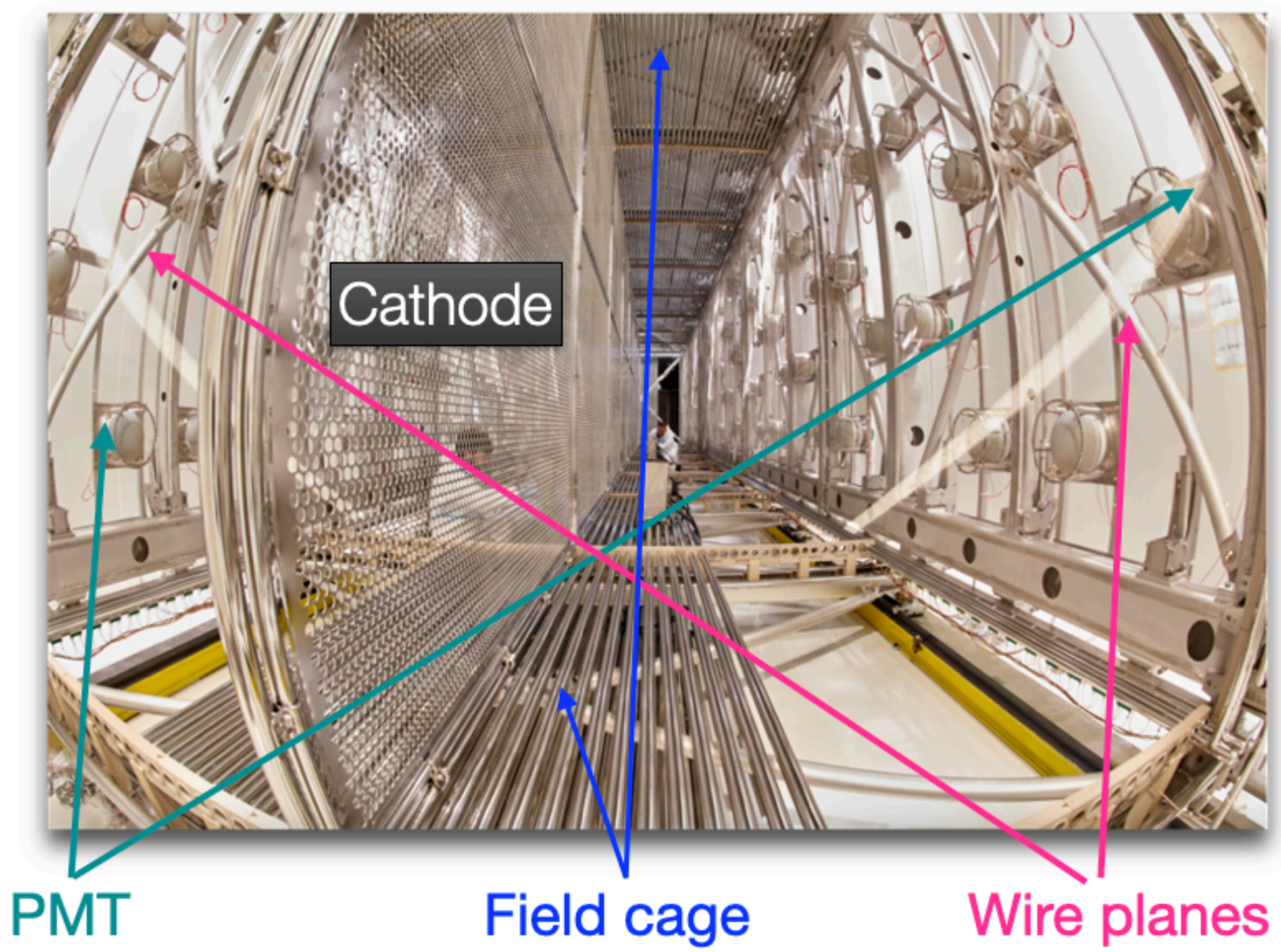


Charged particles generate excited argon molecules that in turn emit **light** (~40000 γ/MeV at λ=128 nm) in a short time ($\lesssim$ 2 μs): we use this signal to identify time of neutrino interactions (**trigger** system)

Charged particles **ionize** argon: 42000 e^-/MeV 500 V/cm **electric field** drifts the e^- (~1.6 m in 1 ms) towards the anode where wire planes are used to generate **2D images** of charged particle tracks

THE ICARUS EXPERIMENT





- **ICARUS T600**: the first large scale LArTPC ever built with 760 tons of pure LAr, **470 tons** active mass
- 2 cryostats (3.6 x 3.9 x 19.6 m^3) with 2 TPCs each and central cathode
- **3 wire planes** at different orientation (54000 wires, 3 mm pitch) to measure the ionization signal
- **360** photomultipliers (**PMTs)** behind the wires measure scintillation light providing trigger (~300 ps resolution)
- 2.85 m concrete **overburden** to suppress and external Cosmic Ray Tagger (**CRT**) to tag **cosmic rays background**
- After **3 yr physics run at LNGS** and **intensive overhaul at CERN** ICARUS detector was moved to Fermilab

DETECTOR OPERATIONS AND DATA ACQUISITION

- CRT (overburden) **installation** completed in 2021(**2022**): **data taking** started in **June 2022**

Collected statistics in 3 physics runs [Proton on Target (PoT)]

Run	Duration	BNB (FHC) [*] positive focusing	NuMI (FHC) [*] positive focusing	NuMI (RHC) [*] negative focusing
1	Jun-July '22	$0.41 \ 10^{20}$	$0.68 \ 10^{20}$	-
2	Dec '22-July '23	$2.05 \ 10^{20}$	$2.74 \ 10^{20}$	-
3	Mar-July '24 [**]	$1.36 \ 10^{20}$	-	$2.82 \ 10^{20}$
Total	/	$3.82 \ 10^{20}$	$3.42 \ 10^{20}$	$2.82 \ 10^{20}$

[*] **FHC** = Forward Horn Current (ν beam mode), **RHC** = Reverse Horn Current ($\bar{\nu}$ beam mode)

[**] Reduced duration → exposure due to prolonged accelerator shutdown

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

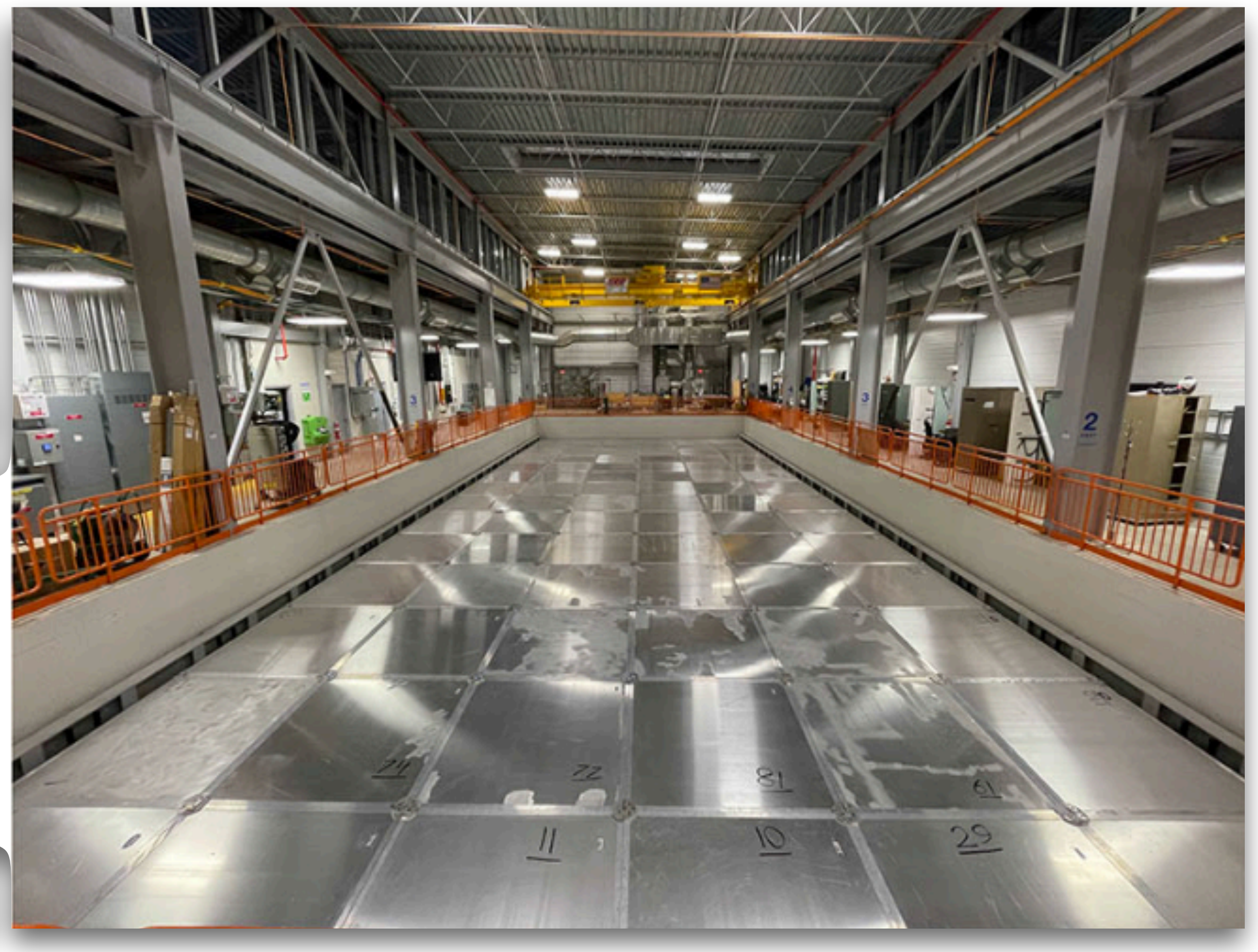
- Three physics runs **completed** so far - **Run 4** started in October 2024 and is currently ongoing
- Steady data taking with excellent **stability** at BNB rates > 4Hz, **>90% efficiency** with E_{dep}>200 MeV
- **Impurities** in LAr ~40 p.p.t. O_2 equivalent → ~full track detection efficiency in the 1.5 m drift
- **Trigger:** light registered simultaneously by 4 PMT pairs in a 6 m longitudinal slice in coincidence with beam

