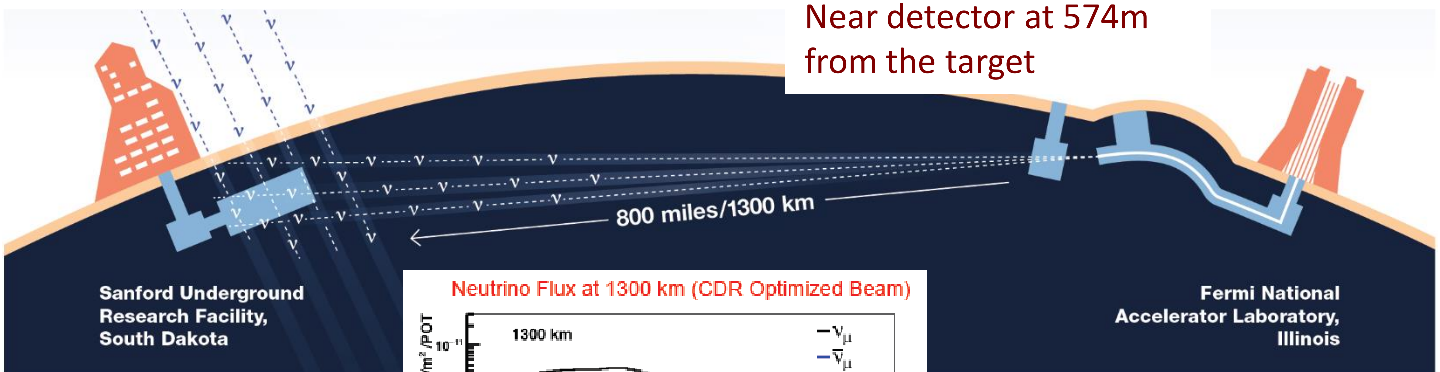
Status of DUNE Near Detector

S. Manly
University of Rochester
on behalf of the DUNE collaboration

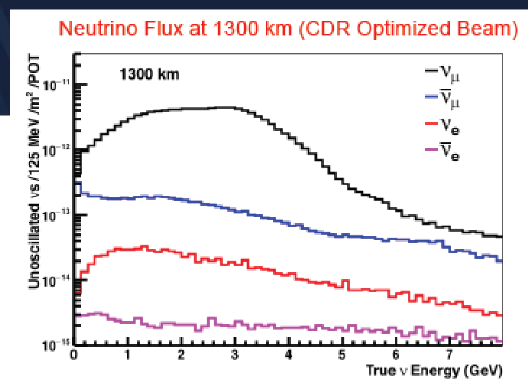
NUINT 2018
L'Aquila, Italy
October 15-19, 2018

steven.manly@rochester.edu

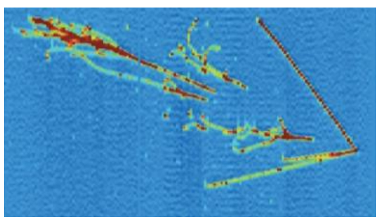
DUNE ≡ DEEP UNDERGROUND NEUTRINO EXPERIMENT



Near detector at 574m from the target



Intense wideband neutrino beam



Far detector: 4x10 kt liquid argon TPC

- Long baseline neutrino oscillations
- Supernova neutrinos
- Proton decay
- Near detector only physics program

As of Sept. 2018: 1144 collaborators from 178 institutions in 32 countries

Dr. Evil ponders the DUNE collaborator map with envy!

Near detector time line

Now

2015 2016 2017 2018 2019 2020 2021 2022

LBNE ND reference design

LBNE to DUNE transition

ND taskforce

ND design concept study

Concept study recommendations accepted

ND design group

ND construction consortia formed

FD TDR, ND CDR-light, ND CDR and TDR to follow

ND component prototypes and beam tests

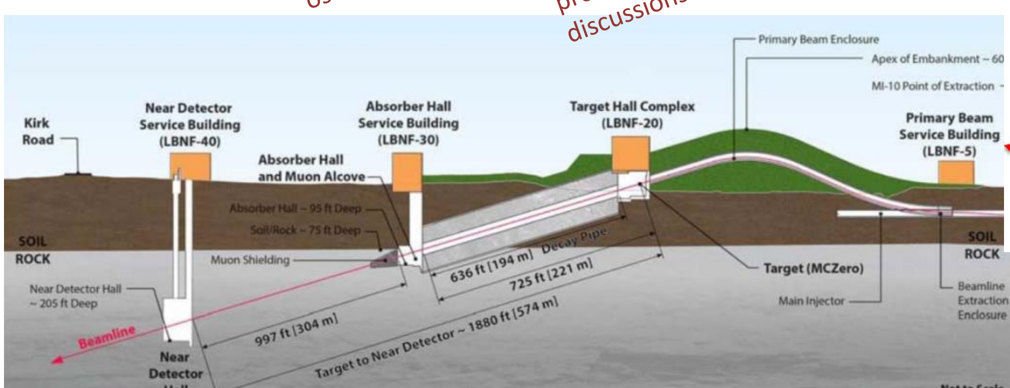
Infrastructure discussions, ND hall site cores taken

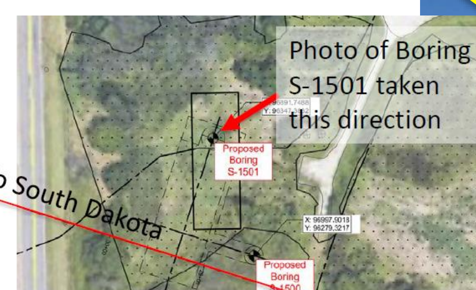
Bring in new collaborators and ideas, revisit old ideas

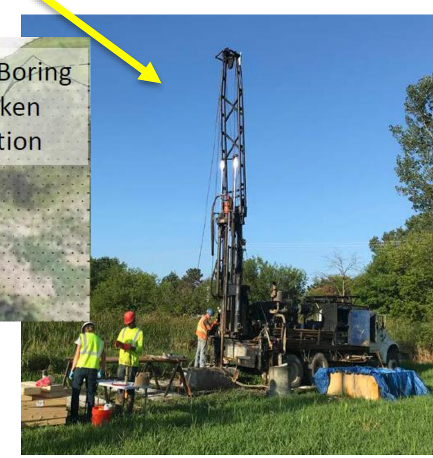
Pull together infrastructure to study ideas and impact on oscillation analysis

Studies, studies, endless discussions, R&D, prototyping, endless discussions

Get serious with prototyping, engineering, software





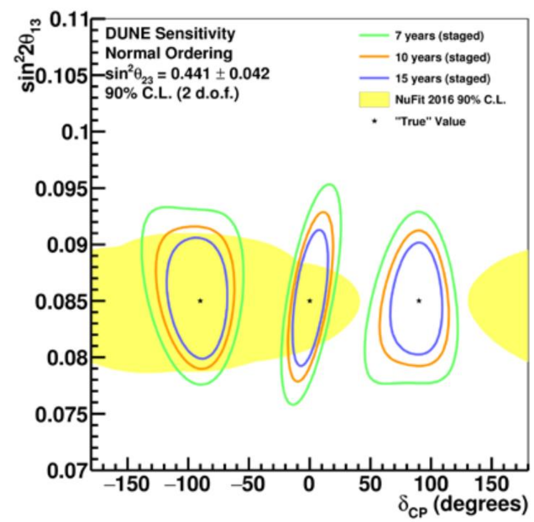


Near detector mission

Reduce systematic errors in the long baseline oscillation analysis

- detector reconstruction effects
- tune flux/xsec model
- reduce sensitivity to nuclear effects
- Beam monitoring
- Improve xsec model errors and constraints

Design choices being driven by far detector oscillation physics program



ND only physics

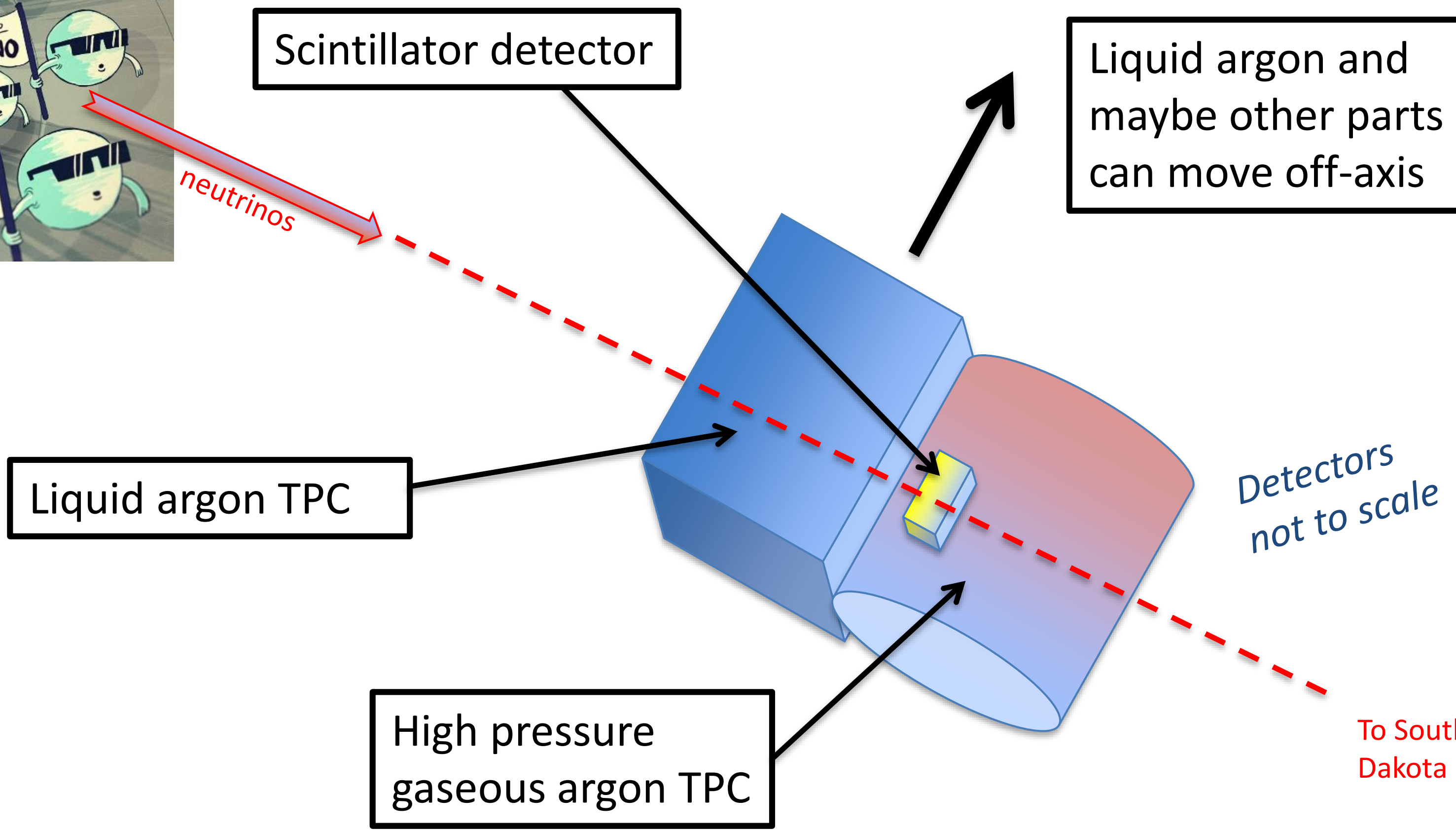
- Cross sections
- Nuclear physics
- QCD
- Electroweak
- Beyond standard model physics

Fortunately, most ND characteristics good for oscillations will be good for ND only physics as well

Near detector concept components

Will discuss the components separately and then come back to examine the role each plays in the integrated whole

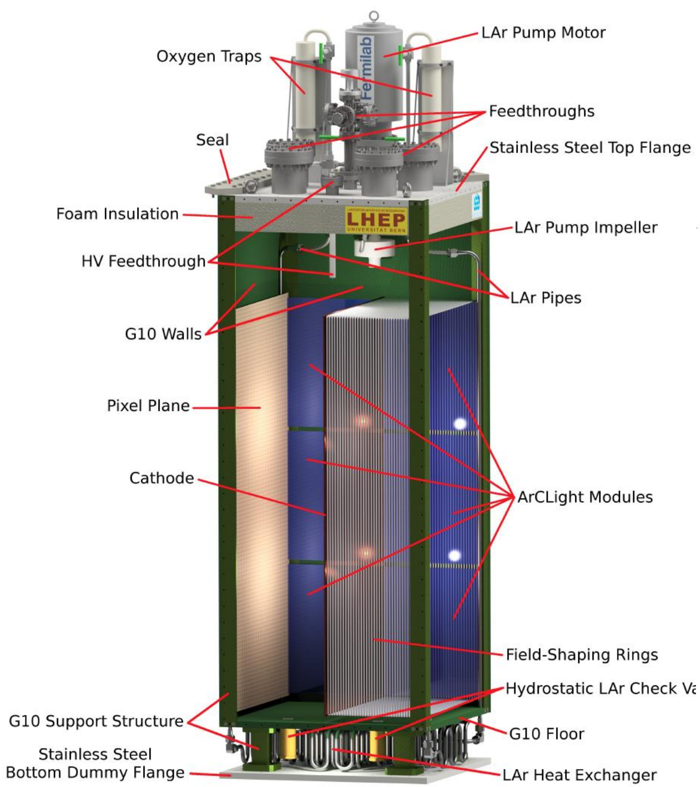
Fig. from Symmetry Magazine



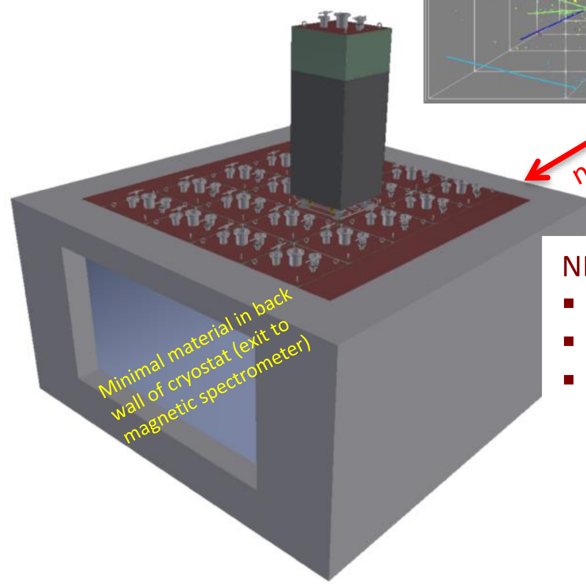
Near detector LArTPC concept

High rate at ND means this LArTPC design differs from FD

- Segmented, optically isolated drift regions
- 0.5 m drift (versus the multimeter drift of FD)
- Pixelated readout, low power electronics
- Continuous resistive plane field shaping

