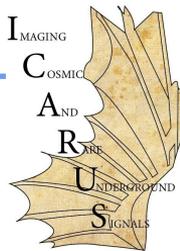


Neutrino Interaction Measurements from the ICARUS Experiment

Jack Smedley (he/him)

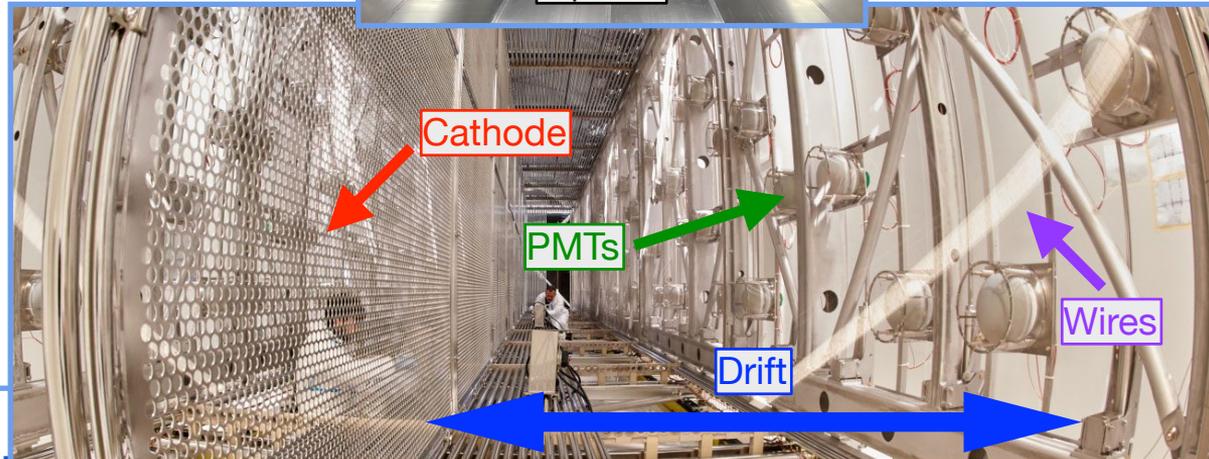
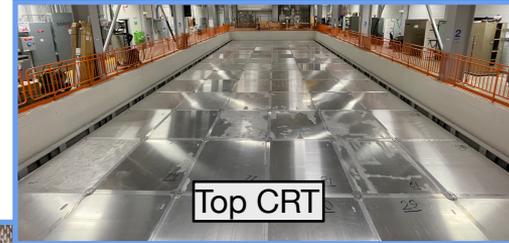
NuFact 2024

Thursday, September 19, 2024



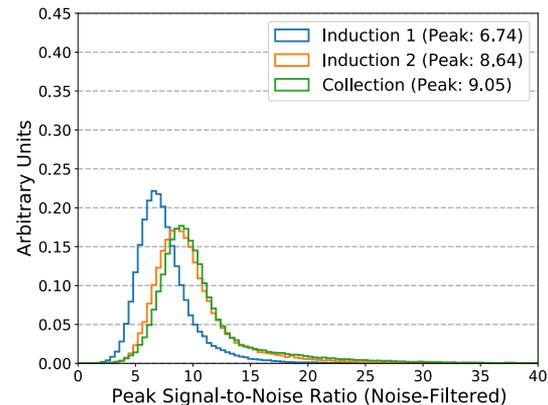
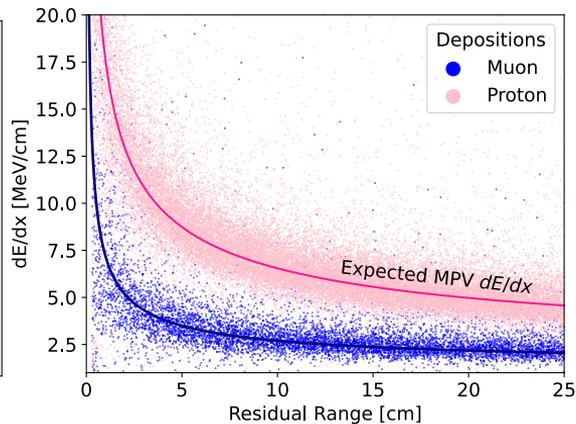
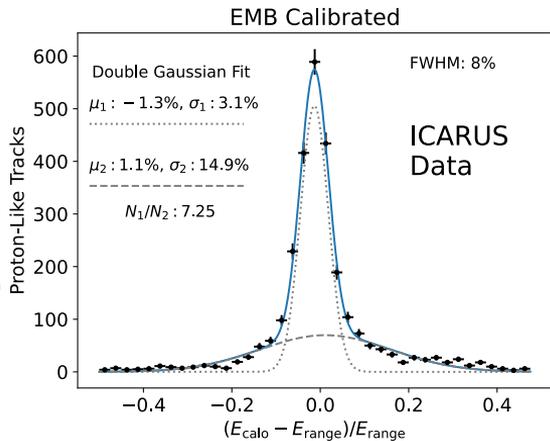
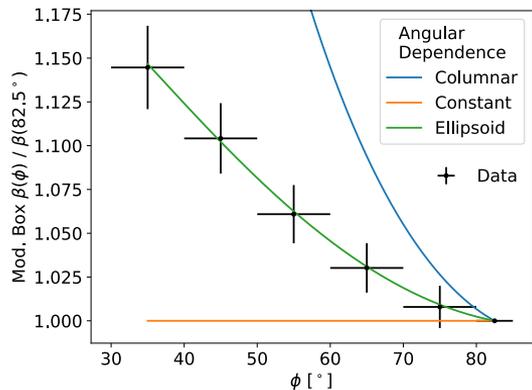
The ICARUS Detector

