CAPTAIN: Status and plans for cross section measurements relevant to DUNE

Lisa Whitehead, University of Houston

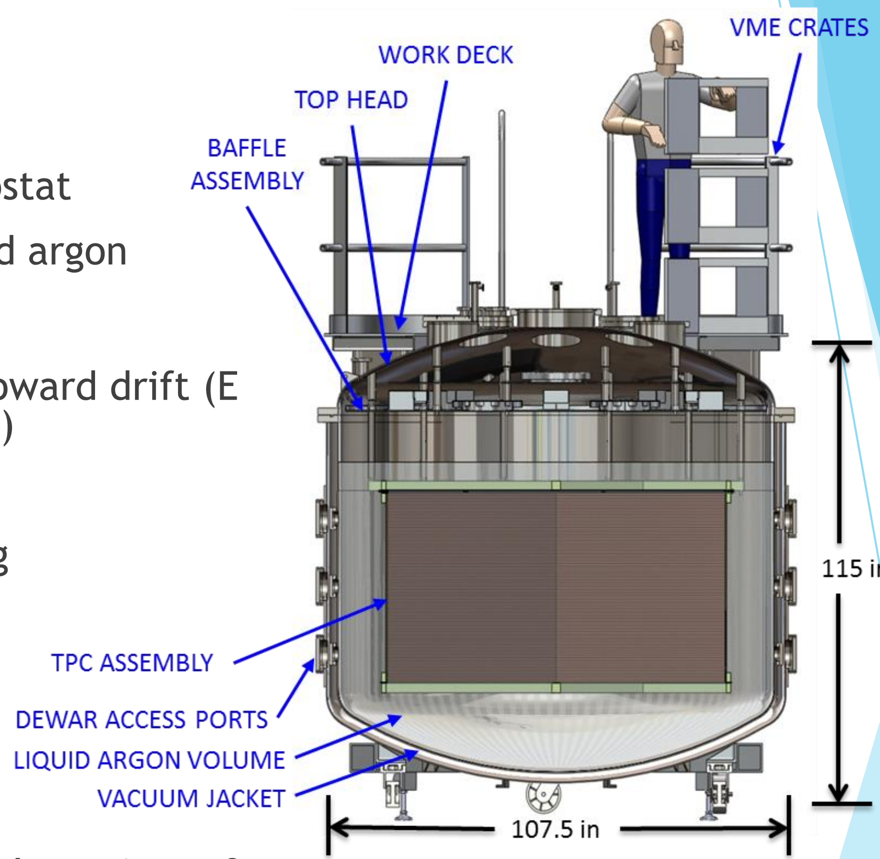
for the CAPTAIN and CAPTAIN-MINERvA collaborations

NNN2015, Stony Brook

October 28, 2015

CAPTAIN

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 5 tons of instrumented liquid argon
- TPC:
  - Hexagonal prism, vertical upward drift ($E = 500$ V/cm, $v_d = 1.6$ mm/μs)
  - 2001 channels (667/plane)
  - 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system
- Electronics chain is the same as MicroBooNE
- Purification system is a scaled version of MicroBooNE's, similar to LArIAT, based on LAPD experience
- Mini-CAPTAIN: a smaller prototype detector (400 kg of instrumented liquid argon)



CAPTAIN Status

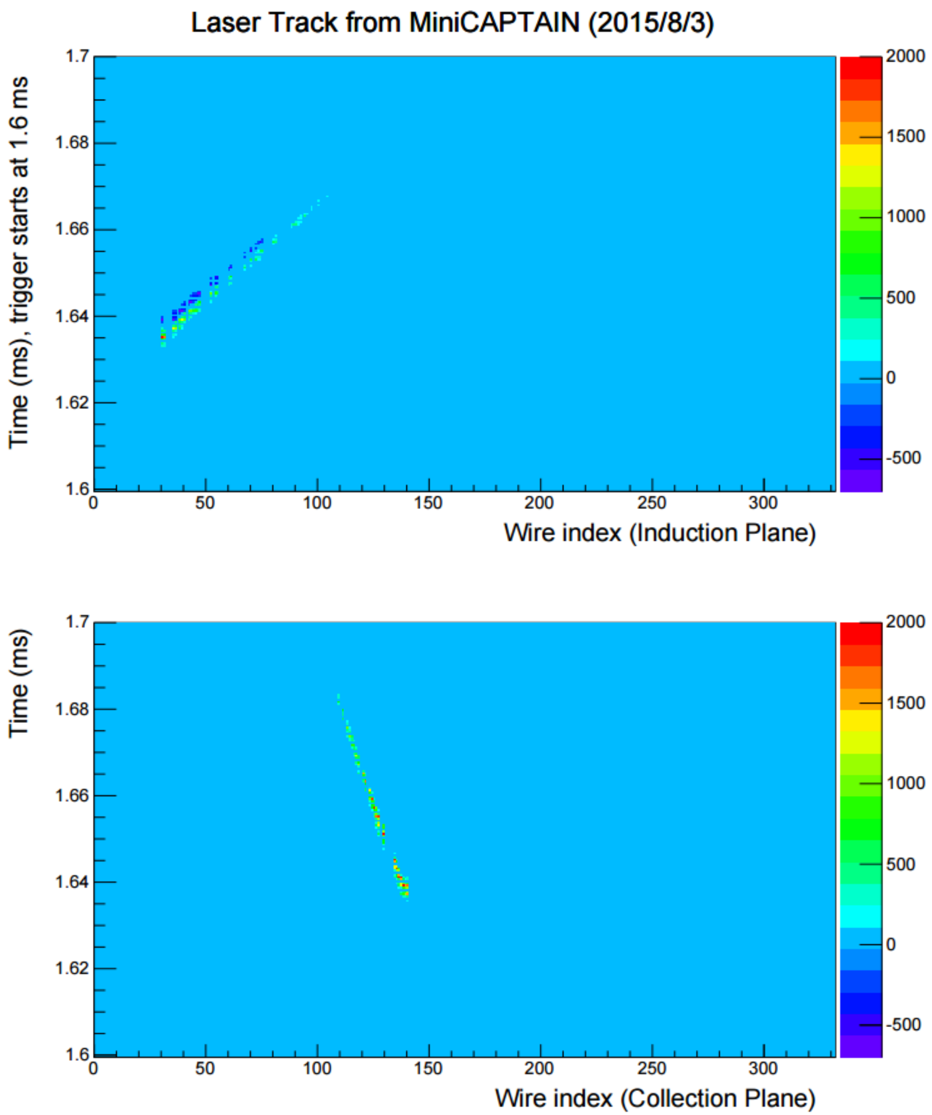
- Cryostat, electronics, and components for wire planes and field cage are in hand
- Recirculation system for liquid argon purification has been assembled

Mini-CAPTAIN Status

- 32 cm upward drift, 1 m width, 400 kg instrumented liquid argon
- Liquid nitrogen fill in Summer 2014: test electronics and TPC, test heat load
- 1st LAr engineering run in Fall 2014: development of filling procedure, test cryogenic and purification system, DAQ development, laser system testing
- 2nd LAr engineering run in March 2015: further development of above items plus installation of gas recirculation system, integration with muon system
- Commissioning run in Summer 2015: more development of electronics and recirculation system – achieved sufficient purity to see tracks

