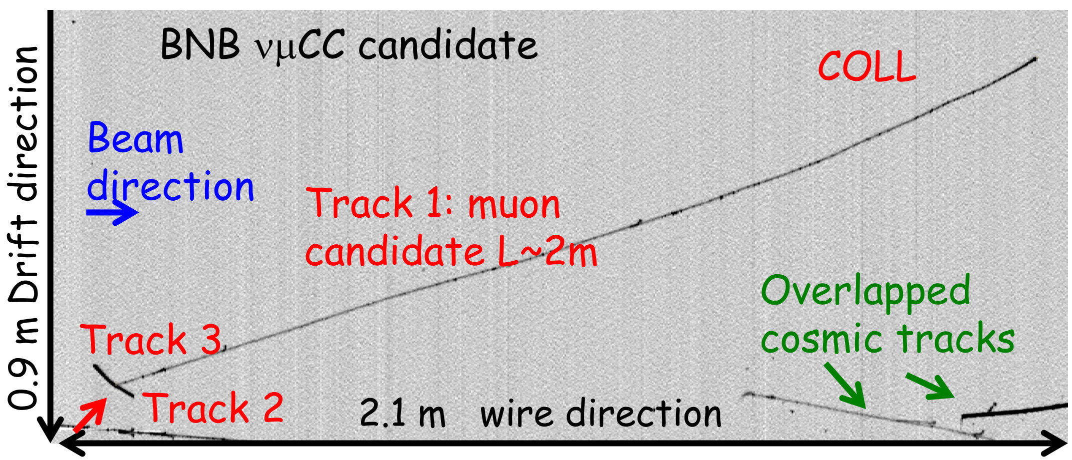
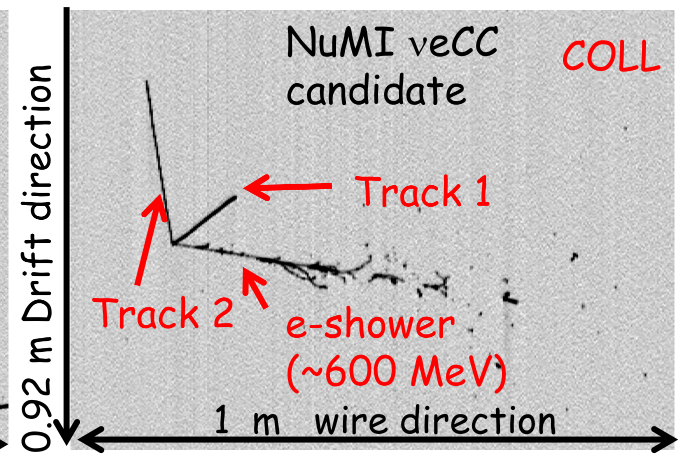
H2020, M. Sklodowska-Curie R&I No. 822185, 858199, 101003460, 101081478

ICARUS at the Short-Baseline Neutrino program: first results

D. Gibin, Padova University and INFN
on behalf of the ICARUS collaboration





XXXI International Conference on Neutrino Physics and Astrophysics, June 17 2024

ICARUS Collaboration at SBN

P. Abratenko[19],N. Abrego-Martinez[3], F. Akbar[23], L. Aliaga Soplin[24], M. Artero Pons[15], 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. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13], T. Boone[4], B. Bottino[8], J Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13], J. Brown[5], H.S. Budd[23], A. Campani[8], A. Campos[27], D. Carber[4] , M. Carneiro[1], I. Caro Terrazas[4], H. Carranza[24], R. Castillo Fernandez[24], S. Centro[15], G. Cerati[5], M. Chalifour[2], A.Chatterjee[26], D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[25], M. Cicerchia[15], T. Coan[18], A. Cocco[14], M. R. Convery[17], L. Cooper-Troendle[22], S. Copello[16], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Dolan[2], S. Donati[25], R. Doubnik[5], F. Drielsma[17], J. Dyer[4], S. Dytman[22], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], N. Gallice[1], C. Gatto[14], M. Geynisman[5], D. Gibin[15], A. Gioiosa[25], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], G. Gurung[24], S. Hahn[5], H. Hausner[5], A. Heggestuen[4], B. Howard[5], J. Hrivnak[2], C. James[5], W. Jang[24], Y.-J. Jwa[17],L. Kashur[4],W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], J. Larkin[1], G. Laurenti[6],Y. Li[1], G. Lukhanin[5], C. Mariani[27], C. Marshall[23], S. Martynenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], A. Menegolli[16], G. Meng[15], O.G. Miranda[3], D. Mladenov[2], 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], T. Nichols[5], S. Palestini[2], M. Pallavicini[8], V. Paolone[22], L. Pasqualini[6], L. Patrizii[6], L. Paudel[4], 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], G.L. Raselli[16], R. Rechenmacher[5], S. Repetto[8], F. Resnati[2], A.M. Ricci[25], E. Richards[22], A. Rigamonti[2], M. Rosemberg[19], M. Rossella[16], P. Roy[27], C. Rubbia[9], M. Saad[22], S. Saha[22], G. Savage[5], A. Scaramelli[16], D. Schmitz[20], A. Schukraft[5], D. Senadheera[22], S.H. Seo[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], J. Smith[1], A. Soha[5], L. Stanco[15], H.Tanaka[17], F. Tapia[24], M. Tenti[6], K.Terao[17] , F. Terranova[13], V.Togo[6], D.Torretta[5], M.Torti[13], R. Triozzi[15], Y.T. Tsai[17], T. Usher[17], F.Varanini[15], S. Ventura[15], M.Vicenzi[1], C. Vignoli[10], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19],A.Wood[21], E. Worcester[1], M. Worcester[1], H. Yu[1], J. Yu[24], A. Zani[12], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico,
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN LNGS, Assergi, Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
18. Southern Methodist University, USA
19. Tufts University, USA
20. University of Chicago, USA
21. University of Houston, USA
22. University of Pittsburgh, USA
23. University of Rochester, USA
24. University of Texas (Arlington),USA
25. INFN Pisa and University, Italy
26. Ramanujan Faculty Phys. Res. India
27. Virginia Tech Institute

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

Spokesperson: C. Rubbia, GSSI

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

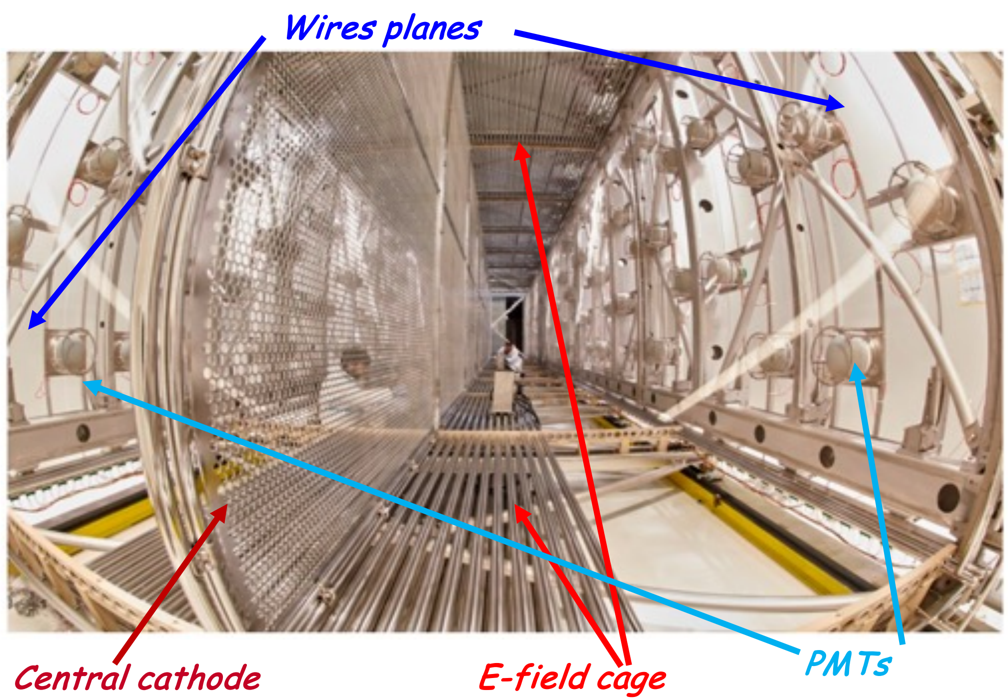
The remarkable evolution of ν-detectors: the ICARUS LAr-TPC

- Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" identifying unambiguously each ionizing track in complex neutrino events, was proposed by C. Rubbia [CERN-EP/77-08] as an alternative to Cherenkov detectors.

  Long INFN/CERN R&D culminated in the first large scale experiment ICARUS-T600, 0.76 kt ultra-pure LAr at LNGS underground lab, successfully exposed to CERN to G. Sasso beam:

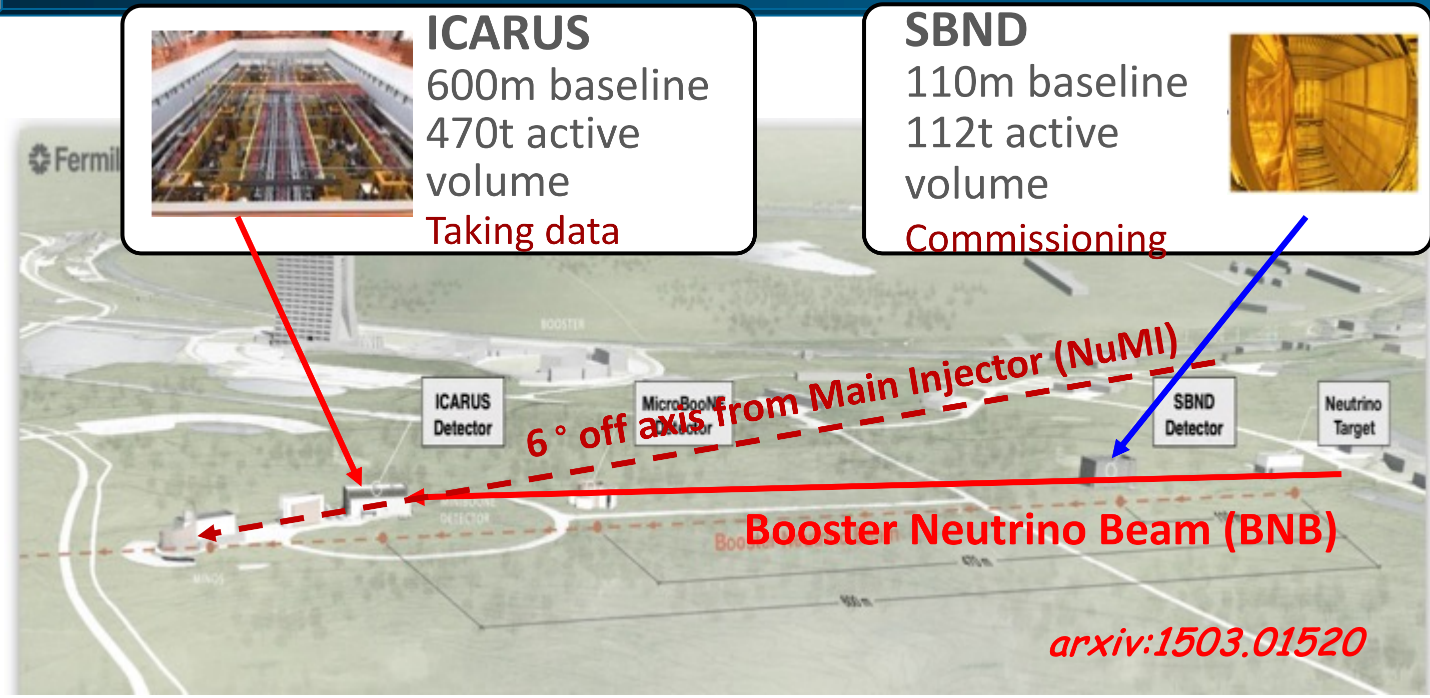
  … paving the way for Long-Baseline experiments