DETECTOR PERFORMANCE

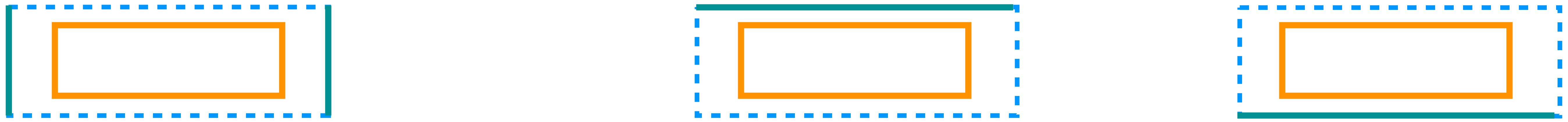
- All **subsystems fully operational** since the start of physics runs:
  - external CRT tag incoming cosmics with ~95% efficiency
  - Inner PMTs have gain equalized within 1% to $G=5\times10^6$
- Measurement of the time of flight (ToF) with signals from **CRT & PMT** systems to **reject cosmics ray background**

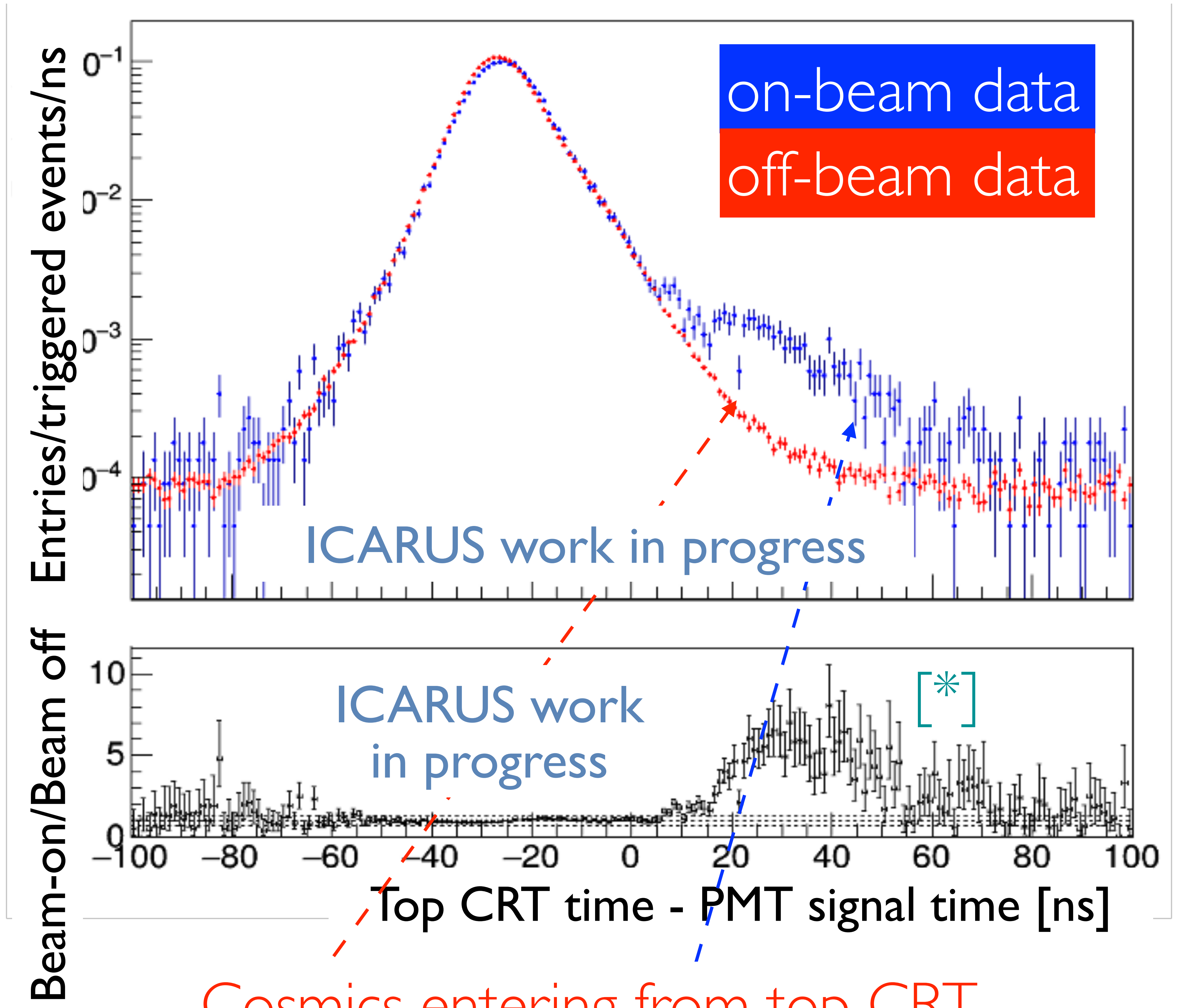
Side CRT

Top CRT



Bottom CRT





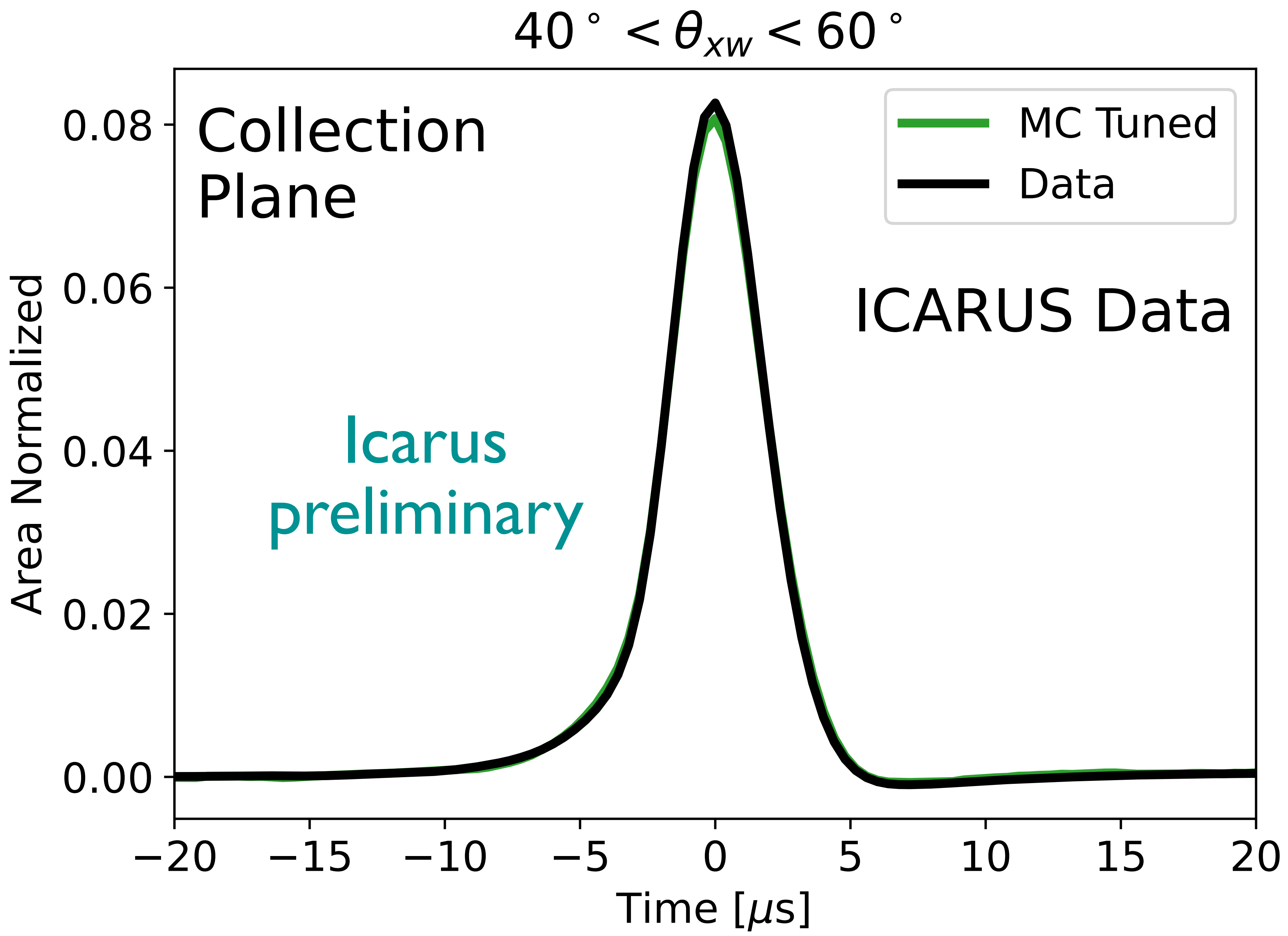
Cosmics entering from top CRT
$\Delta T_{CRT-PMT} < 0$ (bkg)

ν products exiting through top CRT
