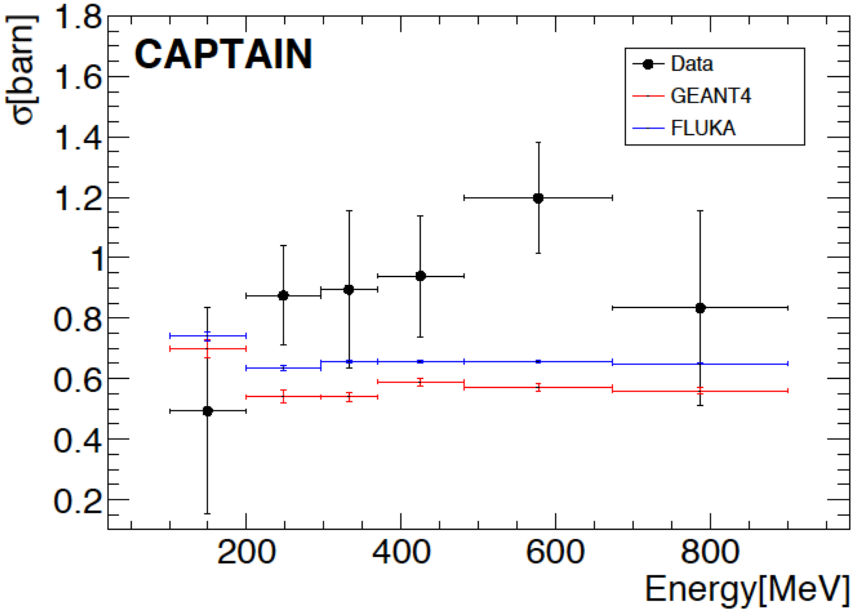
*arXiv:1903.05276*



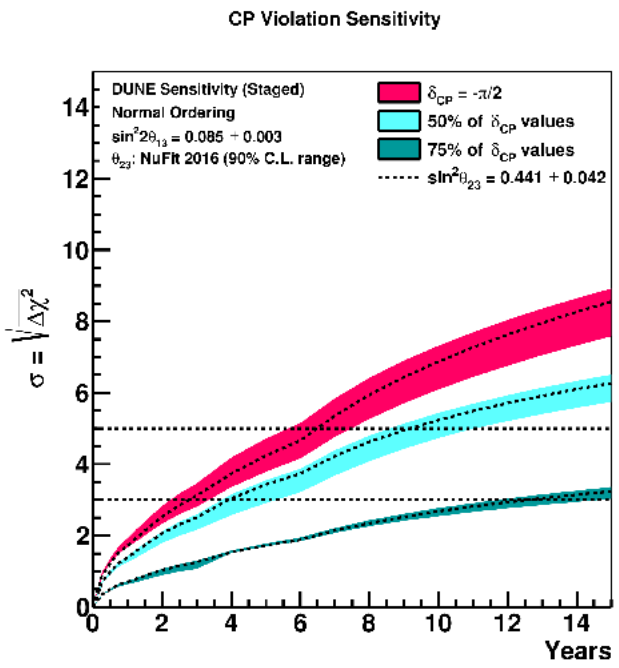
# “First Measurement of the Total Neutron Cross Section on Argon Between 100 and 800 MeV”

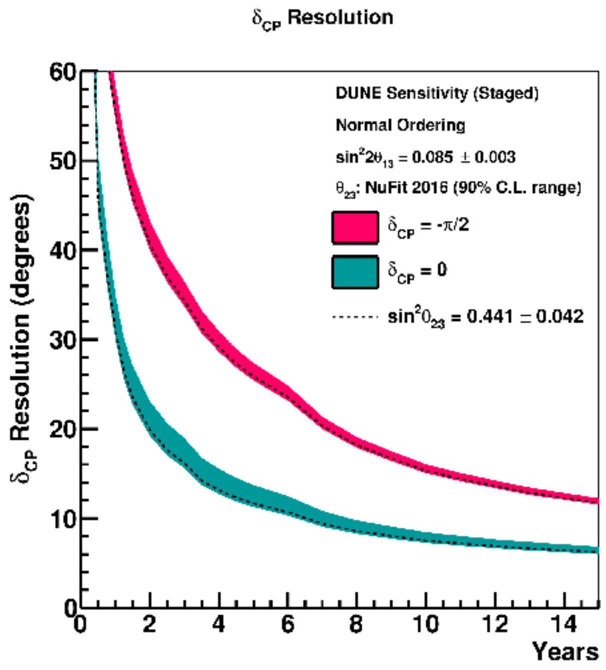
## Christopher Grant

DUNE Calibration Consortium Meeting - March 29, 2019

# Physics Challenges for DUNE

- DUNE will measure the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ as a function of neutrino energy
- Oscillation phenomena (like $\delta_{CP}$, $\theta$'s, $\Delta m^2$'s, etc) depend on the neutrino energy
- A successful DUNE physics program will rely on a detailed understanding of the correlation between the true neutrino energy (from the beam) and the reconstructed neutrino energy (in the detector) – this is especially true for any differences between $\nu$ and $\bar{\nu}$





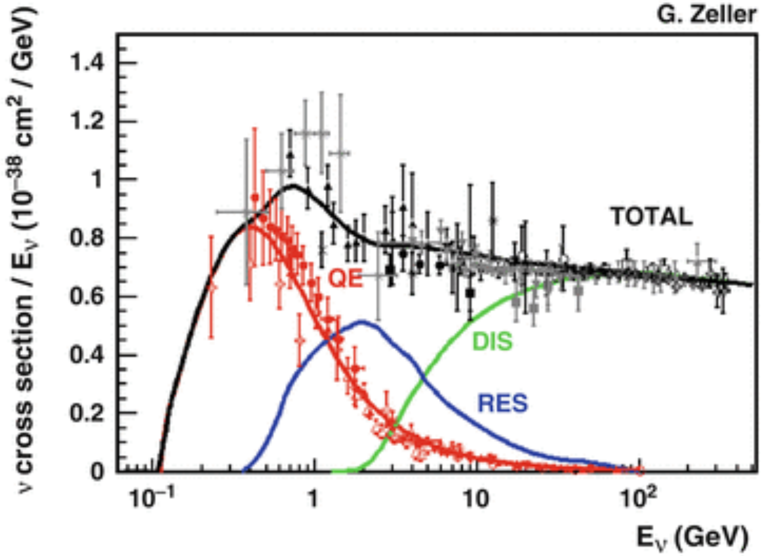
# Physics Challenges for DUNE

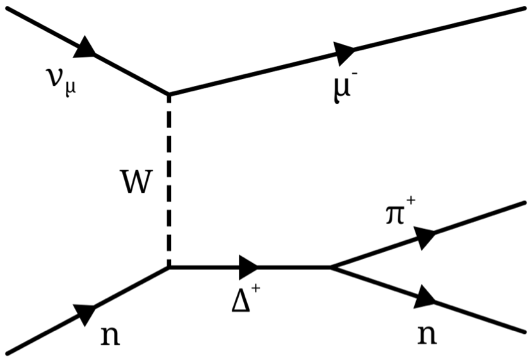
- First oscillation maximum is around 2.4 GeV (near the "resonance production region") - neutrino cross-sections are highly uncertain, especially in this region

- Many of the neutrino interactions in DUNE will involve baryon resonance production

- Final state interactions of the outgoing hadronic system are also uncertain – neutrons are often a part of this system emerging from the nucleus