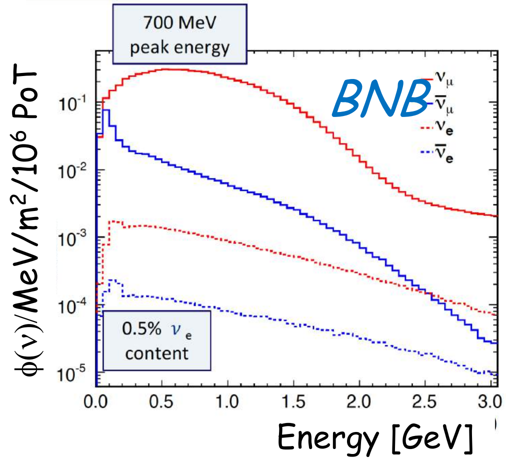
- ICARUS-T600 overhauled in 2014-18 in view of shallow depth operation at Fermilab:
  - 2 modules, 2 TPCs per module with central cathode (1.5 m drift, E_D= 0.5 kV/cm);
  - 3 readout wire planes per TPC, in total 54000 wires at 0, ± 60^0, 3 mm pitch;
  - 360 8" PMTs, TPB coated detecting scintillation light by particles in LAr;
  - LAr /GAr purified by copper filters and molecular sieves for water absorption;
  - Surrounded by ~4π Cosmic Ray Tagger system, protected by ~2.85 m thick concrete overburden.

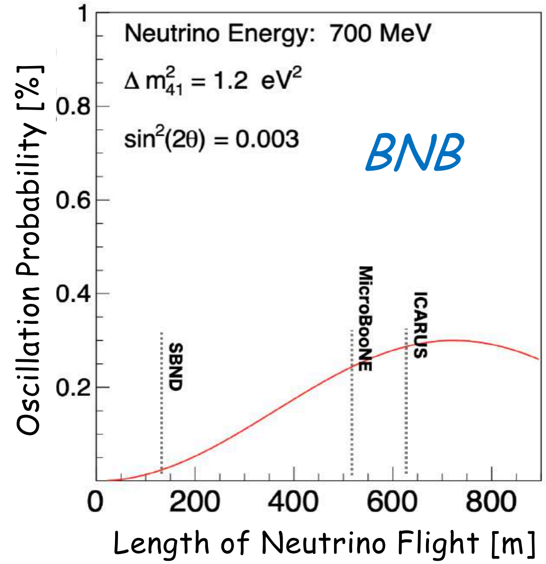


Inner view of a TPC

Short Baseline Neutrino (SBN) at FNAL BNB and NuMI beams: *a definitive answer to sterile neutrinos ?*

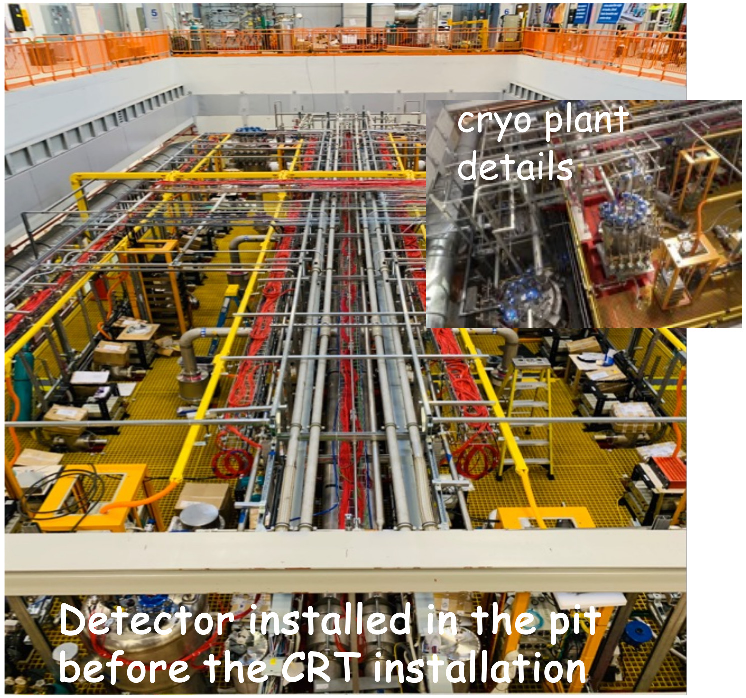




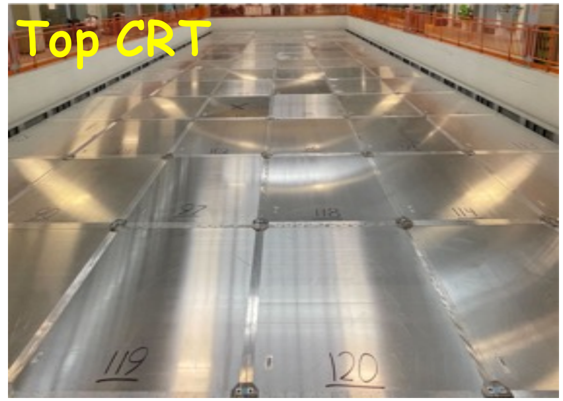


- ICARUS and SBND LAr-TPC's are installed at 600 and 110 m from the Booster p target, searching for sterile-ν oscillations both in appearance and disappearance channels, comparing the neutrino events collected by near and far detectors;
- In addition, ICARUS is exposed to the NuMI beam at ~6° off-axis (ν cross-section and BSM searches).

ICARUS T600 installation and activation

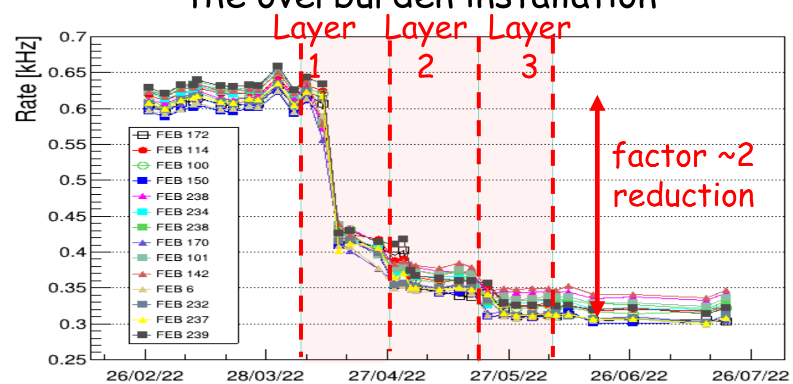


- The Cosmic Ray Tagger system (CRT) encloses the detector: a double layer of scintillator bars (~1000 m^2) tagging incoming cosmics with ~95% efficiency.



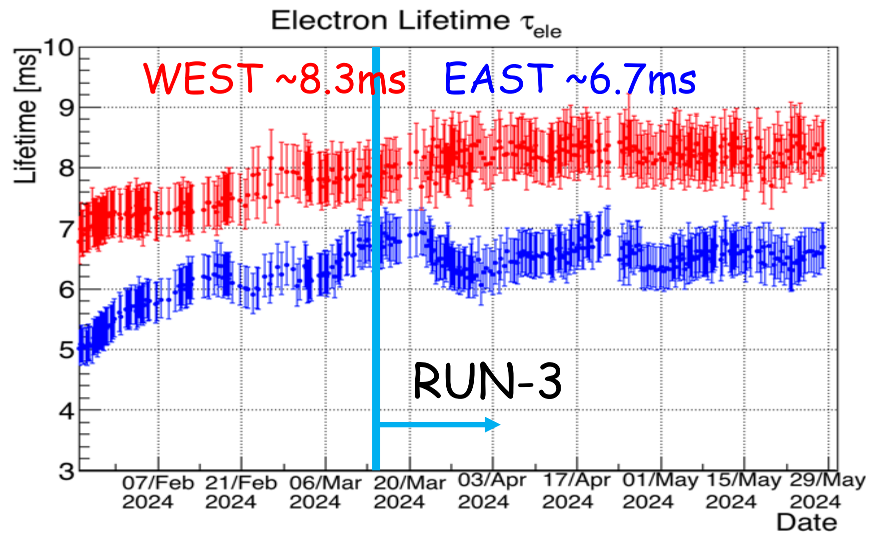
- Cosmic γ's and neutrons are suppressed by ~2.85 m thick concrete overburden installed on top of the CRT.

Rate of cosmic rays measured during the overburden installation



FNAL operation, runs, collected statistics

- June 2022: start of data taking for physics with TPCs, PMT light detection system and CRT fully operational;
- Events are triggered requiring at least 4 fired PMT pairs inside a 6 m longitudinal T600 slice in coincidence with BNB, NuMI beam spills, >90% efficiency for E_{dep} >200 MeV;
- Data acquisition is largely successful, currently with >97% collection efficiency;
- The cryogenic and purification system performed smoothly keeping residual impurities in LAr at ~40 p.p.t. of [O2] equivalent:
  - The free electron drift lifetime τ_{ELE} ≈7-8 ms, results in an almost full track detection efficiency in the whole 1.5 m drift (t ~ 1 ms).