$\Delta T_{CRT-PMT} > 0$ (signal)

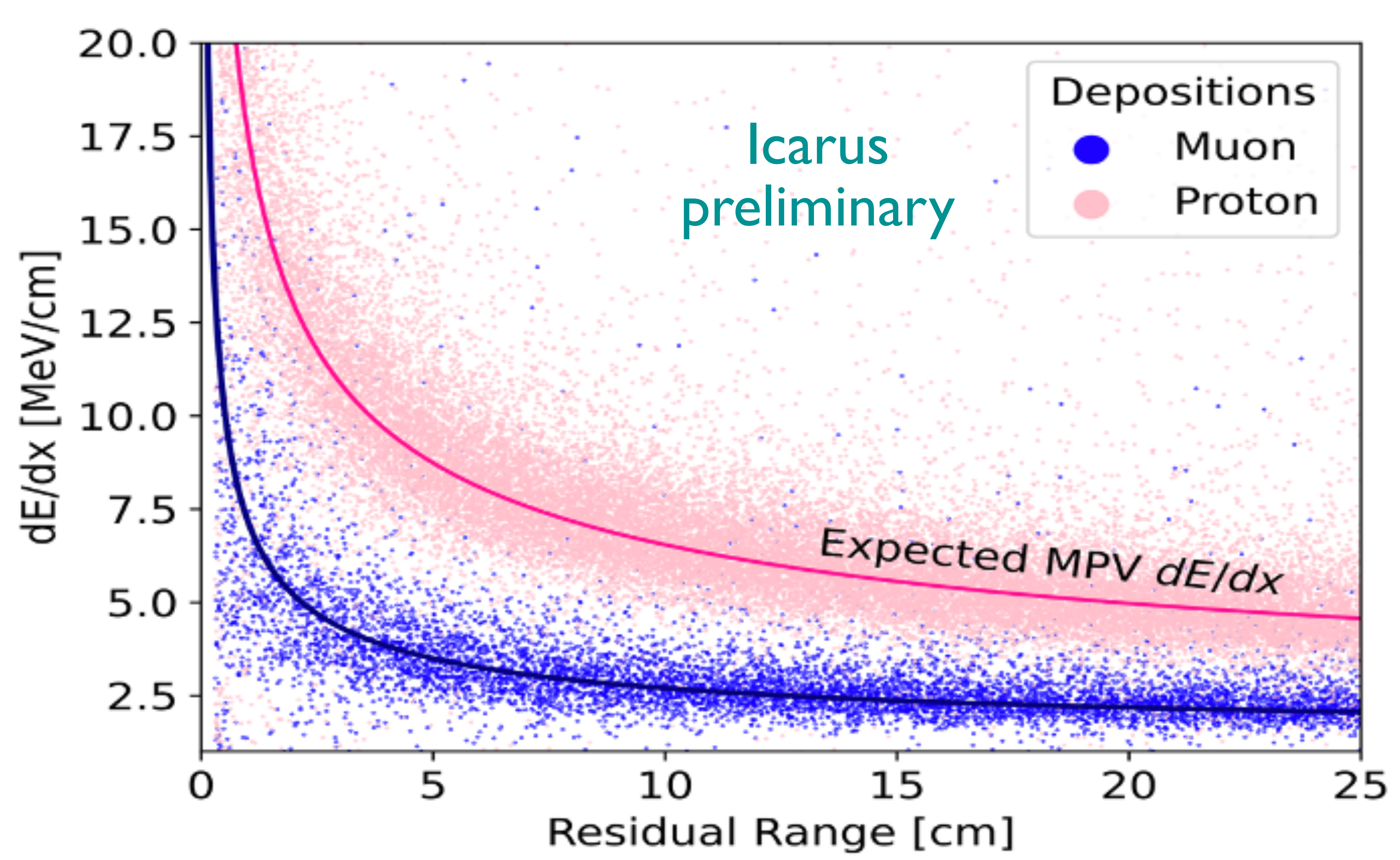
[*] Excess due to ν beam (signal)

DETECTOR CALIBRATION AND MODELLING

- Accurate modeling of the signal from TPC wires and new angular dependent **recombination model** arXiv: 2407.12969
- Our detector response **calibration** is extracted on cosmic muons and protons from ν interactions and the energy reconstruction is validated comparing calorimetric and range-based reconstructions
- We use the energy loss per unit length $(\mathrm{dE/dx})$ vs residual range to identify different particles



