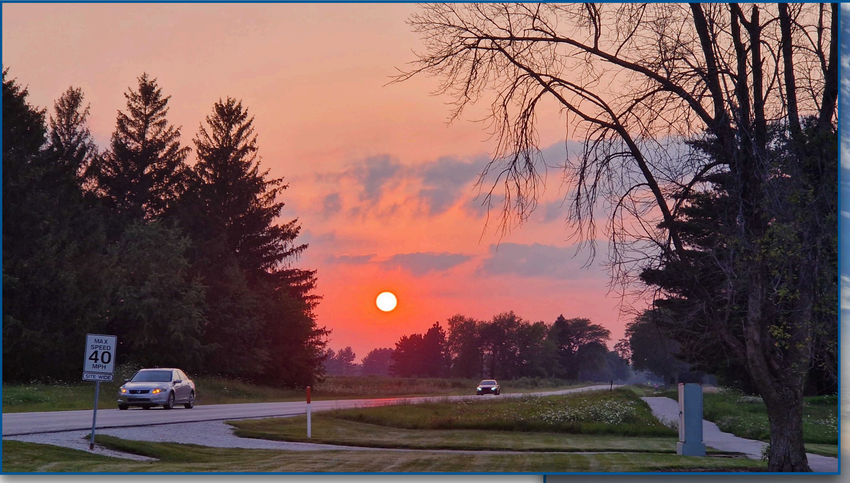
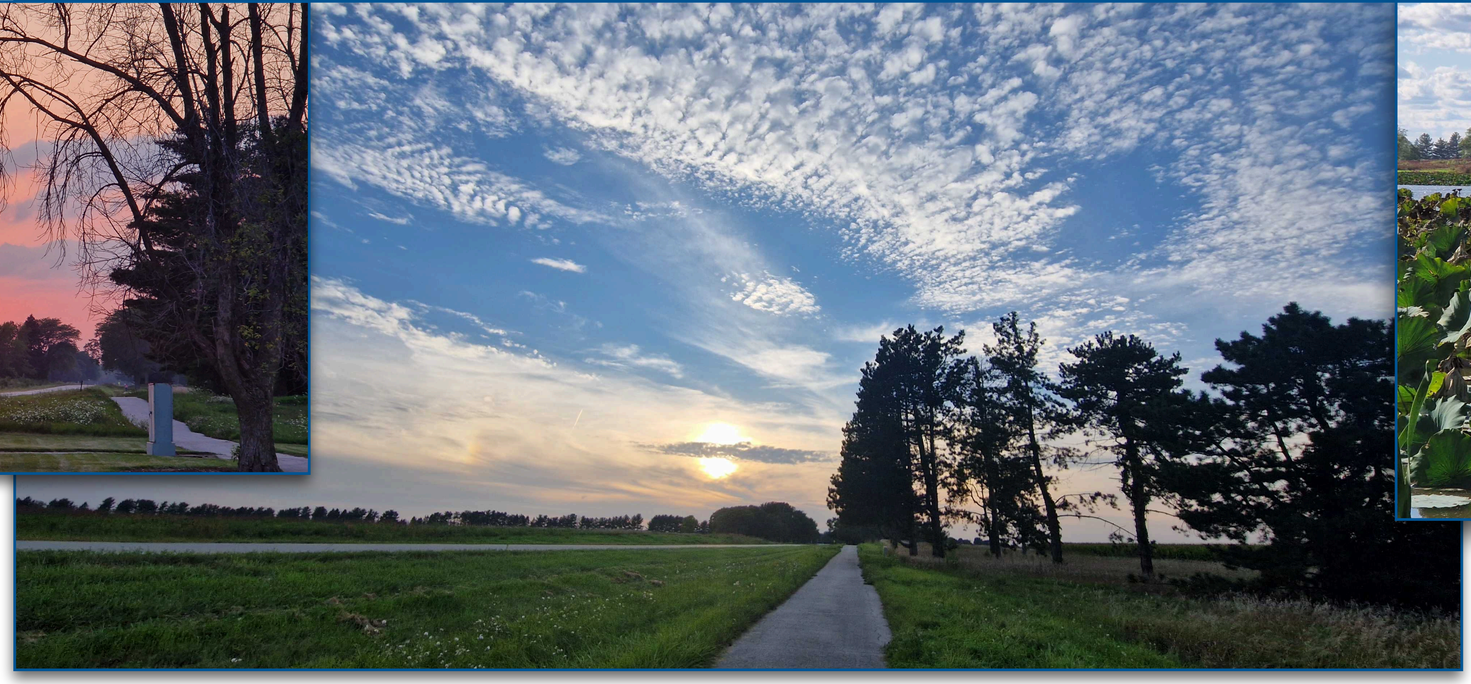




First results from ICARUS at the Short-Baseline Neutrino program

Alice Campani *on behalf of the* ICARUS *collaboration*

35th Recontres de Blois, 22 October 2024

35th Rencontres de Blois October 20–25

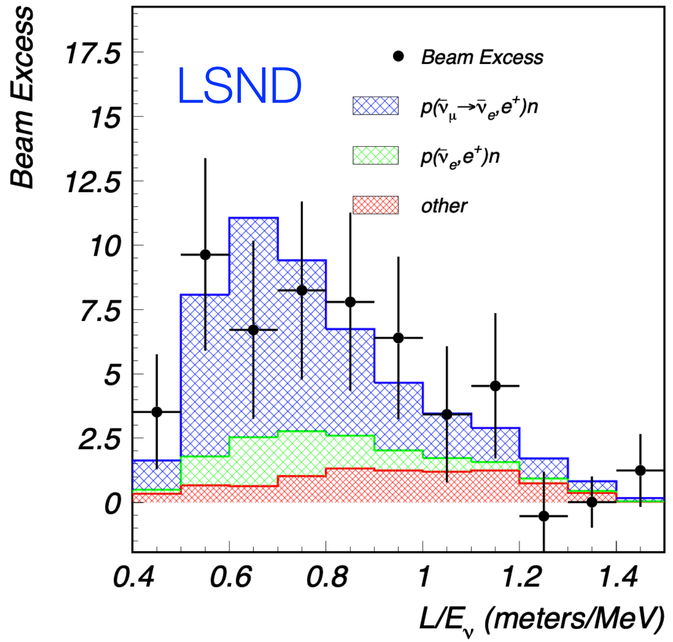
PARTICLE PHYSICS AND COSMOLOGY 2024

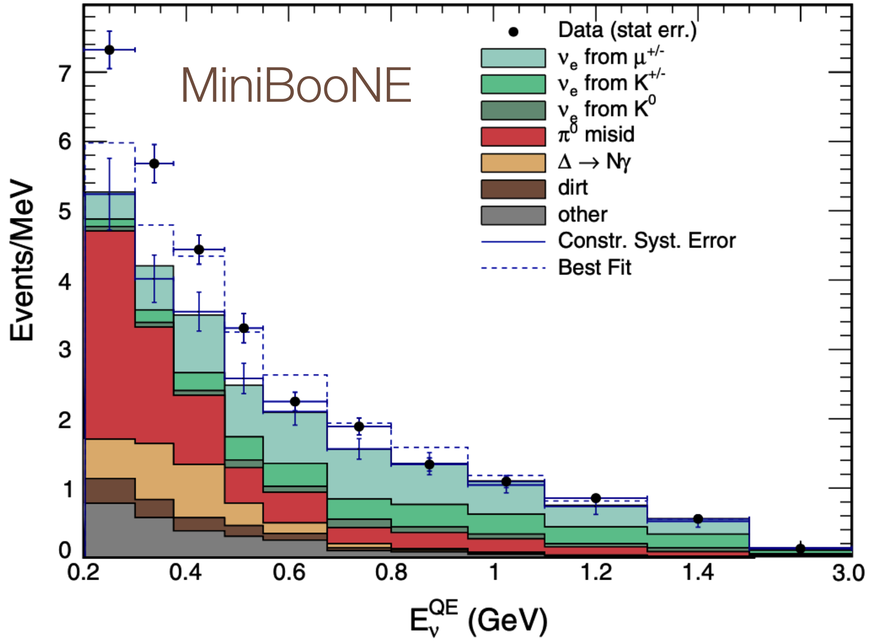
Università di Genova

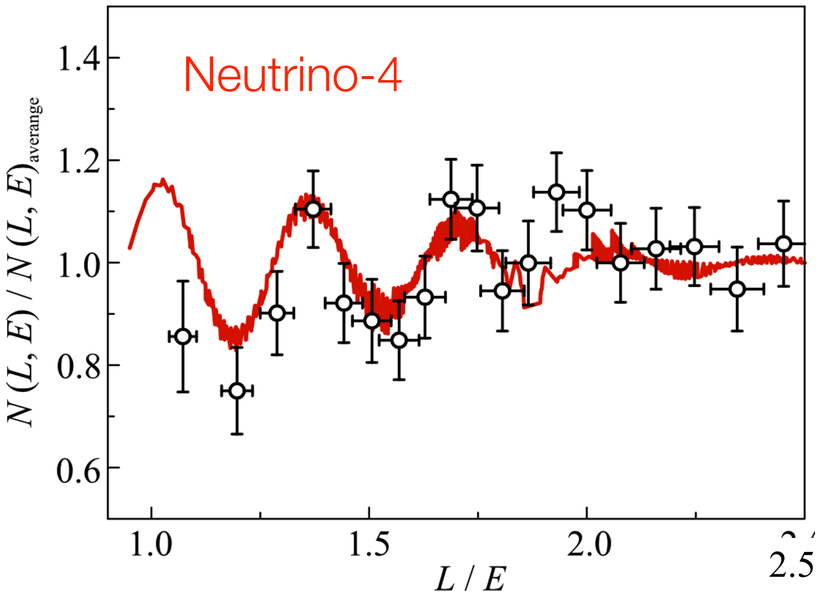
INFN Istituto Nazionale di Fisica Nucleare