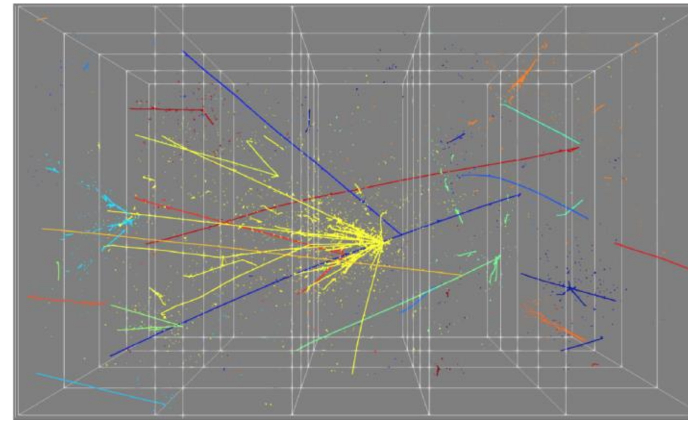


2x2 Demonstrator module.
Note, ND modules will not have individual pumps & filters



Drawing of baseline LAr ND component

Perhaps 7 module wide x 5 modules deep
(7 m x 5 m x 3 m)
Still under study



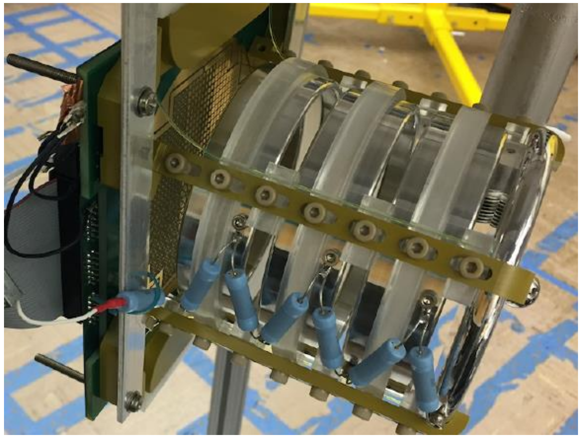
ND studies done with 4mx3mx5m TPC:

- Gives 3mx2mx3m fiducial volume
- FV mass 25 t
- Expect 37M CC ν_μ interactions per year (80 GeV protons, 1.5x10^{21} POT/yr)

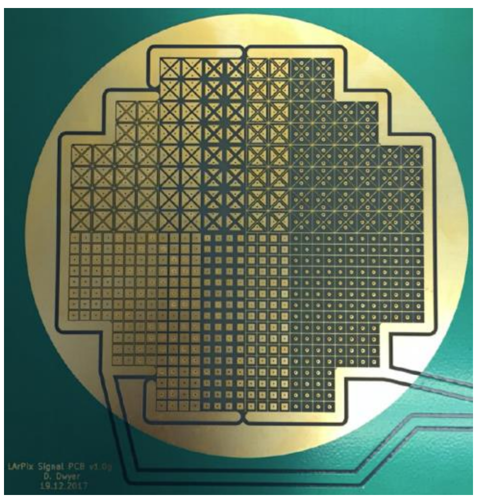
ArgonCube

The ArgonCube collaboration is working on a module design with these characteristics

ND LArTPC prototyping

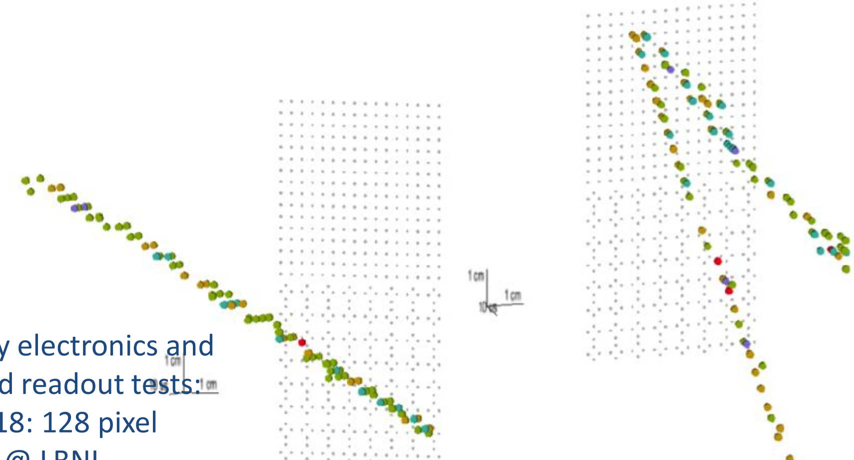


10-cm-drift test TPC



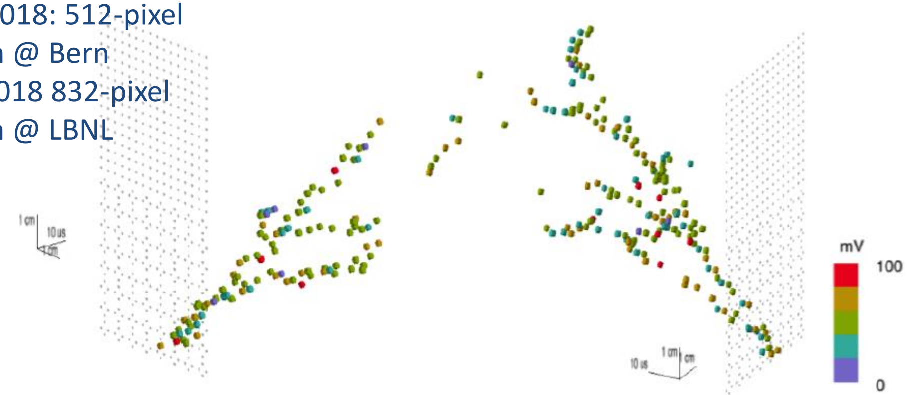
Test readout pixel board

From D.A. Dwyer et al, arXiv:1808.02969, Sept. 2018 (submitted to JINST)



Cosmic ray electronics and pixel board readout tests:

- Feb 2018: 128 pixel system @ LBNL
- April 2018: 512-pixel system @ Bern
- May 2018 832-pixel system @ LBNL

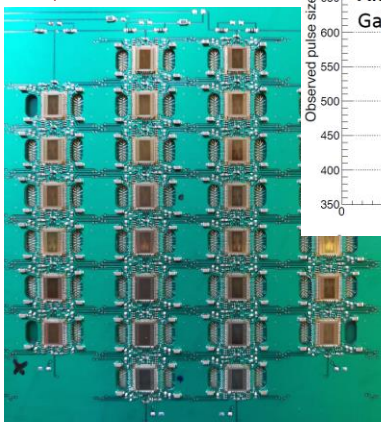


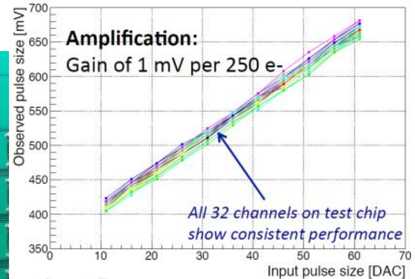
Cosmic ray interactions in test system using 4.8 cm x 9.6 cm pixelated readout in a 60-cm-drift LArTPC

For full 3D examples, see: https://goo.gl/AdVC9s

ND LArTPC prototyping

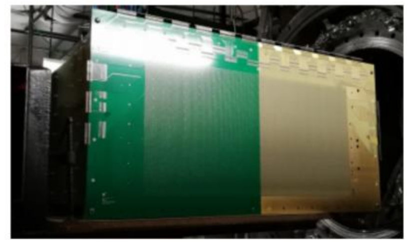
28-chip LArPix data board





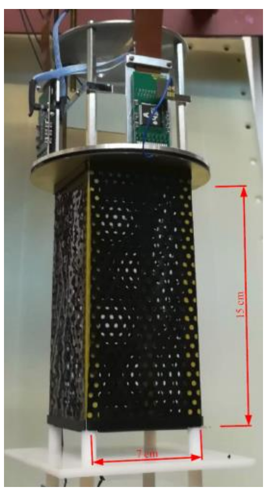
First generation of low power pixel readout chip (LArPix) very successful

LArIAT LArTPC

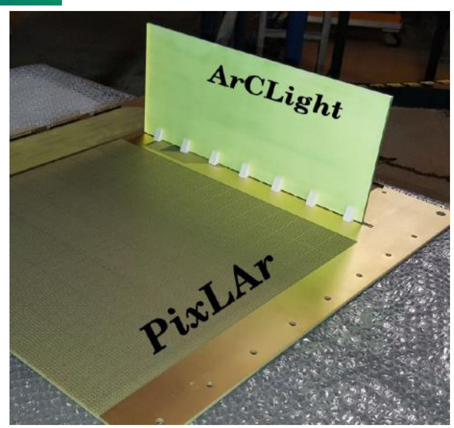


Readout area: 0.36 m^2
pixels: 22.5k
ASICs: 350
Target: Mid 2019

Hope to move to FNAL NuMI beam ~2020 for neutrino beam test (protoDUNE ND)

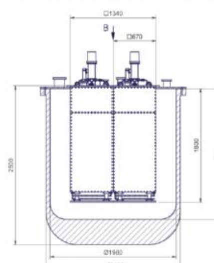


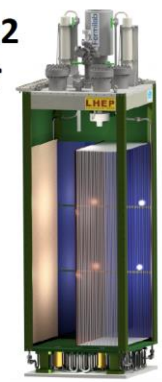
Resistive carbon loaded Kapton field shaping shell test



Delectric light readout prototype. Need good spatial and timing resolution to associate energy from neutron-induced protons with neutrino

ArgonCube 2x2 Demonstrator



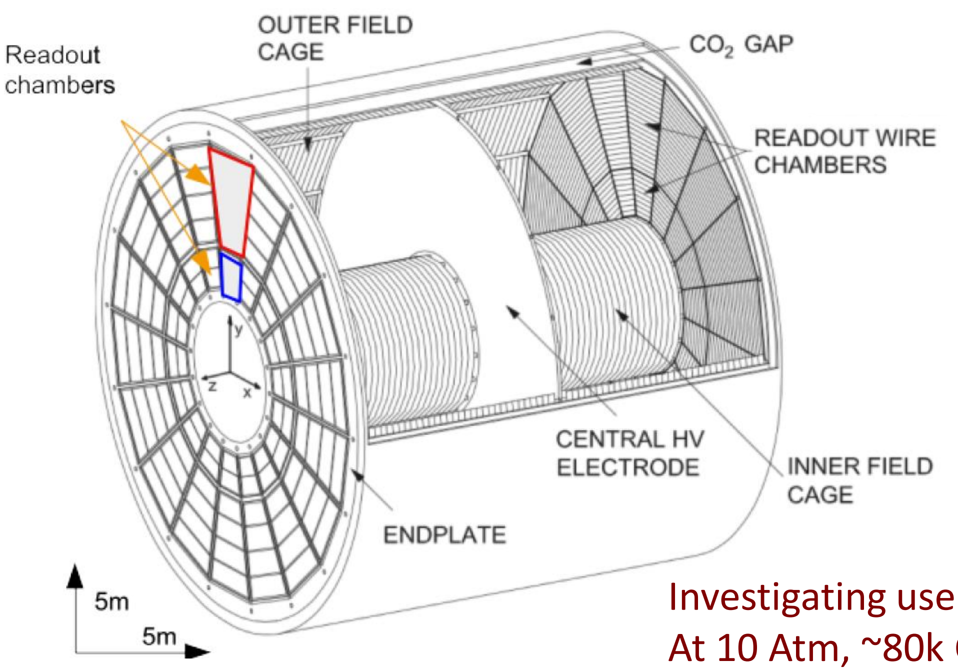


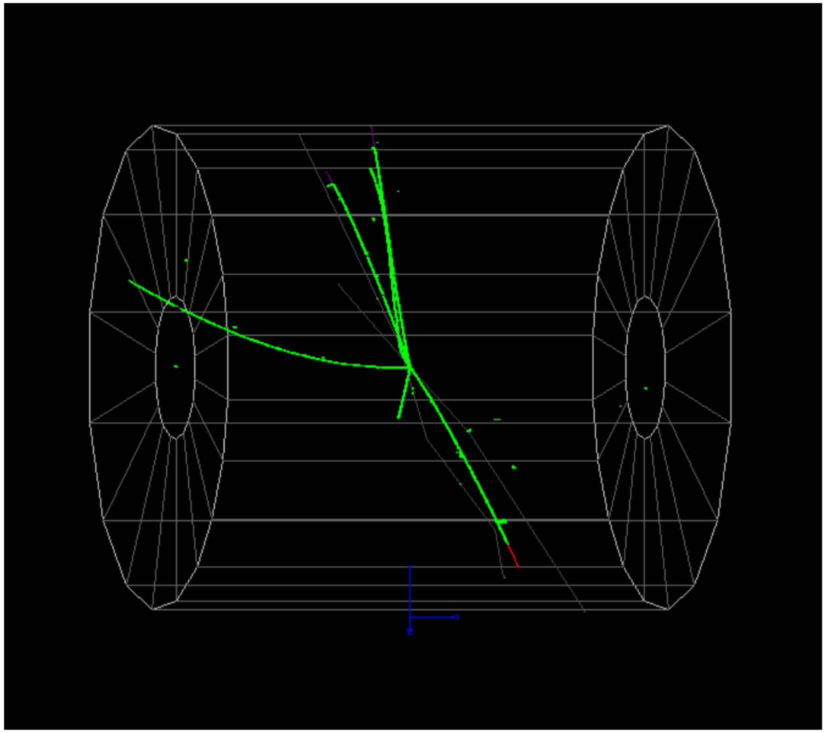
Readout area: 6.4 m^2
pixels: 400k
ASICs: 6.3k
Target: Late 2019

High pressure gaseous Ar TPC

- Copy ALICE TPC (no inner cylinder)
- Repurpose readout chambers (2019)
- Fill the central hole with new chamber
- New front end electronics
- Run with 10 atm mix Ar-CH_4 (90%-10%)
- Surround TPC with high-performance ECAL

Collider track reconstruction not so great for DUNE use. New software, GArSOFT, to be used.



