First Measurement of the Neutron Cross Section on Liquid Argon Between 100 and 800 MeV

Sergey Martynenko
Stony Brook University
for the CAPTAIN collaboration

DPF
07-29-19

CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

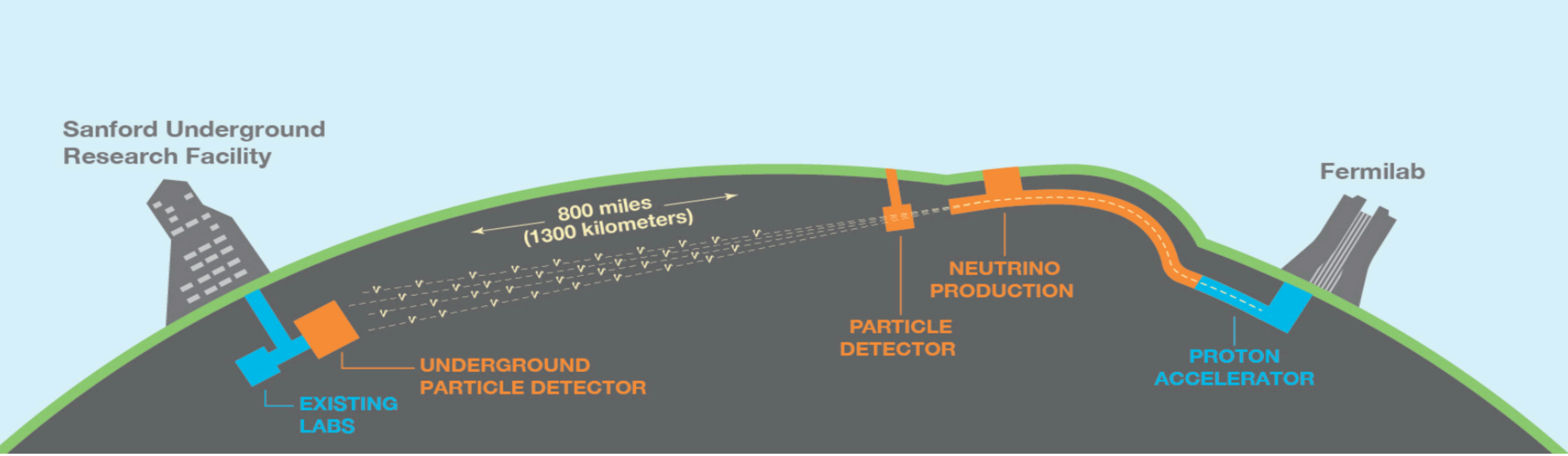
Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

DUNE: Deep Underground Neutrino Experiment

Goals:
- ν oscillation parameters and CP-violation phase;
- ν mass Hierarchy;

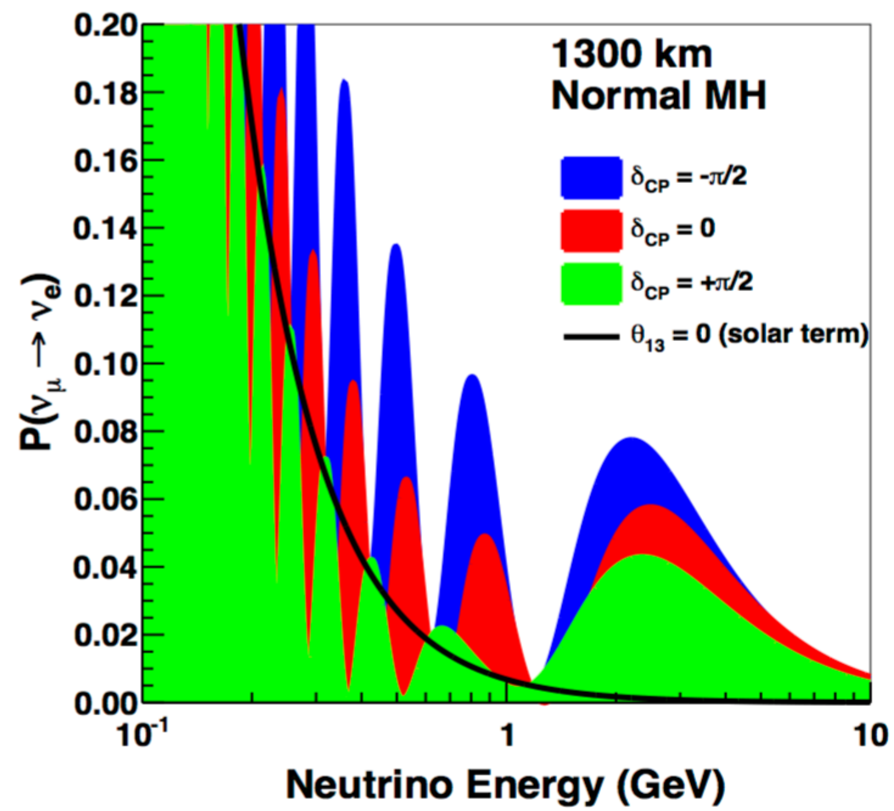
Facility:
- Neutrinos will be produced at the beam line in Fermilab;
- Large Argon detector will be placed 1300km away from the beam in Sanford lab;

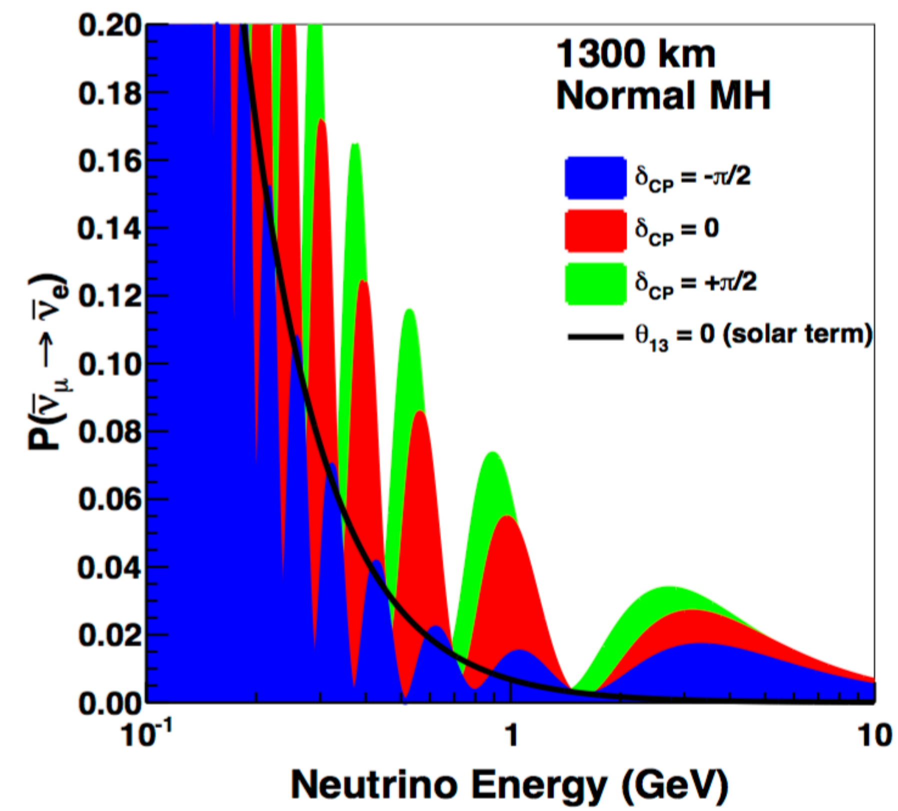


Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 1: The LBNF and DUNE Projects // DUNE Collaboration // arXiv:1601.05471

DUNE Energies

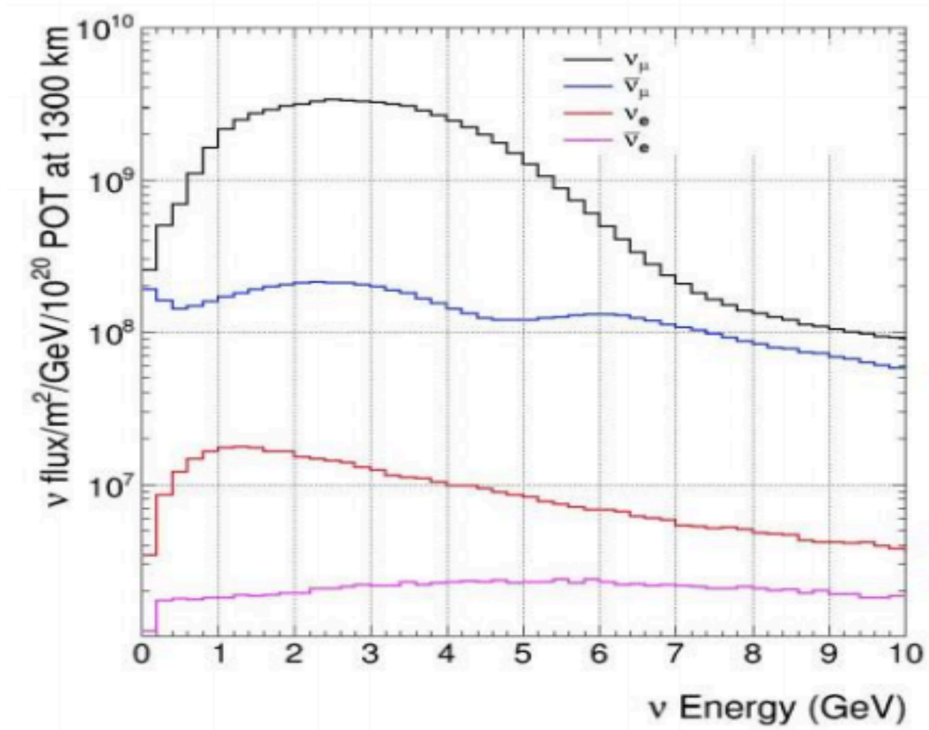
- The experiment will measure neutrino interactions with energies more than ~500MeV;
- Small shift in neutrino energy results in big change in neutrino oscillation probability;
- Incoming neutrino energy must be carefully reconstructed.

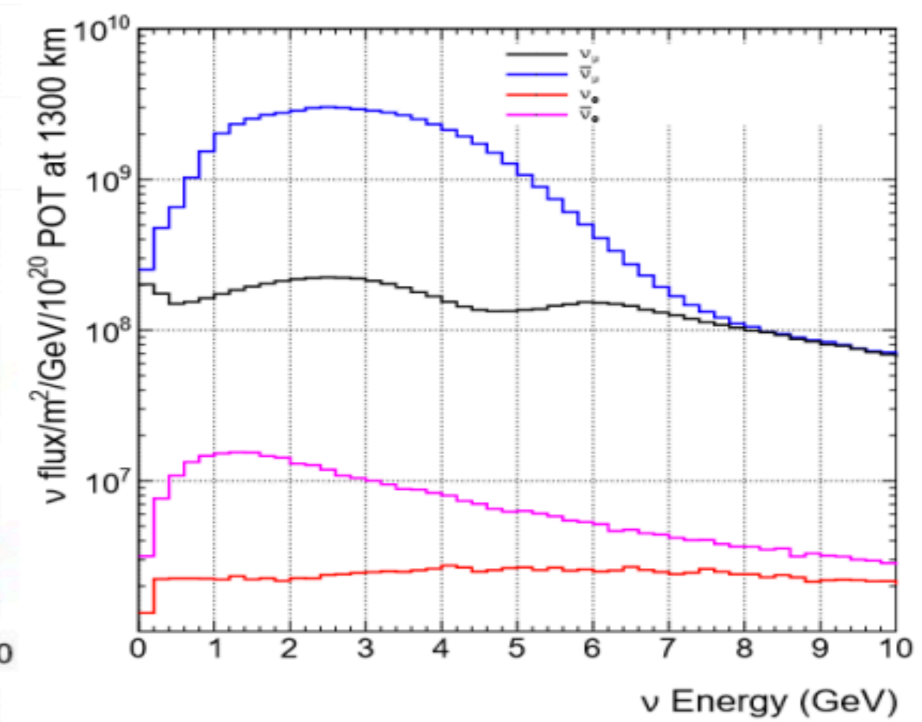




neutrino mode

antineutrino mode





Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The LBNF and DUNE Projects // DUNE Collaboration // arXiv:1512.06148

Sergey Martynenko

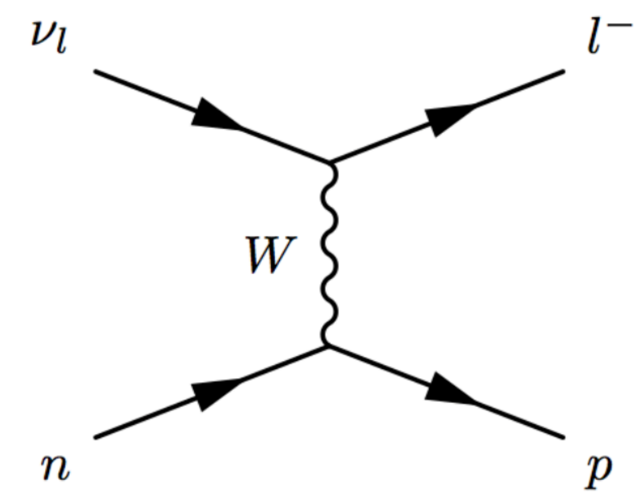
Neutrino interactions

- Neutrino can’t be seen in the detector by itself. Thus, energy reconstruction comes from kinematics of outcome particles from neutrino interactions.

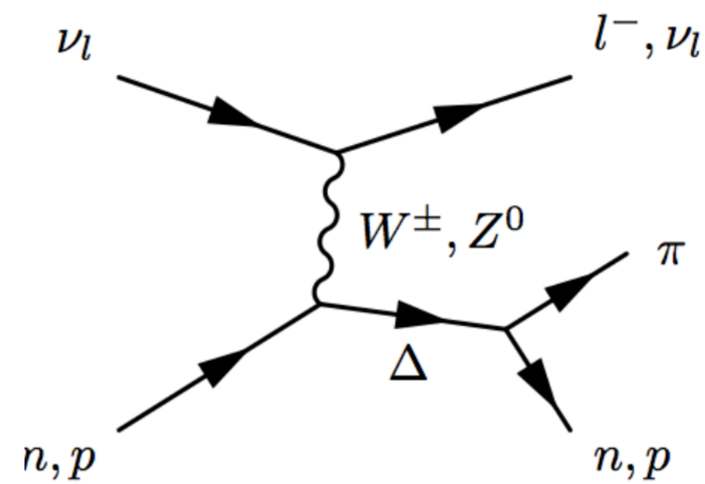
- Interactions:
    - The dominant charged current process for sub-GeV neutrino interactions(A) is the quasi-elastic mode (CCQE) interaction;
    - Resonant production (B). The W boson excites a Δ resonance of the nucleon, which subsequently decays to a nucleon and a pion;
    - Deep inelastic scattering (DIS) processes (C). It happens for neutrinos of higher energies (>=2.5GeV). There is multi pion production in final state.

- Summary:
    - In the DUNE energy window covers all types of neutrino interactions. Thus, we should understand all of them to perform oscillation analysis. The last two reaction types produce significant number of neutrons in final state.