- Four 1.5m (1ms) x 19.6m x 3.9m drift volumes across two identical modules
- 760 tons of LAr, 476 tons in the active volume
- 53248 readout wires
- 360 PMTs
- Top and side cosmic ray taggers

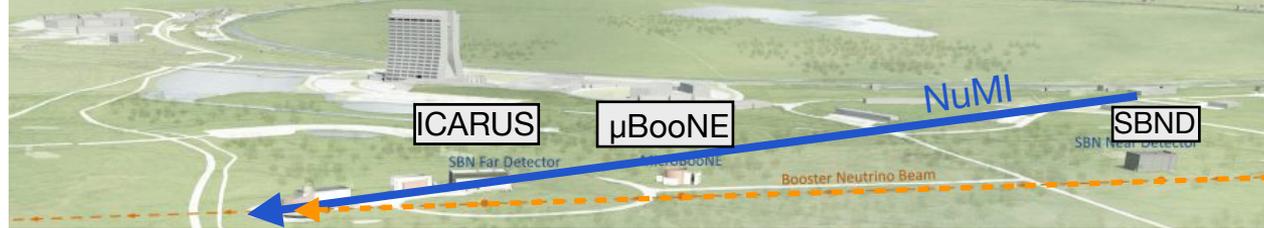


Commissioning, Calibration, and Data Taking

- Installation at Fermilab began in 2018, after moving from LNGS to CERN for upgrades
- Commissioning period spanned from 2020-2022
- Physics data collection started in June 2022, Runs 1-3 now complete
- Commissioning paper published [[Eur. Phys. J. C 83, 467 \(2023\)](#)], first calibration paper submitted [[arXiv:2407.12969](#)]
- Shown here...
 - Singal-to-noise ratio per plane extracted from data
 - dE/dx calibration, including *angular dependent electron-ion recombination measurement (!)*

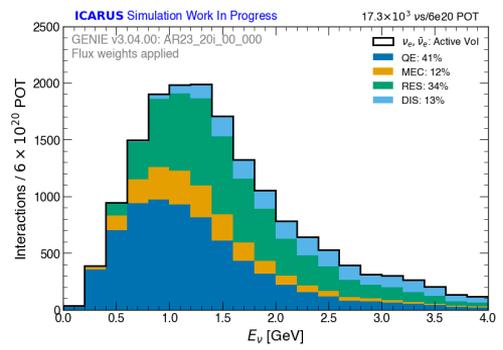
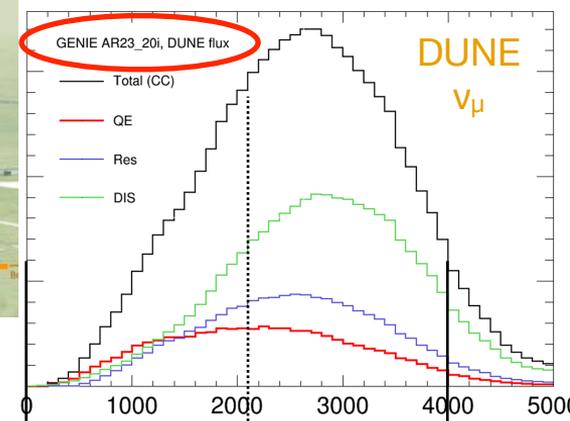


The NuMI Beam as Seen from ICARUS

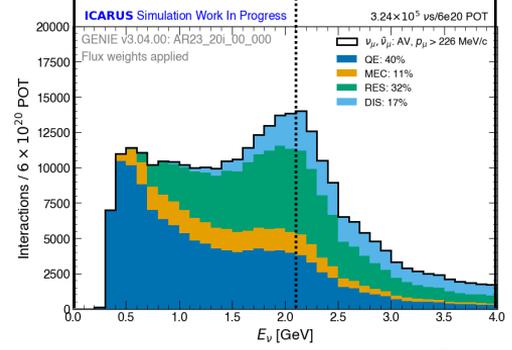


- Beside the BNB, ICARUS is 5.75° off-axis to the NuMI neutrino beam
- NuMI extends the physics reach of ICARUS by providing ...
 - BSM sensitivity through kaon decays in the beam line and in the hadron absorber — [First results presented by Nathaniel Rowe on Monday!](#)
 - A high rate of ν_e interactions relative to ν_μ
 - A secondary ν_μ flux peak at $\sim 2\text{GeV}$, approaching the DUNE oscillation maximum

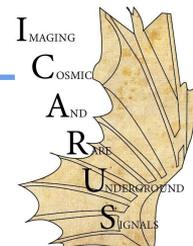
“DUNE Tune”