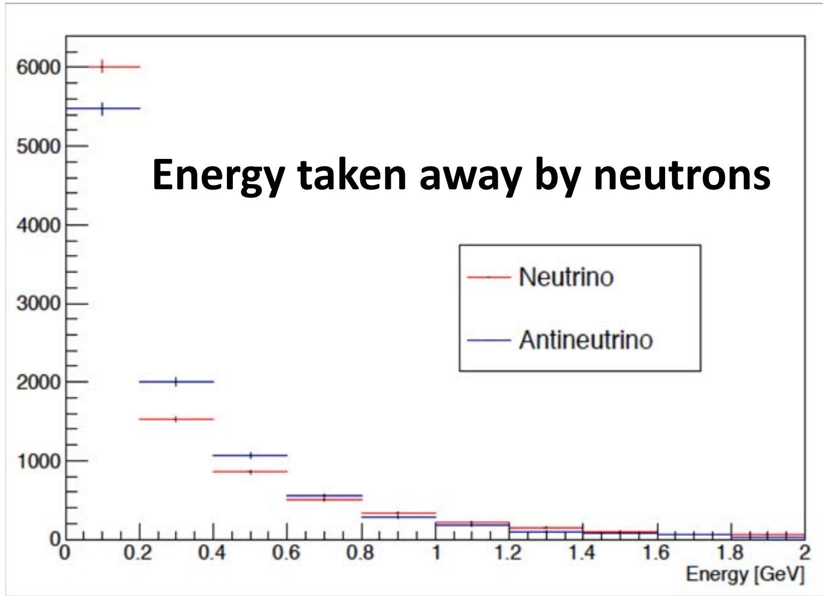
- Typical neutron kinetic energies are on the order of hundreds of MeV – these need to be accounted for when reconstructing the incoming neutrino energy

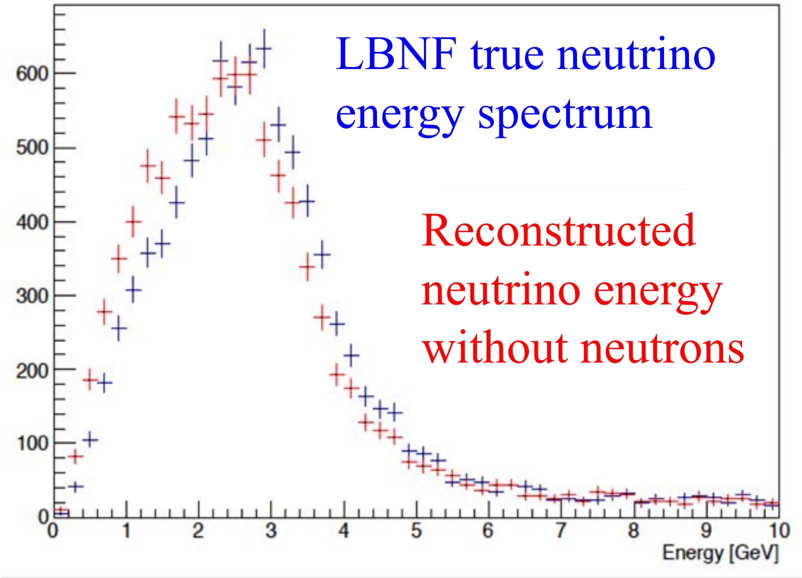




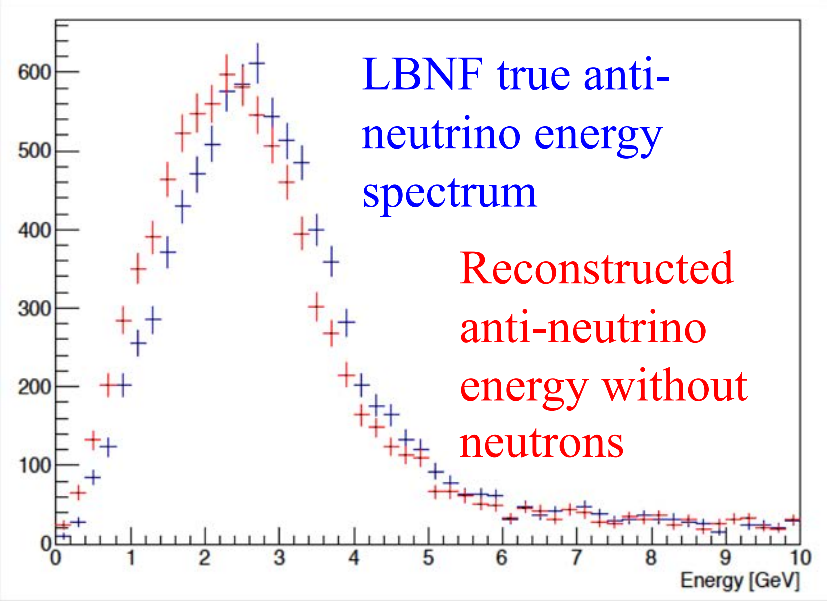
# LBNF Beam Example

- Neutrons carry away considerable amount of energy that escapes detection
- Different amounts of energy carried away between neutrinos and anti-neutrinos
- No neutron-argon cross-section data above 50 MeV (R.R. Winters et al., PRC 43, 492, 1991) – need neutron data at high energies!