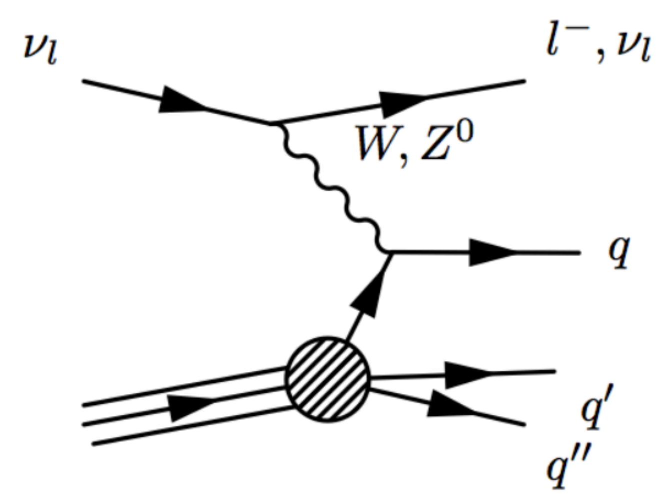
A)



B)

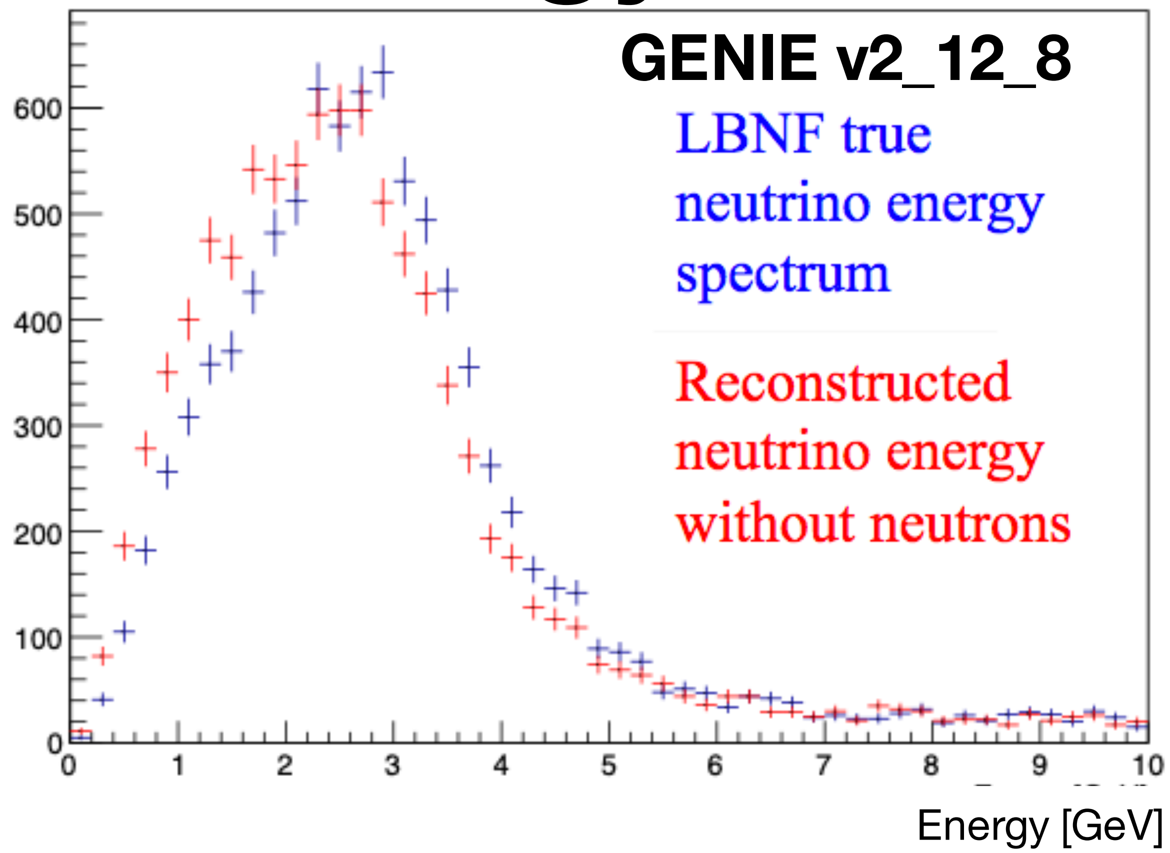


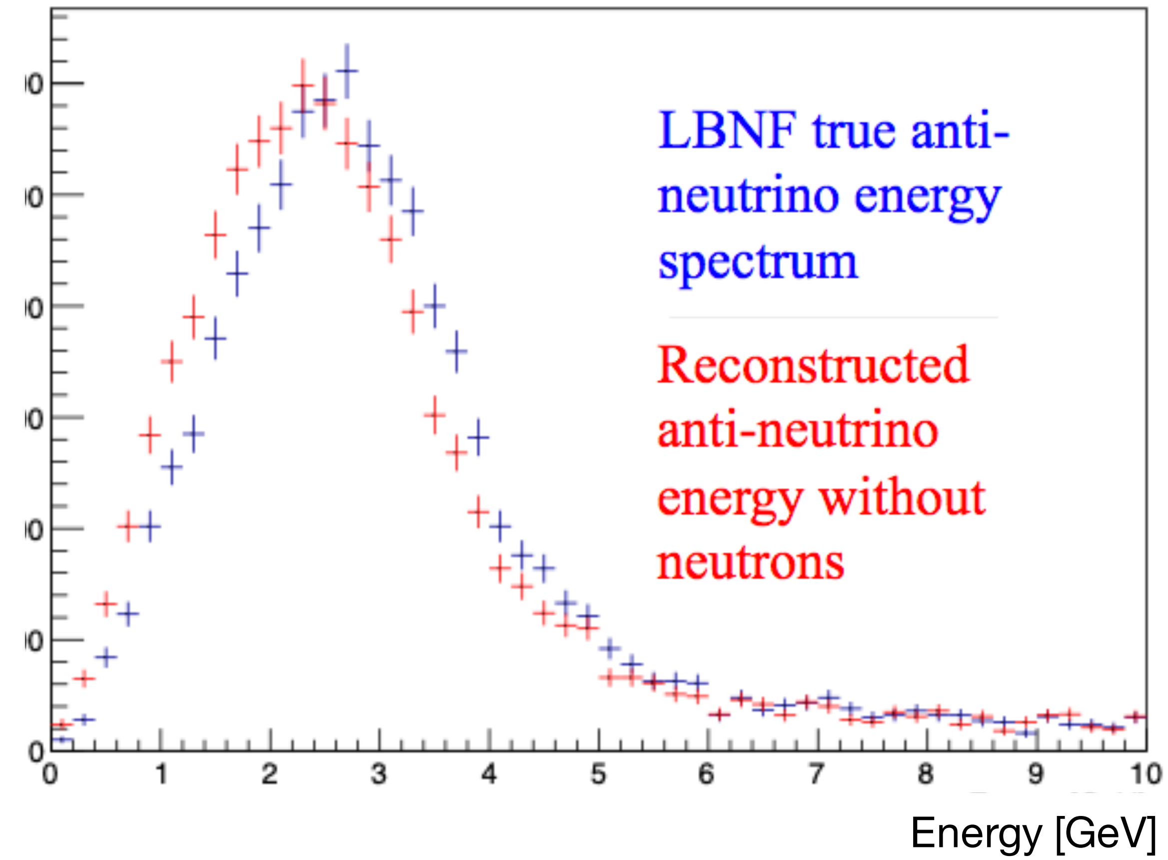
C)



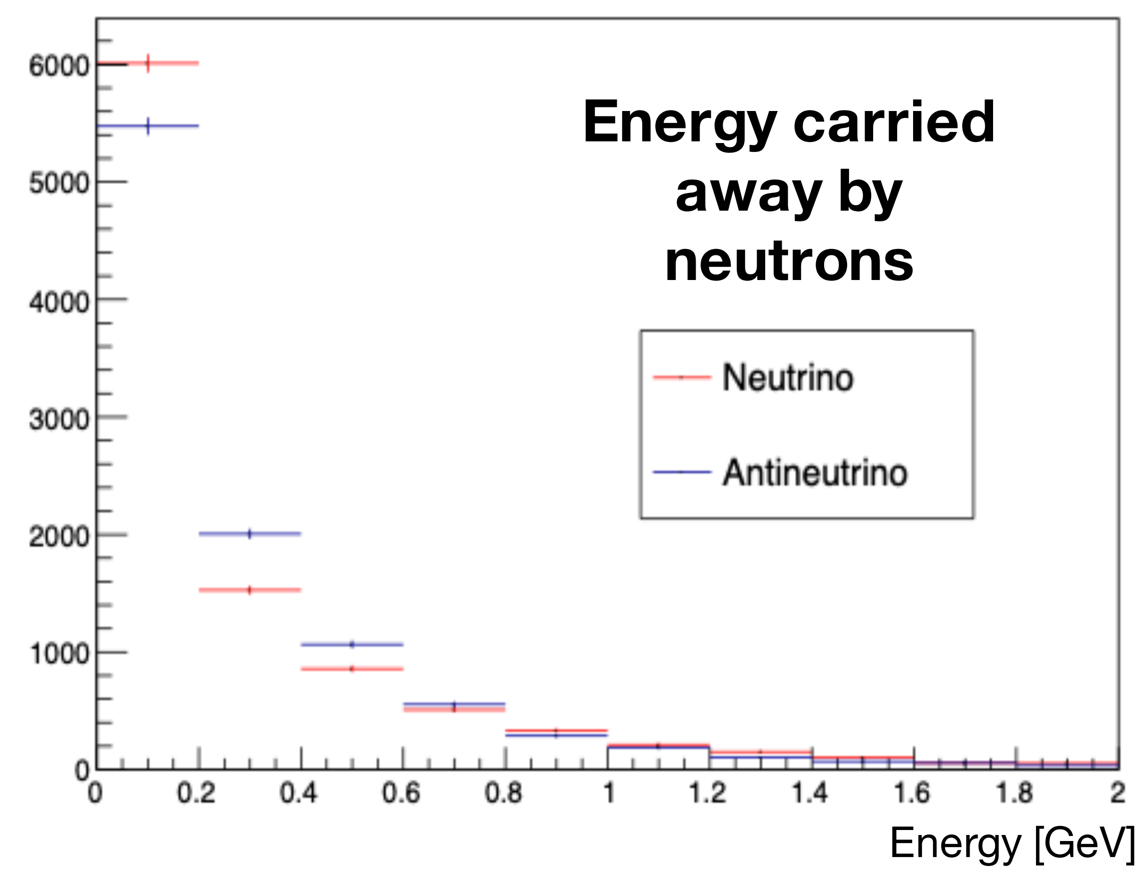
From eV to EeV: Neutrino Cross Sections Across Energy Scales // J.A. Formaggio, G.P. Zeller // Rev. Mod. Phys. 84, 1307 (2012)

Energy reconstruction in DUNE

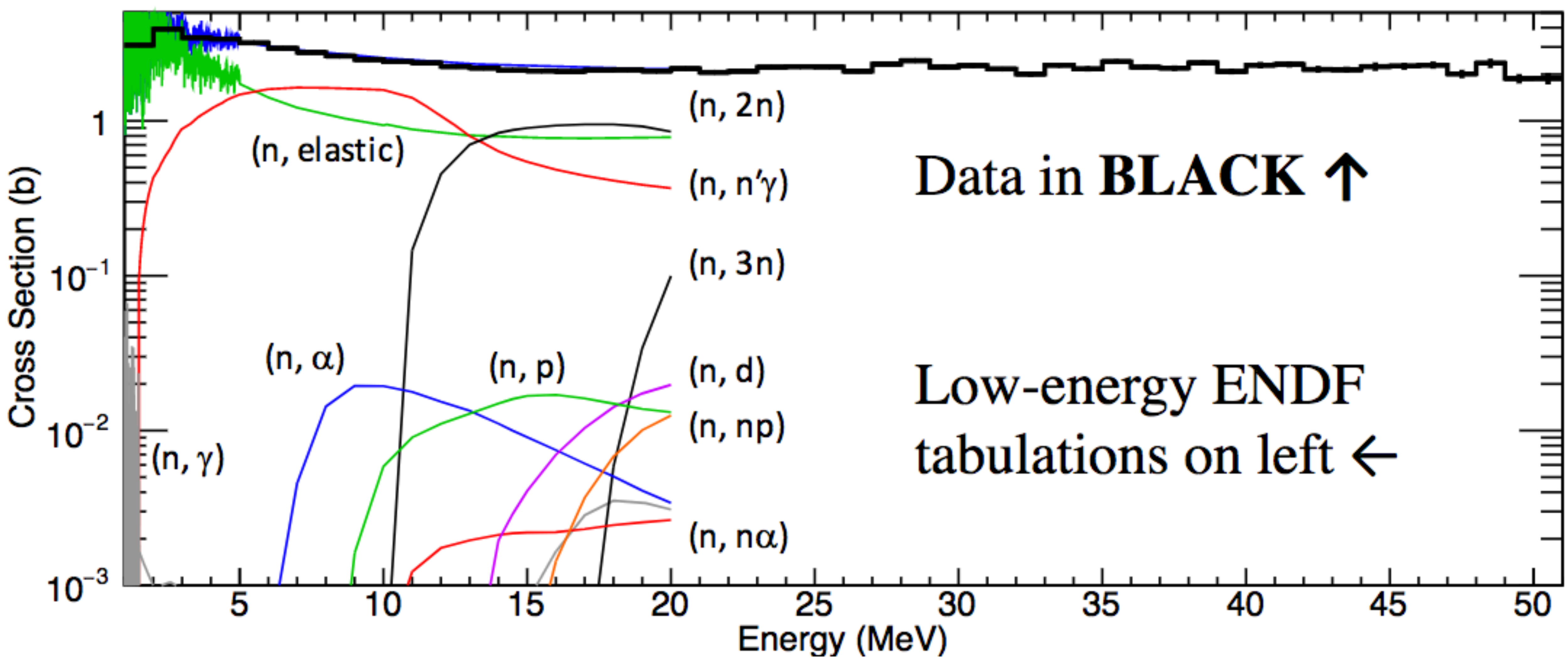




- Neutrons carry considerable energy that escapes detection, thus provide a significant uncertainty to neutrino energy reconstruction.
- Models used to estimate missing energy, including neutrons, have large unconstrained uncertainties.
- Different amount of energy carried by neutrinos and antineutrinos.
- Neutron-Argon cross section data is only published up to 50 MeV of kinetic energy.