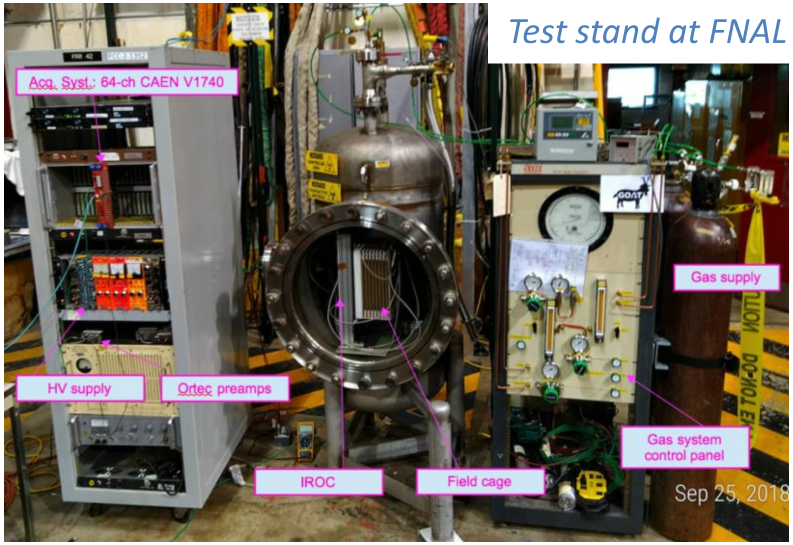


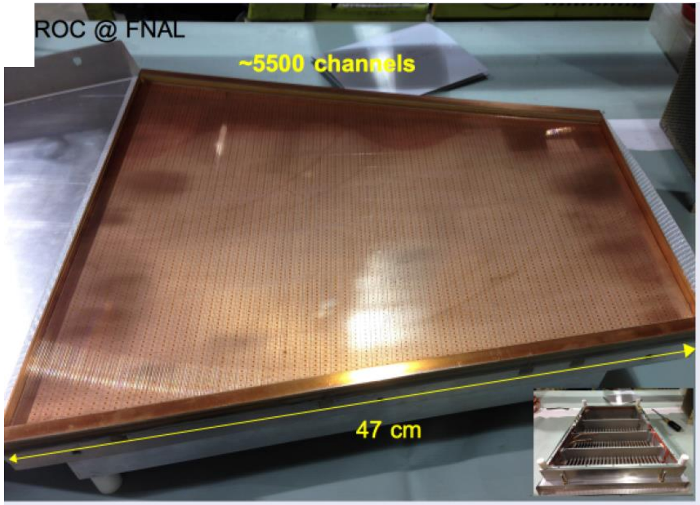
Investigating use of hydrogen
At 10 Atm, ~80k CC ν_μ events/year

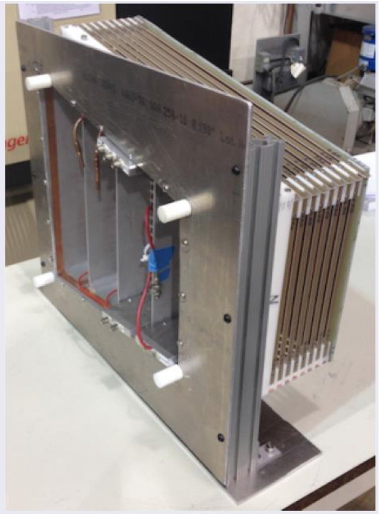
HPgArTPC prototyping

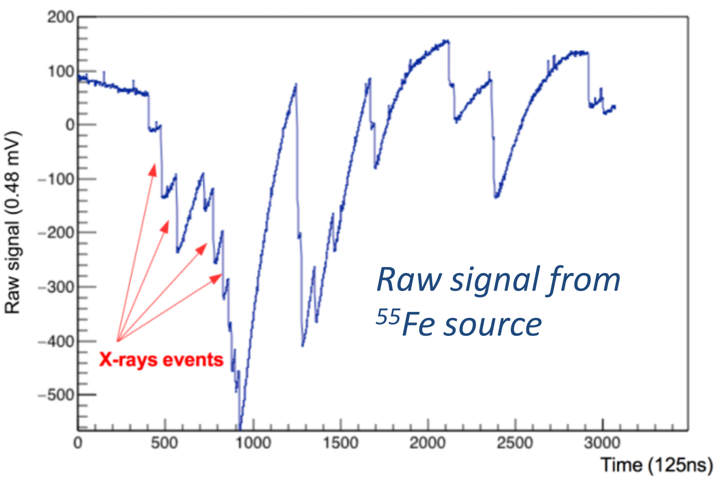
ALICE readout chamber and field cage at FNAL

Test stand at FNAL

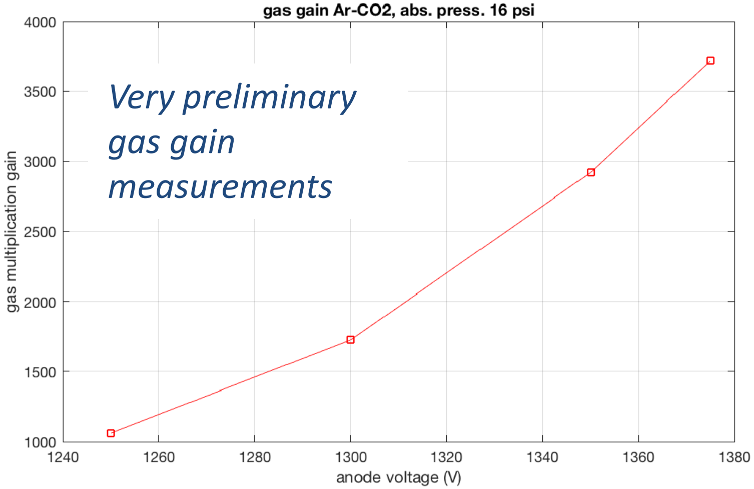








Raw signal from ^{55}Fe source



Very preliminary gas gain measurements

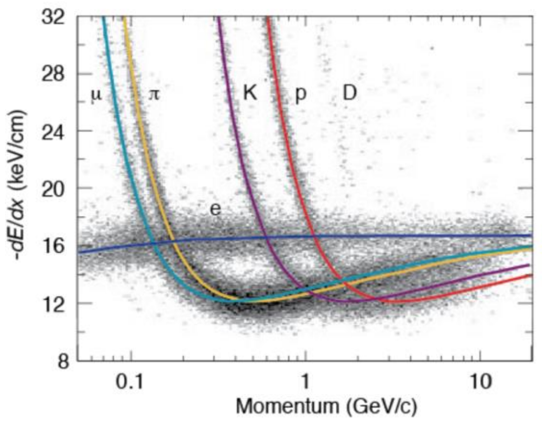
Performance specs await design

Some numbers used in ND studies just to give you an idea:

- ALICE size TPC at 10 Atm has active mass of 1.8 t
- Estimated fiducial mass of 1 t
- Yields 1.6 M CC ν_μ interactions per year (80 GeV protons, 1.5×10^{21} POT/yr) with Ar-CH4 gas mix at 10 Atm

Expectations based on ALICE and PEP4 experience

Parameter	Value	units
σ_x	250	μm
σ_y	250	μm
σ_z	1500	μm
$\sigma_{r\phi}$	<1000	μm
Two-track separation	1	cm
Angular resolution	2-4	mrad
σ(dE/dx)	5	%
σ_{p_T}/p_T	0.7	% (10-1 GeV/c)
σ_{p_T}/p_T	1-2	% (1-0.1 GeV/c)
Energy scale uncertainty	$\lesssim 1$	% (dominated by δ_p/p)
Charge particle detection thresh.	5	MeV (K.E.)



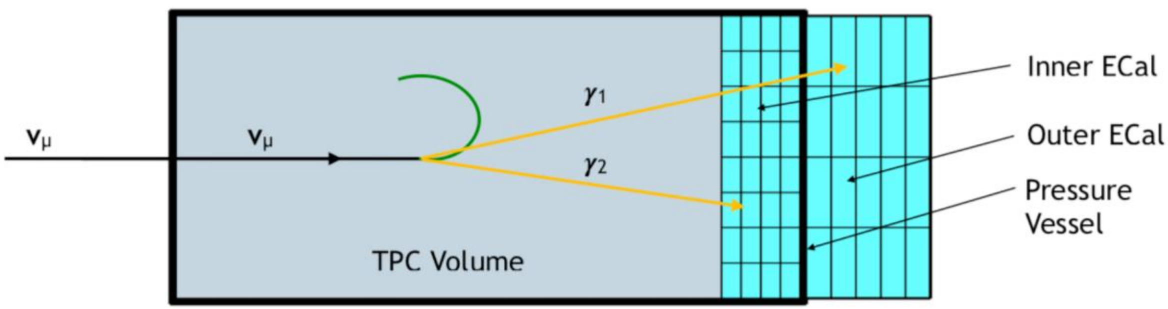
PEP-4/9 TPC (80:20 Ar-CH4, 8.5 Atm)

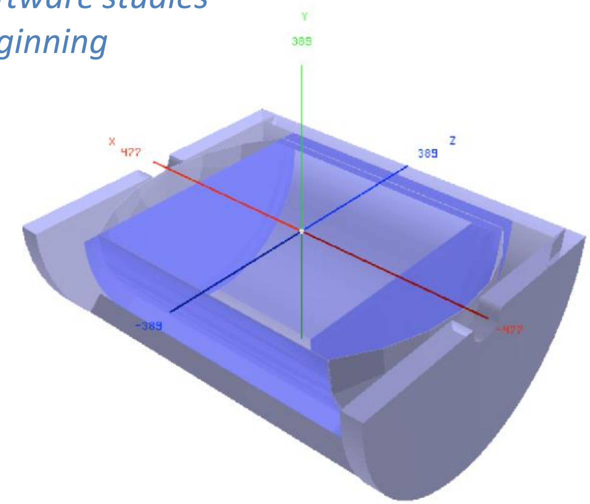
From "High-Pressure Argon Gas TPC Option for the DUNE Near Detector", prepared for submission to JINST and DUNE ND studies, 2018

Electron calorimetry for TPC

- ECAL used for timing t0 for reconstruction
- ECAL used for pizero (photon) reconstruction
- Exploring neutron detection/association performance

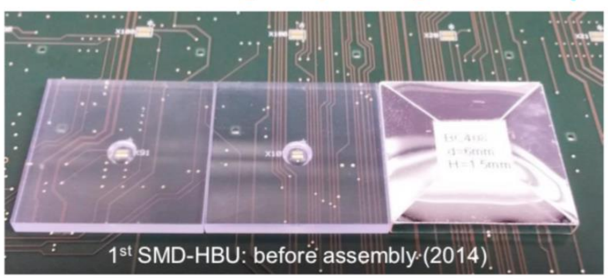
Software studies beginning

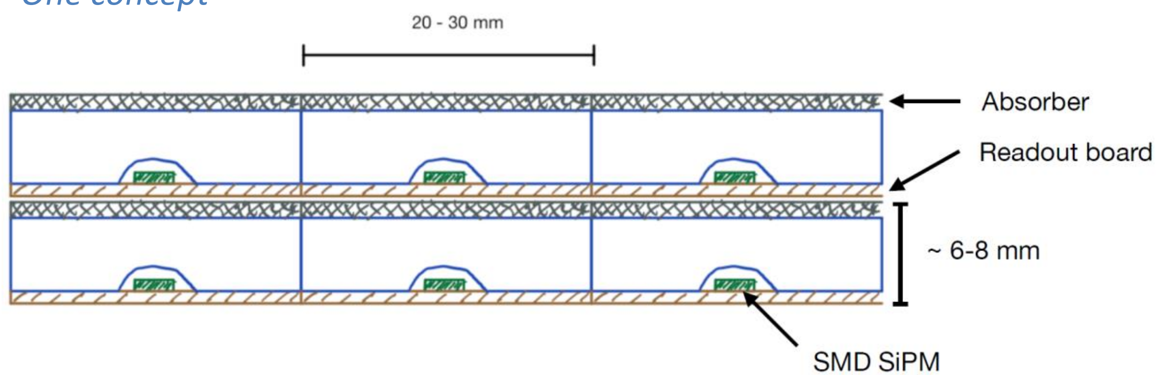




One concept

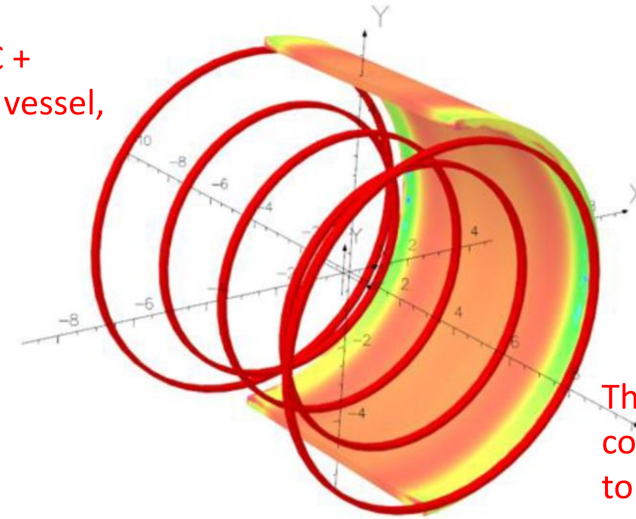
CALICE AHCAL concept





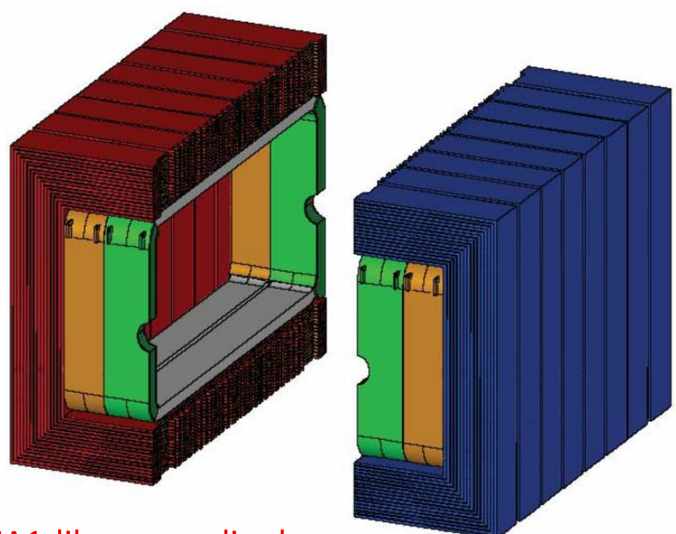
Magnet

Inside coils: TPC + ECAL + pressure vessel, maybe 3DST

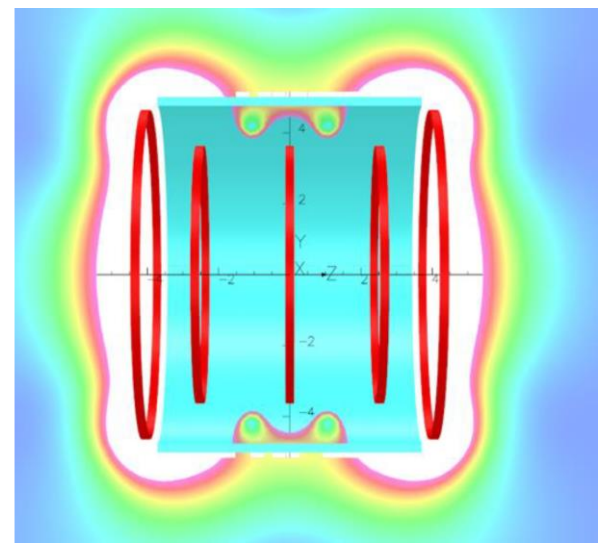


Possible material to help with muon-pion separation and/or deeper calorimetry

Three superconducting coil concept with two kicker coils to minimize flux bleed.