**Energy taken away by neutrons**


LBNF true neutrino energy spectrum

Reconstructed neutrino energy without neutrons


LBNF true anti-neutrino energy spectrum

Reconstructed anti-neutrino energy without neutrons

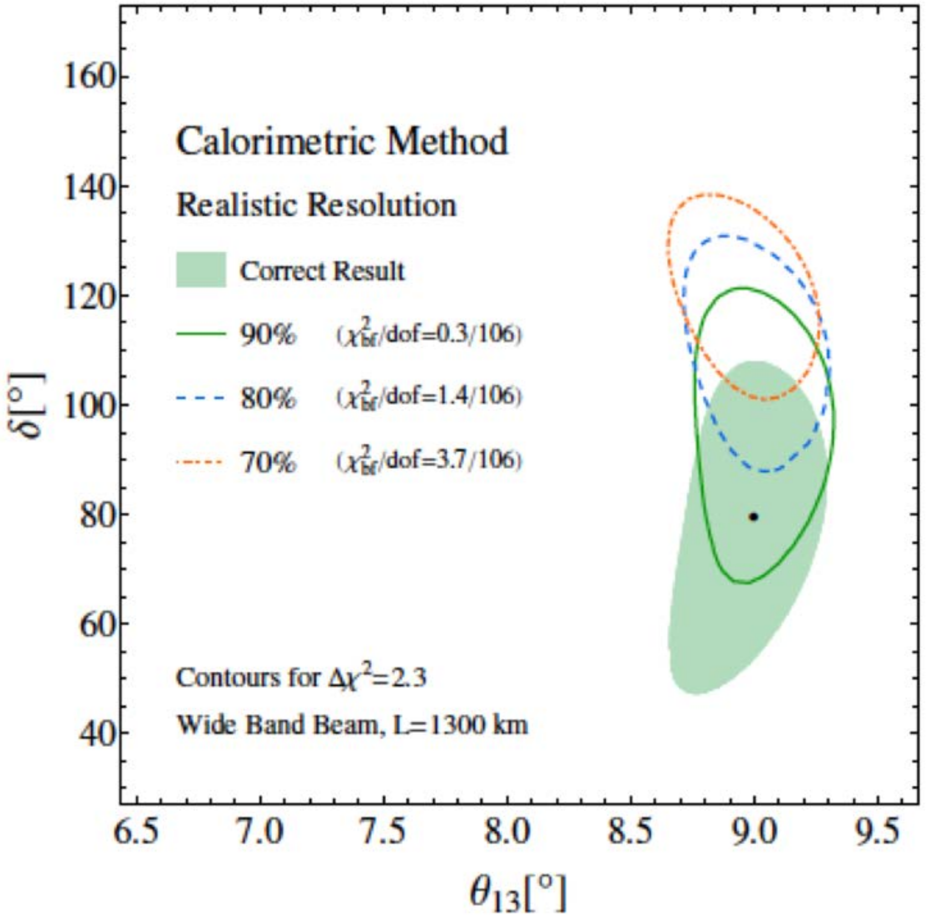
*Plots from J. Chavez*

GENIE used for a simple DUNE LAr volume

# Problems Entering into DUNE Physics

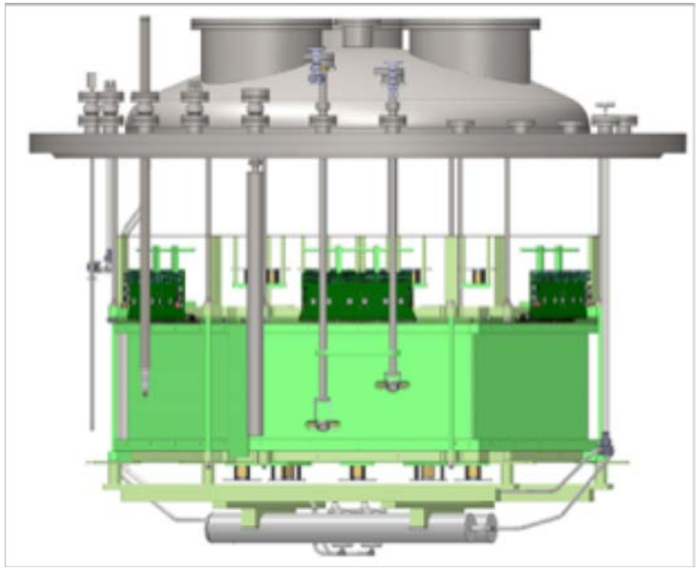
- Authors simulated the effect of missing energy in a calorimetric neutrino energy reconstruction for a “DUNE” detector
- Point represents true oscillation parameters with a green shaded region showing the contour around the correct result
- Fitted allowed region shifts relative to true value as we underestimate the missing energy – this is how wrong we could be (unknowingly)

Phys. Rev. D 92, 091301 (2015)



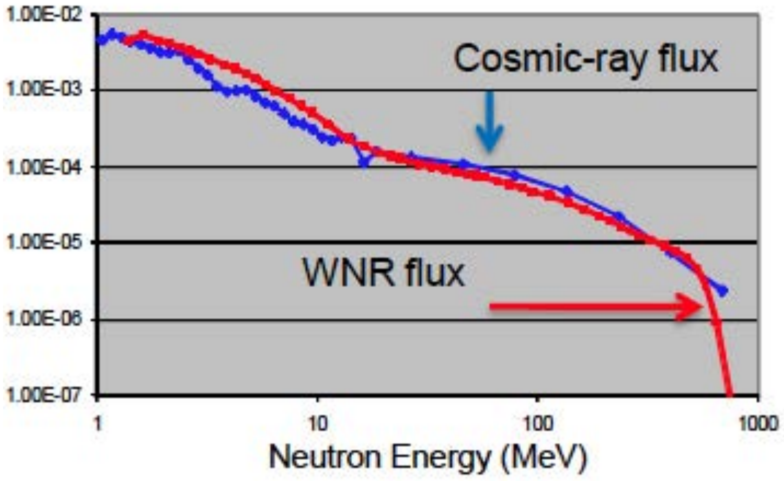
# Mini-CAPTAIN

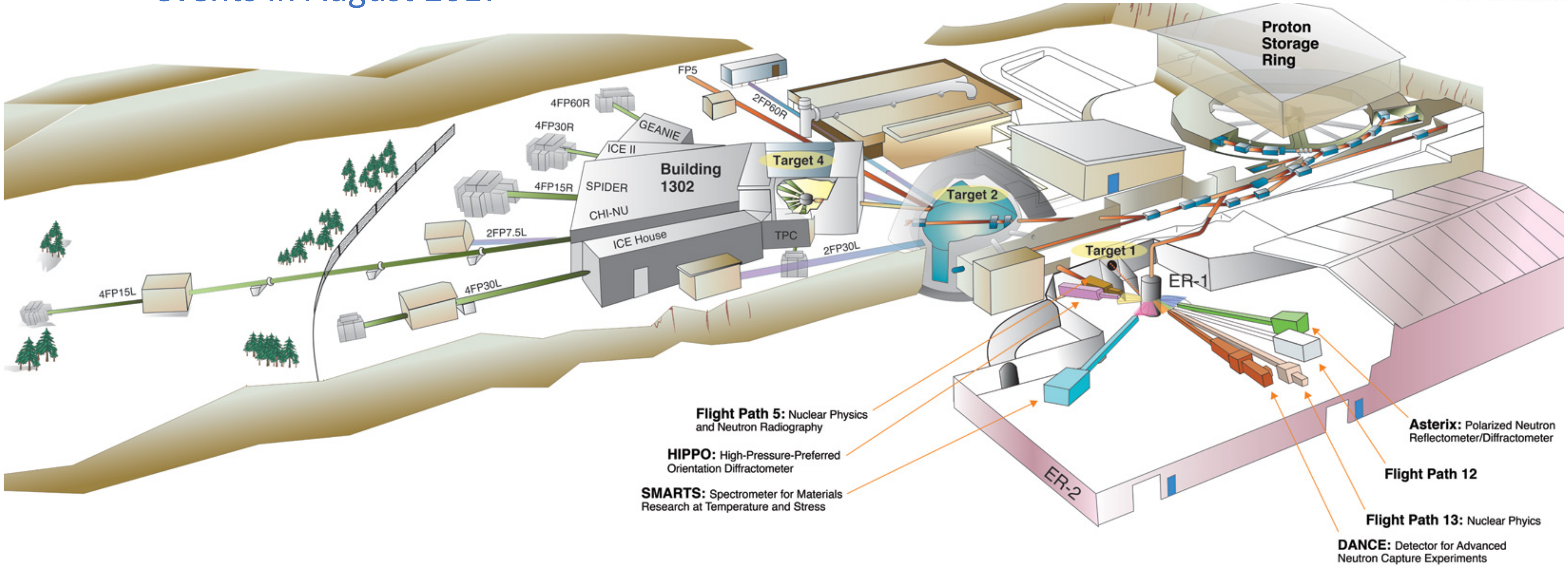
- 400 kg instrumented mass inside a hexagonal TPC with 32 cm drift, 50 cm apothem
- 1000 wire channels, 3mm wire pitch
- 24 x 6 cm$^2$ PMT light detection system (Hamamatsu R8520-506 MOD)
- Same cold electronics as MicroBooNE