Neutron cross section on LAr data available



- Data is sparse at DUNE energies and existing data is from R.R. Winters et al., Phys. Rev. C43, 492 (1991) – www.nndc.bnl.gov

CAPTAIN Physics Program

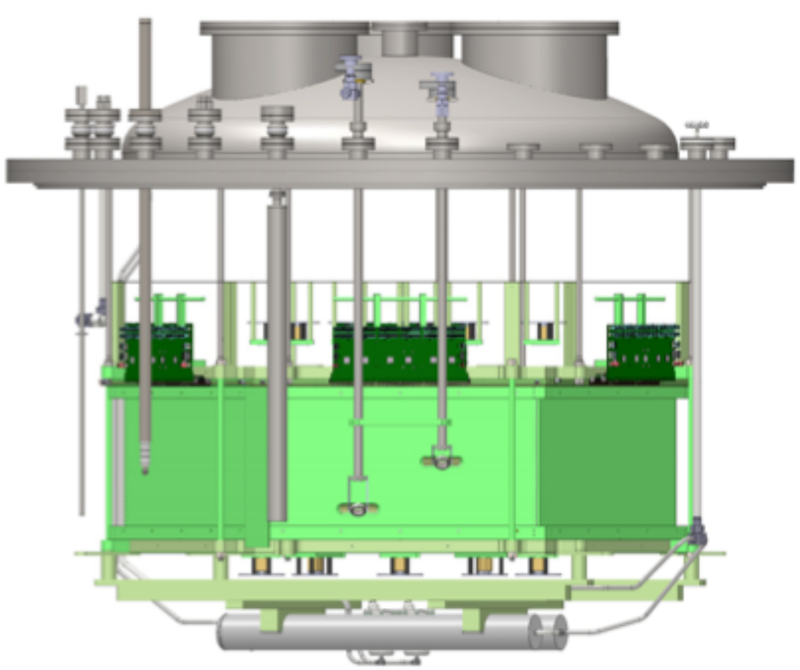
- CAPTAIN is collaboration with the goal to make measurements relevant for the DUNE experiment
- Medium-energy neutrino physics ~100 MeV to 5 GeV~ (Neutron Beam 50MeV to 800MeV):
  - Measure neutron interactions and event signatures (e.g. pion production) to allow us to constrain number and energy of emitted neutrons in neutrino interactions (at DUNE, mean neutron K.E. from the LBNF beam ~ 400 MeV)
  - Measure higher-energy neutron-induced processes that could be backgrounds to ν_e appearance e.g. $^{40}Ar(n,\pi_0)^{40}Ar(*)$
- Low-energy neutrino physics ~below 100 MeV~ (Neutrino Beam):
  - Measure the neutrino CC and NC cross-sections on Argon in the same energy regime as supernova neutrinos
  - Measure the correlation between true neutrino energy and visible energy for events of supernova-neutrino energies

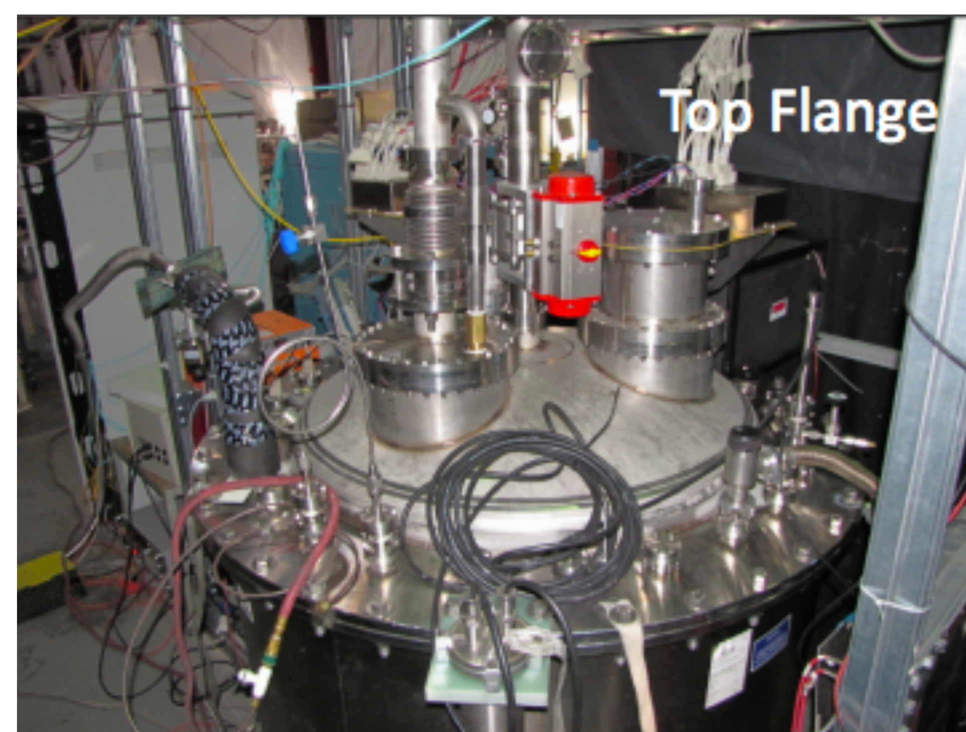
Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Mini-CAPTAIN Detector

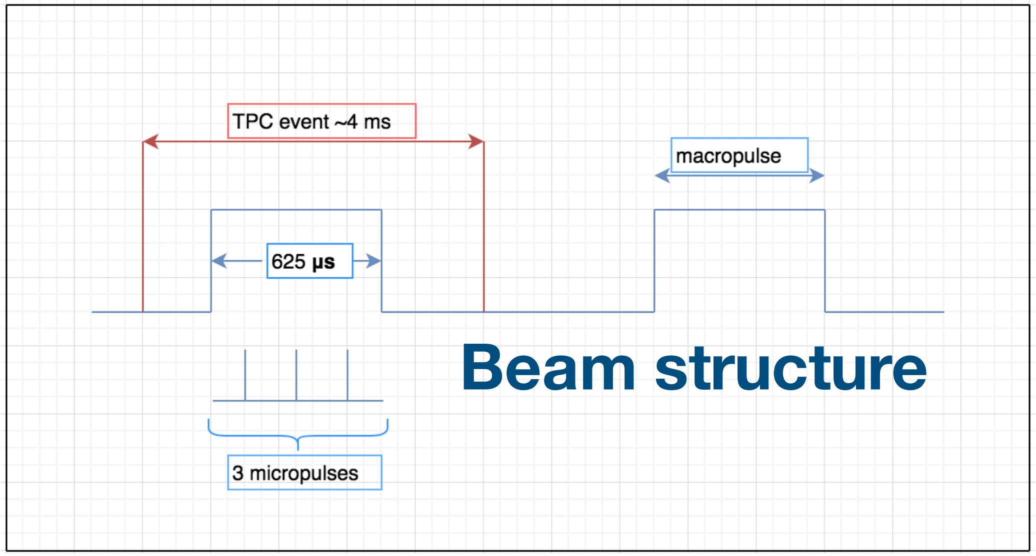
- 400 kg instrumented hexagonal TPC with 32 cm drift, 50 cm apothem
- ~1000 channels, 3 mm wire pitch
- 21 x 6 cm^2 PMT light detection system
- Same cold electronics and electronics chain as MicroBooNE

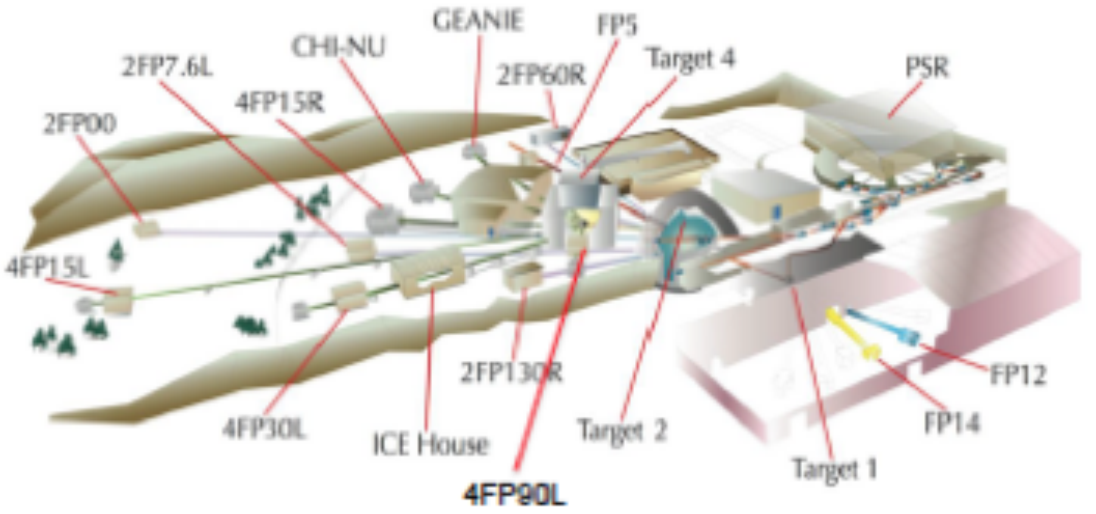


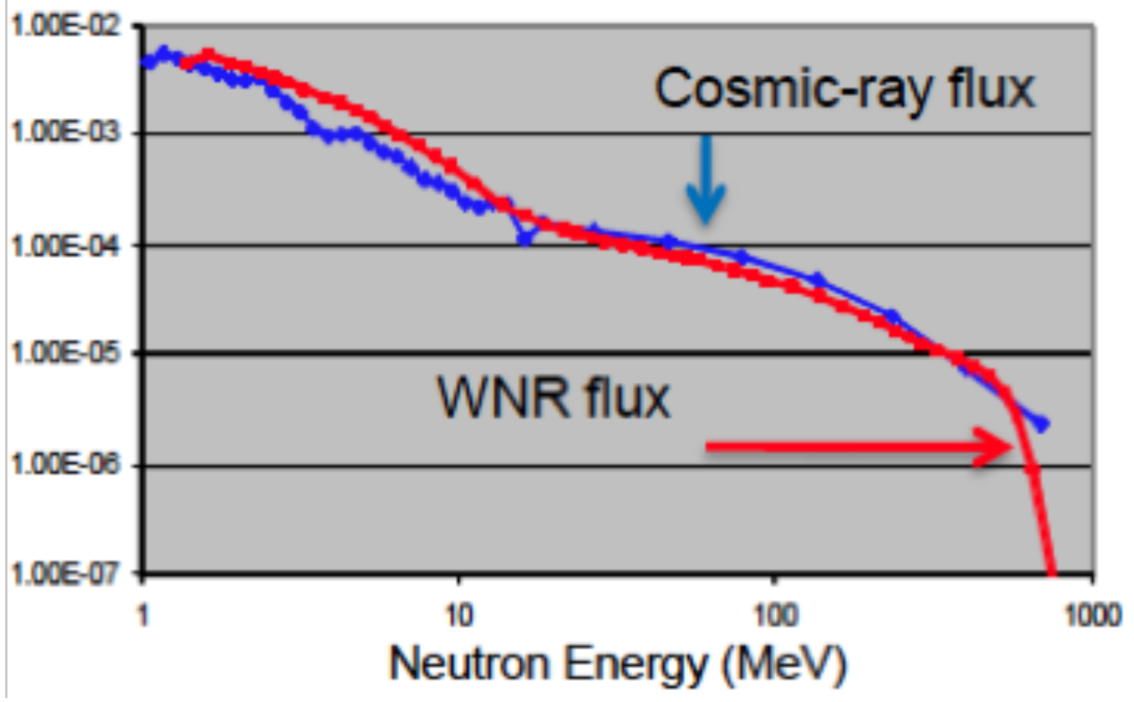


Neutron beam at LANSCE

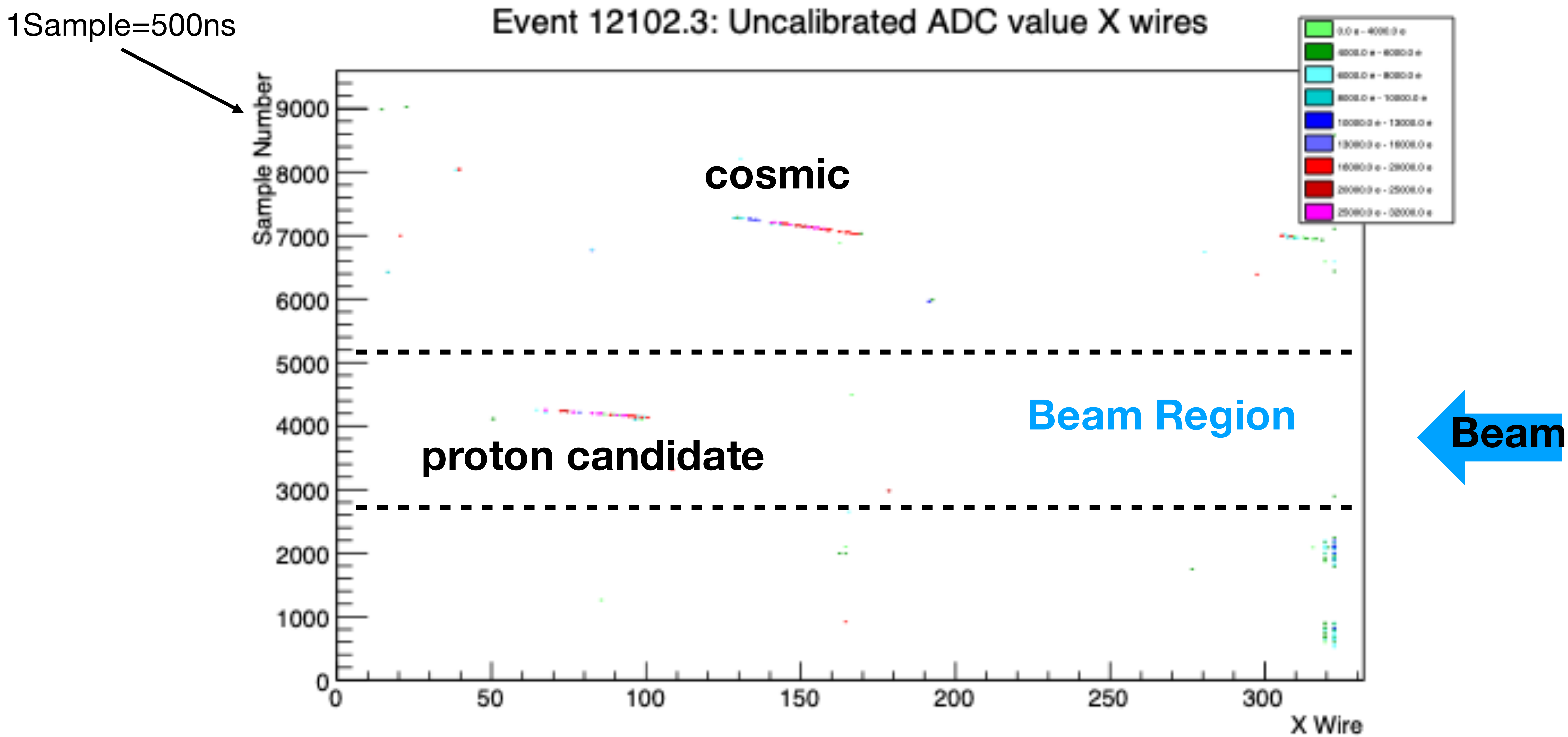
- Los Alamos Neutron Science Center WNR facility provides a high flux neutron beam with a broad energy spectrum similar to the cosmic-ray spectrum at high altitude;
- Neutron Energy spectrum covers most of neutron energies necessary for DUNE;
- Nominal time structure of the beam: micro pulses(100ps width) 1.8 μs apart within a 625 μs long macro pulse;
- CAPTAIN special run of 3 micro pulses 200 μs apart per macro pulse.