THE STERILE NEUTRINO PUZZLE

- Clear tension between **appearance** and **disappearance** results in the past 20 years data







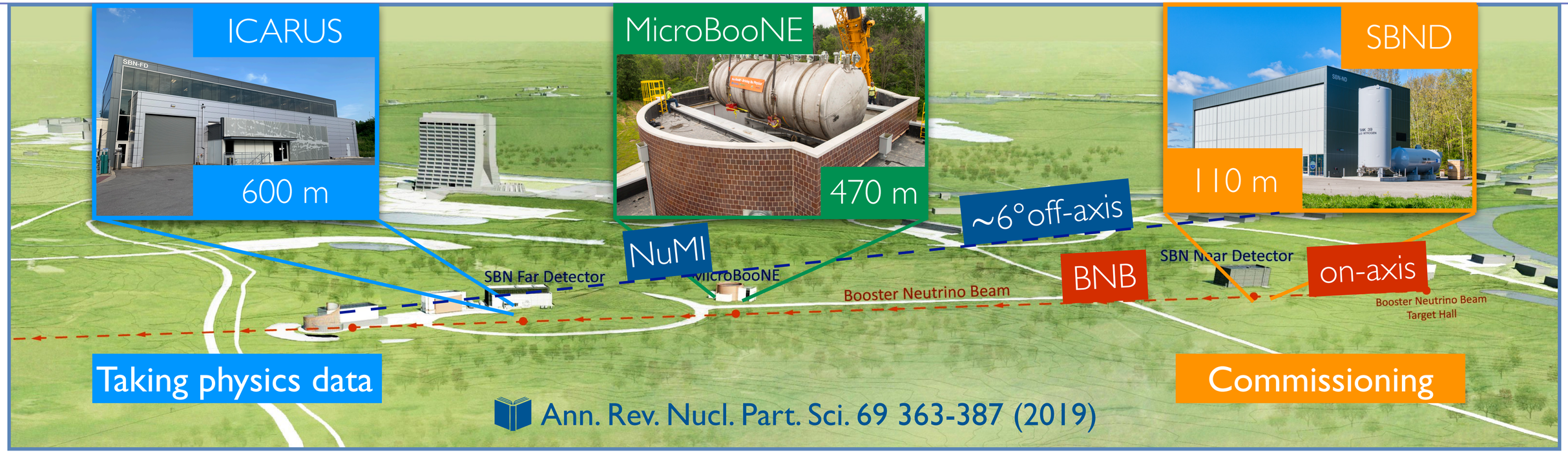
- **LSND** and **MiniBooNE** reported anomalous signals of ν_e **excess at low energy**: this could be explained with an additional $\Delta m^2_{new} \sim 1.0\ eV^2$ driving $\nu_\mu \to \nu_e$ oscillations at small distances and pointing towards the possible existence of **non-standard** heavier **sterile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

- Possible hint from **Neutrino-4**: measurements are compatible with $\Delta m^2_{new} \sim 7.3\ eV^2$ and $\sin^2(2\theta) \sim 0.36$ - same L/E as ICARUS NuMI ν_e dis. channel

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

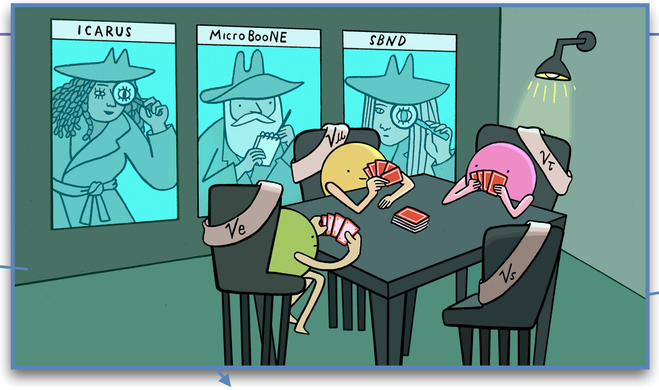
Jetp Lett. 116, 669–682 (2022)

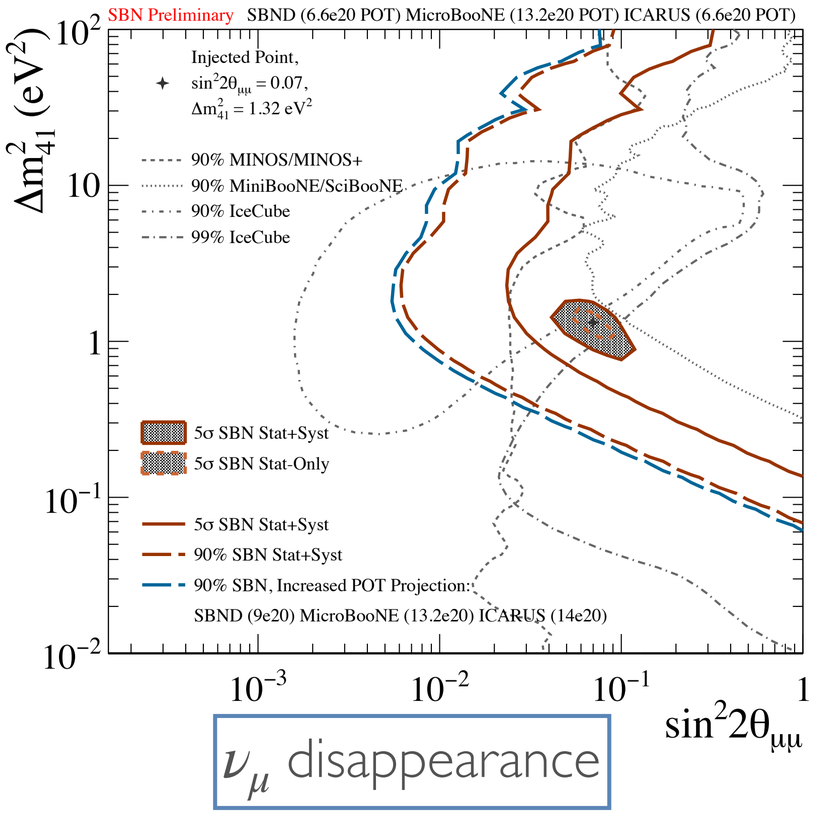
THE SHORT-BASELINE NEUTRINO PROGRAM



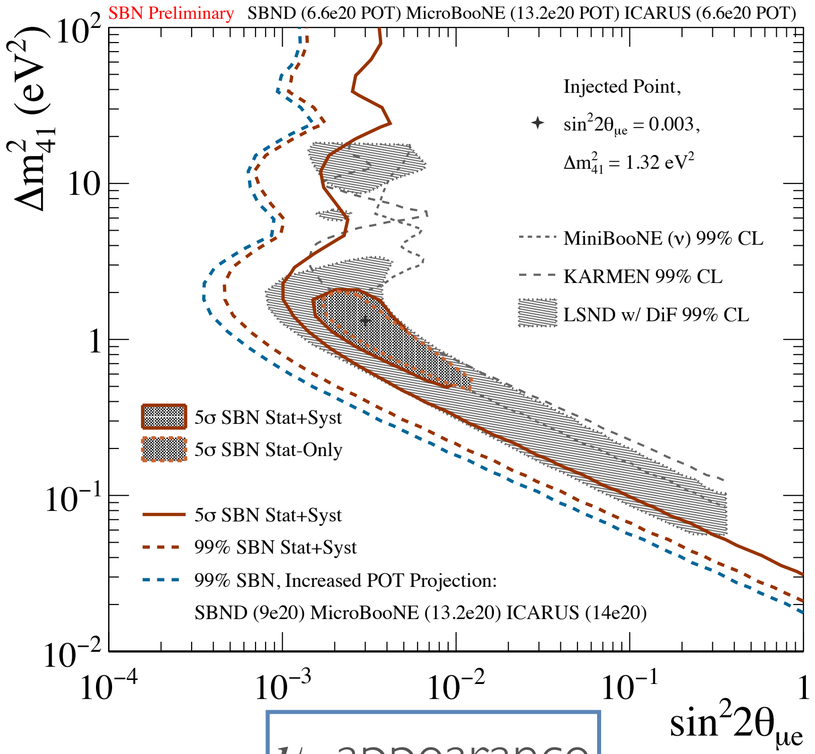
- Same technology (*near*→**SBND**, *far* detector→**ICARUS**) to minimize beam, bkg & detector systematics
- 0.8 GeV Booster Neutrino Beam (**BNB**) and for ICARUS also Neutrino at the Main Injector (**NuMI**)
- Sensitive search in the ν_e (ν_μ) (dis)appearance channels to confirm/rule out past anomalies in data
- Main goals: precision search of **1eV** mass scale **sterile neutrino** and high statistics measurements of ν – Ar **cross sections** in view of **DUNE** - also studies of Beyond Standard Model (**BSM**) channels