UA1-like warm dipole

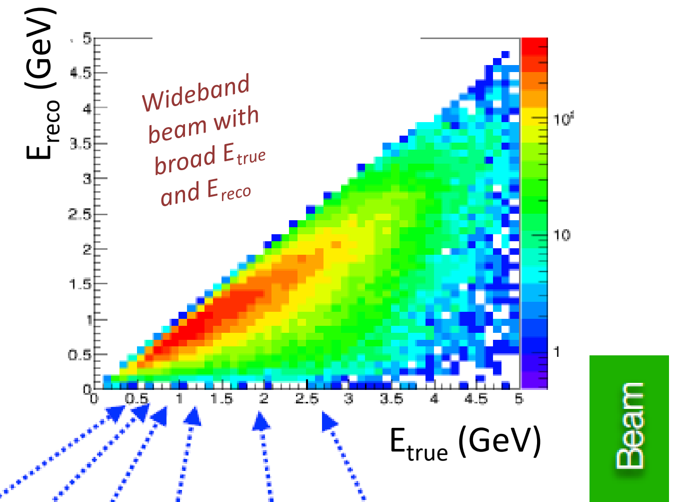


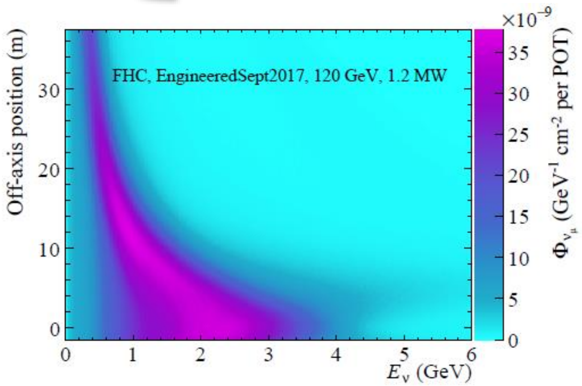
- Getting serious now that ND concept adopted
- Conventional warm "UA1-like" LBNE design being revisited
  - Rectangular volume not optimal for cylindrical TPC
  - Power and cooling significant ongoing cost
- Superconducting designs being considered
- Desire to minimize material between LAr and GArTPC

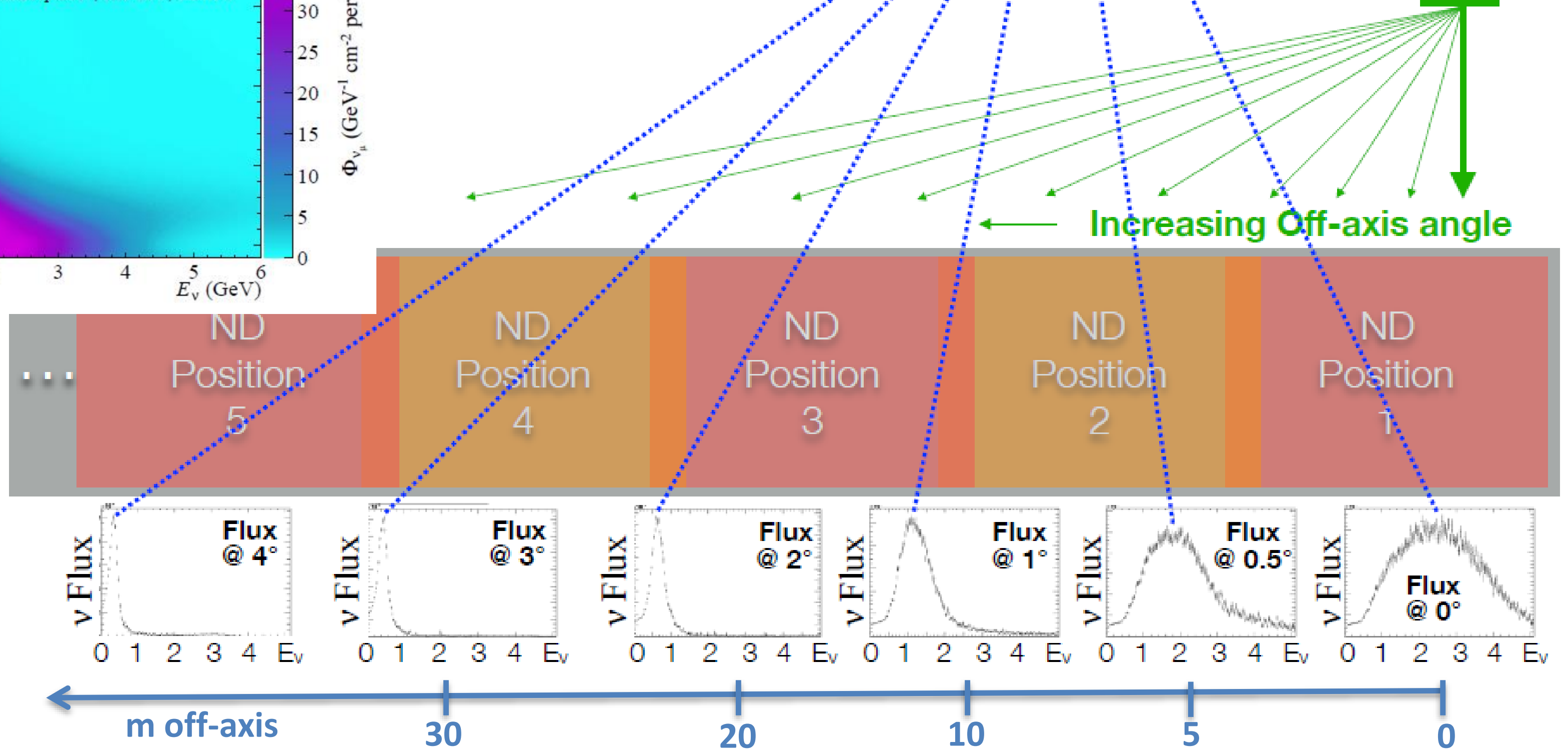
DUNE-PRISM

- Take data with ND in off-axis positions (up to ~27-33 m transverse movement at 574 m from target)
- Changing flux provides a new degree of freedom
  - Deconvolute xsec and flux errors
  - Construct E_{true} vs E_{reco} response matrix
  - Form FD oscillated flux with ND samples
  - Improved sensitivity to second oscillation region
  - Sensitivity to surprises and/or mismodeling

More on following slides

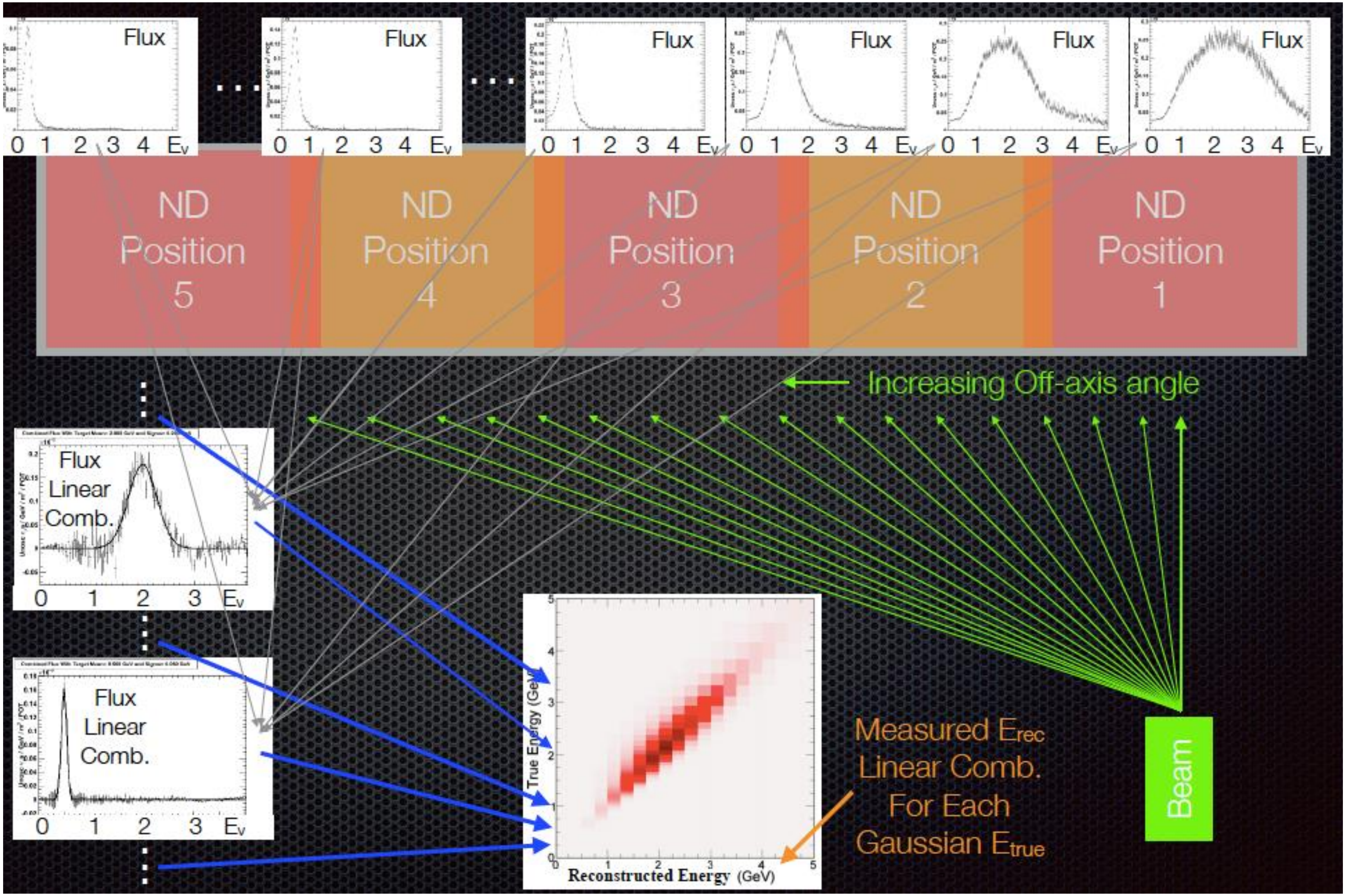






DUNE-PRISM

Instructive exercise – what to do with this information

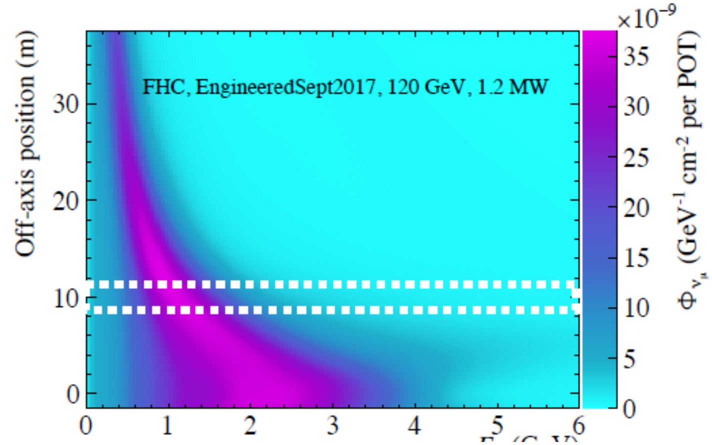


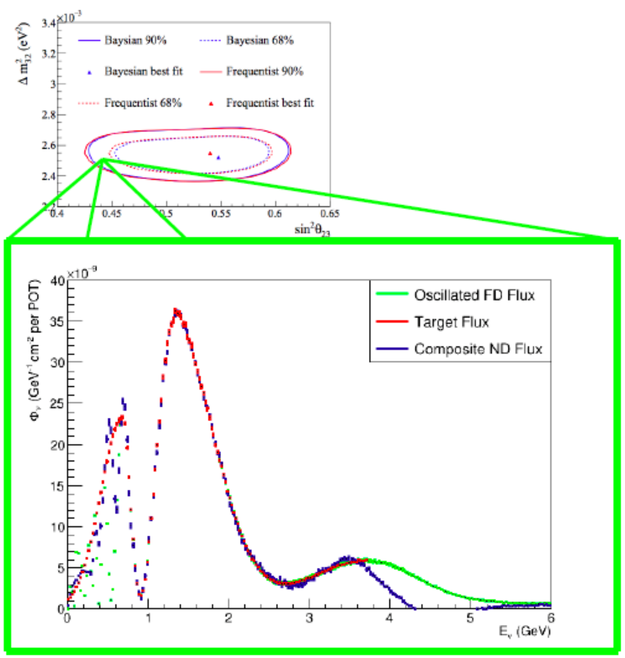
DUNE-PRISM

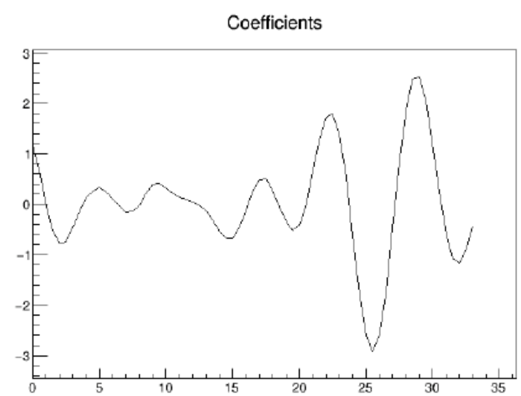
Senior collaborator's guide to something resembling actual use this information in analysis.

I've written this up in Fortran if you want it ☺.

