Status of ICARUS-NuMI interaction cross-section analysis

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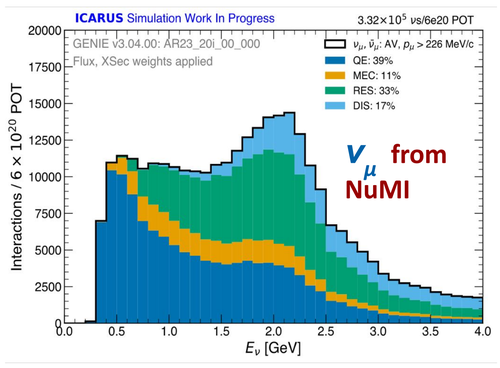
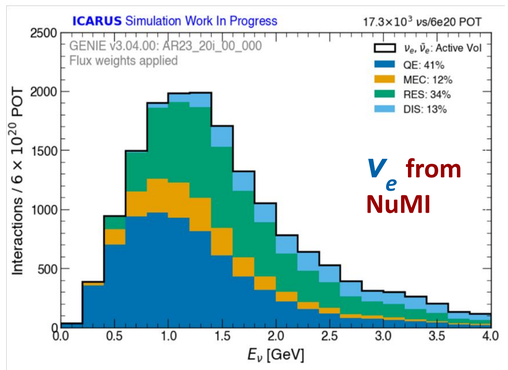
For the ICARUS Collaboration

A — *Introduction and motivation*

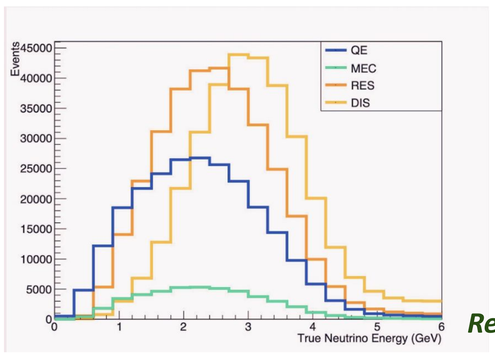
- The ICARUS experiment [1], utilizing LAr TPC, has been installed at Fermilab in Chicago.
- Primary objective is to function as the far detector of the SBN program, seeking sterile neutrino signatures [2].
- Offers diverse physics capabilities- searches beyond the standard model and measurements of cross-sections.
- In addition to being exposed to the common Booster Neutrino (BNB) beamline, it also receives off-axis neutrinos from the Main Injector (NuMI) beam.





- *The energy range of NuMI* ν_μ *interactions in ICARUS is in a similar energy range to that expected by DUNE.*
- ν_e *spectrum from NuMI at ICARUS covers first oscillation peak and provides good coverage of the relevant phase space for the DUNE.*

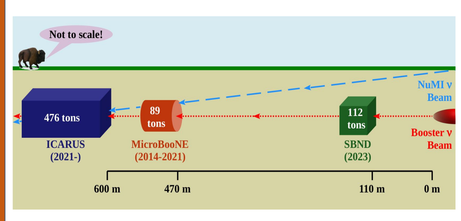
Spectrum at DUNE Near Detector



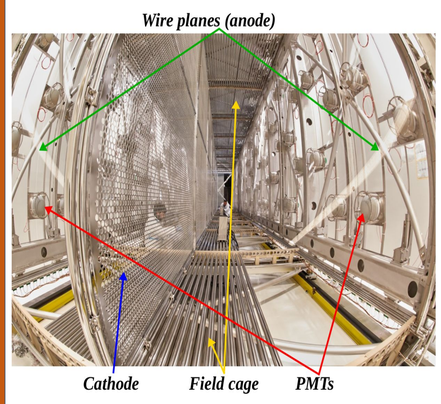
- ν_e *flux is distributed to probe regions - we expect the largest* ν_e/ν_μ *differences (dominant systematic for DUNE-CP violation measurements)*