THE SHORT-BASELINE NEUTRINO PROGRAM

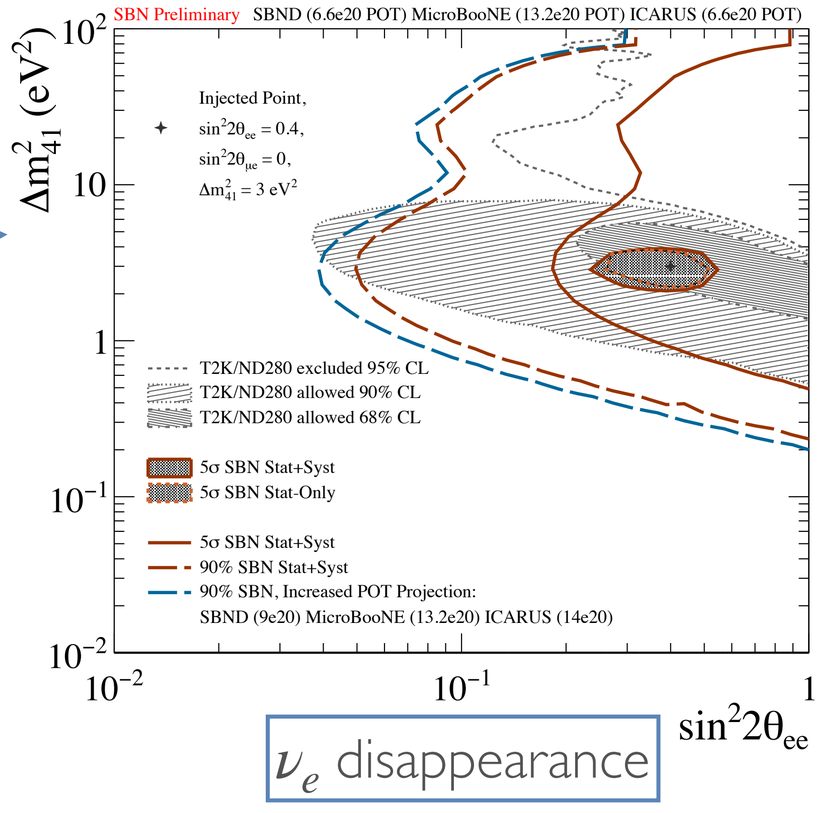




ν_μ disappearance



ν_e appearance



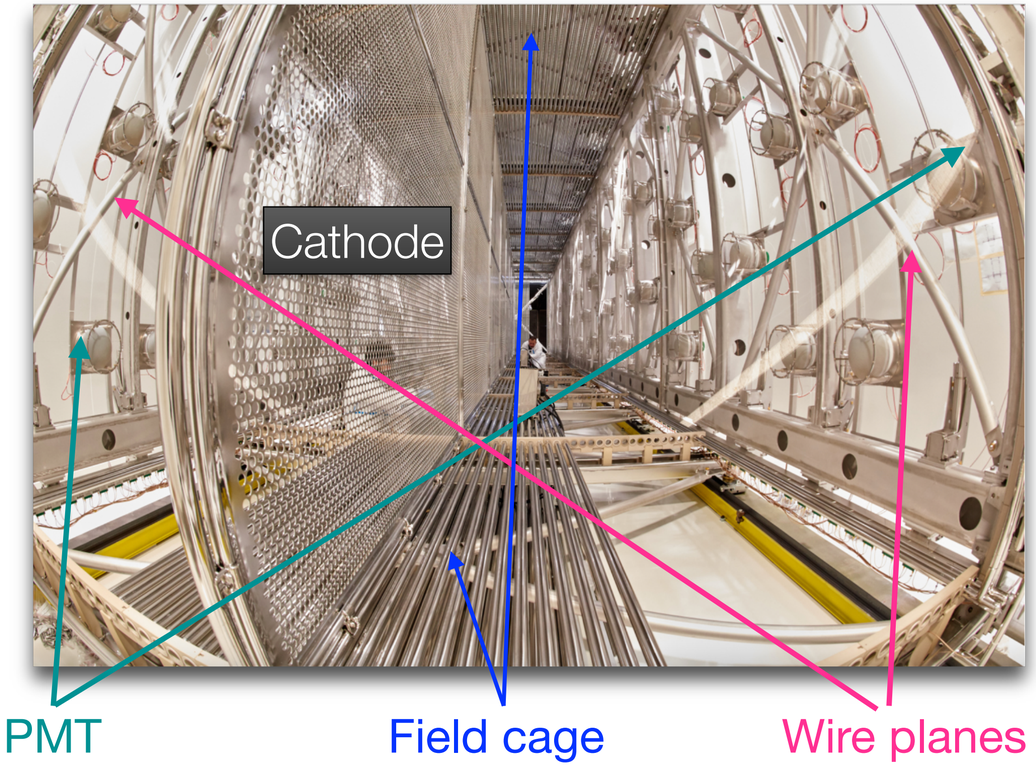
ν_e disappearance

The <u>combined</u> analysis of near and far detector grants the unique capability to study appearance and disappearance channels <u>simultaneously</u>

5σ sensitivity to LSND anomaly in **3 years of data taking** - reactor and gallium anomalies will be also probed

THE ICARUS EXPERIMENT IN A NUTSHELL

- Liquid Argon Time Projection Chambers (**LArTPCs**) [C. Rubbia, 1977] are high granularity, continuously sensitive, self-triggering detectors - 3D imagining, topological and calorimetric reconstruction: ideal for ν **physics**!
- **ICARUS T600**: the first large scale LArTPC
  760 tons of pure LAr, **470 tons** active mass
  LAr purification by copper filters and molecular sieves
- 2 cryostats (3.6 x 3.9 x 19.6 m^3) - 2 TPCs each with central cathode $\mathbf{E_d = 1.5\ kV/cm}$, 1.5 m drift, $\mathbf{t_d \sim 1 ms}$
- **3 planes** at 0, ±60° read ionization charge, 54k wires, 3 mm pitch
- **360** 8" TPB-coated **PMTs** behind the wires measure scintillation light providing t_0 timing and trigger
- 2.85 m **overburden** and external 4π Cosmic Ray Tagger (**CRT**) to suppress and tag incoming cosmics - 11 μ tracks per trigger



- Successful **3 yr physics run at LNGS** and **intensive overhaul at CERN** to upgrade cryogenics, LAr purification system, TPC readout electronics and PMTs - CRT (overburden) **installation** completed in 2021 (**2022**)

DETECTOR OPERATIONS AND ACQUISITION

- **Data taking** started in June 2022, 3 physics run since then: **run 3** (both ν beams) 15 March - 12 July 2024
- 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 → **free $\tau_e \approx$ 7-8 ms**, ~full track det. efficiency in the 1.5 m drift
- **Trigger:** light signal registered simultaneously by 4 PMT pairs in a 6 m longitudinal slice in coincidence with BNB (1.6 μs), NuMI (9.5 μs) beam spills - CRT activity in 2 ms is recorded to tag cosmics (rate ~0.7 Hz)

Collected statistics (PoT)