ICARUS NuMI

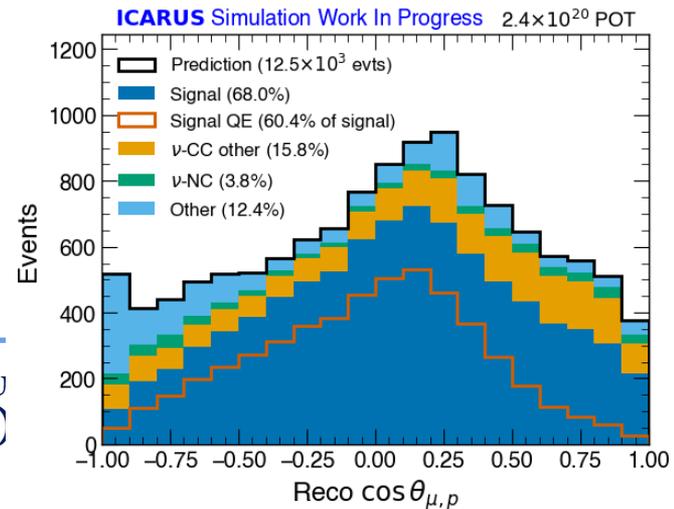
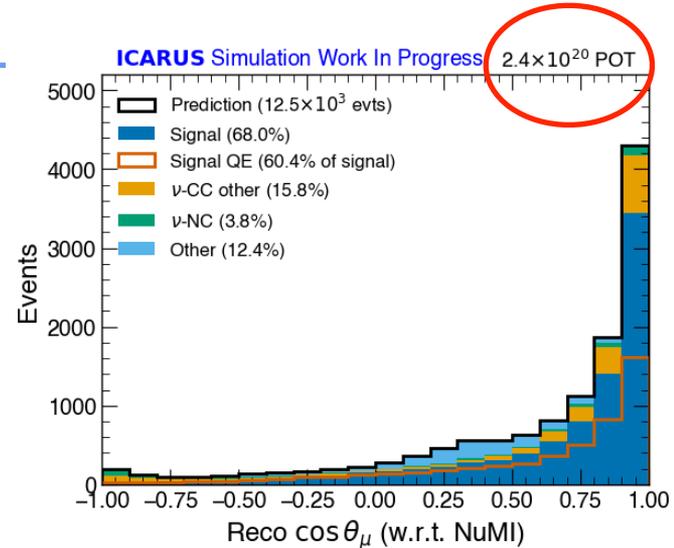


ICARUS NuMI



QE-Like Analysis

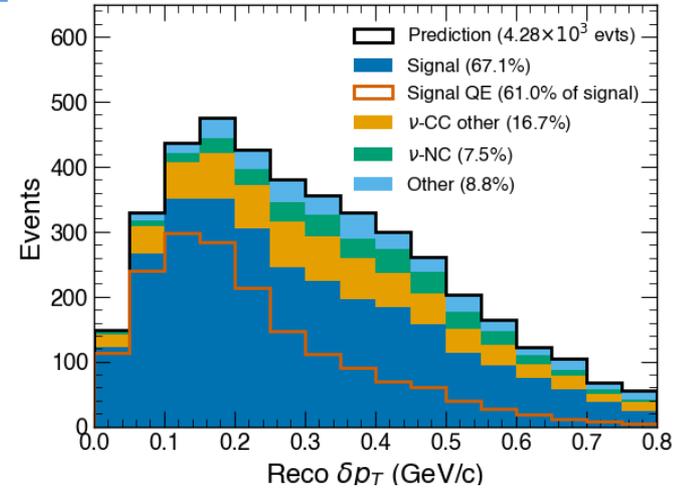
- First results are using the first two physics runs, corresponding to $2.4E20$ POT in neutrino mode
- Targeting a QE-like signal definition
 - Muon with $p > 226\text{MeV}/c$ ($\sim 50\text{cm}$ in LAr)
 - At least 1 proton with $400\text{MeV}/c < p < 1\text{GeV}/c$ ($\sim 5\text{cm}$ in LAr)
 - Any number of additional nucleons
 - Zero post-FSI mesons — *no threshold*
- Focusing on angular observables...



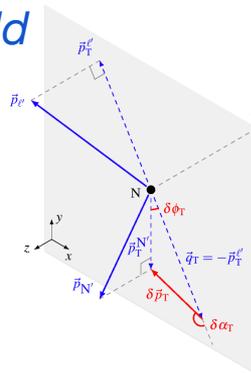
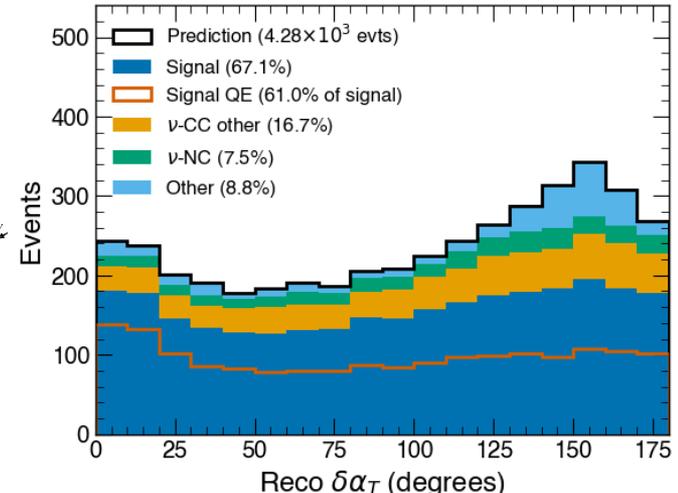
QE-Like Analysis

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 - Zero post-FSI mesons — *no threshold*
- Focusing on angular observables...
- And TKI!