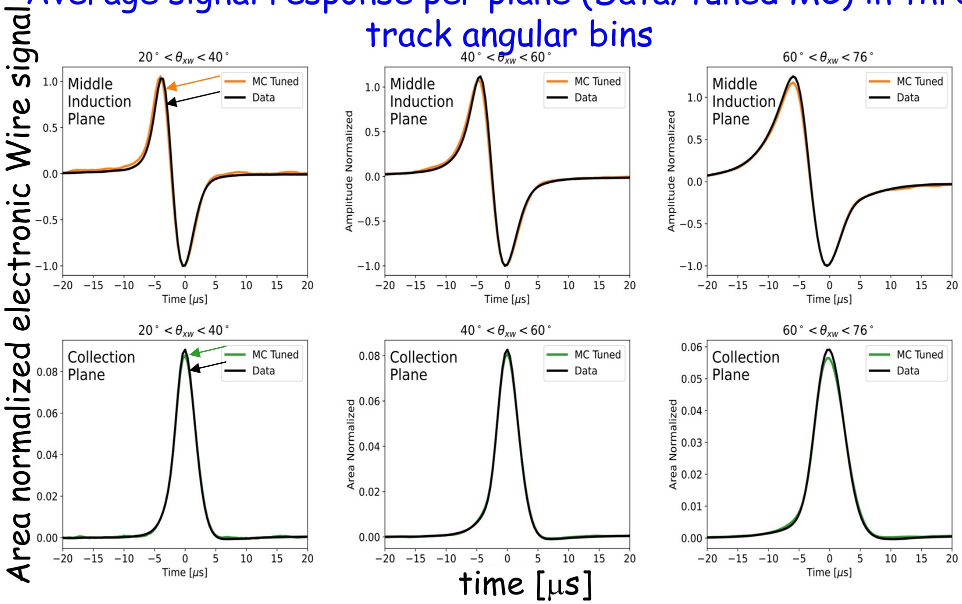
Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.05 10^{20}	2.74 10^{20}	-
RUN-3* (Mar-Jun 13)	0.95 10^{20}	-	2.02 10^{20}
TOTAL (PoT)	3.41 10^{20}	3.42 10^{20}	2.02 10^{20}

* Reduced exposure for RUN-3 due to the prolonged accelerator shutdown

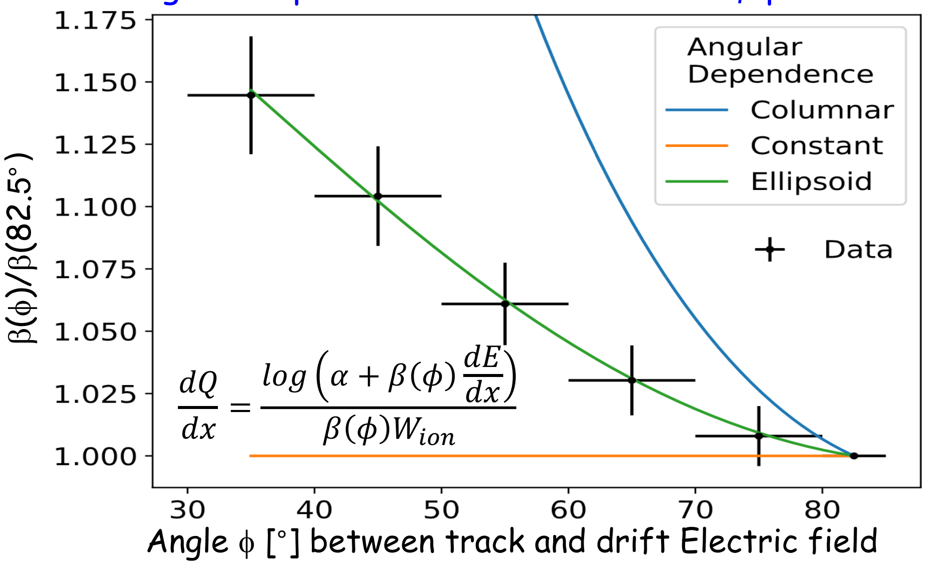
Detector calibration and modelling

- Signals from TPC wires have been accurately characterized and modeled in MC;
- Detector response is calibrated with cosmic muons and protons from ν events, including a new angular dependent recombination model (Ellipsoidal Recombination Model);
- Improved reconstruction is expected from a new processing accounting for charge sharing amongst multiple wires.

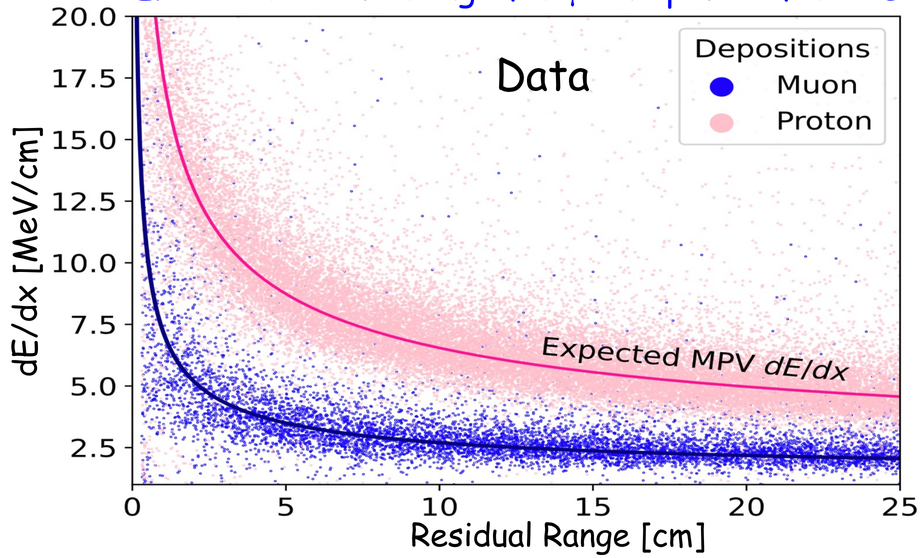
Average signal response per plane (Data/tuned MC) in three track angular bins



Angular dependence of recombination β parameter



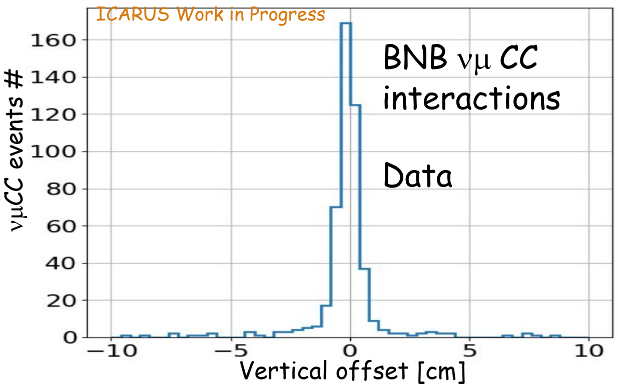
dE/dx vs residual range for μ and p used for PID



Papers in preparation.

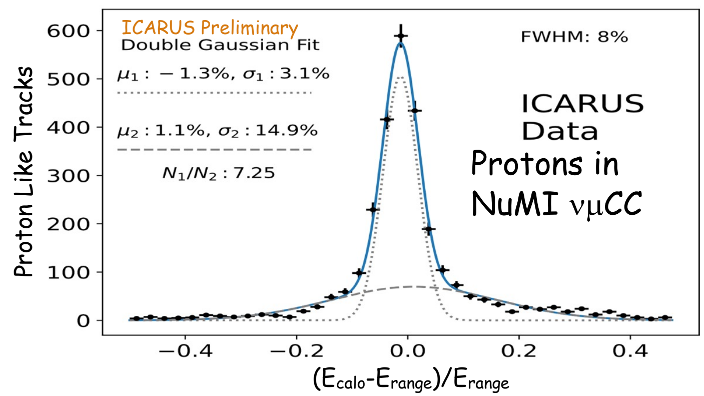
Detector performance and event reconstruction

Neutrino vertex reconstruction

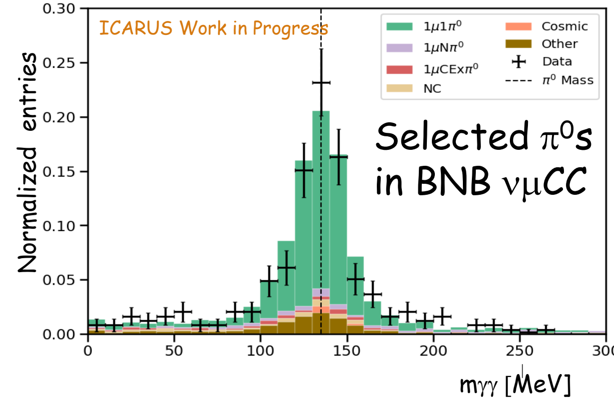


Difference between automatic and visual reconstruction of ν interaction vertex

Calorimetric energy reconstruction

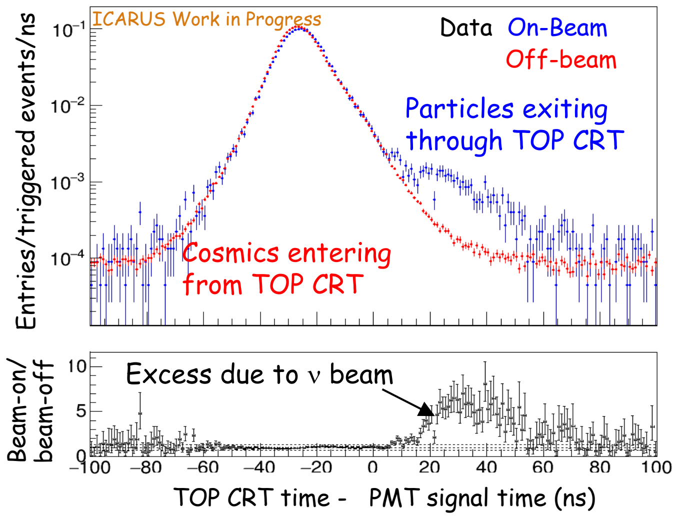


Difference between calorimetric and range measurement of the proton energy

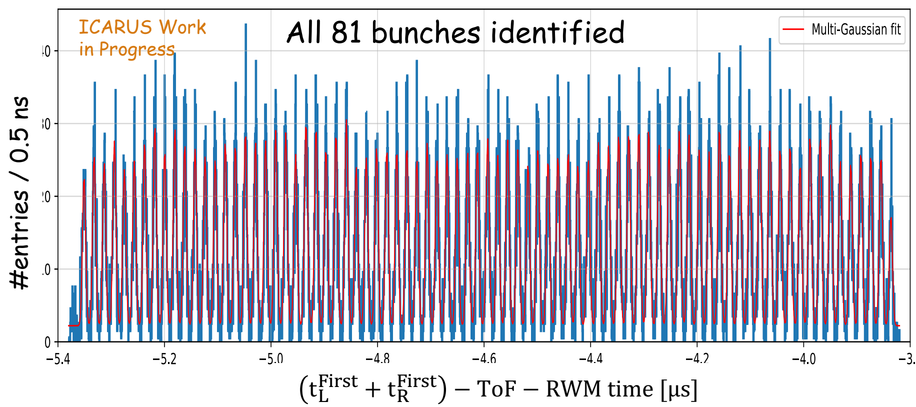


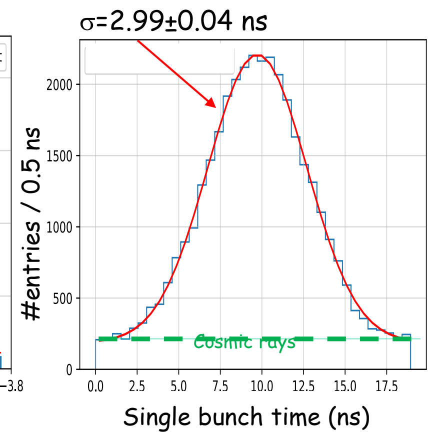
Reconstructed π^0 mass[1)]

Rejection of incoming cosmics by tof [2)]



Reconstruction of bunched structure of beam spill





ν event time (PMTs only) wrt p beam extraction time (RWM counters) after rejecting incoming cosmics (CRT) and correcting for ν flight

See poster by [1)] L. Kashur, [2)] F. Poppi

ICARUS Research Program

- The SBN program is addressing the question of sterile neutrinos with the BNB beam comparing ν_e and ν_μ interactions at different distances from target as measured by ICARUS and SBND LAr-TPCs.