# Neutron Beam at LANL (LANSCE)

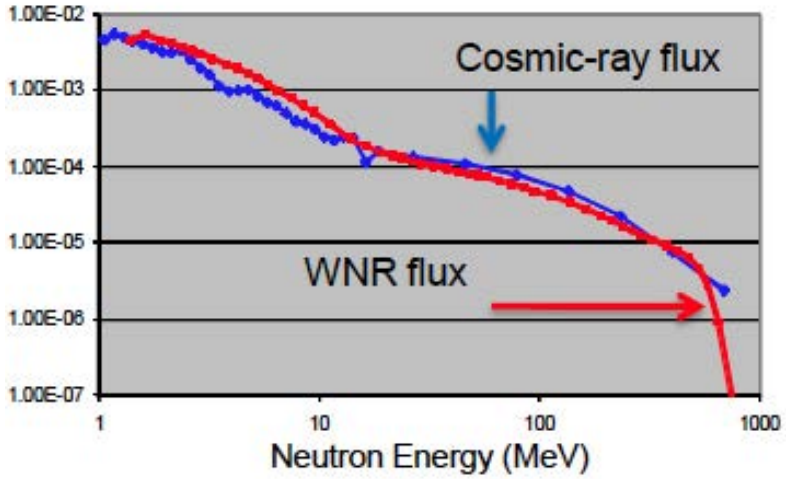
- Los Alamos Neutron Science Center WNR facility provides a high flux neutron beam with a broad energy spectrum up to 800 MeV
- Mini-CAPTAIN utilized this facility to collect high-energy neutron events in August 2017

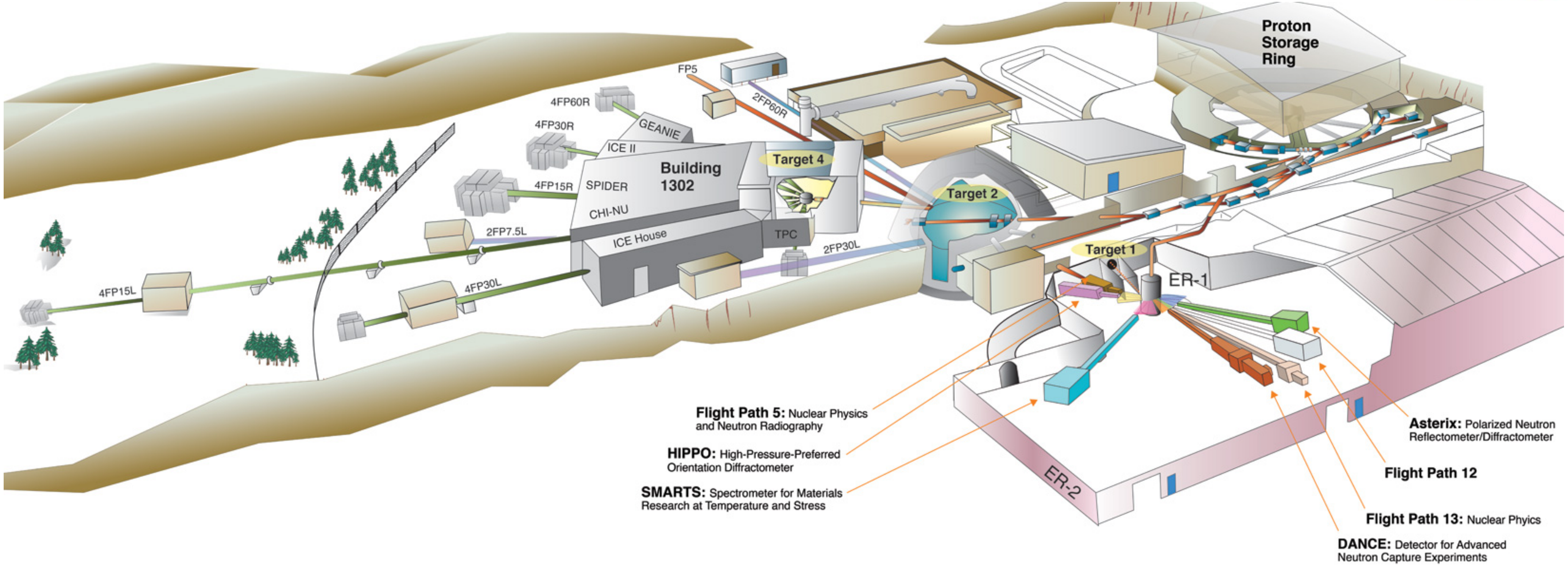




# Mini-CAPTAIN Goals

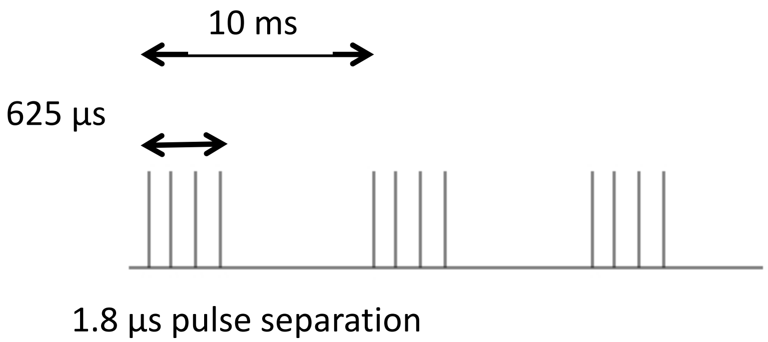
- Produce neutron-argon cross-section measurements (total, exclusive channels) as a function of neutron kinetic energy
- Develop strategies for incorporating neutron ID and reconstruction in DUNE



