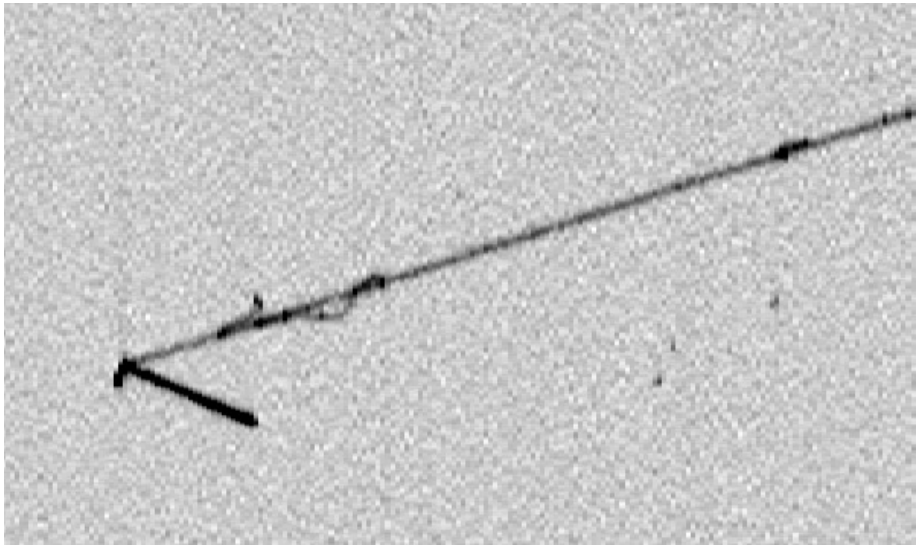
New results from the ICARUS experiment



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ICARUS collaboration

PROBES Annual meeting
Nov 27 st 2025

ICARUS Collaboration at SBN - 2025

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], H. Da Motta[29], 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[28], 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,a], 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. Salmoria[29], 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], F.A. Wieler[29], 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]

Spokesperson: C. Rubbia, GSSI

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*
28. *York University, Canada*
29. *CBPF, Brazil*

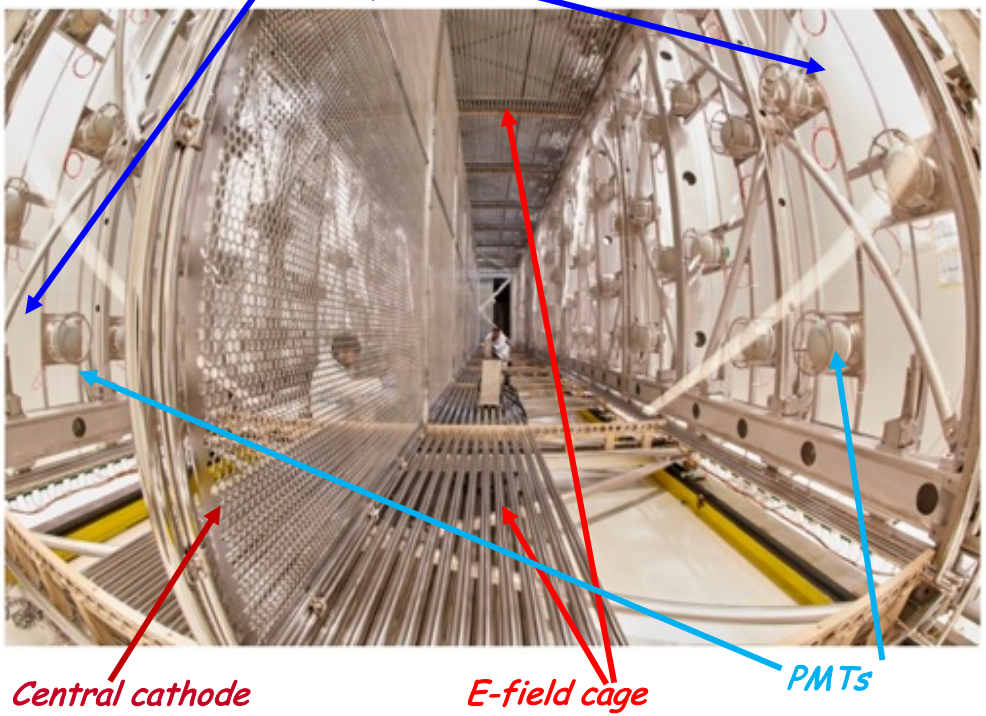
12 INFN groups, 12 US institutions, CERN, 1 Mexican, 1 Canadian, 1 Indian, 1 Brazilian institutions

a On Leave of Absence from INFN Pavia

The ICARUS LAr-TPC detector

- First proposed by C. Rubbia in 1977, LAr-TPCs are high granularity, uniform self-triggering detectors with 3D imaging and calorimetric capabilities: ideal detector for ν physics!
  - After a long R&D by INFN/CERN, the successful operation in 2010-'13 of ICARUS T600 LAr-TPC at the G. Sasso underground lab exposed to CNGS beam, demonstrated the full maturity of this detection technique:

… paving the way for Long-Baseline experiments



Total active mass 476 ton

- ✓ 2 modules, 2 TPCs per module;
- ✓ 1.5 m cathode-anode drift, E_D= 500 V/cm;
- ✓ 3 readout wire planes per TPC, in total 54000 wires at 0, ± 60^0, 3 mm pitch;
- ✓ 360 8" PMTs behind the wires to detect scintillation light with ns accuracy.

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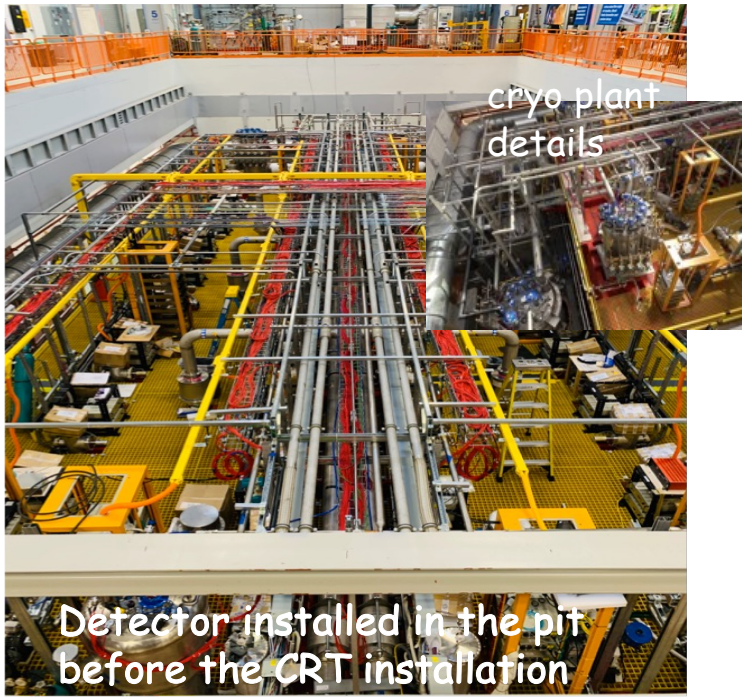
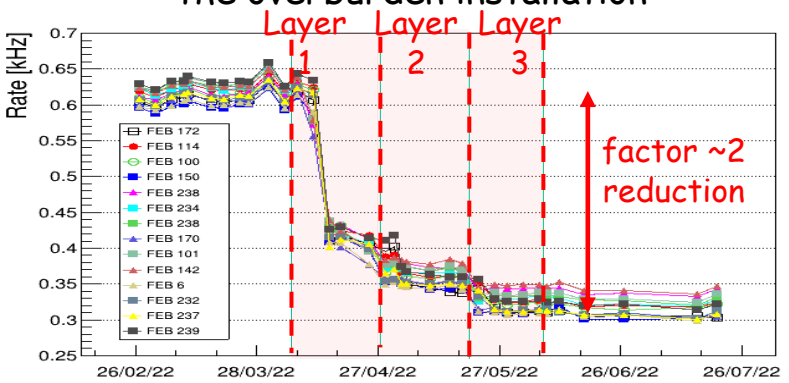
ICARUS T600 cosmic rejection



- 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 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

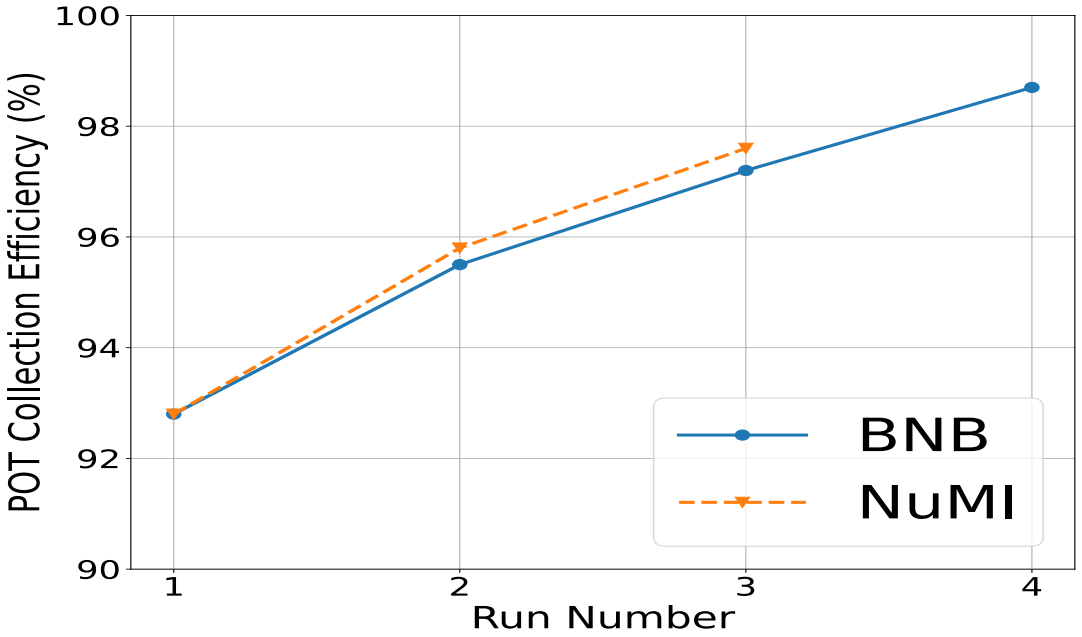


ICARUS operation at FNAL: collected event statistics

- ICARUS detector continues to operate with remarkable stability/performance of all components since its initial activation in 2020;
- Protons on target collected in the different ICARUS Physics runs:

Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul '22)	0.42 10^{20}	0.69 10^{20}	-
RUN-2 (Dec '22-Jul '23)	2.13 10^{20}	2.84 10^{20}	-
RUN-3 (Mar -July '24)	1.36 10^{20}	-	2.82 10^{20}
RUN-4 (Dec '24 - July '25)	3.63 10^{20}	-	-
TOTAL	7.54 10^{20}	3.53 10^{20}	2.82 10^{20}

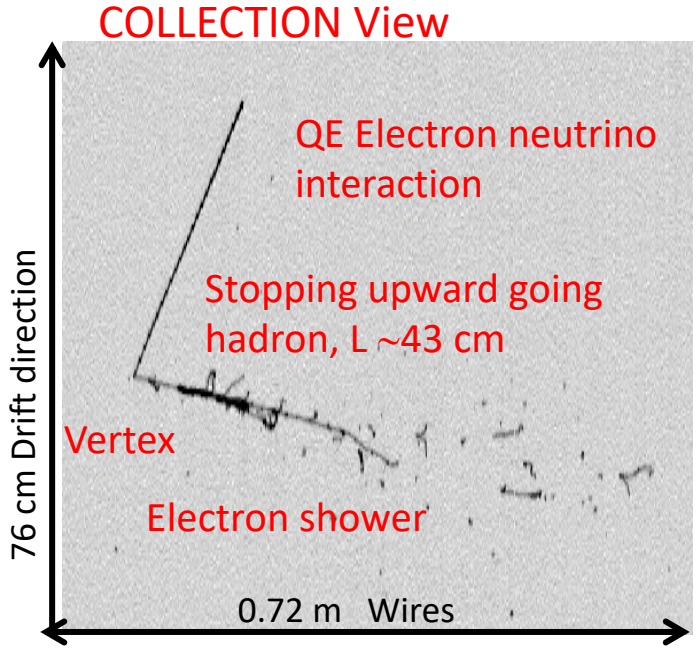
- Last neutrino RUN-4 started on Dec. 10 2024 extending to July 8 2025:
  - Extraordinary performance of Booster Beam: ~ 3.67 10^{20} pot delivered to SBN !
  - 3.63 10^{20} pot collected by ICARUS with an extraordinary 98.7 % efficiency !

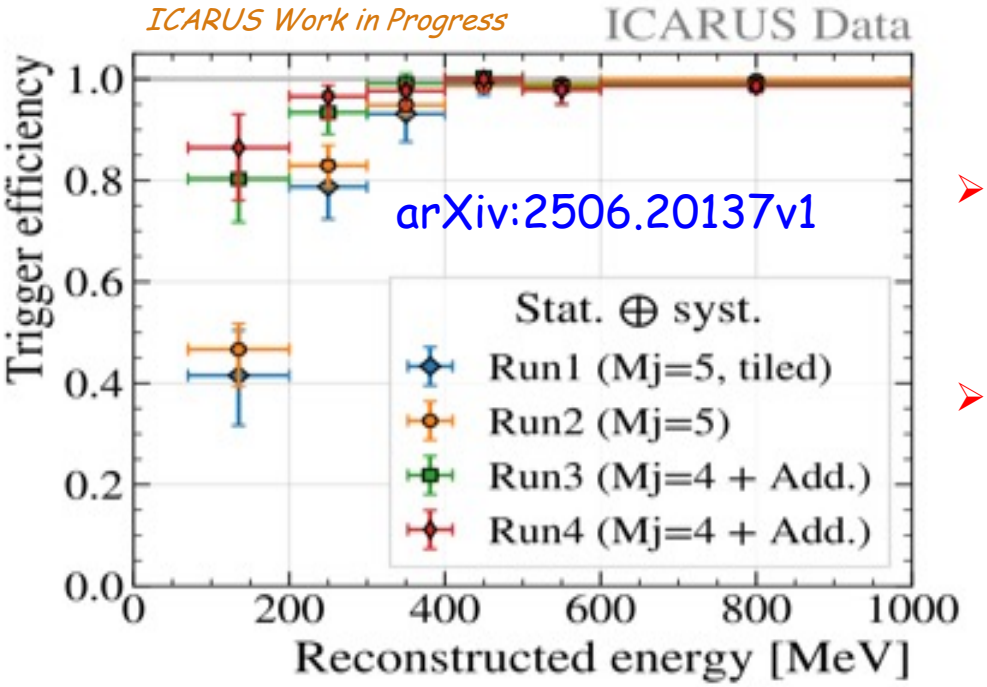


* No NUMI beam during RUN-4

ICARUS performance at FNAL

- The cryogenic/purification system performed smoothly with a free electron drift time in LAr $\tau_{ELE} \approx$ 7-8 ms stable during physics runs:
  => full track detection efficiency in the whole 1.5 m drift, resulting in a superb neutrino event measurement;



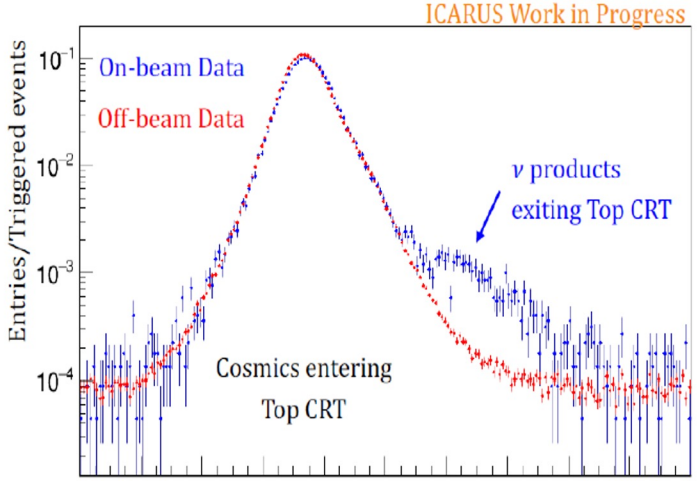


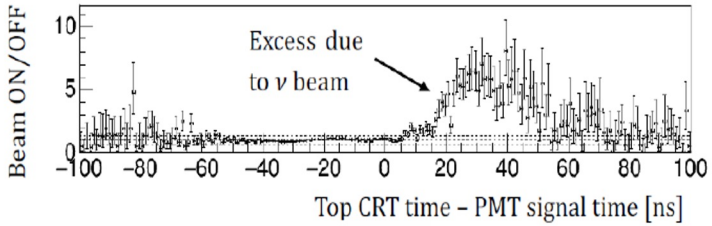
- Events are triggered requiring at least Mj = 5 fired PMT pairs inside a 6 m longitudinal T600 slice in coincidence with BNB, NuMI beam spills;
- A 2nd independent/complementary trigger based on total light signal on the fired PMTs was deployed since Run3 to further increase efficiency at low $E_{DEP.}$

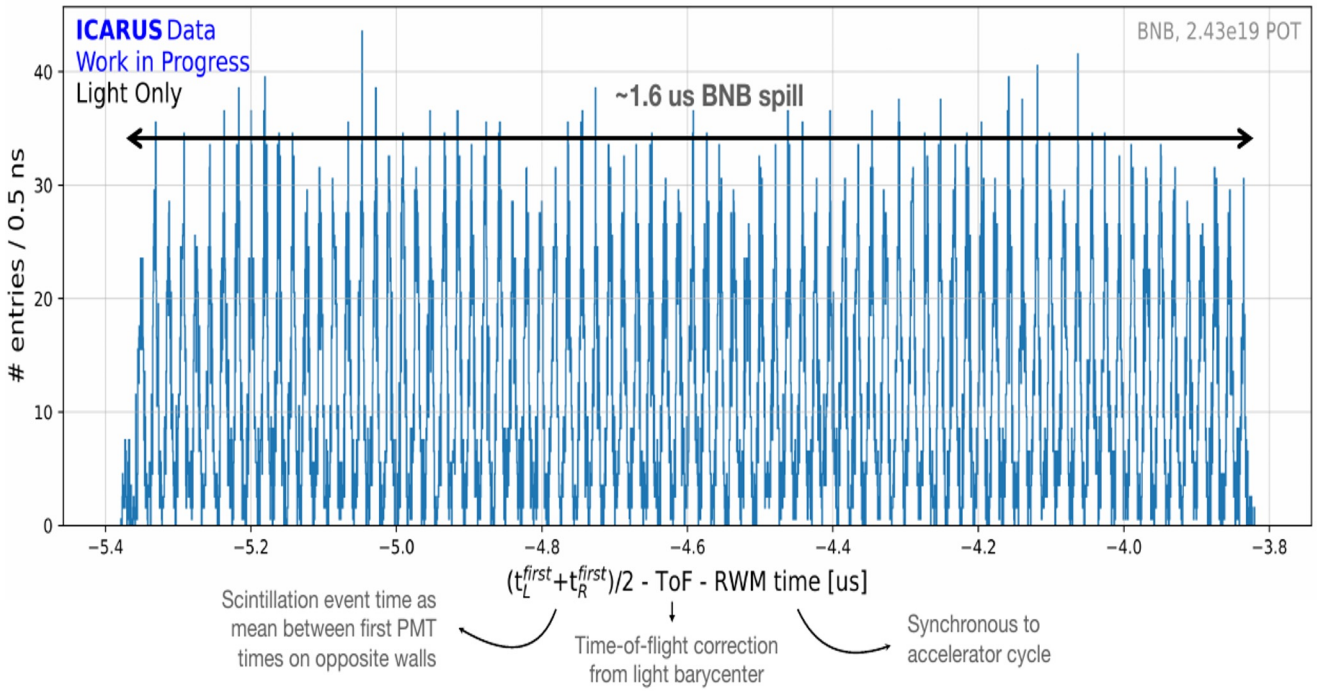
=> A very efficient Trigger down 100 MeV

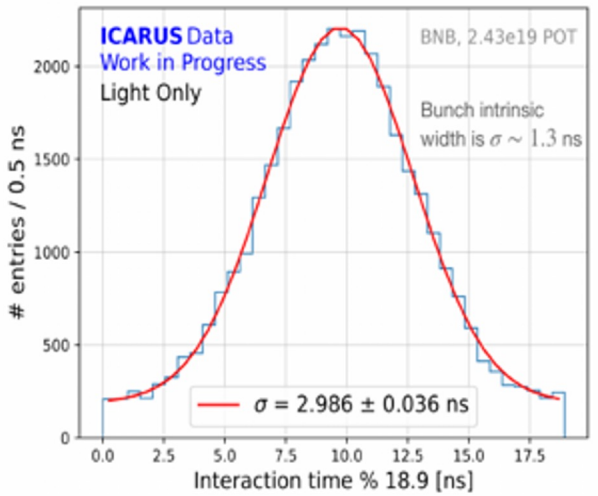
ICARUS performance: timing

- Time-of-flight rejection of incoming cosmic rays using the external CRT and the inner PMT system.
- The bunched structure of beam spill – both BNB and NuMI – is well recognized with ~3 ns resolution using only the PMT system.