Liquid nitrogen run

Laser Track in Mini-CAPTAIN



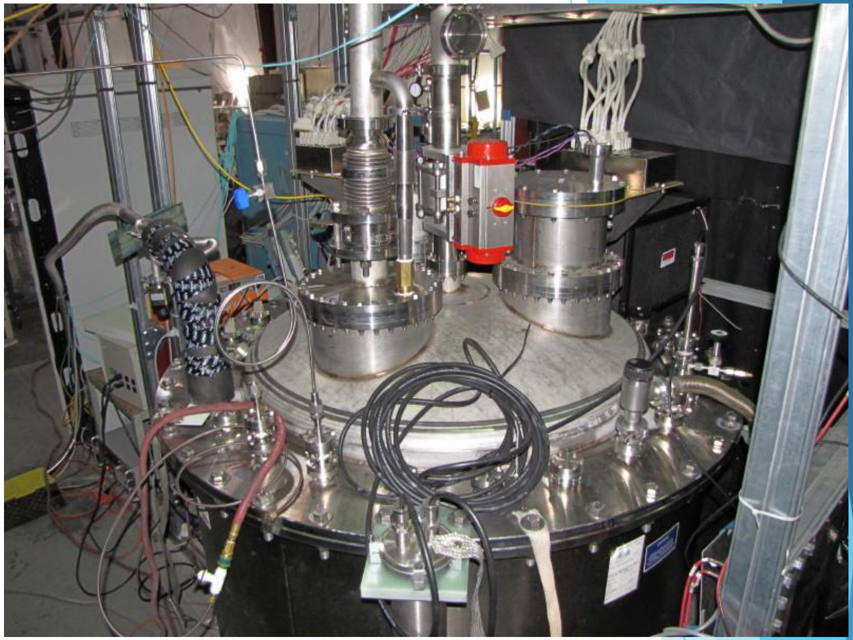
An ionization track from the laser calibration system in Mini-CAPTAIN. The data were collected on August 3, 2015 and were created with a high-intensity UV laser pulse traversing the TPC. The detector was running with one collection plane and one induction plane. The color represents ADC value.

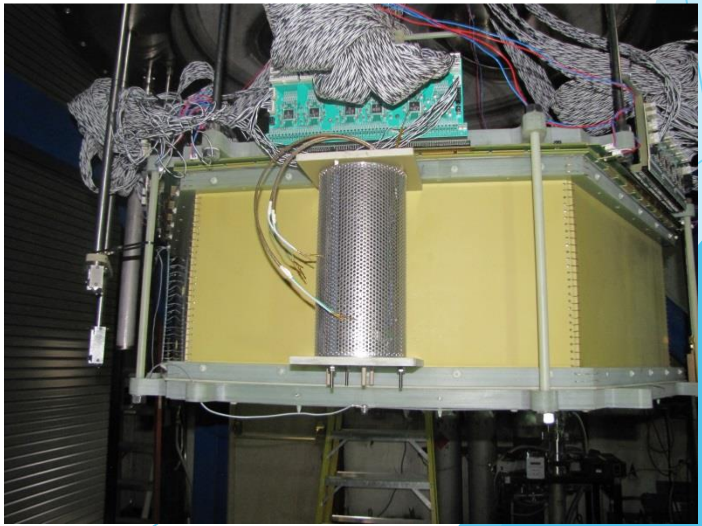
More laser and cosmic-ray data is under analysis.

Mini-CAPTAIN Status

Fall 2014 LAr run

TPC being pulled out after liquid nitrogen run





Purity monitoring system has been installed in Mini-CAPTAIN.

The CAPTAIN Physics Program

- Medium-energy neutrino physics
  - Measure neutron interactions and event signatures to constrain the number and energy of emitted neutrons in neutrino interactions
  - Measure higher-energy neutron-induced processes that could be backgrounds to electron neutrino appearance, e.g. $^{40}Ar(n,\pi^0)^{40}Ar^{(*)}$
  - Measure inclusive and exclusive CC and NC cross sections and event rates in the neutrino energy range relevant for long-baseline neutrino oscillations
  - Test methodologies of total neutrino energy reconstruction with neutron reconstruction
- Low-energy neutrino physics
  - Measure neutron production of spallation products
  - Benchmark simulations of spallation production
  - Measure CC and NC cross sections in the neutrino energy range relevant for supernova neutrino detection
  - Measure the correlation between true neutrino energy and visible energy for events in the neutrino energy range relevant for supernova neutrino detection

The CAPTAIN Physics Program

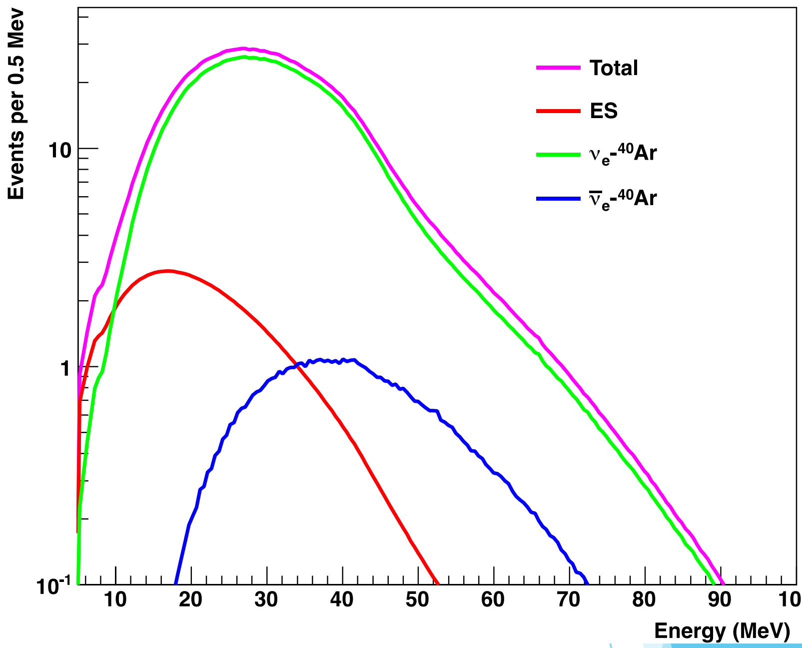
Neutron Beam Medium-Energy Neutrino Beam Low-Energy Neutrino Beam

- Medium-energy neutrino physics
  - Measure neutron interactions and event signatures to constrain the number and energy of emitted neutrons in neutrino interactions
  - Measure higher-energy neutron-induced processes that could be backgrounds to electron neutrino appearance, e.g. $^{40}Ar(n,\pi^0)^{40}Ar^{(*)}$
  - Measure inclusive and exclusive CC and NC cross sections and event rates in the neutrino energy range relevant for long-baseline neutrino oscillations
  - Test methodologies of total neutrino energy reconstruction with neutron reconstruction
- Low-energy neutrino physics
  - Measure neutron production of spallation products
  - Benchmark simulations of spallation production
  - Measure CC and NC cross sections in the neutrino energy range relevant for supernova neutrino detection
  - Measure the correlation between true neutrino energy and visible energy for events in the neutrino energy range relevant for supernova neutrino detection

