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

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on behalf of the ICARUS Collaboration.

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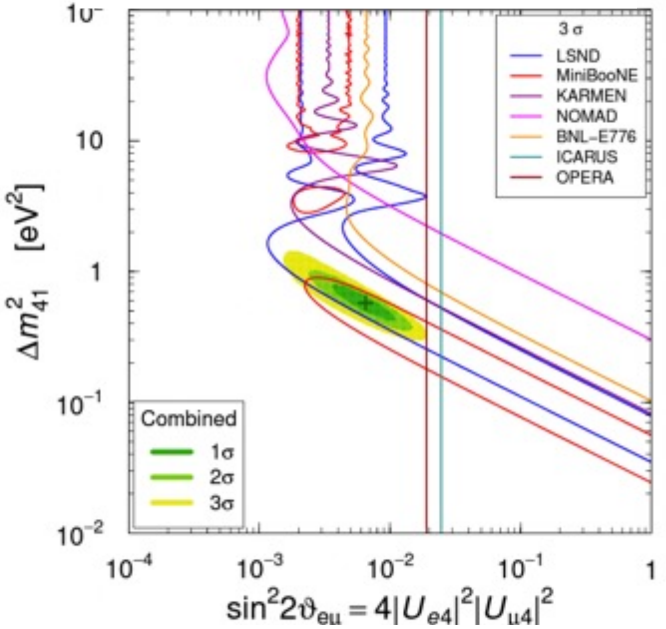
The sterile neutrino puzzle

- ***Anomalies*** from accelerator experiments (LSND and MiniBooNE), reactors and radioactive source have been reported in the last 20 years, unable to fit inside the 3-flavor oscillation scheme
- Results point towards a new *sterile* ν flavor at $\Delta m^2 \sim eV^2$ and a small mixing angle, thus driving short distance oscillations
- The Neutrino-4 collaboration reported a hint of oscillation signature at higher mass splitting [arXiv:2005.05301]
  - Reactor $\bar{\nu}_e$ disappearance with $\Delta m^2 \sim 7\ eV^2$ and $sin^2\, 2\theta \sim 0.26$
- A recent publication combining Neutrino-4 results with data from GALLEX, SAGE, and BEST experiments has increased the confidence in previously claimed results to 5.8σ CL [arXiv:2302.09958]

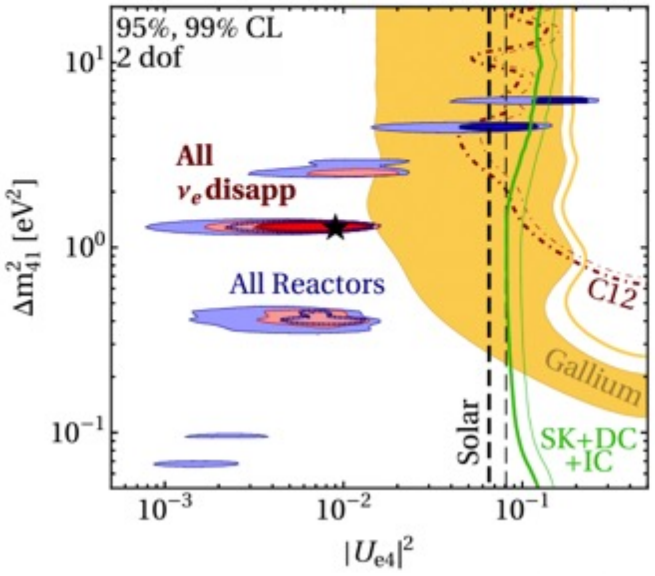
A clear tension between appearance and disappearance experiments, which are characterized by different neutrino energy range and detection technique, is evident

Measuring both channels with the same experiment will help clarify the physics scenario

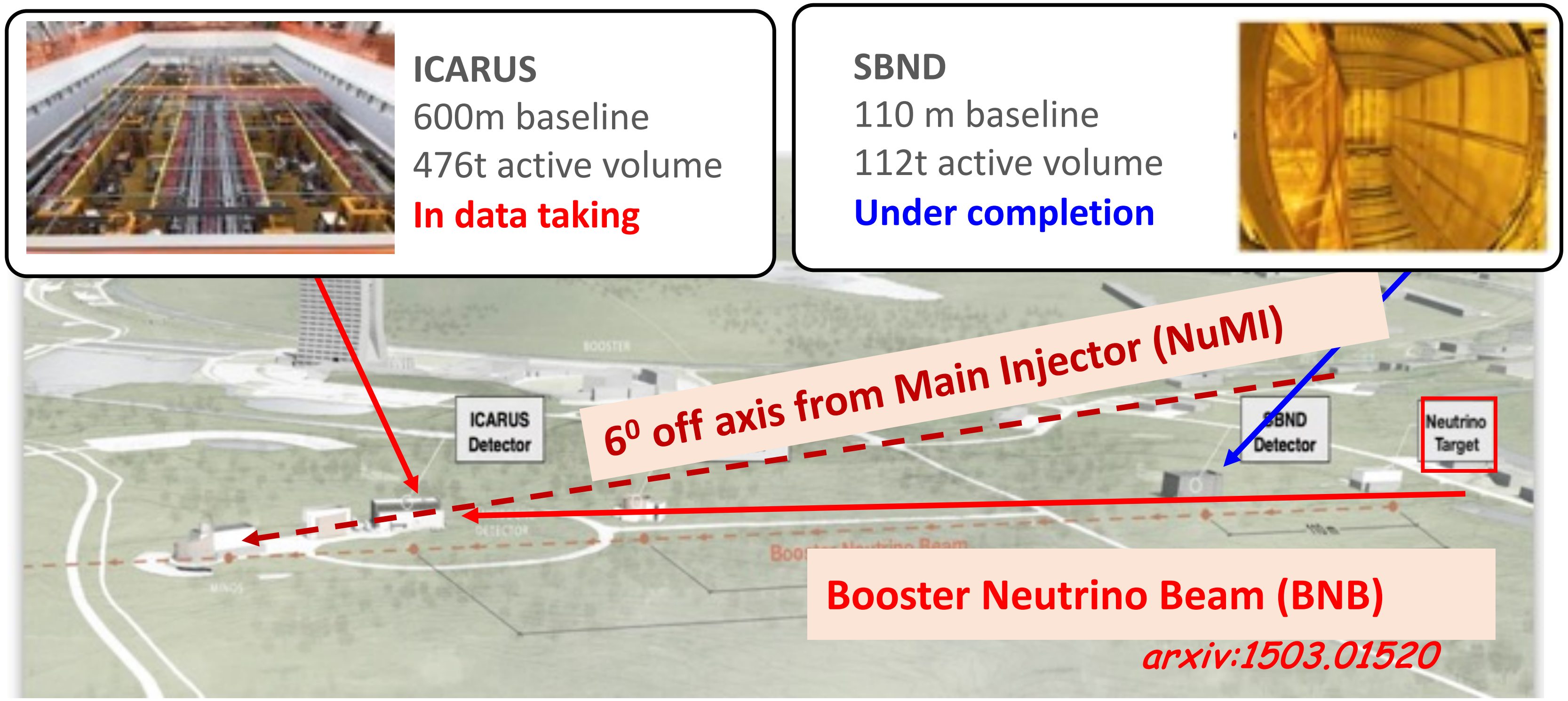
(Anti-) $\nu_\mu \rightarrow \nu_e$ appearance

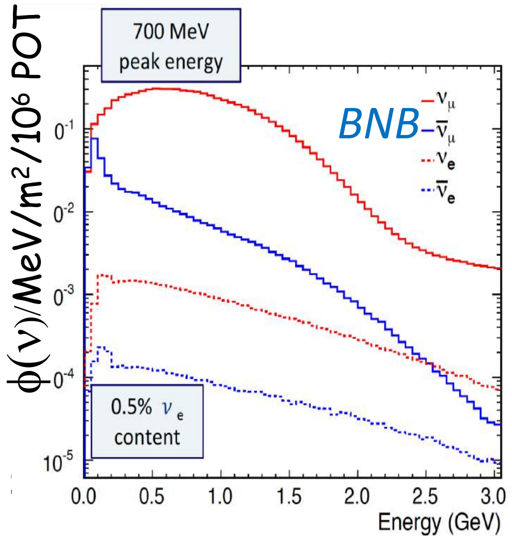


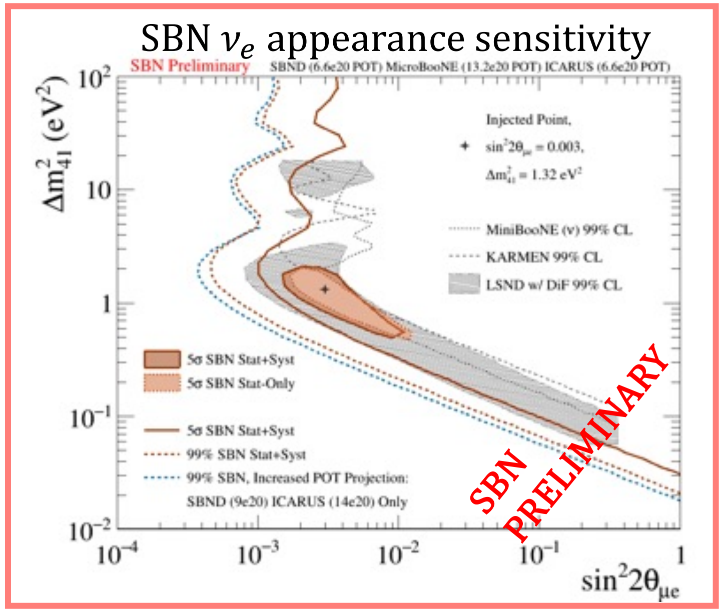
(Anti-) ν_e Disappearance



Short Baseline Neutrino (SBN) at FNAL : *a definite answer to the sterile neutrinos?*