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.
- In preparation for the SBN oscillation analyses, ICARUS is focusing on:

Investigation of ν_μ disappearance with BNB, later complemented by the ν_e disappearance study with off-axis NuMI, hinting for Neutrino-4 claim.
ν_μ event analysis validated, signal unblinding completed

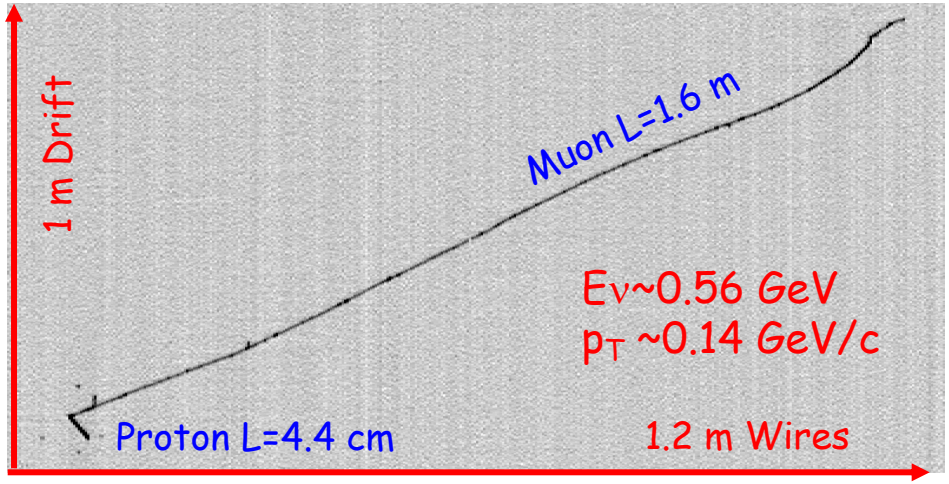
ν_e, ν_μ events studies from off-axis NuMI beam to measure ν-Ar interaction cross section and optimize ν identification /reconstruction in the energy range of interest for DUNE:
completed a first cross section measurement

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

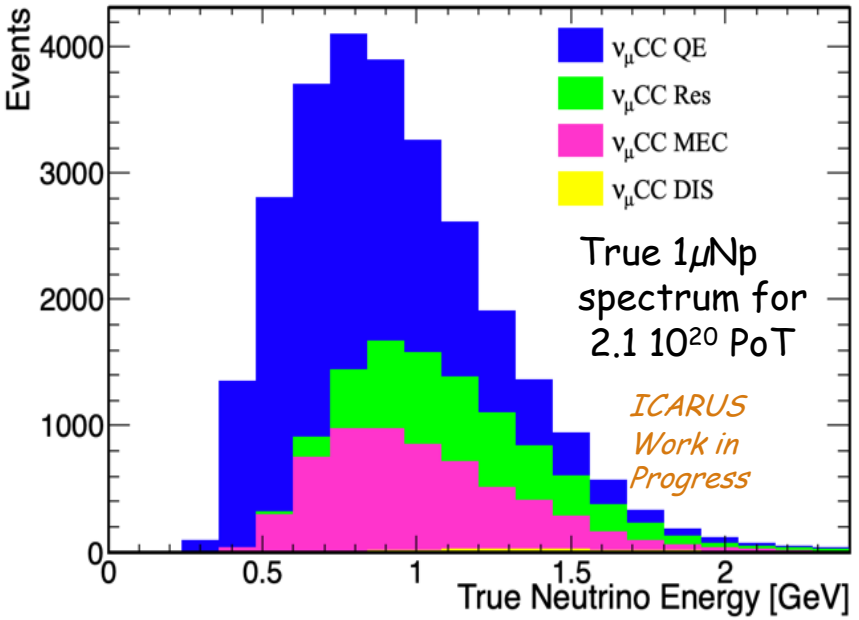
- ICARUS established a blinding policy to ensure robust and unbiased interpretation of the collected data; analyses are initially validated with a subset of collected data.

Ongoing oscillation analysis: 1μNp BNB event selection

- Data collected by ICARUS standalone with BNB beam are being reconstructed and analyzed to perform a νμ disappearance analysis.
  - Study with RUN2 data (2.1 10^{20} PoT);

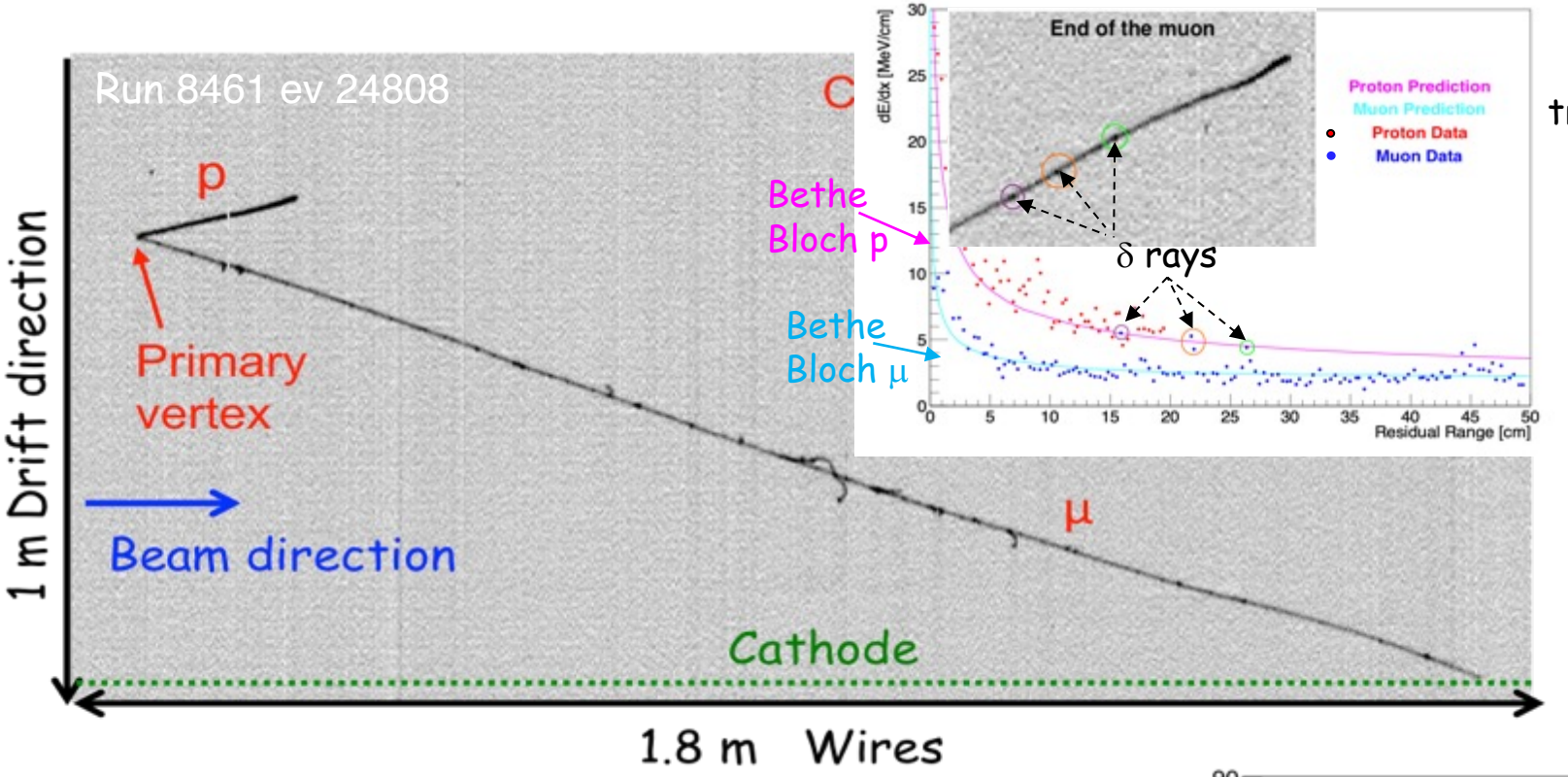


- Fully contained νμCC events with 1μNp are selected requiring:
  a) PMT light signal inside 1.6μs p beam spill window correlated with TPC tracks, no CRT signal;
  b) a muon with L_μ >50 cm and at least one proton track with E_K >50 MeV (L_p >2.3 cm) fully contained and identified by PID scores based on dE/dx;
  c) no additional π, γ.

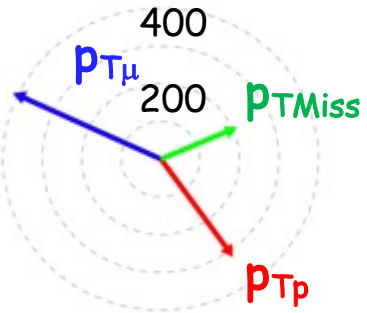


- The global event kinematics is obtained from range measurement of μ and p.
- Residual cosmic backgrounds < 1%.