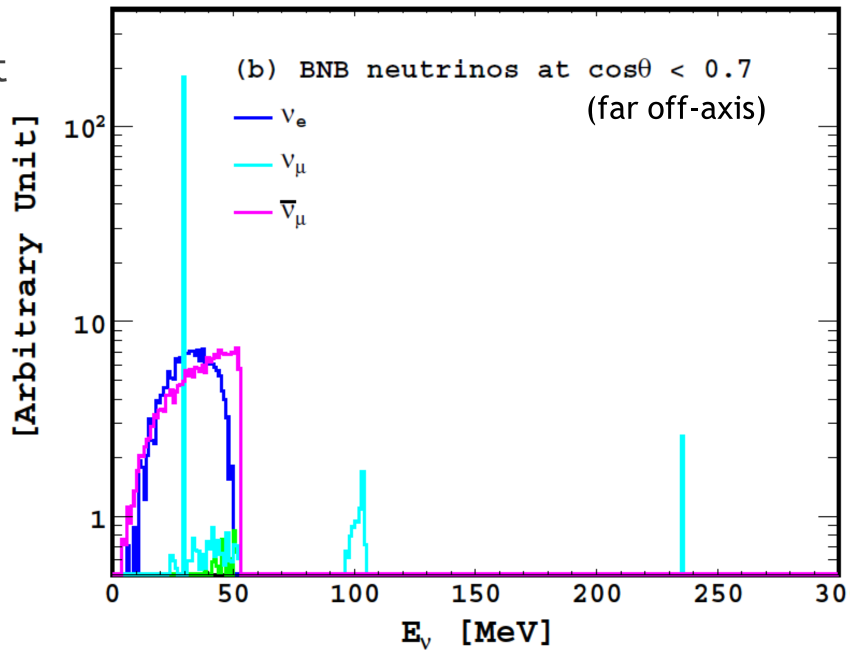
CAPTAIN-BNB

- Goal: Study neutrino-argon interactions in the energy range relevant for supernova detection
  - Cross sections have never been measured in this energy range and have large theoretical uncertainties
- Neutrinos from pion decay-at-rest in an off-axis location near the Booster Neutrino Beam (BNB) target hall (MI-12)
- Goals
  - Measure the neutrino-argon xsec to about 10% for neutrino energies of O(10) MeV
  - Test the ability of detecting SNe with LAr detectors (triggering, timing)
- LOI Submitted to Fermilab PAC in January 2015
  - Studies of beam-induced neutron background around the BNB ongoing
- Other alternatives are being considered (NuMI absorber)

SN @ 10 kpc , 17-kton LAr

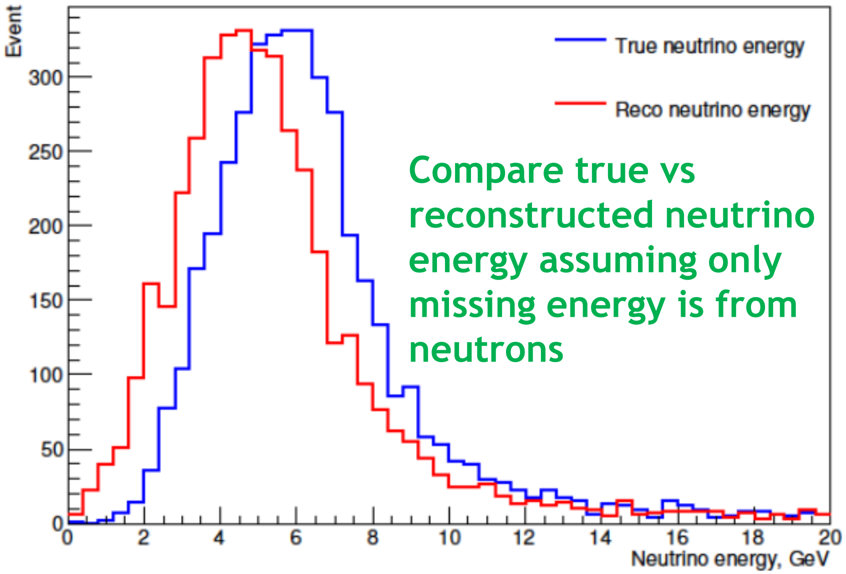


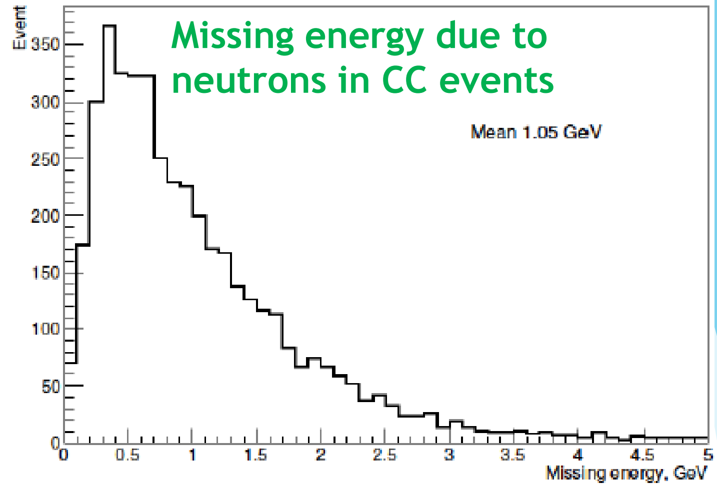
K. Scholberg: arXiv 1205.6003 astro-ph
GKVM model: arXiv 0902.0317 hep-ph
(Gava, Kneller, Volpe, McLaughlin)

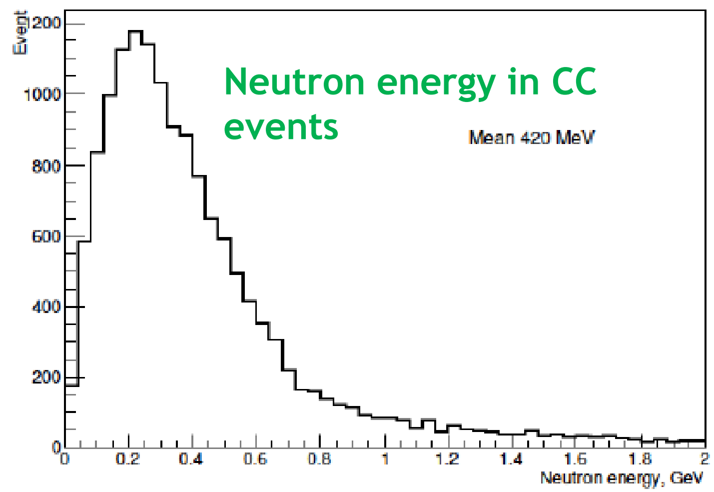


Phys. Rev. D89 (2014) 072004 (arXiv 1311.5958 physics.ins-det)

Neutrons in neutrino interactions



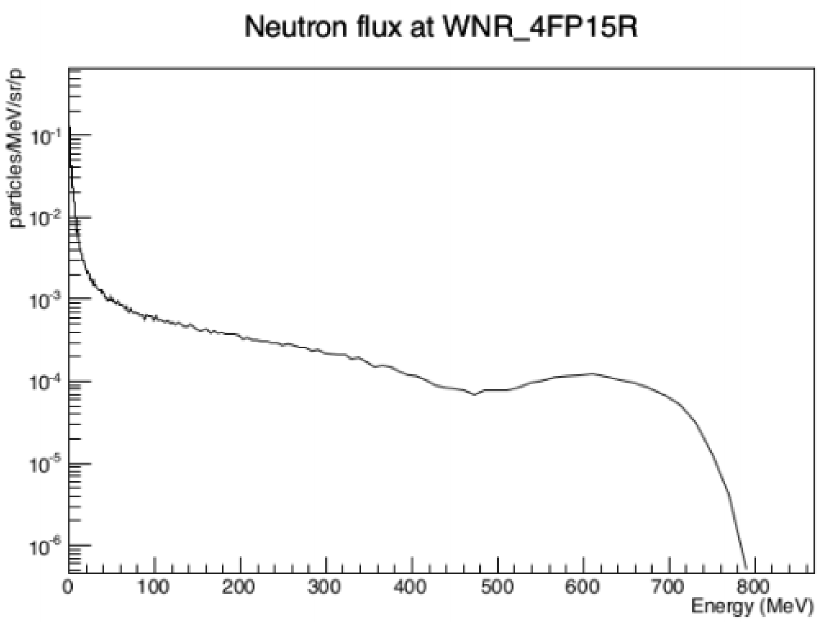




Simulation studies using NuMI medium-energy flux and GENIE (Q. Liu)