Tracks from 2017 run

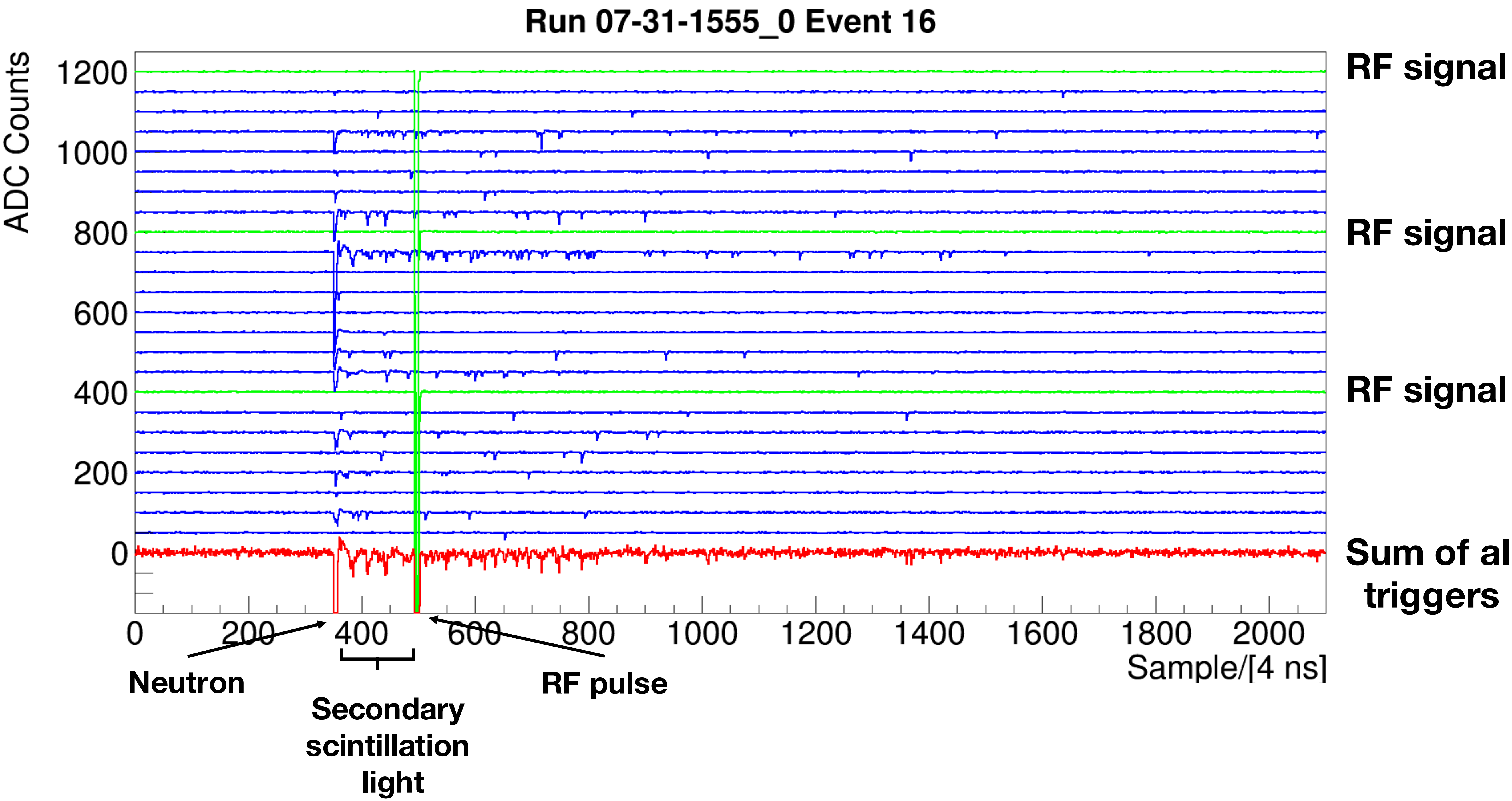


Neutron event from low intensity run

- Full TPC and PDS used in the 2017 Physics Run : July 23 – Aug 05
- Special low intensity run taken on July 31st.

Sergey Martynenko

Photon triggers on PDS



- Triggering event during our low intensity run
- Each blue line corresponds to a single PMT

Outline

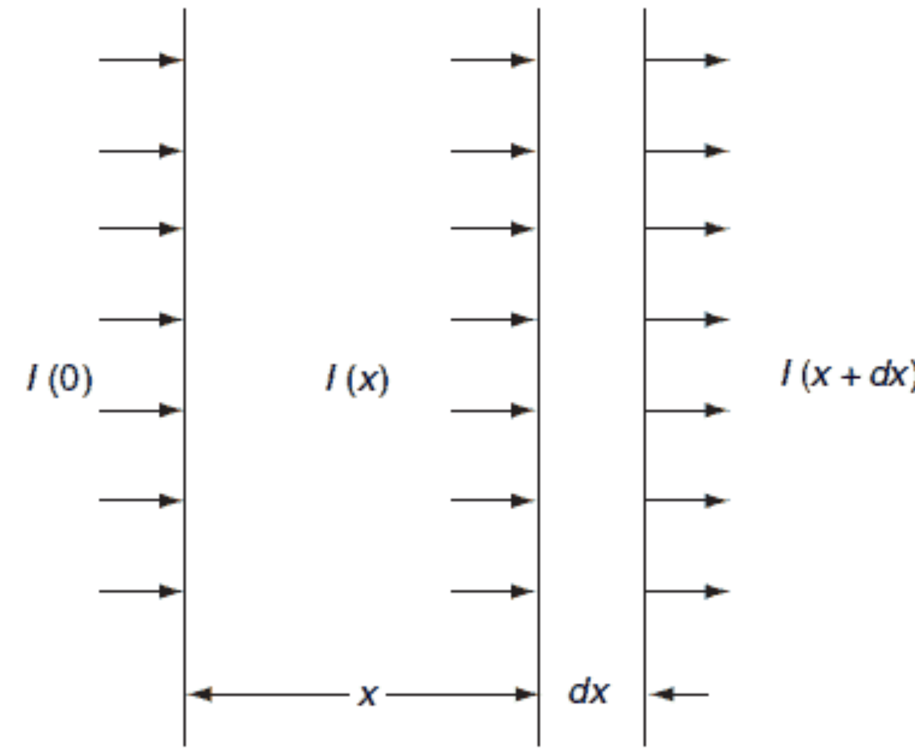
- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Neutron kinetic energy

- The photon detection system provides an independent measure of neutron kinetic energy for each neutron based on time-of-flight(ToF) measurements;
- TPC and PDS data stored in separate streams and have been matched;
- For every reconstructed track we can assign a kinetic energy for the neutron that created it.

Measuring the neutron cross section

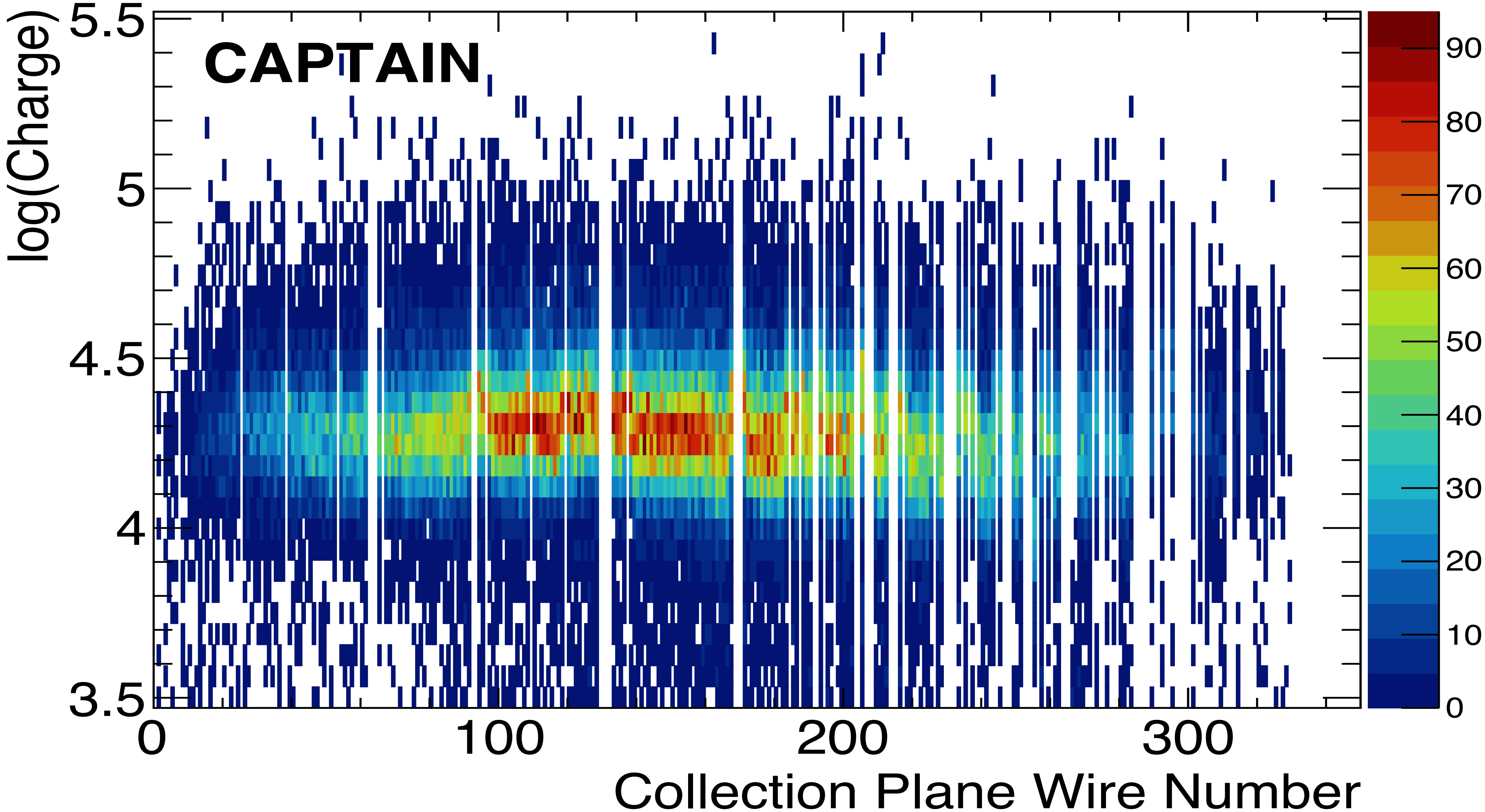
- Survival probability of neutrons decreases exponentially as a function of depth in detector and only depends on cross section and target density;
- Fit an exponential to the starting positions of the tracks to get the cross section;
- Bin data in energy bins based on neutron ToF.



$$I(x) = I_0 e^{-N\sigma x}$$

σ = Total Cross Section

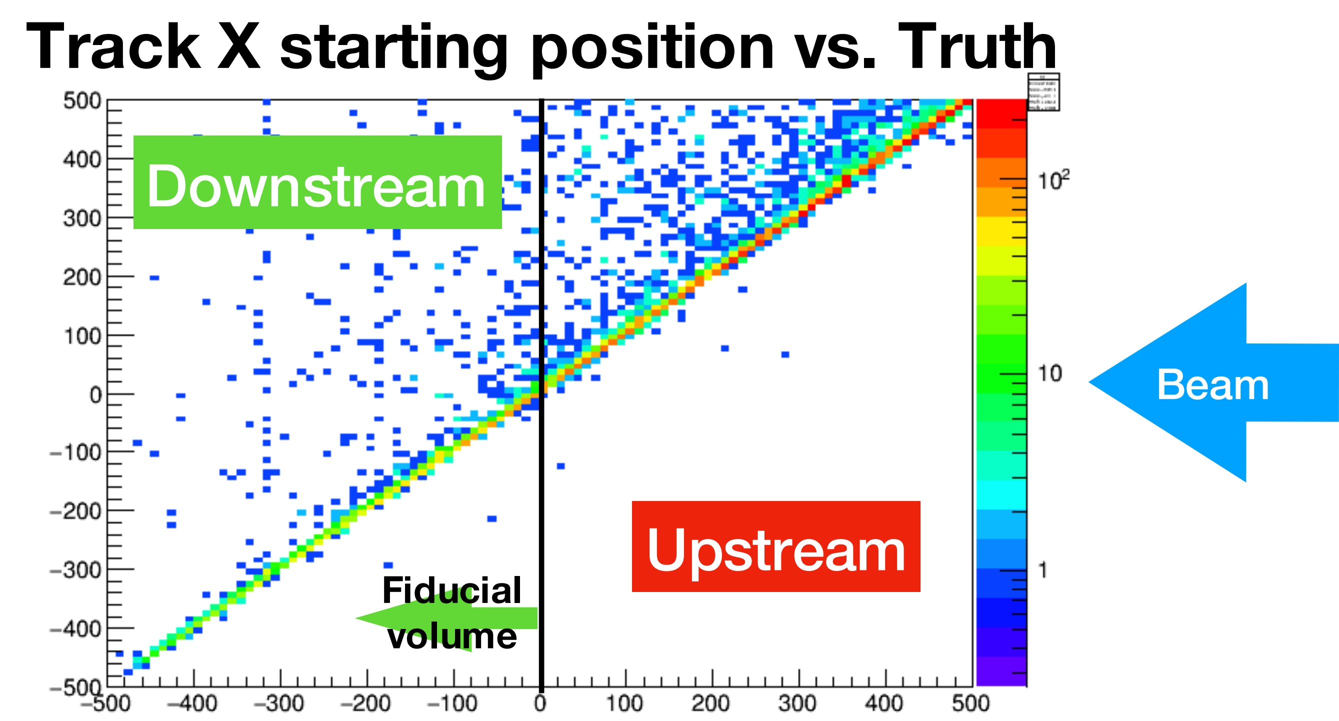
Signal Uniformity

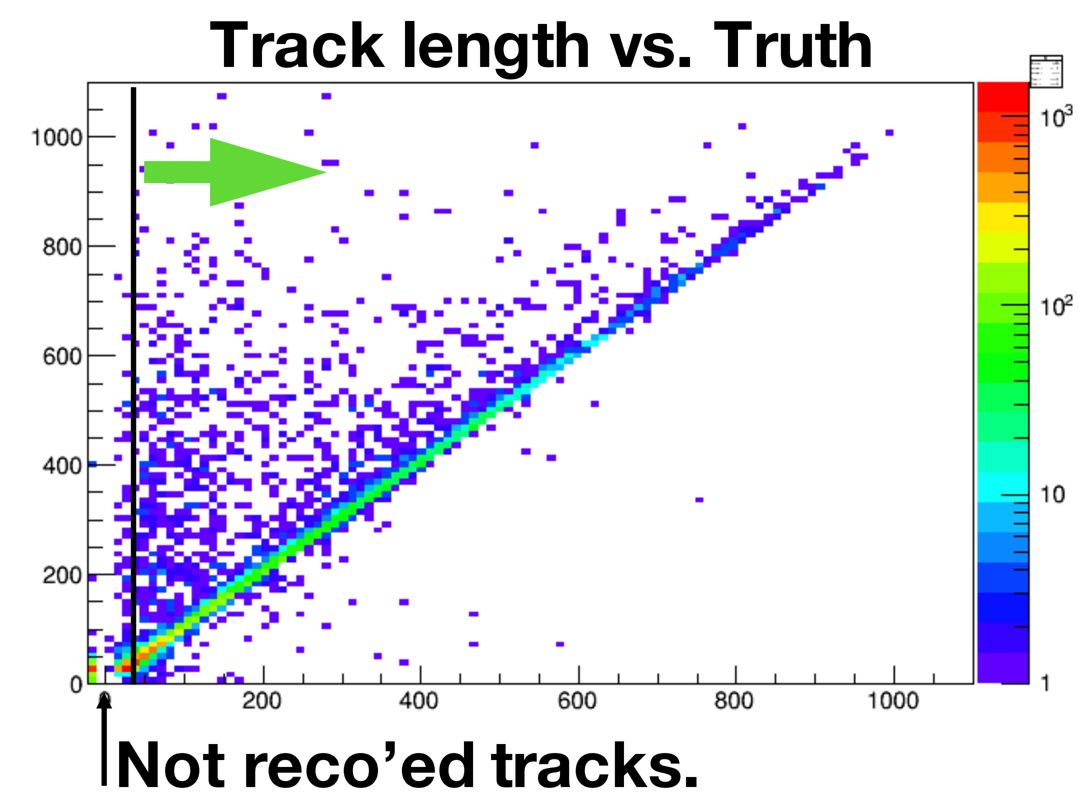


- For Exponential hypothesis to work the signal should be uniform across all the detector
- Many dead wires seen upstream of the detector
- Only consider tracks in the downstream of the detector

