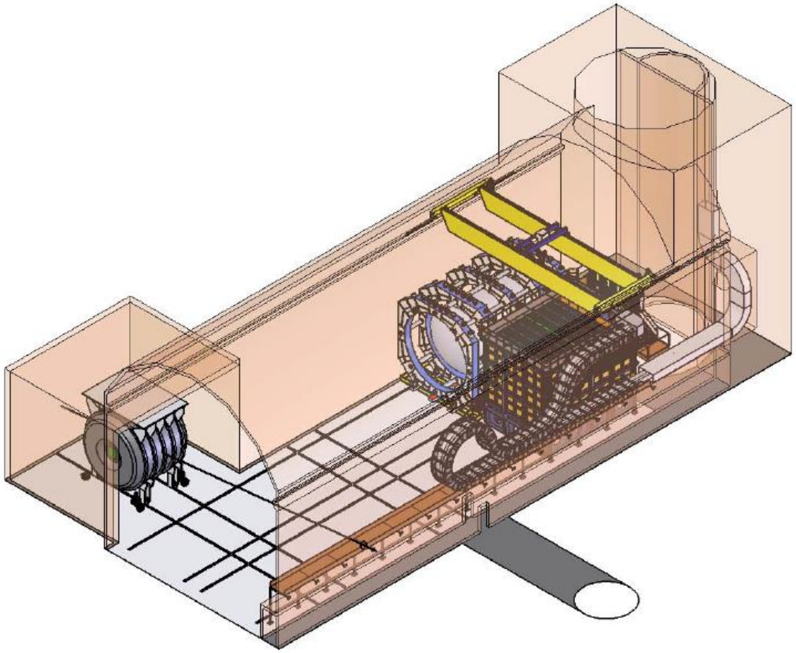
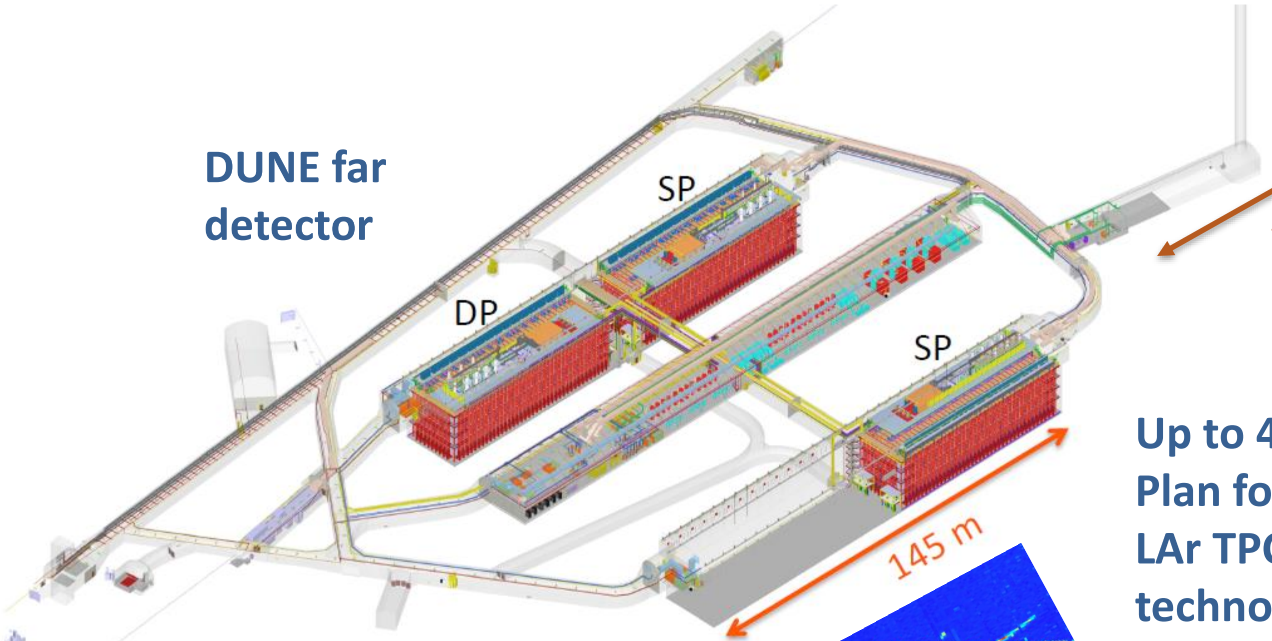
New physics at the DUNE near detector
Part 1: the DUNE near detector
(design in progress)

Steve Manly
CERN neutrino cross talk
March 20, 2020

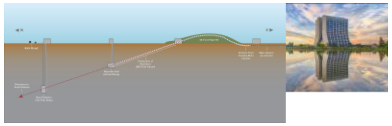


DUNE – a long baseline experiment
What near detector? – A view from South Dakota

DUNE far detector

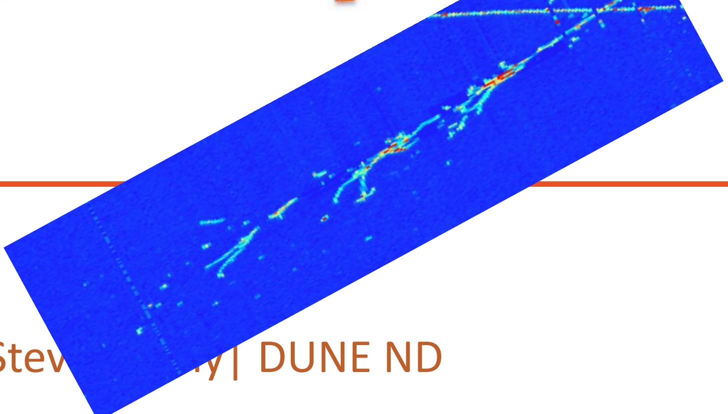


1300 km



Powerful wideband neutrino beam from some lab near Chicago

Up to 40 kt fiducial of liquid argon. Plan for single and double-phase LAr TPC readout. 4th module technology not specified yet.



The primary mission of the ND

- The ND provides the control samples for the oscillation analysis
- Measures the neutrino energy spectrum before oscillations occur
- The measured rate is a convolution of three ingredients:

$$\text{ND Rate} = \int [\text{Flux}] \times [\text{CrossSection}] \times [\text{Det.Response}]$$

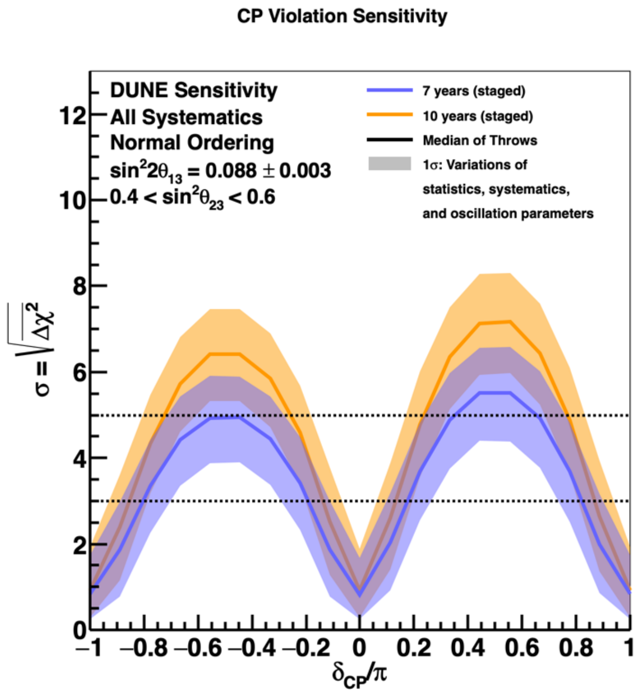
- The ND must allow the experiment to predict the FD spectrum:

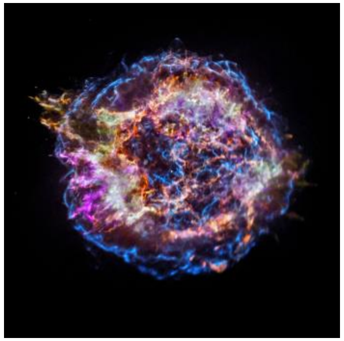
$$\text{FD Rate} = \int [\text{OscProb}] \times [\text{Flux}] \times [\text{CrossSection}] \times [\text{Det.Response}]$$

- The ingredients are not necessarily well known. The ND must have the ability to deconvolve them to make the FD prediction and to set systematic errors confidently.

The primary mission of the ND

- Design choices and funding arguments (in the US) are driven by the long baseline oscillation program
- And a bit by supernova physics and nucleon decay.





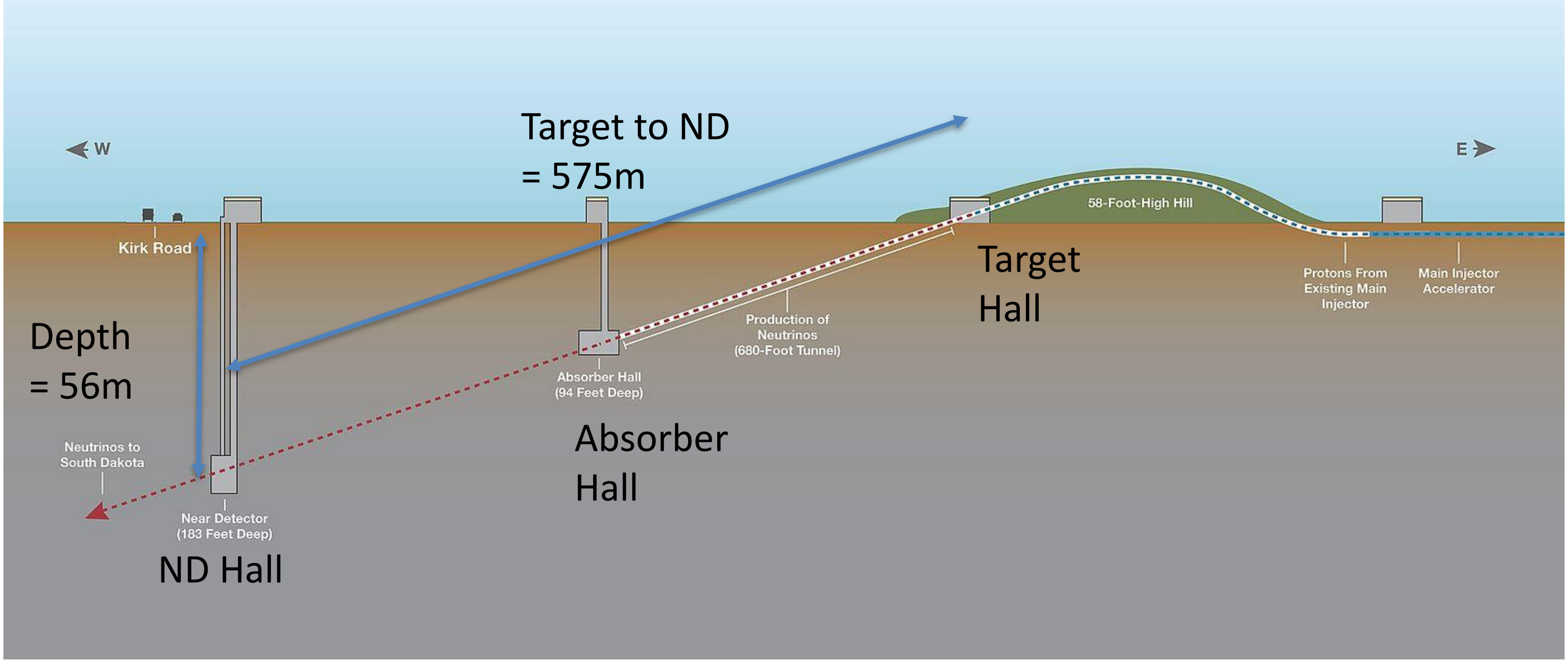
We will do program of BSM, SM, neutrino interactions physics but not emphasized to date.