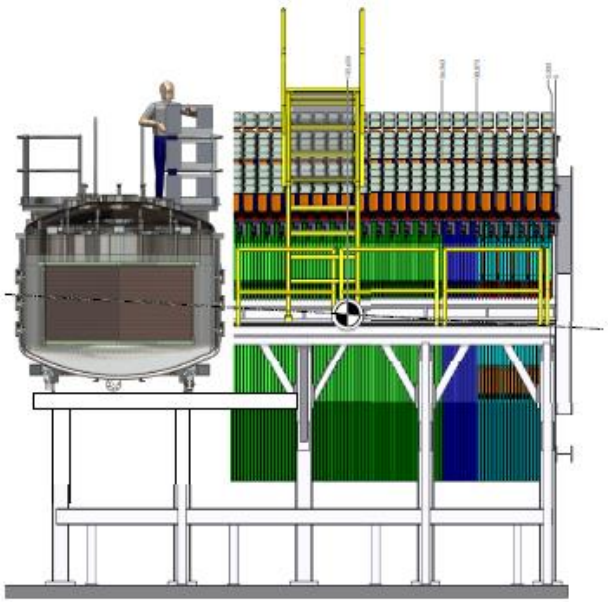
Neutron measurements

- Mini-CAPTAIN neutron run
  - At the Los Alamos Neutron Science Center (LANSCE) at LANL
  - Anticipate running in Jan 2016 (upcoming beam cycle), again in Oct 2016 (the following beam cycle)
- Planned measurements
  - High-energy neutrons: address neutron energy reconstruction for DUNE by studying the signature of neutrons of known kinetic energy (by time-of-flight)
  - Low-energy neutrons: Study $n^{40}Ar \rightarrow n^{40}Ar^{(*)}$ to gain insight into identifying NC interactions of supernova neutrinos $\nu^{40}Ar \rightarrow \nu^{40}Ar^{(*)}$



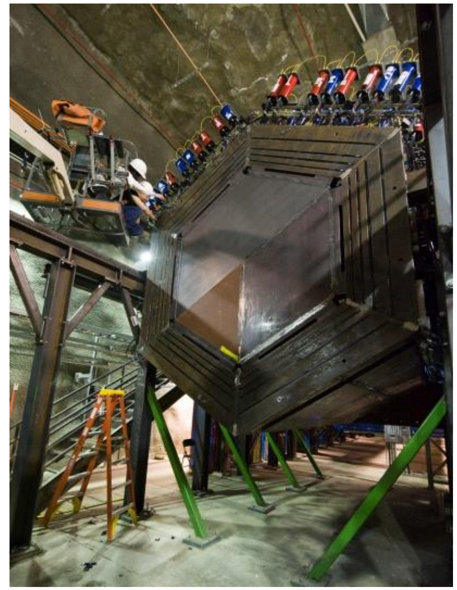
CAPTAIN-MINERvA

- Install the CAPTAIN detector in MINERvA to study neutrino-argon interactions in the medium-energy NuMI beam
- CAPTAIN will serve as the vertex detector, and outgoing particles will be tracked in MINERvA.
- The MINOS Near Detector will continue to be used as the downstream muon spectrometer.

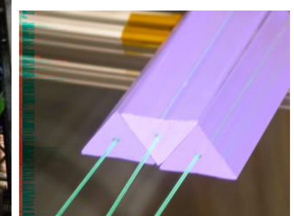


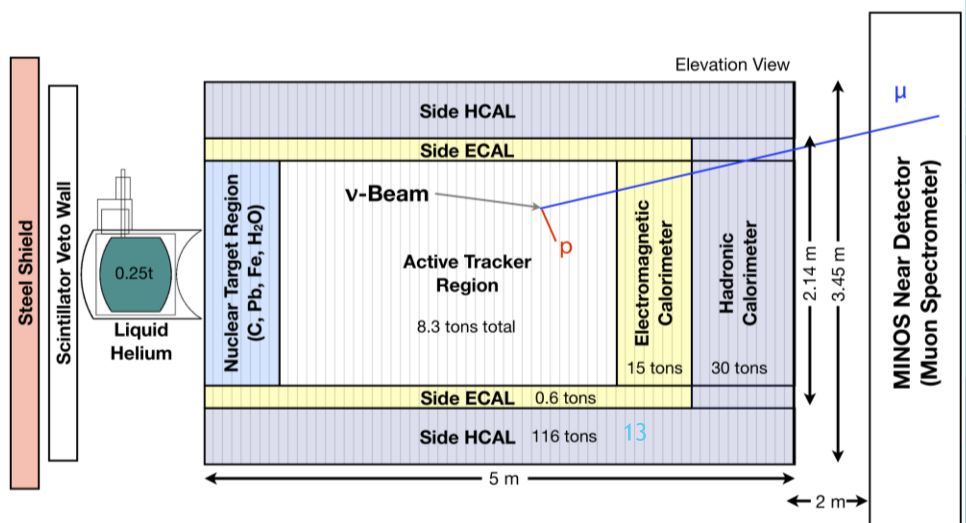
MINERvA

- Nuclear Targets
  - Allows side by side comparisons between different nuclei
  - Pure C, Fe, Pb, LHe, water
- Solid scintillator (CH) tracker
  - Tracking, particle ID, calorimetric energy measurements
  - Low visible energy thresholds
- Side and downstream electromagnetic and hadronic calorimetry
  - Good event energy containment
- MINOS Near Detector
  - Provides muon charge and momentum