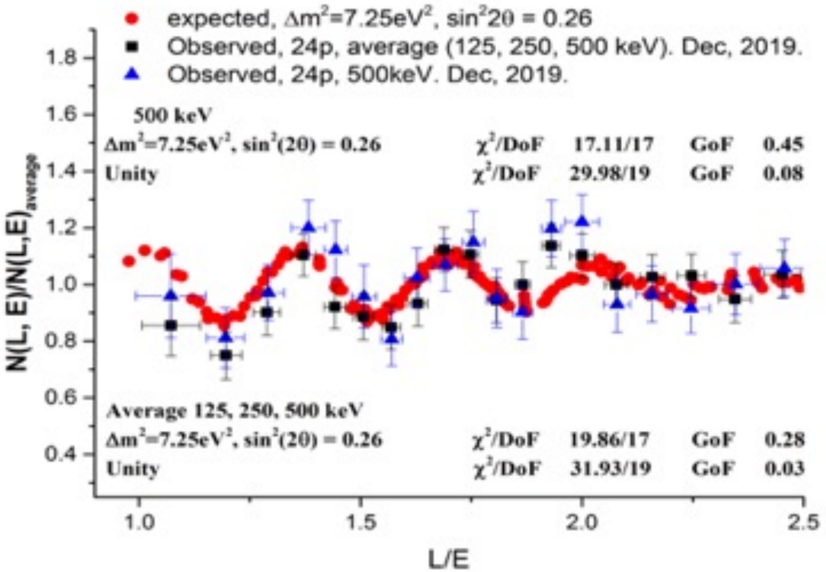
- ICARUS and SBND LAr-TPC's are installed at 600 and 110 m from the Booster target, searching for sterile- ν oscillations both in appearance and disappearance channels.
- In addition will produce a high-statistics ν -Ar cross-section measurements and event identification & reconstruction studies in view of DUNE.
- ICARUS is also exposed off-axis to the NuMI beam and can access the ν_e rich component of the spectrum (up to 3 GeV) which will grants access to a rich BSM (Beyond the SM) search program .

ICARUS exclusive capability of testing Neutrino-4 claim

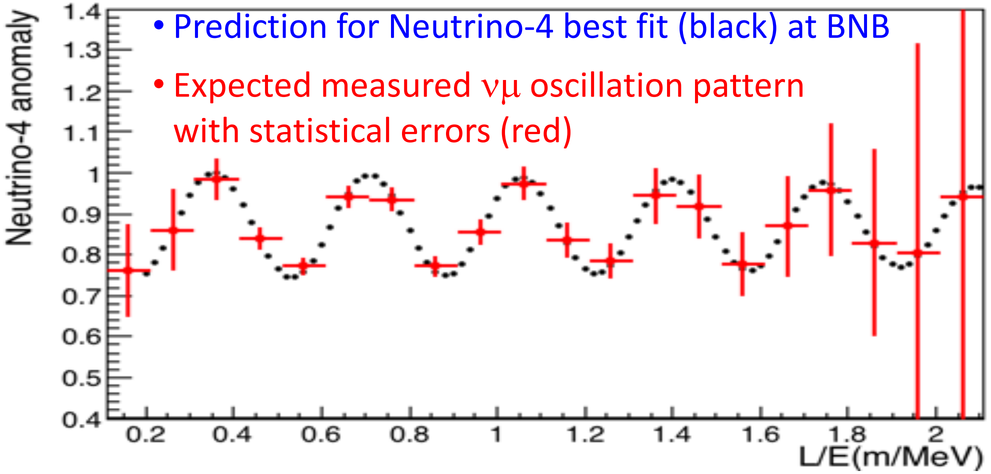
Jetp Lett. 116, 669–682 (2022)

- **Neutrino-4 Collab**. at Dimitrovgrad SM-3 reactor gave evidence of neutrino oscillation into sterile- ν showing a disappearance signal with a clear **L/En** ~ 1-3 m/MeV modulation.

- **ICARUS at FNAL** presents ***remarkable similarities to NEUTRINO-4*** which should allow to settle the NEUTRINO-4 sterile- ν claims in the initial ICARUS-only run with BNB and NuMI in the same L/E ~ 1-3 m/MeV but with events collected at ~100 times the energy

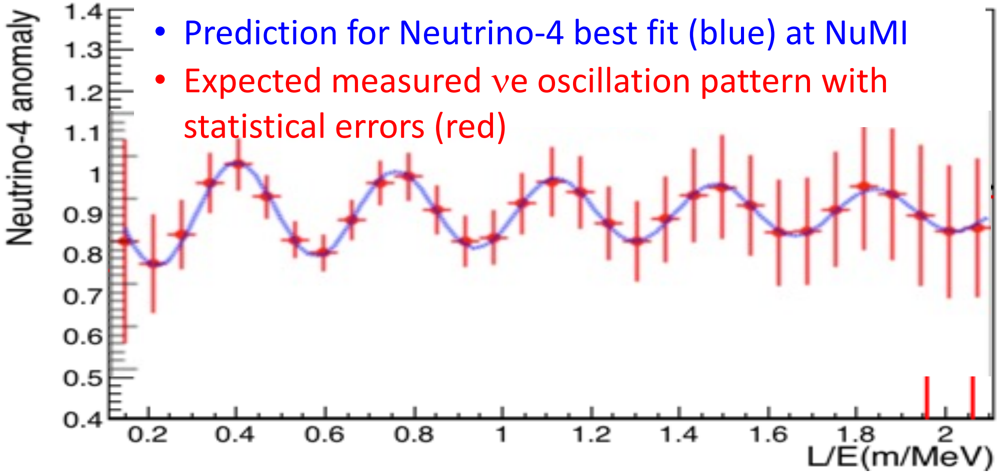


Δm^2=7.25 eV^2, $\sin^2 2\theta$=0.26



νμ survival oscillation probability at Booster:

~8500 QE events with >50 cm contained μ track,



νe survival oscillation probability at NuMI:

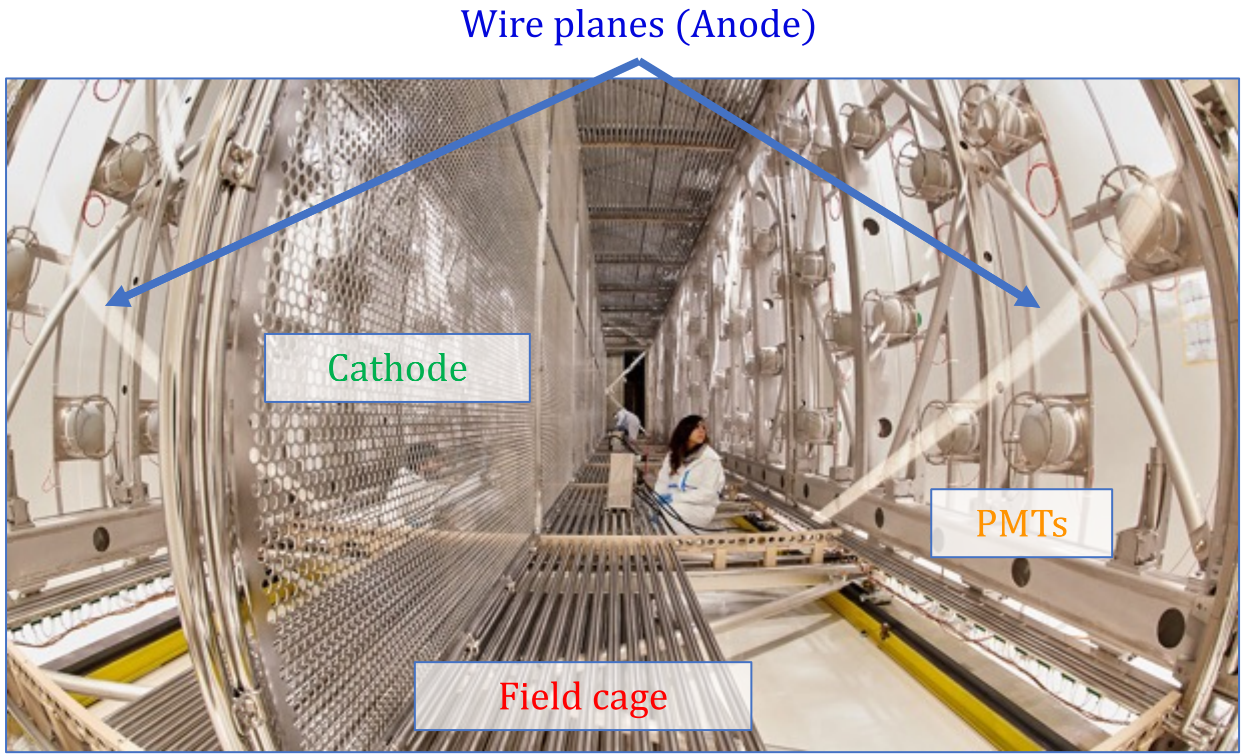
~ 5200 QE events with contained E.M. shower,

The ICARUS detector

- Uniform Liquid Argon Time-Projection Chamber detector (LArTPC)
- The largest LArTPC in operation and consists of 2 identical modules filled with 760t of LAr , and 476t total active mass
- Self-triggering detector, with precise 3D imaging and calorimetric capabilities
- ICARUS moved to FNAL in 2017 after ***extensive overhauling*** phase at CERN and INFN Labs in view of the shallow depth operations, that included major upgrades in
  - the cryogenics,
  - the Lar purification system,
  - the TPC readout electronics,
  - the light collection system.