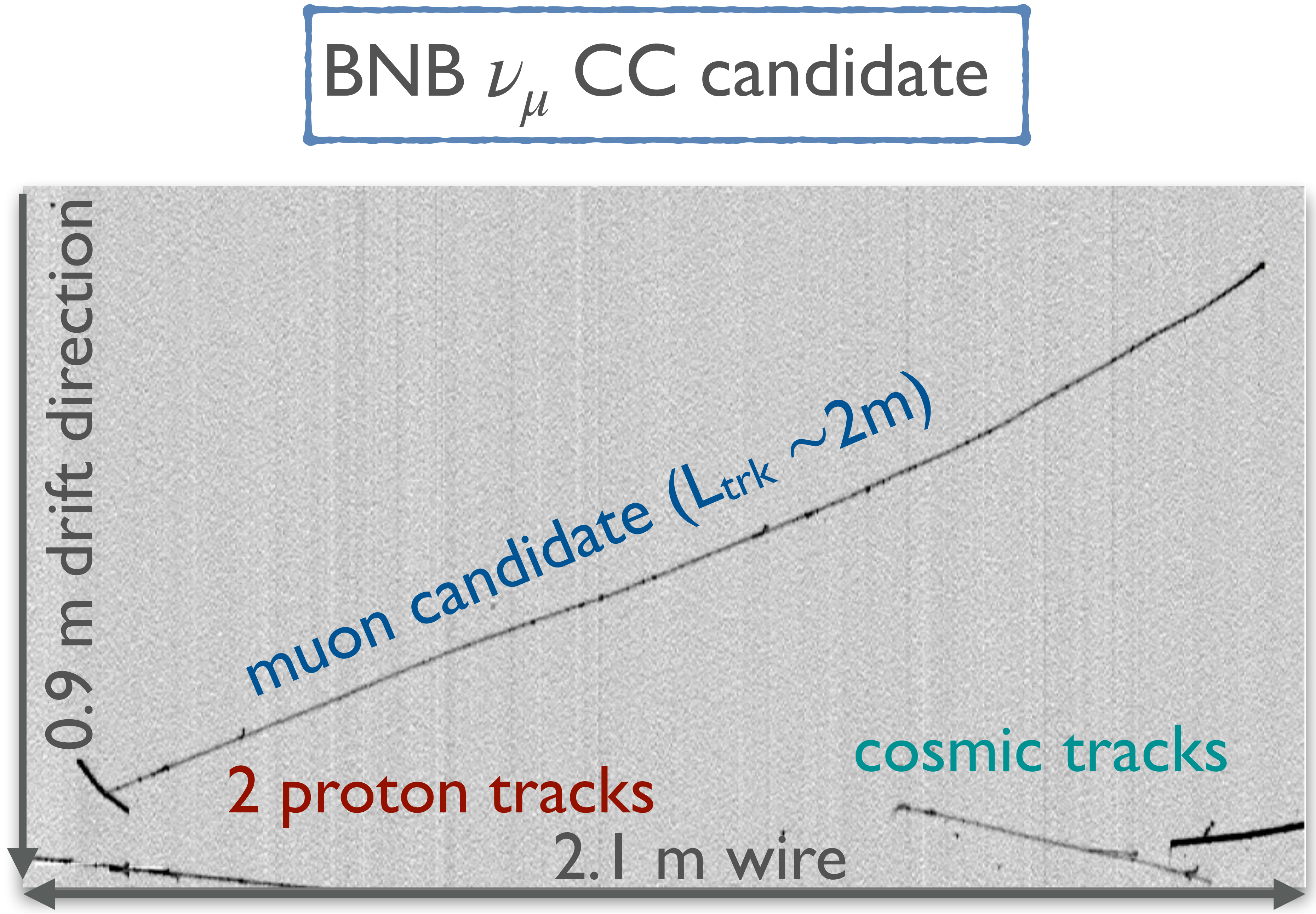
arXiv: 2407.11925



Average signal response for a track angular bin

NEUTRINO CANDIDATES EVENT RECONSTRUCTION

- Two reconstruction frameworks to characterize neutrino events:
  - **Pandora**, pattern recognition software widely used in LArTPCs
  - **SPINE**, entirely based on Machine Learning techiques (arxiv)
- Continuous effort to improve reconstruction and data/simulations agreement
- Validation using the **visual scanning** of collected events
  - Interaction point (*vertex*) reconstruction
  - Agreement between light and charge signal barycenters along the longitudinal (beam) direction is within 1 m



THE ICARUS PHYSICS PROGRAM

- **SBN joint (SBND+ICARUS) physics program** for the **sterile neutrino** search with the BNB ν_μ, ν_e events
- Before the joint oscillation analysis with SBND, ICARUS is now focusing on a **standalone physics program:**
  - Analysis of the ν_μ **disappearance channel with BNB**, to be complemented with ν_e **disappearance from NuMI** beam data, being 6 degrees off-axis it has enriched ν_e composition
    The goal is to verify the **Neutrino-4 experiment claim**
  - Study of ν_μ, ν_e interactions from the NuMI beam to **measure ν-Ar cross sections** and optimize our event reconstruction in the energy range that **DUNE** will explore
  - Search for evidence of physics **Beyond Standard Model** in other channels using NuMI data
    A channel was already explored (analysis finalized): **dark matter decay in a di-muon state**

ν_μ DISAPPEARANCE ANALYSIS WITH BNB BEAM DATA

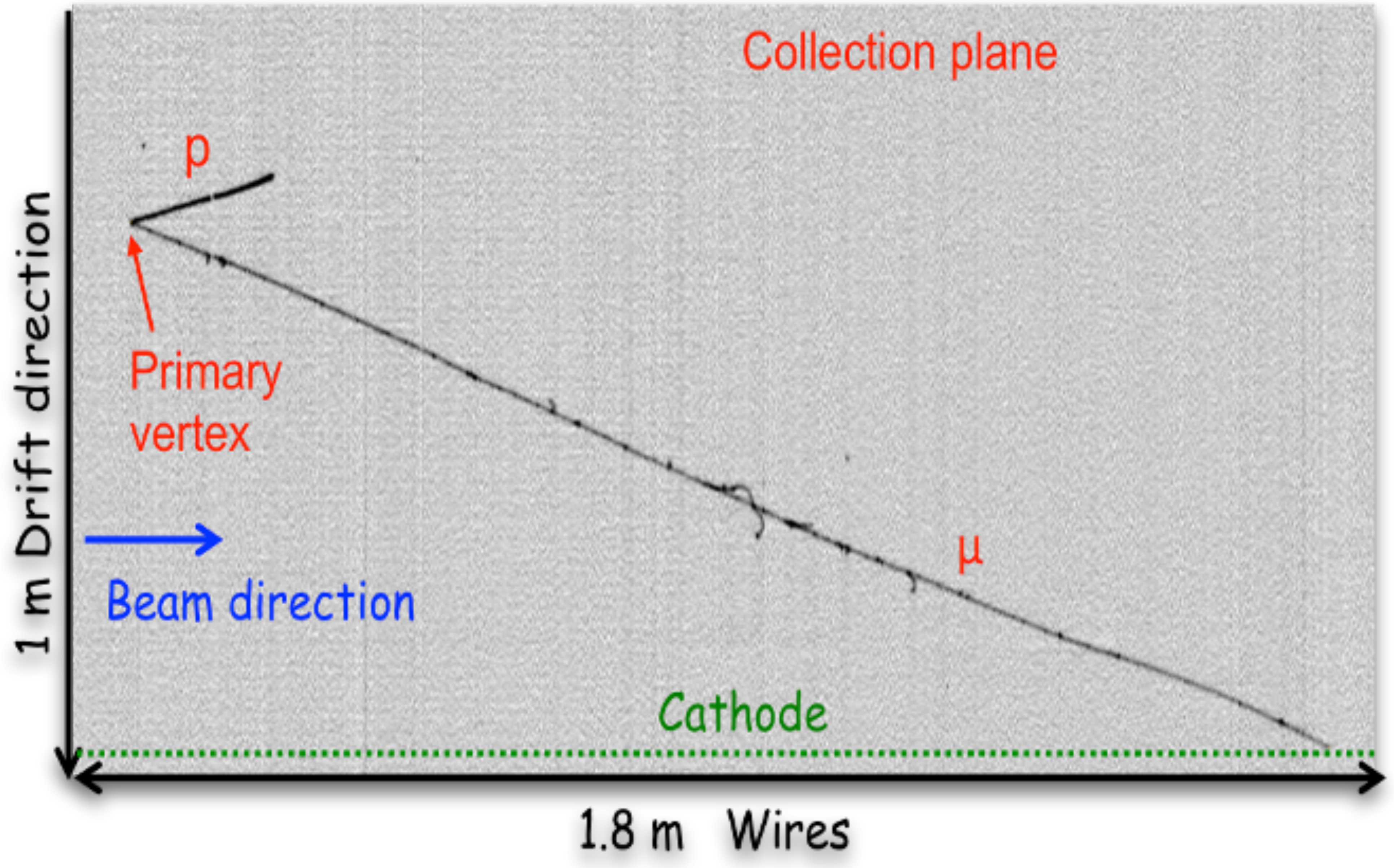
- Selection of **fully contained ν_μ** charged current events with **1μ+N protons in the final state**

  Event kinematic extracted from range measurements

  (I) Light signal within 1.6 μs beam spill in coincidence with reconstructed TPC tracks and no CRT signal

  (II) A muon with L_{track}>50 cm, $N > 1$ protons with E_K>50 MeV (L_{track}>2.3 cm)

  (III) No additional pion/photon



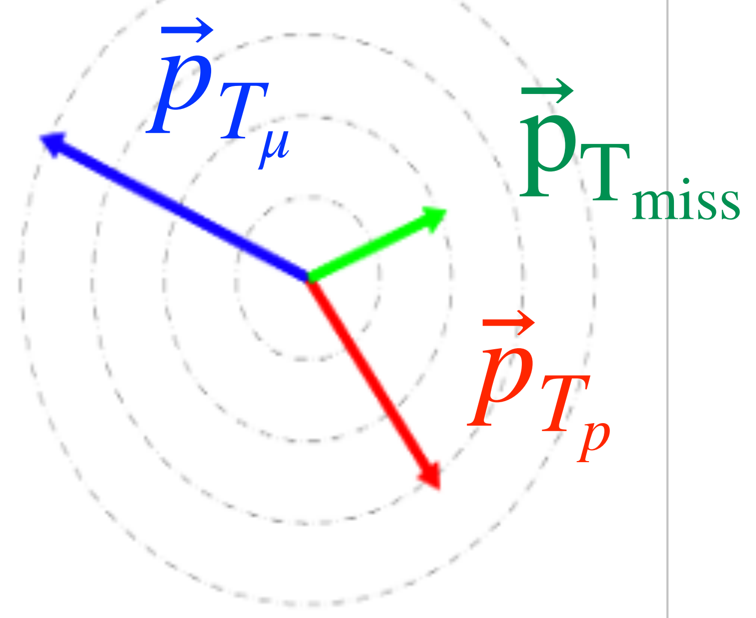
- Residual cosmic background <1%
- We included systematic uncertainties on our measurement due to:
  - neutrino flux
  - models of neutrino interactions (cross sections)