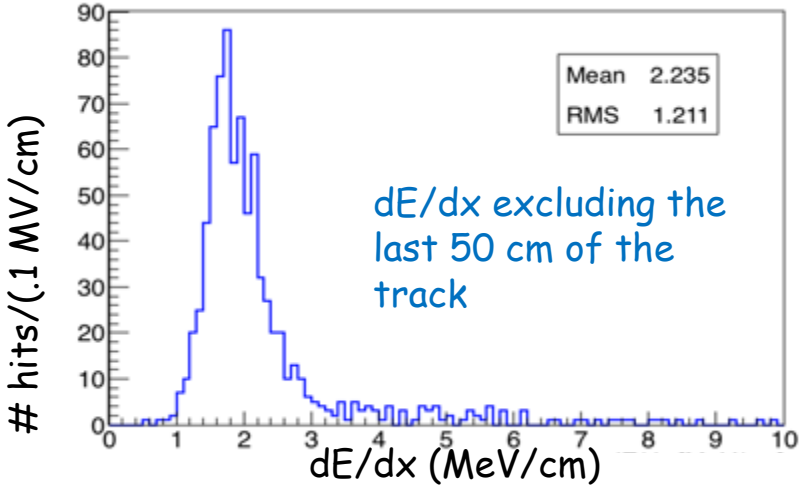
A typical νμCCQE like candidate automatically selected



Momentum in the transverse plane (MeV/c)



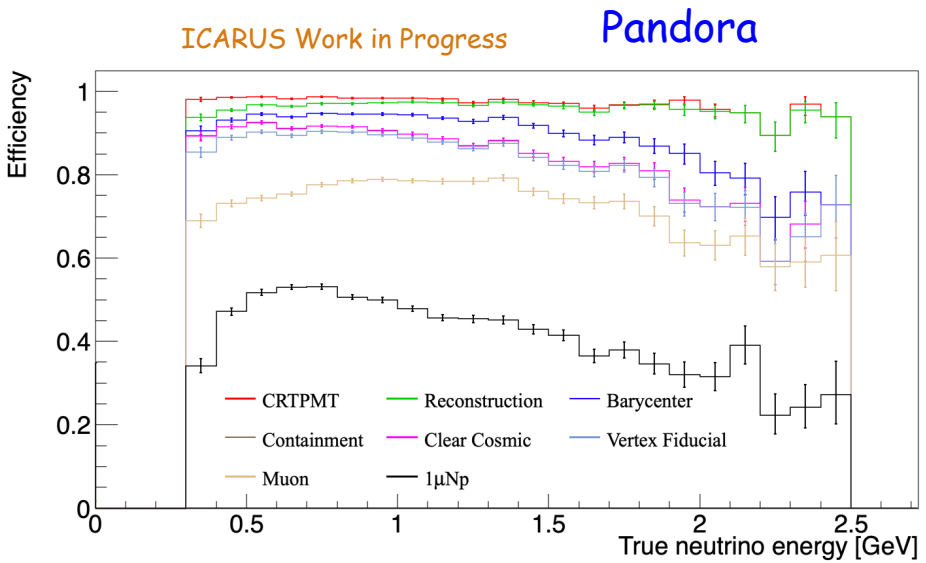
- 3.8 m long (cathode crossing) stopping muon;
- ~20 cm long stopping proton;
- Total deposited energy ~1.1 GeV;
- Total momentum $\overrightarrow{p_{tot}} = \overrightarrow{p_\mu} + \overrightarrow{p_\mu}$ at 8⁰ from the beam axis;
- Total transverse momentum ~200 MeV/c.

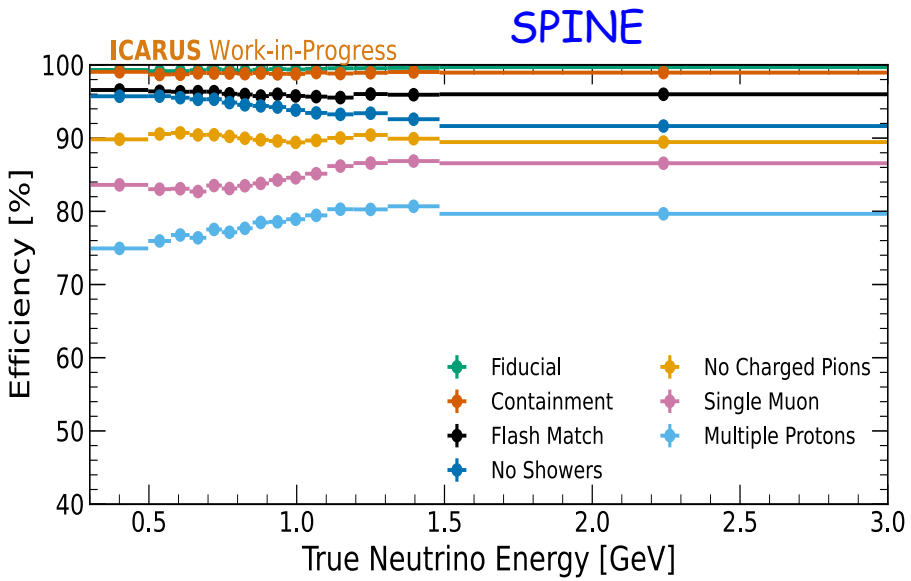


Event selection performance

- The analysis relies on two almost independent pattern recognition and event reconstruction frameworks: Pandora and SPINE (Machine Learning based), cross-compared and validated by visual scanning.
  - ➢ The validation of the analysis has been completed, together with the estimation of systematic uncertainties (ν flux, ν interaction model, and detector systematics).

- Selection efficiency for the 1μNp events as a function of the neutrino energy



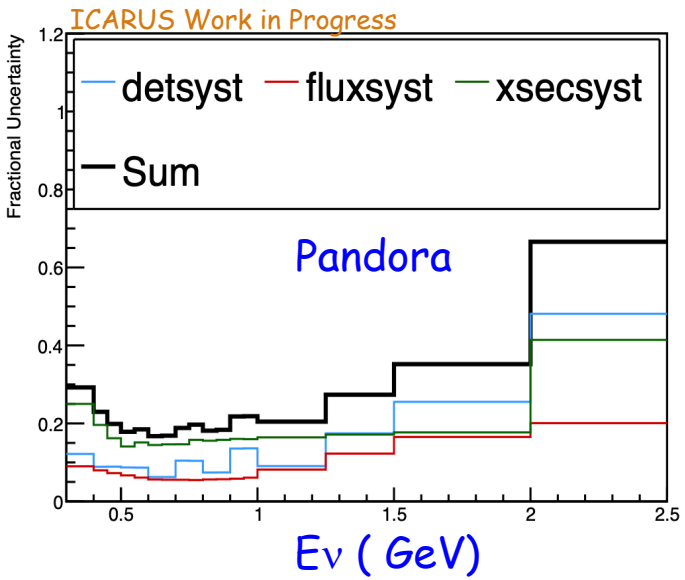


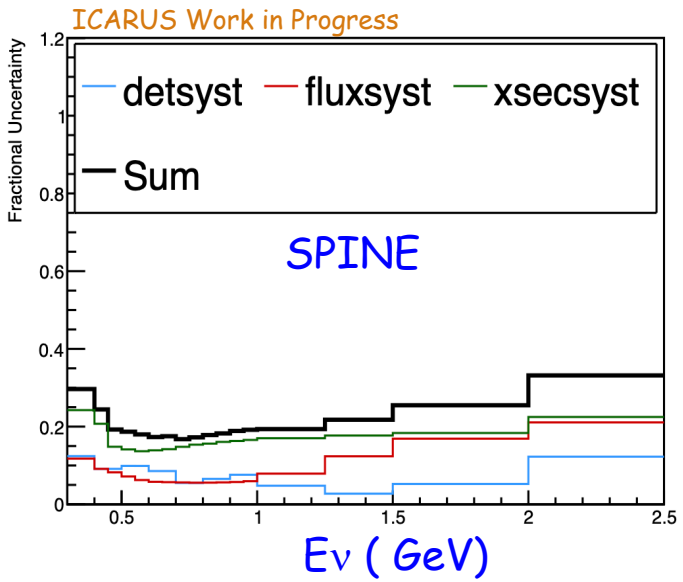
	PANDORA	SPINE
Global Efficiency	48.5%	78.2%
Global Purity	82%	91.5%

Systematic uncertainties

- Flux uncertainties are taken from MicroBooNE.
- The adopted interaction model is GENIE AR23, shared within SBN and DUNE.
  - Suite of systematic uncertainties and priors are taken mainly from GENIE.
- The impact of detector systematics is evaluated comparing calibrated and uncalibrated MC samples; a MC sample was generated varying by 1 σ each associated parameter
  - the ongoing simulation improvements reducing residual Data/MC discrepancies are expected to reduce these detector systematics.