- Before the start of joint operation and in preparation for the SBN oscillation analyses, ICARUS is focusing on standalone physics program:

  - Investigation of ν_μ disappearance with BNB ν beam, later complemented by the study of ν_e[1)] disappearance with off-axis NuMI beam, addressing the Neutrino-4 claim*. BNB ν_μ event selection: ready and validated [2)3)];

  - Study of ν_e[4)], ν_μ events from off-axis NuMI beam, to measure ν-Ar interaction cross sections and optimize ν reconstruction/identification in an energy range of interest for DUNE. ν_μ event selection ready, sidebands studied for a subset of data[5)];

  - Exploit the off-axis NuMI beam to investigate sub-GeV Beyond Standard Model signatures: signal box opened for $\mu\mu$ decay channel;

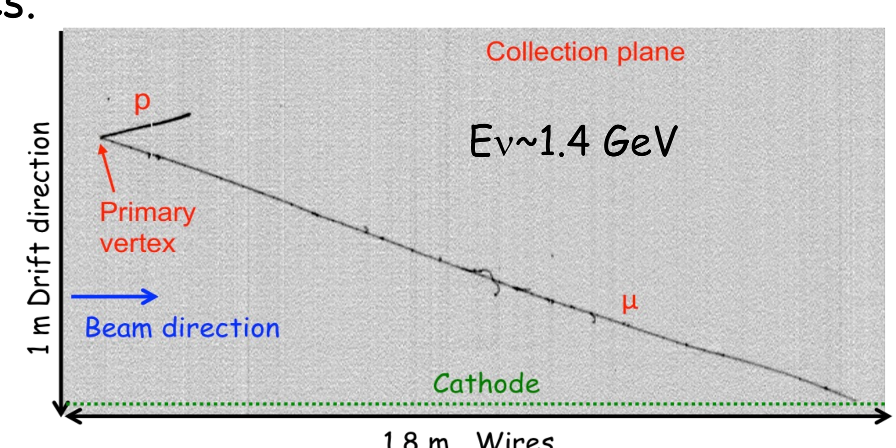
- ICARUS established a blinding policy to ensure robust and unbiased interpretation of the collected data; analyses are initially validated with a subset of collected data.

See: [1)] D.H. Koh, [2)]M. Artero Pons, [3)] J. Mueller, [4)] D. Carber. [5)] P. Roy posters

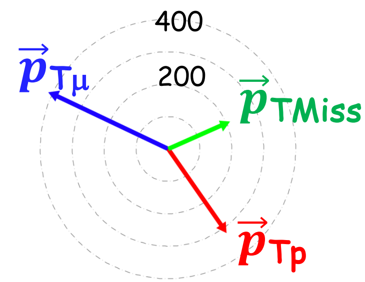
* A.P. Serebrov et al., Phys. Rev. D 104, 032003, arXiv:2306.09962

ν_μ event selection for disappearance analysis at BNB

- Fully contained ν_μCC events with 1μ+N protons are studied, requiring:
  a) PMT light signal inside 1.6 μs p beam spill window correlated with TPC tracks [2], with no CRT signal [1] ;
  b) a muon with L_μ >50 cm and at least one proton track[3] with E_K >50 MeV (L_p >2.3 cm) fully contained and identified by PID scores based on dE/dx;
  c) no additional π, γ.
- Residual cosmic backgrounds are less than 1%.
- Two independent analysis streams are considered, respectively based on:
  a) Pandora pattern recognition [4] and
  b) machine learning (ML) reconstruction code [5].
- A visual selection of ν candidates is used to validate the performance of selection/ reconstr. procedures for both analyses.
- The global event kinematics is obtained from range measurement of μ and p.



Momentum in the transverse plane (MeV/c)

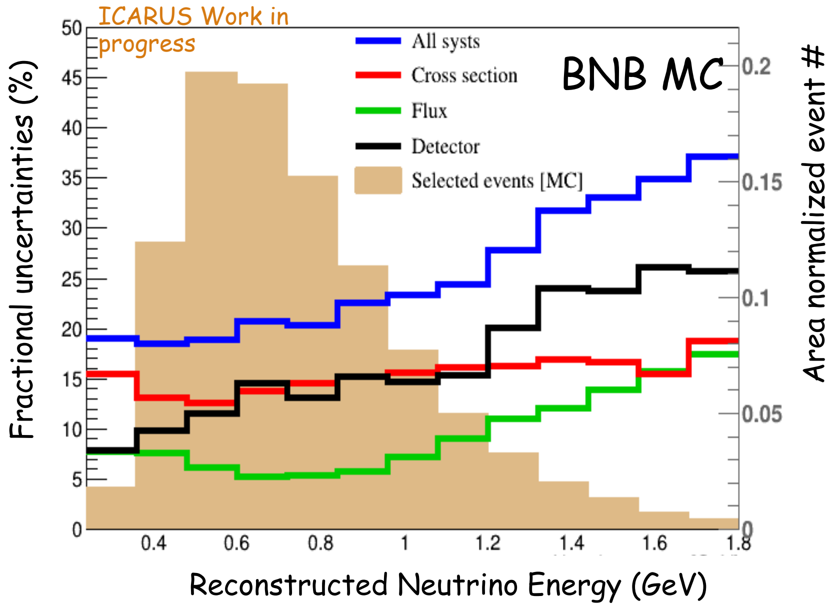


See posters by: [1] F.Poppi, [2] M. Cicerchia , [3] A. Campani, [4] M. Artero-Pons , [5] J. Mueller,

ν_μ event selection for disappearance analysis at BNB – cont'd

- At present flux/cross section and detector systematics ~equally contribute to the total systematic uncertainty;
  - Possible mitigation of cross section impact from the study of several kinematic variables;
  - Substantial cancellation of cross section and flux uncertainties in the joint SBN analysis;
  - Preliminarily, the impact on event analysis is evaluated comparing calibrated and uncalibrated MC samples[1];
  - The ongoing simulation improvements[2] reducing residual Data/MC discrepancies are expected to reduce also detector systematics;
  - Common detector systematics (f.i. recombination) are expected to cancel out in the joint SBN analysis.

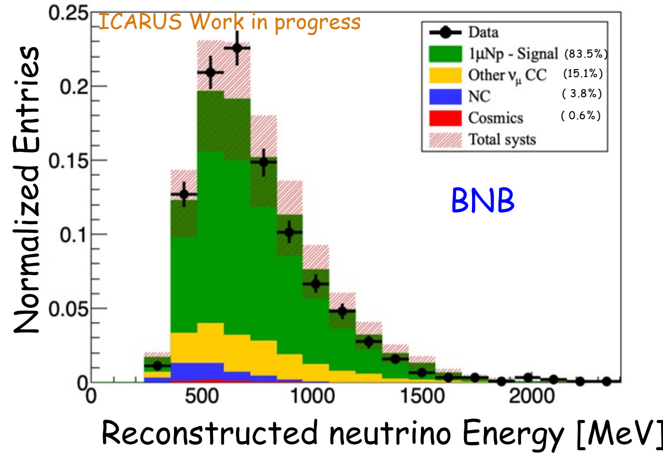
Example: BNB ν_μCC 1μNp Pandora selection

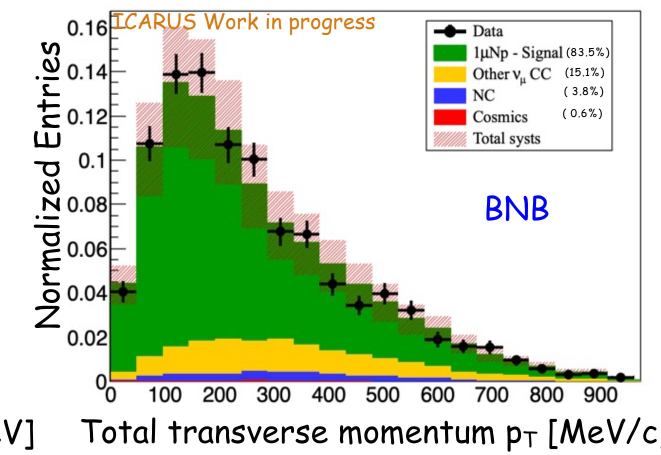


See [1] J. Zettlemoyer, [2] I. Caro Terrazas poster

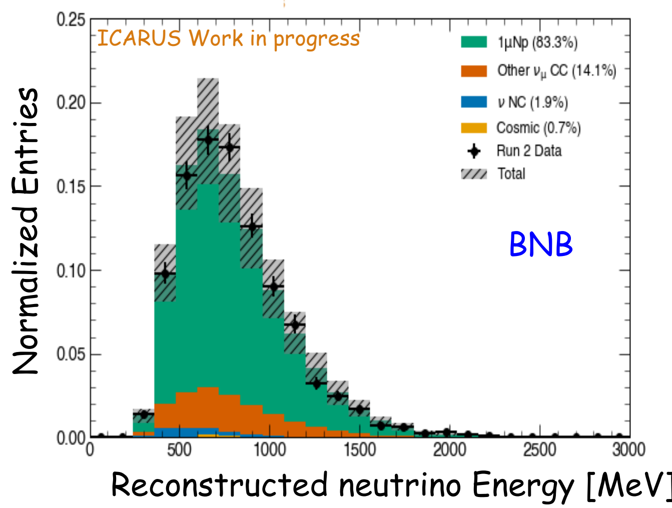
1μNp analysis – event selection results

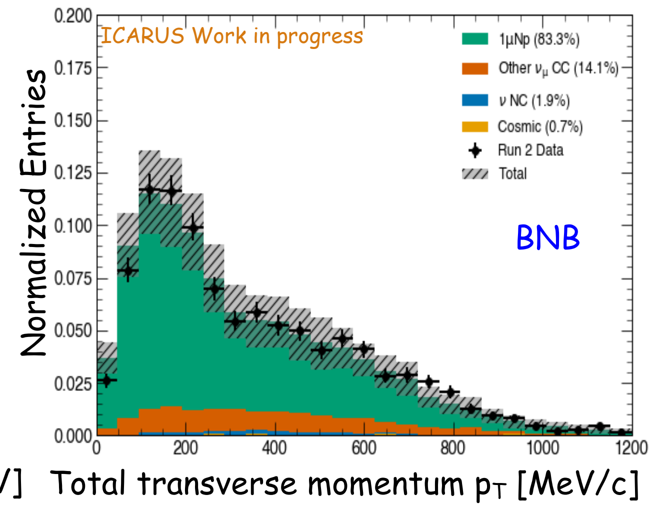
- Data- MC agree within systematics for all studied event kinematic variables; (10% of RUN-2 data analyzed, 20 time more data available) ;
- Pandora based analysis[1] with ~50% efficiency for the signal: BNB beam 1.93 10^{19} PoT (~34 k events for 3.89 10^{20} PoT)





- ML based analysis[2] with >50% efficiency for the signal: BNB beam 1.92 10^{19} PoT (~42 k events for 3.89 10^{20} PoT)





- Ready for the next analysis steps: enlarge the control sample size to confirm the analysis robustness and then proceed to full dataset unblinding and oscillation fit.