ICARUS Simulation Work In Progress 2.4×10^{20} POT

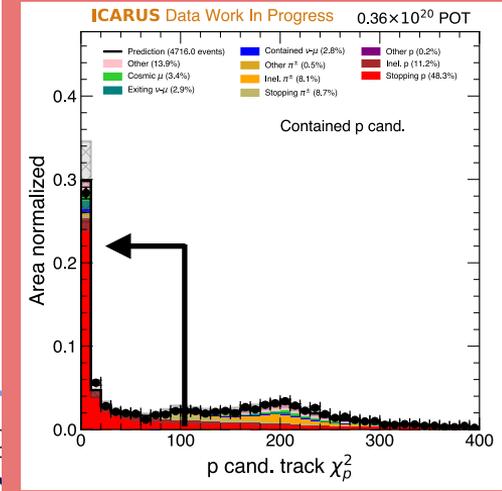
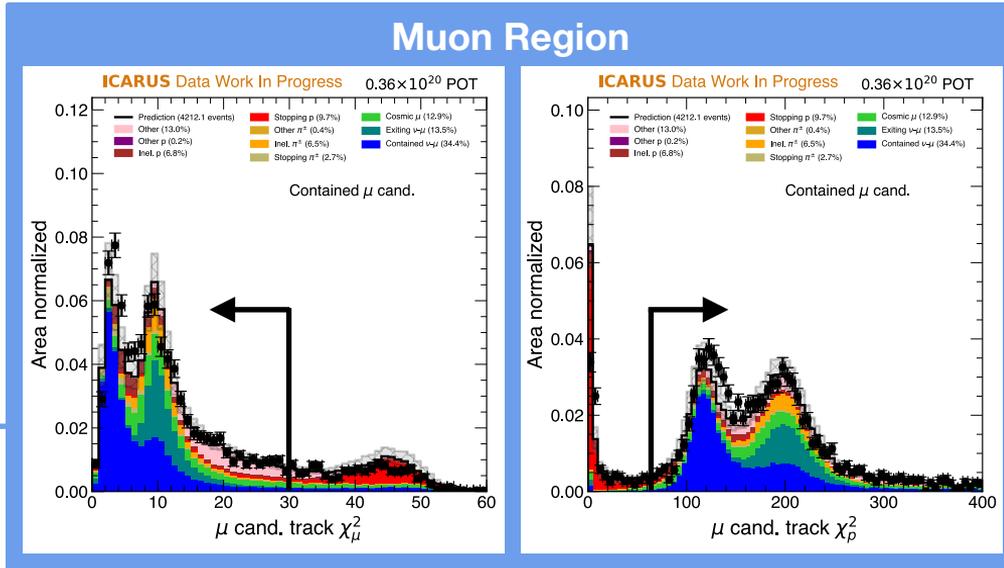
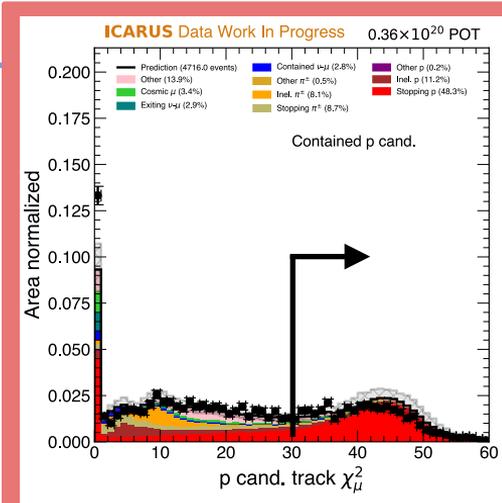


ICARUS Simulation Work In Progress 2.4×10^{20} POT



Event Selection and Particle ID

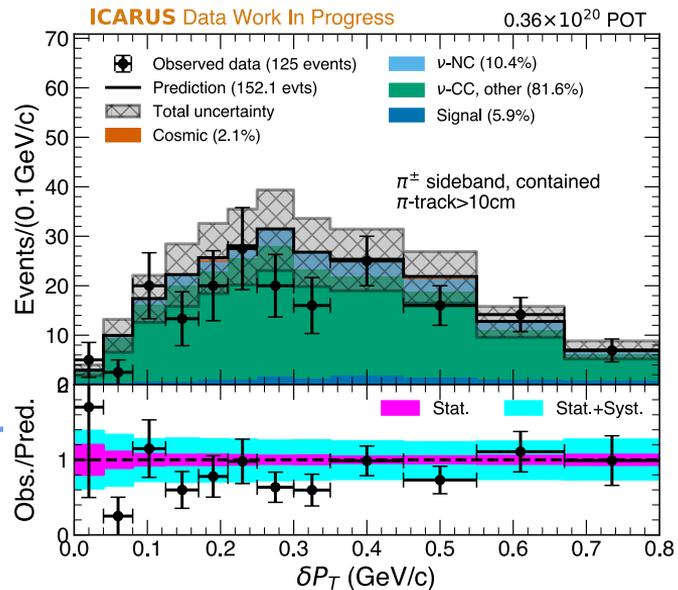
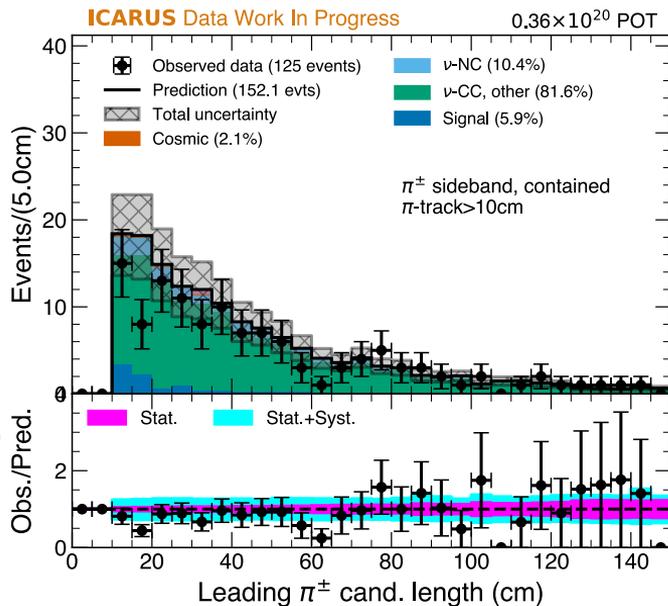
- Muon and proton candidates are identified by comparing the stopping dE/dx profile to a template
- Events with additional MIP-like tracks or photon-like showers are rejected
- **For the TKI sample, the muon candidate must be contained