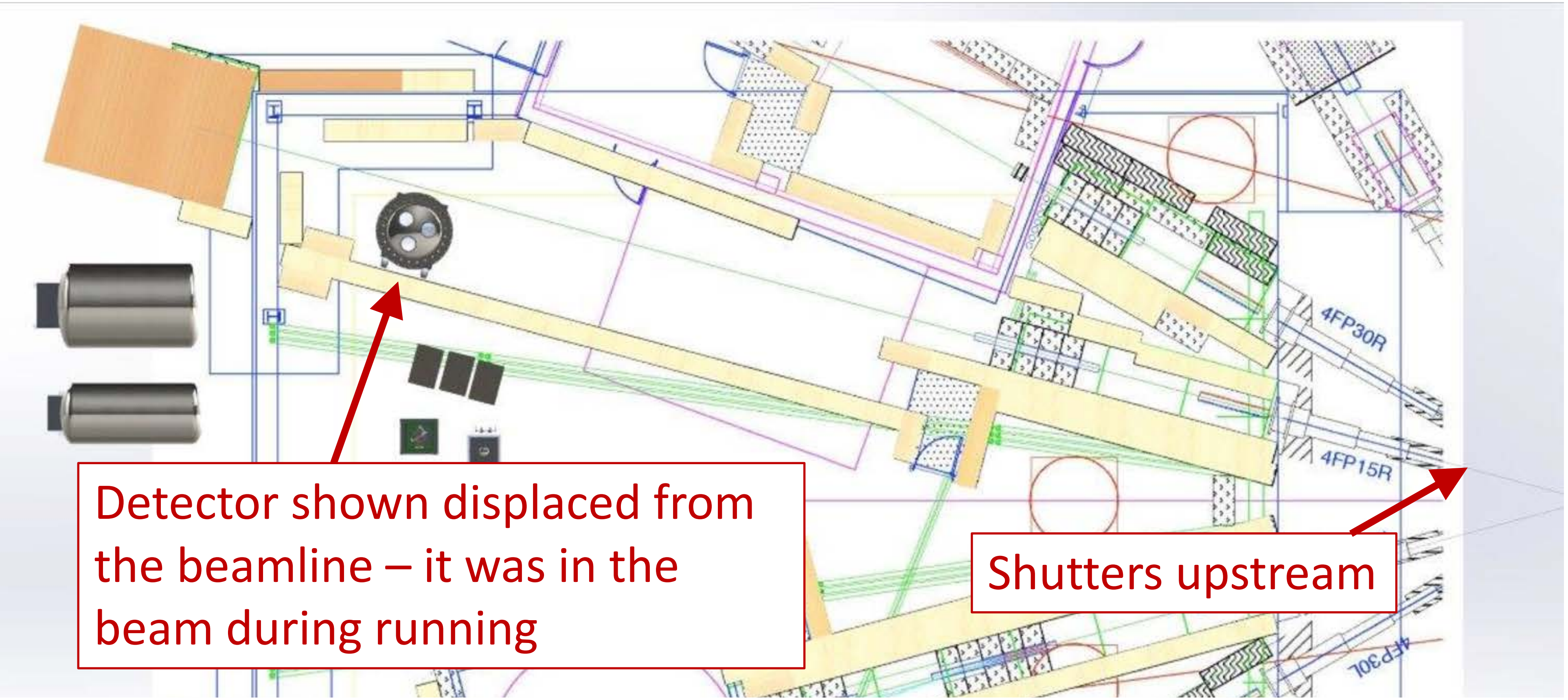


# Neutron Beam Structure

- Nominal time structure of the beam
  - sub-nanosecond pulses 1.8 microseconds apart within a 625 µs long macro pulse
  - Repetition rate: 100 Hz



- Facility is designed to deliver high flux – we want <1 neutron per TPC drift length (200 $\mu s$)
- Broad energy spectrum – we would like our measurements to be as a function of neutron kinetic energy

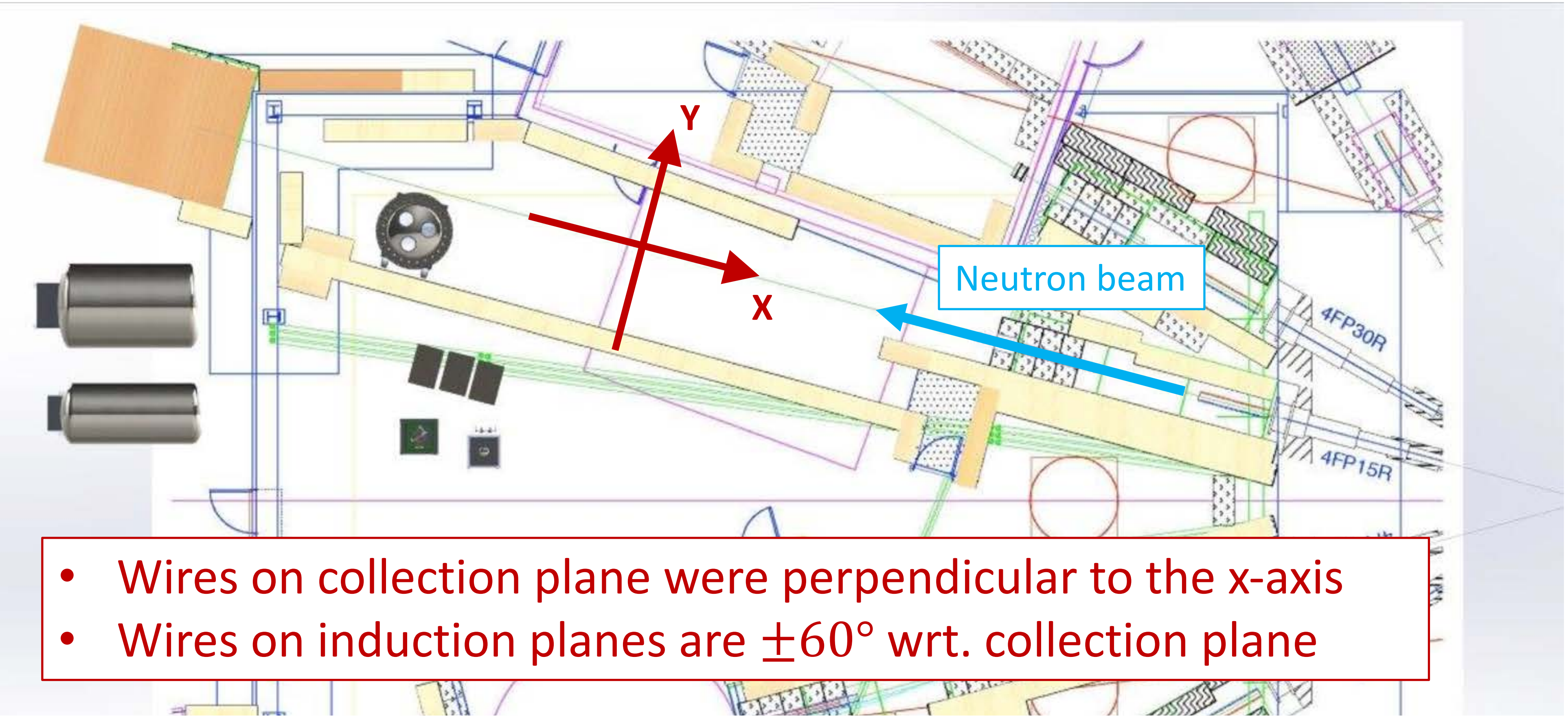


Detector shown displaced from the beamline – it was in the beam during running

Shutters upstream

- To achieve low neutron flux:
  - Constrain the shutters
  - Special low-intensity running – nominal bunch spacing changed from 1.8 $\mu$s to 200 $\mu$s yielding 3 bunches per macropulse

- We ran in two modes:
  1. highly constrained shutters – doesn't impact other users
  2. moderately constrained shutters with special bunch spacing – annoys every other user in the facility



- Wires on collection plane were perpendicular to the x-axis
- Wires on induction planes are ±60° wrt. collection plane

- To achieve low neutron flux:
  - Constrain the shutters
  - Special low-intensity running – nominal bunch spacing changed from 1.8 $\mu s$ to 200 $\mu s$ yielding 3 bunches per macro-pulse

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# Neutron flux monitors

- For some measurements, an external understanding of the neutron spectrum may be important
- Fission chamber – useful for high neutron fluxes (~$10^{-5}$ interaction rate) – standard facility equipment
- Scintillator detector (stilbene) – useful for low neutron fluxes (~$10^{-2}$ interaction rate) – deployed by CAPTAIN
- Cross-calibrate scintillator detector with fission chamber at moderately high flux

Fission chamber in 4FP15R

# CAPTAIN Collaboration

- Alabama: Ion Stancu
- LBL: Craig Tull
- Boston University: Christopher Grant
- 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
- Hawaii: Jelena Maricic, Marc Rosen, Yujing Sun
- Houston: Lisa Whitehead
- LANL: Elena Guardincerri, Nicholas 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
- 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, Keith Wiley
- Stony Brook: Neha Dokania, Clark McGrew, Sergey Martynenko, Chiaki Yanagisawa