ICARUS installation at FNAL FD

The ICARUS detector at Fermilab



Internal view of one cryostat during the upgrade at CERN

- 2 TPCs per cryostat, with a common central cathode
  - 1.5 m drift length and $E_{Drift} = 500\ V/cm$
    gives $t_{drift} \sim$ 1ms, $v_{drift} \sim$ 1.6mm/μs
- Ionization charge continuously read (400 ns sampling time) by 3 readout wire planes per TPC, ≈ 54000 wires at $0°$, $\pm 60°$ w.r.t. horizontal and 3 mm pitch
- 360 8” PMTs located behind the wires for timing and triggering purposes:
  - Precise identification of interaction time, $\sim ns$ time resolution
  - Localization of events with spatial resolution $< 50\ cm$

By 2022, ICARUS was filled, activated and successfully commissioned at Fermilab!
[see Eur.Phys. J.C 83 (2023), 6.467) for initial detector operations]

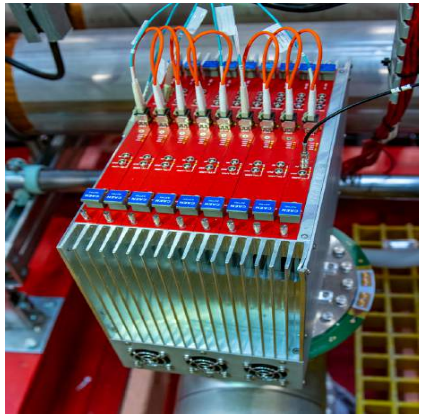
The TPC read-out electronics

Higher performance TPC readout electronics compliant with higher data rates at shallow depths;

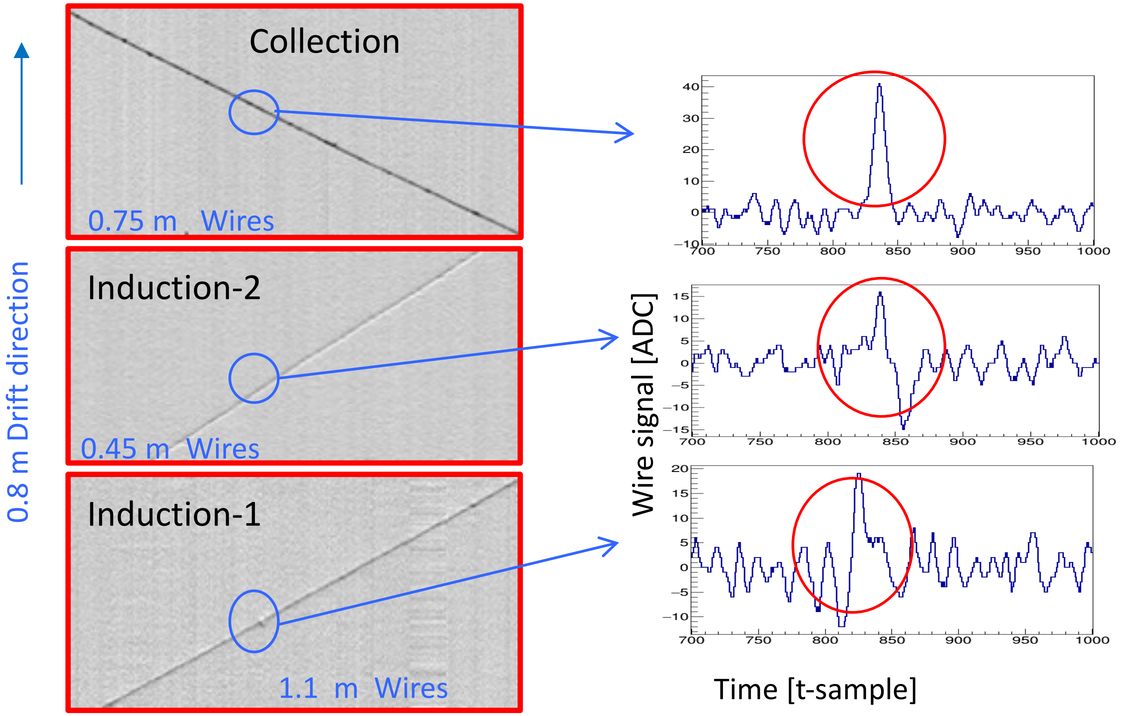
Front-end based on analogue low noise, charge sensitive pre-Amp;

Compact layout with both analog/digital electronics in a single board.

Signal shaping ~1.3 μs to match *e*- transit time between Induction-1, 2 and Collection wire planes (3 mm apart) improving hits position resolution;

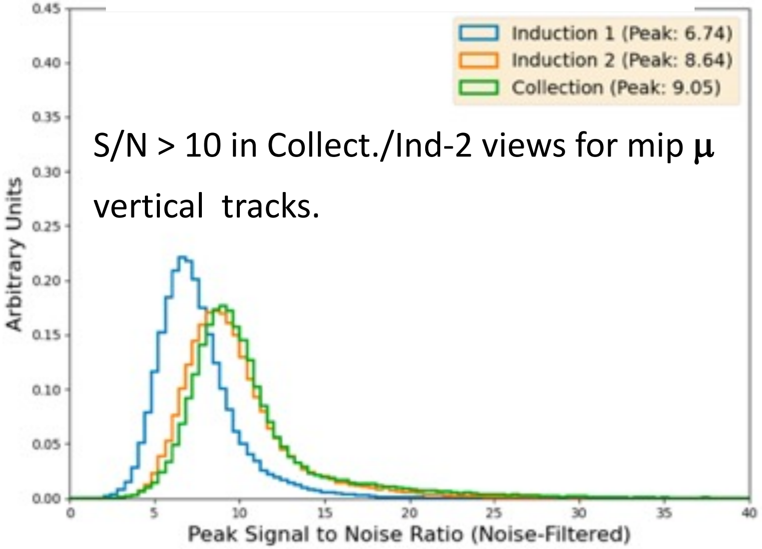


TPC mini-crate on a feed-through hosting 9 boards (576 wires)



Recorded cosmic muon track: bipolar shape of *e*-signals traversing wire planes as seen in Induction-1 & 2 views.

ICARUS Signal to Noise ratio



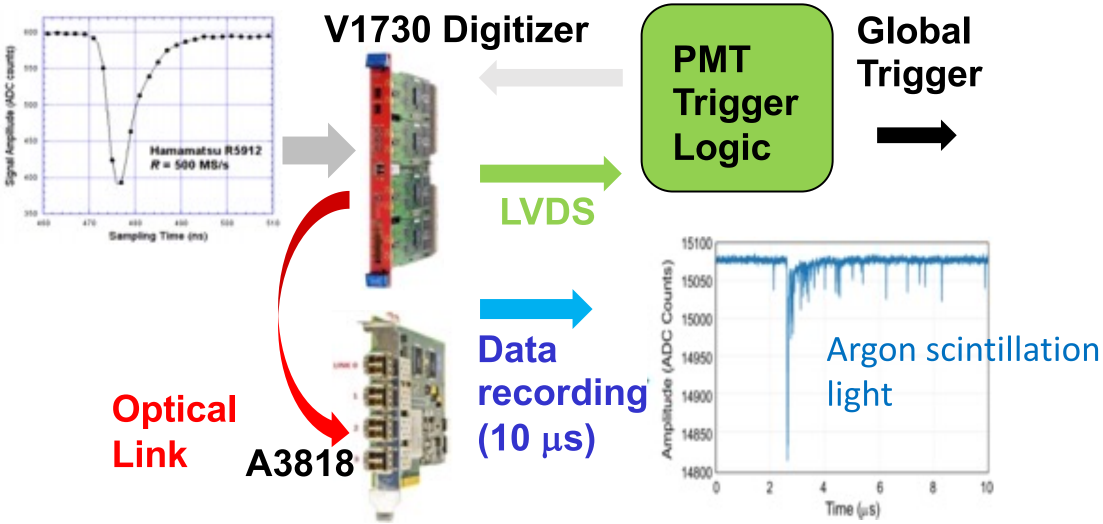
S/N > 10 in Collect./Ind-2 views for mip μ vertical tracks.

The Light Collection system

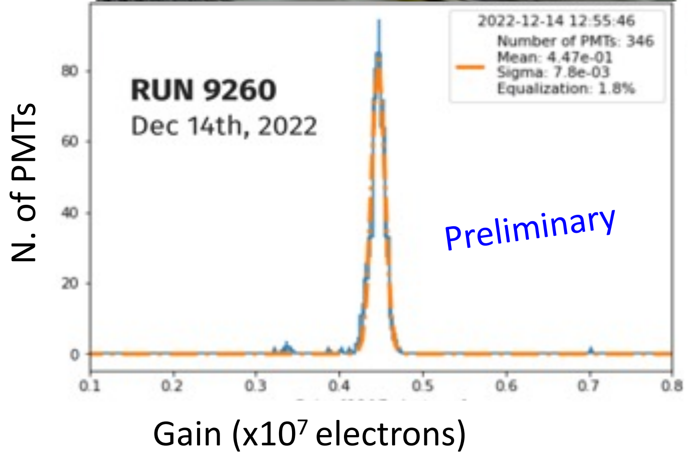
Consists of 360 Hamamatsu 8“ PMT (5% coverage, 15 phe/MeV) installed behind the wire planes, 90 PMTs per TPC chamber

Continuous read-out, digitization, discrimination and waveform recording of PMTs signals (V1730 digitizers);

PMT signals sampled every 2 ns, recorded in 10 μs windows.

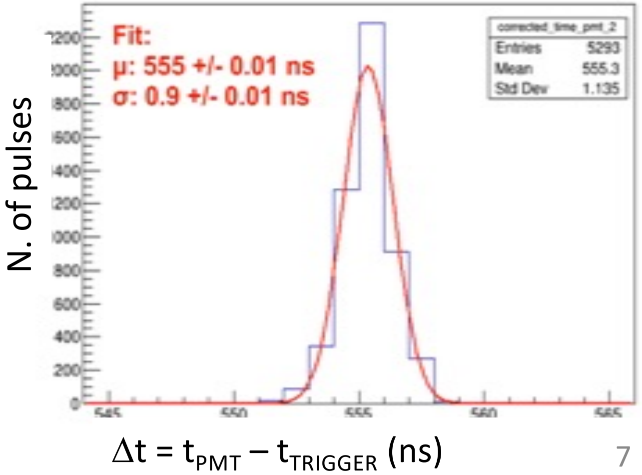


PMT signals in a limited TPC window are the foundation of the trigger logic



PMT gain is equalized at ~ 0.45 10^7±1% and measuring ~4 mV PMT response to single photoelectron

PMT signals timing w.r.t. the trigger is measured with 1 ns resolution by mean of a λ ~ 405 nm laser pulses, to precisely determine the time of collected events.



See G.L. Raselli poster ” Time calibration and synchronization of the scintillation light detection system in ICARUS-T600” for more details.