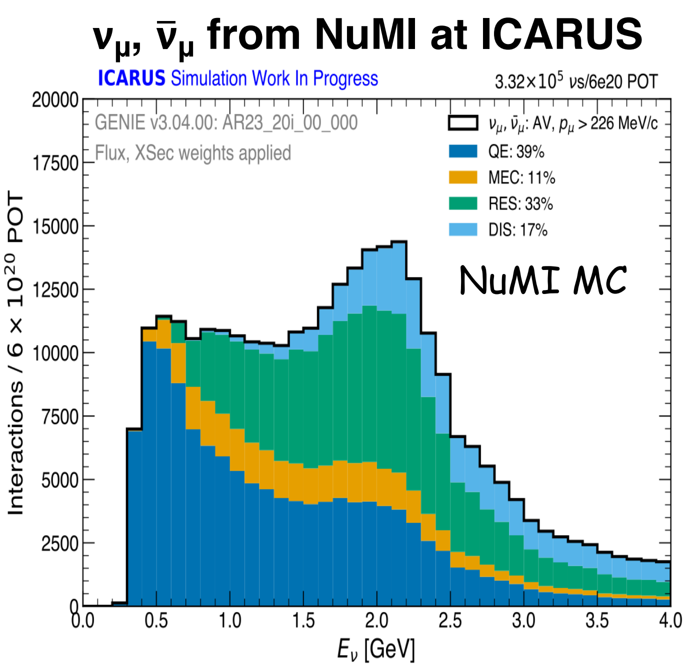
see [1]M. Artero-Pons, [2]J. Mueller poster

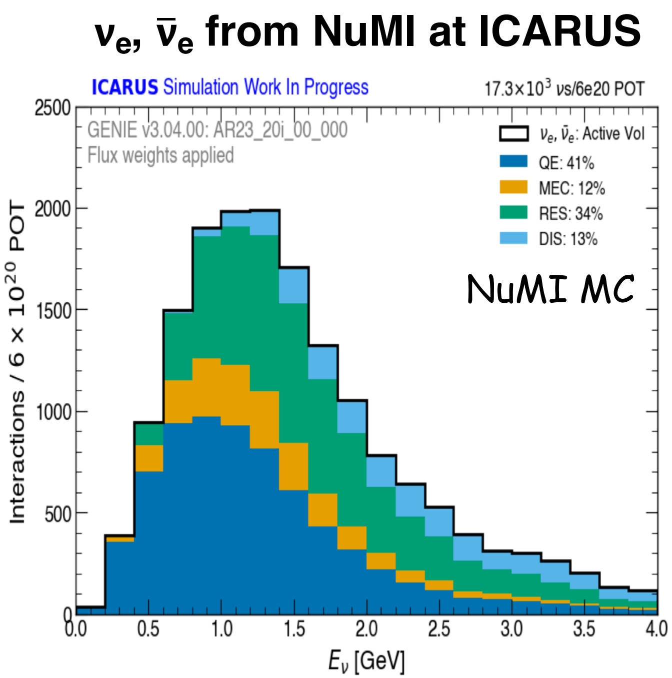
Neutrino Interactions from NuMI off axis at ICARUS

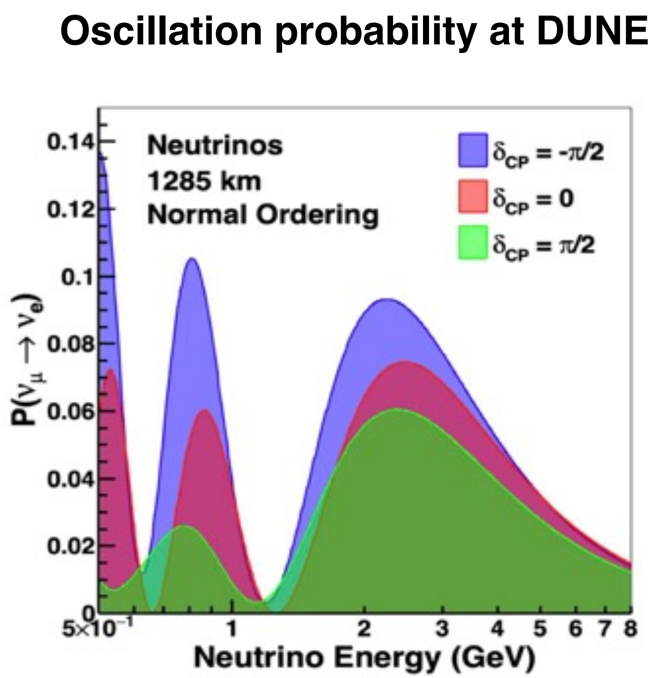
- Excellent statistics to measure cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos:

  CC events/6 10^{20} PoT : ν_μ 332,000 and ν_e 17,000.

- Neutrino energy spectrum from NuMI at ICARUS covers the first oscillation peak and good coverage of the relevant phase space for DUNE experiment.



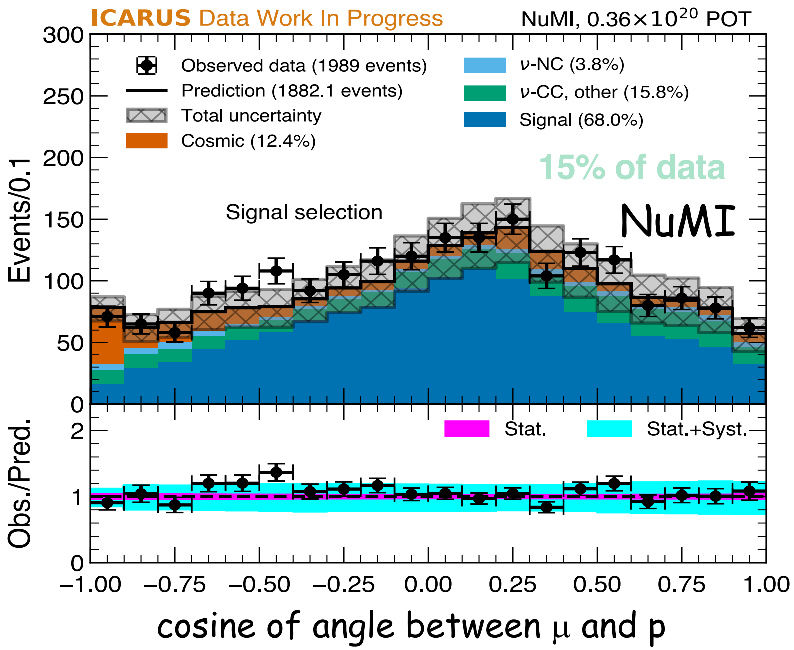


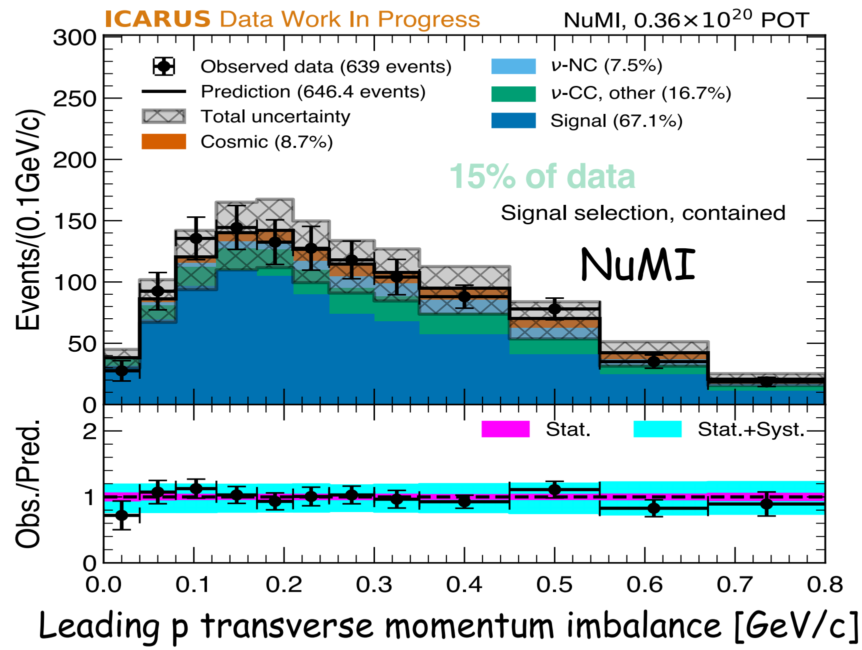


- Available data ~3.42 10^{20} PoT for physics analysis now

CC 0π analysis – results for the selected sample

- First analysis: $1\mu+Np+0\pi$ enhanced in quasi elastic and 2p2h interactions[1]:
  - Signal definition: one μ with p_μ > 226 MeV/c, any proton with p_p between 400 MeV/c and 1 GeV/c, no $\pi^\pm$ or π^0 in the final state;
  - Selection: at least two primary tracks, a μ and p candidates, identified by PID;
  - Flux, interaction model and detector systematic uncertainties have been included.
  - The angle between μ and leading p candidates is expected to encode information about Final State Interactions for all events;
  - Transverse kinematic observables are sensitive to Initial and Final State effects.