  Should cancel out with a joint SBN analysis

  - detector effects (signal collection/reconstruction efficiencies, …)

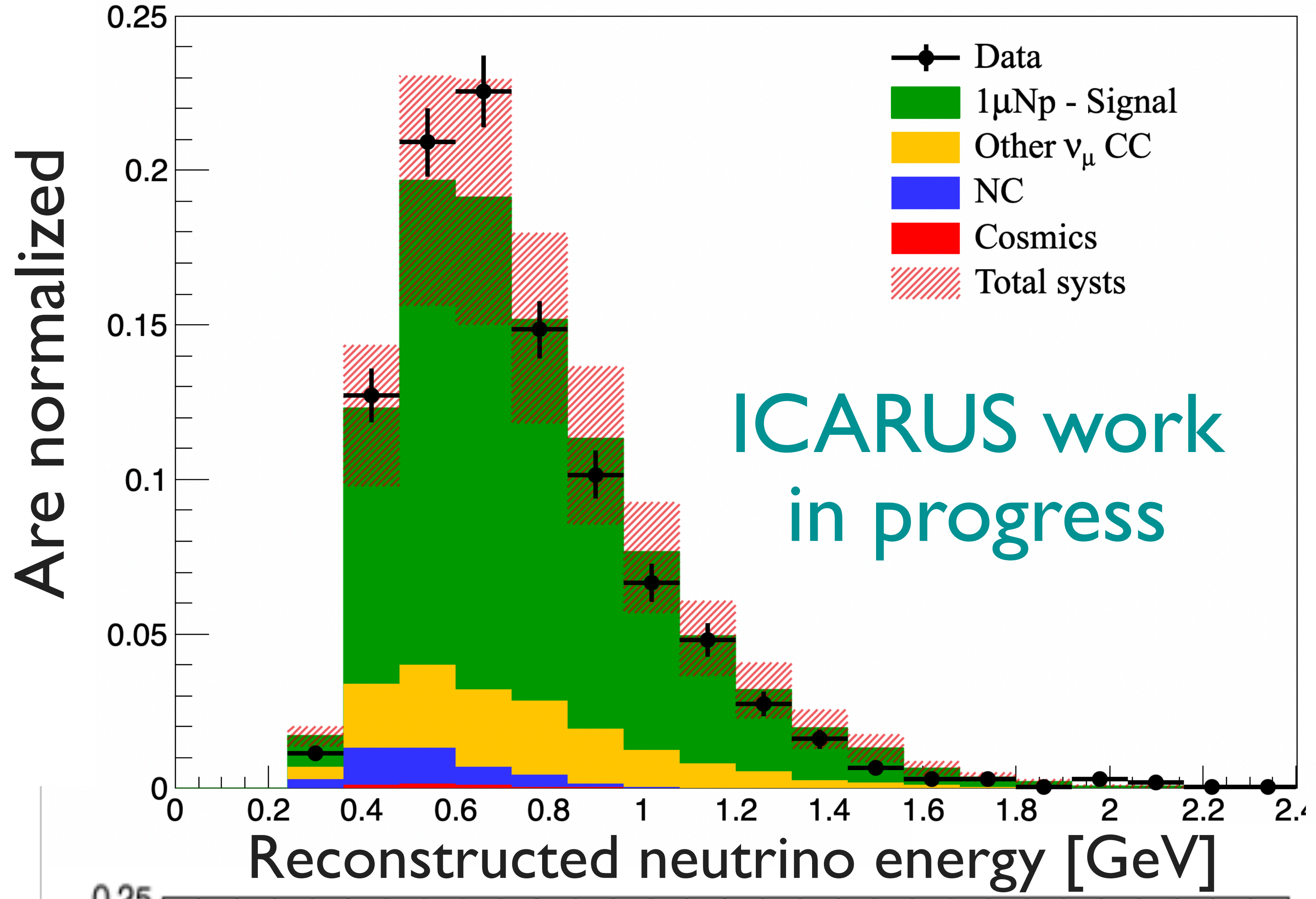
  Conservative estimates extracted while improving our simulations