Overarching ND Requirements

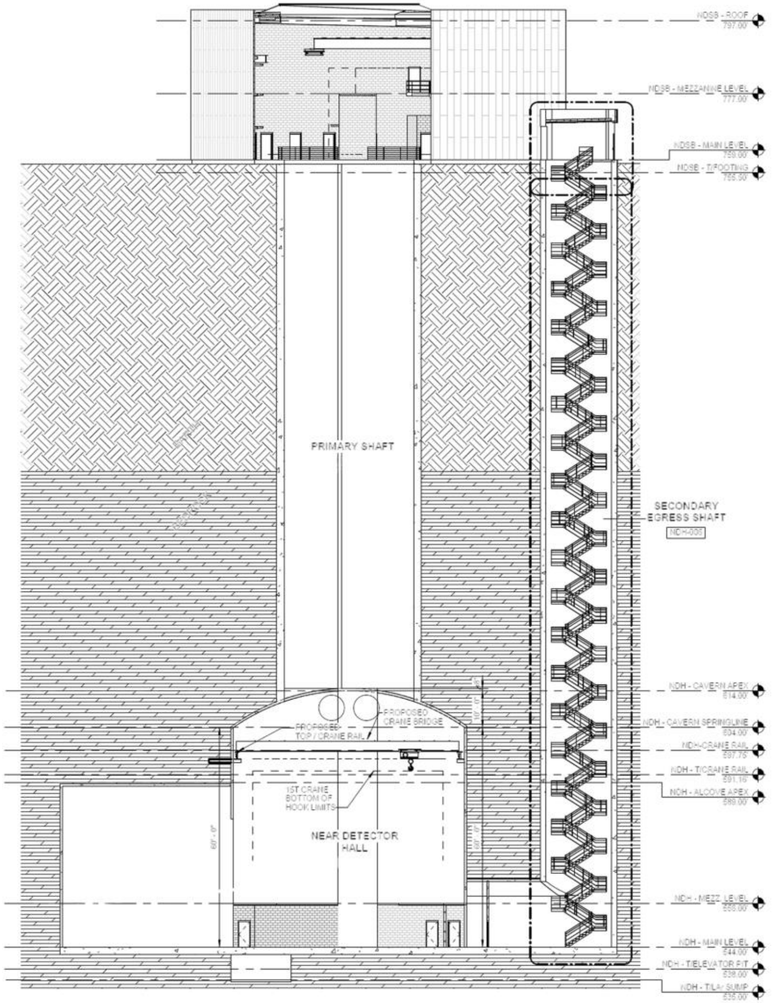
O0: Predict the neutrino spectrum at the FD: The Near Detector (ND) must measure neutrino events as a function of flavor and neutrino energy. This allows for neutrino cross-section measurements to be made and constrains the beam model and the extrapolation of neutrino energy event spectra from the ND to the FD.

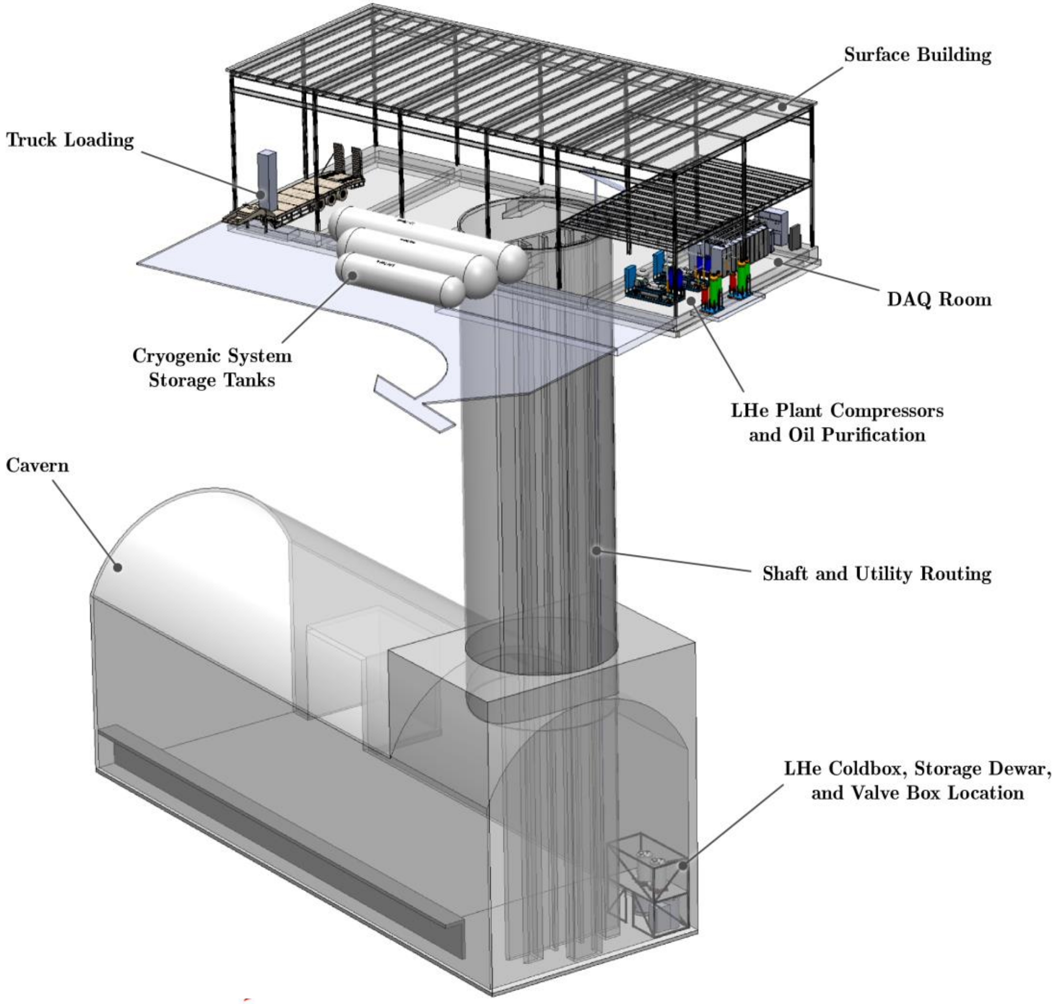
O0.1	**Measure interactions on argon**	Measure neutrino interactions on argon, determine the neutrino flavor, and measure the full kinematic range of the interactions that will be seen at the FD.
O0.2	**Measure the neutrino energy**	Reconstruct the neutrino energy in CC events and control for any biases in energy scale or resolution.
O0.3	**Constrain the xsec model**	Measure neutrino cross-sections in order to constrain the cross section model used in the oscillation analysis.
O0.4	**Measure neutrino flux**	Measure neutrino fluxes as a function of flavor and neutrino energy.
O0.5	**Obtain data with different neutrino fluxes**	Measure neutrino interactions in different beam fluxes in order to disentangle flux and cross sections and verify the beam model. **(PRISM)**
O0.6	**Monitor the neutrino beam**	Monitor the neutrino beam energy spectrum with sufficient statistics to be sensitive to intentional or accidental changes in the beam on short timescales.