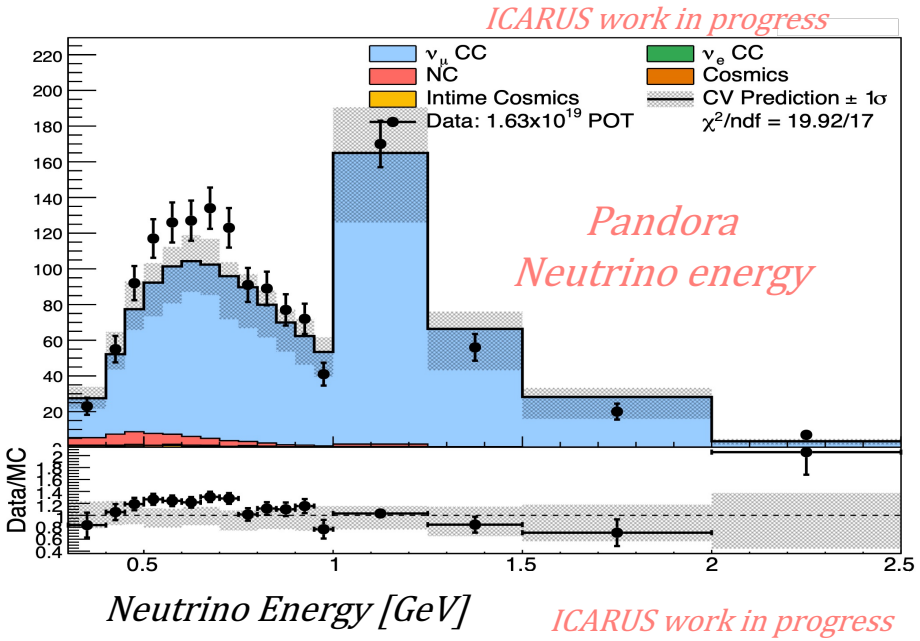
Total systematic uncertainties (flux, cross-section, detector)

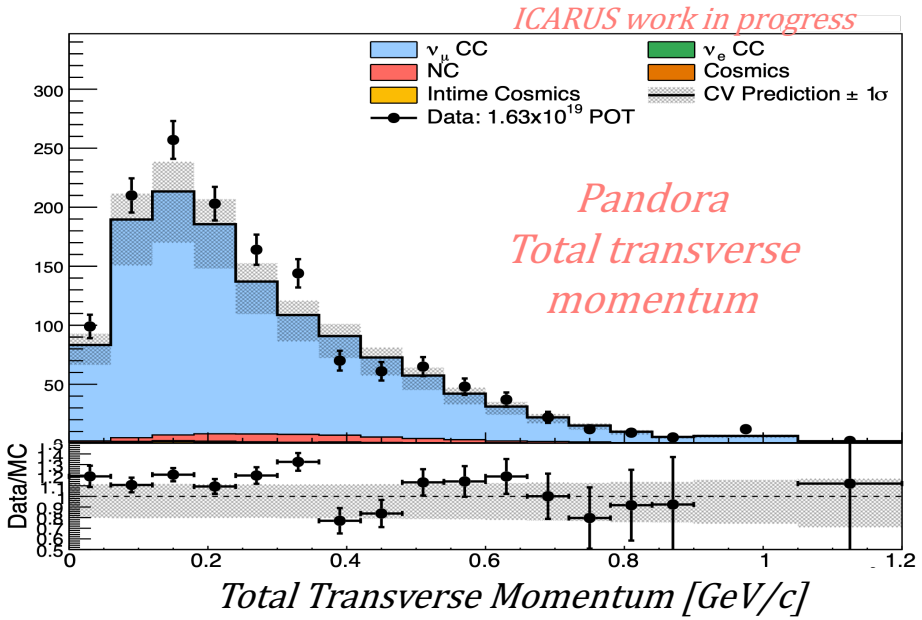


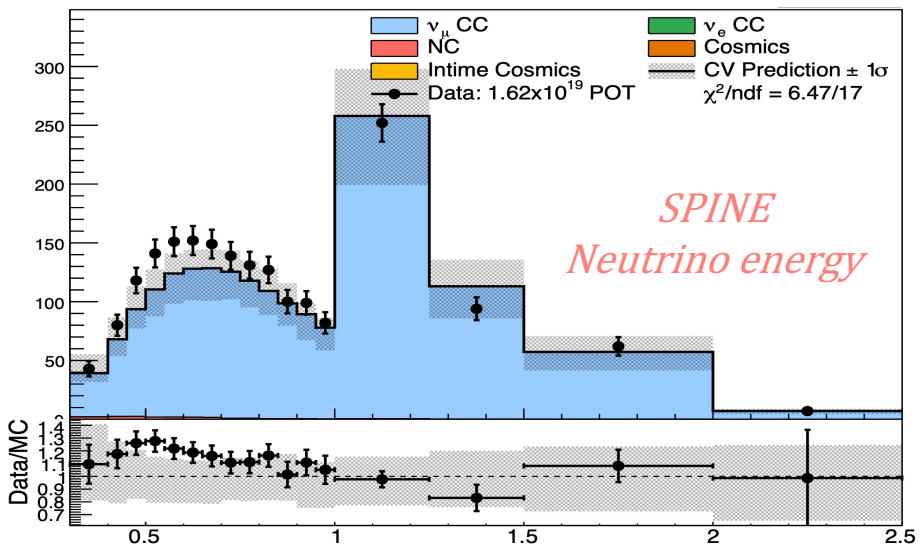


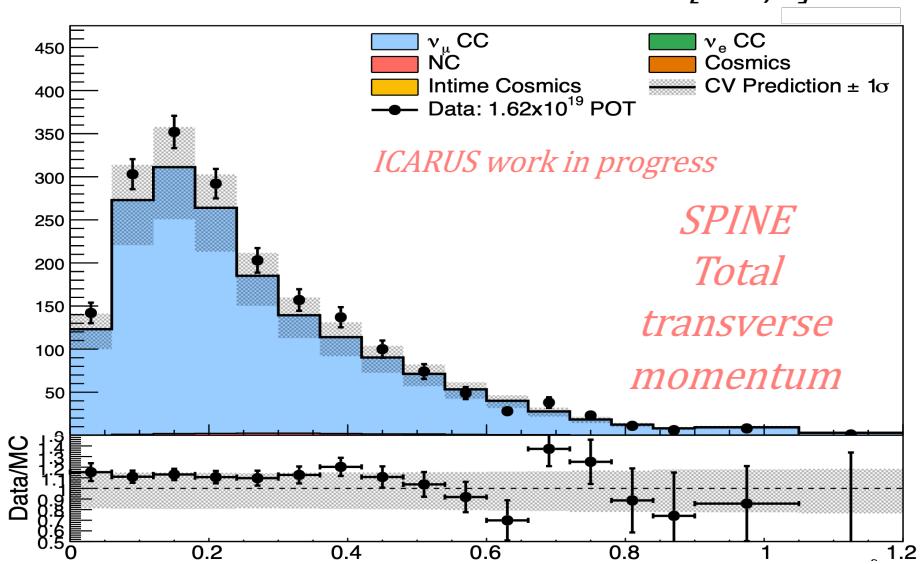
Substantial cancellation of cross section and flux uncertainties and of common detector systematics is expected in the joint SBN analysis;

Data/MC comparison: 10% of Run2 Data





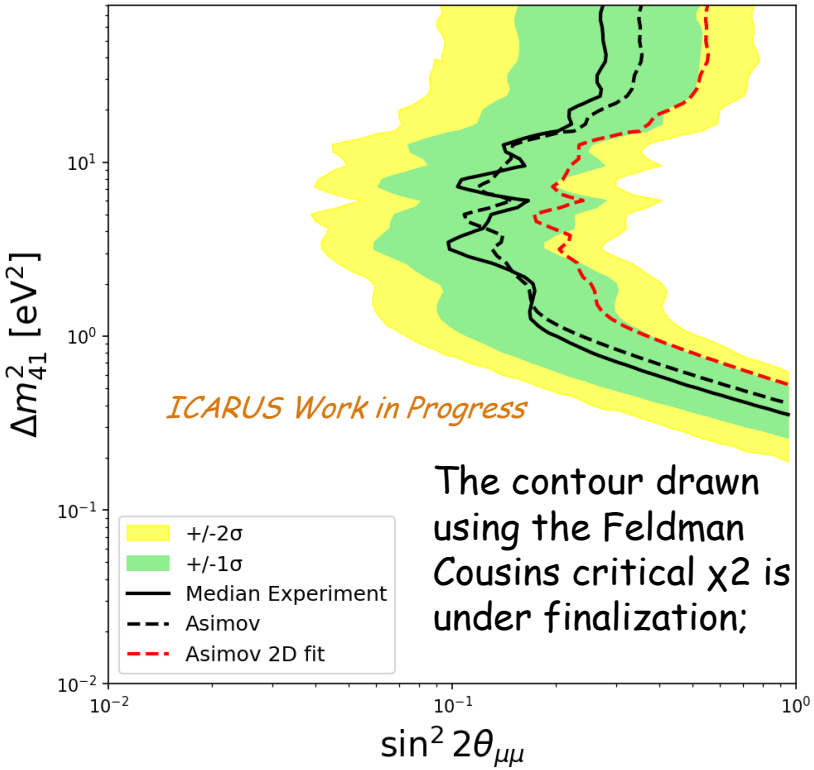




- All plots shown here use 10% of Run 2 data. No data fits have been performed.

Sensitivity for the 1μNp BNB disappearance analysis

- The 90% confidence level Brazil bands for the Pandora based selection analysis and including all the systematics:
  - These sensitivity studies show the potential for discovery of oscillation in the case of a large value of the mass splitting and sterile mixing angle.



- Before starting the unblinding procedure, the 30% of Run 2 data was also used for data/MC comparisons of variables not sensitive to oscillation.

- The νμ disappearance search has now completed the procedure for the signal unblinding for the 100% RUN2 event statistics;
  - Detailed Data/Data or Data/MC comparisons and oscillation fit of the Data performed;

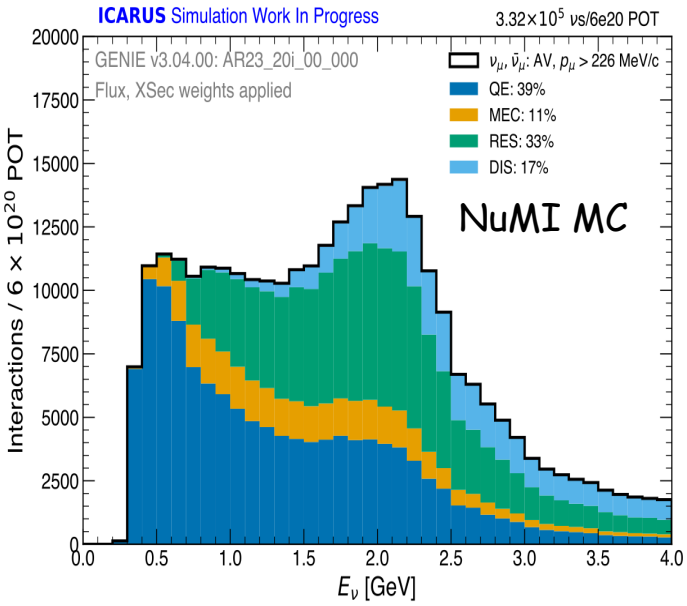
Stay tuned to see the final analysis result!