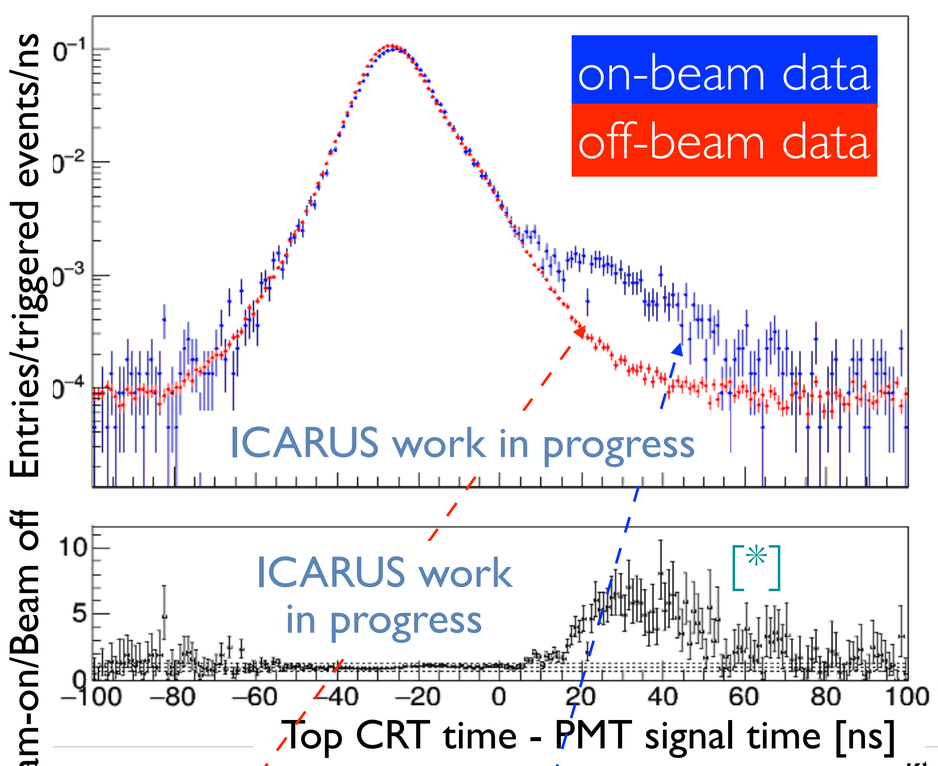
Run	Duration	BNB (FHC) [*] positive focusing	NuMI (FHC) [*] positive focusing	NuMI (RHC) [*] negative focusing
1	Jun-July '22	0.41 10^{20}	0.68 10^{20}	-
2	Dec '22-July '23	2.05 10^{20}	2.74 10^{20}	-
3	Mar-July '24 [**]	1.36 10^{20}	-	2.82 10^{20}
Total	/	3.82 10^{20}	3.42 10^{20}	2.82 10^{20}

[*] **FHC** = Forward Horn Current, **RHC** = Reverse Horn Current

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

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

DETECTOR PERFORMANCE



Cosmics entering from top CRT

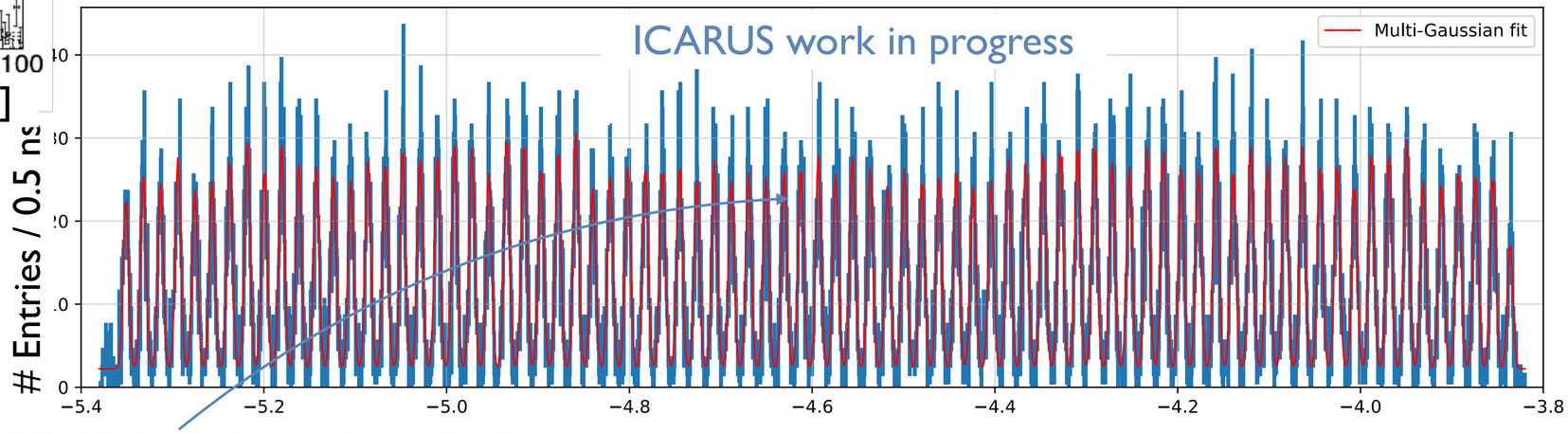
$\Delta T_{CRT-PMT} < 0$ (bkg)

ν products exiting through top CRT

$\Delta T_{CRT-PMT} > 0$ (signal)

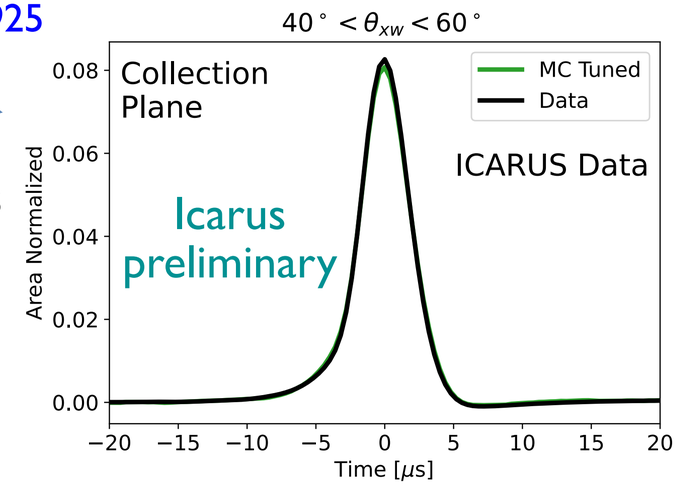
[*] Excess due to ν beam (signal)

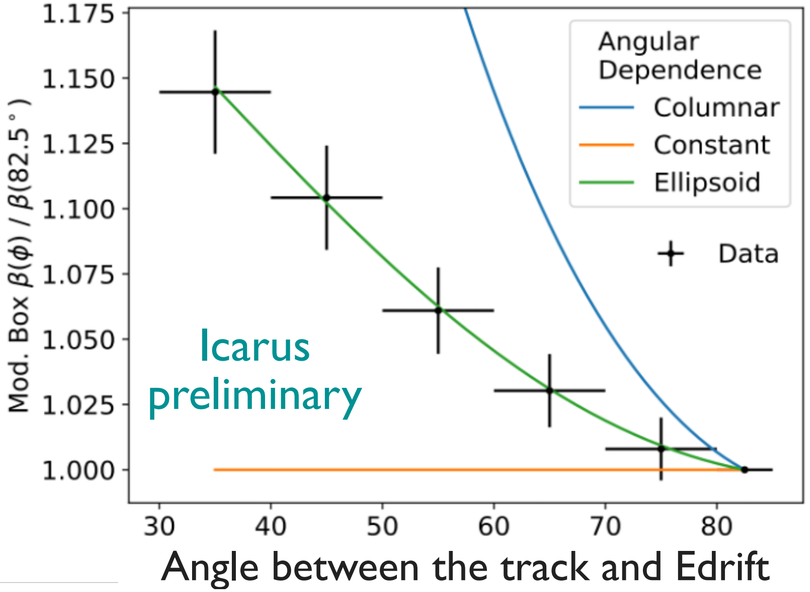
- All **subsystems fully operational** since the start of physics data taking
  - external CRT tag incoming cosmics with ~95% efficiency
  - Inner PMTs have gain equalized within 1% to G=5x10^6
- Time of flight (ToF) **rejection of cosmics** using **CRT & PMT** systems
- **Bunched structure** of BNB, NuMI **beam spill identified** with neutrino interaction time (PMT) with respect to the proton beam extraction counters post cosmics rejection (CRT) & correction for the neutrino ToF distance

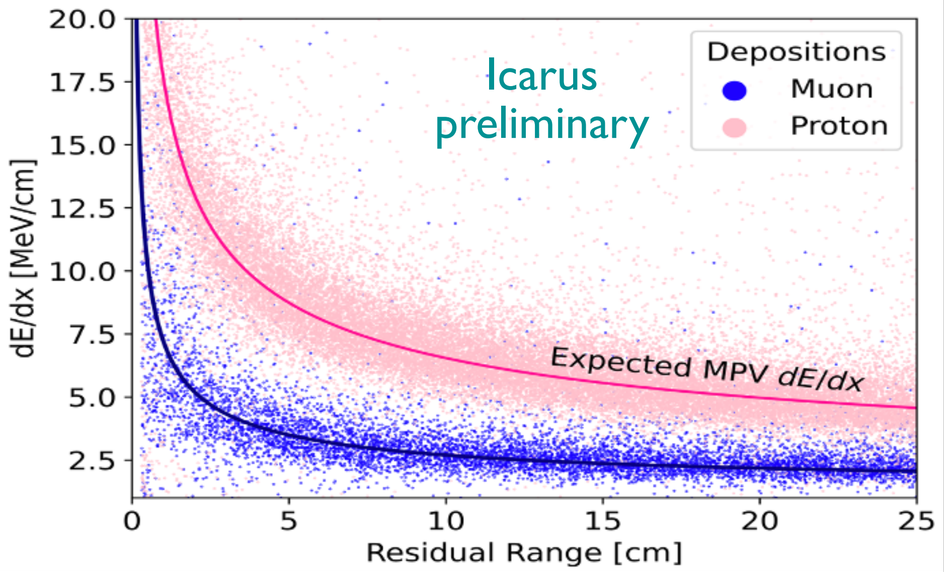


DETECTOR CALIBRATION AND MODELLING

- Accurate TPC wire signal characterization/modeling in Monte Carlo arXiv: 2407.11925
  Average signal response per plane per track angular bin evaluated
- Detector response **calibration**: cosmic muons (MIP), protons from ν interactions
- Future data processing to account for charge shared amongst nearby wires
- New angular dependent (***Ellipsoidal***) **recombination model** arXiv: 2407.12969
- Energy loss per unit length (dE/dx) vs residual range for μs and protons **PID**