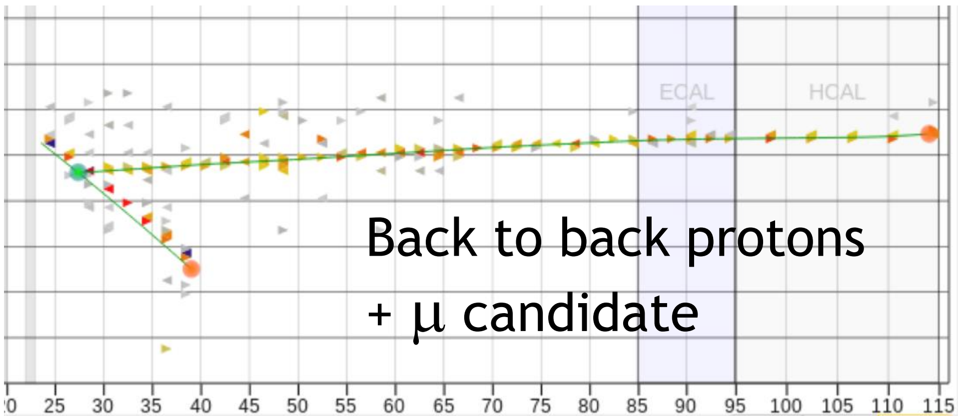
LHe cryotarget

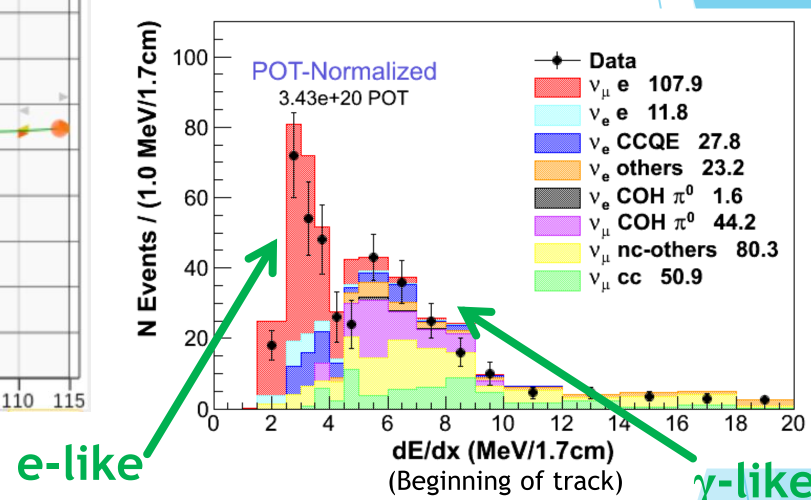


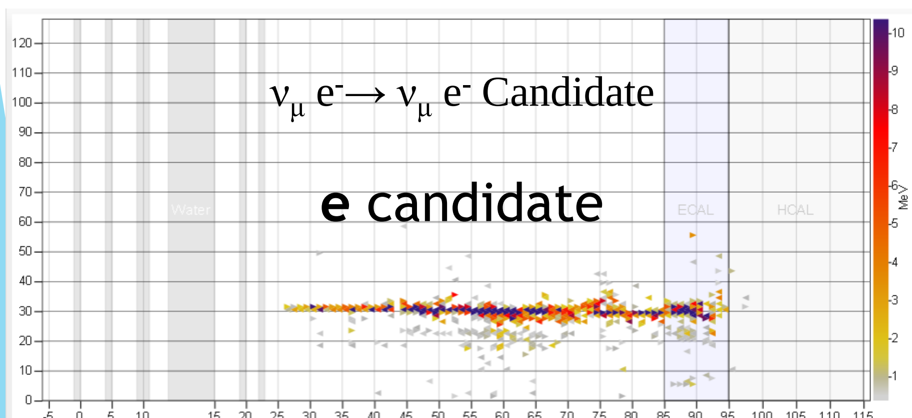


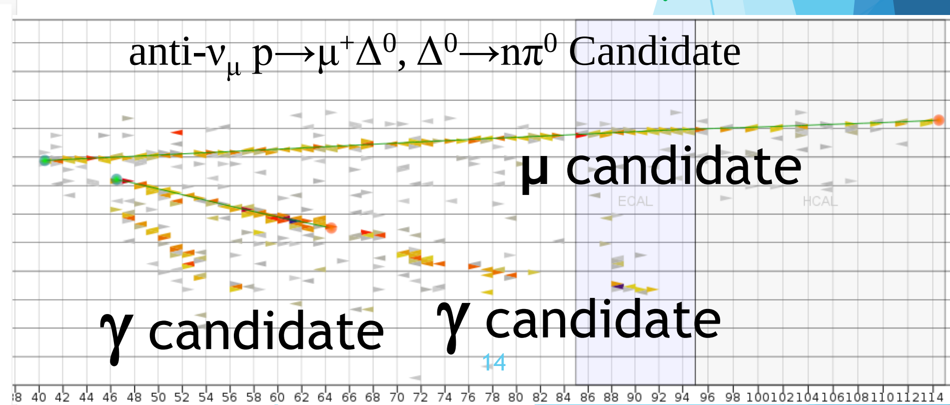
Events in MINERvA

Fine granularity allows exclusive state reconstruction, a close look at the vertex of events, and good e/γ separation!



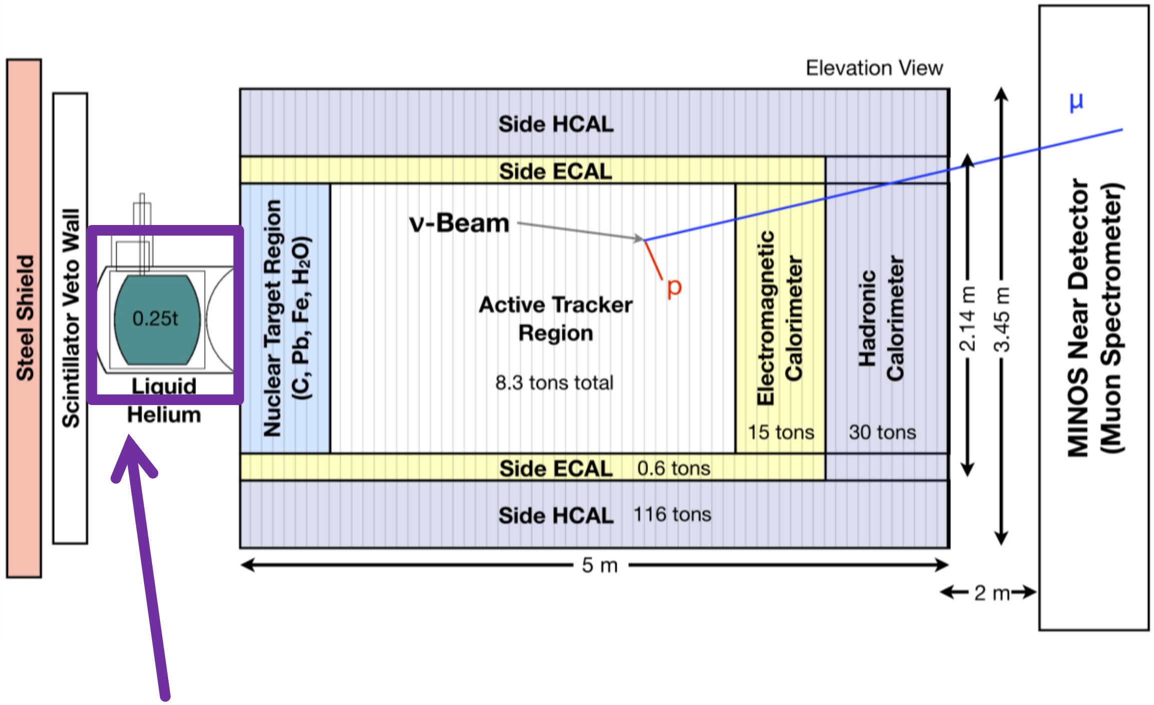






One out of three views shown, color = energy

CAPTAIN-MINERvA



Studies presented here assume we will replace MINERvA's He target with CAPTAIN

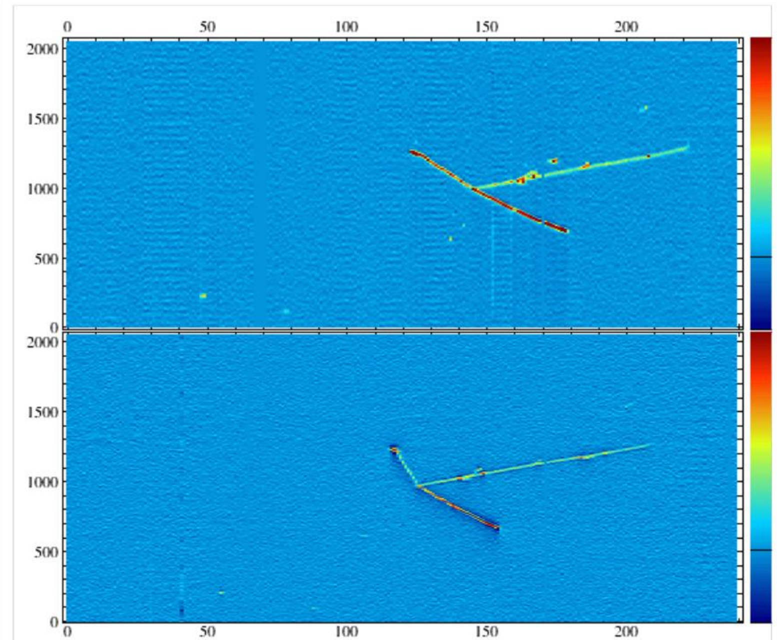
Minimal impact on MINERvA operations - they don't need the He target for the antineutrino running

How is this program unique?

- Only experiment making high-statistics measurements of neutrino interactions on argon in the medium energy range before DUNE
  - Neutrino-argon cross-sections
  - Development of neutrino event reconstruction in LAr
- CAPTAIN-MINERvA can measure cross section ratios (i.e., argon to carbon)
  - Study how processes vary on different nuclei
  - More stringent tests of the models can be performed with ratios due to cancellation of large systematic uncertainties such as the neutrino flux
- CAPTAIN-MINERvA can constrain the essentially unknown nuclear model of argon by measuring the energy dependence of nuclear effects convolved with cross section.
  - The incoming neutrino energy distribution is different in the DUNE far detector compared to the DUNE near detector → different energy-dependent nuclear effects in the two detectors

How is this program unique?