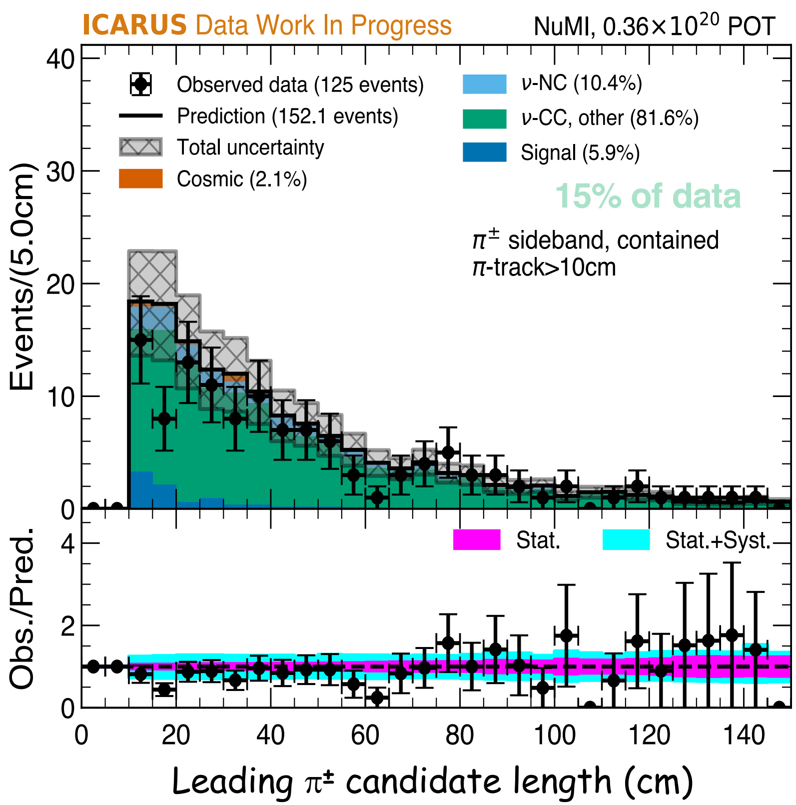


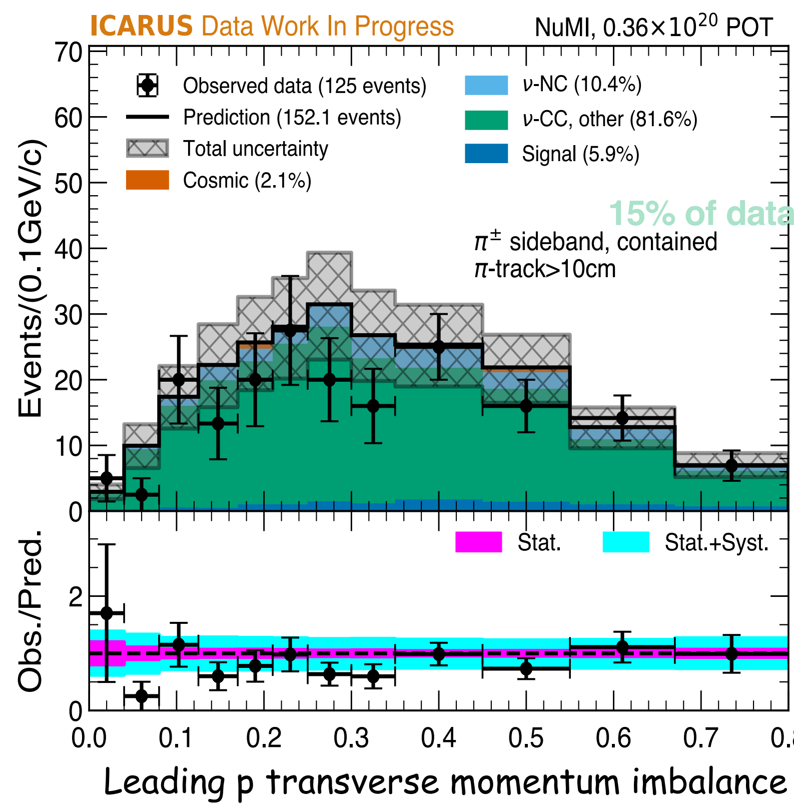


[1] See P. Roy poster

Charged Current Pion Control Sample

- The major background is represented by events with undetected/misidentified pions;
- To characterize this background an event control sample has been selected with charged pion candidates (requiring the presence of a secondary muon-like track);
- The control sample is initially studied with 15% of data. Ready to study sidebands with the full Run-1 + Run-2 event statistics.

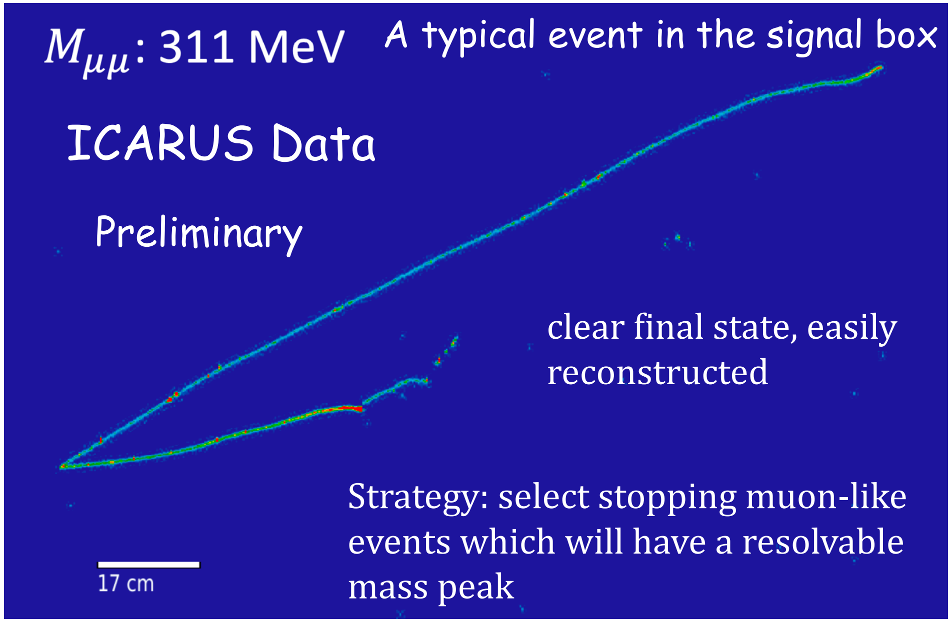




Dark sector models investigation by ICARUS

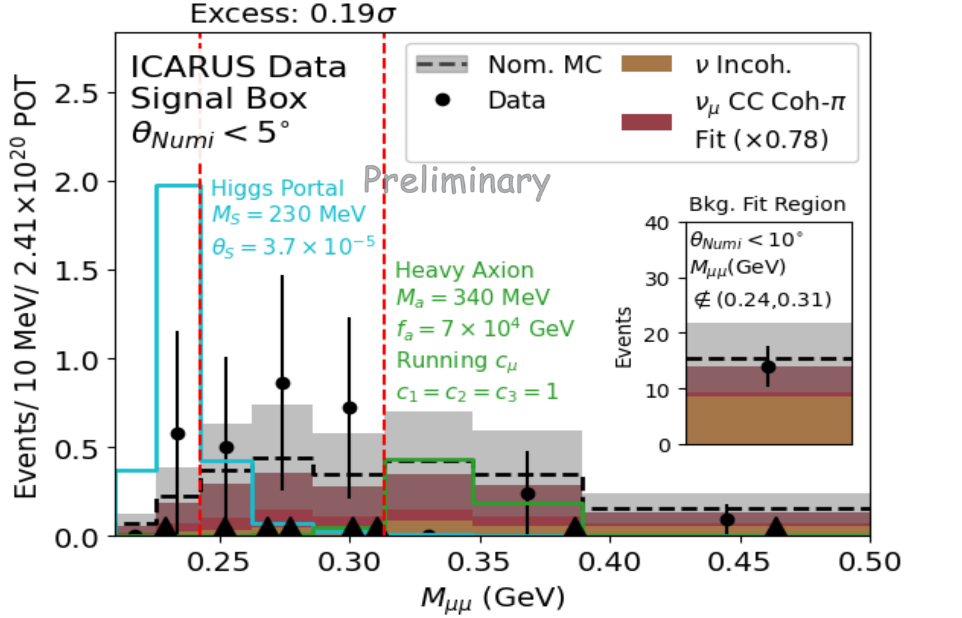
- A rich Beyond Standard Model search program, DM, heavy neutral leptons,… The experimental search has been pursued exploiting the off-axis NuMI beam;
- The models considered so far involve dark particles coupling to Standard Model particles via Scalar Portal Interactions:
  - Higgs portal Scalar (HPS): Scalar dark sector particles – interactions by mixing with the Higgs boson;
  - Heavy QCD axion (ALP): Pseudoscalar particles – interactions by mixing with pseudo-scalar mesons;

- An analysis with contained di-muon final state topology has been completed.
- Events with 2 stopping μs are selected, to reconstruct the scalar mass peak;
  - The signal is expected at small angle to beam ($\theta_S < 5^0$);
- Flux, interaction model and detector systematic uncertainties have been included.

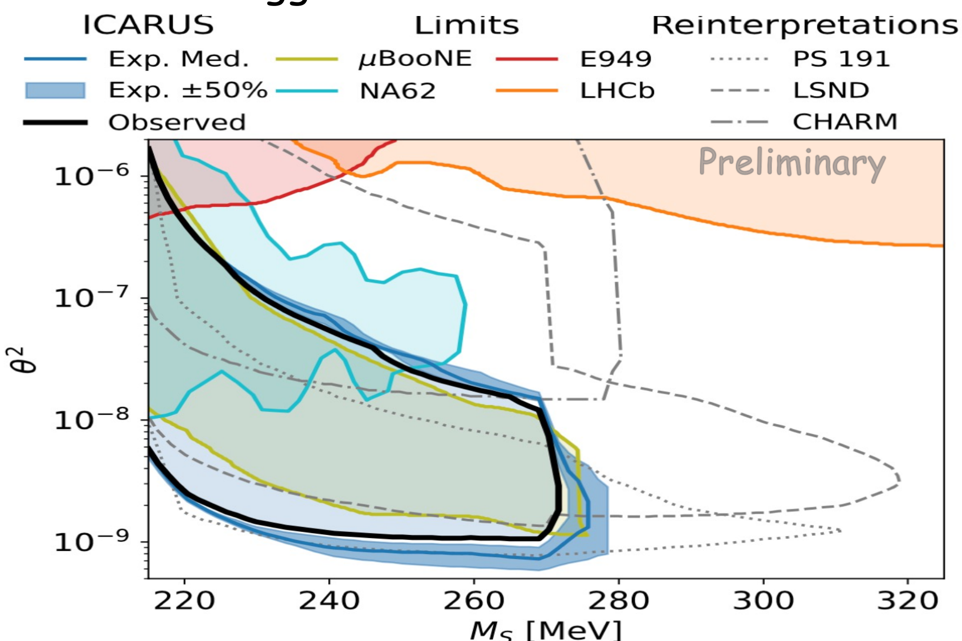


Search for BSM scalar decays in $\mu^+\mu^-$ with NuMI - results

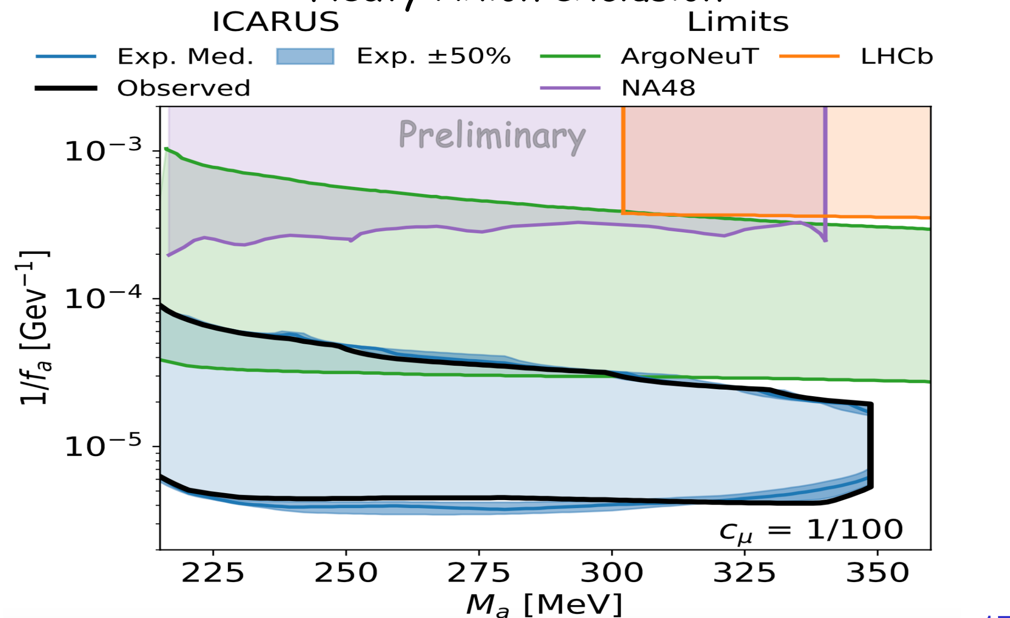
- Open box result: 8 events observed, compared to MC expectations of 8 events, mostly from $\nu\mu$CC coherent π production;
- No new physics signal was observed, the maximum excess being 0.19 σ;
- Exclusion contour plots in progress.
- See G. Putnam poster.