- Use linear combination of off-axis fluxes to generate an ND flux that looks like the oscillated FD flux, i.e., minimize ND and FD flux difference and associated systematics
  - Make oscillated FD flux prediction with given parameters
  - Use linear combination of near detector flux slices to build FD flux prediction
  - Use coefficients of this fit to build linear sum of any ND efficiency-corrected observable
  - Apply FD efficiency
  - Gives data-driven FD prediction in this observable (minimal model dependence)







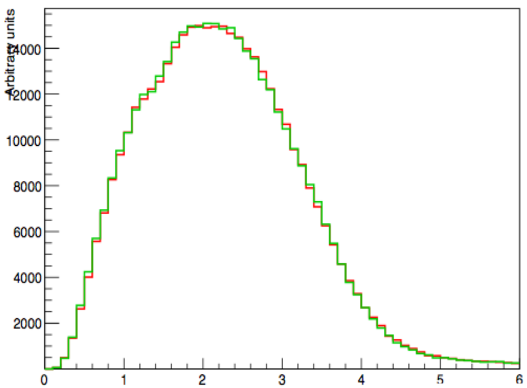
- $\Delta m^2_{23} = 0.0025$ eV²/c⁴
- $\sin^2\theta_{23} = 0.43$

DUNE-PRISM – ID hidden systematics

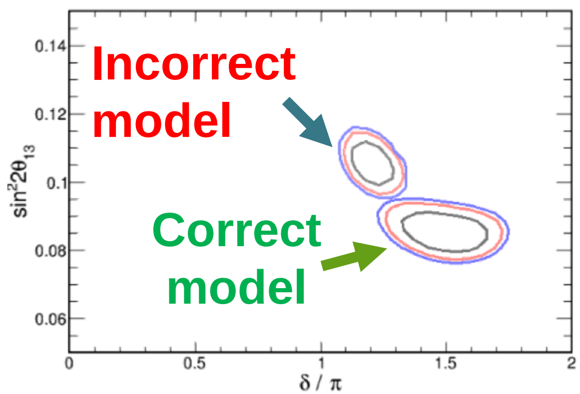
- Off-axis flux might be sensitive to problems not seen on axis
- Example fake data case study
  - Move 20% of proton energy to neutrons
  - ND on-axis fit fixes this by modifying xsec

My name is Steve and
I'm a bad-model-aholic

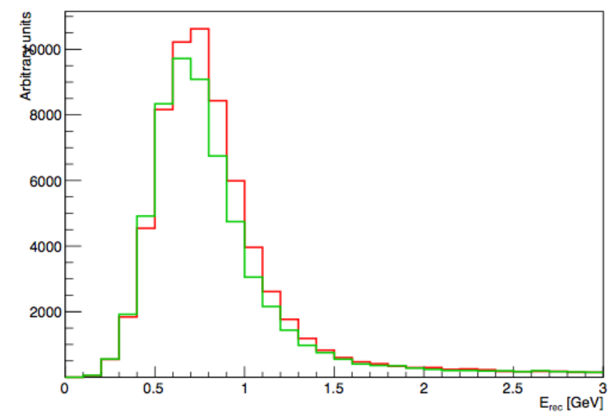
The first step toward
fixing a problem is
recognizing you have one



ND E_{reco} on-axis



Oscillation Contours



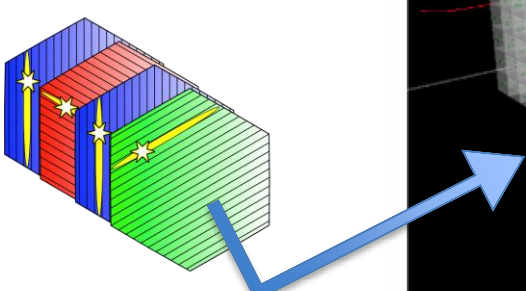
ND E_{reco}
18 m Off-Axis

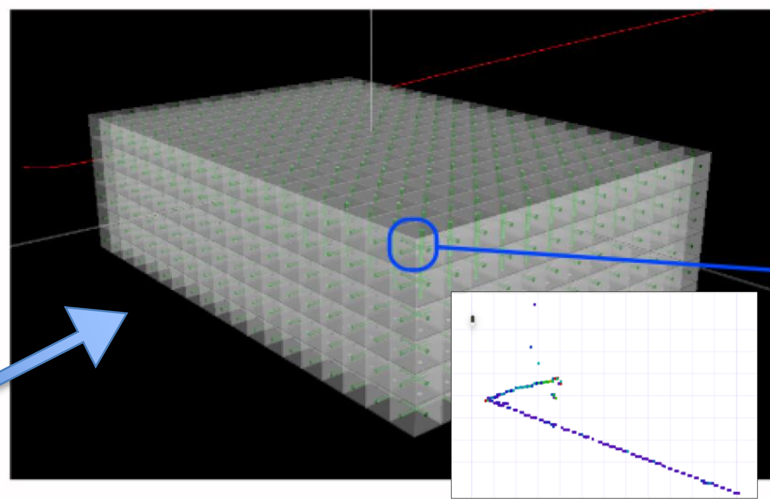
3D scintillator tracker

- Use 1cm cubes with WLS fiber along three (2 under study) orthogonal dimensions
  - Avoids performance drop at 90° typical of planar geometries
- Design functionally identical to T2K's ND280 upgrade SuperFGD detector
- Size and how device integrates with the rest of ND detector under study
  - Inside pressure vessel of HPgTPC
  - In own magnet with muon spectrometer and stays on axis when other parts move off axis
  - Other?

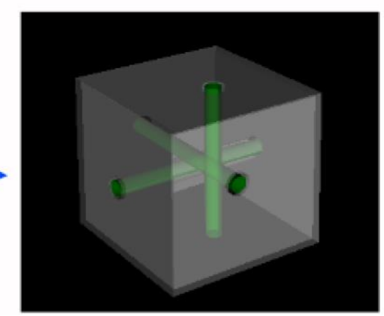
- If in TPC, tension over space
- Relatively high efficiency neutron tag in ~1m (more later in talk)
- Contain e^- showers from expected ν-e^- scattering with ~$12X_o$ of material (need backup ECAL)
- Example of statistics: 2mx2mx2m 3DST is 8.5 t (6.2 t fiducial mass) and give over 9M events/year in fiducial volume

For comparison MINERvA tracker fiducial volume ~5.6 t



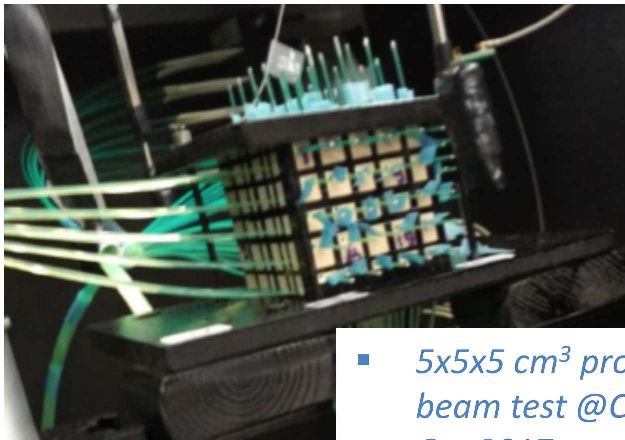


1 cm³

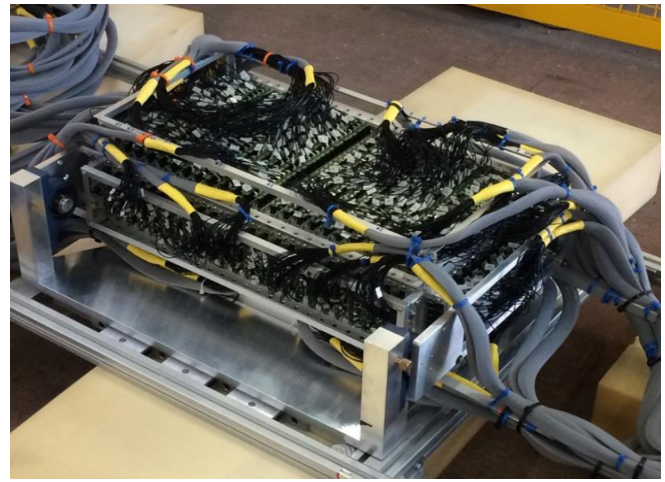


Yuri Kudenko – Scintillating perspective, 2017

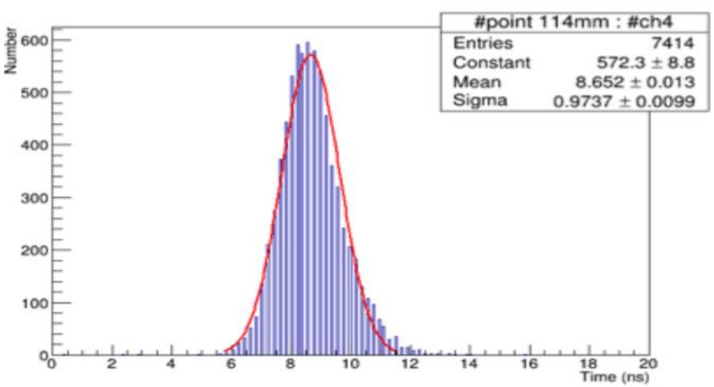
3DST (&SuperFGD) prototyping



- *5x5x5 cm^3 prototype beam test @CERN, Oct 2017*

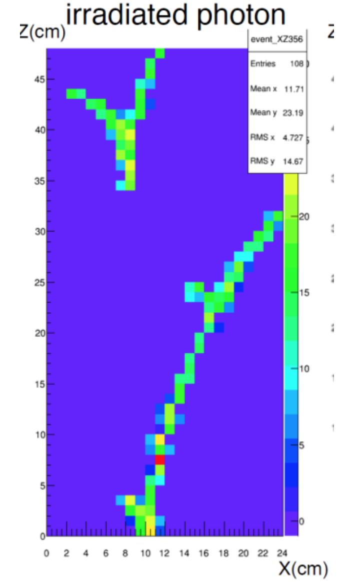


- *48x24x8 cm^3 prototype beam tests @CERN, summer 2018.*
- *0.2-0.7 T B field*
- *data under analysis*



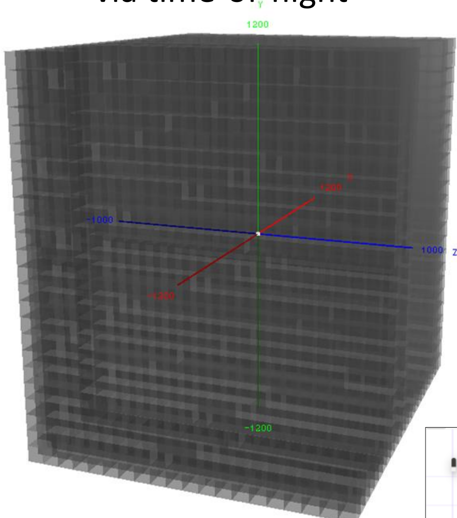
- *Ave light yield~41 p.e./fiber*
- *Ave σ_t~0.92 ns/fiber, 0.7 ns 2 fibers*

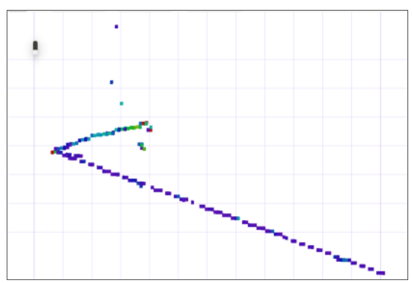
Electron w/ irradiated photon



DUNE ND and neutrons

- Early studies indicate the 3DST and/or ECAL around the HPgTPC should be useful for tagging neutrons and possibly reconstructing neutrons via time-of-flight



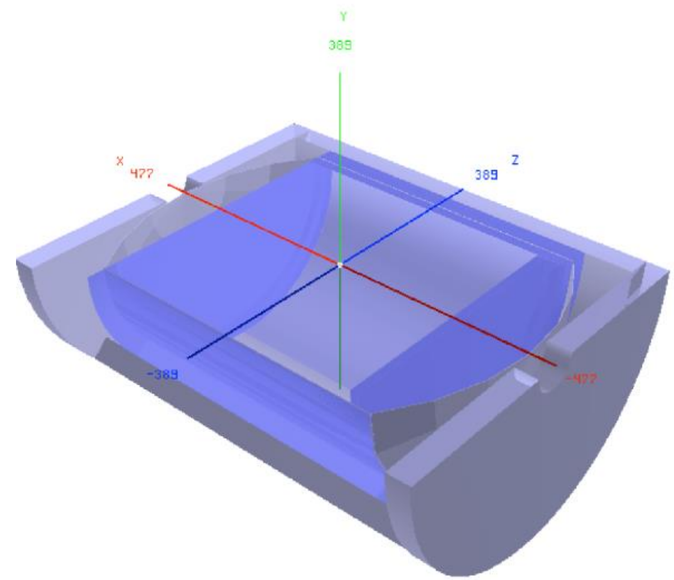


- Able to achieve neutron detection efficiencies in the 30%-80% range

- Neutron flight distance
- Background rate
- energy threshold
- Size of 3DST
- Sampling fraction and thickness of ECAL