The Cosmic-Rays Tagger (CRT) system

- ICARUS is on the surface and hence exposed to a huge comic activity that can mimic neutrino interactions
- Without shielding, ICARUS would be overwhelmed by the hadronic and soft energy component of the cosmic background
- In order to mitigate as much as possible its contribution, ICARUS is instrumented with
  - $\sim 3\ m$ concrete overburden placed on top of the detector
  - 4π Cosmic Ray Tagger (CRT): 3 subsystems with double layer scintillation bars ($\sim 1000\ m^2$) equipped with SiPMs ($2.4\ ns$ time resolution), tagging incoming cosmics with $\sim 95\%$ efficiency
- Coincidence of CRT signal with the light and charge signals in the TPC for background rejection

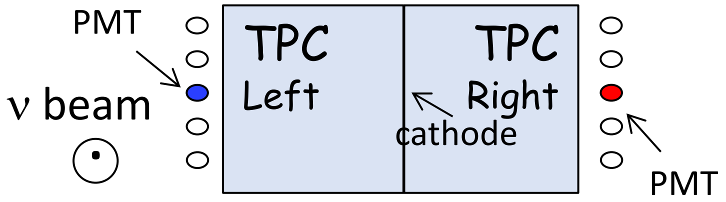
Side CRT

Top CRT

Overburden

The Trigger system

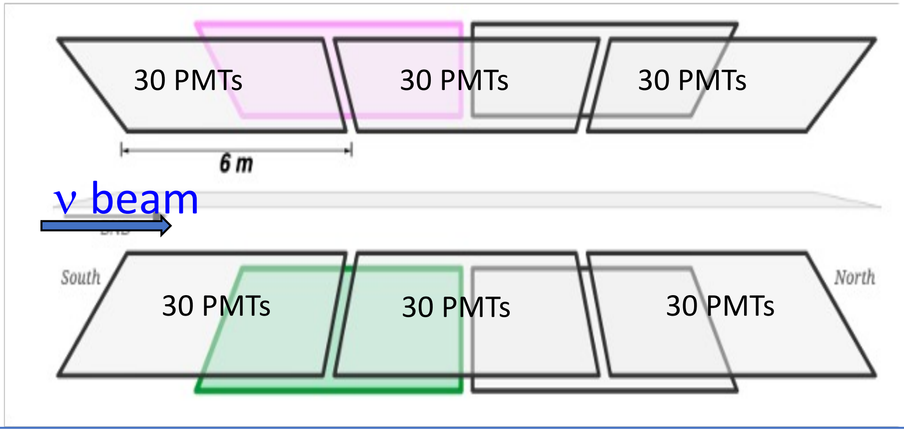
The ICARUS trigger system exploits the coincidence of the BNB and NuMI beams spills, 1.6 μs and 9.5 μs respectively, with the prompt scintillation light detected by the PMTs. The beams' Early Warning signals of proton beam extractions are distributed to the experiment via a fully deployed White Rabbit (WR) network.

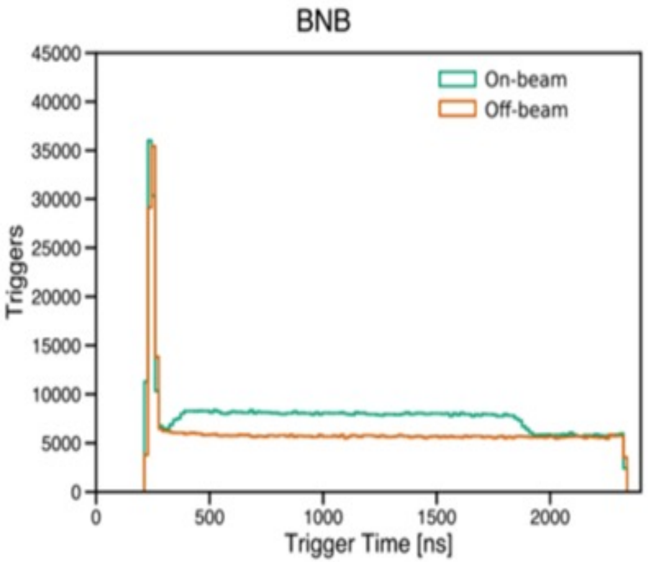


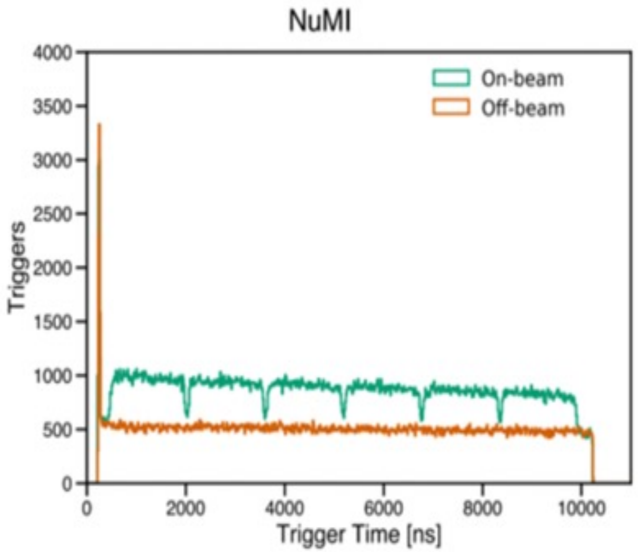
Beam events are collected requiring ***at least 5 fired PMT pairs*** (Mj =5) inside one of the 6 m longitudinal slices (30 PMTs left + 30 PMTs right);

PMT and CRT signals also recorded in 2 ms around the trigger to recognize cosmic rays crossing the LAr-TPCs during the 1 ms e-drift time

Additional trigger signals are generated in correspondence with beam spills w/o any request on the light (MinBias) and outside of the beam spills to the detect CR interactions for calibration and background studies



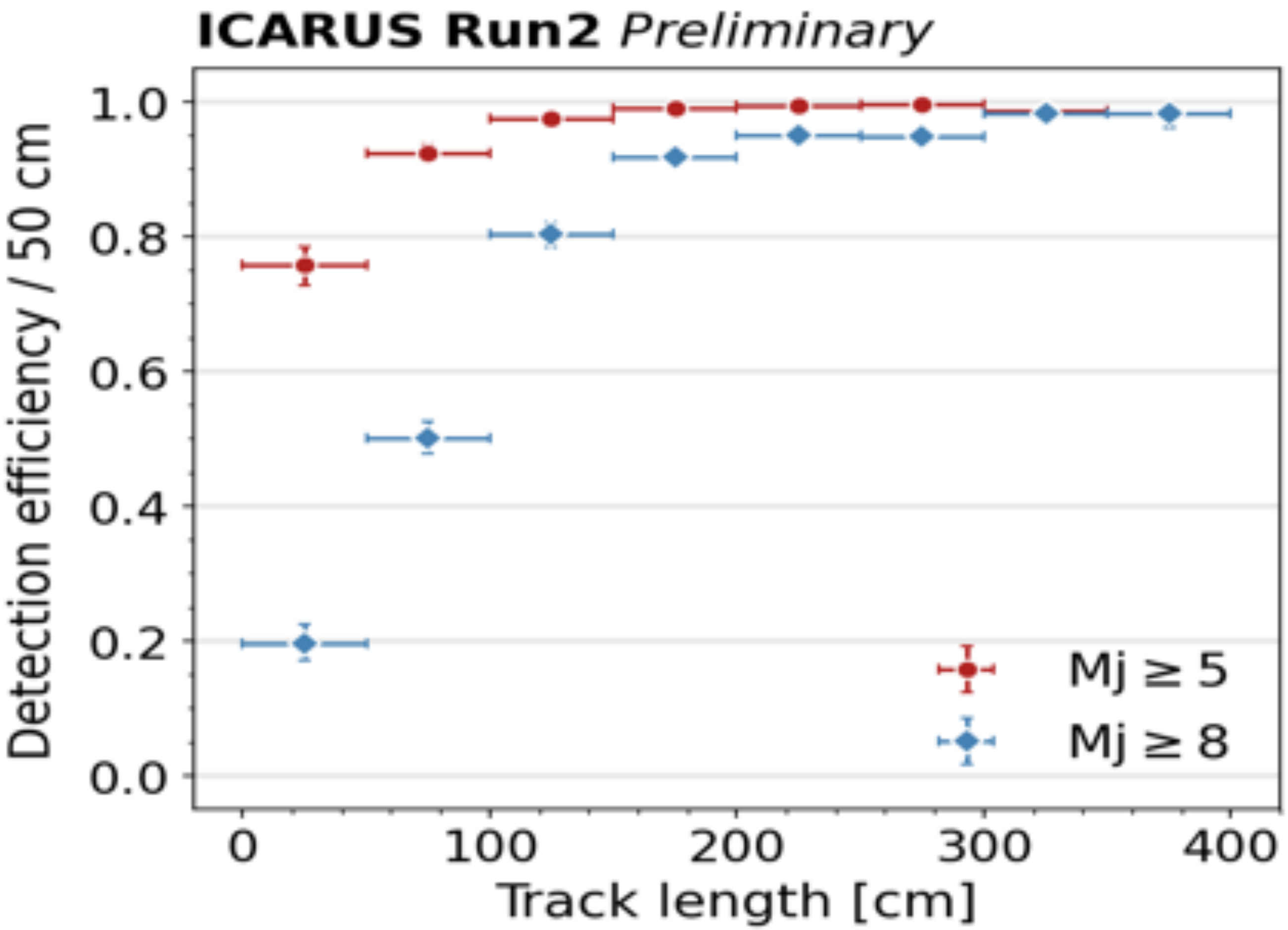




Triggered events in ICARUS configurations with and without beam, clearly showing an excess due to neutrino interactions. The spills durations of the two beams are well recognized.