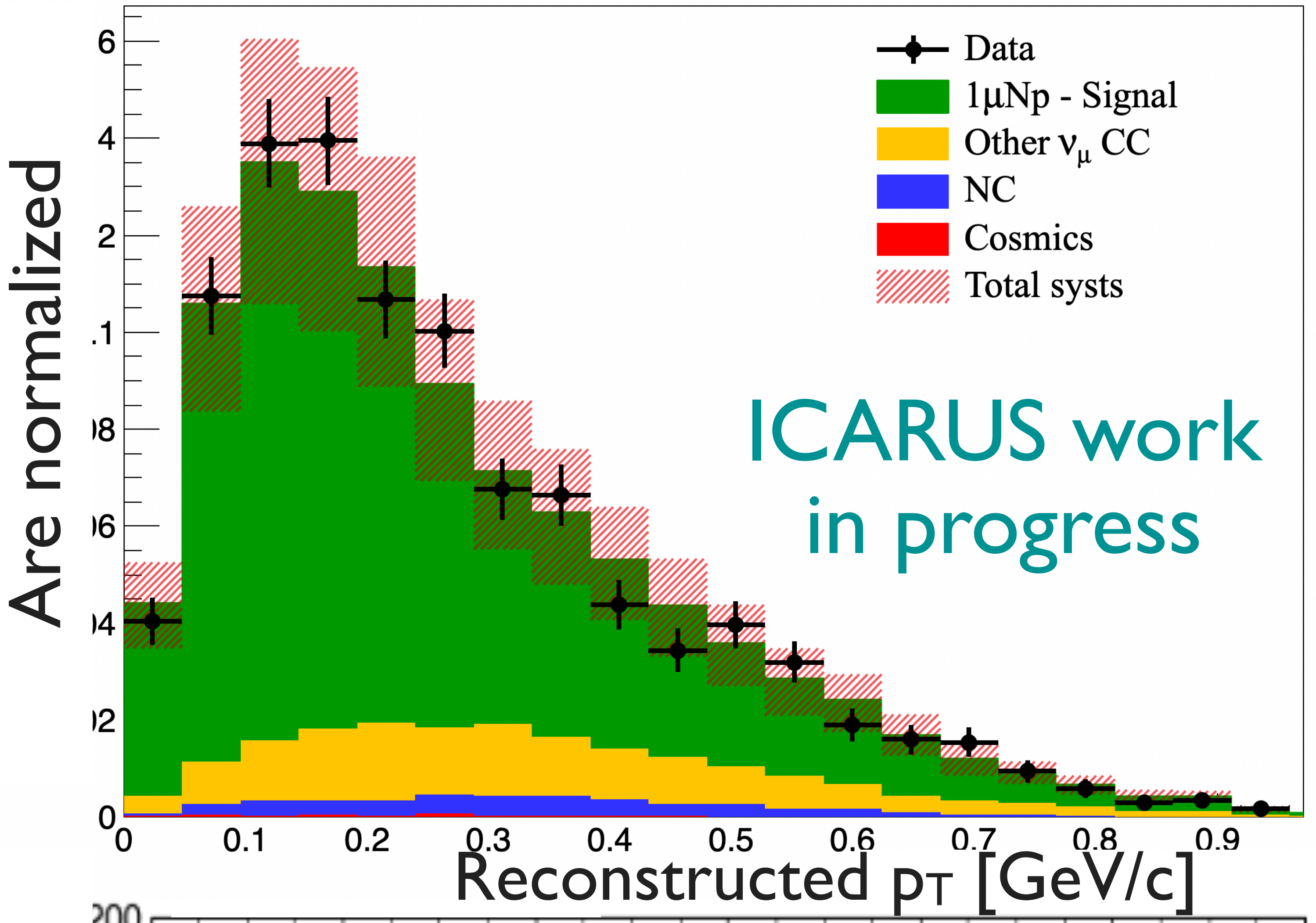
Momentum in the transver plane

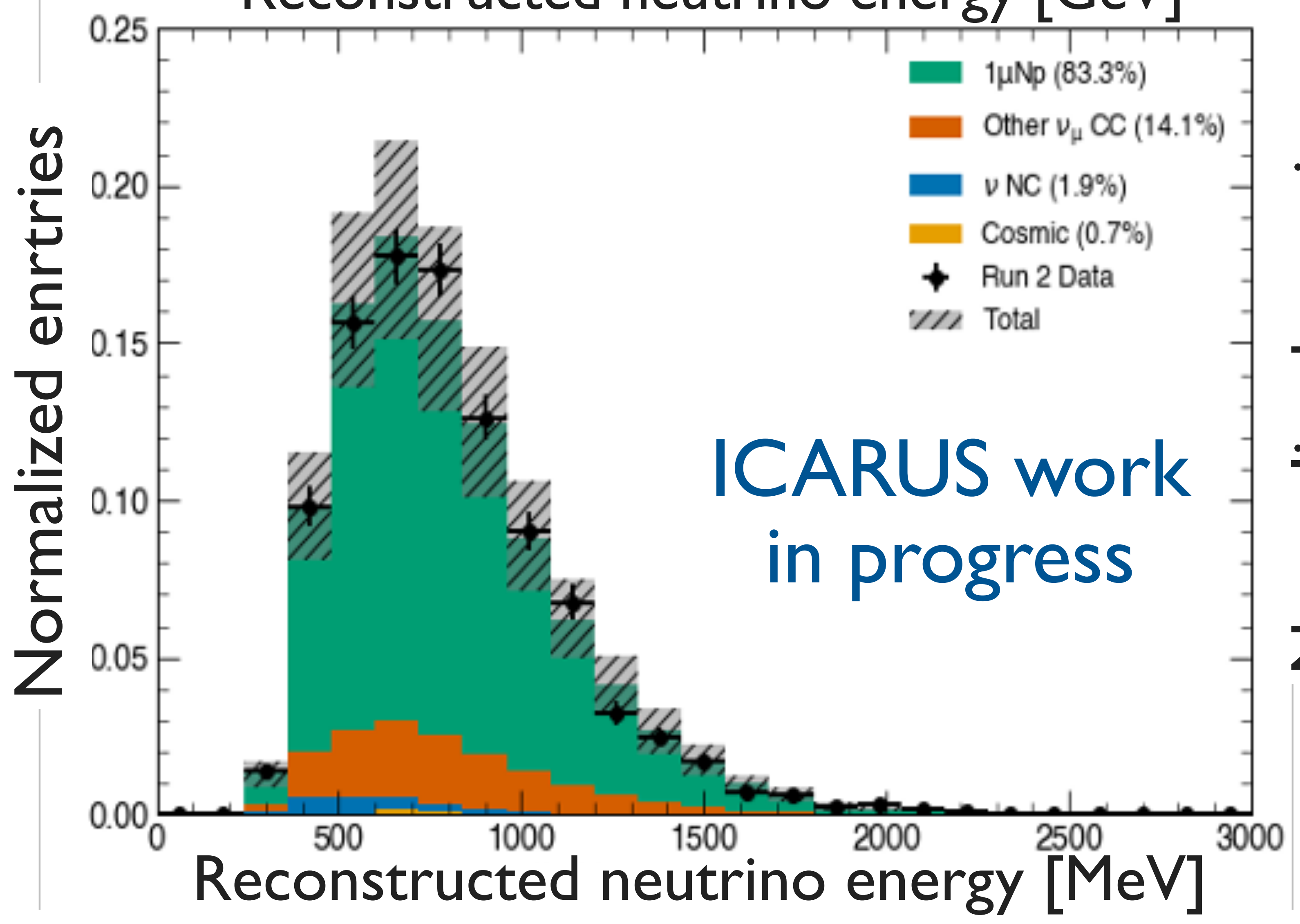


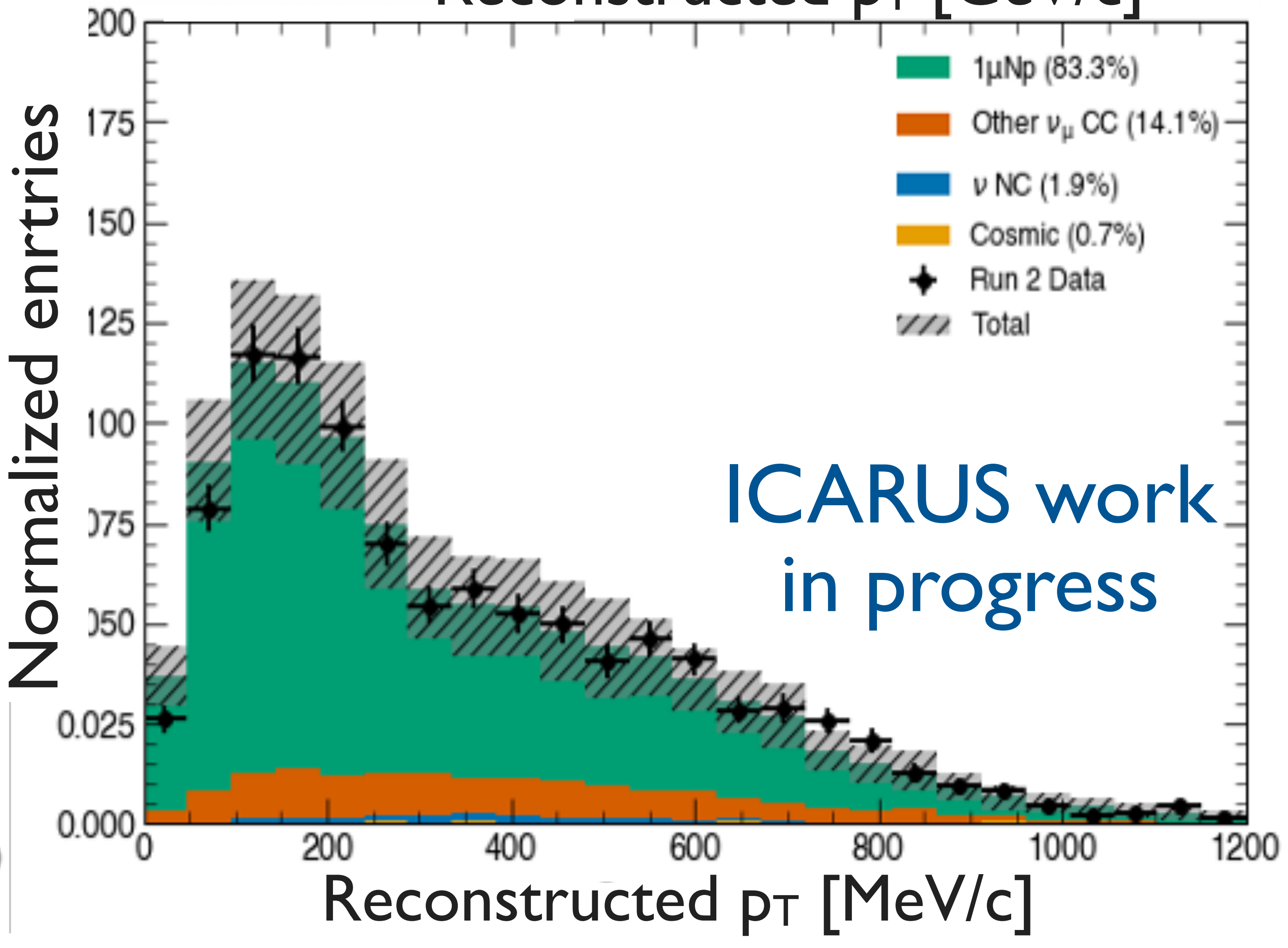
ν_μ DISAPPEARANCE ANALYSIS: PRELIMINARY RESULTS

- **10%** of the data analysed (~20 x data available) showing data/MC agreement within systematic effects









- **Pandora-based** reconstruction selection

  ~50% signal efficiency, **80%** signal purity

  1.93 x 10^{19} Proton on Target **(PoT)**

  34000 events (Run1-3)