Track Reconstruction

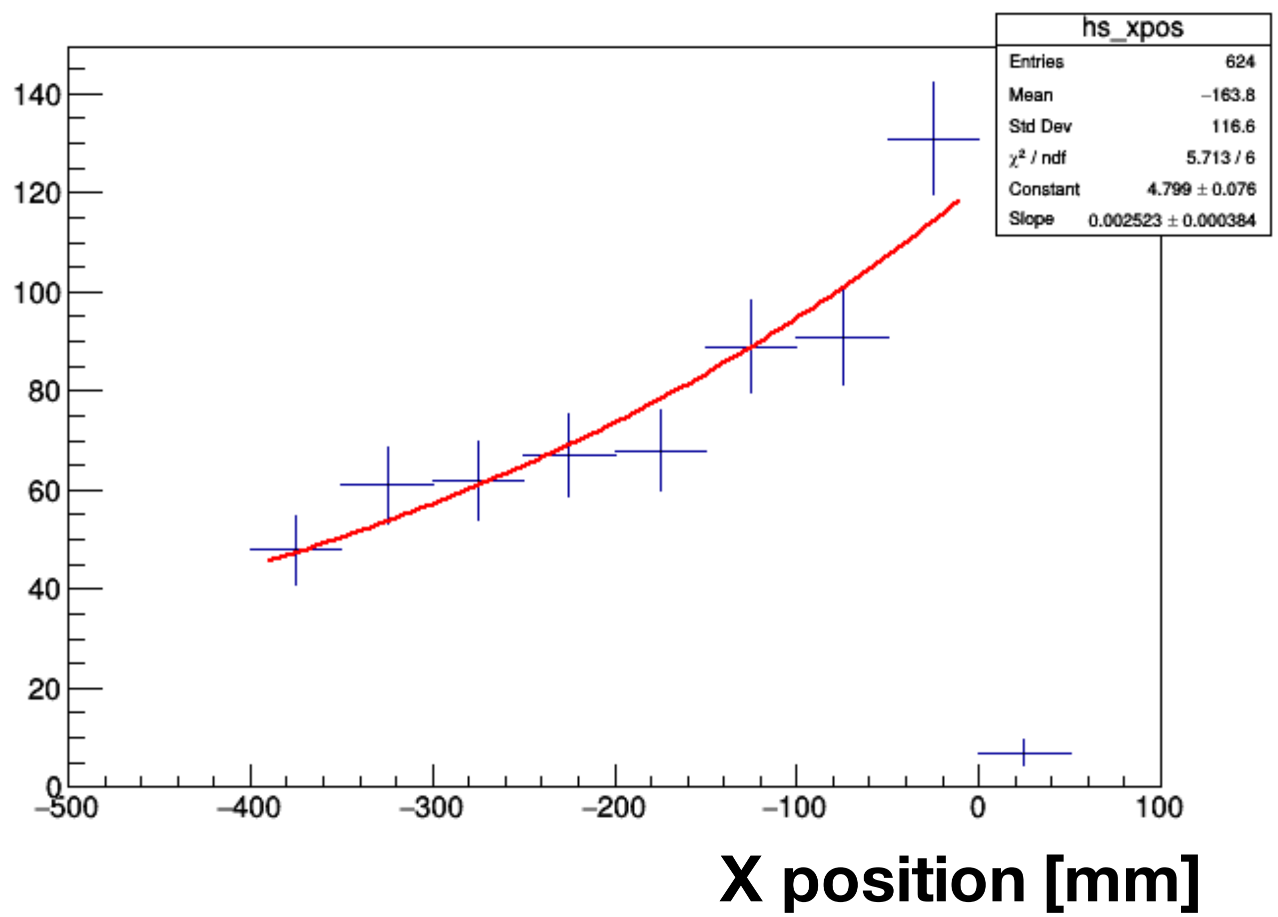
- We are considering only using the downstream of the detector to avoid the wire inefficient seen upstream:
    - Further studies are under way to understand the effect of this behavior;
- Very short tracks are not reconstructed by our algorithm:
    - Cut tracks shorter than 15 mm;
    - No tracks below 100 MeV.



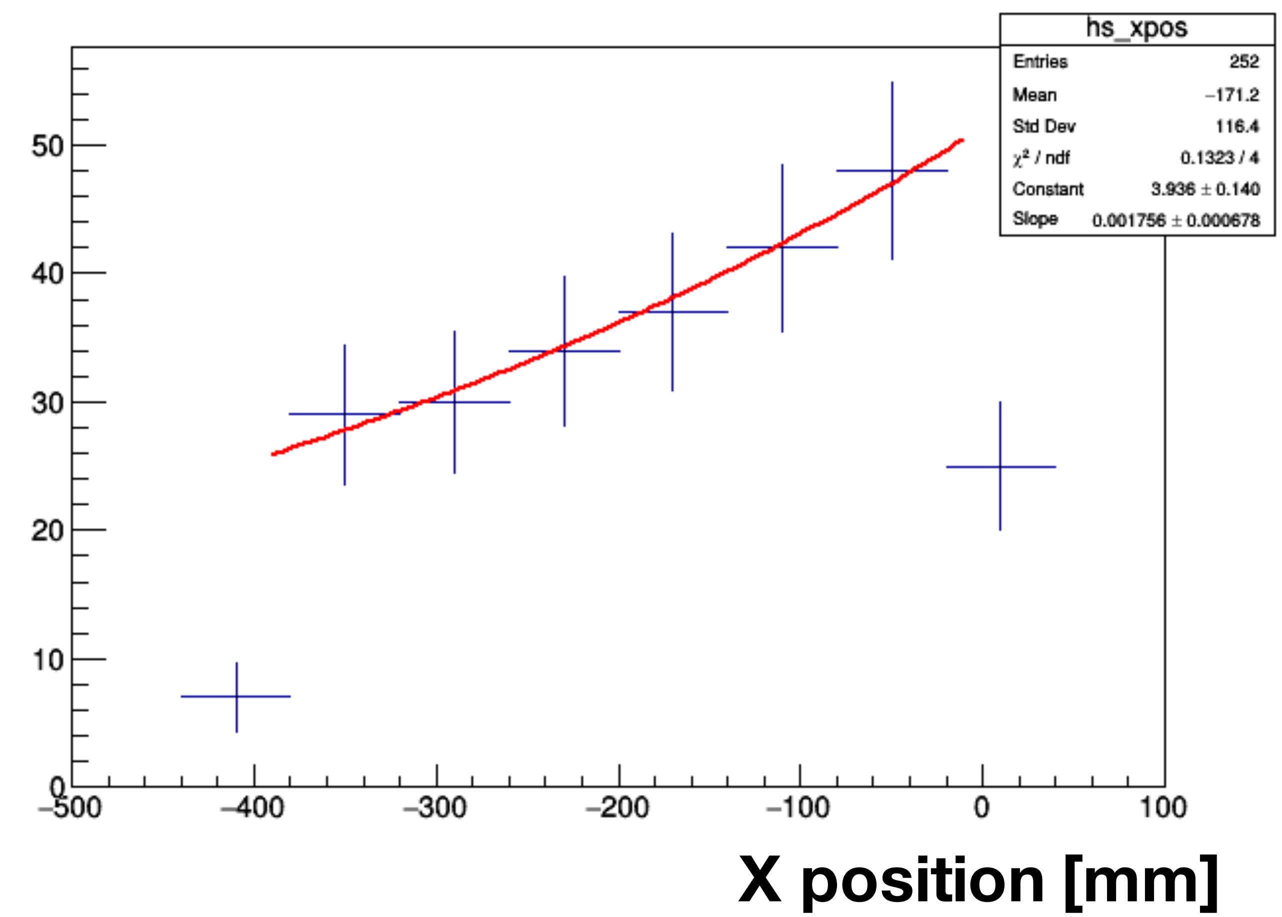


Cross section fit

481-674 MeV

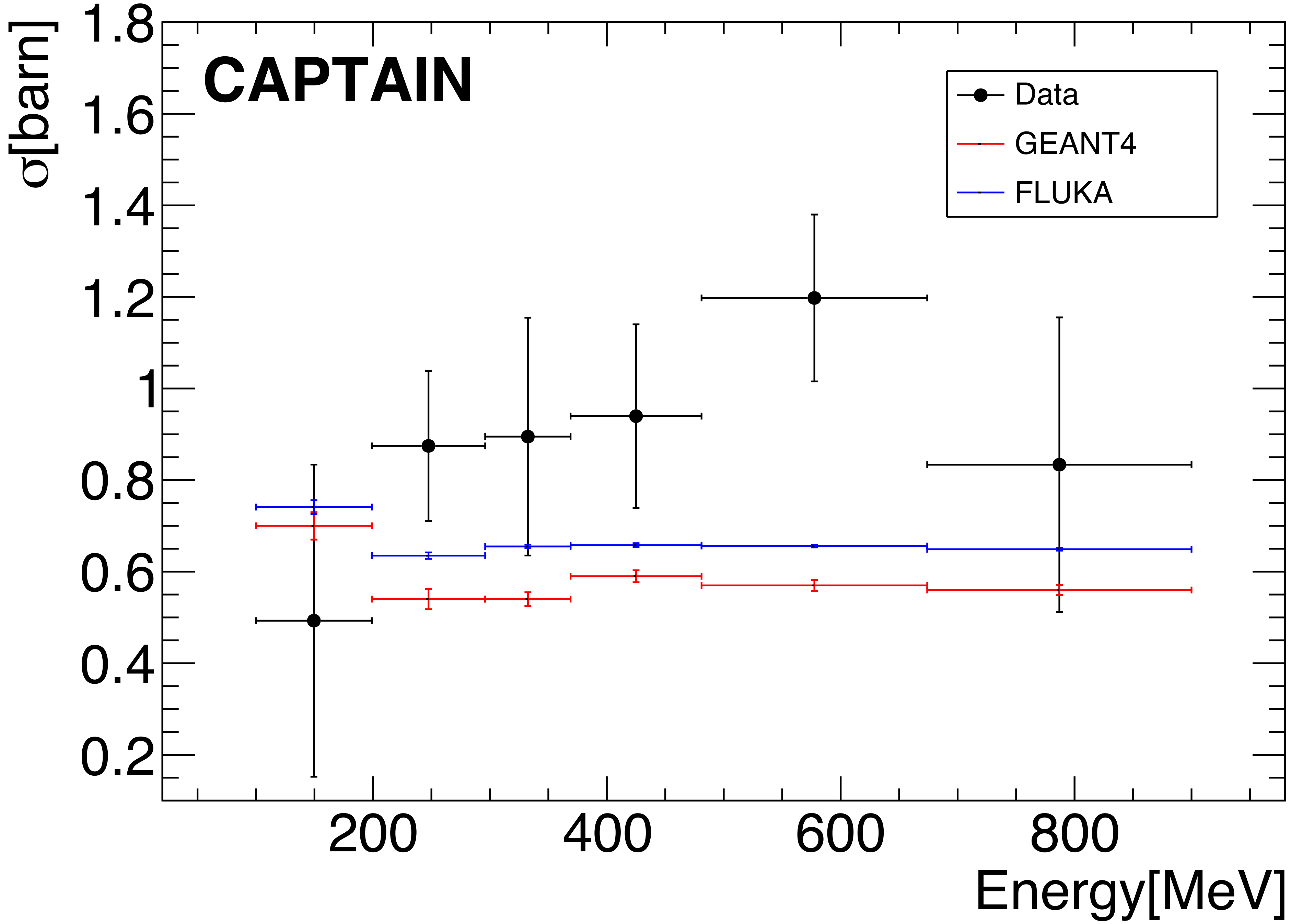


674-900 MeV



- For a given energy, the total cross section is proportional to the exponential coefficient of the neutron flux depletion rate for a given topology
- Exponential fits with binning based on ToF

Neutron cross sections



GEANT4 and FLUKA data was obtained by applying our analysis technique to neutron beam, simulated using each of these packages.

Neutron cross sections

Energy range [MeV]	Cross Section [barns]	χ^2/ndof	Number of tracks
100-199	0.49±0.34	1.48/3	264
199-296	0.88±0.16	11.81/7	536
296-369	0.89±0.26	4.739/5	329
369-481	0.94±0.20	8.262/6	413
481-674	1.20±0.18	5.713/6	624
674-900	0.83±0.32	0.1323/4	252

- Dominant systematic uncertainty caused by neutron double scattering estimated to be 10%
- Cross section energy-weighted average is 0.91±0.10(stat)±0.09(sys) barns

Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Present status: Neutron measurements with Mini-CAPTAIN

- Absolute cross section result paper accepted to PRL;
- Physics analyses ongoing with neutron data taken at WNR summer 2017:
  - Extend Data sample by adding upstream part of the detector;
  - More data exist from regular neutron run (many micro pulses per macro pulse);
  - Calculate differential cross sections for protons and pions.

Summary

- Understanding neutron interactions with Argon is crucial for an accurate reconstruction of neutrino energy.
  - Specially important for the measurements that DUNE wants to do.
- Mini-CAPTAIN collected neutron data in summer 2017;
- Total neutron cross section measurement is obtained.

CAPTAIN collaboration (several people are missing)

- Picture from the physics run summer 2017 in front of MiniCAPTAIN in the WNR flight path at LANSCE.