DUNE near site

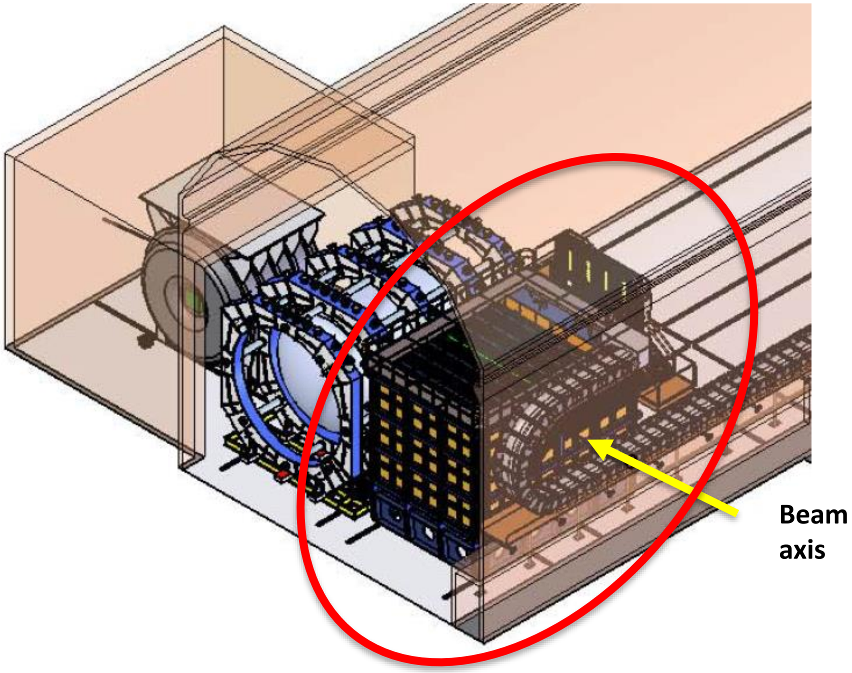


DUNE near detector hall





DUNE near detector
Primary subcomponents

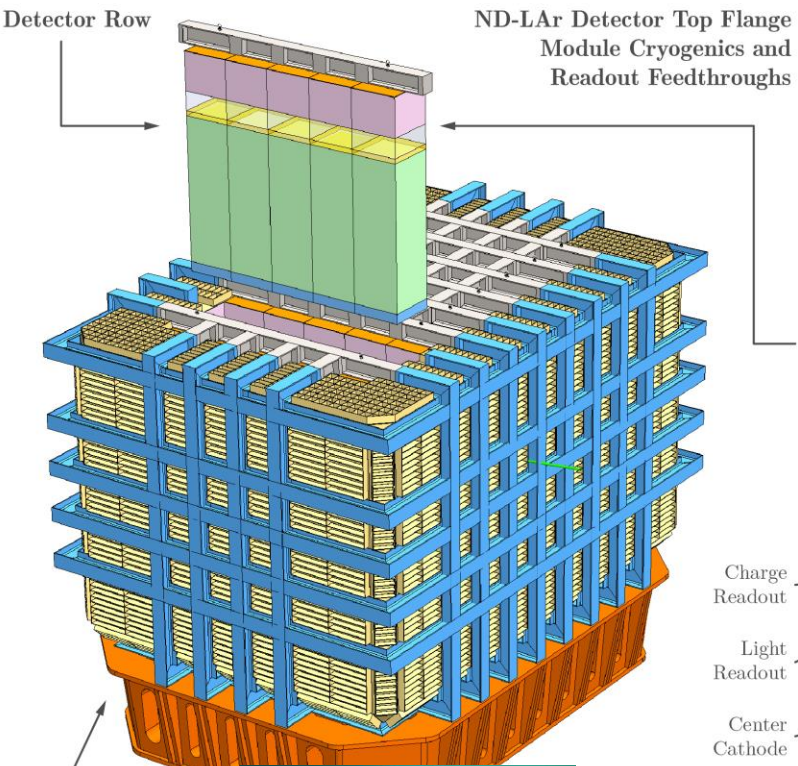


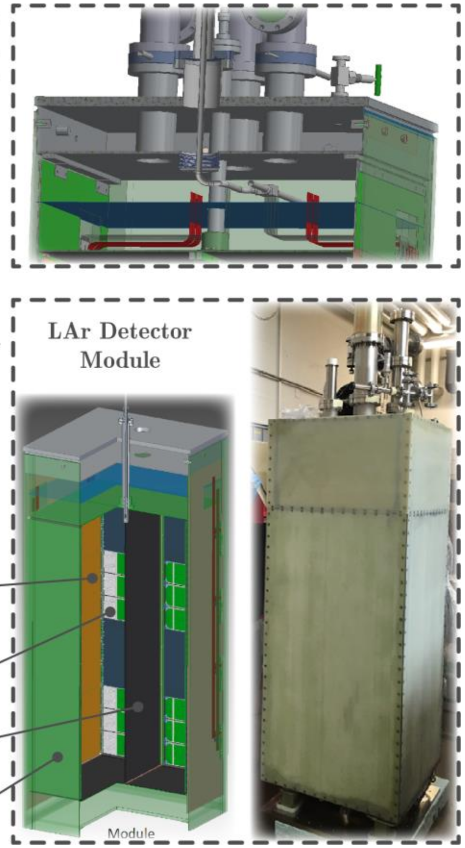
Primary target for ND for the oscillation analysis

- **Liquid argon target**
- **Big mass**
- **Similar target nucleus and technology/detector to the far detector**
- **Able to do critical flux measurements: numu CC, nu-e-, low-nu**

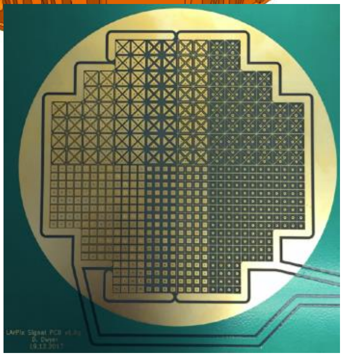
But … must handle the rate

ND-LAr – ArgonCube technology

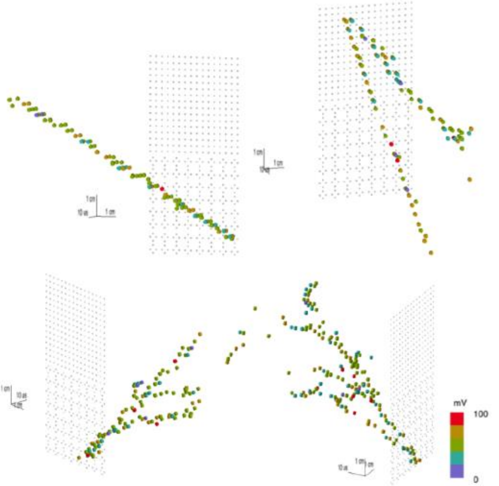




- **LAr**
- **Optically isolated modules**
- **Short drift (0.5 m)**
- **Pixelized readout**



Test readout pixel board

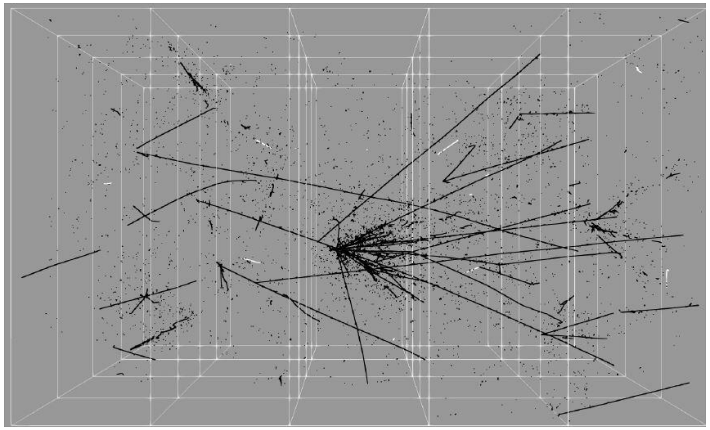


Cosmic ray interactions in test system using 4.8 cm x 9.6 cm pixelated readout in a 60-cm-drift LArTPC

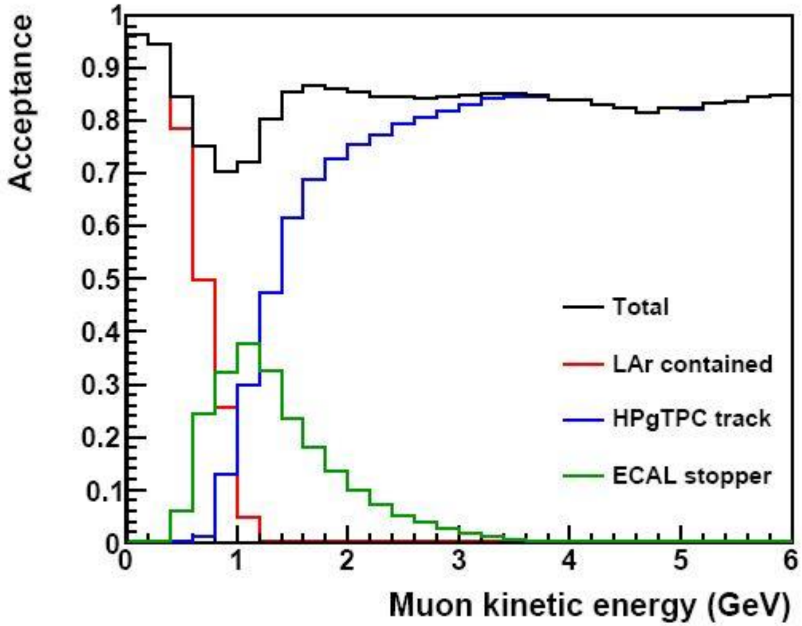
DUNE near detector

- 3m height: hall height and crane.
- 5m depth: hadronic shower containment with use of symmetry.
- 7m width: shower + side muon containment
- Muons with energy > 1GeV are not contained well so a spectrometer is needed downstream.

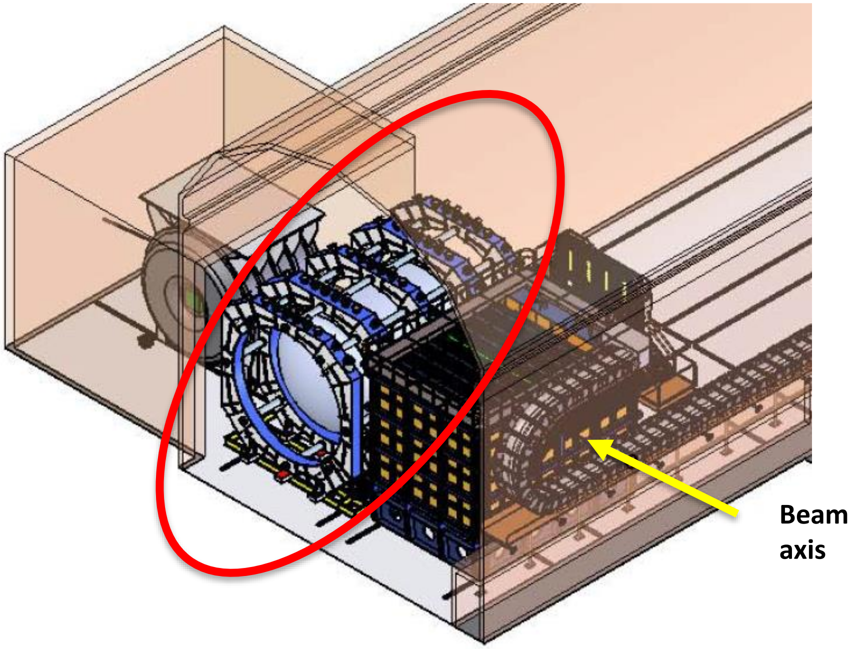
- **50 t fiducial volume**
- **50 M ν_μ CC evts/yr**



θ_μ < 20 degrees



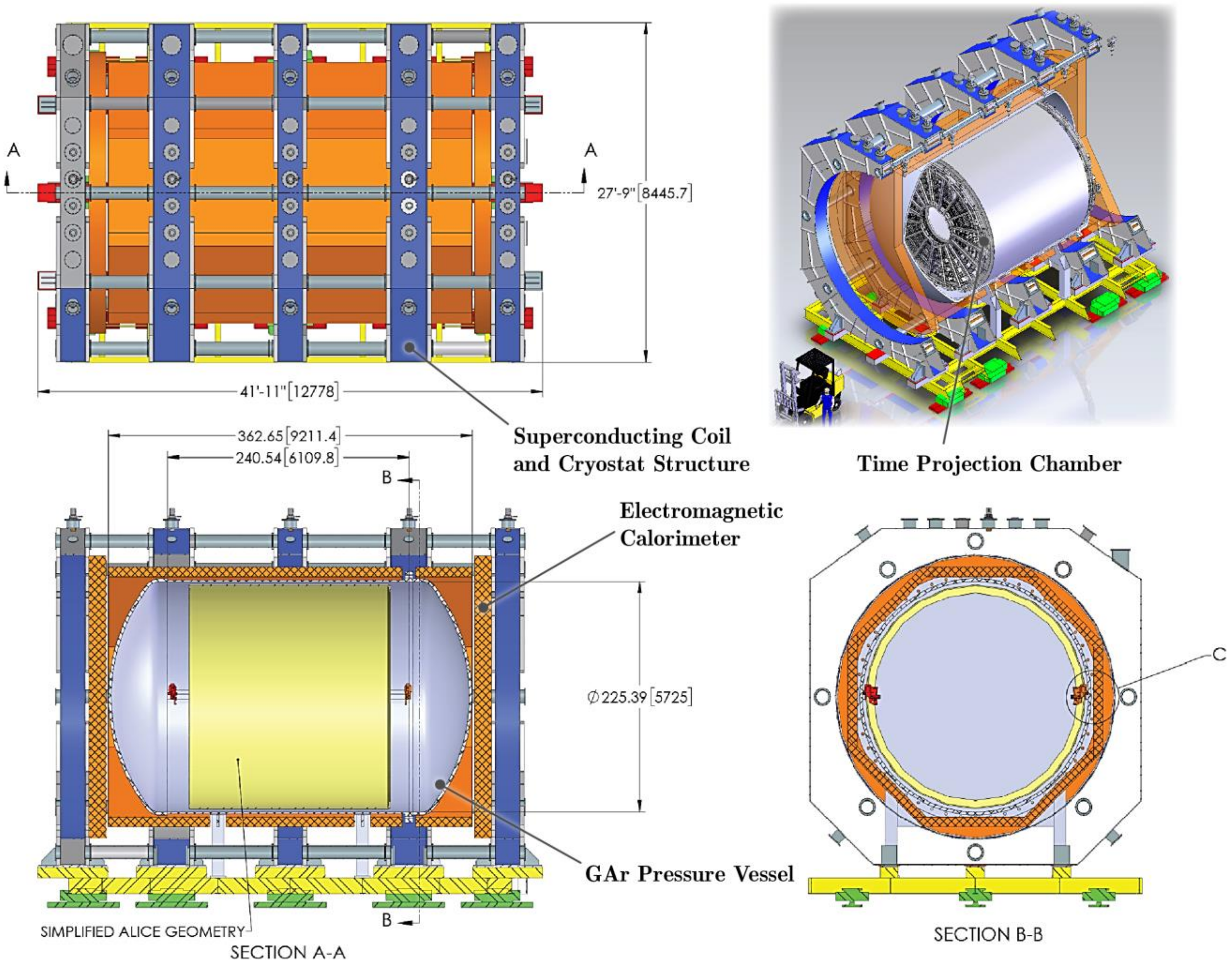
DUNE near detector
Primary subcomponents