Ref: NuINT talk by Minerba Betancourt

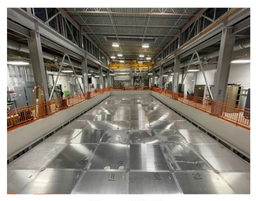
B — *ICARUS detector at Fermilab*

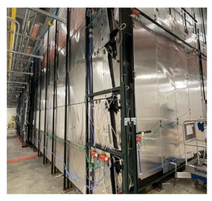


- ICARUS is located on-axis from the Booster beam and **5.75° off-axis** from the NuMI beam [1].
- **2 Cryostats with 2 TPCs** per module with central cathode.
- **3 readout wire planes** (2 induction+collection) per TPC.
- **360 (8" PMTs)**: Scintillation light detected to provide ns event time and trigger.
- **4π coverage with CRTs**: Bottom CRT, Side CRT and Top CRT and 3 m concrete overburden (6m water equivalent)



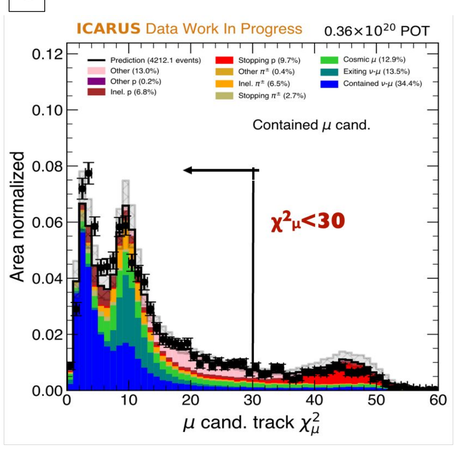
One of the ICARUS modules


Top CRT


Side CRT


Bottom CRT

C — *CC 0π event selection*

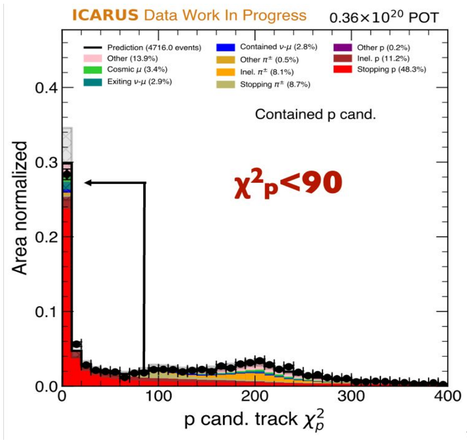


Selecting events with muons

- Vertex to be in fiducial volume (25 cm on sides and top/bottom, 30 cm upstream and 50 cm downstream)
- Events tagged as clear cosmics by Pandora [4] rejected
- At least two primary tracks
- Chi² PID scores consistent with a moun over a proton

Selecting events with muons and protons

- Vertex in fiducial volume
- Events tagged as Pandora clear cosmics are rejected
- At least two primary tracks
- Muon track: **same as above**
- Proton track: Chi² PID scores consistent with a proton, **proton momentum > 0.4 GeV/c** and **< 1 GeV/c, the longest such track is the leading proton candidate**

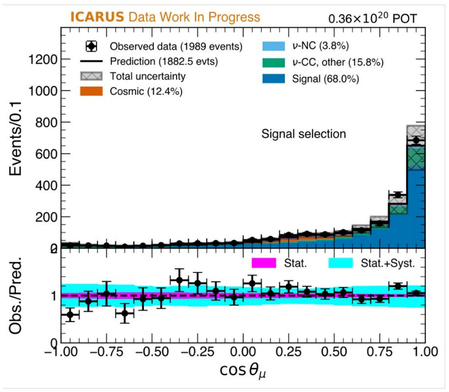


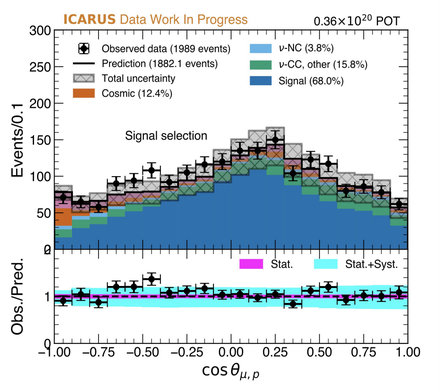
D — *CC0π+Np: Our first Cross-section Analysis*

CC 0π selected events

- First analysis: 1μ+Nproton+0π
- Signal: One muon with $\mathbf{p}_{muon}$ > 226 MeV/c, any proton with 400 MeV/c < $\mathbf{p}_{proton}$ < 1 GeV/c, no charged or neutral pions in the final state.