Neutrino Interactions from NuMI off axis at ICARUS

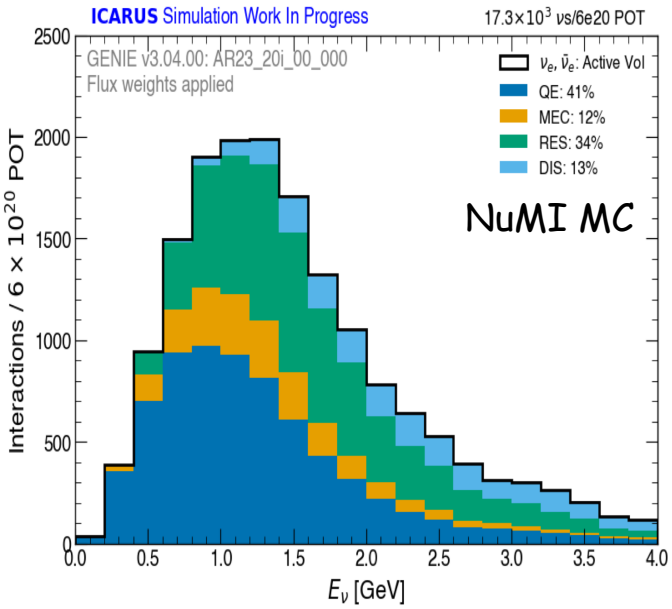
- Excellent statistics to measure cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos;
- Available data ~3.53E20 POT for physics analysis now

  Expected CC events in the available statistics : ν_μ 195,000 and ν_e 10,000.
- Neutrino energy spectrum from NuMI at ICARUS covers the first oscillation peak and good coverage of the relevant phase space for DUNE experiment.

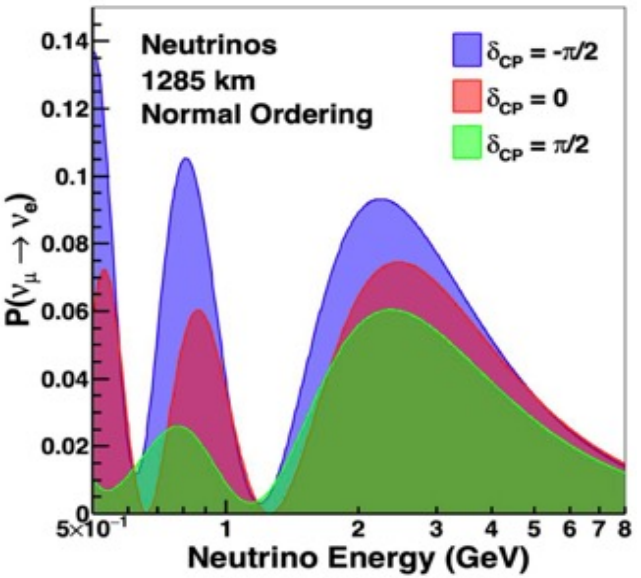
ν_μ, $\bar{\nu}_\mu$ from NuMI at ICARUS



ν_e, $\bar{\nu}_e$ from NuMI at ICARUS



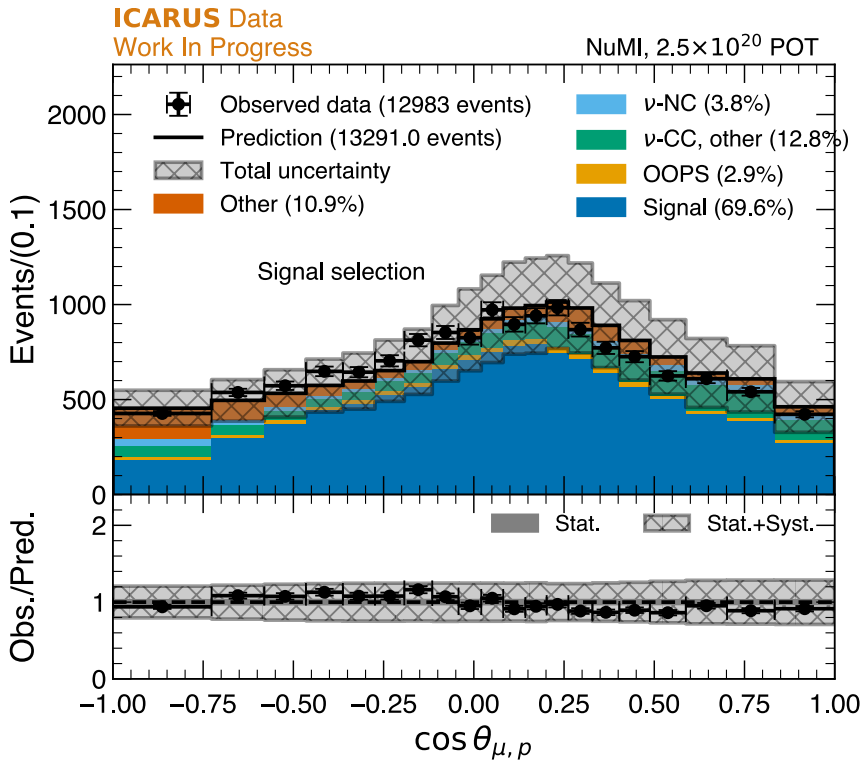
Oscillation probability at DUNE



CC 0π analysis – results for the selected sample

- First analysis targets $\nu\mu$CC 1μNp0π , enhanced in quasi elastic and 2p2h interactions:
  - Signal definition: one μ with momentum > 226 MeV/c, any proton with momentum between 400 MeV/c and 1 GeV/c, no $\pi^{\pm}$ or π^{0} in the final state;
  - Major background: events with undetected/misidentified pions. To directly characterize this background an event control sample has been selected with charged pion candidates (requiring the presence of a secondary muon-like track);

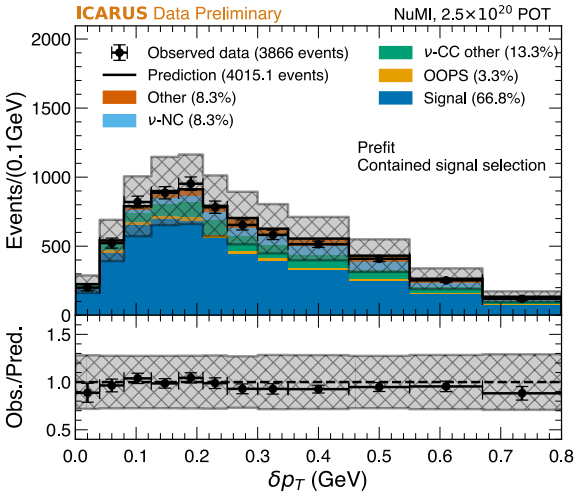
- Cross section measurement recently completed!
- Signal box opening: analyzed exposure is 2.5 10^{20} POT.
  - The angle between μ and leading p candidates populates broadly the phase space and is expected to encode information about Final State Interactions for all events;

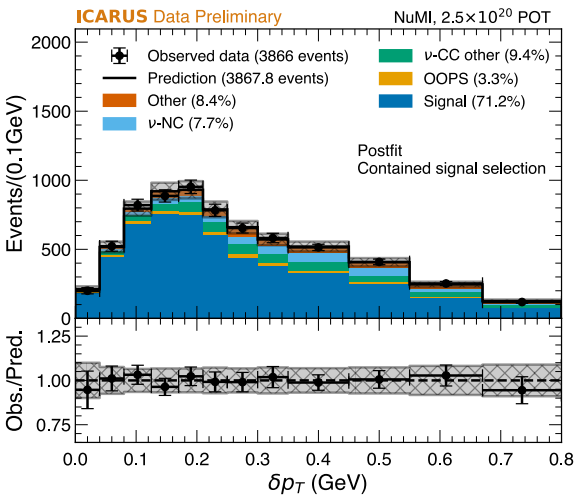


Cross section measurement: $\nu\mu$CC 1μNp0π δp_T variable

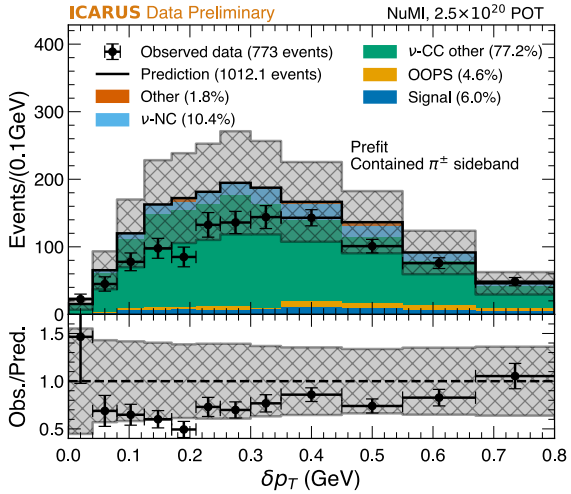
- Distributions of the total transverse momentum δp_T.