Muon spectrometer to momentum analyze the muons that escape ND-LAr

- **Large high pressure gaseous argon TPC with surrounding calorimeter in a magnetic field**
- **Provides muon analysis plus additional ability to study ν-Ar interactions in fine detail**

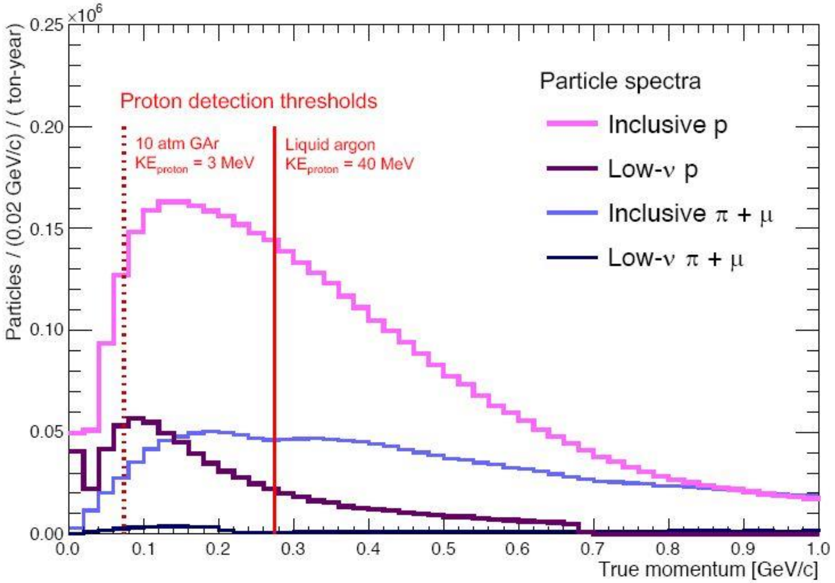
ND-GAr (aka MPD)



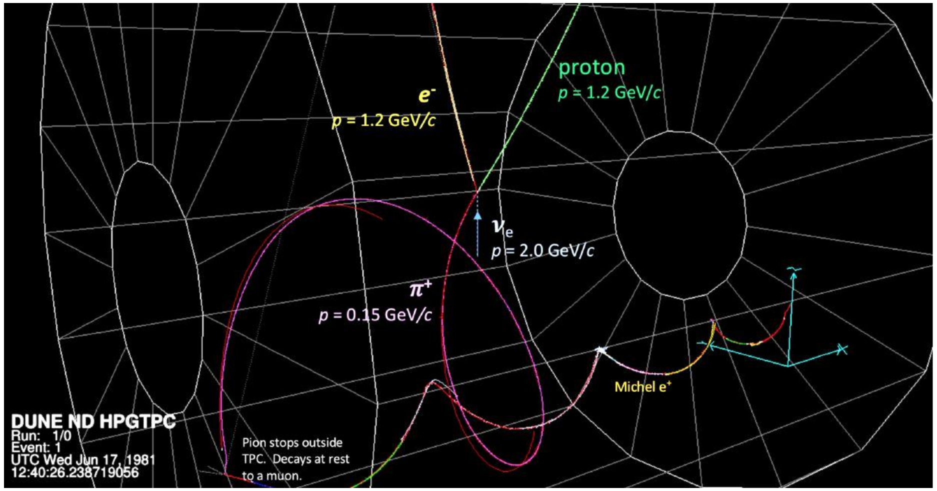
- "Alice" TPC
- 10 atmospheres
- 1 t fiducial volume
- 0.5 T B field
- Surrounding ECAL
- Low p charged particle detection threshold
- Relatively less secondary confusion
- Able to analyze higher multiplicity events

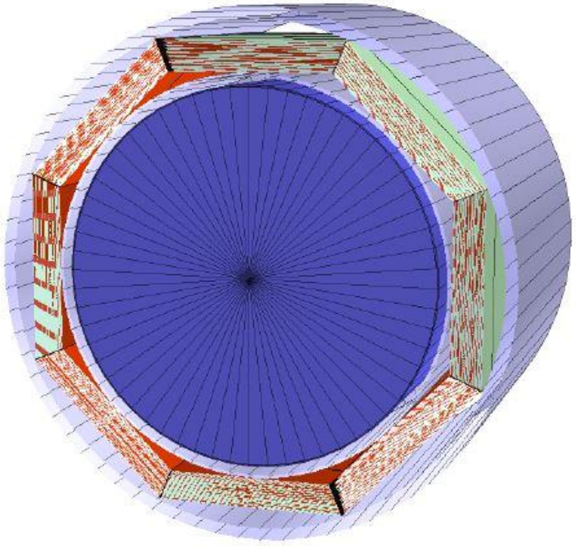
Valuable for understanding interaction model and for refining detector response model

ND-GAr (aka MPD)

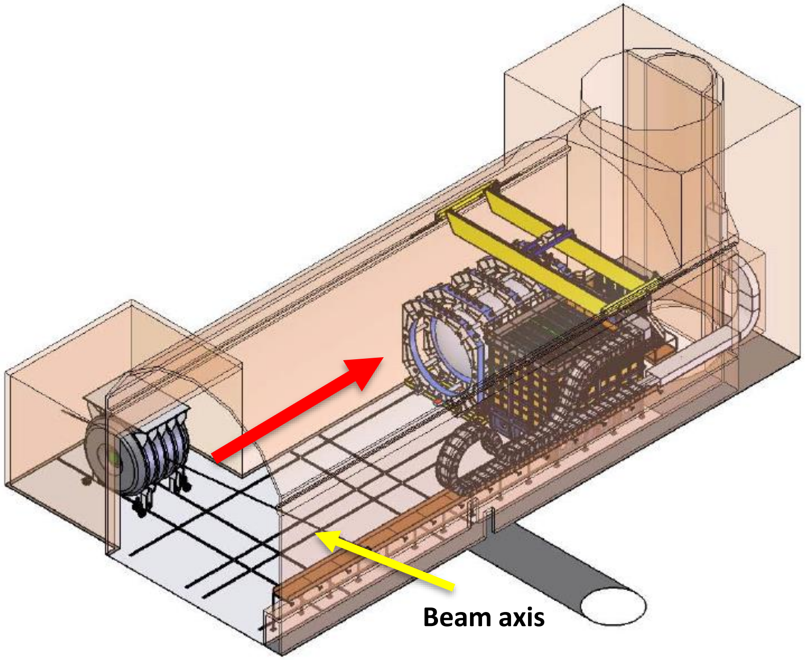


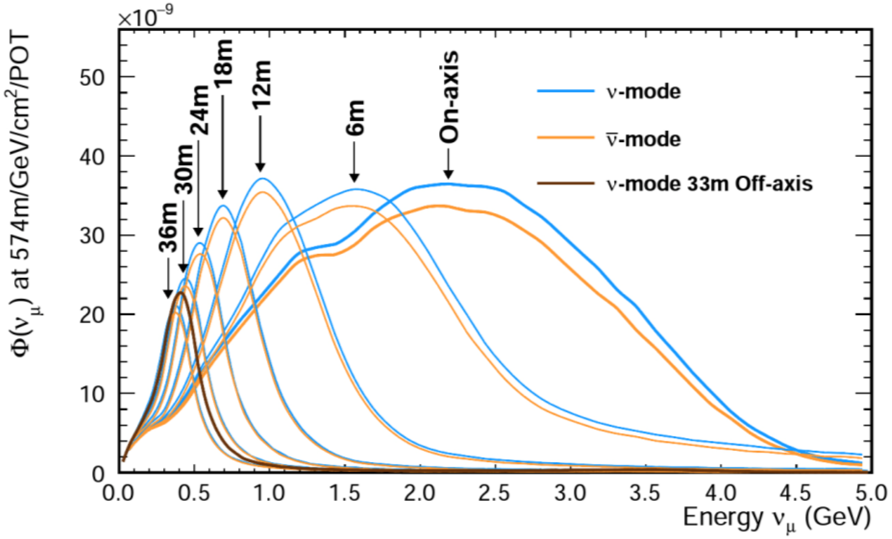
- ~1M ν_μ CC/year
- Higher KE Neutrons via TOF in ECAL under study (50% purity, 45% purity)