The high peak is the tail of scintillation light from cosmic rays earlier in the beam gate opening. Its easily removed by looking at the trigger time

The Trigger system efficiency

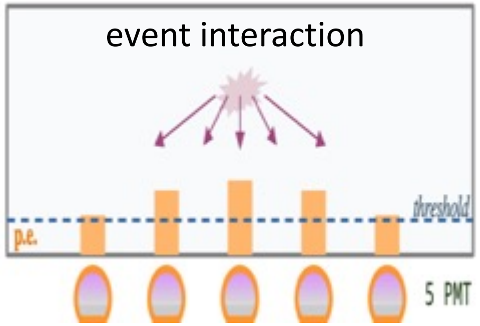


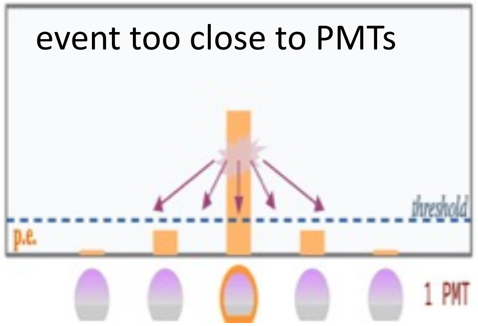
Trigger efficiency measured selecting vertical cosmic muons in TPC tracks matched to CRT signals without any requirement on PMT light signals :

- ~ full efficiency is found for in-spill events with track length > 1 m (E_{DEP}~ 200 MeV)
- out-of–spill cosmic are instead recognized with 90% efficiency for L > 1.5 m when requiring >= 8 fired PMT pairs

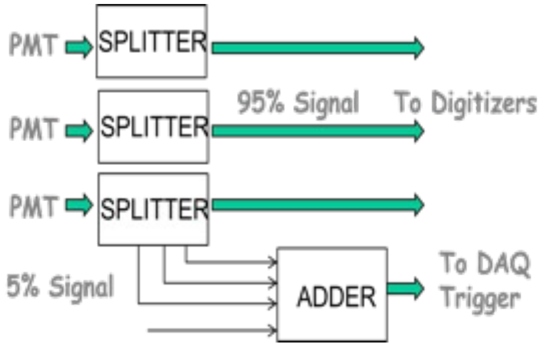
The Trigger system ongoing upgrade

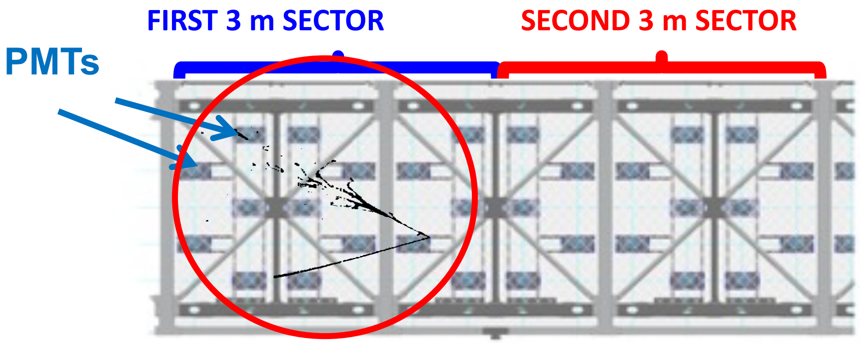
To improve the trigger performance at low energy events E_{DEP} < 150 MeV, an additional/independent trigger, based on the scintillation light signal amplitude instead of multiplicity of fired PMTs, is under study.





ADDER boards summing up 5% of signal from each group of 15 PMTs in a 3 m detector slice have been installed





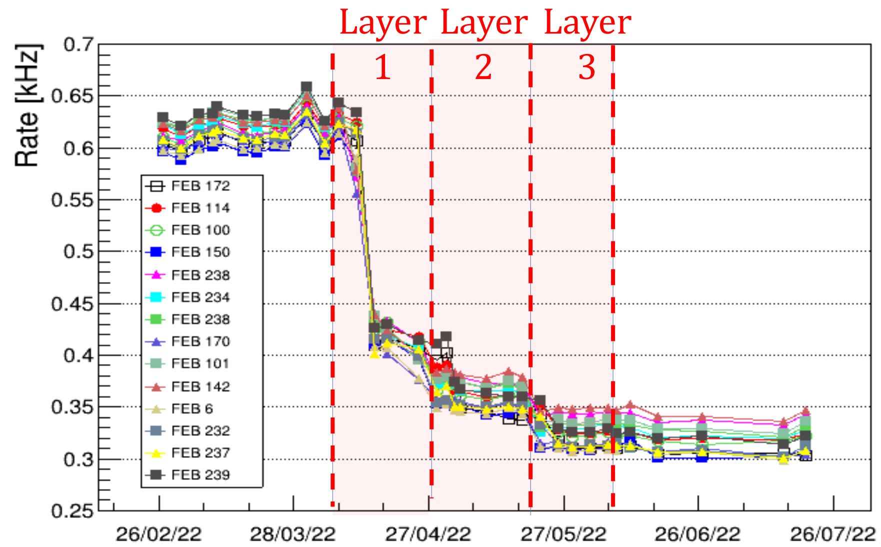
Commissioning !

Data collected with exploratory ADDER triggers is being analyzed to evaluate their efficiency in recovering events missed by the Mj trigger.

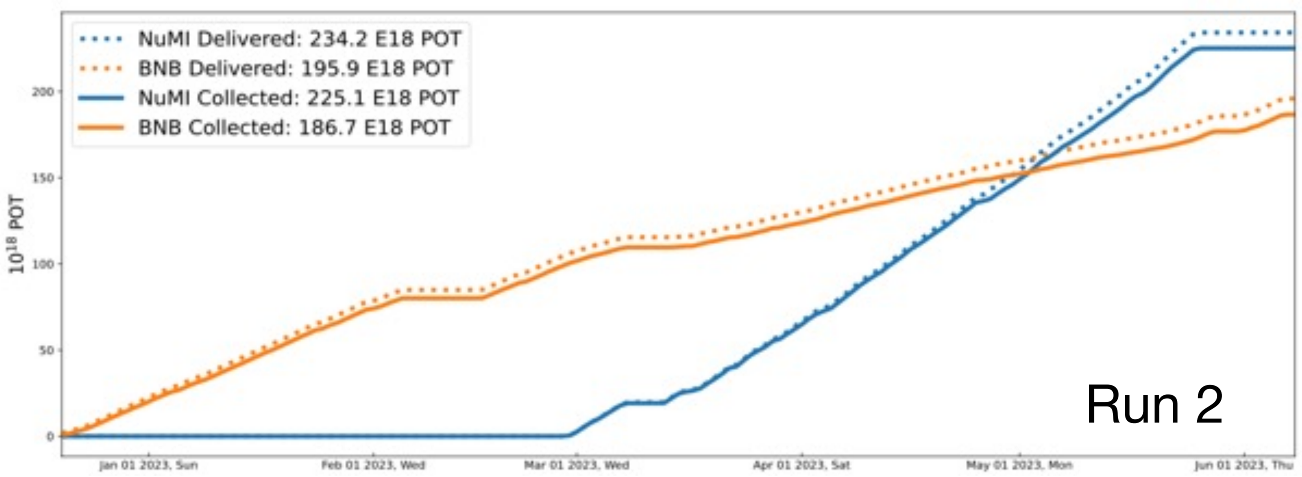
Data taking and overall detector performance

Commissioning runs started in March 2021; physics quality data started in June 2022 - two physics runs since

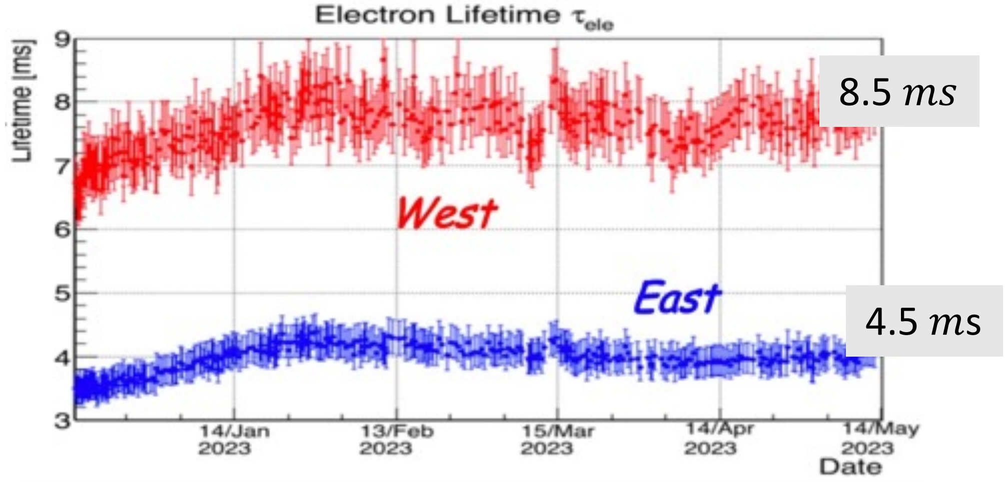
Rate of cosmic rays for Top CRT



Run 2 Data collected



- The overburden installation resulted in a factor ~ 2 reduction of cosmic rays signal on Top CRT
- Steady data taking with DAQ uptime ~93%, excellent stability on long runs at BNB rates > 4 Hz
- Liquid argon purity level is continuously monitored measuring signal attenuation along drift direction of μ tracks: the planned regeneration of the filters for the east cryostat will increase electron lifetime τ_{ele} and improve uniformity.



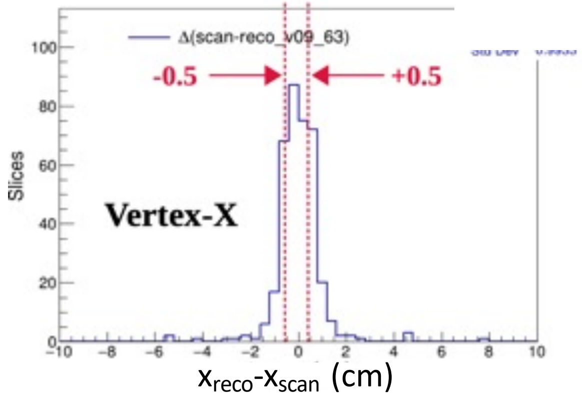
The ongoing and future ICARUS research program

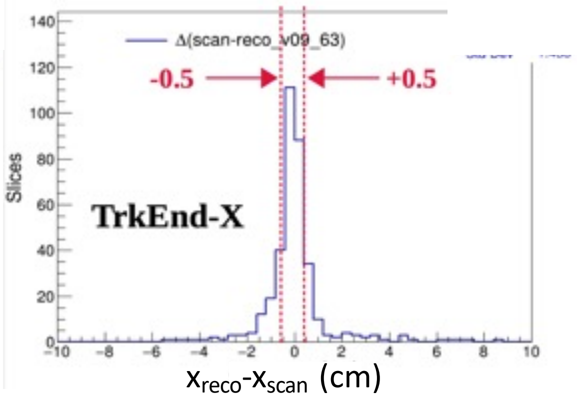
- The Neutrino-4 analysis is the major ongoing investigation by ICARUS with Booster and NuMI beams data.
  - In total ~1500 $\nu\mu$CC candidates have been visually selected/measured and are exploited to qualify the automatic event selection (resolution, efficiency, purity,…) and address the major event reconstruction issues.
  - Calibration of the whole data set and the tuning of the reconstruction of the wire signals are being pursued. Run-1 and Run-2 are expected to be reprocessed in the fall, including the code improvements, supported by a production of ~1 Million MC events.
- In parallel, the study of ν_e, ν_μ events from NuMI will also allow ICARUS to measure ν-Ar interaction cross sections and optimize ν reconstruction/identification in an energy range of interest for DUNE. The NuMI beam will also allow a search for sub-GeV Dark Matter signals.