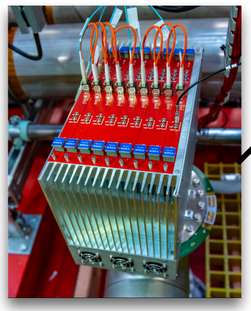




Calorimetric reconstruction of Edep is validated with:

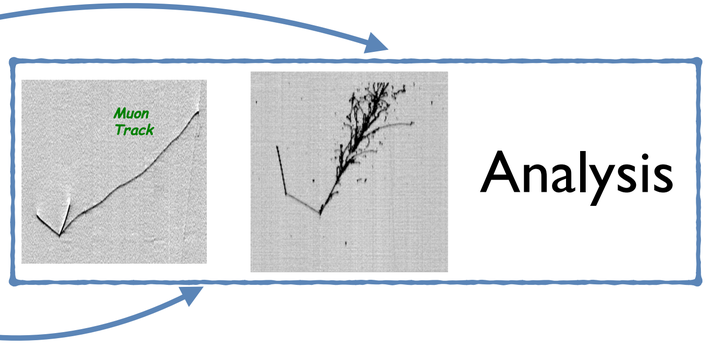
- sample of π^0 from **BNB** ν_μ CC interactions (~10% resolution on $m_{\gamma\gamma}$)
- **stopping protons** in **NuMI** ν_μ CC interactions (~3%)

NEUTRINO CANDIDATES EVENT RECONSTRUCTION



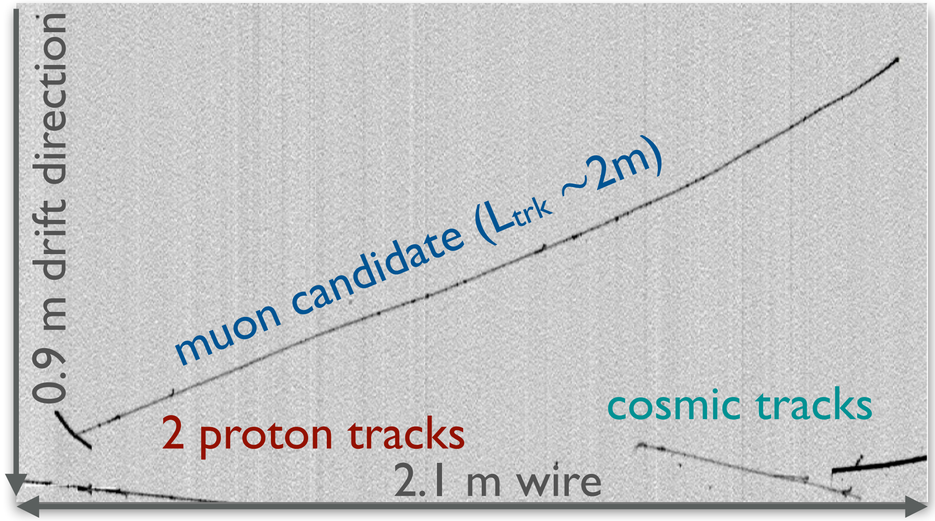
Raw data

Decoding → Deconvolution → Hit Finding → Gauss fit → 3D cluster → Pandora reco / SPINE reco → Analysis



- Two LArTPC event reconstruction frameworks:
  - **Pandora**, pattern recognition software widely used in LArTPCs
  - **SPINE**, entirely based on Machine Learning techiques (arxiv)
- Powerful tool to validate data processing and analysis and study data/MC agreeemnt is the **visual scanning** of collected events:
  - reconstruction of the ν vertex using a BNB ν_μ CC sample
  - matching of light & charge signals: ~1m agreement along beam
  - test selection/reconstruction performance in view of analyses

BNB ν_μ CC candidate



ICARUS PHYSICS PROGRAM

- **SBN physics program**: **sterile neutrino** search with the study of BNB ν_μ, ν_e interactions measured at different distances from the beam target thanks to SBND and ICARUS LArTPCs
- Before the joint-analysis with SBND, ICARUS focuses on a **standalone physics program:**
  - **Blinding policy** defined to ensure robust and unbiased interpretation of the collected data: analyses are validated using sidebands, a subset of the full dataset and variables insensitive to oscillation
  - Analysis of the ν_μ **disappearance channel with BNB** (selection ready and validated), to be complemented with ν_e **disappearance from NuMI** data - the goal is to verify the **Neutrino-4 claim**
  - study of ν_μ, ν_e interactions from NuMI to **measure ν-Ar cross sections** and optimize reconstruction in the energy range that **DUNE** will explore (selection ready, sidebands studied on a fraction of data)
  - search for **sub-GeV BSM signals** using NuMI
    forthcoming publication of the **di-muon decay channel** analysis

ν_μ DISAPPEARANCE ANALYSIS: SELECTION & SYSTEMATICS

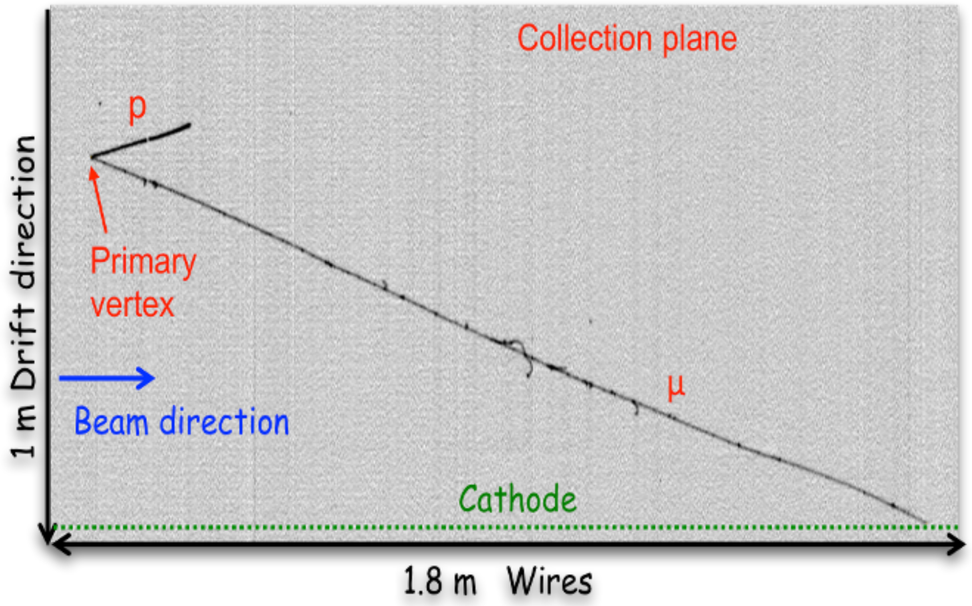
- Selection of **fully contained** ν_μ CC events with **1μ+N protons**

  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), PID scores in range

  (III) No additional pion/photon

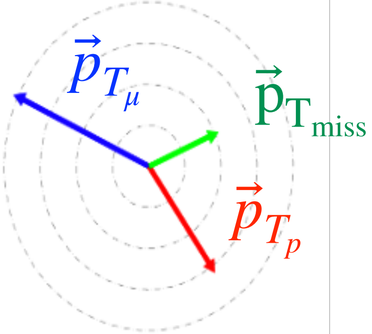


- Residual cosmic background <1%
- Φ, σ and (conservative) detector **systematic uncertainties** included (~equal):
  - comparison of (un)calibrated MC gives preliminary estimates of detector effects

A reduction of the impact of detector systematics is expected from improved MC, while Φ, σ effects should **cancel** with a **joint** SBND/ICARUS spectra analysis