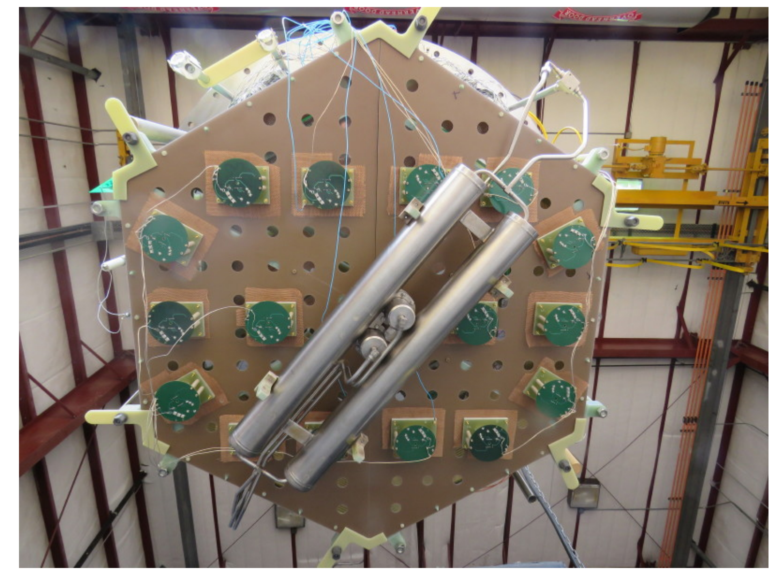
BACKUP

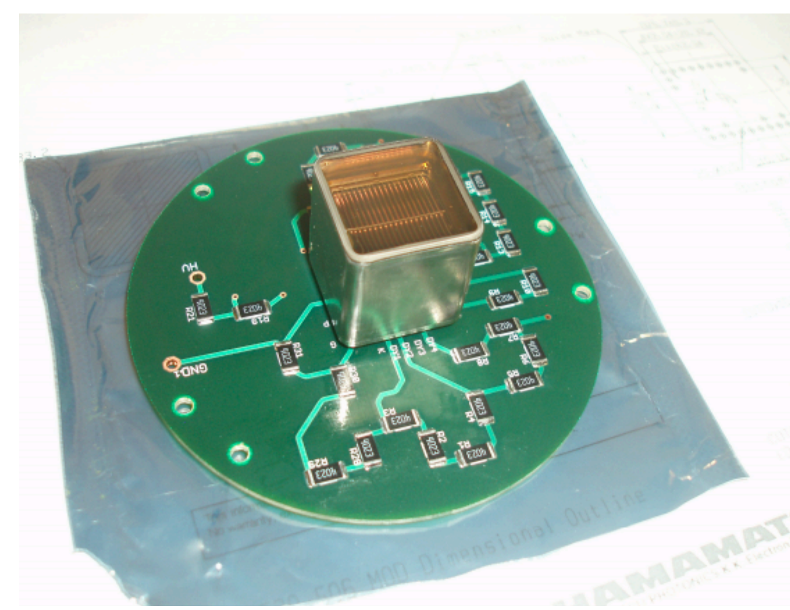
CAPTAIN collaboration

- University of Alabama: Ion Stancu
- LBL: Craig Tull
- BNL: Hucheng Chen, Veljko Radeka, Craig Thorn
- UC Davis: Daine Danielson, Steven Gardiner, Emilja Pantic, Robert Svoboda
- UC Irvine: Jianming Bian, Scott Locke, Michael Smy
- UC Los Angeles: David Cline, Hanguo Wang
- UC San Diego: George Fuller
- University of Hawaii: Jelena Maricic, Marc Rosen, Yujing Sun
- University of Houston: Lisa Whitehead Koerner
- LANL: Elena Guardincerri, Nicolas Kamp, David Lee, William Louis, Geoff Mills, Jacqueline Mirabal-Martinez, Jason Medina, John Ramsey, Keith Rielage, Constantine Sinnis, Walter Sondheim, Charles Taylor, Richard Van de Water, Peter Madigan, Qiuguang Liu
- University of New Mexico: Michael Gold, Alexandre Mills, Brad Philipbar
- New Mexico State: Robert Cooper
- University of Pennsylvania: Connor Callahan, Jorge Chaves, Shannon Glavin, Avery Karlin, Christopher Mauger
- SUNY Stony Brook: Neha Dokania, Clark McGrew, Sergey Martynenko, Chiaki Yanagisawa

Photon Detection System

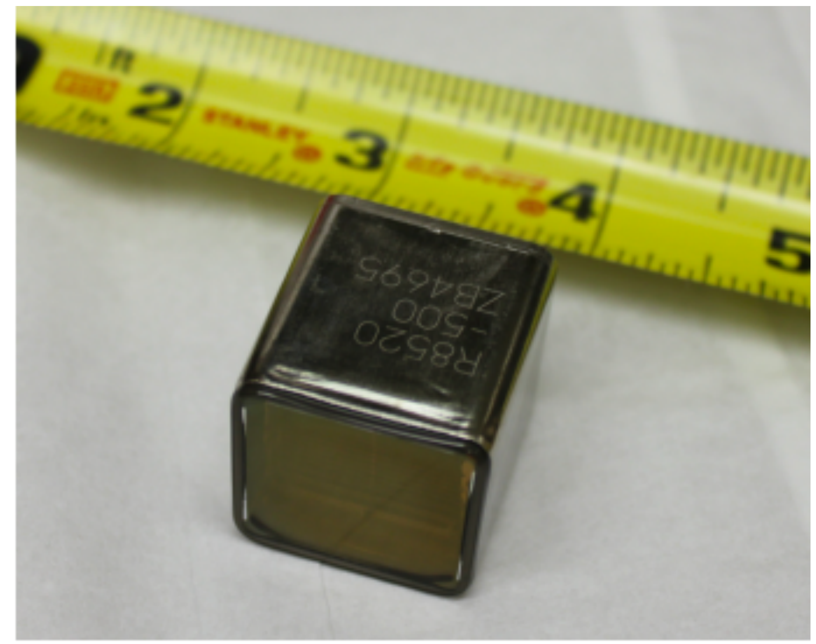
- Goals of CAPTAIN PDS:
  - Triggering of non-beam events
  - Evaluation of photon timing from prompt Argon scintillation signal to improve event reconstruction
  - Complement TPC to improve the energy resolution measurements
  - Time of flight for neutron run
- Baseline PDS will provide:
  - 11 pe/MeV in Mini-CAPTAIN
  - 2.2 pe/MeV in CAPTAIN

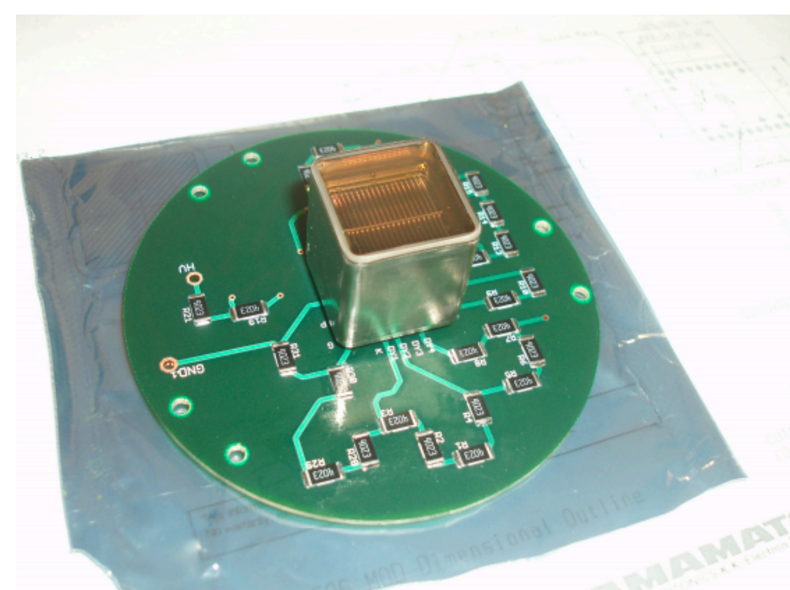


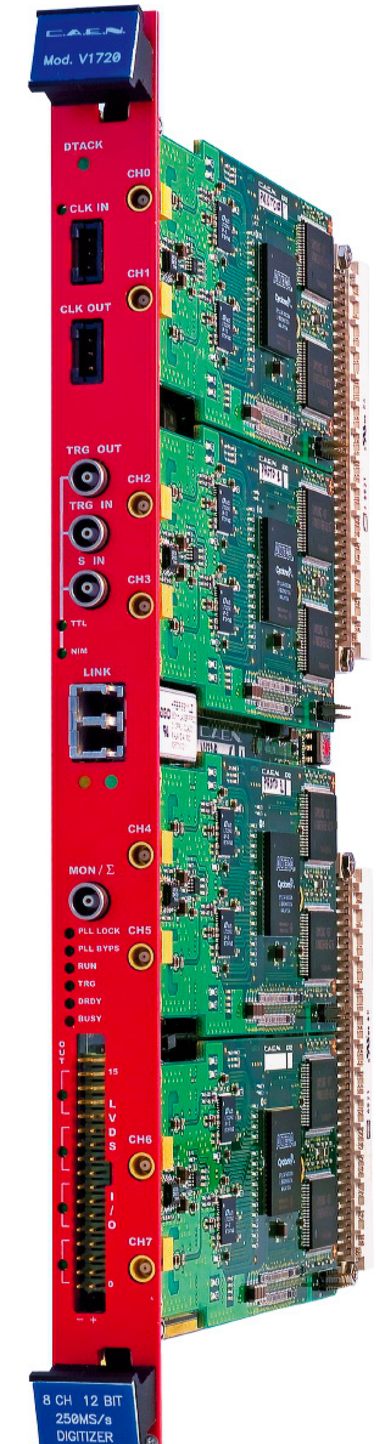


Photon detectors and electronics

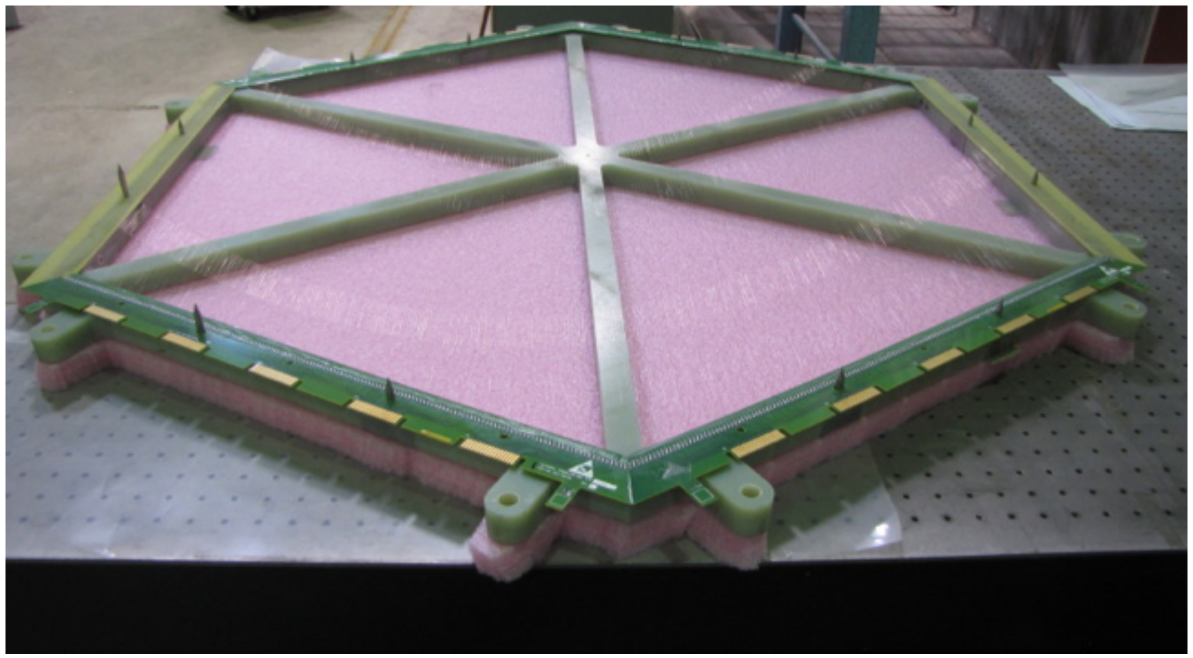
- Hamamatsu R8520-506 MOD
  - 1” square
  - 25% QE at LAr temperature, special Bialkali LT
- 24 PMTs installed in Mini-CAPTAIN
- Digitizer:
  - Three CAEN V1720
  - Eight channels each, 250 MSamples
  - 12-bit digitizer across 2 Vpp