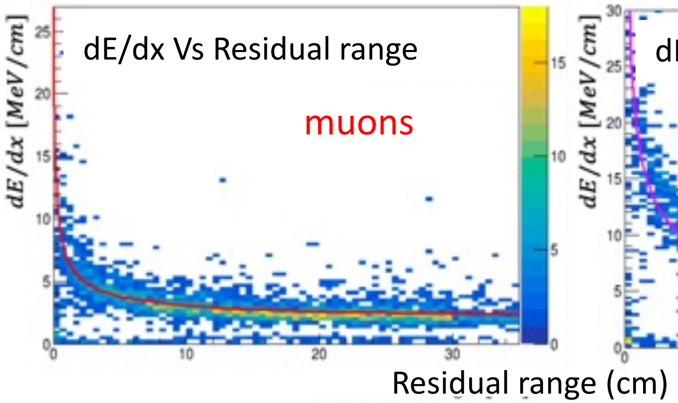
Tuning of events reconstruction with visually selected $\nu\mu$CC events

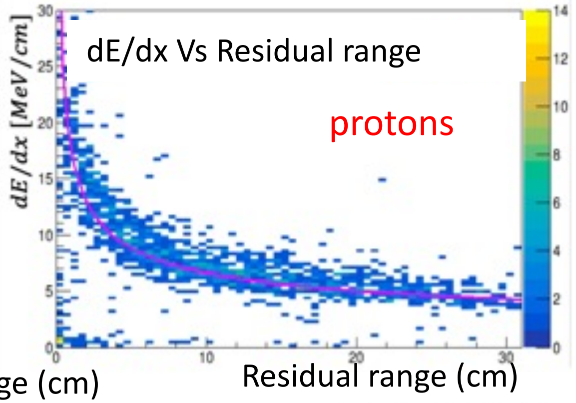
Automatic procedures for selecting 1μ 1p $\nu\mu$CCQE interactions fully contained in LAr active volume are under tuning/validation:

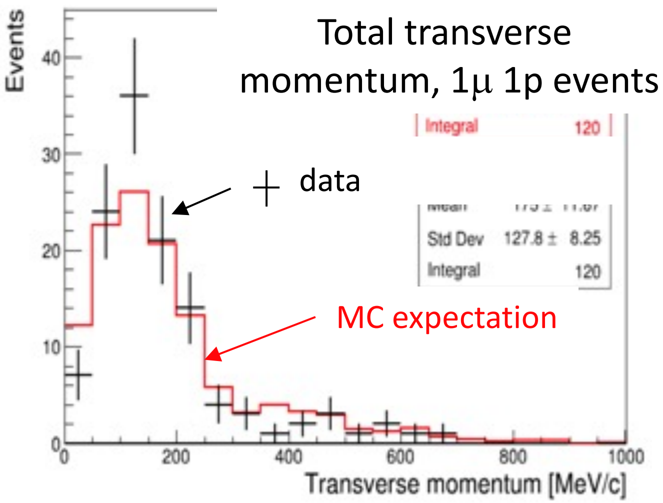
- Reconstructed ν interaction vertex and μ end-point (x_{reco}) within ~2 cm from the measured one (x_{scan}) ;
- Study P-ID for muons and protons;
- 1μ 1p fully contained ν candidates: demonstrating particle identification and kinematic reconstruction capabilities in the transverse plane









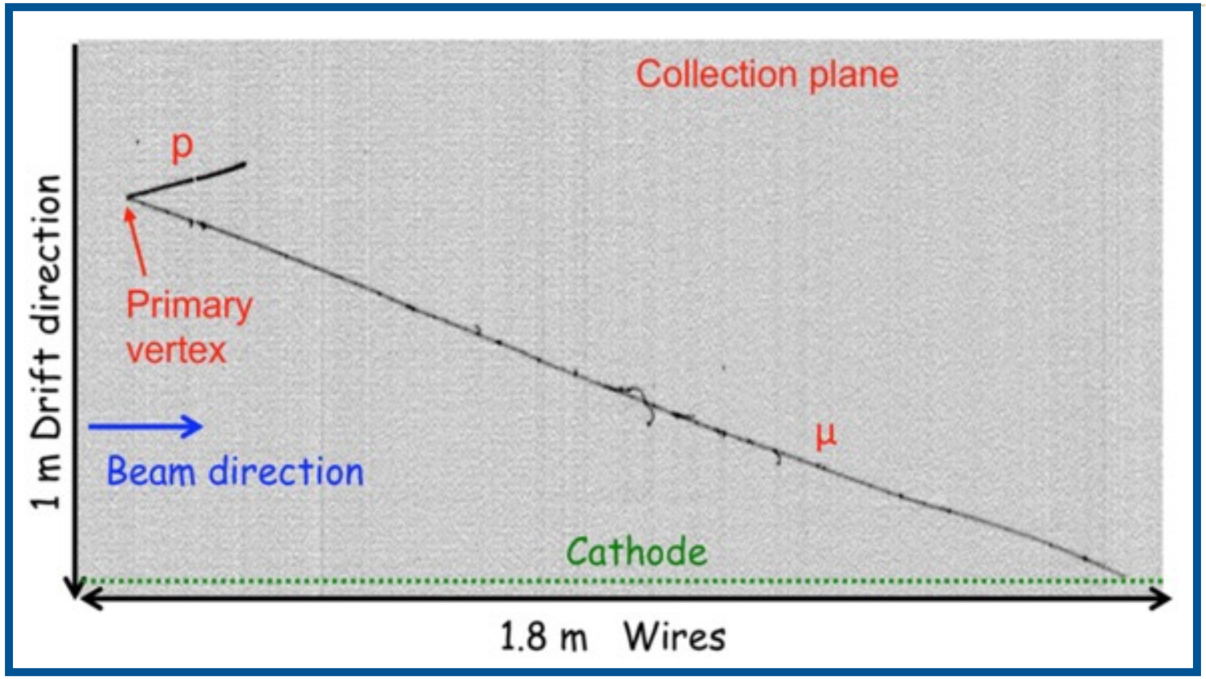


Conclusions and Perspectives

- ICARUS installation and commissioning was completed by mid 2022. Run-2 has smoothly finished collecting data from both Booster and NuMI beams with a ***total collected event statistics: ~2.5 10^{20} BNB, ~3.4 10^{20} NuMI.***
- Neutrino candidates have been successfully collected and are being used to further develop and tune automatic selection and reconstruction software tools
- ICARUS early phase's primary focus is the study of the Neutrino-4 claims searching for ν_μ disappearance with BNB and ν_e disappearance in the NuMI off-axis beam $\longrightarrow$ Data collected are being actively analysed and first physics results expected by the end of this year
- After the ICARUS-only phase, the SBND detector will join soon as near detector from the BNB target to perform a definitive 5σ analysis of sterile neutrinos search

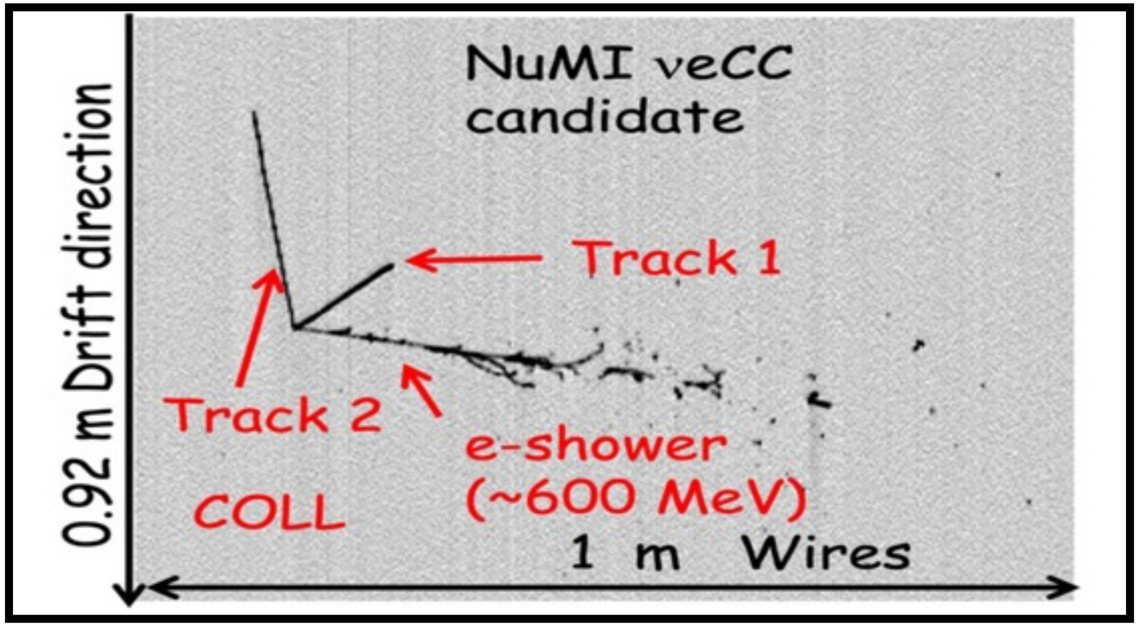
ICARUS is well on its way to report exciting results in fundamental physics searches !