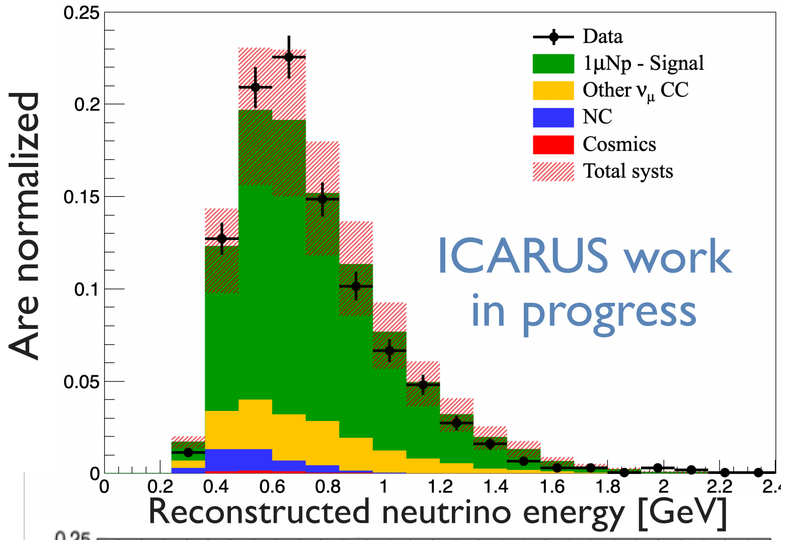
Current estimates are flux ~**10%** / cross section ~**15%** / detector effects ~**15%**

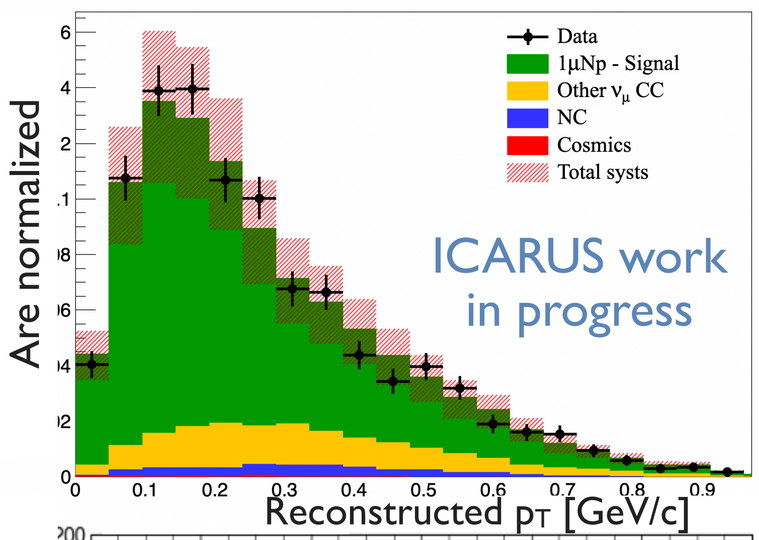
Momentum in the transver plane

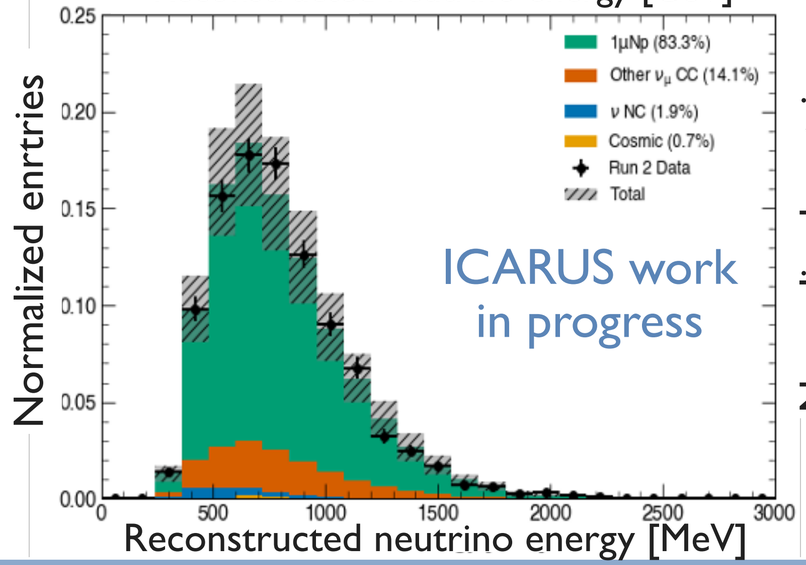


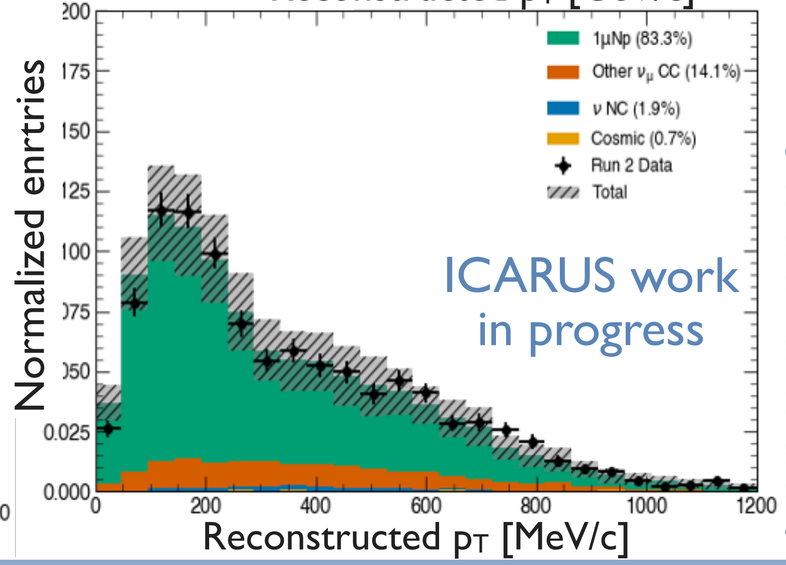
ν_μ DISAPPEARANCE ANALYSIS: PRELIMINARY RESULTS

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









- **Pandora-based** analysis on **BNB** ν beam
  ~**50%** signal efficiency, **80%** signal purity
  1.93 x 10^{19} Proton on Target **(PoT)**
  34000 events (Run1-3)

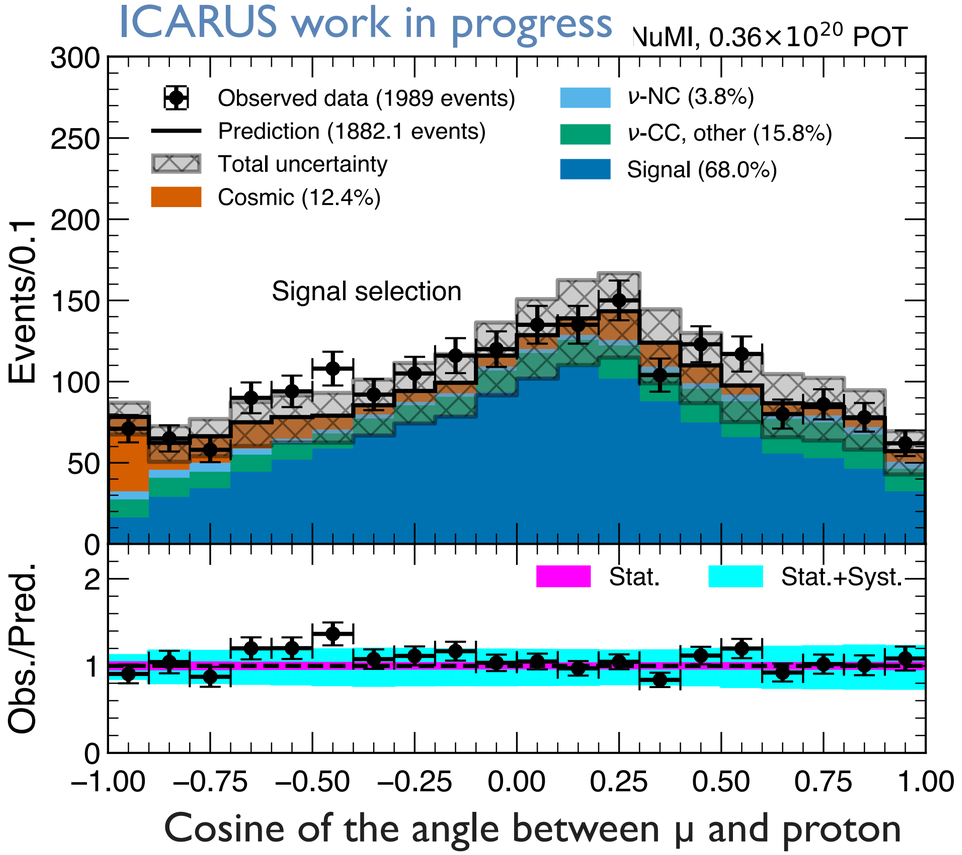
- **SPINE**-based analysis on BNB ν beam
  ~**75%** signal efficiency, **80%** purity
  1.92 x 10^{19} PoT
  47000 events (Run 1-3)