- Compared to ArgoNEUT*
  - Took data in NuMI low-energy configuration (peak energy ~3 GeV)
  - With 20x the fiducial mass and roughly 10x more POT in neutrinos in one year, CAPTAIN will have more statistics and better containment
- Compared to MicroBooNE
  - BNB with neutrino energy ~1 GeV, consistent with 2nd oscillation maximum at 1300 km; will be complementary to CAPTAIN-MINERvA's measurements at 1st oscillation maximum
  - MicroBooNE interactions will mostly be quasi-elastic (~60%); approximately 68% of interactions in CAPTAIN-MINERvA will have a pion in the final state – gives us a unique opportunity to study events with large particle multiplicities



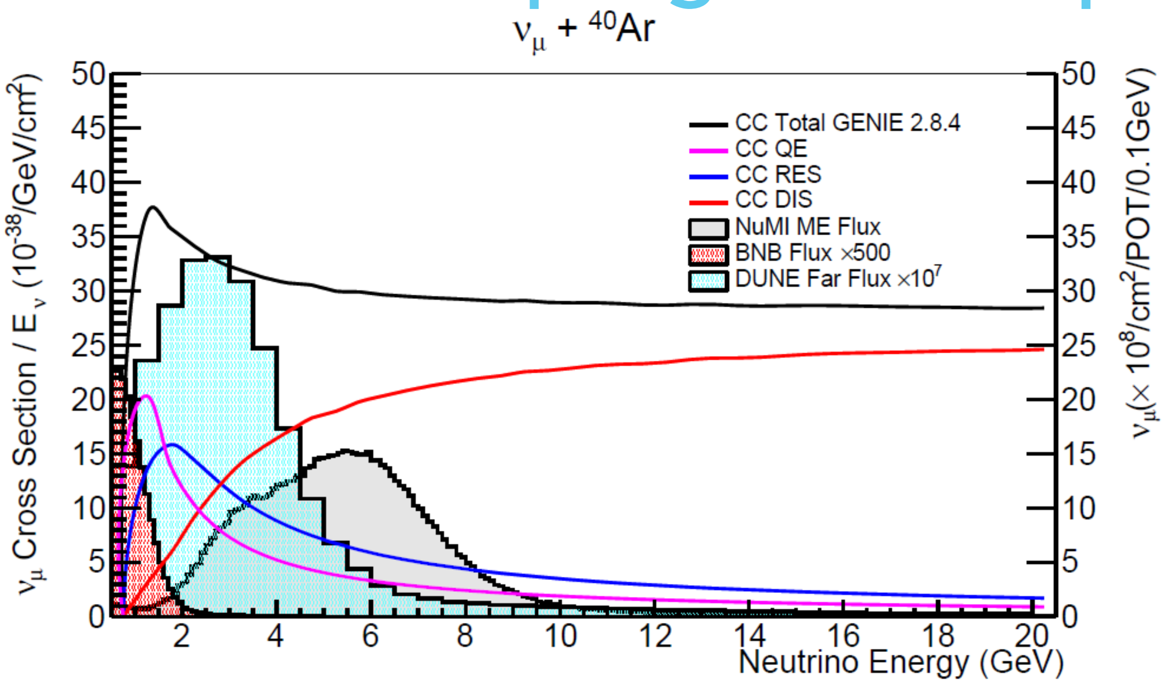
O. Palamara, NuInt 14

Real neutrino event in ArgoNEUT (back-to-back proton + muon candidate).

We expect similarly excellent resolution in CAPTAIN.

Cross section results from ArgoNEUT: e.g. R.Acciarri et al, Phys. Rev. D 89, 112003 (2014)

How is this program unique?



- Very important for DUNE oscillation measurements to understand the cross sections near and above the 1st oscillation maximum
- At 1300 km, the 1st oscillation maximum is ~2.5 GeV and the 2nd oscillation maximum is ~1 GeV
- Right around 1st oscillation max is where the cross section changes to being dominated by single/multi pion production rather than QE

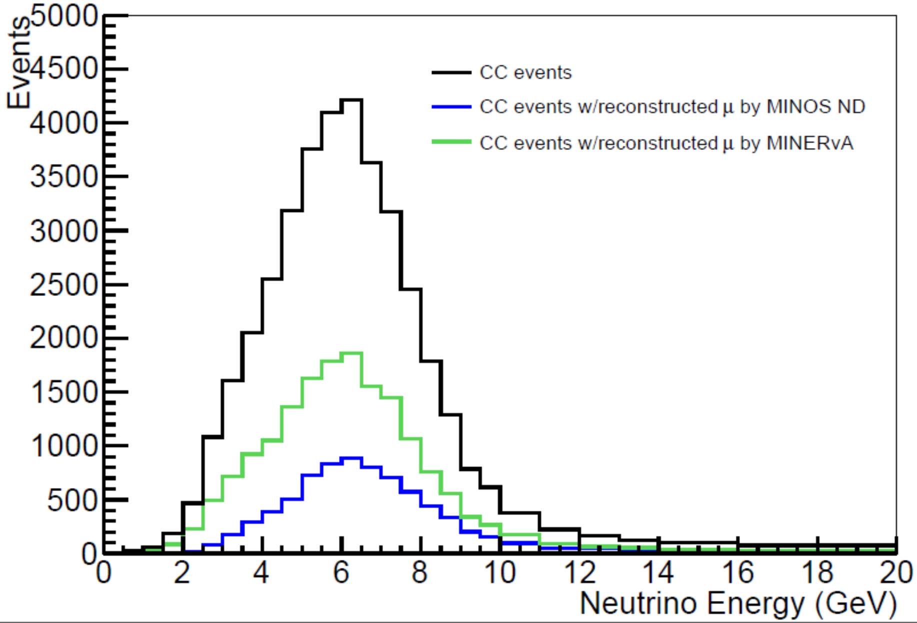
Event rates

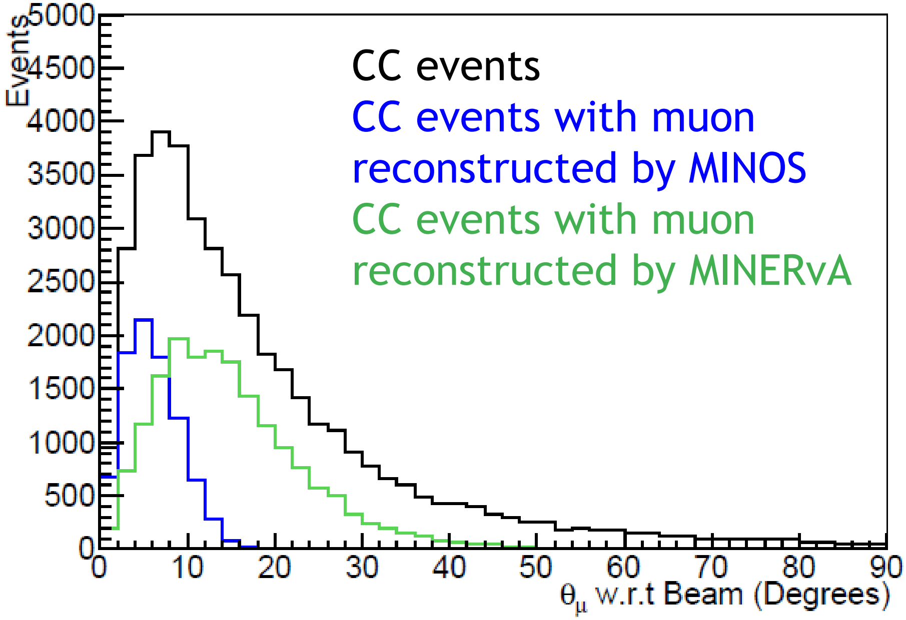
6×10^{20} POT Neutrino mode	CC interactions on argon with muon reconstructed (MINOS or MINERvA) Events w/ reco μ	CC interactions on argon with muon reconstructed by MINOS Events w/ reco μ and charge
CCQE-like	916k	784k
$CC1\pi^{\pm}$	1953k	966k
$CC1\pi^{0}$	1553k	597k

Results presented here show only neutrino mode; we hope to run for 2 years and acquire 6×10^{20} POT in neutrino mode plus 6×10^{20} POT in antineutrino mode.