THANK YOU !



ν_μ CC candidate
from BNB

ν_e CC candidate
from NuMI



ICARUS Collaboration at SBN

P. Abratenko[19], A. Aduszkiewicz[21], F. Akbar[23], M. Artero Pons[15], J. Asaadi[24], M. Babicz[2], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Berkman[5], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13], T. Boone[4], B. Bottino[8], A. Braggiotti[15], J Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13], J. Brown[5], H. Budd[23], A. Campani[8], A. Campos[27], D. Carber[4], M. Carneiro[1], H. Carranza[24], D. Casazza[8], A. Castro[3], M. Cicerchia[15], S. Centro[15], G. Cerati[5], M. Chalifour[2], A.Chatterjee[26],D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[25], T. Coan[18], A. Cocco[14], M. R. Convery[17], S. Copello[16], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Donati[25], J. Dyer[4], S. Dytman[22], S. Dolan[2], F. Dolek[27], L. Domine[17], R. Doubnik[5], F. Drielsma[17], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], F. Ferraro[8], F. Garcia[17], C. Gatto[14], M. Geynisman[5], D. Gibin[15], A. Gioiosa[25], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], S. Hahn[5], A. Heggestuen[4], B. Howard[5], R.Howell[23], J. Hrivnak[2], C. James[5], W. Jang[24],L. Kashur[4],W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], U. Kose[2], J. Larkin[1], G. Laurenti[6], G. Lukhanin[5], A. Maria[26], C. Mariani[27], C. Marshall[23], S. Martinenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], G. Meng[15], A. Menegolli[16], O.G. Miranda[3], D. Mladenov[2], A.Mogan[4], N. Moggi[6], N.Montagna[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], M. Murphy[27], D. Naples[22], M. Nessi[2], T. Nichols[5], S. Palestini[2], M. Pallavicini[8], V. Paolone[22], R. Papaleo[11], L. Pasqualini[6], L. Patrizii[6], G. Petrillo[17], C. Petta[7], V. Pia[6], F. Pietropaolo[2,a], F. Poppi[6], M. Pozzato[6], A. Prosser[5], G. Putnam[20], X. Qian[1], A. Rappoldi[16], R. Rechenmacher[5], L. Rice[22], E. Richards[22], F. Resnati[2], A.M. Ricci[25], A.Rigamonti[2], G.L. Raselli[16], M. Rosemberg[19], M. Rossella[16], C. Rubbia[9], G. Savage[5], A. Scaramelli[16], D. Schmitz[20], A. Schukraft[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], A. Soha[5],L. Stanco[15],J. Stewart[1],N.B. Suarez[22], H.Tanaka[17], M. Tenti[6], K.Terao[17] , F. Terranova[13], V.Togo[6], D.Torretta[5], M.Torti[13], Y.T. Tsai[17], S.Tufanli[2], T. Usher[17], F.Varanini[15], S. Ventura[15], M.Vicenzi[1], C. Vignoli[10], B.Viren[1], D. Warner[4], Z. Williams[24], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19], A. Wood[21], E. Worcester[1], M. Worcester[1], M. Wospakrik[5], H. Yu[1], J. Yu[24], A. Zani[12], C. Zhang[1], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

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27. Virginia Tech Institute

a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

Spokesperson: C. Rubbia, GSSI

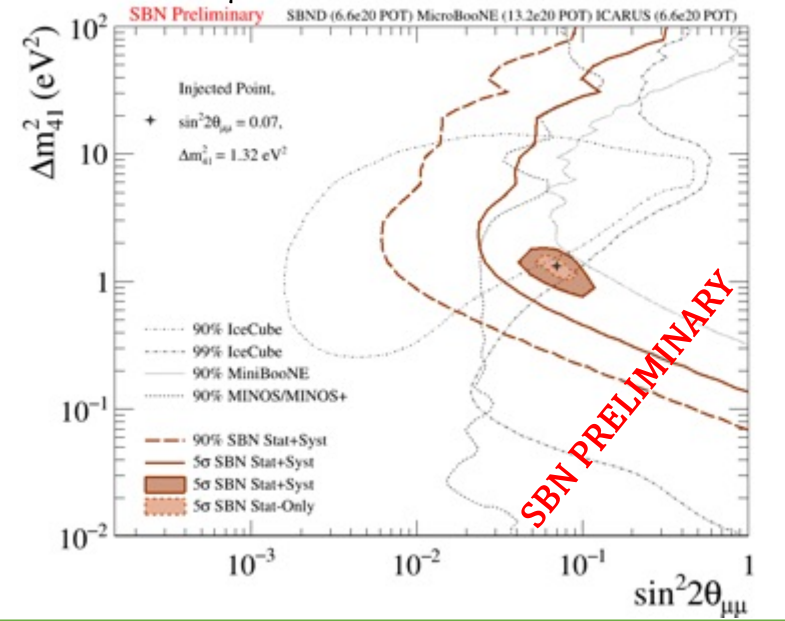
~180 *collaboratos*, 12 INFN groups, 12 US institutions, CERN, 1 Institution from Mexico and India

Backup slides

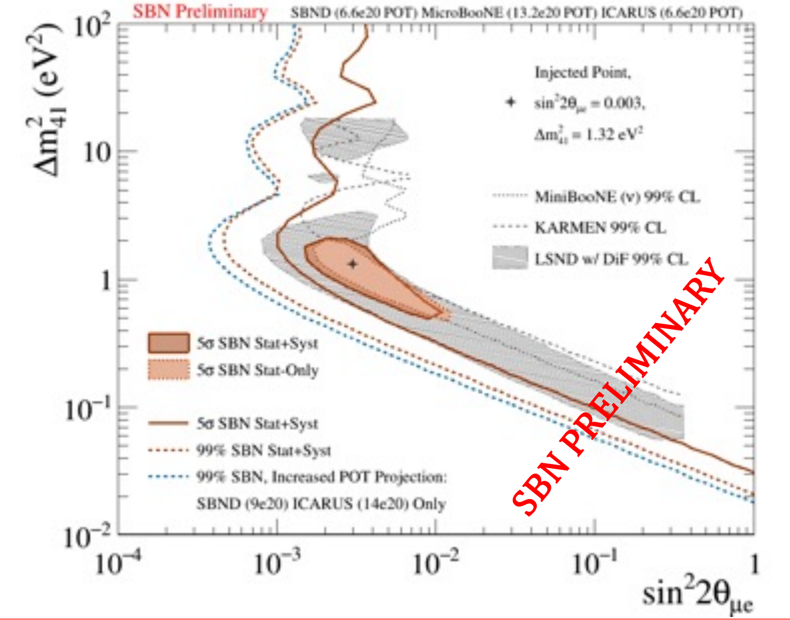
SBN program expected sensitivities

- The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5σ sensitivity both in appearance and disappearance channels in 3 years of data taking ($6.6 \cdot 10^{20}$ POT)

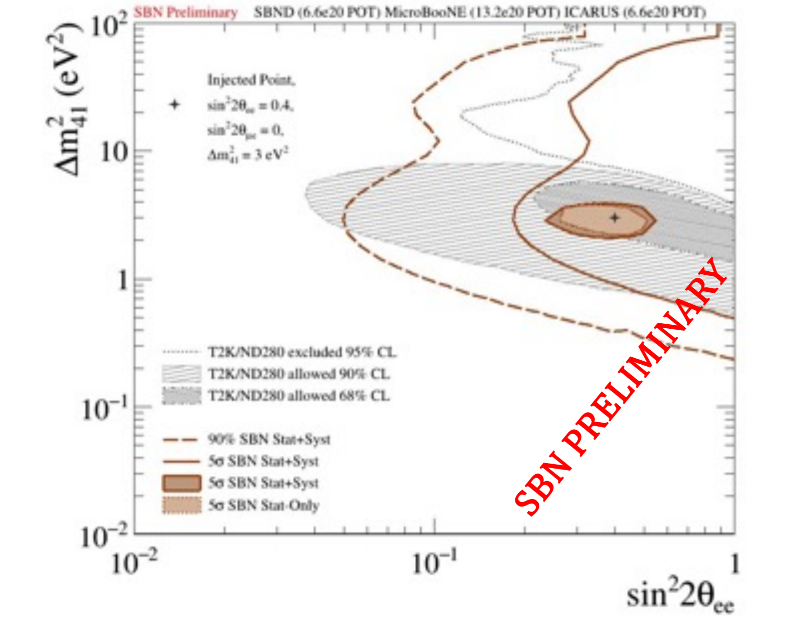
SBN ν_μ disappearance sensitivity



SBN ν_e appearance sensitivity



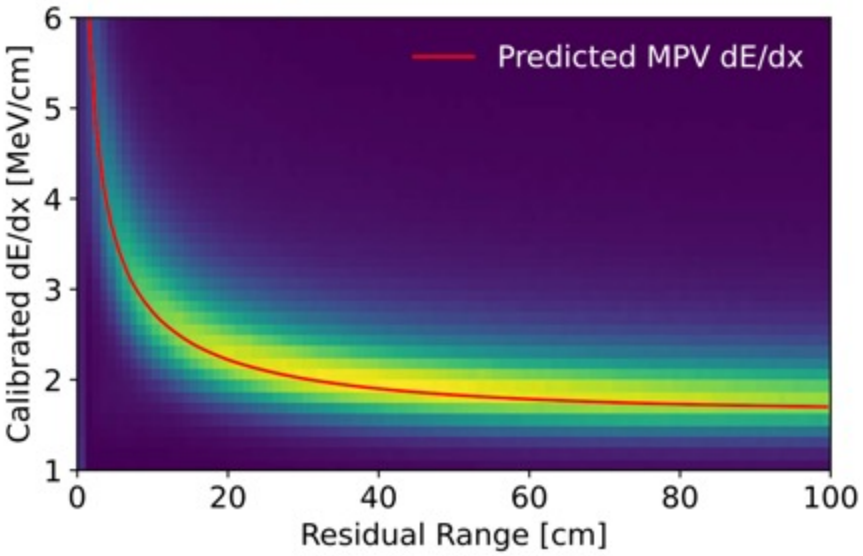
SBN ν_e disappearance sensitivity



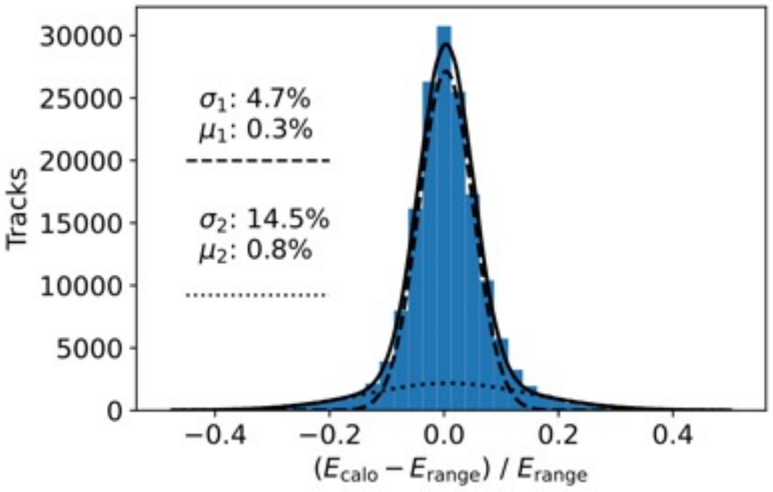
- Using the same detector technology will greatly reduce systematic errors
  - Near detector will provide the initial beam composition and spectrum
  - The clear electron neutrino identification capability will greatly reduce backgrounds