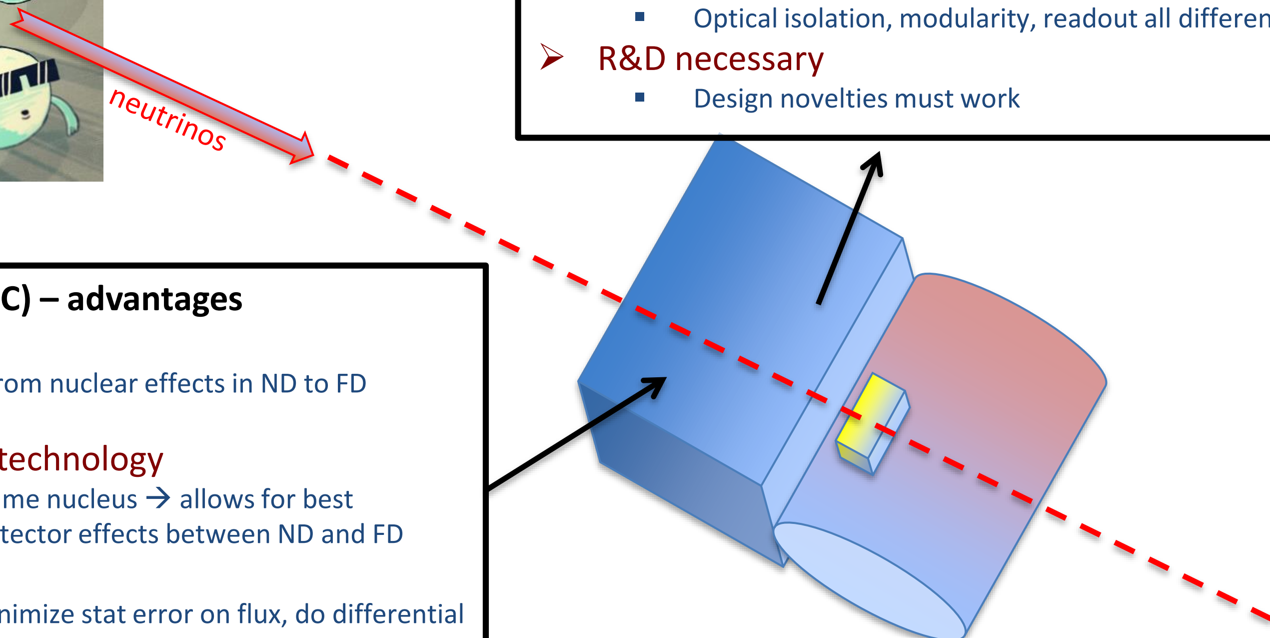
- Studies continuing

Interplay of all these things are important



Near detector concept

Fig. from Symmetry Magazine



LArTPC – challenges

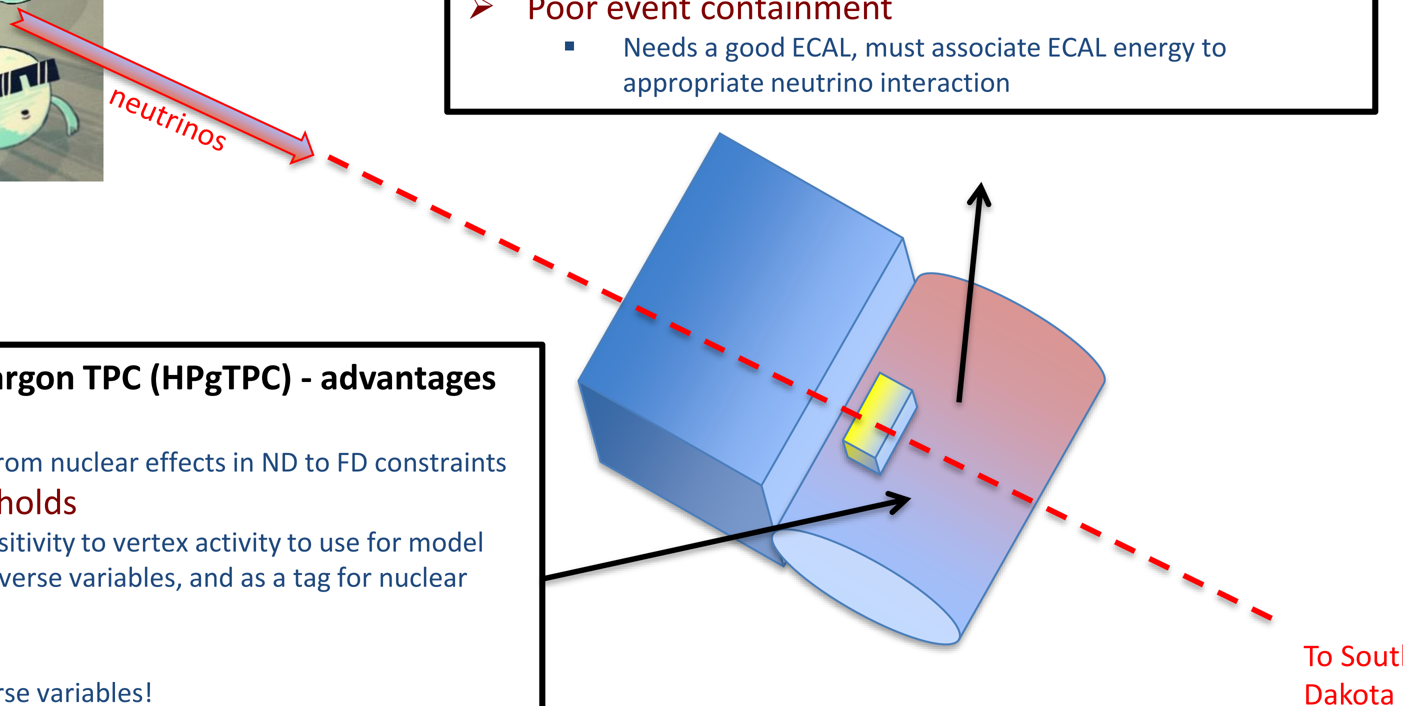
- ➢ Intense beam → high rate
  - Need to be able to trigger and associate tracks to correct events
- ➢ Rate-driven design → not same as FD
  - Optical isolation, modularity, readout all different
- ➢ R&D necessary
  - Design novelties must work

Liquid argon TPC (LArTPC) – advantages

- ➢ Same nucleus as FD
  - Minimize errors from nuclear effects in ND to FD constraints
- ➢ Functionally similar technology
  - Combined with same nucleus → allows for best cancellation of detector effects between ND and FD
- ➢ Large mass
  - High statistics, minimize stat error on flux, do differential analysis, ν-e- scattering
  - High rate, good for beam monitoring

Near detector concept

Fig. from Symmetry Magazine



High pressure gaseous argon TPC (HPgTPC) - challenges

- Relatively low rate
  - Minimize errors from nuclear effects in ND to FD constraints
- Poor event containment
  - Needs a good ECAL, must associate ECAL energy to appropriate neutrino interaction

High pressure gaseous argon TPC (HPgTPC) - advantages

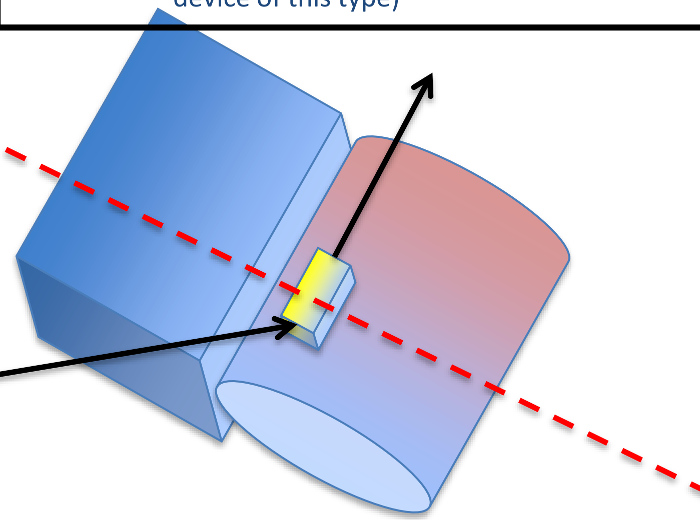
- Same nucleus
  - Minimize errors from nuclear effects in ND to FD constraints
- Low detection thresholds
  - Provides best sensitivity to vertex activity to use for model refinement, transverse variables, and as a tag for nuclear effects
- Exquisite resolution
  - Great for transverse variables!
- Minimal acceptance bias
- May be able to reconstruct neutrons in ECAL via TOF

Near detector concept

Fig. from Symmetry Magazine

3D scintillator tracker - challenges

- Not argon
  - How well do results map to constraining Argon?
- Relatively poor resolution, track separation
  - Good for scintillator, but this is not a TPC
- Integration issues
- R&D
  - Construction/design (SuperFGD will be first large-scale device of this type)



3D scintillator tracker - advantages

- High rate
  - Beam monitoring, differential analysis
- Good containment
- Fast timing
  - May help us understand backgrounds if bad
- Neutrons
  - Can likely include neutrons in reconstruction with high efficiency
- Connects to large catalog of carbon/CH data
- Minimal acceptance bias for CH detector
- Functionally similar to SuperFGD

Near detector concept

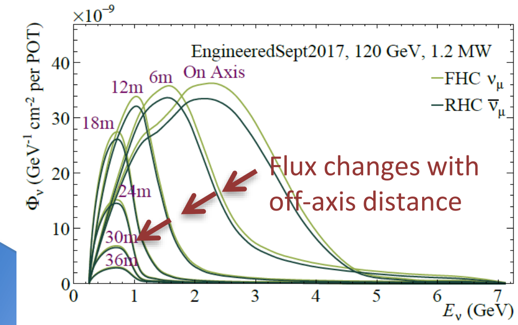
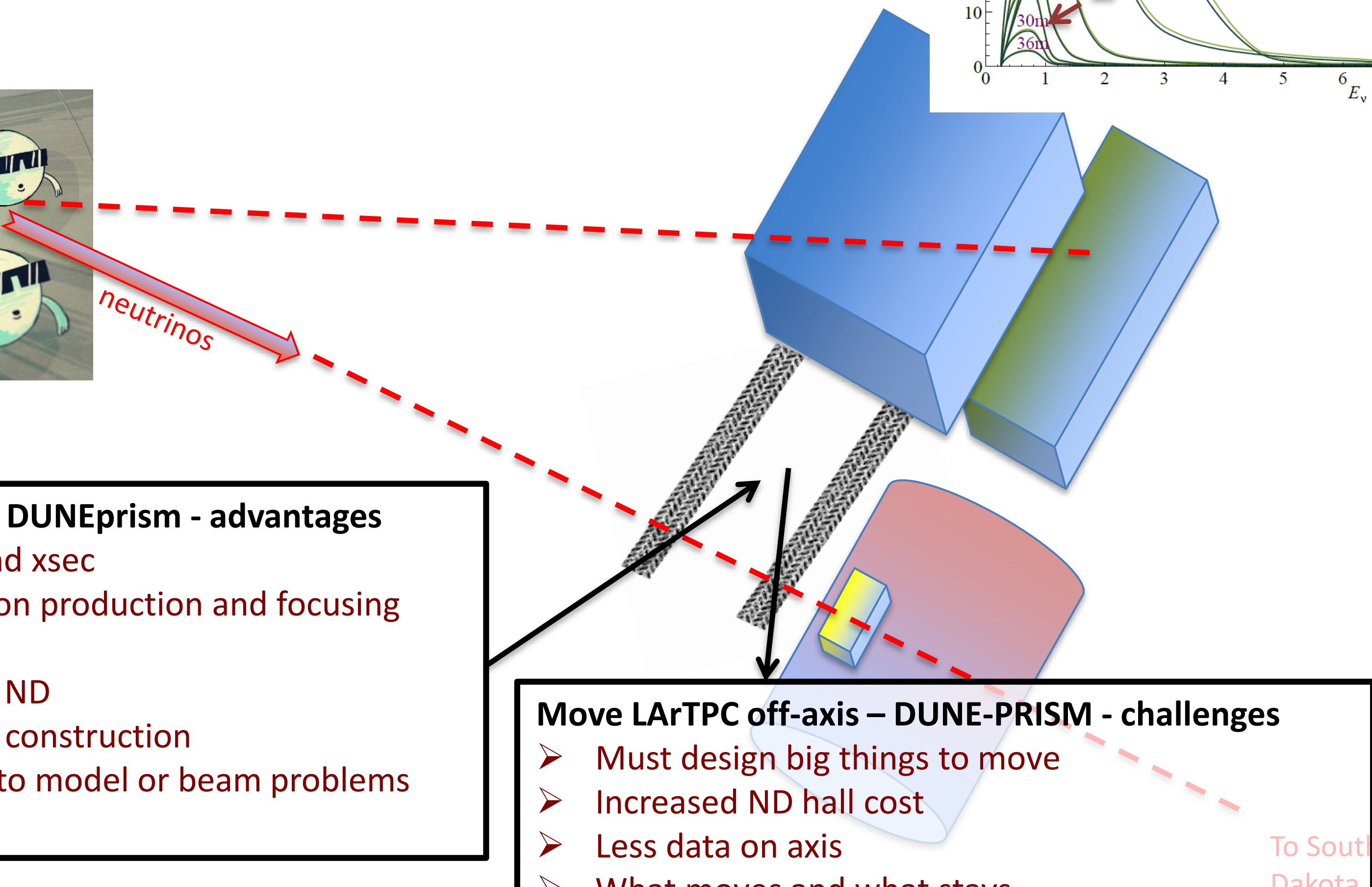


Fig. from Symmetry Magazine



Move LArTPC off-axis – DUNEprism - advantages

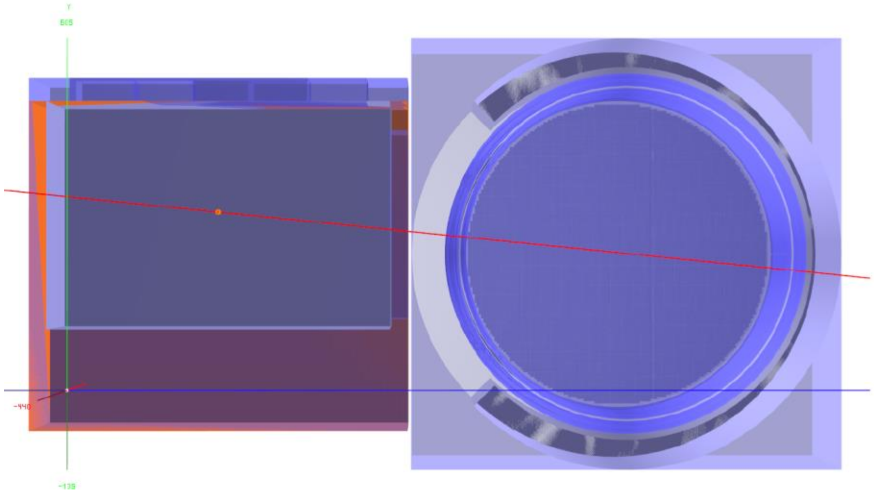
- Deconvolute flux and xsec
- Help untangle hadron production and focusing errors in flux
- FD flux modeling at ND
- True-to-reco matrix construction
- Possible sensitivity to model or beam problems not seen otherwise

Move LArTPC off-axis – DUNE-PRISM - challenges

- Must design big things to move
- Increased ND hall cost
- Less data on axis
- What moves and what stays
  - want same detector on axis and off axis
  - need spectrometer
  - want stable on axis measurement and monitoring

Where we are headed …

- Confronting conceptual issues
  - What moves for DUNE-PRISM
    - LAr + gTPC moves, leaving 3DST plus muon spectrometer on-axis?
    - LAr + muon spectrometer moves, leaves gTPC + 3DST on-axis?
    - Other?
  - Magnet design
  - 3DST size, shape, environment
  - Additional muon spectrometer
- Continued R&D on all fronts
- Design and cost issues
  - Magnet
  - Size of ND hall (DUNEprism movement)
  - Size of LArTPC
- Support FD TDR submission in late spring 2019
- ND CDR 2019
- Form detailed design/construction consortia in 2019