Spokesperson: Christopher Mauger; Deputy Spokesperson: Clark McGrew

# Getting Ready for the Neutron Beam Run in 2017

# Triggering Mini-CAPTAIN

- Beam facility provides an RF signal for every micro pulse that is then distributed to TPC and photon detection system
- TPC takes data for 4.75 ms when the first RF from a 625 $\mu s$ macro pulse is received
    - 1.85 ms of buffered pre-trigger data
    - $\sim$ 2.3 ms of post-trigger data; cosmics collected during this time (for calibration)
- All 3 micro pulses of a macro pulse fall within the same TPC acquisition window
- Photon detection system receives the RF signal independently and needs to be synced with TPC offline
    - Also allowed to self-trigger, independent of the RF trigger, if enough light is collected
    - Provided an accurate measure of the beginning of the drift time

# Proton Candidate with a Cosmic Candidate

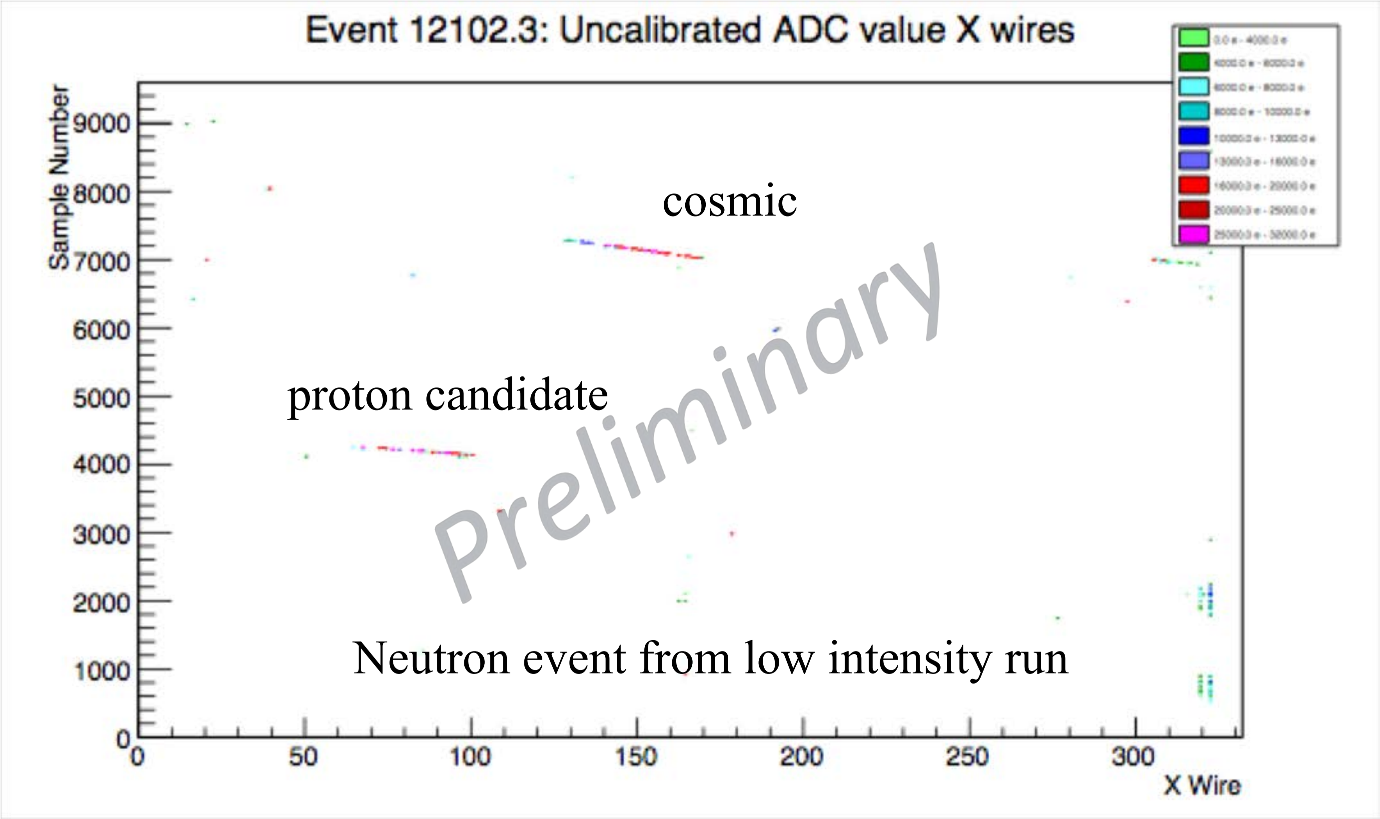
- Several hundred thousand beam triggers were collected

- Currently analyzed our special low-intensity run sample (“golden sample”) – 3 bunches per macropulse

- Good LAr purity ($e^-$ lifetime > 72 $\mu$s)

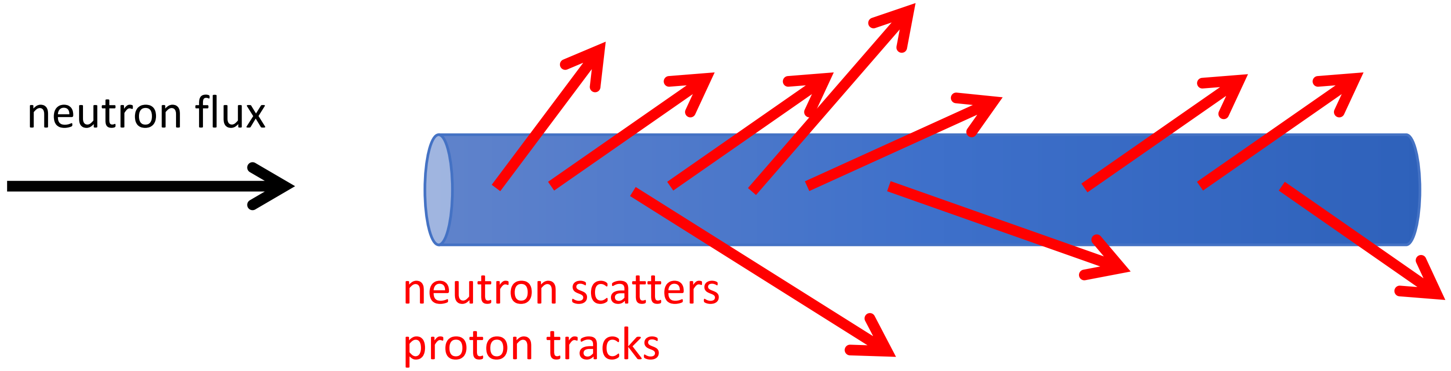
- Low electronics noise

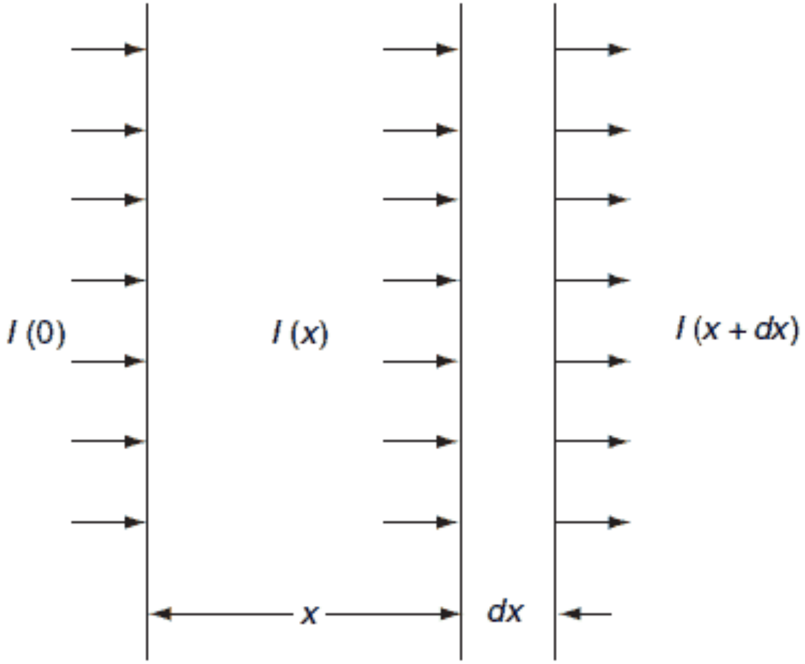
- 1st measurement is an absolute total cross-section – also looking for exclusive channels