Higgs Portal Scalar exclusion



Heavy Axion exclusion



Conclusions

- ICARUS is smoothly running in physics mode since June 2022, exposed to the Booster and to the NuMI neutrino beams;
- The detector is calibrated with cosmic muons and protons from neutrino interactions, electronic response and physical properties have been accurately qualified and are being fully modeled in simulation. Papers are in preparation.
- While waiting for the joint operation within SBN, several single detector analyses are quite advanced:
  - Study of $\nu\mu$ disappearance with the BNB beam;
  - Measurement of $\nu\mu$ cross-sections with NuMI beam;
  - Search for Sub-GeV DM candidates in NuMI beam. A first search for new particle decaying into di-muon has been completed and now a paper is in preparation.
- Analyses ready to proceed to validation with larger control samples in view of the full signal unblinding.

ICARUS posters

Poster session and reception 1 (18 Jun)

51. M. Artero-Pons, "Neutrino reconstruction analysis at ICARUS detector"
439. A. Campani, "Track vs shower discrimination in the event reconstruction of the ICARUS experiment"
38. M. Cicerchia, "Data vs. MC comparison of light signal from cosmic rays in the ICARUS detectors"
252. Y. Jwa, "Michel Electron Reconstruction Using a Novel Deep-Learning-Based Multi-Level Event Reconstruction in ICARUS";
280. D.H. Koh," Deep-learning applications for BNB electron neutrino reconstruction in the ICARUS experiment";
394. F. Poppi, "Cosmic Background Rejection of the ICARUS experiment at Fermilab"
259. J. Zettlemoyer, "Evaluating the Effect of Detector Modeling Uncertainties on Sterile Neutrino Oscillation Analysis with the ICARUS Detector"

Poster session and reception 2 (21 Jun)

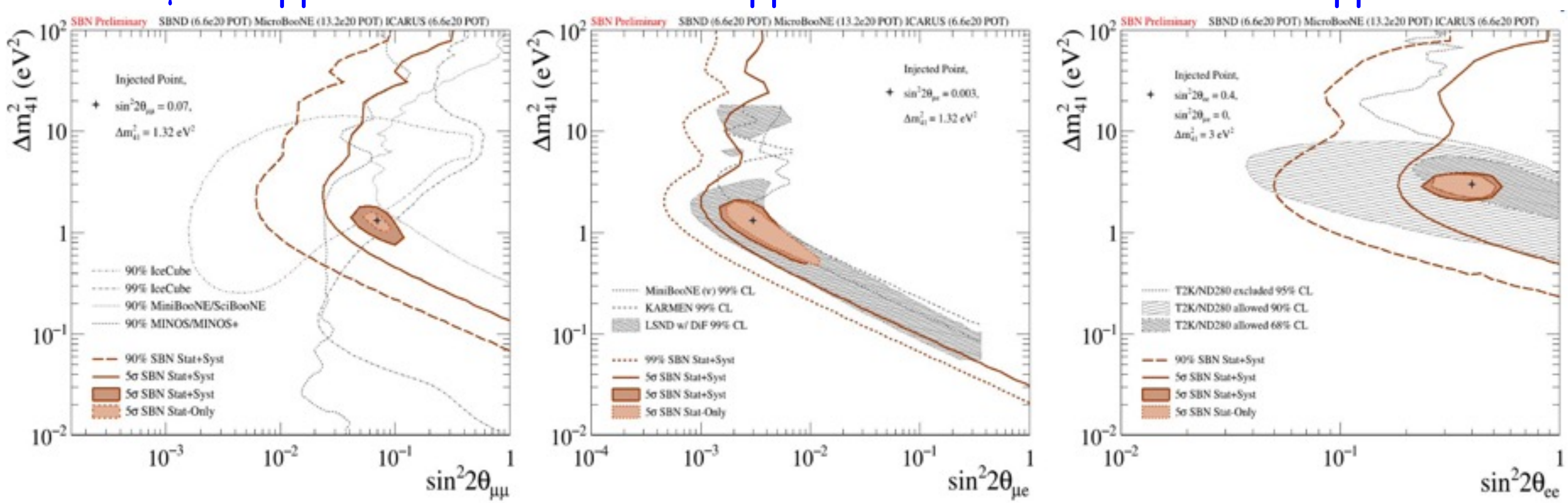
156. D. Carber, "NuMI Electron Neutrino Selection at ICARUS with Machine Learning Reconstruction "
433. I. Caro Terrazas, "Enhancing Neutrino Event Simulation through Overlays at the ICARUS Experiment on the Short-Baseline Neutrino Program"
394. L. Kashur,J. Mueller, "Muon Neutrino Reconstruction at ICARUS with Machine Learning"
99. G. Putnam, "Search for a Long-Lived $\mu\mu$ Resonance at ICARUS in SBN "
44. P. Roy, "Status of ICARUS-NuMI interaction cross-section analysis"

Thank you !

SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} PoT)

- Combined analysis of events collected far by ICARUS at far site and by SBND at near using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPCs rejecting NC event background;
  - “Initial” BNB beam composition and spectrum provided by SBND detector.

νμ disappearance — νe appearance — νe disappearance



5σ coverage of the parameter area relevant to LSND anomaly

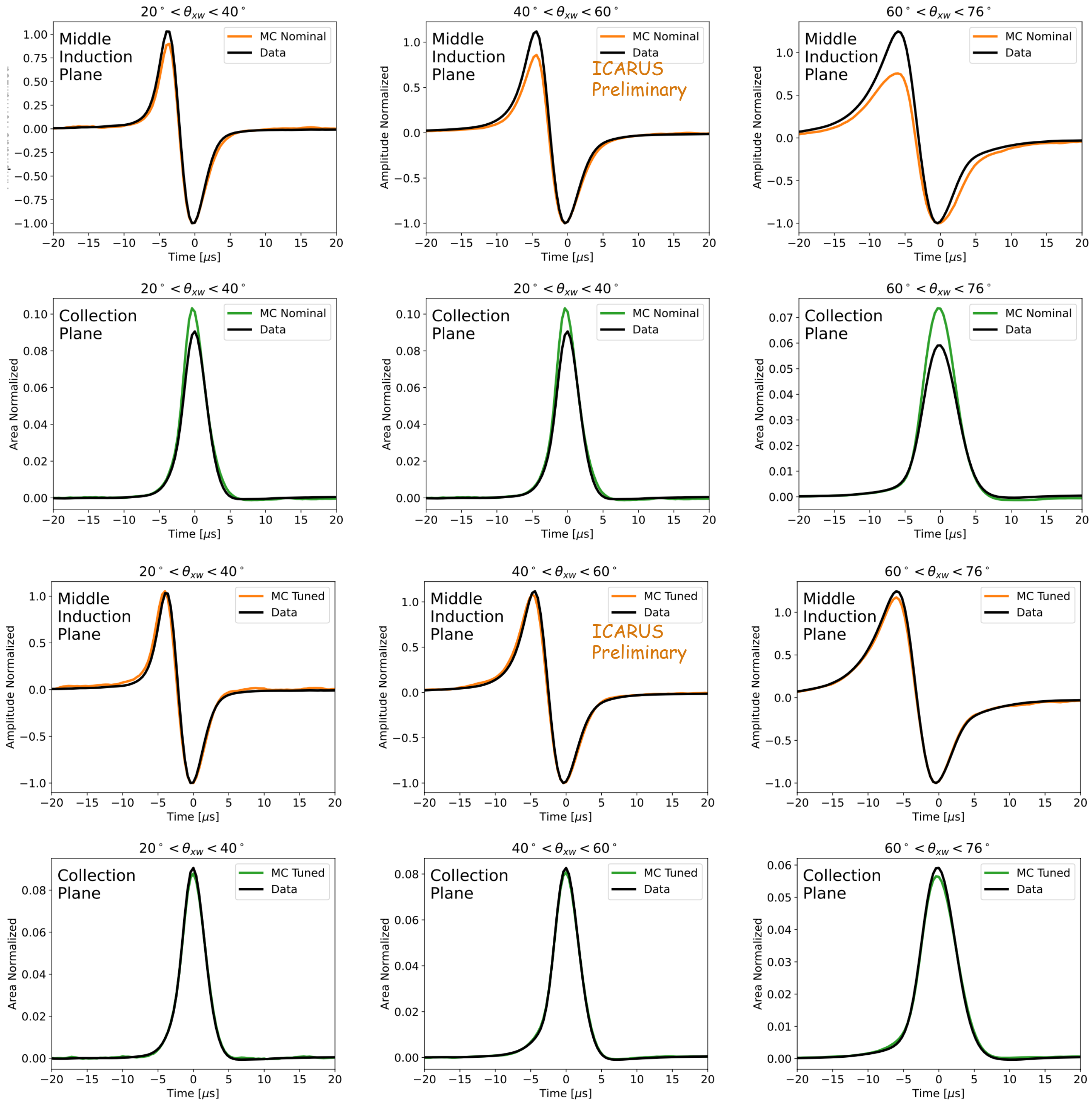
Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study neutrino appearance and disappearance simultaneously