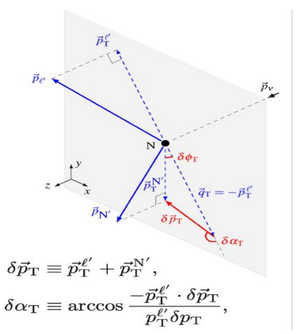
Events with contained and exiting muons



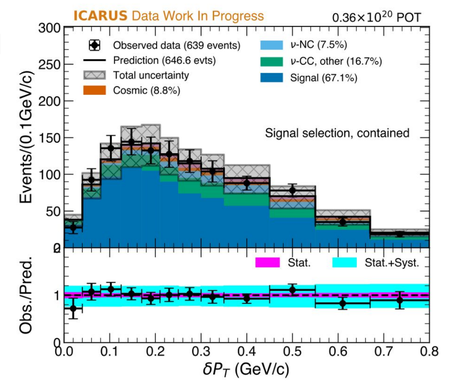


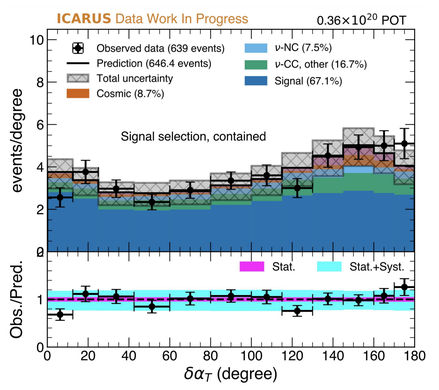
CC 0π Event Selection for fully contained Events

- Transverse kinematic imbalance observables $\boldsymbol{\delta}P_T$ and $\boldsymbol{\delta\alpha}_T$ studied using the leading proton.
- Main background is **pions.**

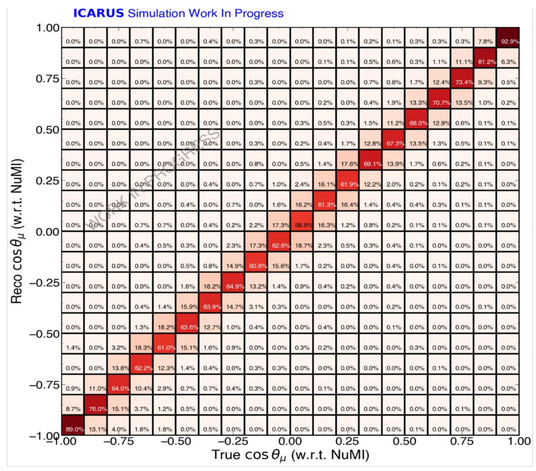


Events with contained muons and protons



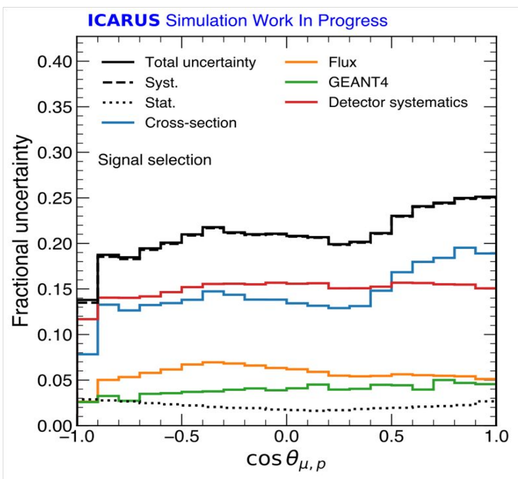


Reconstructed vs True



Cosine $\boldsymbol{\theta}_\mu$

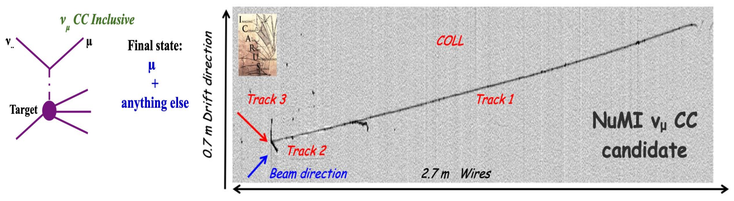
Systematic uncertainties



Several systematics uncertainties evaluated: ***Flux systematics, Geant4 and detector systematics***.