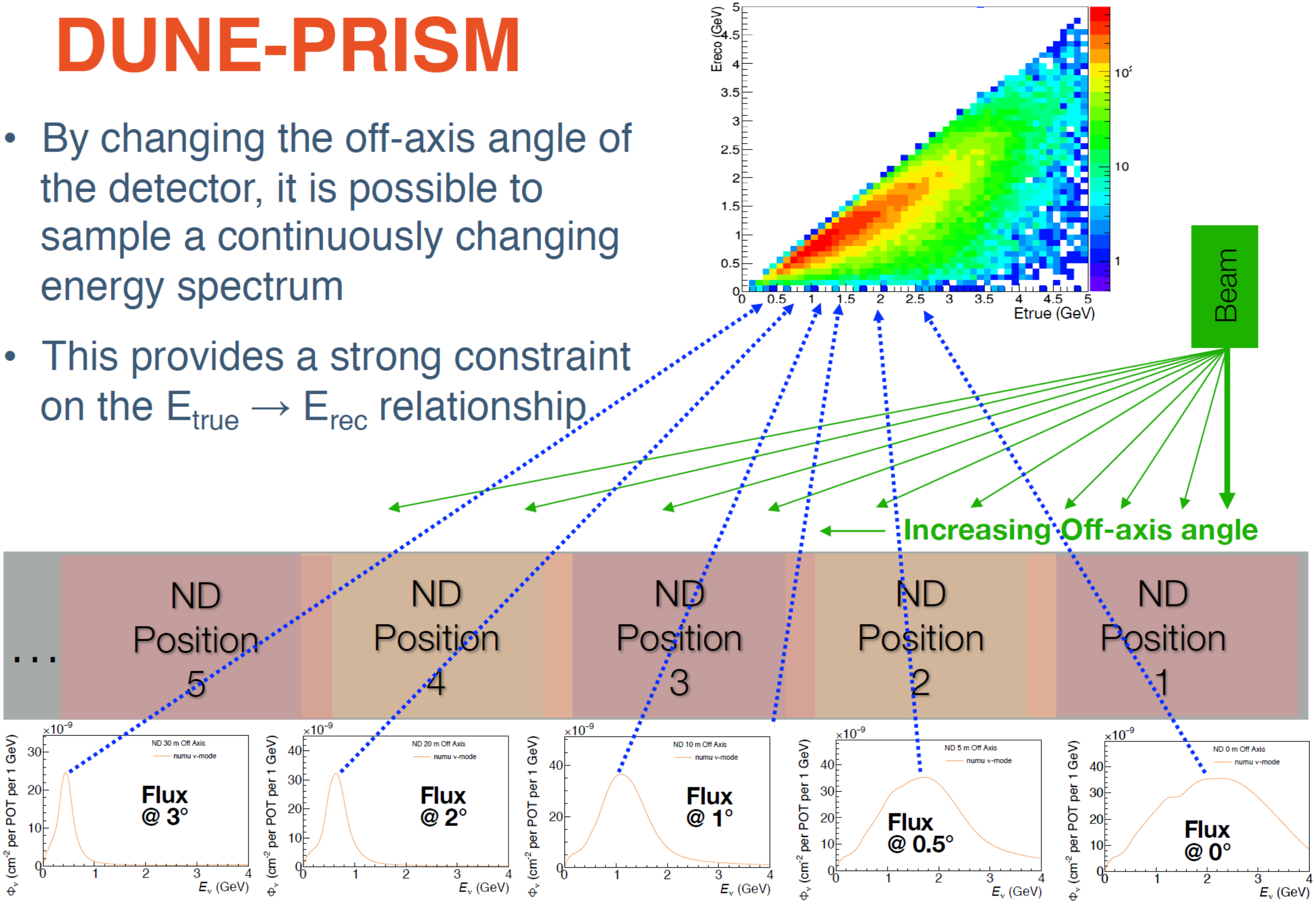
PRISM capability





DUNE-PRISM

- By changing the off-axis angle of the detector, it is possible to sample a continuously changing energy spectrum
- This provides a strong constraint on the $E_{true} \rightarrow E_{rec}$ relationship

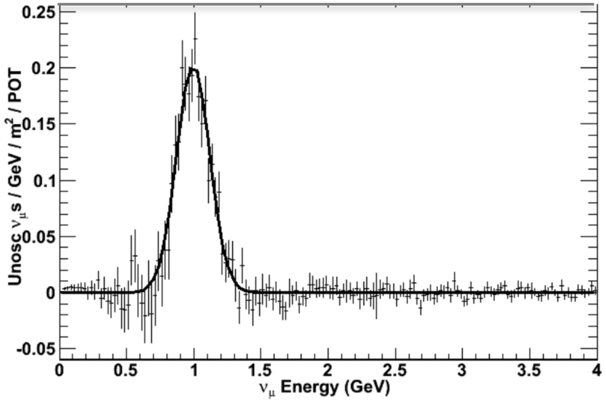


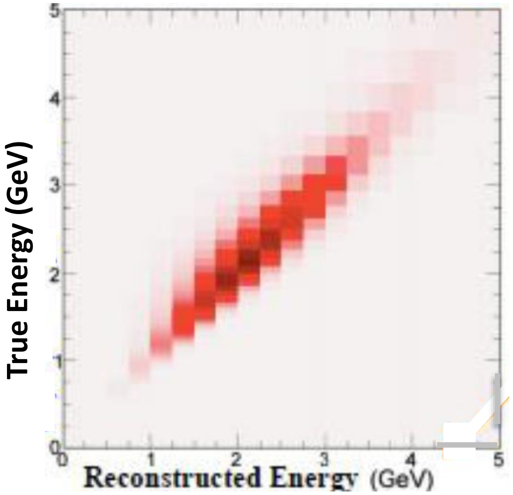
Slide from M. Wilking

Calibrating ND response with DUNE-PRISM

- Can create Gaussian distributions at given true E_ν from linear combinations of the expected true fluxes
- Map out the response at that E_ν by comparing to the data for the same linear combination
- Repeat for different E_ν

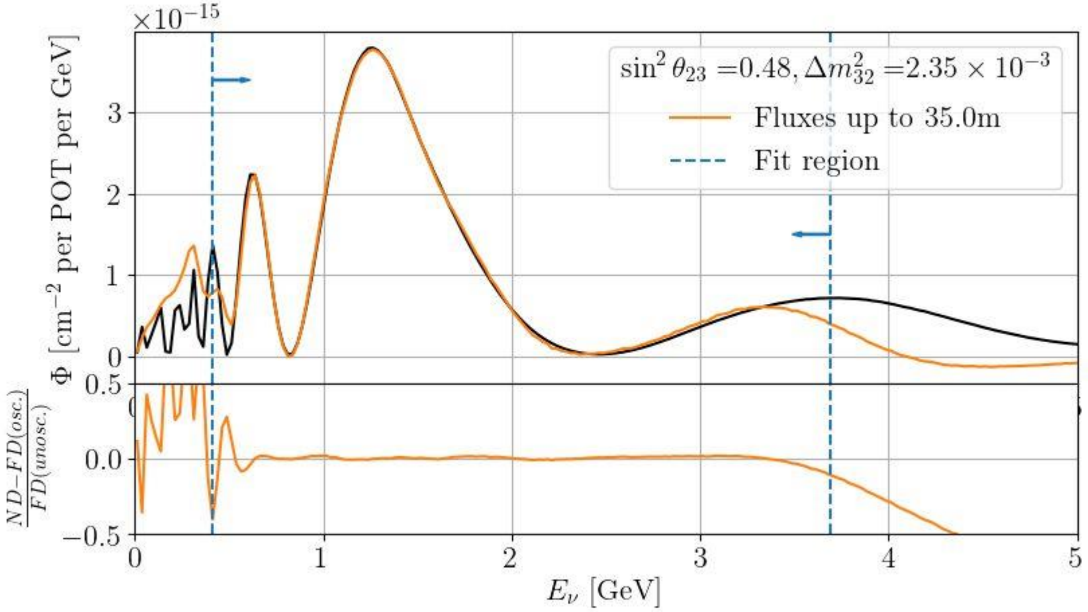
- Map out detector response matrix





Modeling FD spectrum using DUNE-PRISM

- Instead of gaussians → find linear combination that is the same as FD oscillated (appearance or disappearance) spectrum

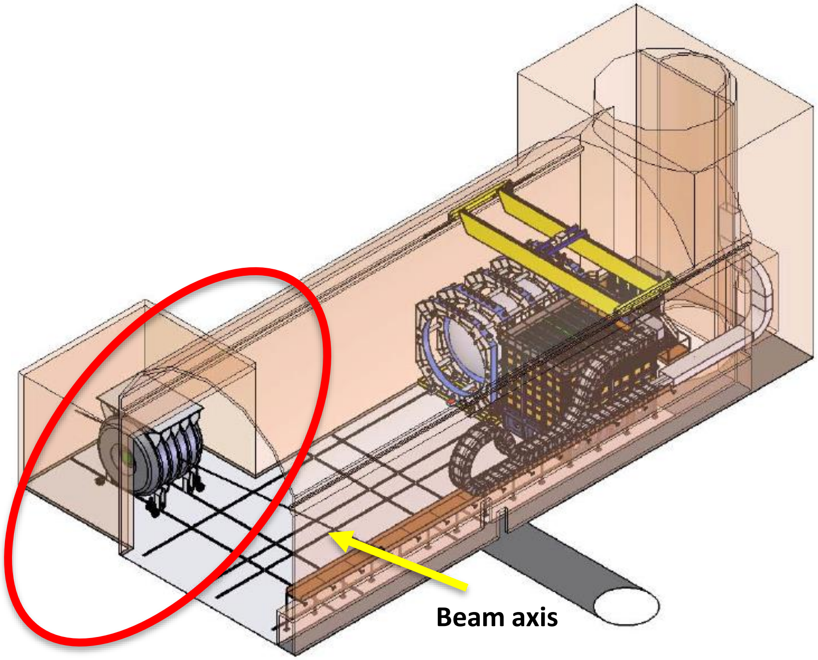


Particular numu (oscillated) flux for specific parameters

Linear combination of ND prism fluxes

- Minimizes ND-FD flux spectral difference and reduces model dependence via a data-driven ND to FD comparison for extracting oscillation parameters

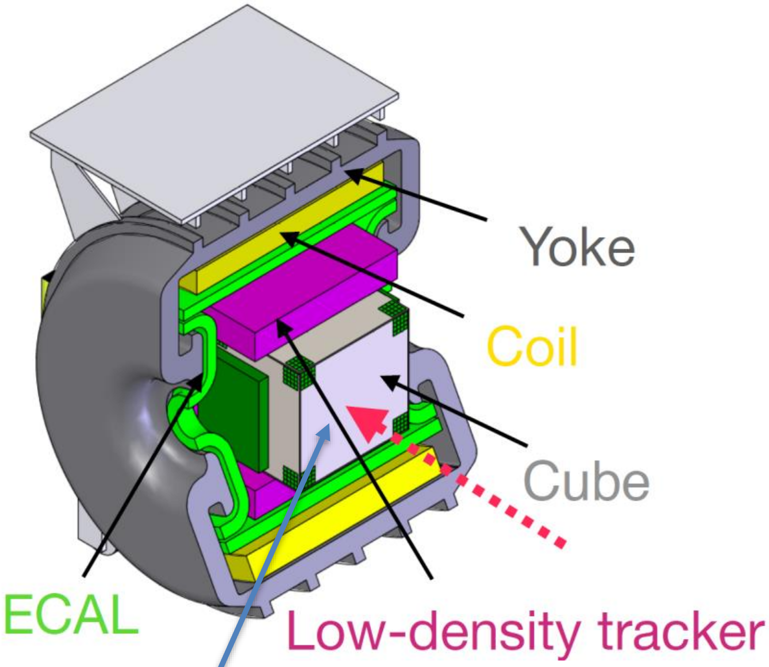
DUNE near detector Primary subcomponents