Proton Region

Pion Sideband Selection

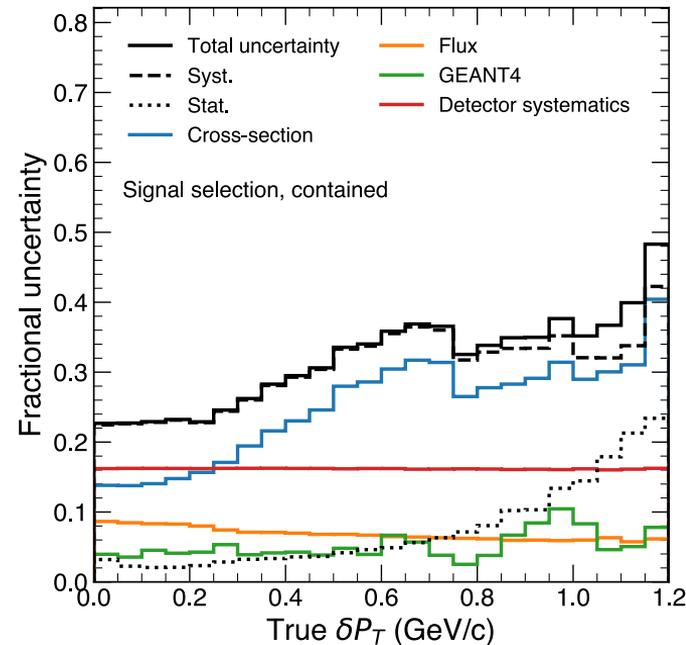
- Control sample with an additional MIP-like track selected to constrain pion backgrounds
 - Selection shown here on 15% of the data, ***the 100% sample has been unblinded!***
- Additional constraints for low energy pion production extracted from MINERvA data



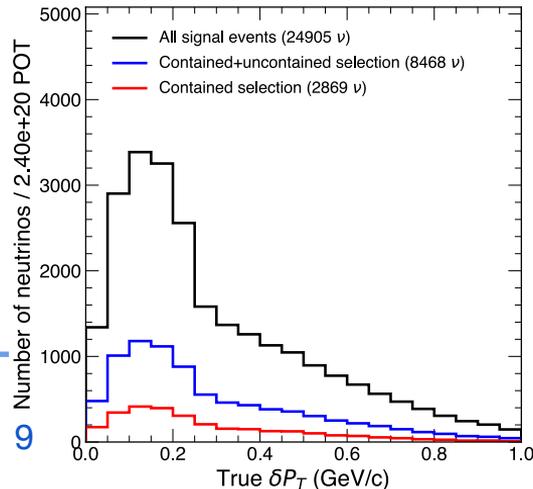
Efficiency and Systematic Uncertainties

- Systematic assessments are mature but ongoing
- The leading uncertainty on the *measurement* will be detector systematics
 - Estimated very conservatively, room to improve in a future iteration
- ~35% efficiency overall, limited to ~10% for fully contained sample