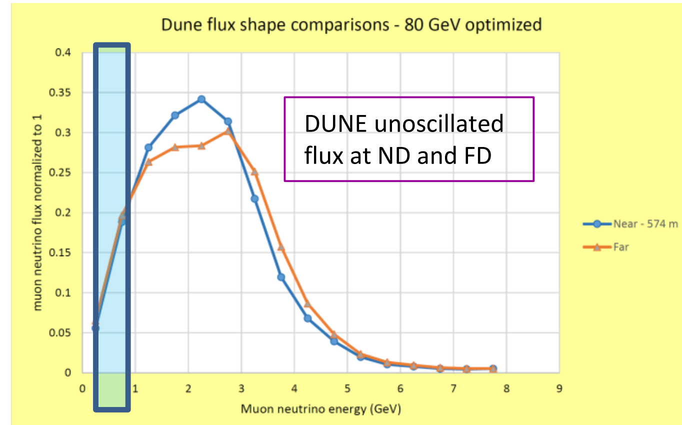


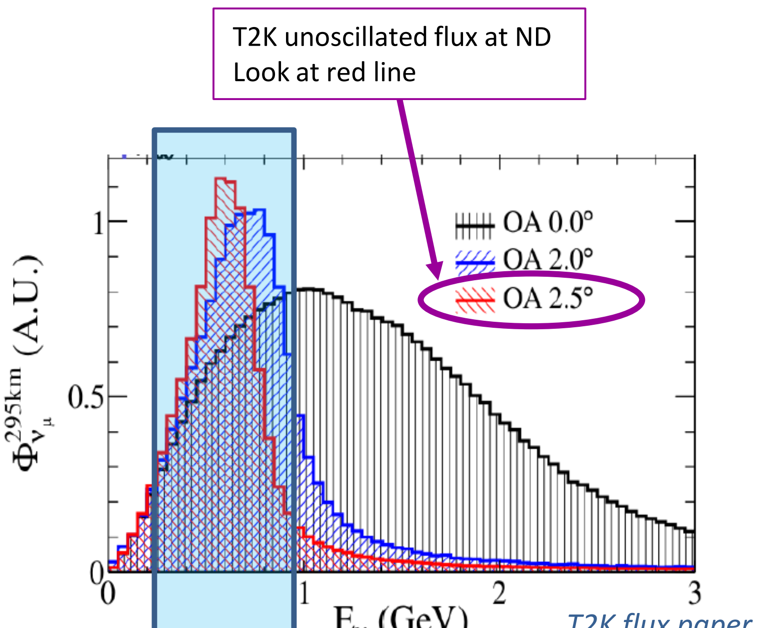
Much formative fun still left to be had! Interested collaborators welcome!!

Backups

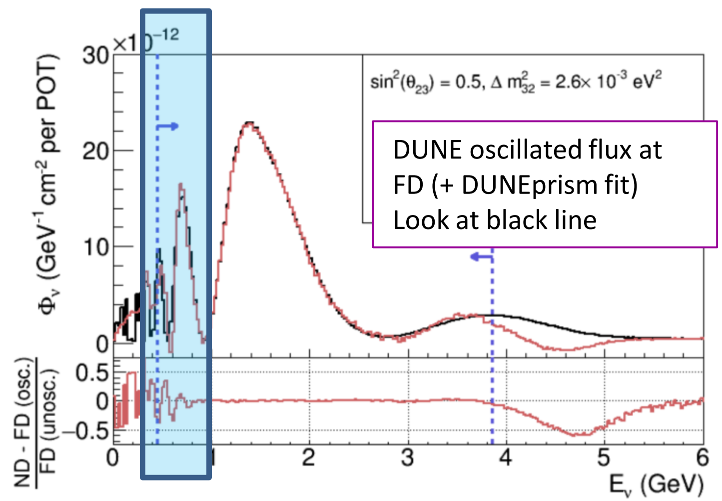
3DST and SuperFGD complementarity

- SuperFGD functionally identical to 3DST
- SuperFGD sees flux in DUNE 2nd oscillation energy region
- DUNE has ND flux in the same region but also has higher energy flux that might confuse matters (e.g. misreconstructions and NC backgrounds)
- Potentially valuable handle for DUNE to understand response function and backgrounds in second oscillation region





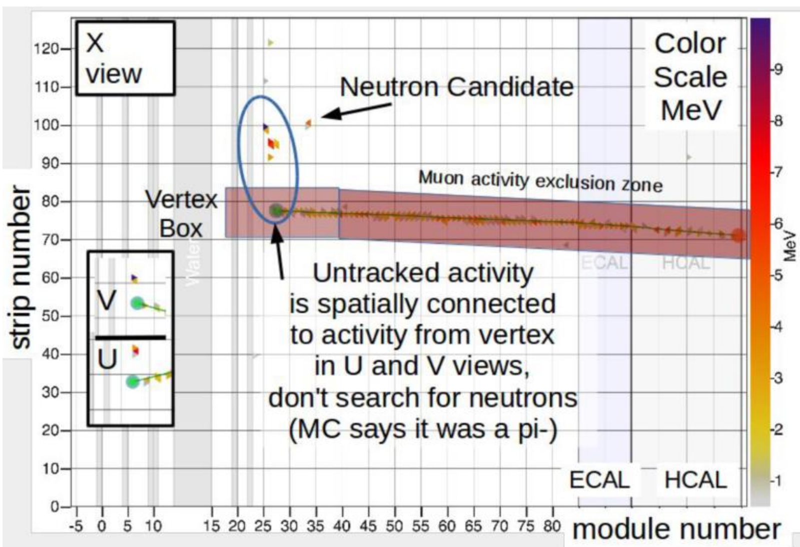
T2K flux paper

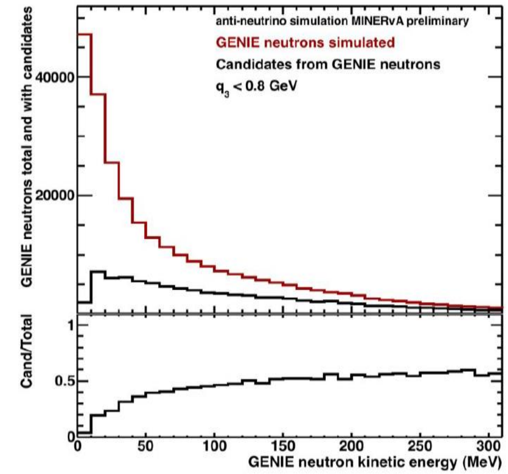


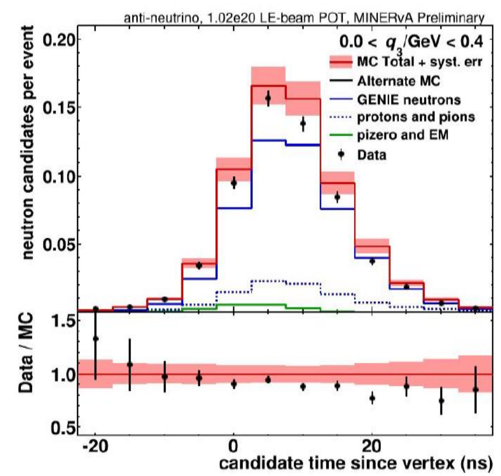
Neutrons

- MINERvA has demonstrated ability to detect neutrons
  - Low KE neutrons – planar geometry means no 3D
  - Higher KE neutrons – 3D reconstruction
- Multiplicity, energy and spatial distributions, timing all fairly well described by simulation

Recall Miranda Elkins' poster at last NUINT!
Fermilab Wine and Cheese talk on Nov. 3, 2017 by Rik Gran
Tejin Cai, Fermilab Xsec Workshop, March 2018

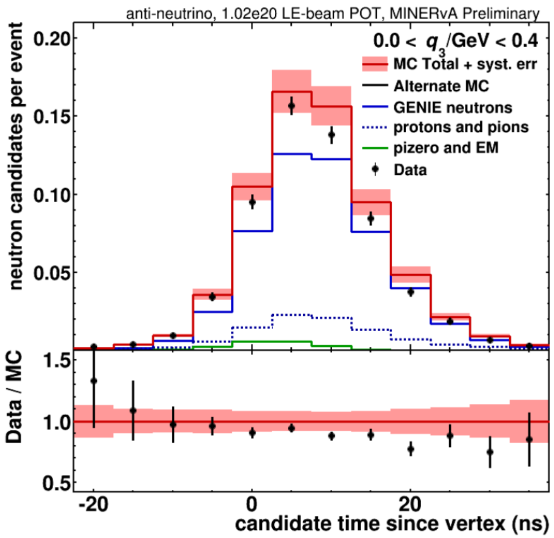




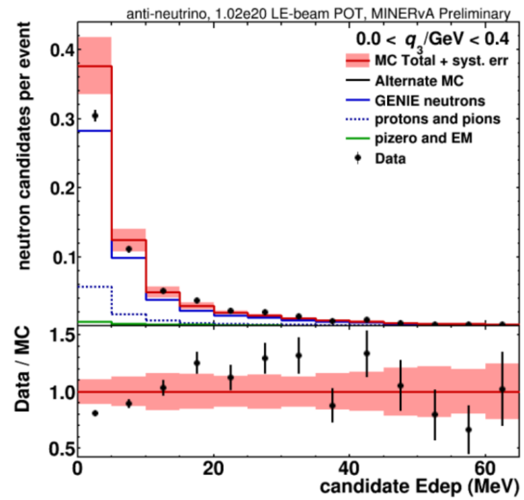


MINERvA data

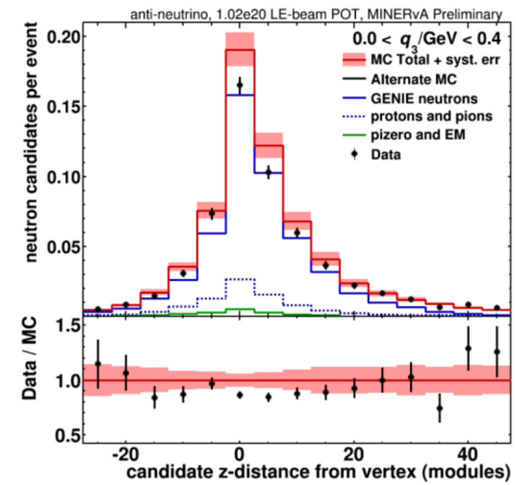
From MINERvA (R. Gran), FNAL Joint Experimental and Theoretical Seminar, Nov. 3, 2017



Time since interaction



Deposited energy per candidate

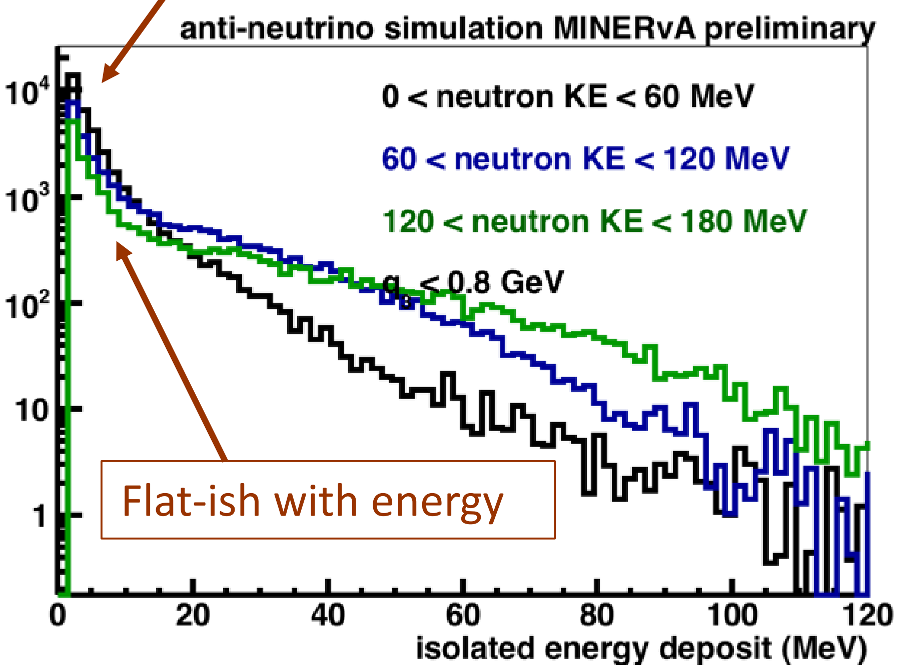


Position relative to interaction (upstream vs. downstream)

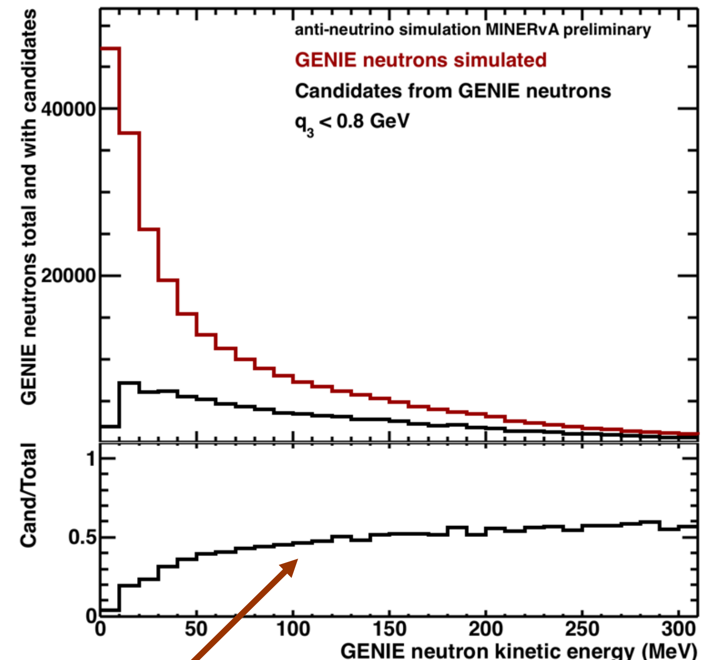
- MINERvA seems to see the neutrons.
- Dominated by the low energy (2-6 MeV) candidates in this analysis
- Data-MC agreement not so bad (surprisingly?)
- MINERvA only able to get Z position for the low energy candidates
- Can get 3D reconstruction only for higher energy candidates (multiple planes)