Untuned and tuned wire signal response

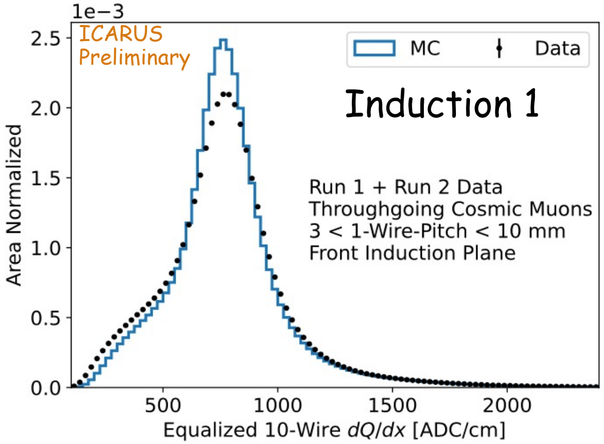
- MC with untuned electronic response

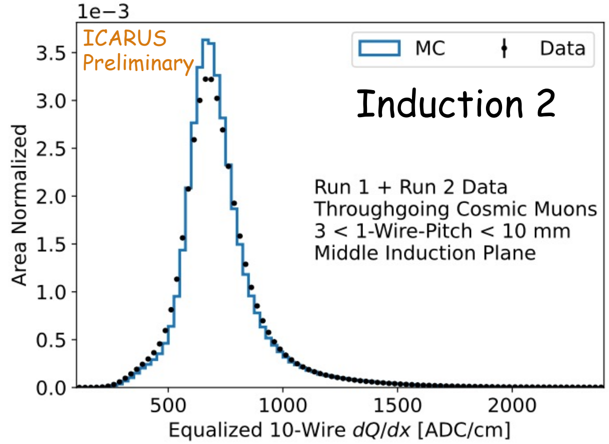
- After electronic response tuning in MC

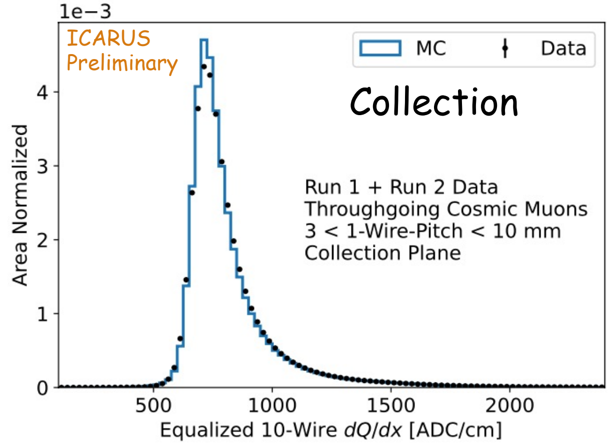


Validation of the equalization procedure and MC simulation

- A large sample of throughgoing cosmic muons has been studied to validate the calibration, the equalization of the individual wire response and the tuning of the electronic response modeling in MC;
- The distribution of the ionization density distribution for Data and MC has been compared, showing a good agreement in all planes.
- Residual Data/MC differences are traced to position dependent effects which have been mapped and are being included in the simulation (mainly in Induction 1).

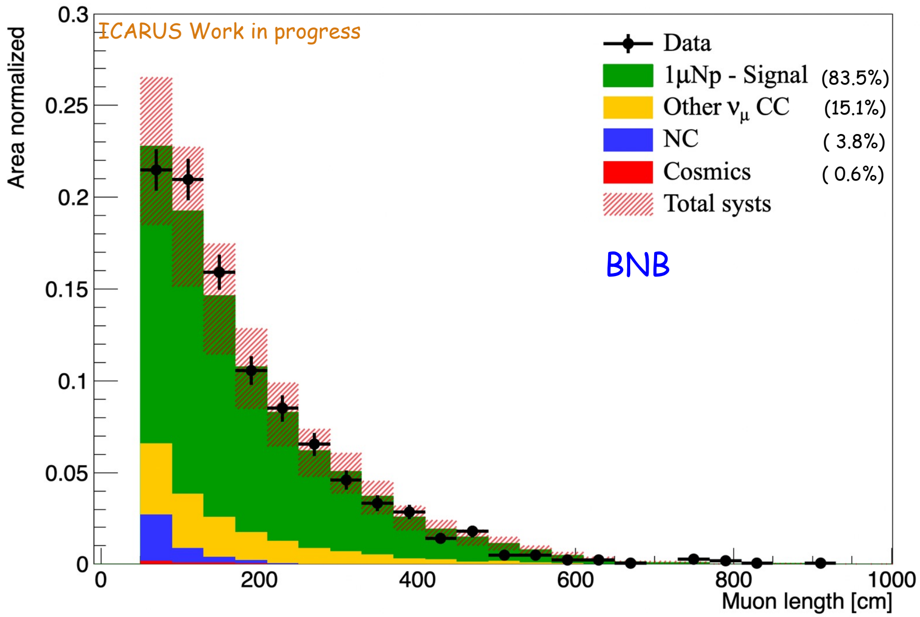


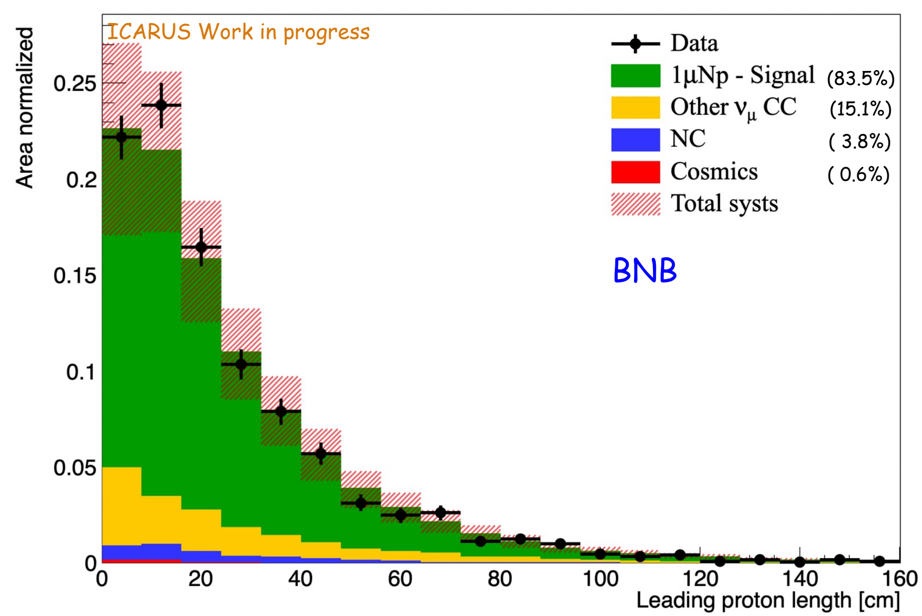




1μNp analysis – event selection results

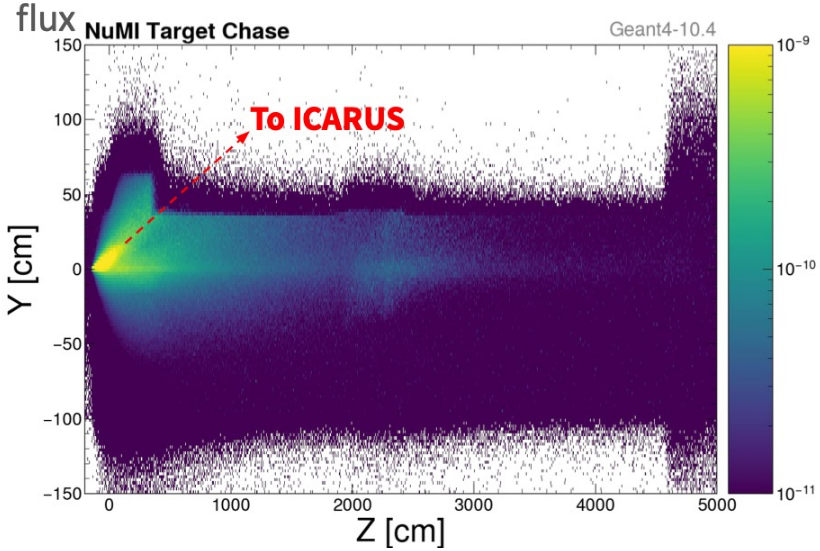
- Data- MC distributions agree within systematics also for the reconstructed muon and proton lengths;

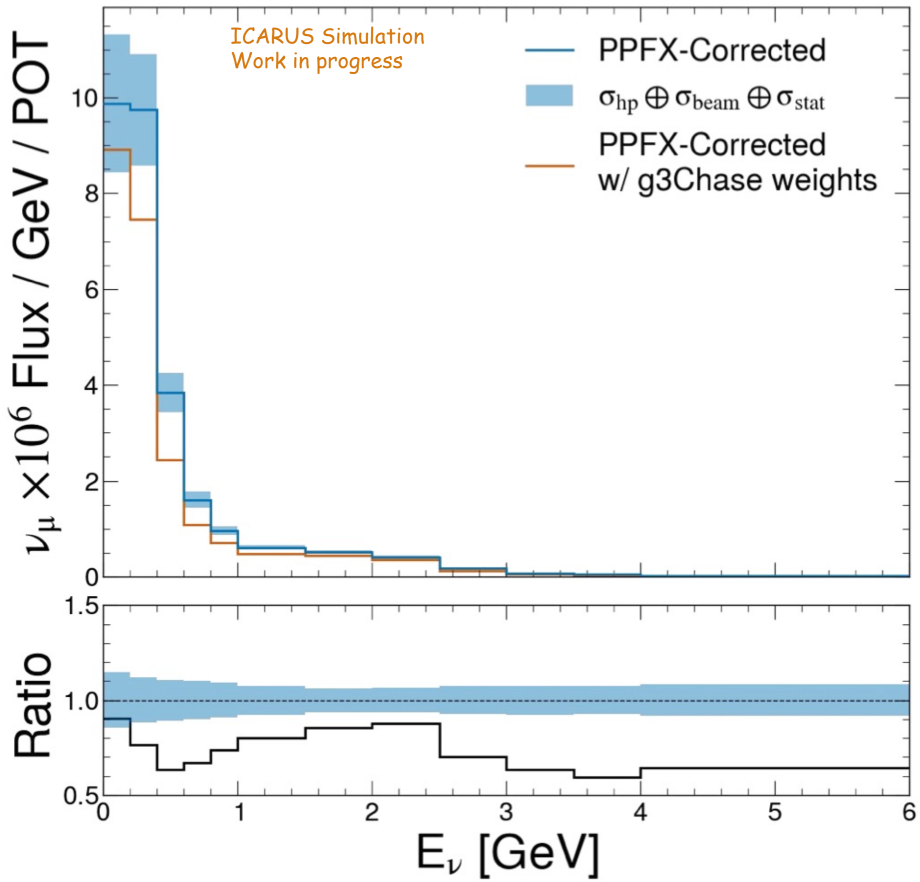




NuMI Flux Attenuation from added External Material (MC)

- Additional material added resulted in ~20-30% (avg) attenuation of the flux
  - Less space for π/K to decay in flight
- Calculated weights based on the new geometry and applied to the PPFX-corrected flux





Systematic Uncertainties for NuMI cross section measurement

- Several systematic uncertainties have been evaluated: Flux systematics, GENIE, Geant4 and detector systematics;
- Systematics from nuclear effects NuSystematics (DUNE) and remaining detector systematics will be evaluated soon;
- Uncertainties are propagated to the reco-level distributions.