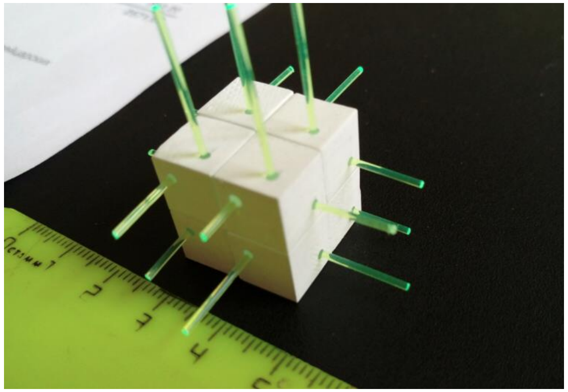


Monitor the beam spectrum on axis at all times

- Necessary in scenario with prism
- Mass
- Spectral muon analysis requires magnet
- Design so it can also provide information useful for neutrino interaction model development
- Some complementary information for oscillation measurements

SAND – System for on-Axis Neutrino Detection





- ➢ KLOE experiment magnet
- ➢ KLOE ECAL
- ➢ 3DST
- ➢ TPC or straw tube tracking outside of 3DST
- ➢ Ongoing discussion of innards

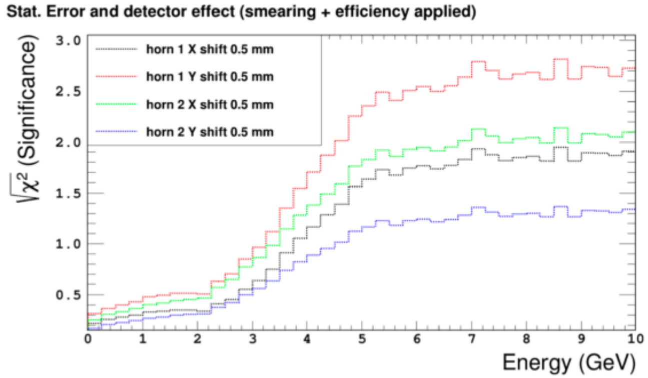
- ➢ Beam Monitoring

But also

- ➢ Reconstruction with neutrons
- ➢ A dependence
- ➢ Different systematics

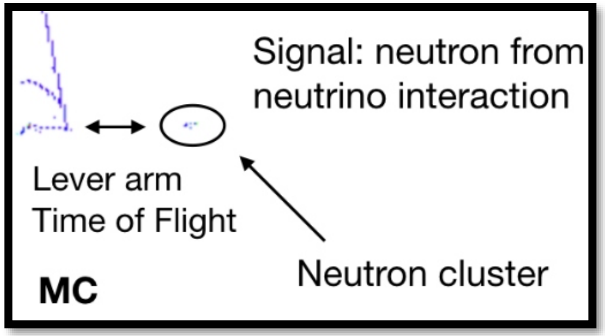
SAND

Muon spectra in 3DST in 0.6T B field. Shift seen relative to nominal in one day



Muon spectra in 3DST in 0.6T B field (one day) versus rate only detector (4 7-ton modules at 0,1,2,3 m) over one week

	Significance, $\sqrt{\chi^2}$	
Changed beam parameter	Rate-only monitor	3DST-S
proton target density	1.9	7.8
proton beam width	3.0	6.6
proton beam offset x	0.7	20.0
proton beam theta phi	0.2	12.5
horn 1 along x	1.9	8.8
horn 2 along x	0.7	12.8
horn 1 along y	0.2	9.9
horn 2 along y	0.4	6.3



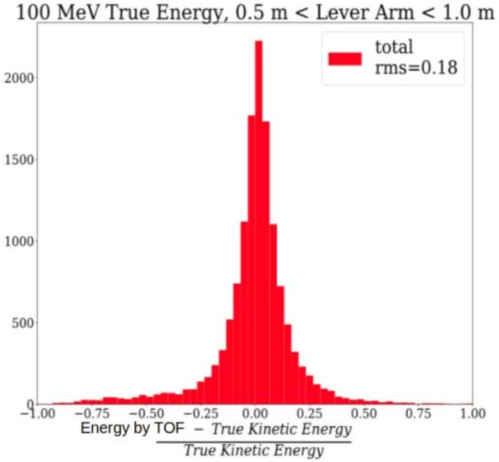
Signal: neutron from neutrino interaction

Lever arm
Time of Flight

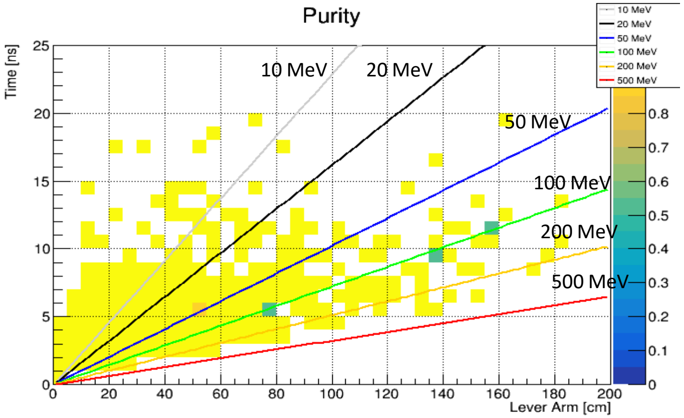
Neutron cluster

MC

Neutron detection with energy determination via time-of-flight

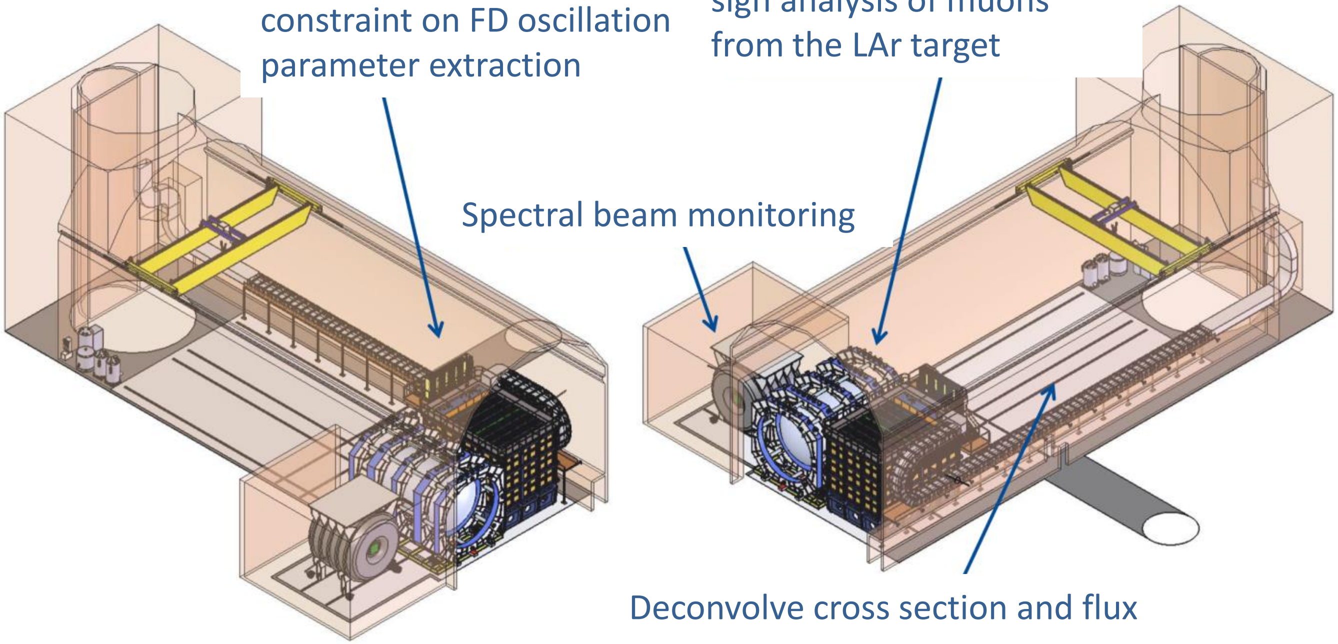


Only out of fiducial background considered. Secondaries under study.



DUNE near detector

- **Holistic view: each element plays a critical role in the basic oscillation analysis.**



Primary target for ND constraint on FD oscillation parameter extraction

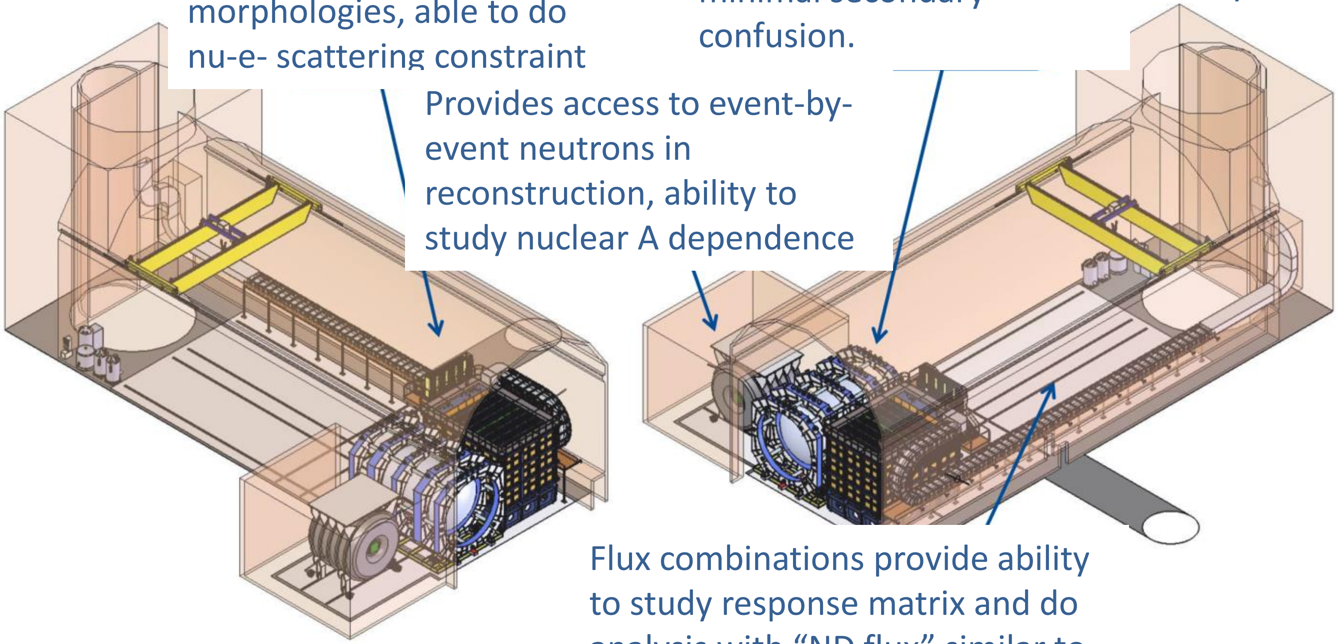
Momentum and charge-sign analysis of muons from the LAr target

Spectral beam monitoring

Deconvolve cross section and flux

DUNE near detector

- **Each element plays largely unique roles in helping to reduce the overall systematic error budget.**



Ar target, explores final state in more detail with low threshold detection of charged particles, sign determination of pions, higher KE neutrons, minimal secondary confusion.