E — *Other Ongoing Analyses: ν_μ CC Inclusive and CC0π+2p*

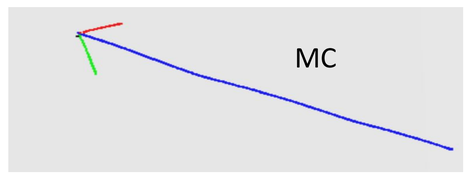
ν_μ CC Inclusive analysis



ν_μ CC Inclusive event section

- Events tagged as Pandora clear cosmic rejected.
- Vertex in Fiducial Volume(FV).
- A cut on the longest track's Y-direction: Cosine$\theta_{LongestCRY}$ > **-0.7**
- Barycenter Flash Matching < **1m**
- Muon track: Distance from Vertex < **10 cm**
  - Contained: Length**>50cm**
  - Exiting: Length**>100cm**

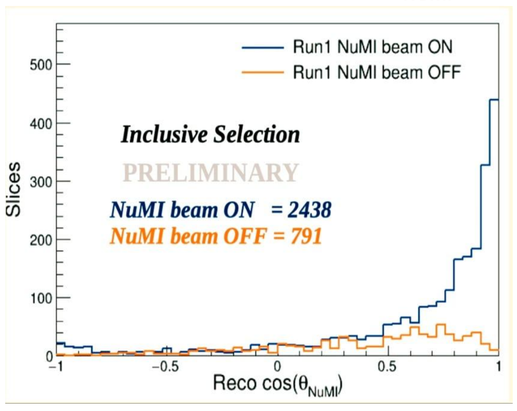
CC 0π with 2 protons



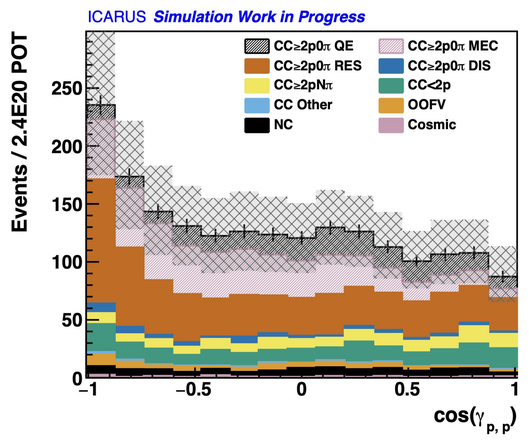
Event selection for CC 0π 2p

- Vertex in FV and not Clear Cosmic.
- All selected tracks tagged as primary and start < 10cm from the vertex
- Muon candidate track: at least 50 cm long
- Proton candidate tracks: **At least 2** of them, **Reco momentum > 350MeV/c**
- Hadronic system is fully contained

Distribution of Cosine θ_{NUMI}



2protons opening angle distribution



Conclusion

- ICARUS at Fermilab underwent a period of commissioning and first operations.
- Rich physics program for neutrino-argon scattering measurements using *NuMI.*
- Conducting neutrino cross-section and interaction measurements using neutrinos from NuMI beam in a similar kinematic regime as *DUNE*: Opportunity to test and constrain models to be used in *DUNE*.

REFERENCES

[1]Abratenko, P. et al. Eur. Phys. J. C 83, 467 (2023)
[2] P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146
[3] The DUNE Collaboration. arXiv:2006.16043
[4] Acciarri, R., Adams, C., An, R. et al. Eur. Phys. J. C 78, 82 (2018)

ACKNOWLEDGMENTS

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