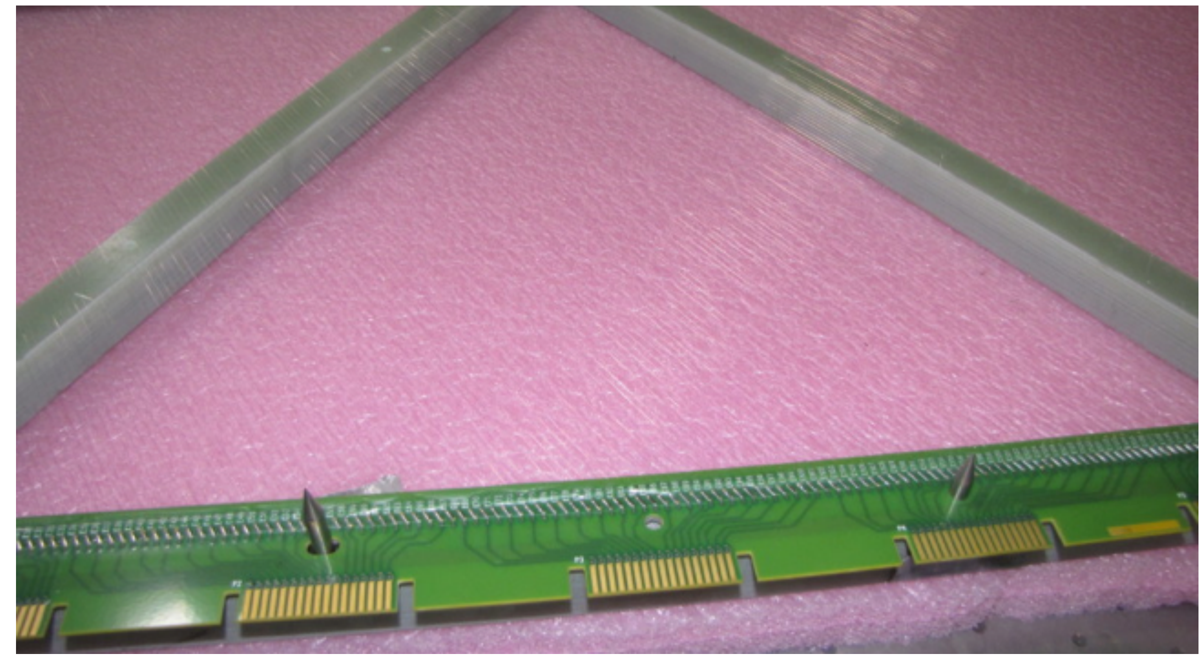


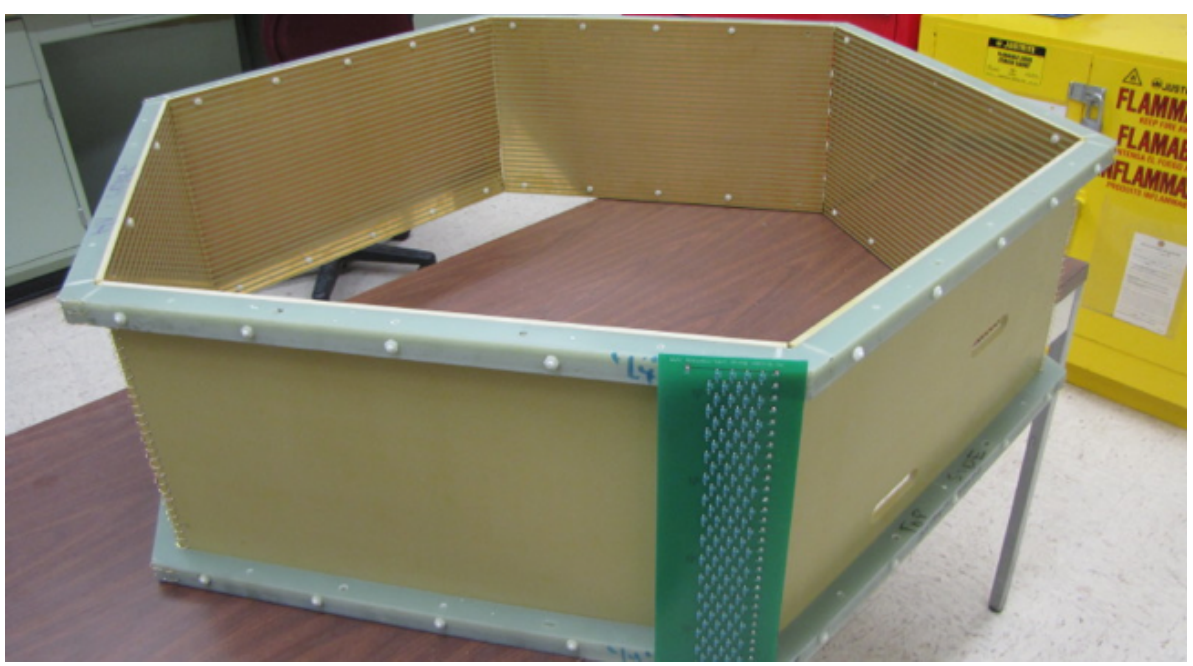


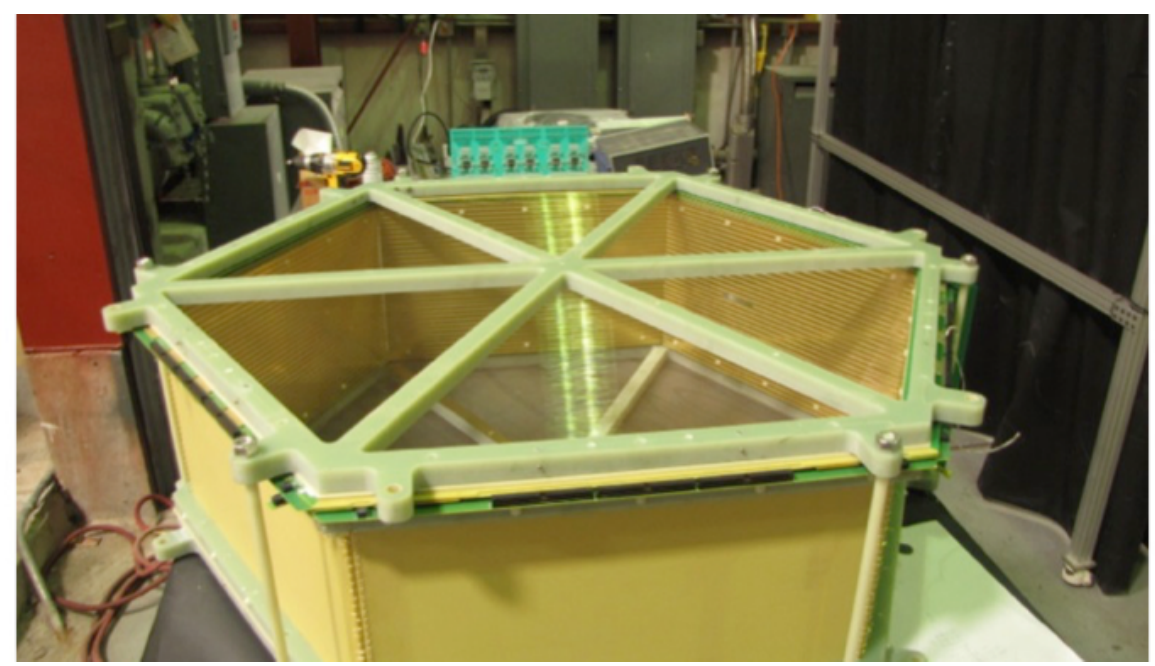


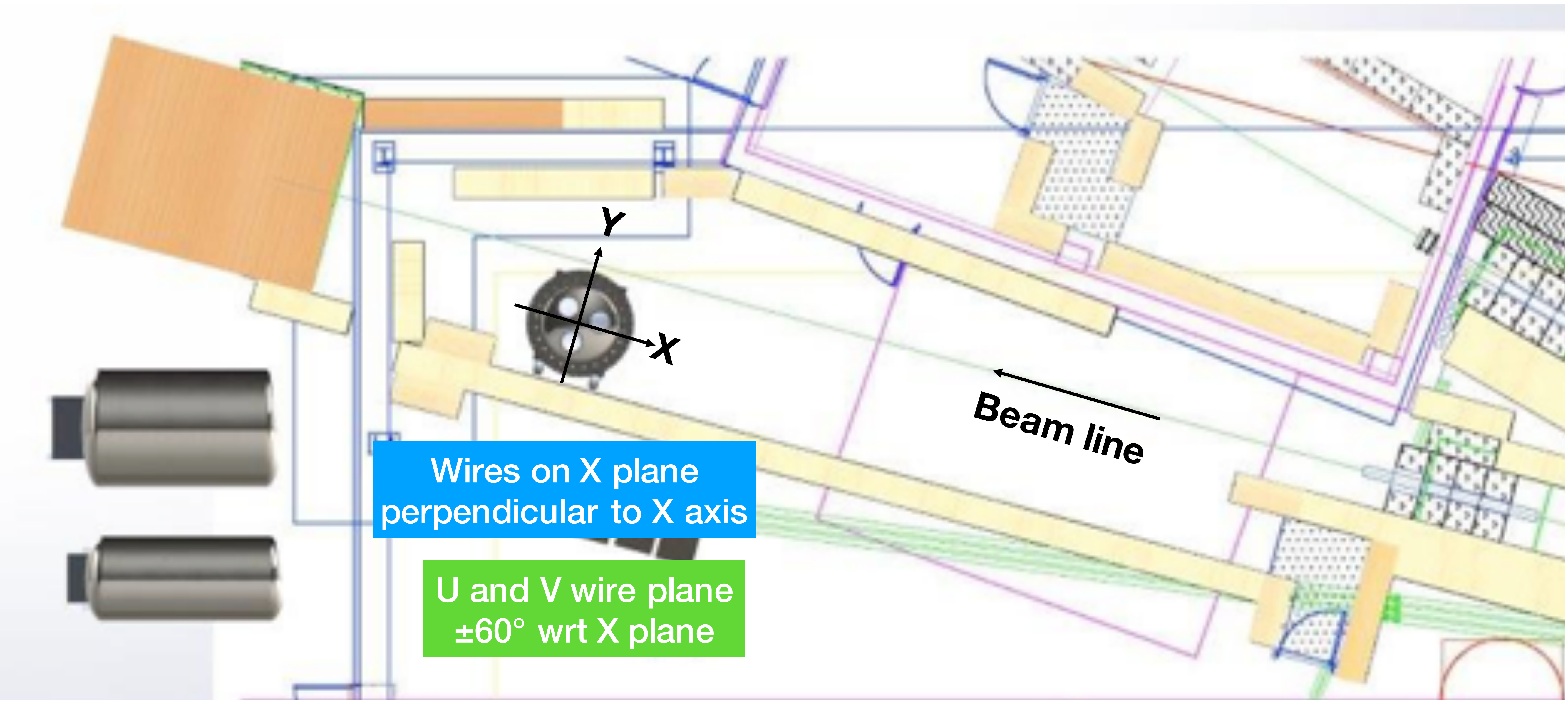
MiniCAPTAIN assembly





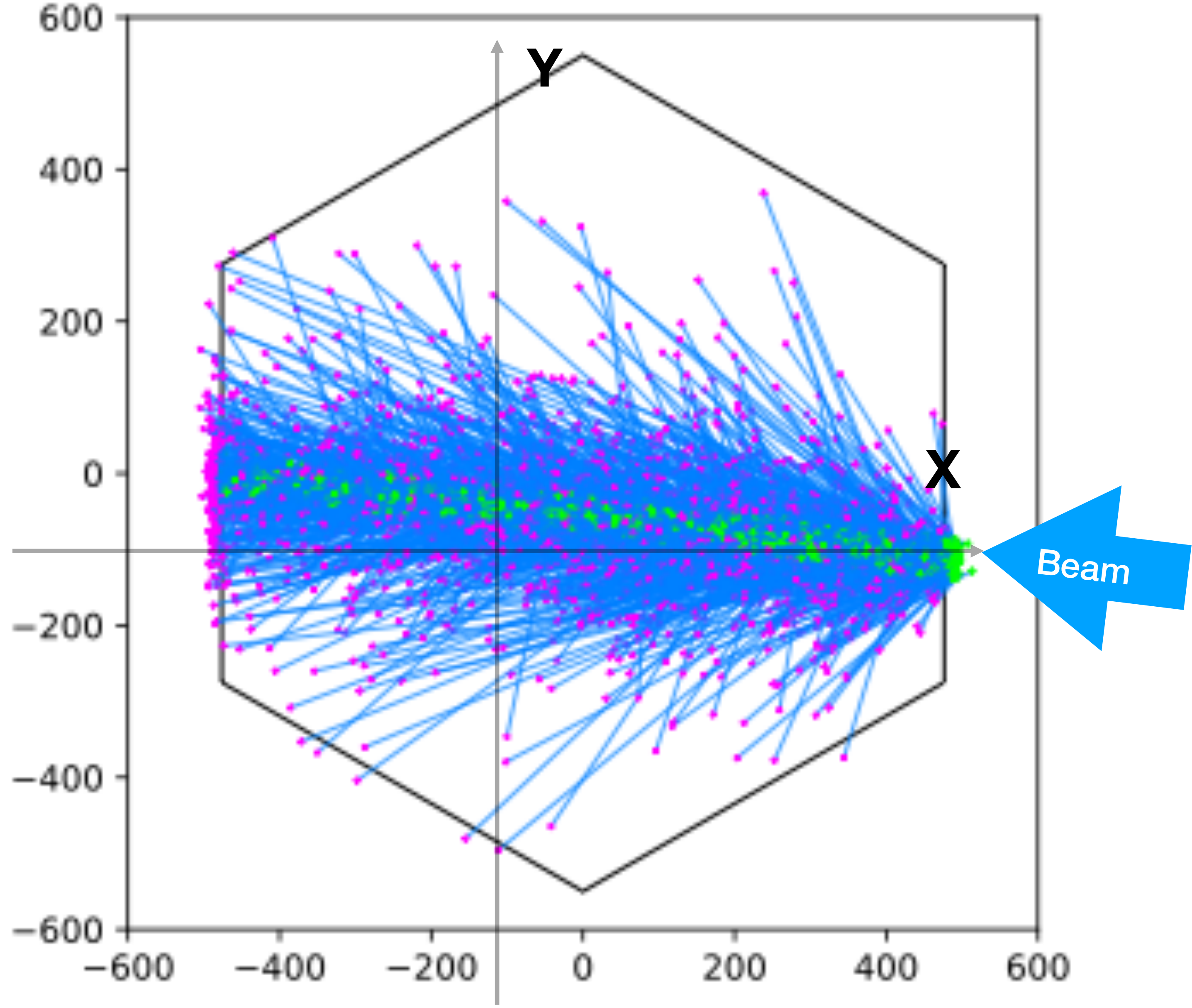




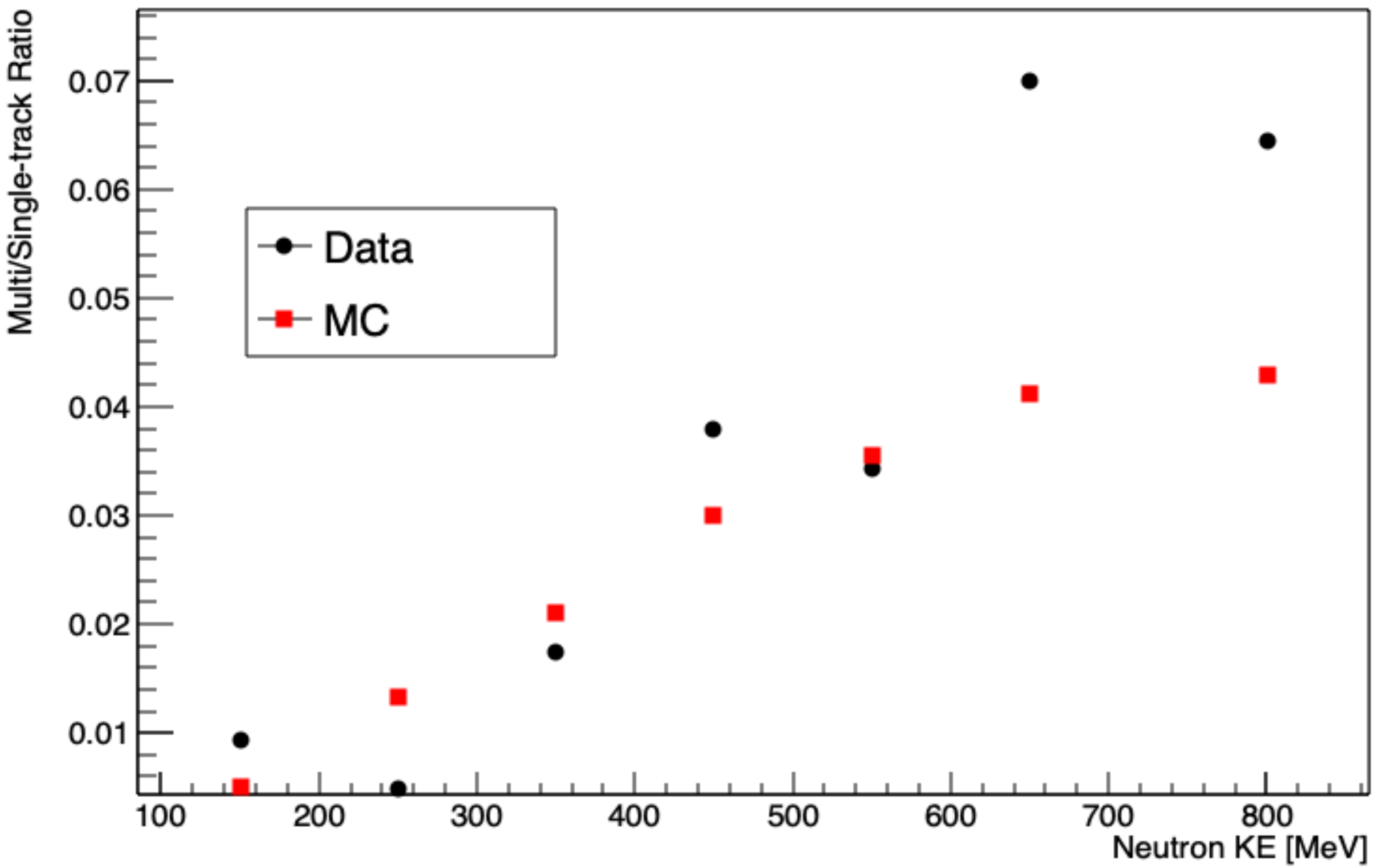

Y
X
Beam line
Wires on X plane perpendicular to X axis
U and V wire plane ±60° wrt X plane

Tracks in Mini-CAPTAIN

- Two-dimensional projection of the detector;
- Green dots are starting points of the tracks and purple dots are ending points;
- Low intensity beam with ~1 neutron every 6 micro pulses;
- Detector is slightly rotated with respect to beam line.