Expectation from MINERvA GENIE/GEANT simulation

Bulk of neutron energy depositions are small (2-6 MeV) – Note log scale



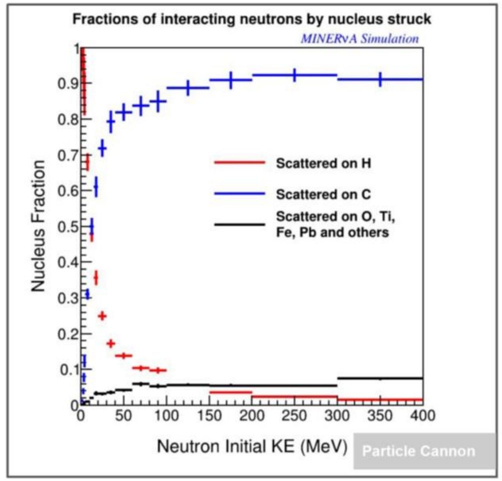
Flat-ish with energy

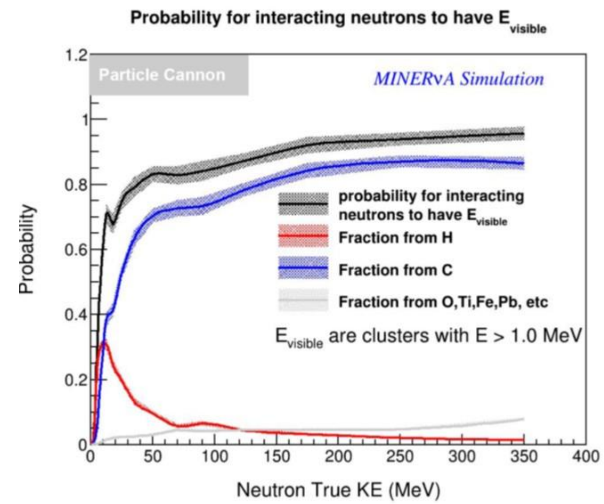


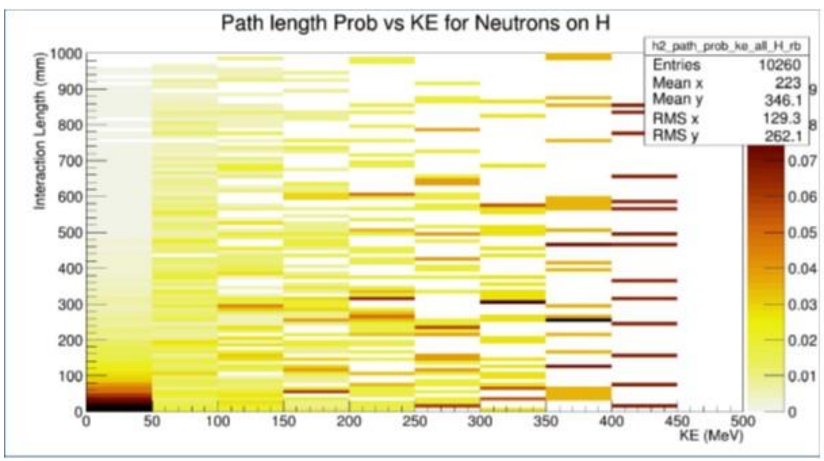
Neutron detection efficiency rises with neutron KE and reaches 50-60% for KE>50 MeV

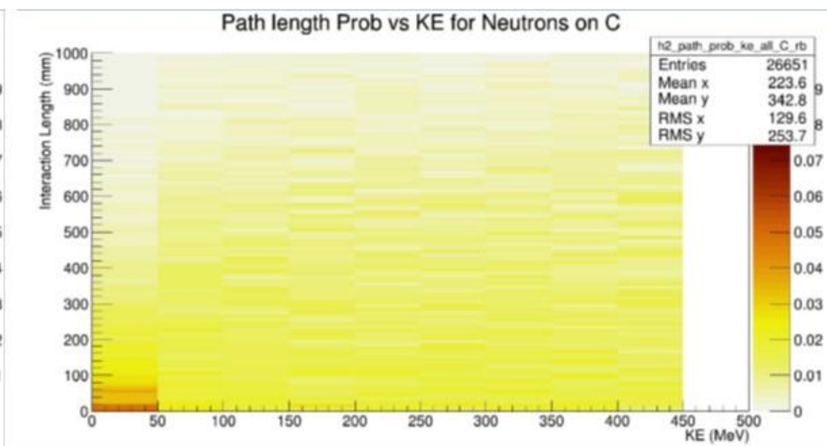
Particle gun studies from MINERvA (Tejin Cai), presented at Xsec workshop at FNAL, March 13, 2018

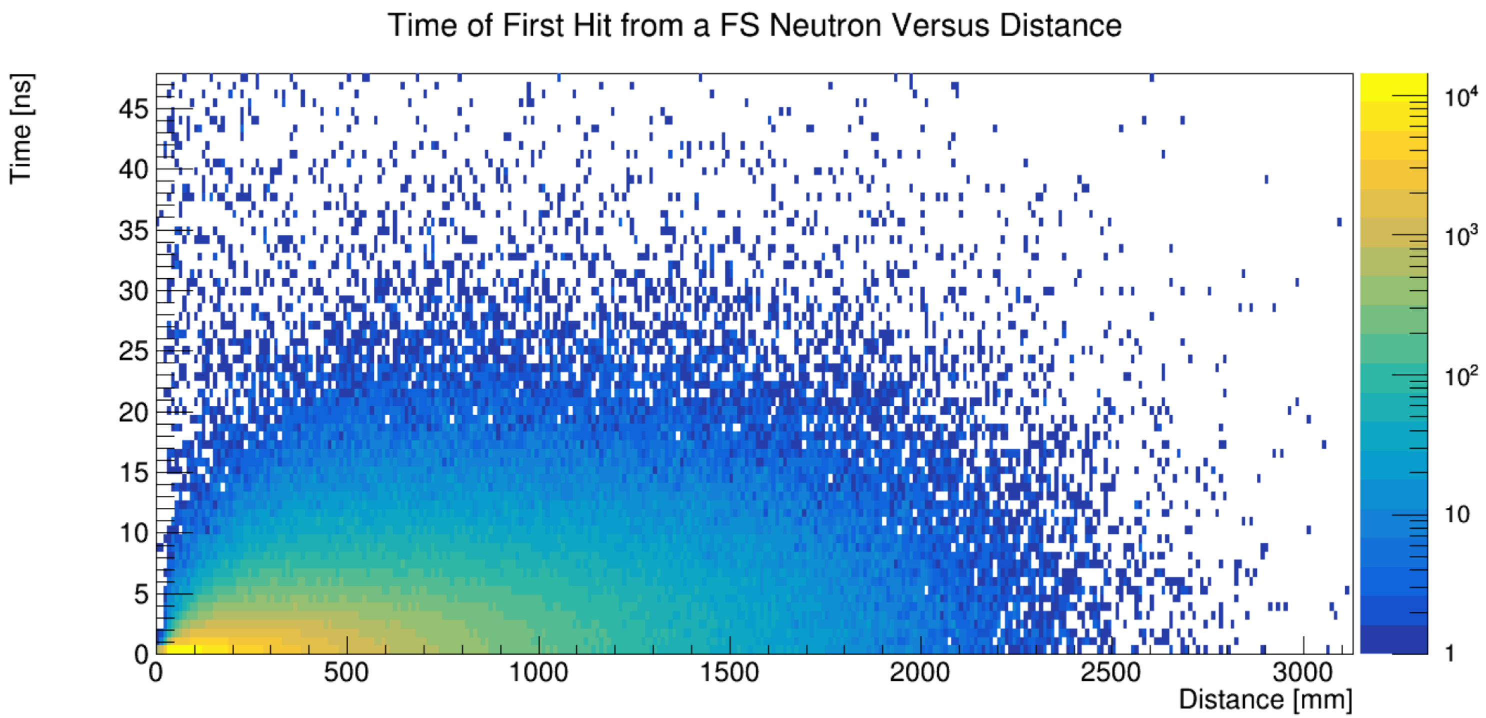
- Low n KE, more likely to interact on H
- Interactions on C more likely to leave visible energy
- Energy deposits happen fairly close to interaction vertex







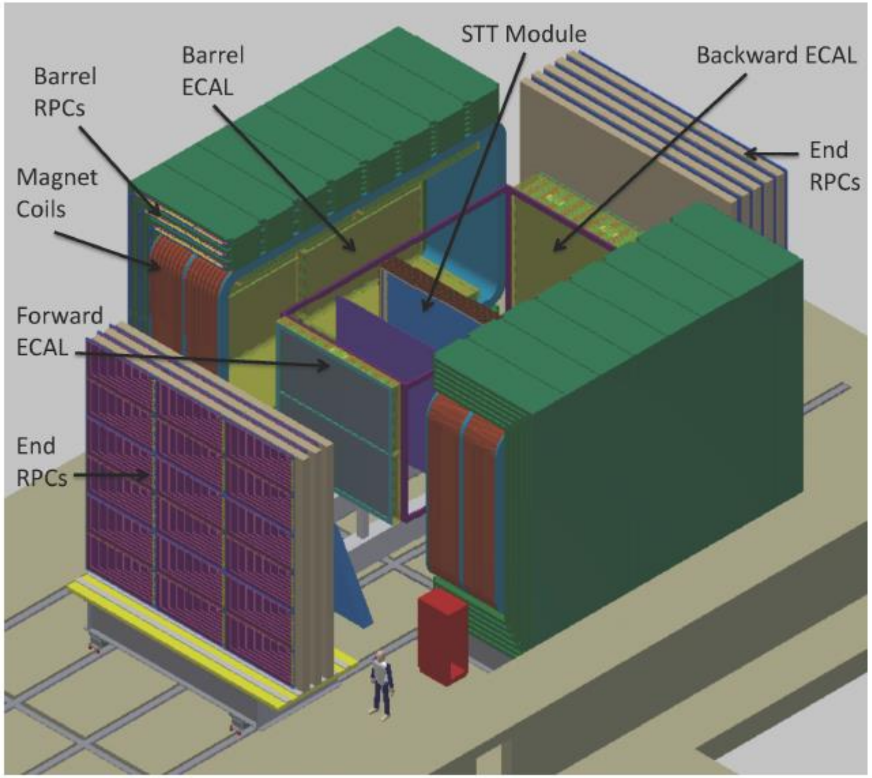




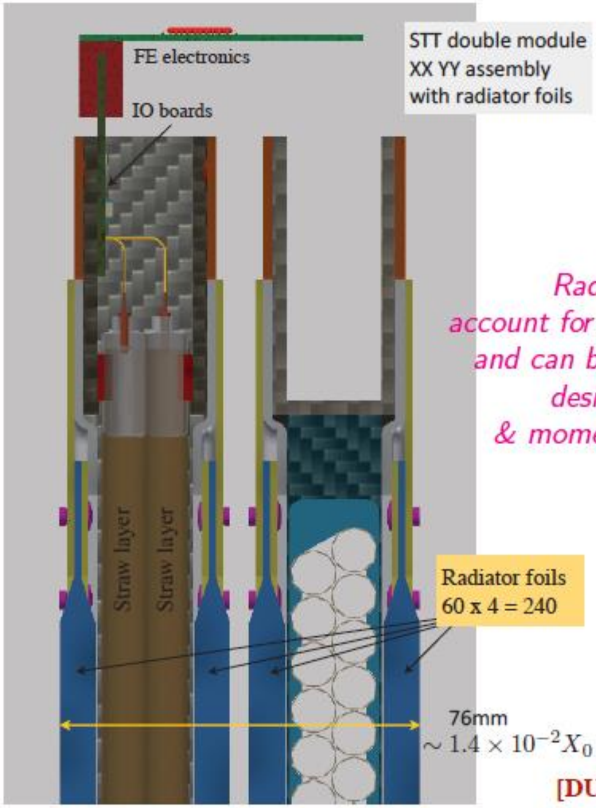
- Note that 1m includes most of the neutrons
- For this purpose, a 2mx2mx2m cube of 3DST/superFGD

STT (straw tube tracker)

- The CD1/CD1R detector

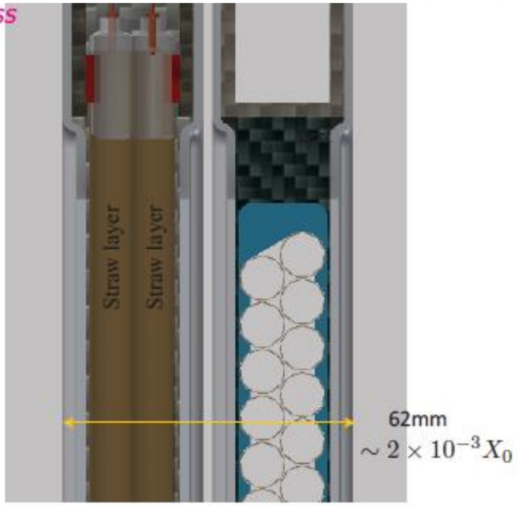


STT module with radiators

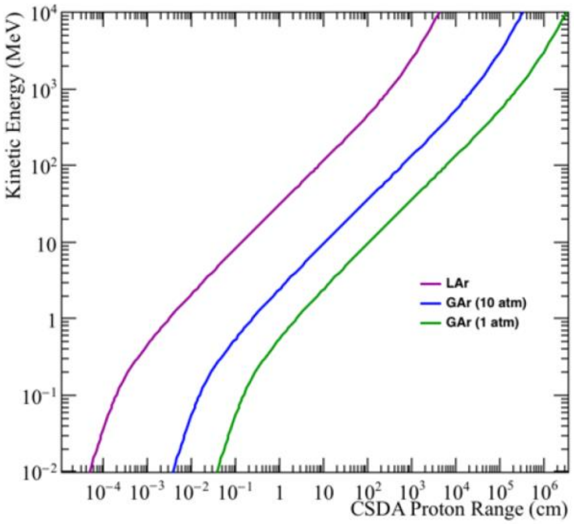


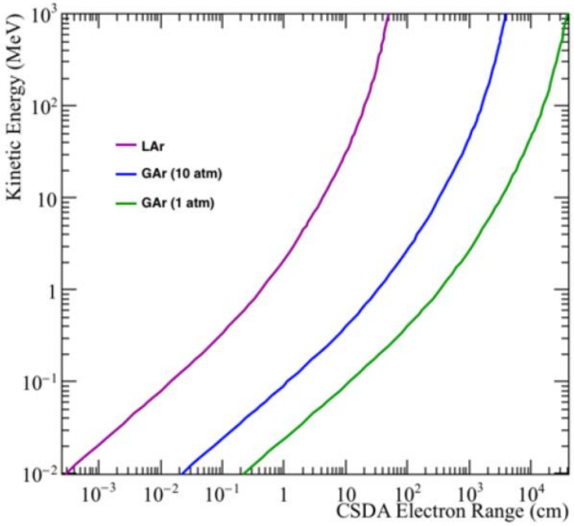
Radiator targets account for 82.6% of STT mass and can be tuned to achieve desired statistics & momentum resolution

[DUNE CDR Volume 4]



Particle ranges





From gTPC report, NIST[8] reference