Signal

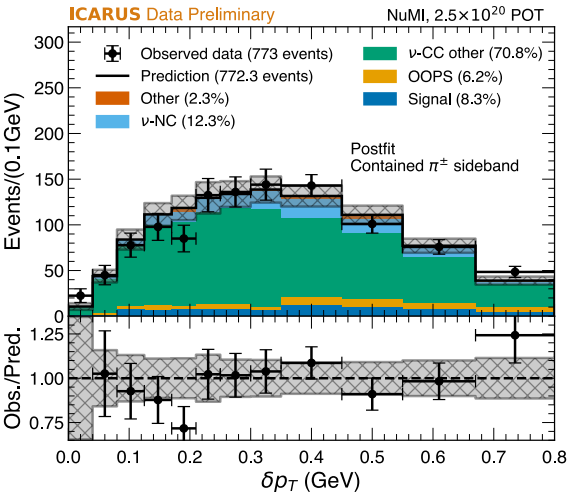




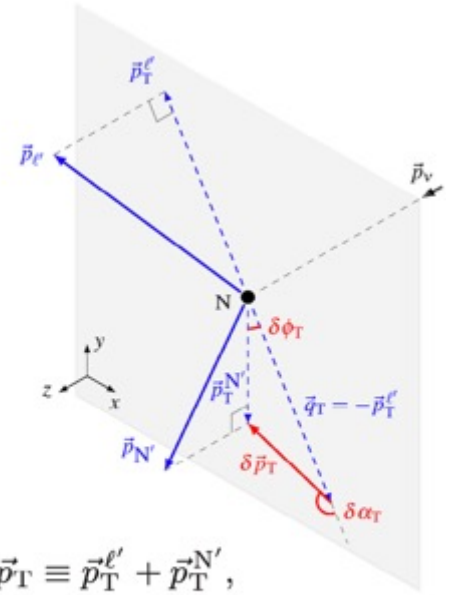
Control sample



← Pre-fit



← Post-fit

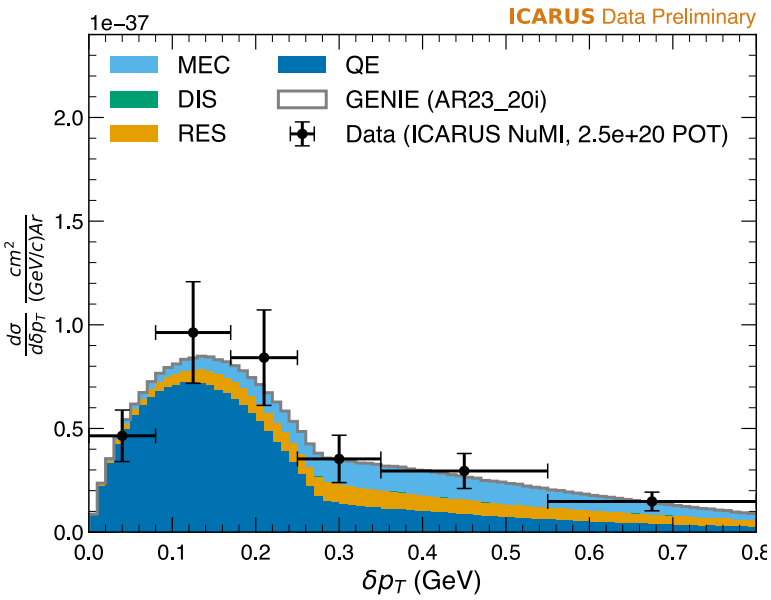


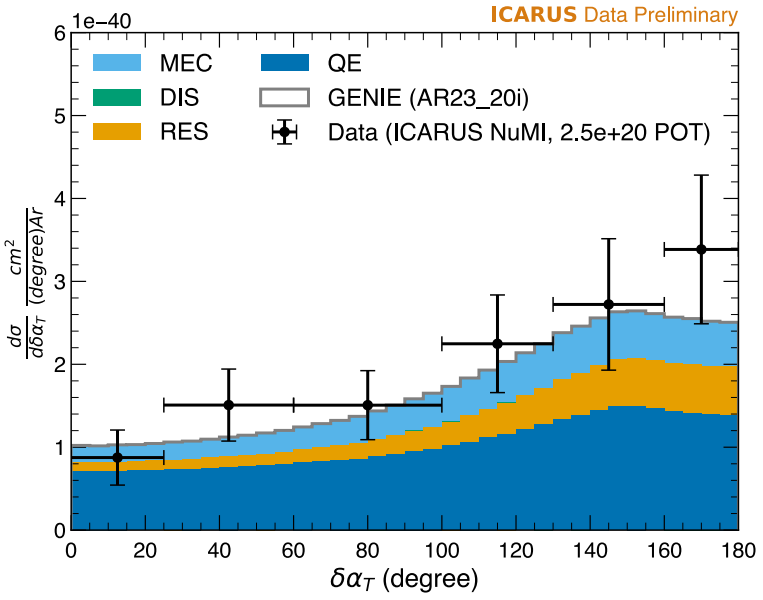
$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'},$$

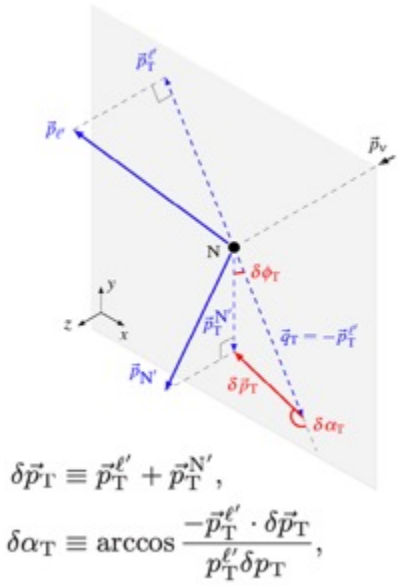
$$\delta\alpha_{\mathrm{T}} \equiv \arccos\frac{-\vec{p}_{\mathrm{T}}^{\,\ell'}\cdot\delta\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}^{\ell'}\delta p_{\mathrm{T}}},$$

Results: νμCC 1μNp0π

- Measured cross section as a function of δp_T and $\delta \alpha_T$.
- The measurement is compared with the default event generator GENIEv3 Ar23 (shared within SBN and DUNE).





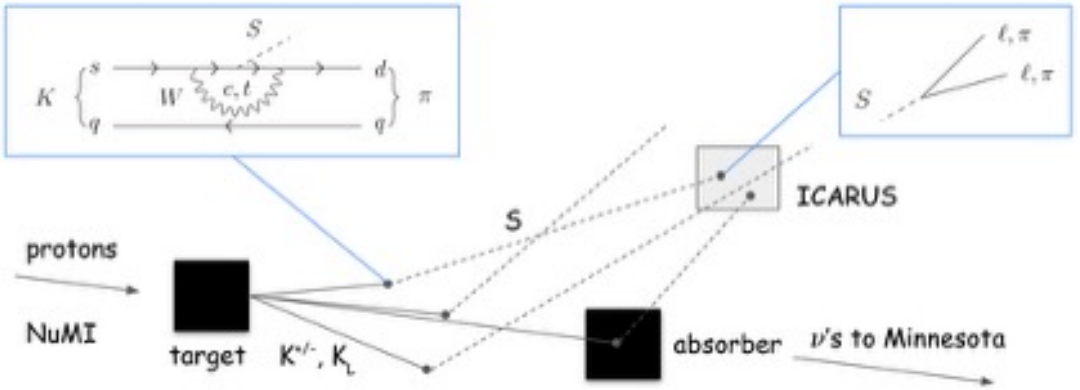


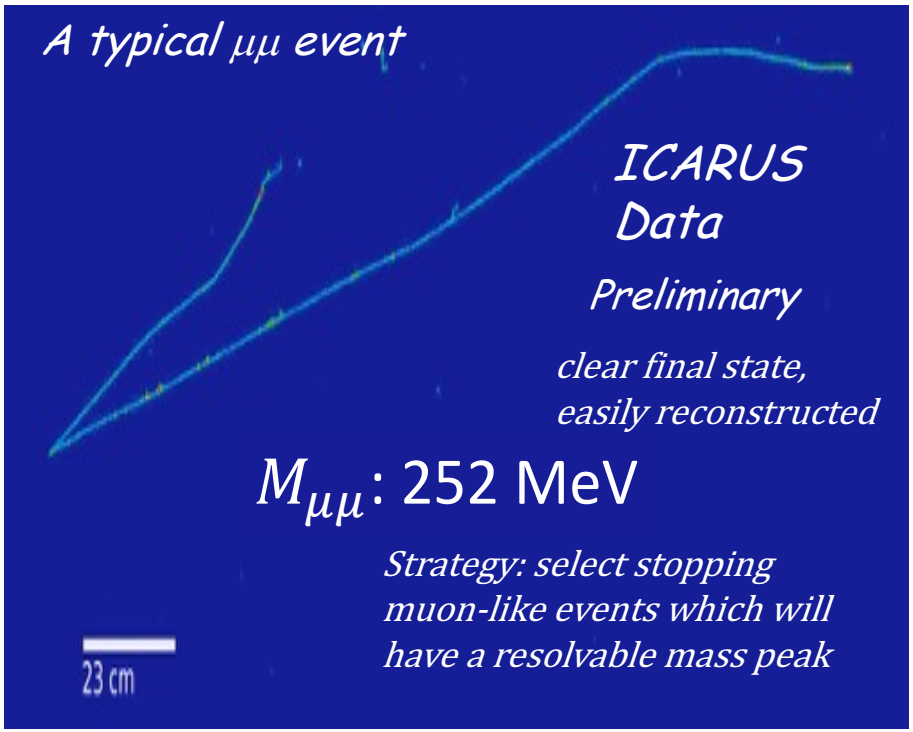
- The ICARUS measurement of CC0π+proton at higher energy on Argon fills a crucial gap. T2K : lower E on Carbon Hydrogen, MINERvA: higher E on Carbon Hydrogen, μBooNE: lower E on Argon.

Paper under preparation with more cross section measurements and interpretations: stay tuned!