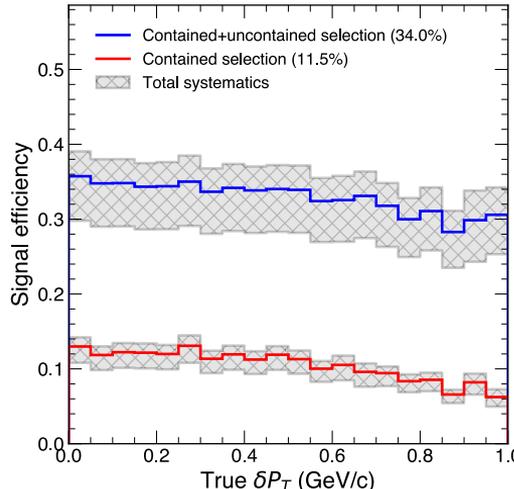
ICARUS Simulation Work In Progress

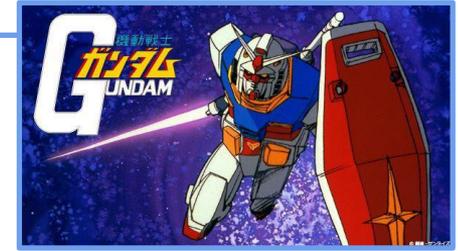


ICARUS Simulation Work In Progress

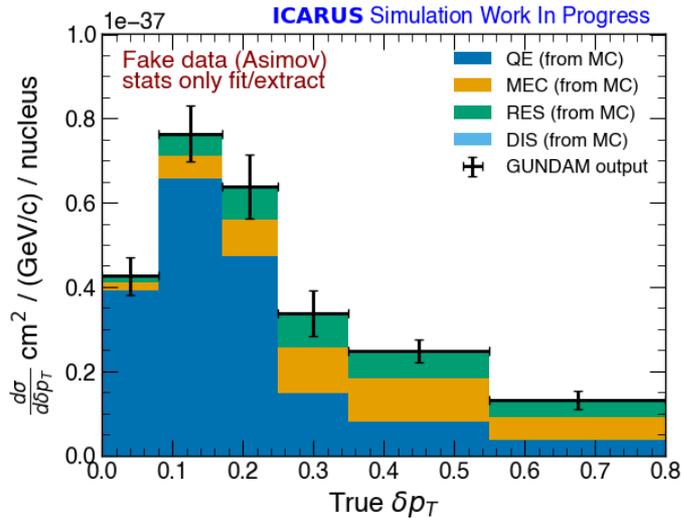


ICARUS Simulation Work In Progress



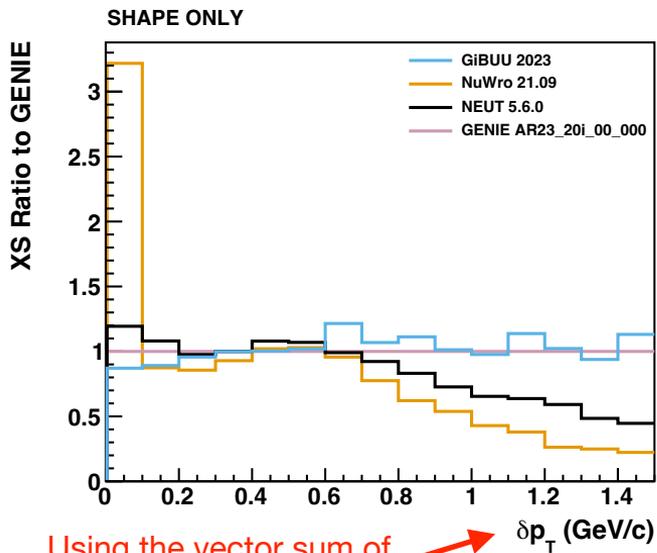


Fitting and Extracting with GUNDAM



- Unfolding and cross section extraction performed with GUNDAM, a binned maximum likelihood fitter developed within the T2K collaboration
- Method is described in this reference [[Phys. Rev. D 98, 032003 \(2018\)](#)], and [the code is open-source!](#)
- Many fake data studies performed to ensure the fitter can recover the variation you've fed into it and that we have sufficient uncertainty coverage
- End-to-end extraction procedure validated on Asimov data

Multi-Proton Analysis

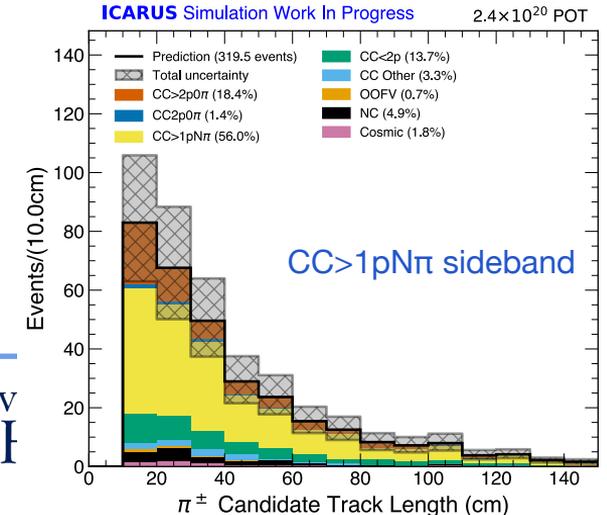
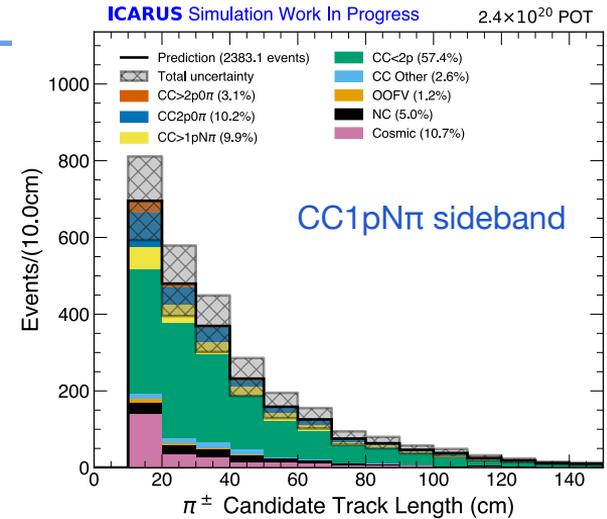
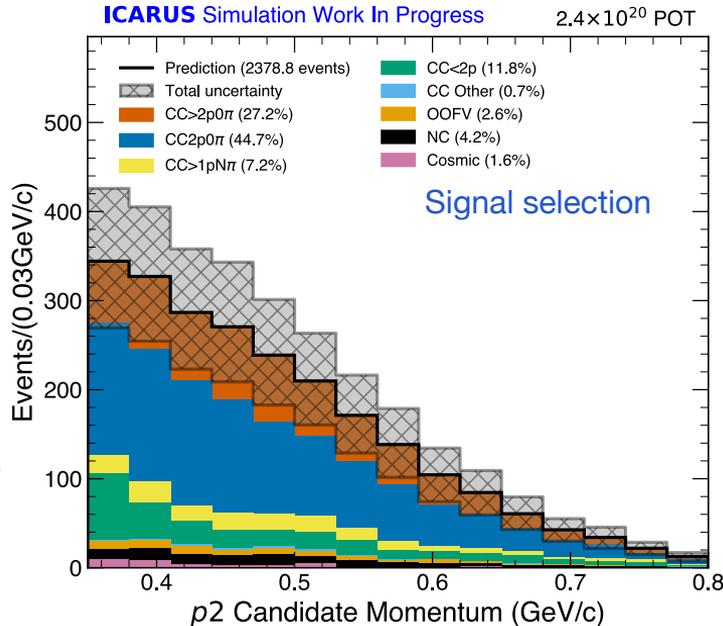


- In parallel with the the QE-like, we're developing a **multi-proton zero pion** analysis
 - Largely a subset of the QE-like signal definition, requiring at least two protons over threshold of 350MeV/c
- More sensitivity to the non-QE processes that come with a QE-like signal definition, like **2p2h** and **FSI pion absorption (a much larger component here than in the BNB flux!)**
- Recall that the momentum sharing prediction in multi-nucleon events is not theory-motivated in current generators**

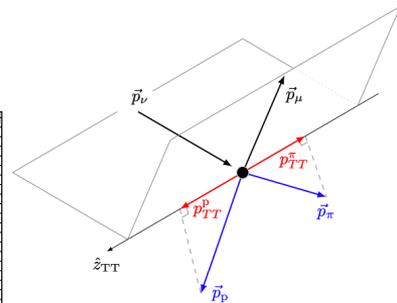
**NuWro makes an additional assumption about the initial state. Not necessarily more correct, but it does something...