- **SPINE-based** reconstruction selection

  ~75% signal efficiency, **80%** purity

  1.92 x 10^{19} PoT

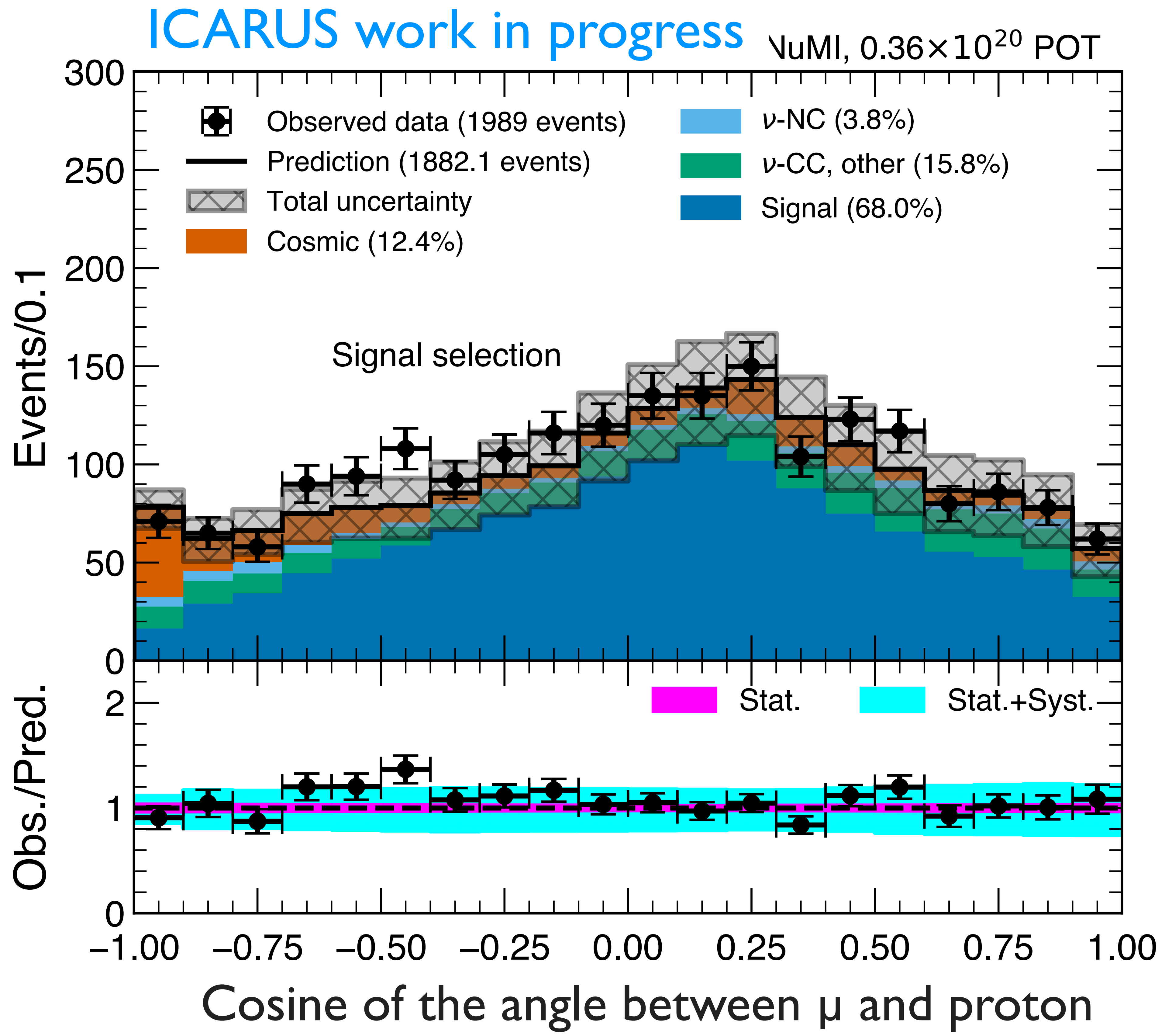
  47000 events (Run 1-3)

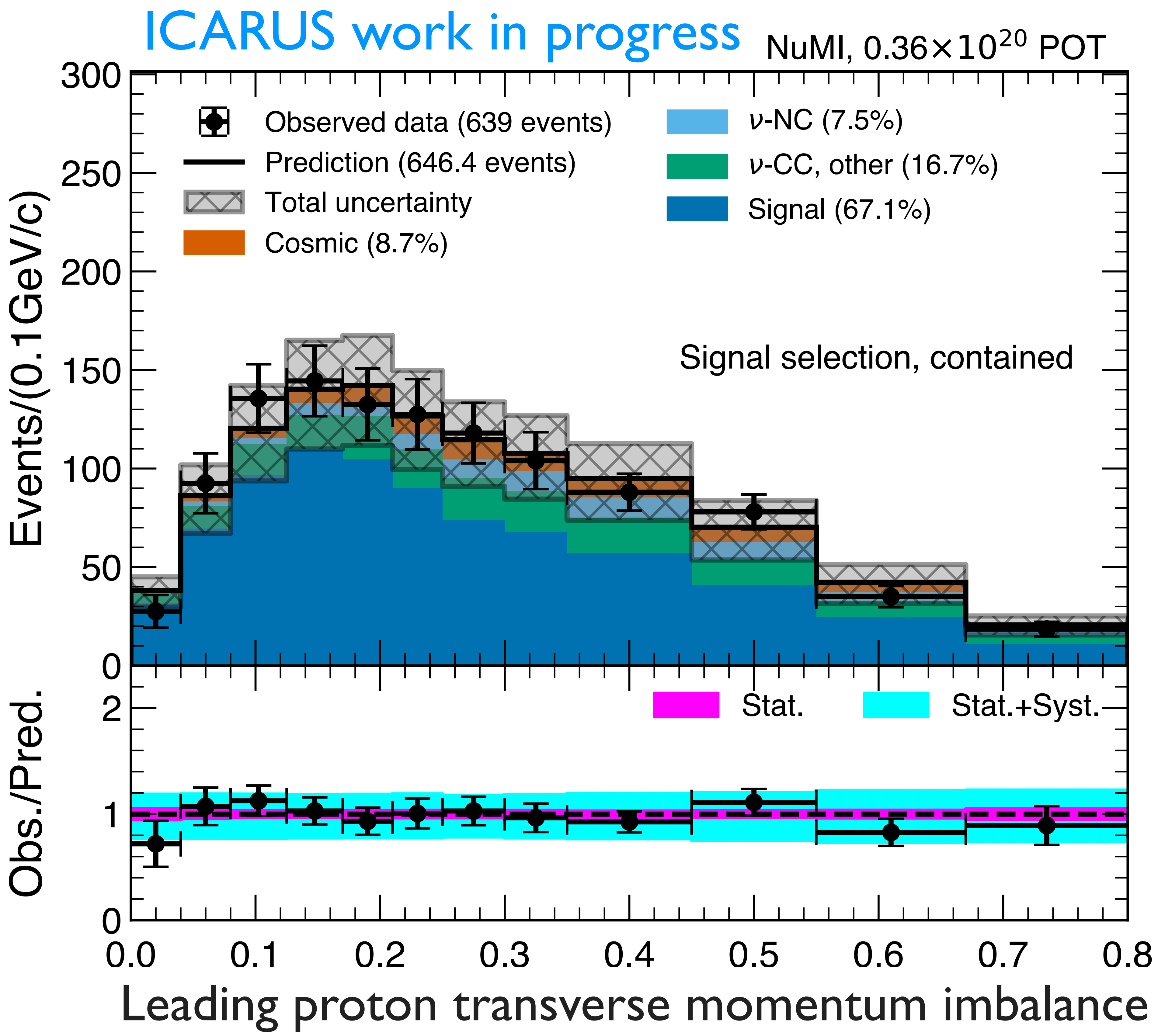
We are ready for the next analysis steps:

- **enlarge the control sample** to confirm the robustness of the analysis
- proceed to full data unblinding and oscillation fit

CROSS SECTION MEASUREMENTS WITH NUMI BEAM DATA

- **Huge statistics** to measure ν_μ, ν_e cross sections for different types of interactions
  With 6 x 10^{20} PoT: **332 000** ν_μ, **17000** ν_e - 3.42 x 10^{20} PoT are already available for the present analysis
- First oscillation peak & **relevant phase space for DUNE** is **covered** by NuMI energy spectrum @ ICARUS