Simulation studies using NuMI medium-energy flux, GENIE, and MINERvA detector simulation (A. Higuera)

Charged-Current Interactions

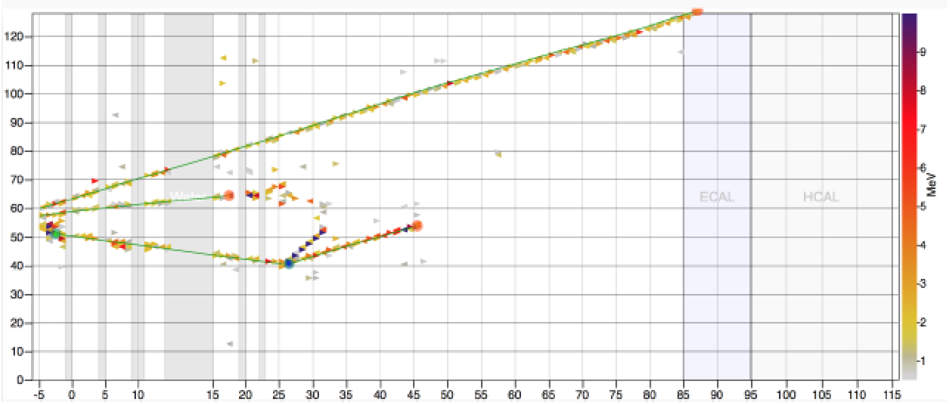


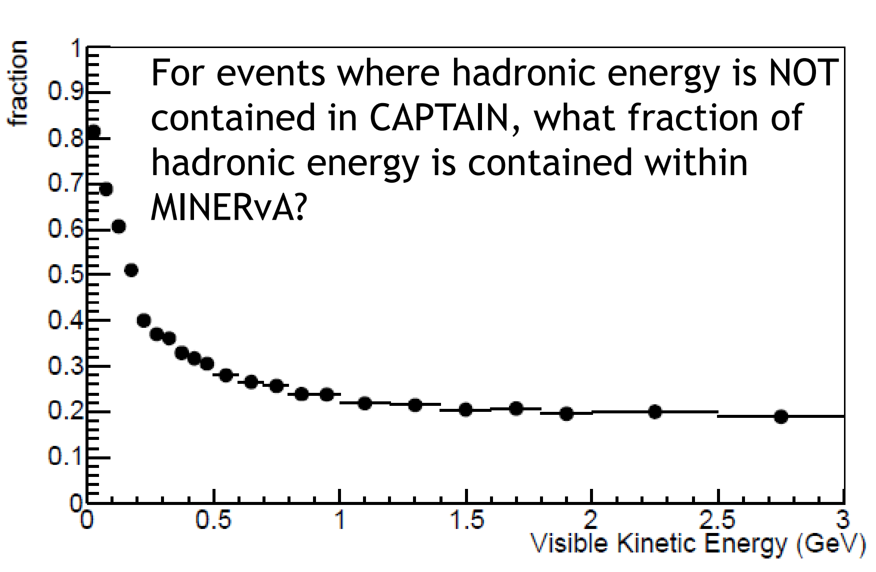


- Muon reconstruction by MINOS or MINERvA
  - Consider solid angle, minimum number of planes to form a track, etc
  - 64% of CC events will have muon reconstructed by MINOS or MINERvA (23% MINOS + 41% MINERvA)
- For remaining CC interactions, CAPTAIN will have some ability to tag muons that miss MINERvA or MINOS by looking for MIP-like tracks

Energy Containment

A neutrino interaction on LAr upstream of the MINERvA detector; the hadronic system is fully contained within MINERvA.





~10-15% of CC interactions will have the hadronic energy contained in CAPTAIN and have a muon reconstructed by MINOS or MINERvA.

MINERvA will be used as a hadronic calorimeter for events where final state particles exit CAPTAIN.

CAPTAIN-MINERvA Status

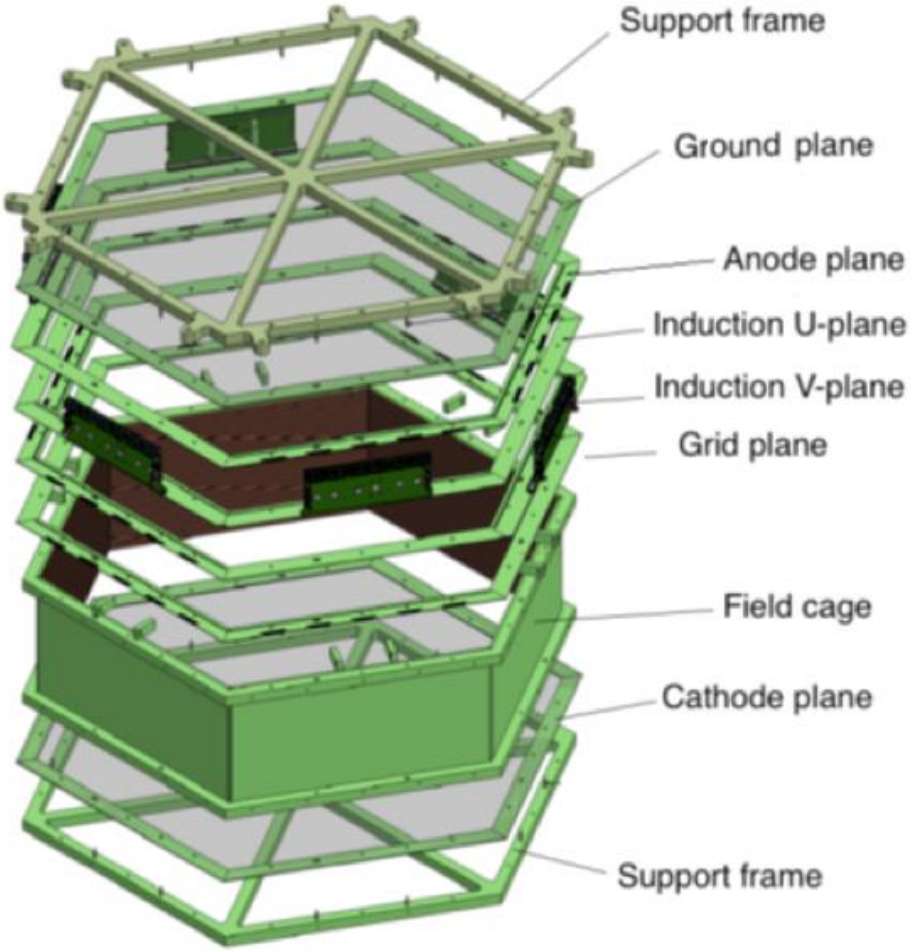
- Members of the current CAPTAIN and MINERvA collaborations will join together to form a single new collaboration (CAPTAIN-MINERvA)
- Presented LOI to the Fermilab PAC in January 2015
- Presented proposal to Fermilab PAC in June 2015
- Received Stage 1 approval from Fermilab Director in July 2015
- Submitted proposal for funding from DOE's Intermediate Neutrino Research Program in September 2015
- The CAPTAIN detector will be commissioned at a surface location at Fermilab beginning in ~2017, with preparations beginning in 2016
- Neutrino data with CAPTAIN-MINERvA beginning in ~2018
- One year (6×10^{20} POT) in neutrino mode + one year in antineutrino mode (contingent on NuMI schedule)