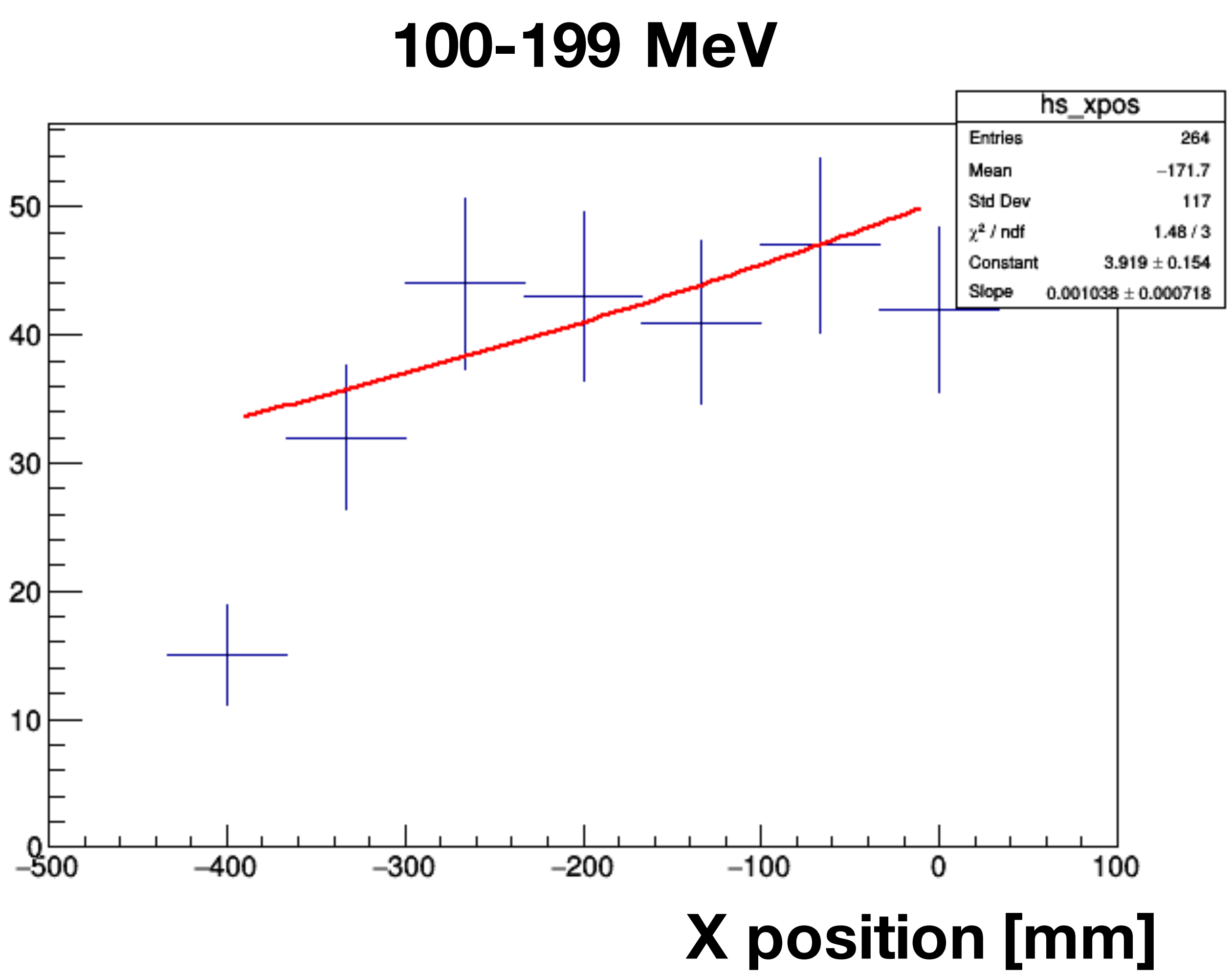


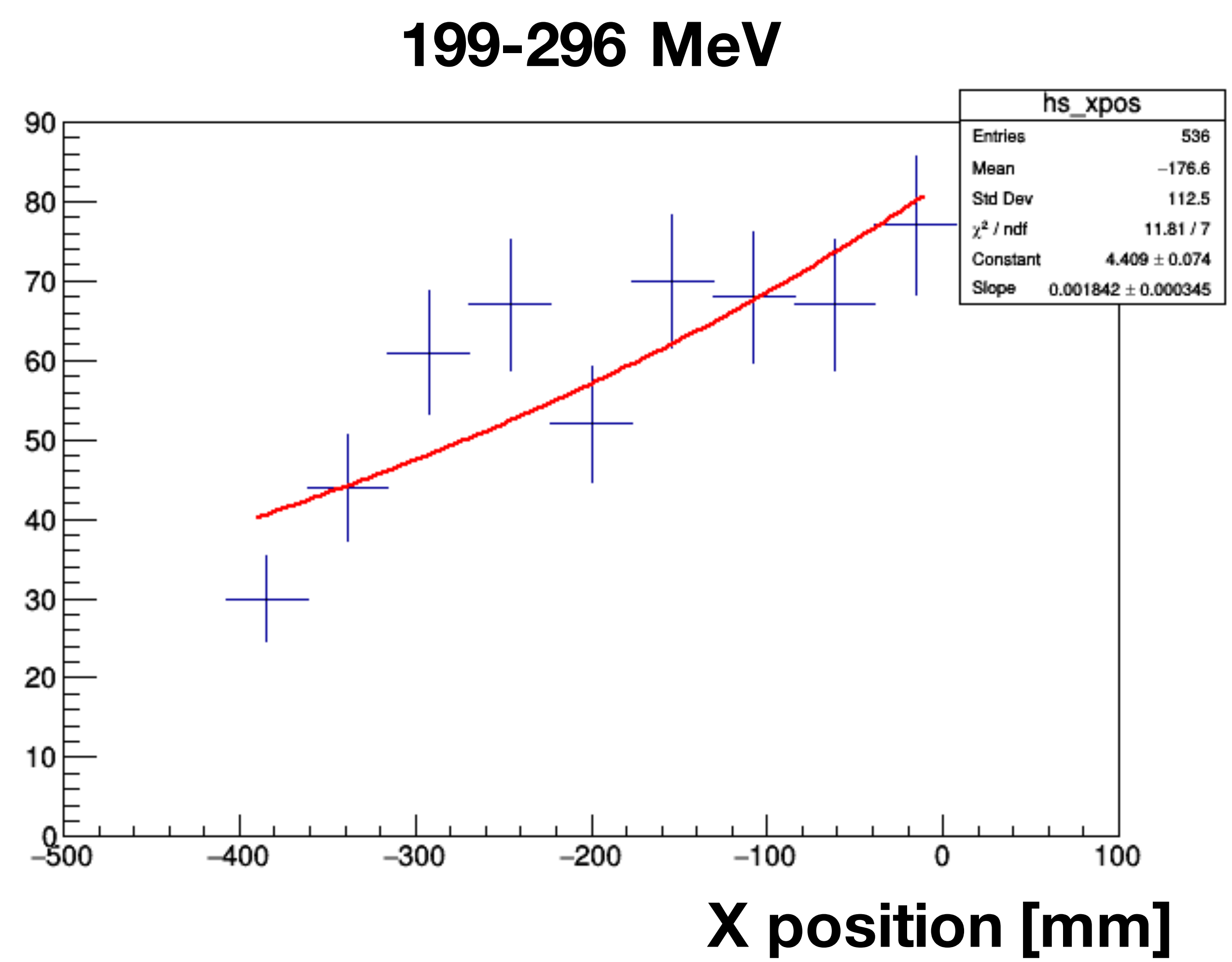
Multi-track events



- Simulation predicts at most a change of 10% in the cross section due to multi-track events

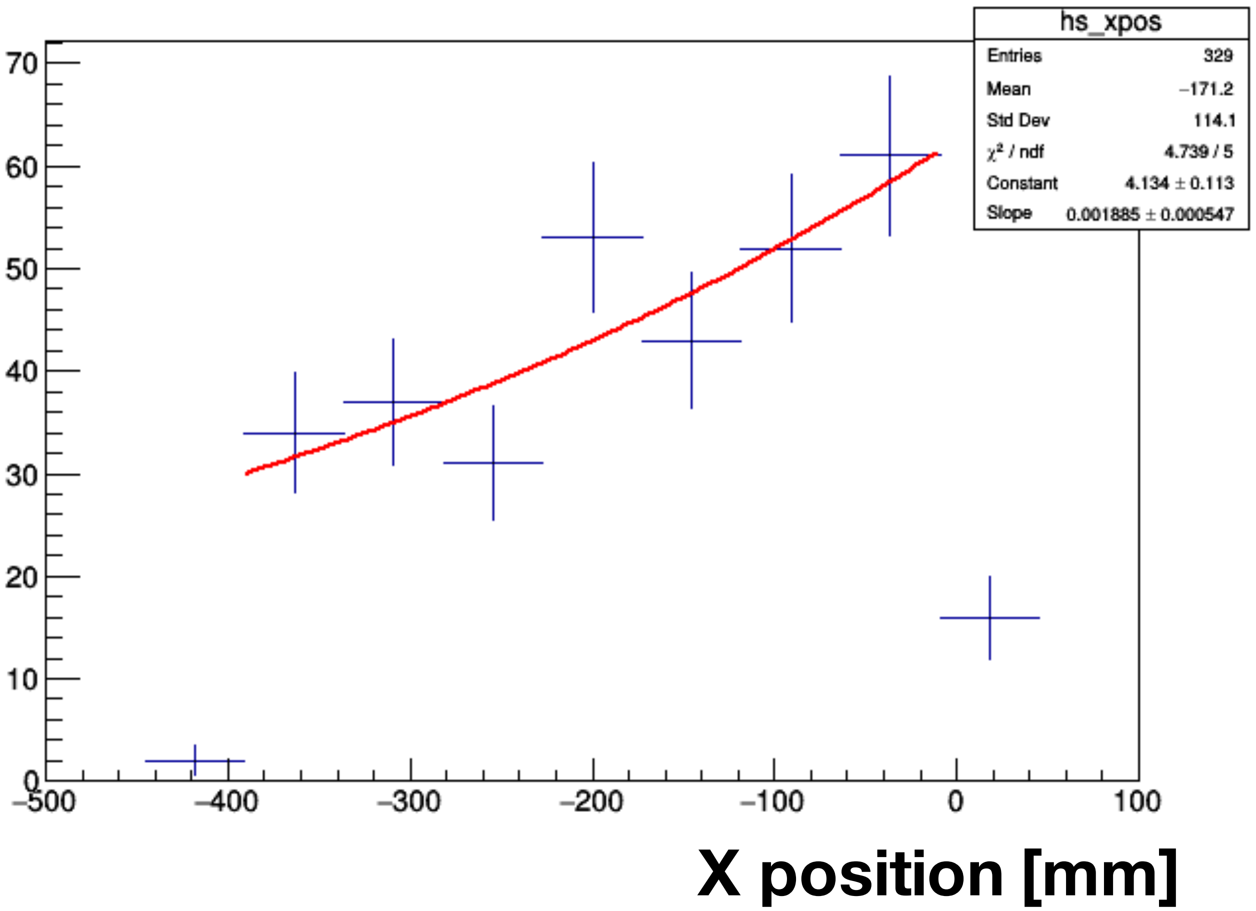
Cross section fit



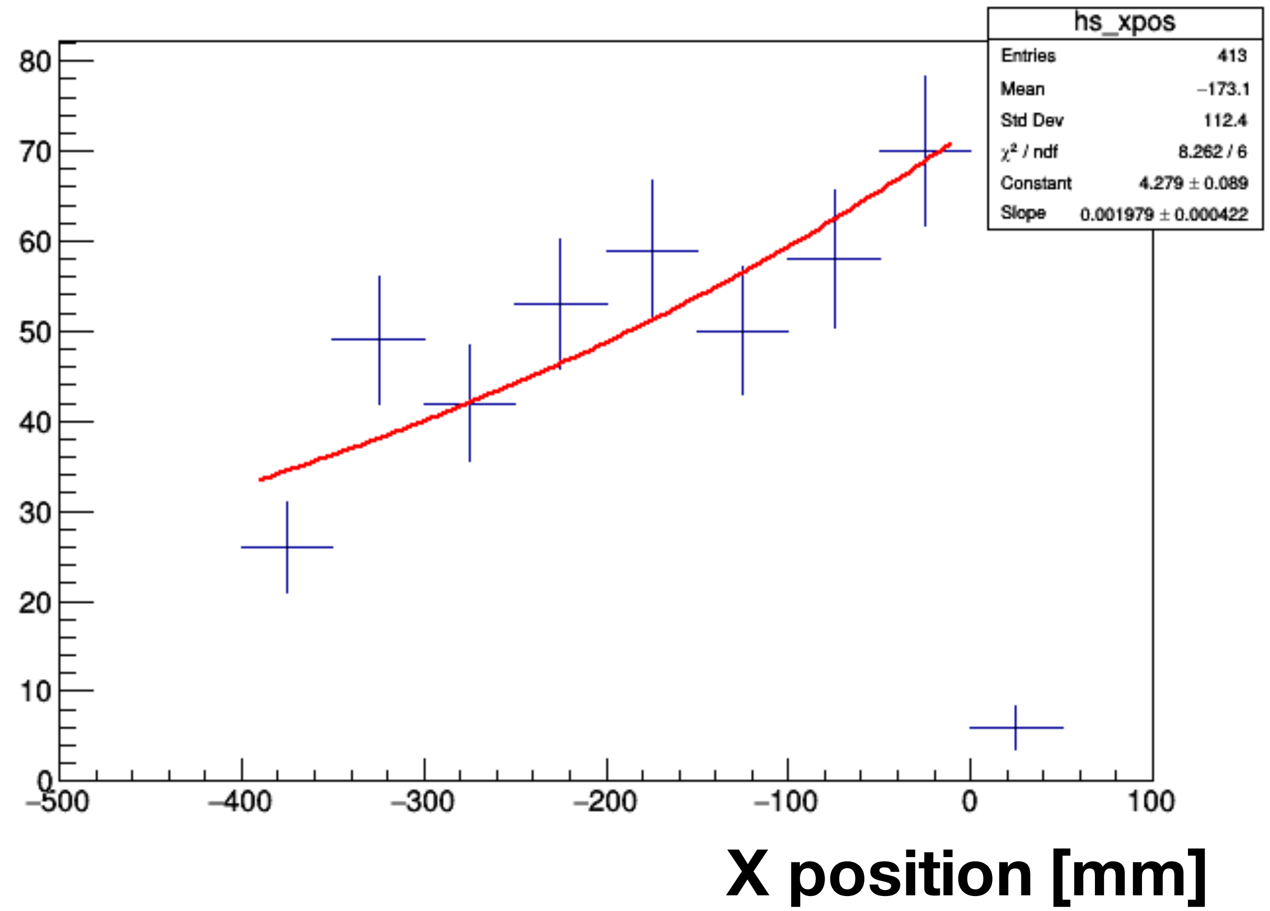


Cross section fit

296-369 MeV



369-481 MeV



Looking to the future: Neutrino cross sections with CAPTAIN

- An important goal of DUNE is to be able to detect supernova neutrinos.
    - We need to understand what the detector response/efficiency should be.
- CAPTAIN is a fairly sized LArTPC that can provide some insight into these requirements before DUNE is built
    - Possibly deployed at the Spallation Neutron Source (SNS) at Oak Ridge.
- In addition, the CC/NC cross sections of low energy neutrinos have not been measured in Argon.
- CAPTAIN detector can serve as a testbed for some of the technology needed for a large TPC, but it is also more flexible when it comes to where it can be located.