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)

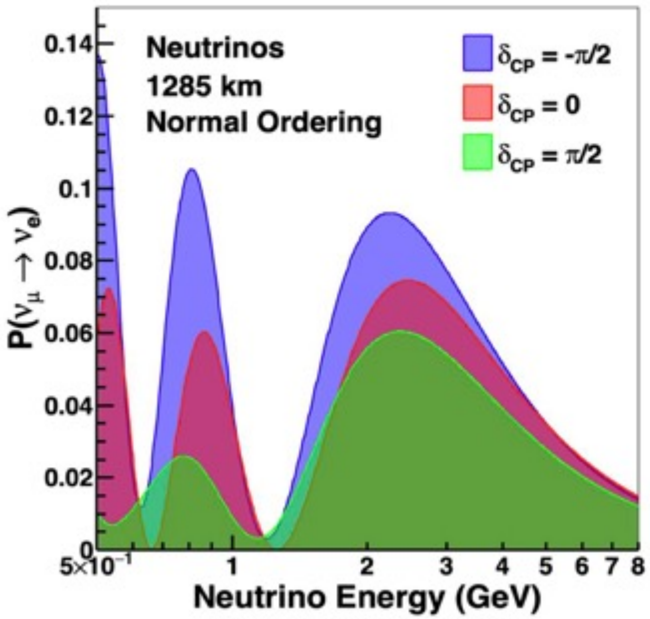
Physics searches with NuMI beam

Analysis of the NuMI Off-Axis beam (6^0 from ICARUS) data will allow:

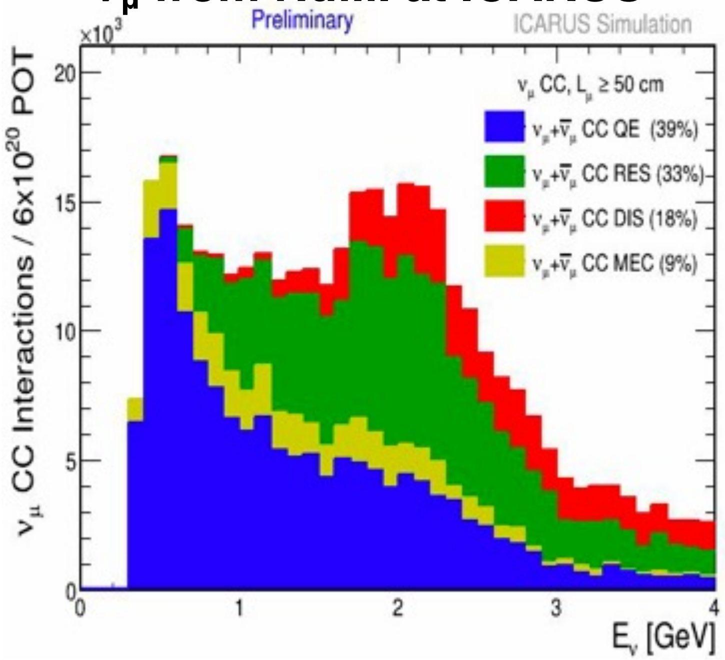
High statistics measurements of ν-Ar cross sections (~10^4 νeCC events/year) and tests of interaction models in the few hundred MeV to few GeV energy range, of great importance for SBN oscillation studies and DUNE.

A rich Beyond Standard Model search program: Higgs portal scalar, ν tridents, light dark matter, heavy neutral leptons …

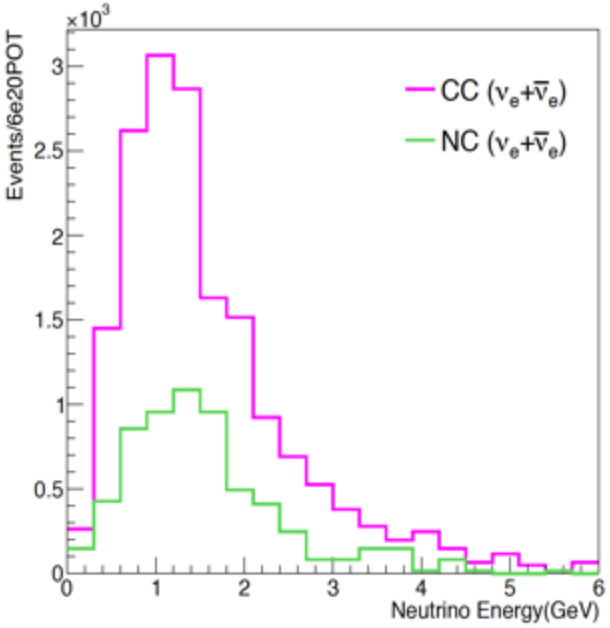
Oscillation probability at DUNE



ν_μ from NuMI at ICARUS

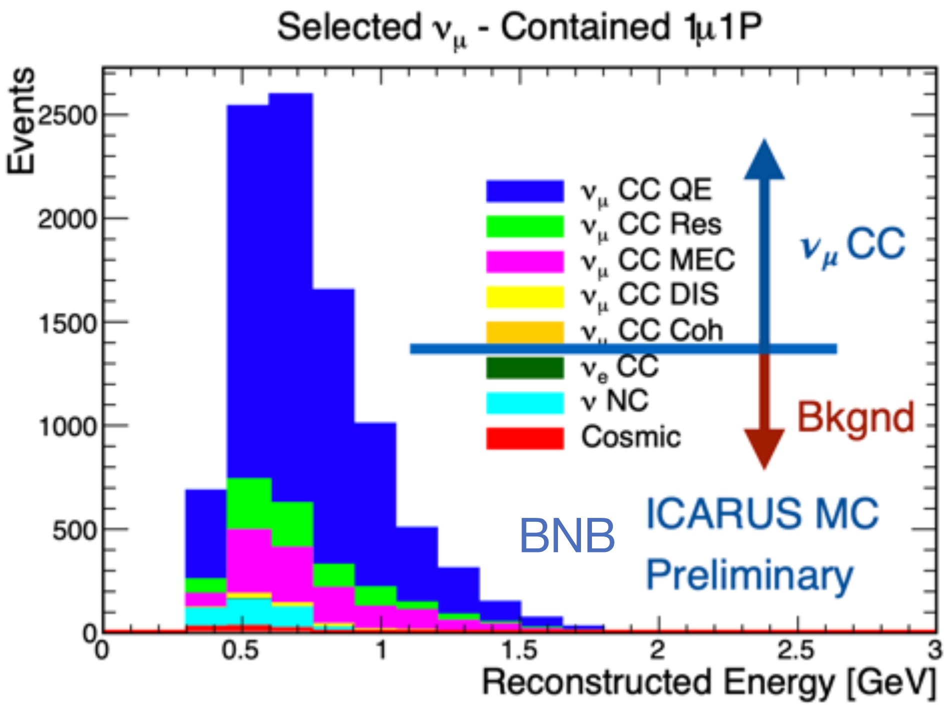


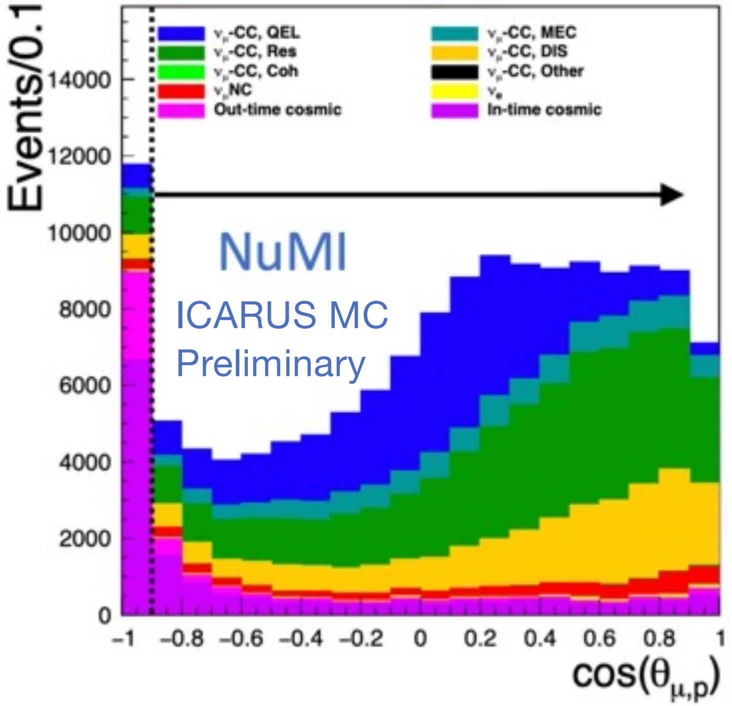
ν_e from NuMI at ICARUS



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 cosmic rays 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