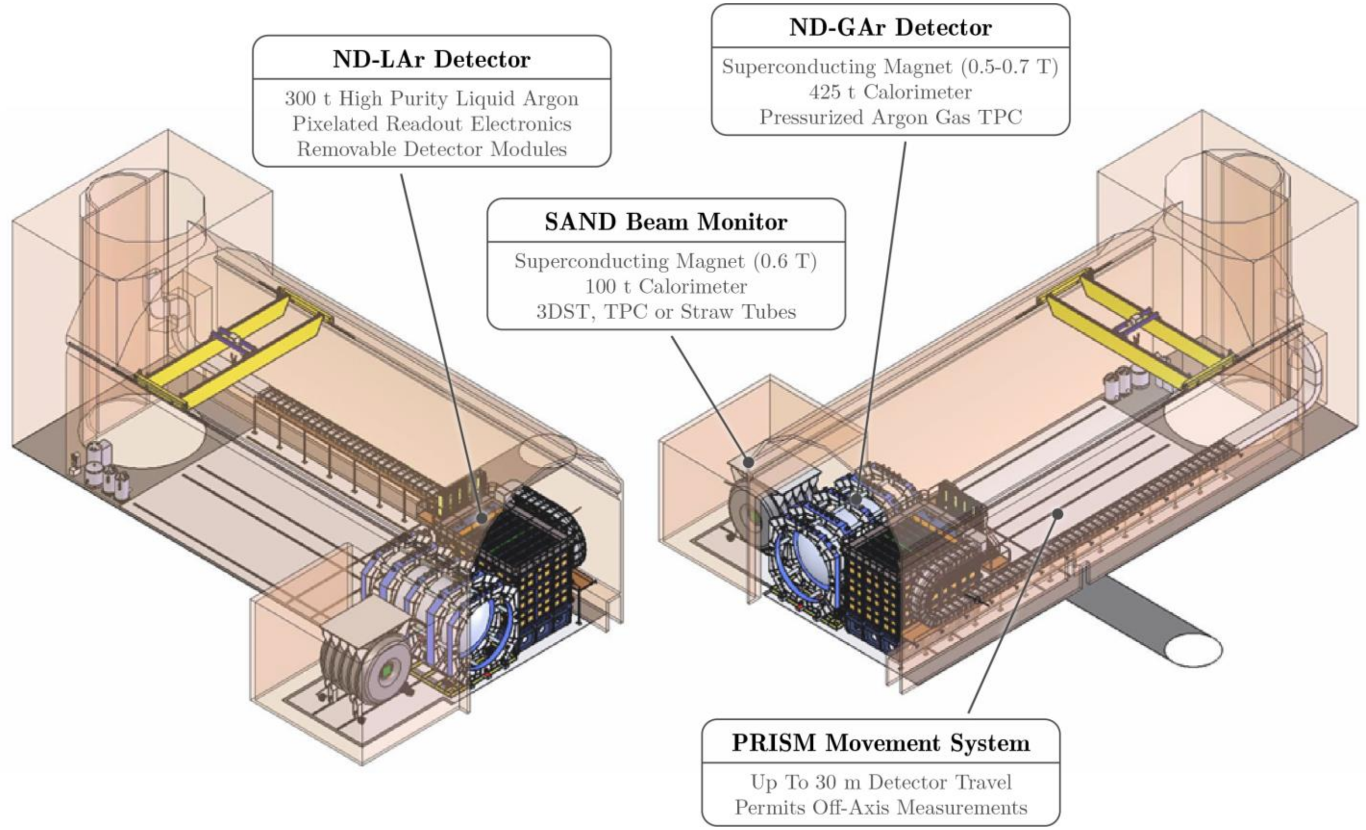
Three detector subsystems all can do low-nu with different systematic errors

Ar target, similar technology to FD, able to measure many morphologies, able to do nu-e- scattering constraint

Provides access to event-by-event neutrons in reconstruction, ability to study nuclear A dependence

Flux combinations provide ability to study response matrix and do analysis with "ND flux" similar to FD oscillated flux

DUNE near detector



ND-LAr Detector

300 t High Purity Liquid Argon
Pixelated Readout Electronics
Removable Detector Modules

ND-GAr Detector

Superconducting Magnet (0.5-0.7 T)
425 t Calorimeter
Pressurized Argon Gas TPC

SAND Beam Monitor

Superconducting Magnet (0.6 T)
100 t Calorimeter
3DST, TPC or Straw Tubes

PRISM Movement System

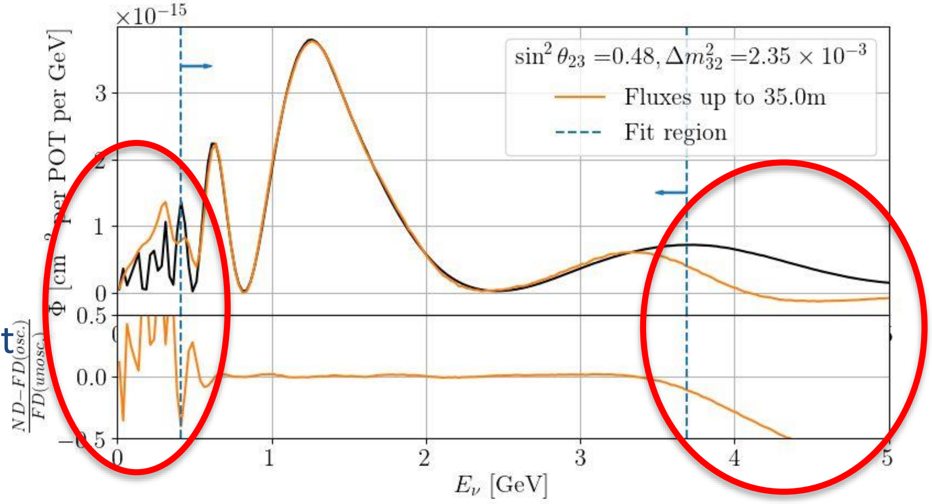
Up To 30 m Detector Travel
Permits Off-Axis Measurements

Backups

Modeling FD spectrum using DUNE-PRISM

- 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 (modeled fluxes)
  - 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)

- Limits of energy range of input spectra (and stats at low end) means ability to model FD flux breaks down at high and low energy regions
- Correct those regions with model as necessary
- Those regions relatively unimportant for oscillations
- In limit that the modeled fluxes are perfect, the fit is perfect, and systematic variations are same for FD and fit model, this is a model independent measurement

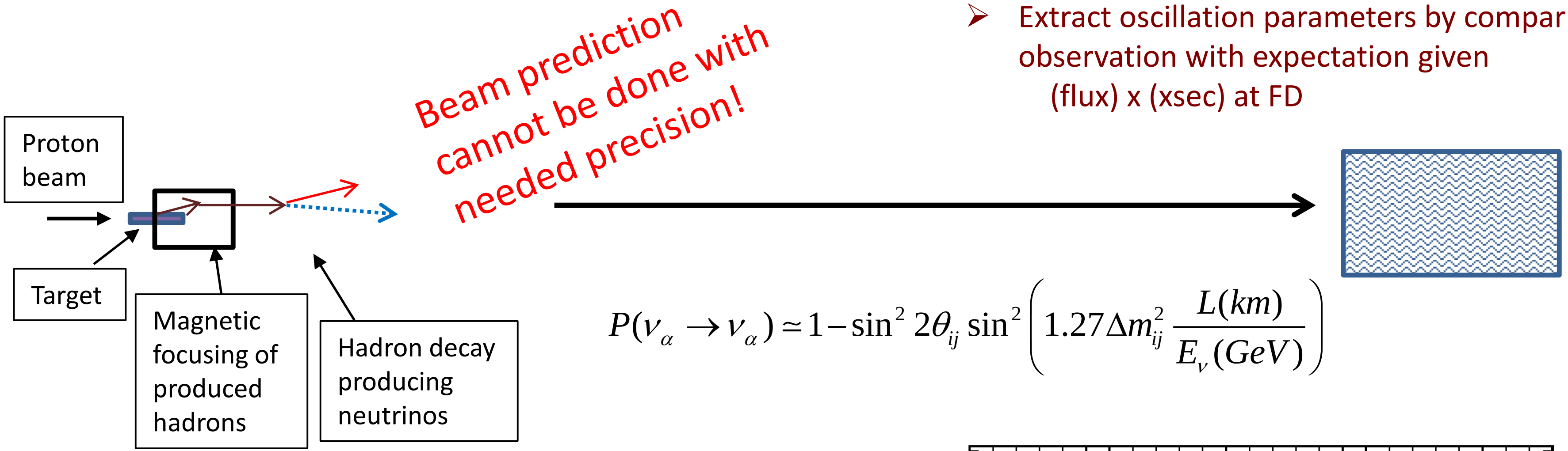


- All this not quite true. Reduces but does not eliminate model dependence for FD prediction and systematic error determination

Need for near detector

Far detector (FD):

- ➢ Measure neutrino spectra as function of E_ν
- ➢ Extract oscillation parameters by comparing observation with expectation given
  (flux) x (xsec) at FD



Beam prediction cannot be done with needed precision!

Proton beam

Target

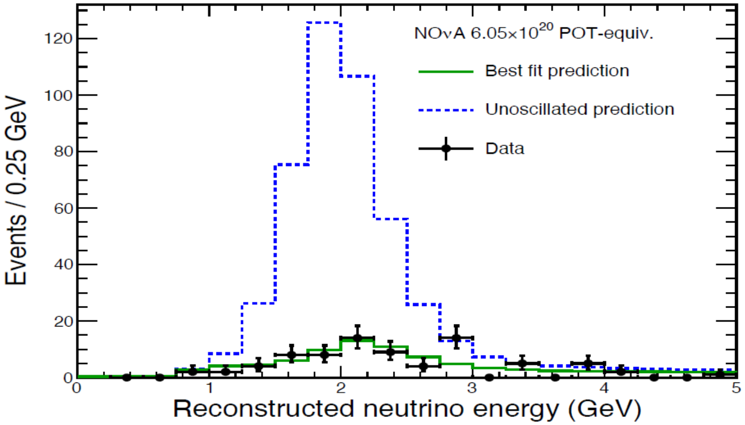
Magnetic focusing of produced hadrons

Hadron decay producing neutrinos

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - \sin^2 2\theta_{ij} \sin^2\left(1.27\Delta m^2_{ij} \frac{L(km)}{E_\nu(GeV)}\right)$$

Beam:

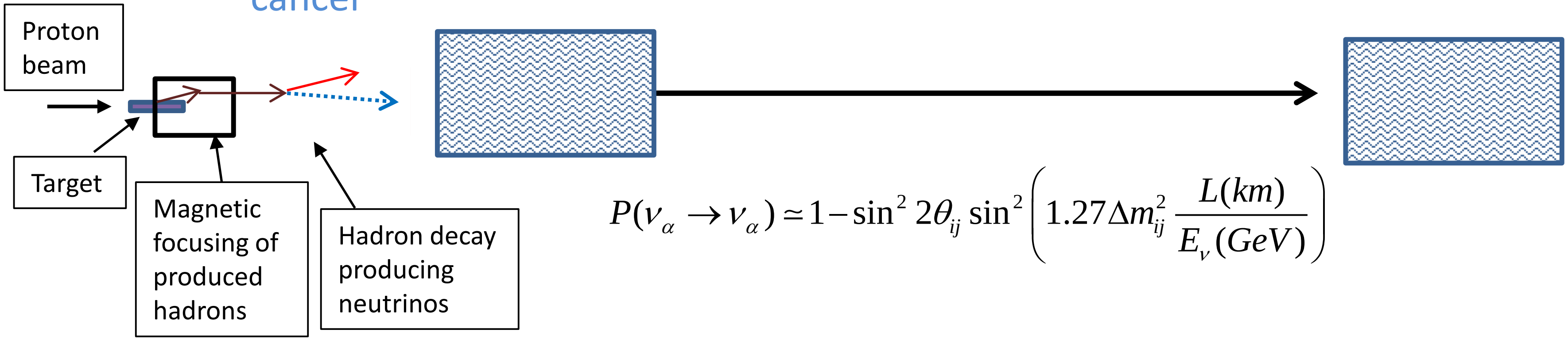
- ➢ Production of hadrons
- ➢ Focusing effects
- ➢ Can achieve 10-15% errors in flux prediction with external hadron production measurements (i.e., NA61)



Need for near detector

Put detector in near position (no oscillations) that is identical to far detector and uncertainties largely cancel

Far detector (FD):
- ➢ Measure neutrino spectra as function of E_ν
- ➢ Extract oscillation parameters by comparing observation with expectation given (flux) x (xsec) at FD



Proton beam

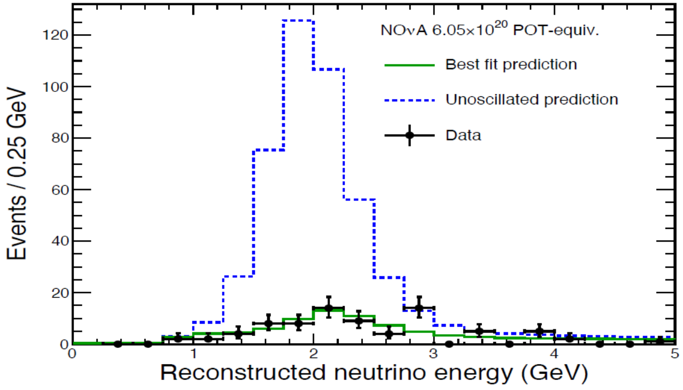
Target

Magnetic focusing of produced hadrons

Hadron decay producing neutrinos

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - \sin^2 2\theta_{ij} \sin^2\left(1.27\Delta m^2_{ij} \frac{L(km)}{E_\nu (GeV)}\right)$$

This sounds good … but:
- ▪ ND cannot be identical to FD
- ▪ Flux at ND and FD different (geometry and oscillations)

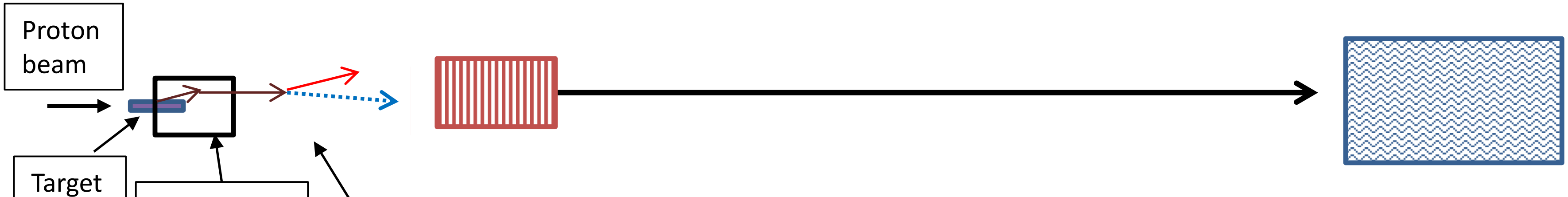


Need for near detector

Use ND as close to identical to FD as reasonably possible

Far detector (FD):

- Measure neutrino spectra as function of E_ν
- Extract oscillation parameters by comparing observation with expectation given (flux) x (xsec) at FD



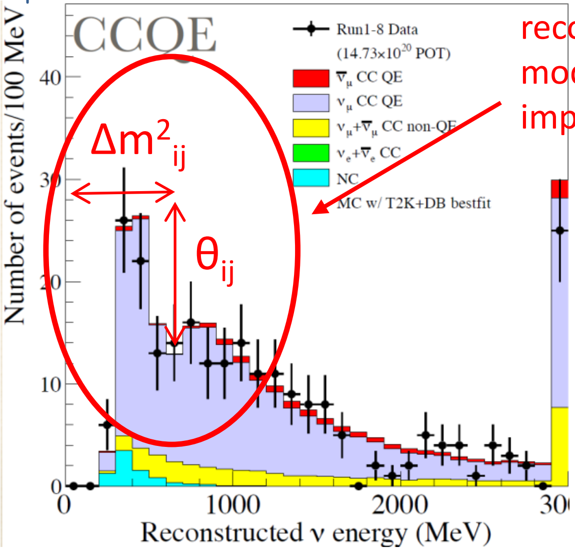
Proton beam

Target

Magnetic focusing of produced hadrons

Hadron decay producing neutrinos

T2K ν_μ disappearance



Neutrino energy reconstruction, and modeling of same, is important!

Use ND to constrain flux, nuclear effects, detector effects in model used to simulate what is seen in the FD (and to extract the oscillation parameters)

Need for near detector

Use ND as close to identical to FD as reasonably possible

Far detector (FD):

- Measure neutrino spectra as function of E_ν
- Extract oscillation parameters by comparing observation with expectation given
  (flux) x (xsec) at FD

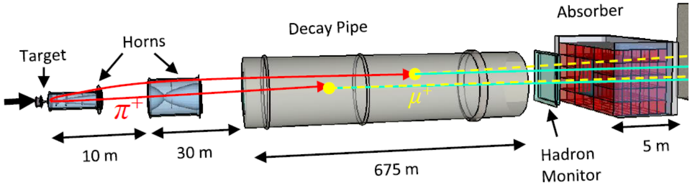
Proton beam

Target

Magnetic focusing of produced hadrons

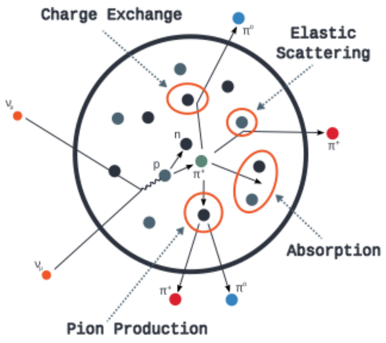
Hadron decay producing neutrinos

All of this varies with neutrino energy

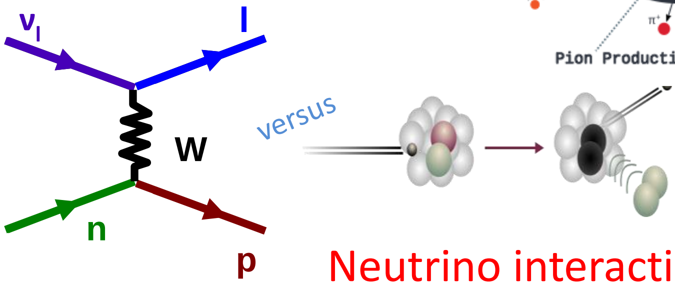


Beam mismodeling

Nuclear effects



Use ND to constrain flux, nuclear effects, detector effects in model used to simulate what is seen in the FD (and to extract the oscillation parameters)



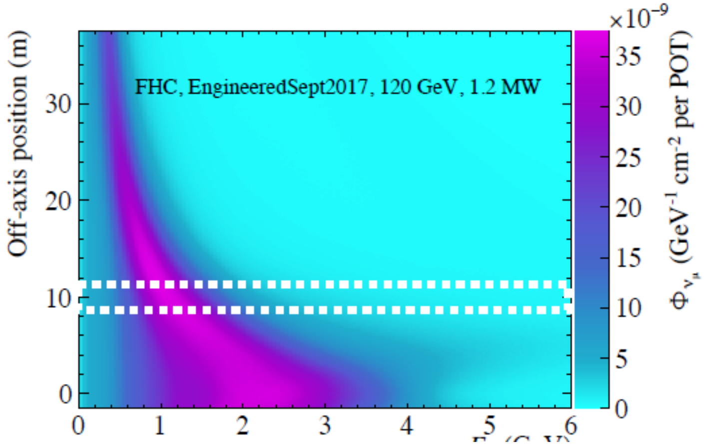
Neutrino interaction model

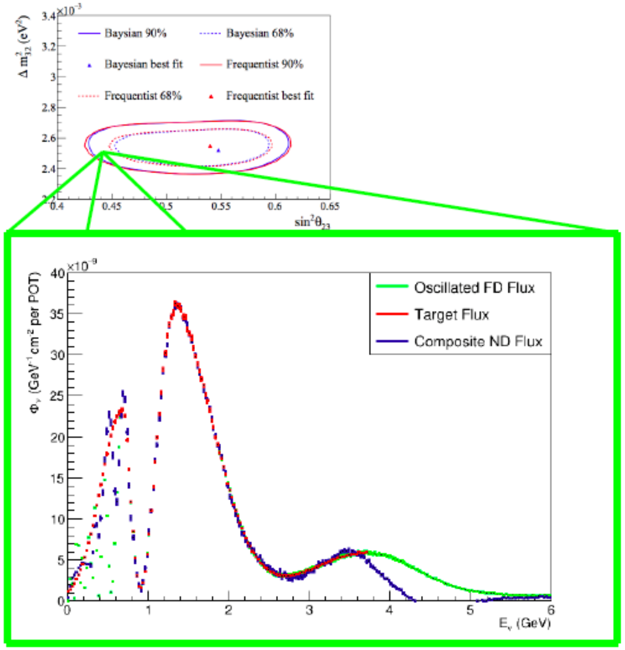
DUNE-PRISM

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

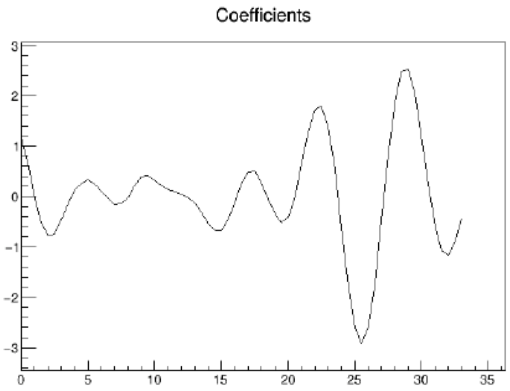
I've written this up in Fortran if you want it ☺.

- 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)





Coefficients



- $\Delta m_{23}^2 = 0.0025$ eV^2/c^4
- $\sin^2\theta_{23} = 0.43$