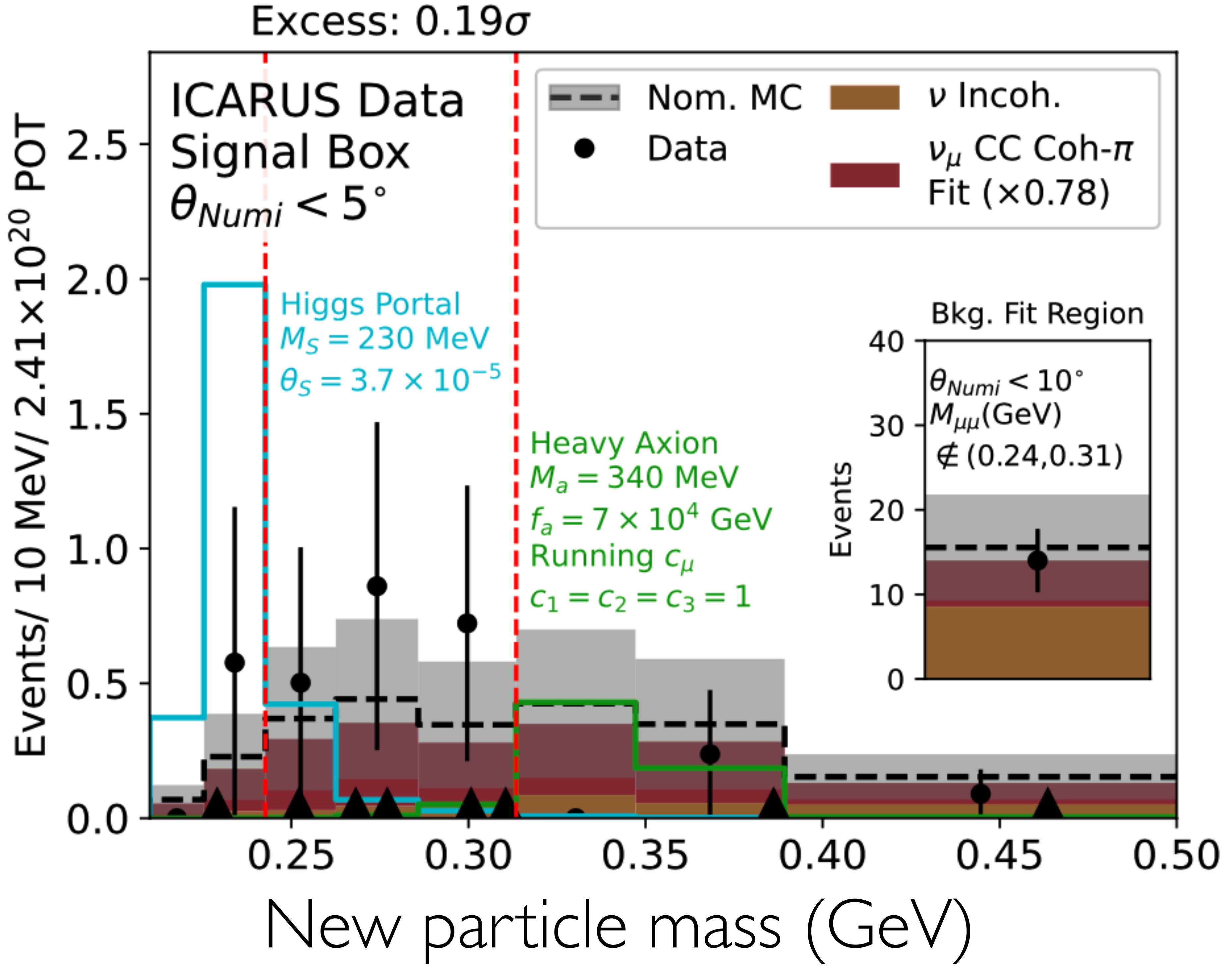




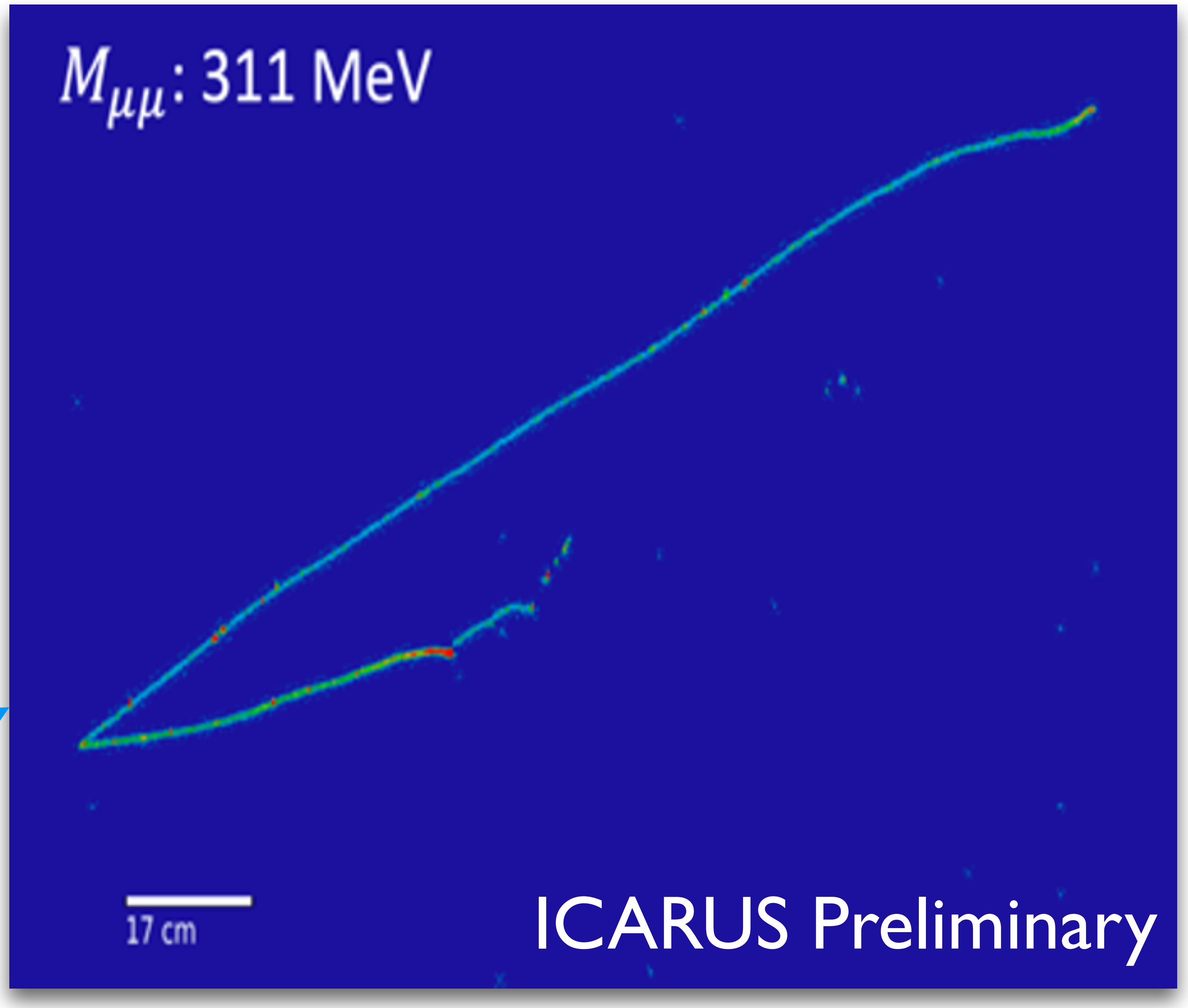
- First analysis: signal events with 1 muon, N>1 protons and no π/γ in the final state
- Control sample and systematics analysed
- 15% of data analysed
- Ready to enlarge the statistics

BEYOND STANDARD MODEL SEARCHES

- First search for a particle beyond the Standard Model decaying into a **di-muon** state **completed**
  - Signal candidates: events with 2 stopping μ-like particles fully contained in the detector
  - Signal peak expected at small angles with respect to NUMI beam ($\theta_{\mathrm{NuMI}} < 5°$)
  - All systematics included and data unblinded



No evidence of a new **signal:** 8 events observed out of 8 expected in the *null* (no signal) hypothesis



Typical signal candidate

CONCLUSIONS AND NEXT STEPS

- ICARUS is **running stably** and acquiring physics runs since summer 2022, esposed to both on-axis BNB (ν-mode) and off-axis NuMI (ν- and $\bar{\nu}$-mode) neutrino beams
- **Accurate** detector **calibration** and response **modelling** now fully embedded in our simulations
- Waiting and also in view of the upcoming joint-SBN analyses, several **single detector studies**:
  - ν_μ **disappearance** channel with **BNB** beam → control sample will be enlarged to complete validation
  - Recent effort to improve ν_e reconstruction(s) in view of a ν_e **disappearance** analysis with **NuMI**
  - **ν-Ar cross section measurements** with **NuMI** beam, first selection includes 1μNp0π events
  - Rich program for the search for **physics beyond the Standard Model** with **NuMI** beam data
    - Search for decay in a ***di-muon*** final state completed - no evidence of a signal observed
- Interesting results are foreseen soon while we continue our effort to improve event simulation and reconstruction

THANKS FOR YOUR ATTENTION