Signal Selection and Backgrounds

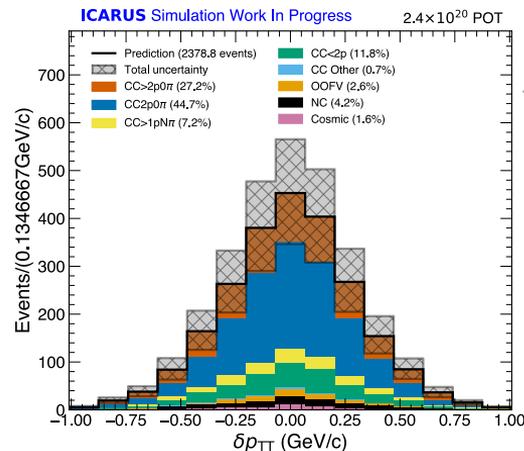
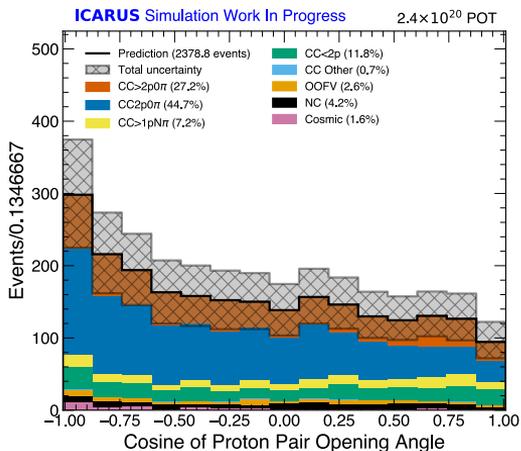
- >70% signal purity, 45% CC2p0 π and 27% CC>2p0 π considering a true proton threshold of 350MeV/c
- Sideband selections to constrain pion-induced backgrounds with a single proton and with multiple protons



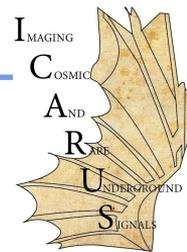
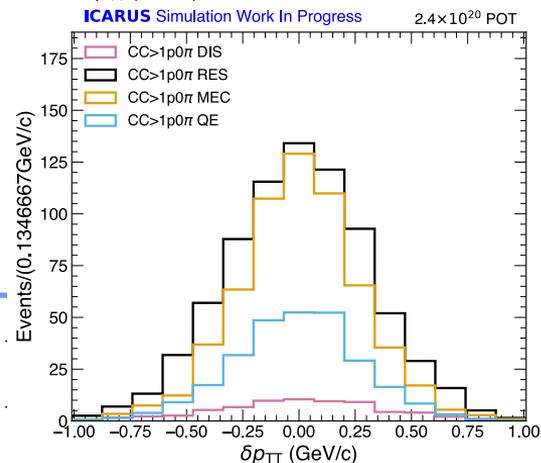
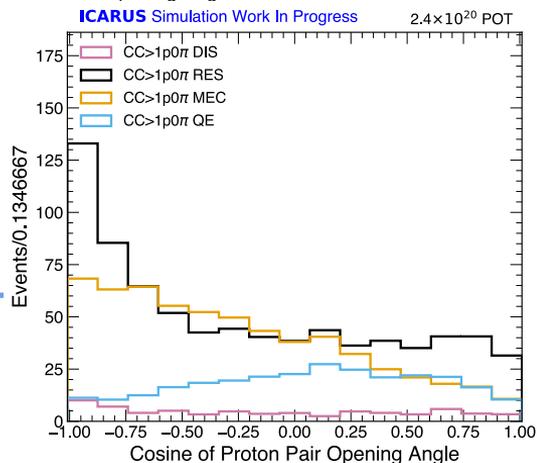
Some Exciting Observables



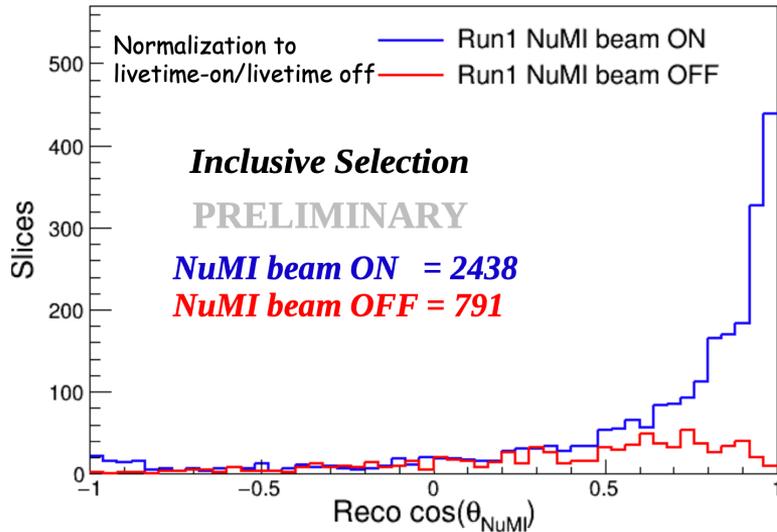
Double transverse momentum imbalance
[\[Phys. Rev. D 103, 112009 \(2021\)\]](#)



Opening angle between the leading two protons



Other Analyses in Progress

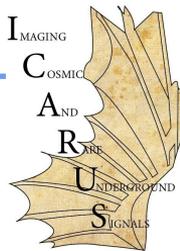


- ν_{μ} CC inclusive selection, relying on the precise timing capabilities of the ICARUS PMT and CRT systems to reject cosmic ray muons
- ν_{μ} CC single charged pion production
- ν_e CC QE-like measurement using the SPINE machine learning reconstruction framework

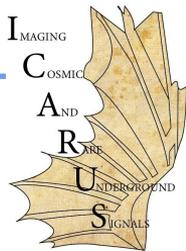
Summary

- ICARUS at FNAL has completed its first three data collection runs and first analyses are well underway
- The off-axis position of ICARUS relative to the NuMI beam provides a wealth of physics potential for DUNE in both ν_μ and ν_e cross sections
- Our first cross section, a QE-like analysis, is nearly complete
 - Cross section extraction machinery has been validated end-to-end
 - Studies presently ongoing with fully unblinded sideband, signal region soon to follow!
- Exclusive multi-proton zero pion measurement is in development and will provide enhanced sensitivity to 2p2h and FSI pion absorption
- Much much more exciting progress on the way!