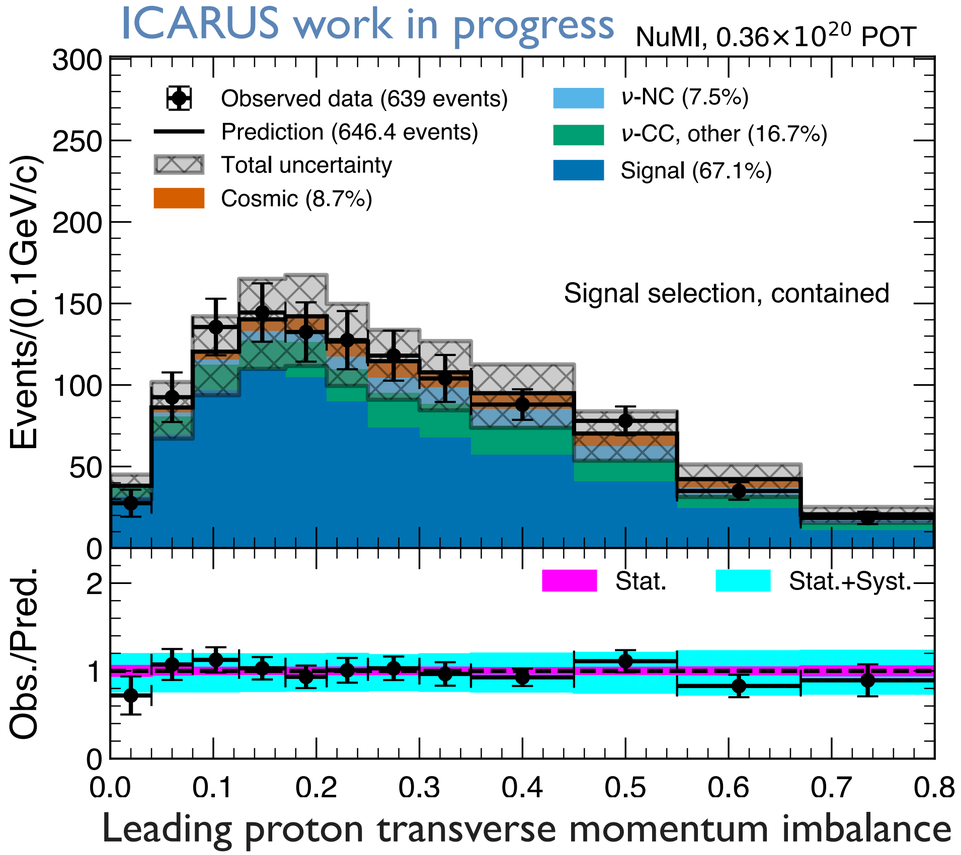
We are ready for the next analysis steps:

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

NUMI 1μ Np 0π ANALYSIS

- **Huge statistics** to measure quasi-elastic (QE), resonance and deep inelastic scattering ν_μ, ν_e cross sections
  CC events/6 x 10^{20} PoT: **332 000** ν_μ, **17000** ν_e - 3.42 x 10^{20} PoT already available for the present analysis
- First oscillation peak & **relevant phase space for DUNE** is **covered** by NuMI energy spectrum @ ICARUS





- First analysis targets 1μNp0π <u>enhanced</u> in QE and 2p2h interactions
- Event selection, relevant variables, including systematics and control sample in the next slide

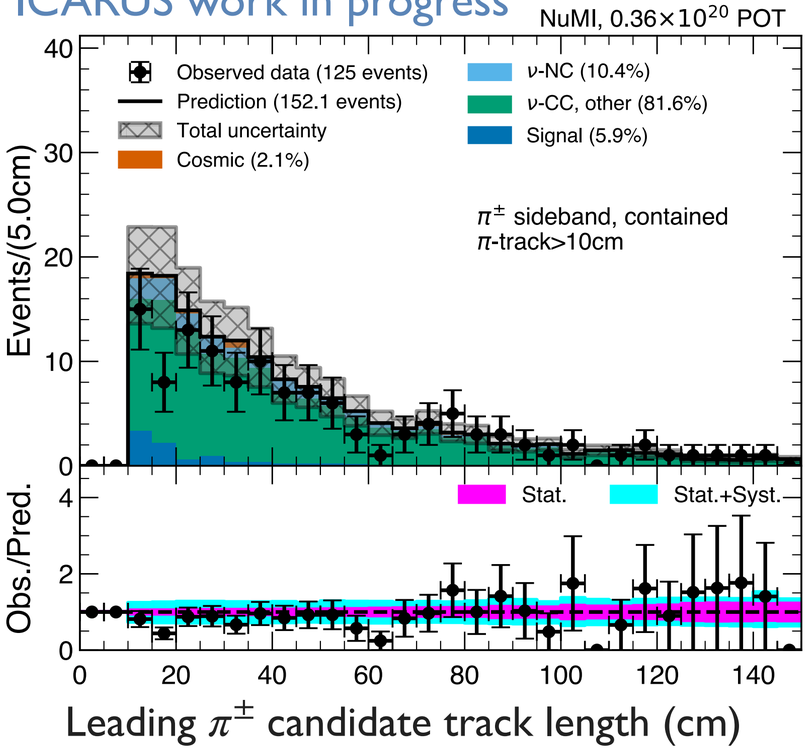
NUMI 1μ Np 0π ANALYSIS

- Signal: no π/γ, at least 1μ with p>226 MeV/c and proton(s) with $p \in$ [0.4, 1] GeV/c identified w/ PID
  $\cos\theta_{\mu,p}$ should encode all info about **Final State Interactions**, transverse kinematic variables are relevant
- Systematics: flux, interaction model and detector systematic uncertainties (same as BNB) included

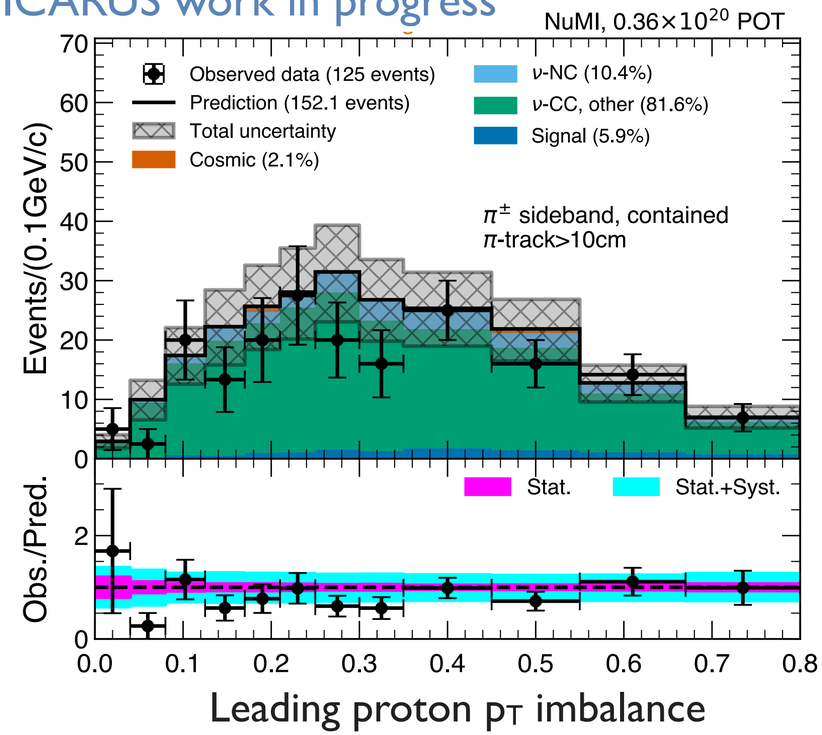
- **Major background:** events with undetected or misidentified **pions**
- **Control sample** w/ $\pi^{\pm}$ and secondary μ-like track
- First study using 15% of the data