# Basic Analysis Strategy

- Find tracks in the time-projection chamber (TPC) in time with the beam and in the beam spot
- Match the tracks in the TPC to hits in the photon detection system (PDS)
- Use the timing from the PDS to determine the neutron energy – kinetic energy bin
- For tracks (track starting position) in each kinetic energy bin, fit an exponential decay function





Flux is attenuated as a function of depth $x$ in the TPC!

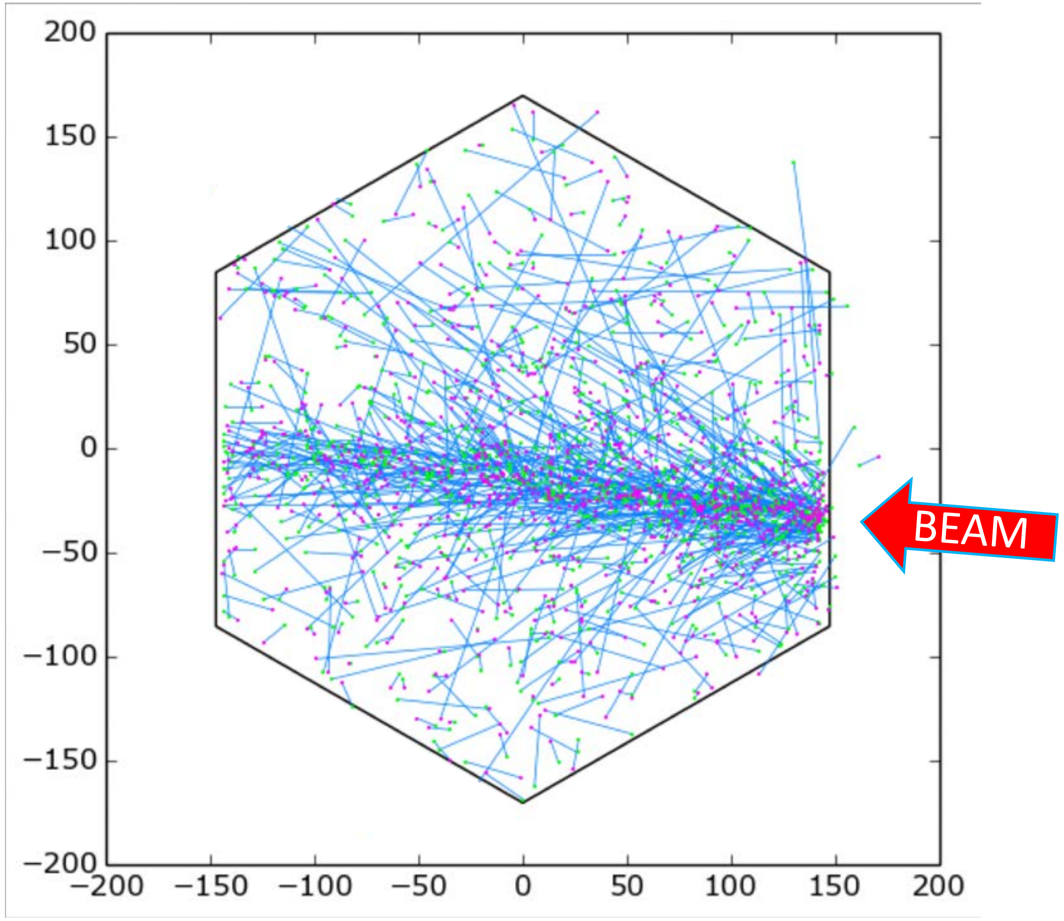
$$I(x) = I_0 e^{-n\sigma x}$$

$n$ = number density of Argon targets

# Finding Tracks

- Raw signals from TPC wires were filtered for electronic noise – hits were formed from waveform peaks
- Custom-made algorithm found 2D clusters in a single plane and build 3D tracks from one track in collection plane and one track in an induction plane
- Beam is not precisely in the x-direction – detector was slightly rotated relative to the beam direction
- Track cannot be more than ±27 mm away from the beam path through the TPC

Plenty of possible cosmics and secondary interactions can be seen in addition to beam events



# Hit-finding efficiency

- Exposure of 4.3 hours at WNR yielded 115,880 reconstructed tracks

  Require the following:
  - at least 10 MeV track
  - within 32 $\mu$s of an RF signal
  - no more than ±27mm from beam line

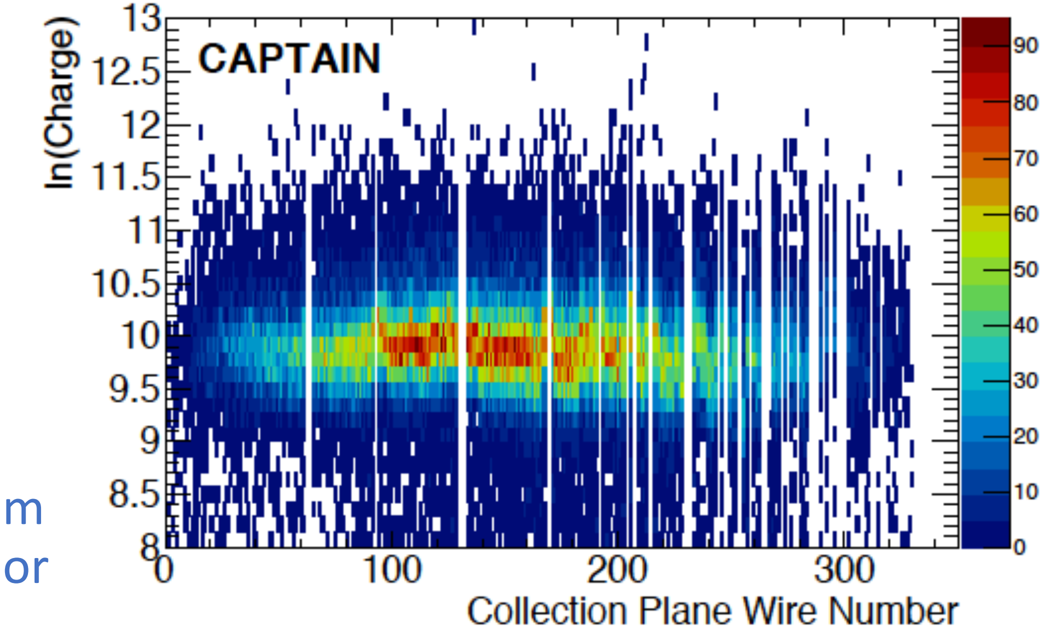
  → These cuts yield 9,911 tracks

- Lower x (downstream) has higher efficiency than upstream – data analyses only uses downstream tracks (starting at or below wire 180) to avoid this inefficiency problem