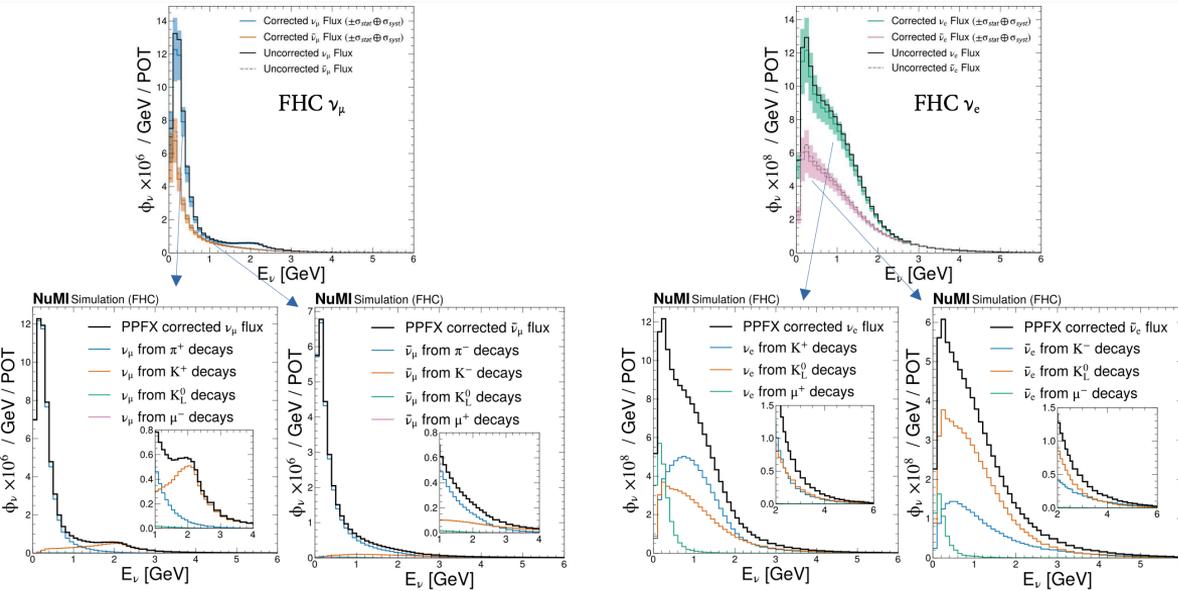
Thank you!



Backups



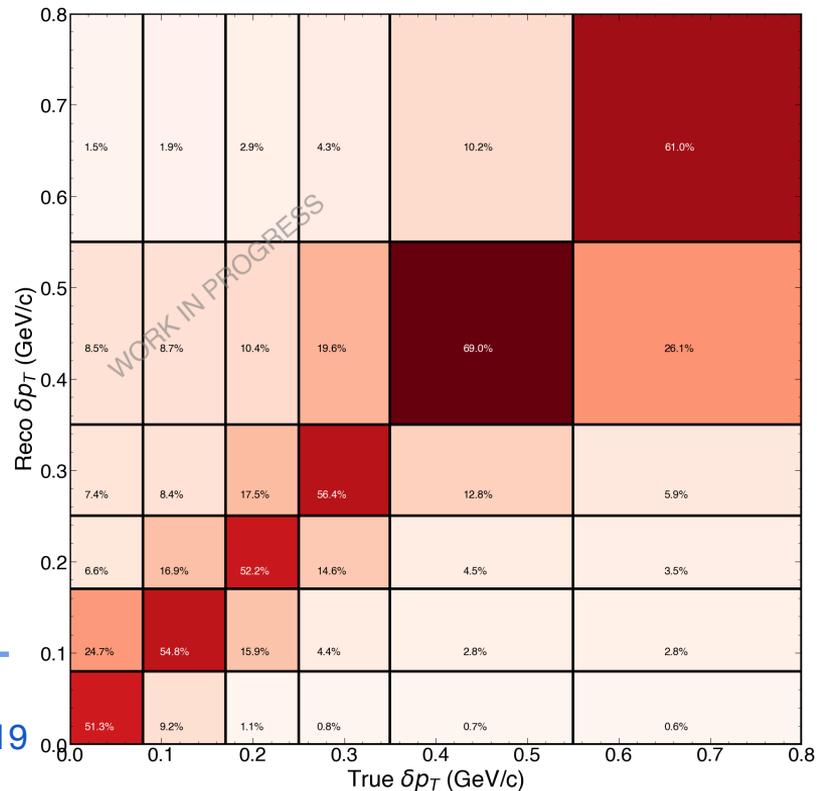
Flux Prediction and PPFX



- Using PPFX for flux prediction, same package used MINERvA and NOvA
- CV reweight on top of the G4NuMI simulation from fixed target hadron production data
- Detailed systematic uncertainties on beam line parameters and principle components of the hadron production covariance matrix
- Worked closely with G4NuMI team to update flux predictions to reflect recent updates to the geometry in the beam line simulation

Migration Matrices

ICARUS Simulation Work In Progress



ICARUS Simulation Work In Progress