We are ready to study the sidebands with the full Run1 & Run2 event statistics

ICARUS work in progress



ICARUS work in progress

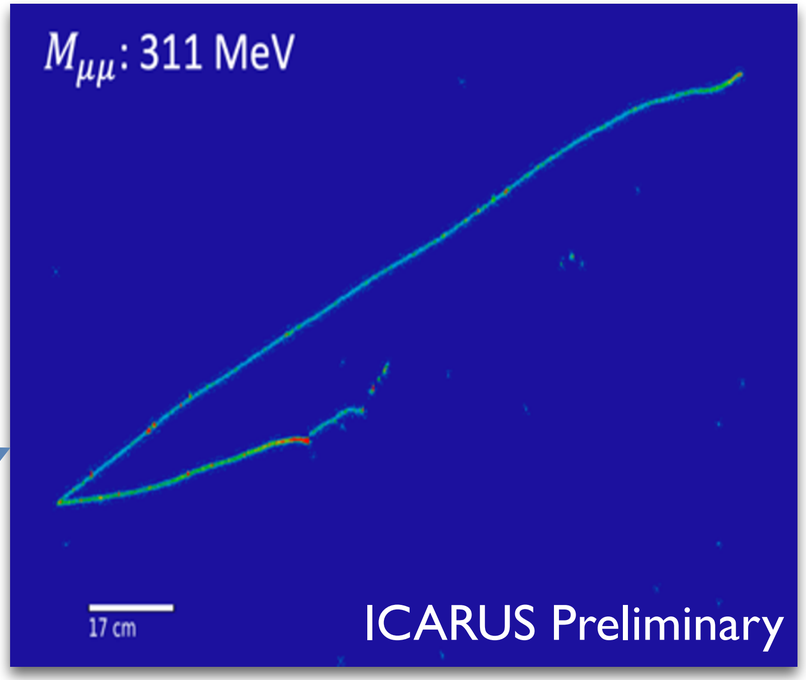


BEYOND STANDARD MODEL PHYSICS PROGRAM

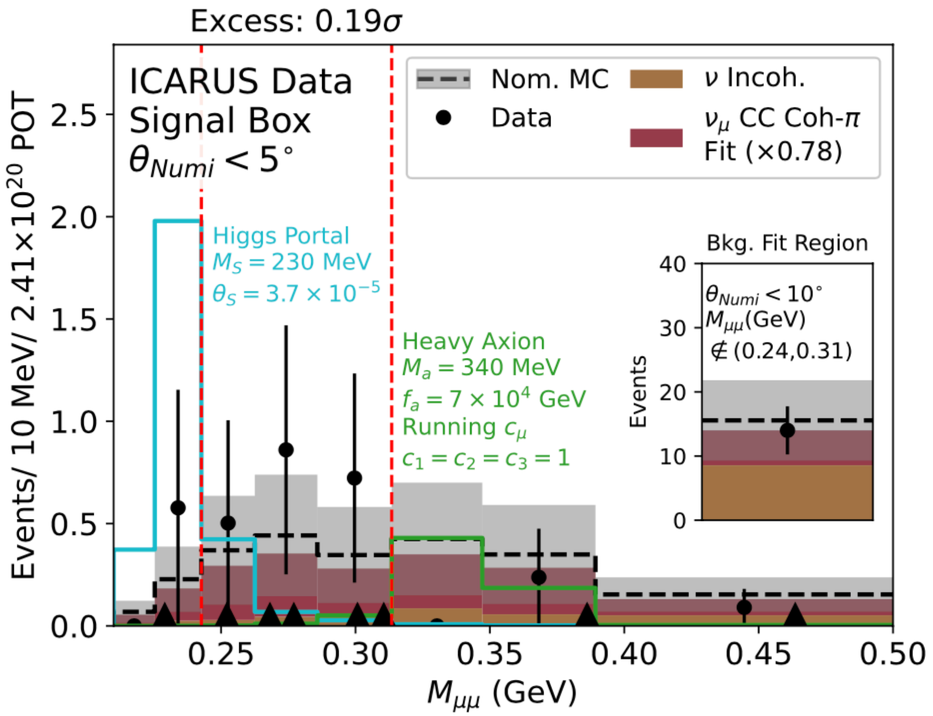
- Rich BSM search program (dark matter, heavy neutrial leptons, …) based on the off-axis **NuMI** beam
- **Models** explored so far feature dark particles coupling to SM particles via **Scalar Portal Interactions**
  - **Higgs Portal Scalar:** scalar dark particles, interacting with SM particles with Higgs boson mixing
  - **Heavy QCD axion:** pseudo-scalar particles, interacting with SM ones via pseudo-scalar mesons

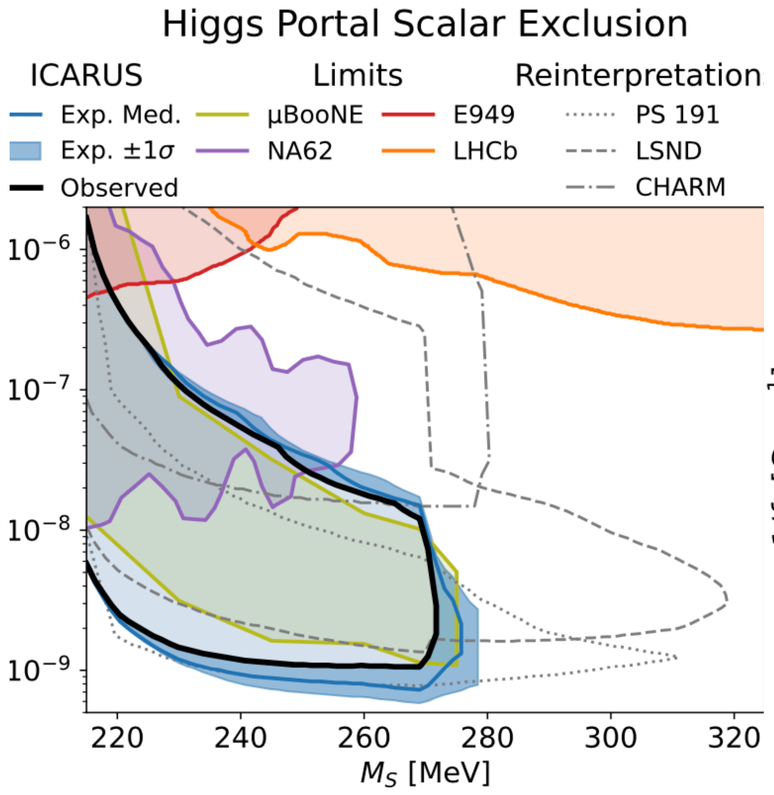
- First search for BSM particle decaying into **di-muon** just **completed**
  - Event selection: 2 stopping μ-like particles (fully contained) with resolvable mass peak, proxy of the scalar particle mass
  - Signal peak expected at small angles wrt beam ($\theta_{\mathrm{NuMI}} < 5^{\circ}$)
  - All systematics (flux, cross section and detector) included

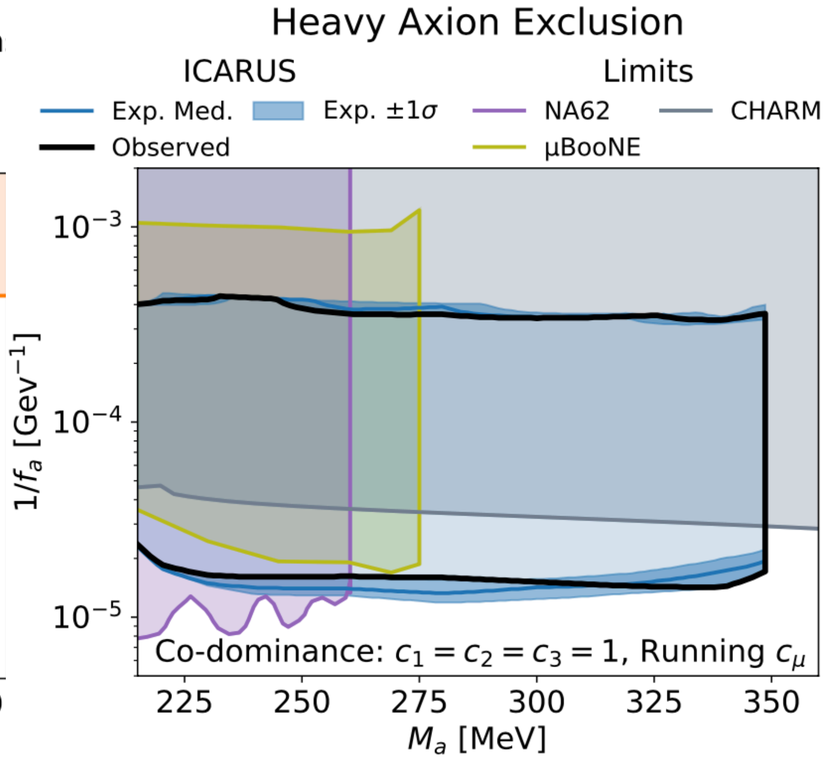
Typical signal candidate



DI-LEPTON ANALYSIS







- **Data unblinding**: 8 events vs 8 events expected
  mostly from ν_μCC coherent π production in the null hypothesis
- **No** evidence of a new **signal:** maximum **excess** is **0.19σ**

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** (electronic and calorimetric) extracted
  exploiting cosmic μs and protons from ν interactions and now fully embedded in our simulations
- Both waiting and in view of the upcoming joint-SBN analyses, several **single detector studies**
  are progressing and **quite advanced**:
  - ν_μ **disappearance** channel with **BNB** beam → control sample will be enlarged to complete validation
  - ν**-Ar cross section measurements** with **NuMI** beam, first selection includes 1μNp0π events
    → ready to study the sidebands with the full statistics available
  - Search for **sub-GeV dark matter particles** with **NuMI** beam data
    - Search for ***di-muon*** final state topology available → first results available: analysis completed
- Interesting results are foreseen soon (ν_e analyses on BNB, NuMI data are starting) so **stay tuned!**

THANKS FOR YOUR ATTENTION