Summary

- CAPTAIN is a LArTPC designed to make measurements relevant for DUNE
- The prototype, Mini-CAPTAIN, has been commissioned and will be used for neutron measurements next year
- With CAPTAIN-MINERvA, we will measure neutrino-argon cross sections and test nuclear models
- **Please see our posters!**
  - **Babu Bhandari, "Neutron measurements in Mini-CAPTAIN"**
  - **Chuck Taylor, "Commissioning of the Primary CAPTAIN Detector"**
  - **Jieun Yoo, "The CAPTAIN-MINERvA Experiment"**

Backup

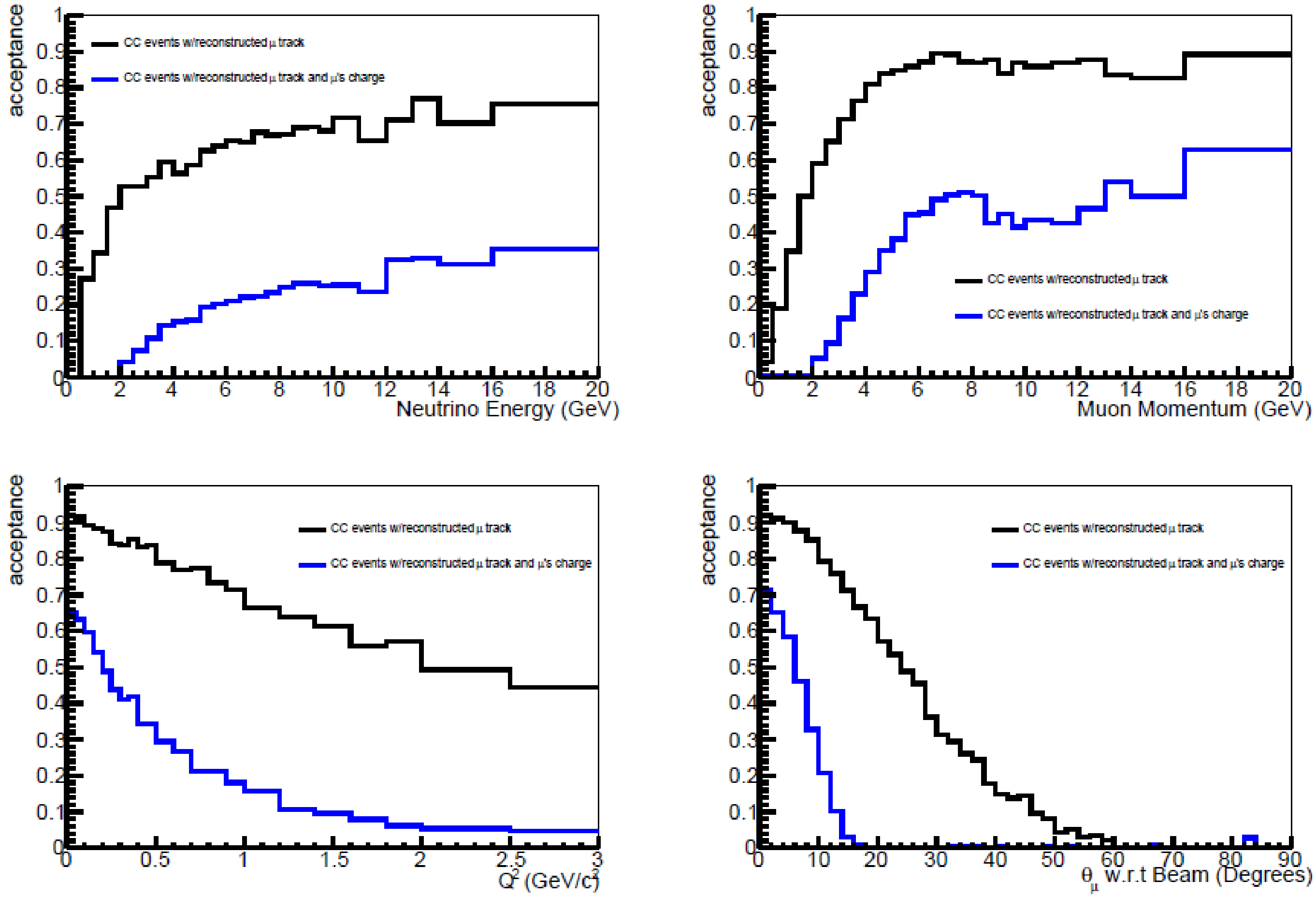
CAPTAIN TPC


Support frame
Ground plane
Anode plane
Induction U-plane
Induction V-plane
Grid plane
Field cage
Cathode plane
Support frame

Neutrinos in DUNE

- Neutrino interaction data are needed to constrain the models of nuclear effects that will be used for true-to-visible energy conversions (important because the oscillation probability is energy-dependent), predictions of signal and background rates in the far detector based on near detector data, etc.
  - Particularly important: an understanding of the effects of the nuclear environment on underlying neutrino-nucleon interactions
- Interaction models used in neutrino event generators are constrained by:
  - Charged lepton data for the vector contribution to neutrino interactions
  - Neutrino data for the axial contribution and multi-nucleon initial states
  - Pion scattering data for final state interactions
- The models are mostly based on nuclear targets other than argon
- There is very little neutrino-argon data in the neutrino energy range relevant for DUNE. A high-statistics neutrino-argon data set can be used to
  - Test the extrapolations of the models for different nuclei
  - Improve the models
  - Test energy-dependence of models

Muon Acceptance



CC events with muon reconstructed (MINOS or MINERvA)

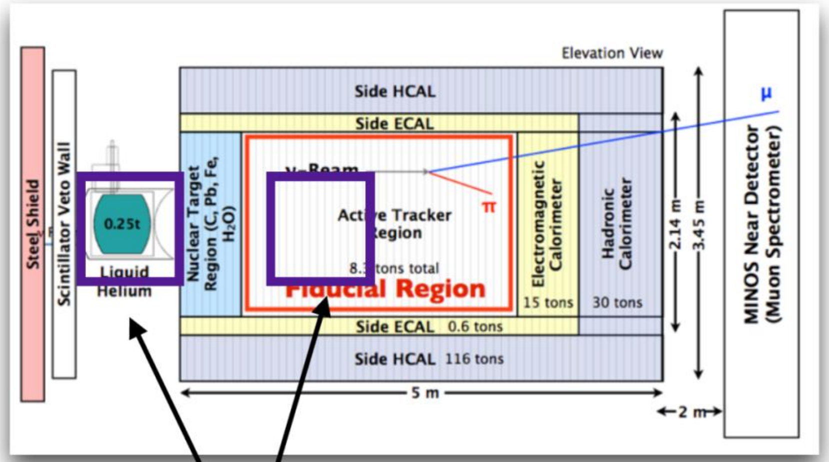
CC events with muon reconstructed by MINOS

Pulling out extra MINERvA modules

- In order to remove MINERvA's helium target and install CAPTAIN, we estimate 1.5 months of downtime when MINERvA cannot take data.
- In order to remove enough modules to remove the nuclear target region and half the tracker region, it would take another 3 months.
- For a 1-year run or longer it makes sense to take the extra time, if MINERvA has already received its 12E20POT in antineutrino running

MINOS/MINERvA Hall

unscaled



Two posible locations
a) at the position of the He target
b) at the module 30 (removing half of the tracker)

Channel	ratio
CCQE-like	1.33
CC 1 π^+	1.51
CC 1 π^0	1.58