Dark sector models investigation by ICARUS

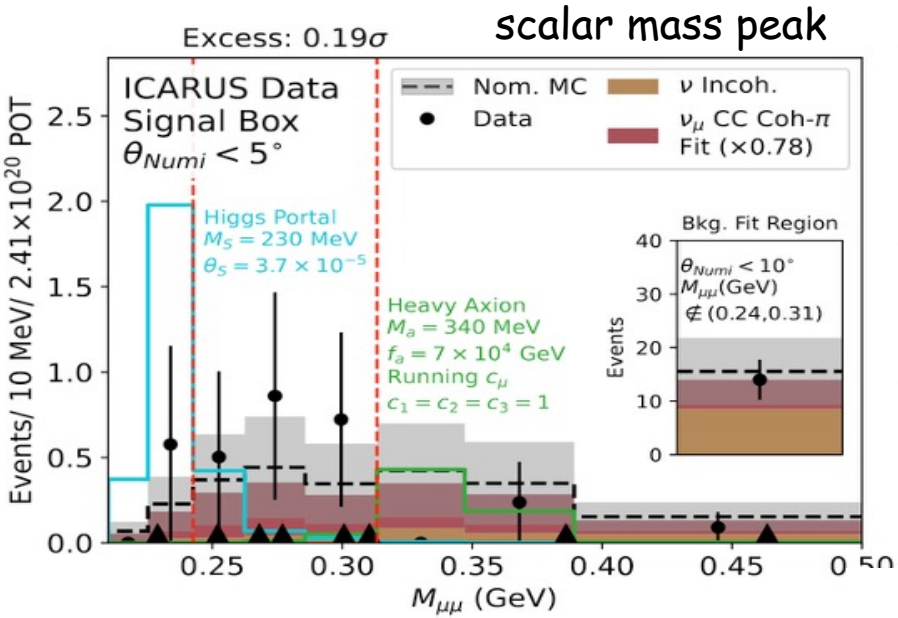
- A rich Beyond Standard Model search program (DM, heavy neutral leptons,…) has been pursued exploiting the off-axis NuMI beam;
- Models considered so far involve dark particles coupling to Standard Model particles via Scalar Portal Interactions:
  - Higgs portal Scalar: Scalar dark sector particles, interactions by mixing with Higgs boson;
  - Heavy QCD axion: Pseudo-scalar particles, interactions by mixing with pseudo-scalar mesons.
- A first search for new particle decaying into di-muon has been recently completed:





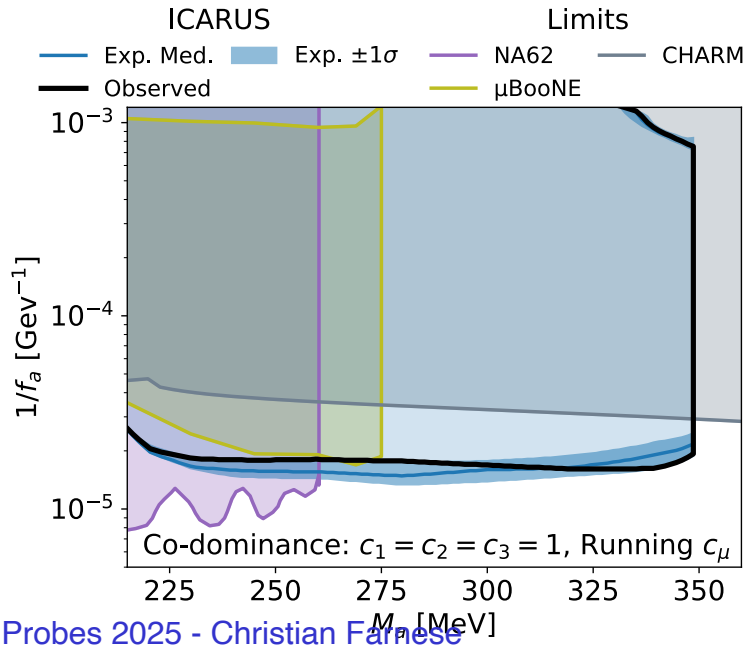
- Events with 2 stopping μs are selected to reconstruct the scalar mass peak: signal expected at small angle to beam (θ_{NuMI} <5^0);
- Flux, interaction model and detector systematic uncertainties have been included.

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

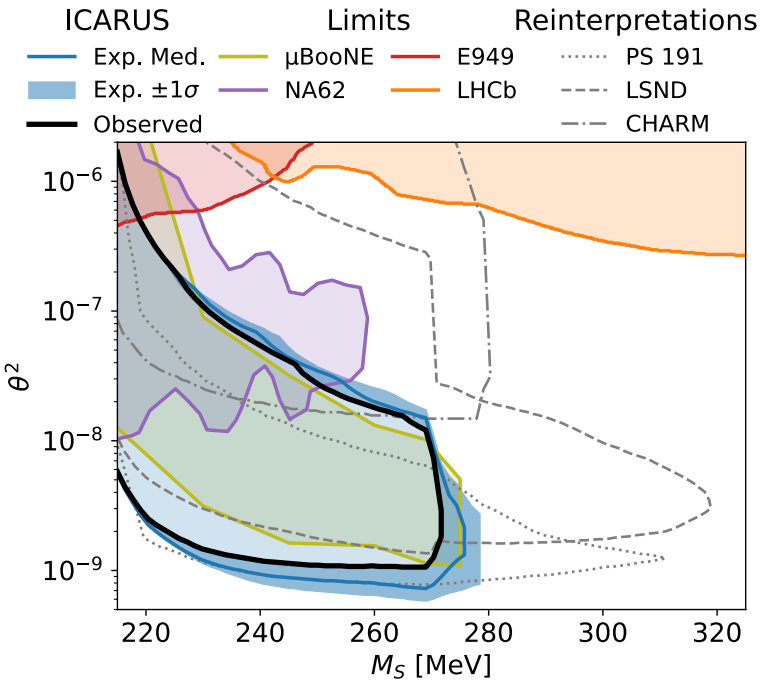


- Open box result: 8 events observed, compared to 8 MC expectation, mostly from $\nu\mu$CC coherent π production;
- No new physics signal observed, maximum excess being 0.19 σ;
- Ongoing analysis with uncontained muon candidates to increase the sensitivity;

Heavy Axion Exclusion



Higgs Portal Scalar Exclusion



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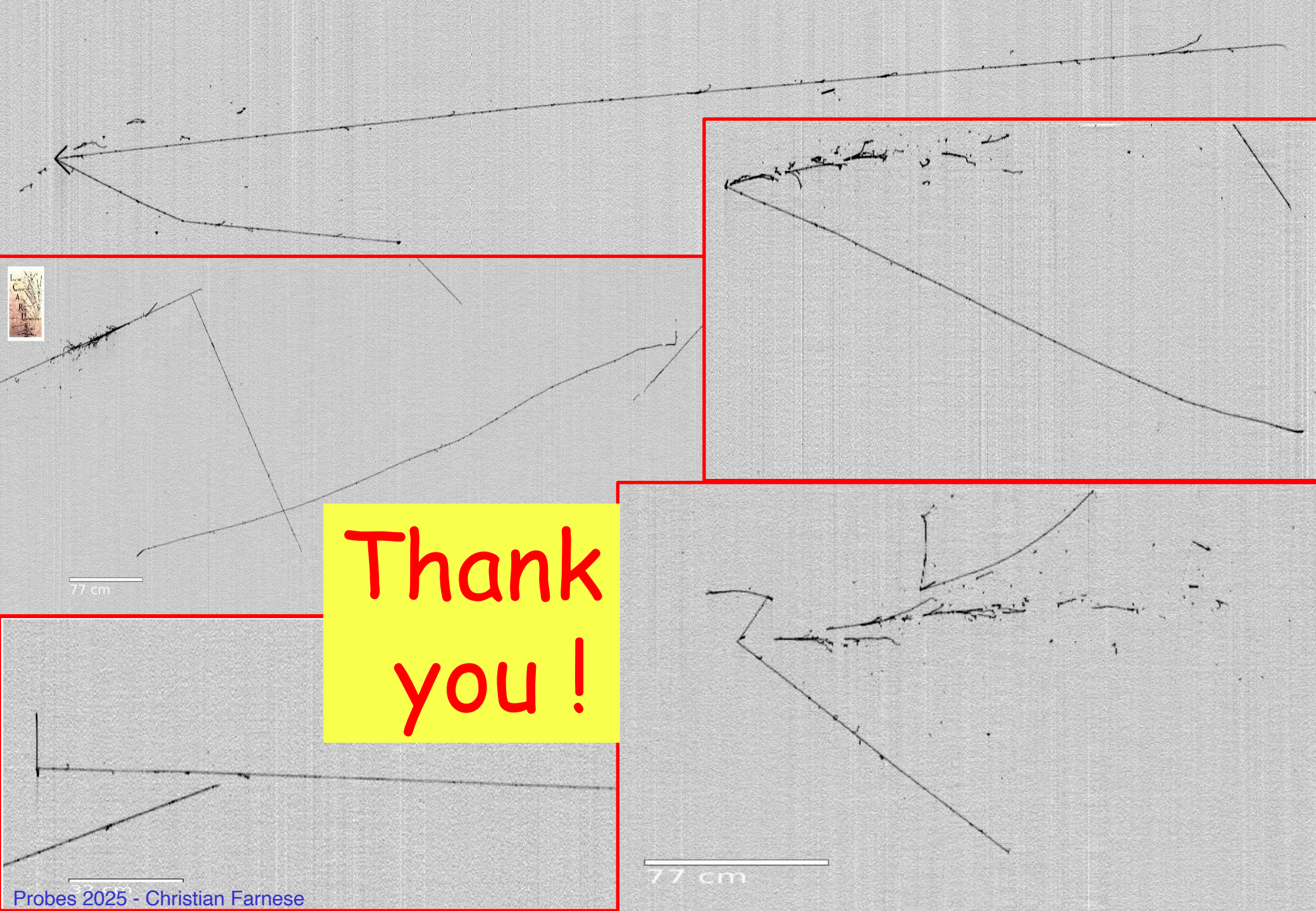
Conclusions

- ICARUS detector continues to operate with remarkable stability/performance of all components since its activation in 2020: *5 year operations!!*
- Several single detector analyses:
  - Study of $\nu\mu$ disappearance with the BNB beam: 1mNp analysis completed and results will be released soon;
  - Measurement of $\nu\mu$ cross-sections with NuMI beam: a first cross section measurement for the 1mNp0p channel has been recently completed;
  - Search for Sub-GeV DM candidates in NuMI beam. A first analysis with di-muon final state topology has been completed.
- ICARUS data recorded in Gran Sasso used for a search for Inelastic Boosted Dark Matter signals demonstrating the sensitivity of LArTPC in the DM search for DUNE next experiment!

STAY TUNED !


77 cm
Thank you !
77 cm