  → Left with 2,631 tracks after this selection criteria

Beam entered from the right side (high wire number)

*arXiv:1903.05276*



Gaps in the plot are wires that have been masked due to low efficiency

# Cross section measurement

- Tracks are binned based on their kinetic energy – distributions of starting positions ($x$) fit in the direction of the beam with an exponential function

$$N(x) = N_0 e^{-n\sigma_T x} \qquad n = \rho_{Ar} \times \frac{N_A}{m_{Ar}} = 2.11\times10^{22}\ \text{cm}^{-3}$$

$\rho_{Ar} = 1.3973$ g/cm$^3$
$N_A = 6.022\times10^{22}$ n/mol
$m_{Ar} = 39.948$ g/mol

- Cross section extracted in each kinetic energy bin (shown below)

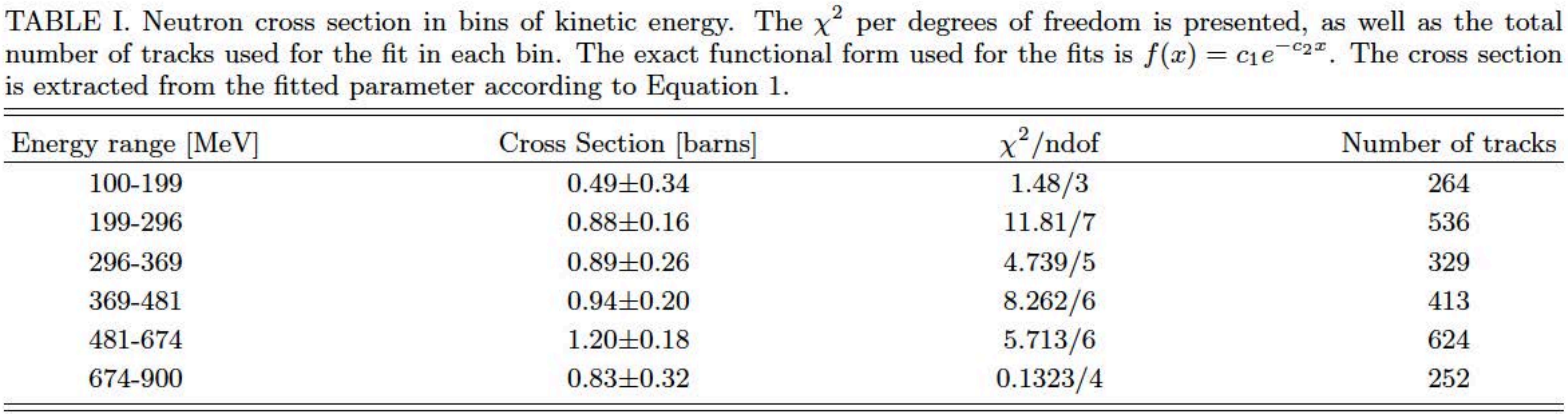


TABLE I. Neutron cross section in bins of kinetic energy. The $\chi^2$ per degrees of freedom is presented, as well as the total number of tracks used for the fit in each bin. The exact functional form used for the fits is $f(x) = c_1 e^{-c_2 x}$. The cross section is extracted from the fitted parameter according to Equation 1.

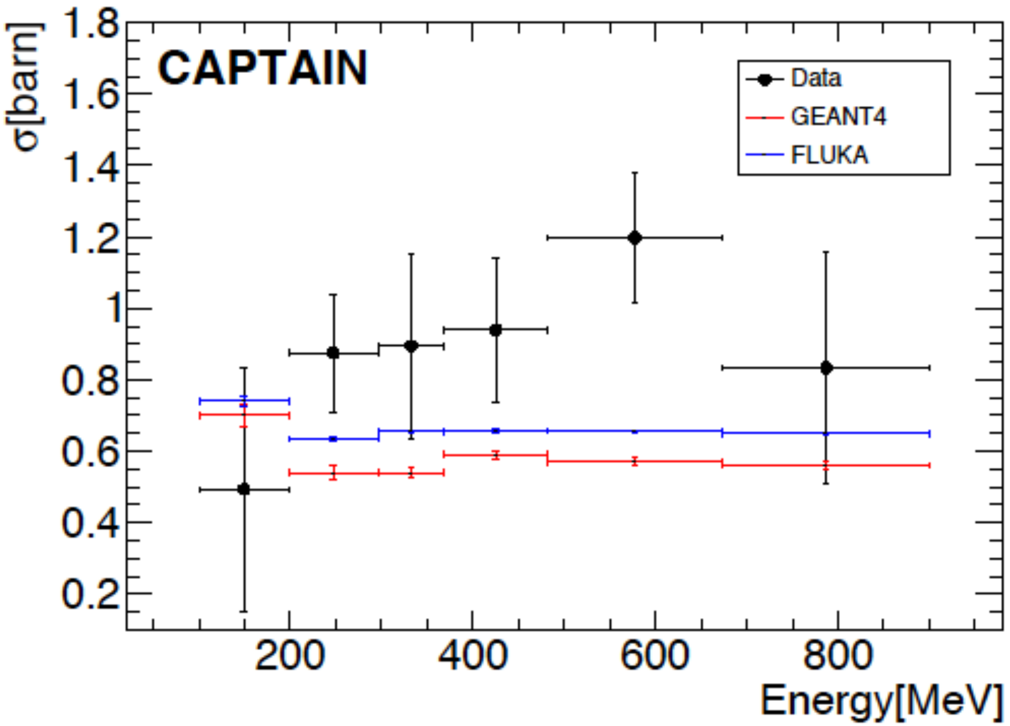
| Energy range [MeV] | Cross Section [barns] | $\chi^2$/ndof | Number of tracks |
|---|---|---|---|
| 100-199 | 0.49±0.34 | 1.48/3 | 264 |
| 199-296 | 0.88±0.16 | 11.81/7 | 536 |
| 296-369 | 0.89±0.26 | 4.739/5 | 329 |
| 369-481 | 0.94±0.20 | 8.262/6 | 413 |
| 481-674 | 1.20±0.18 | 5.713/6 | 624 |
|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

*arXiv:1903.05276*

# Cross section Measurement

- Current cross section measurement is dominated by statistical uncertainty
    - Uncertainty on position reconstruction of tracks was less than 4% and is negligible compared to statistical uncertainty
    - Reconstructed angle of track has less than a few percent uncertainty
    - Multiple track events could introduce as much as 10% variation in our cross-section – still not as large as statistical uncertainty
- Measured cross section is more or less consistent with models used in GEANT4 (QGSP_BERT) and FLUKA. However, some fine-tuning of models could provide better agreement with the Mini-CAPTAIN data.

*arXiv:1903.05276*



Note: noticeable deviation of data from models around 600 MeV

# Conclusions

- Measured total neutron cross section on argon by Mini-CAPTAIN consistent with an energy averaged cross section of:

$$0.91 \pm 0.10\ (\text{stat.}) \pm 0.09\ (\text{sys.})\ \text{barns}$$

- Measurements will help constrain uncertainties in models of neutron transport and help improve reconstruction performance in DUNE
- Data set used for this analysis corresponded to lowest intensity beam configuration – in future we will include additional data sets in other beam configurations