The DUNE Near Detector Complex

Alan Bross

Physics Opportunities in the Near DUNE Detector Hall

December 3rd, 2018

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Outline

- Motivation and overview of the baseline facility
- Flux, event rates and beam systematics
- Physics program (Chris Marshall)
- Brief introduction to the DUNE Near detectors
  - LAr (James Sinclair)
  - Multi-purpose Detector (MPD) (Tanaz Mohayai)
  - 3DST (Clark McGrew)
  - DUNE-PRISM (Christovao Vilela)
- Near detector hall
- Conclusions and outlook

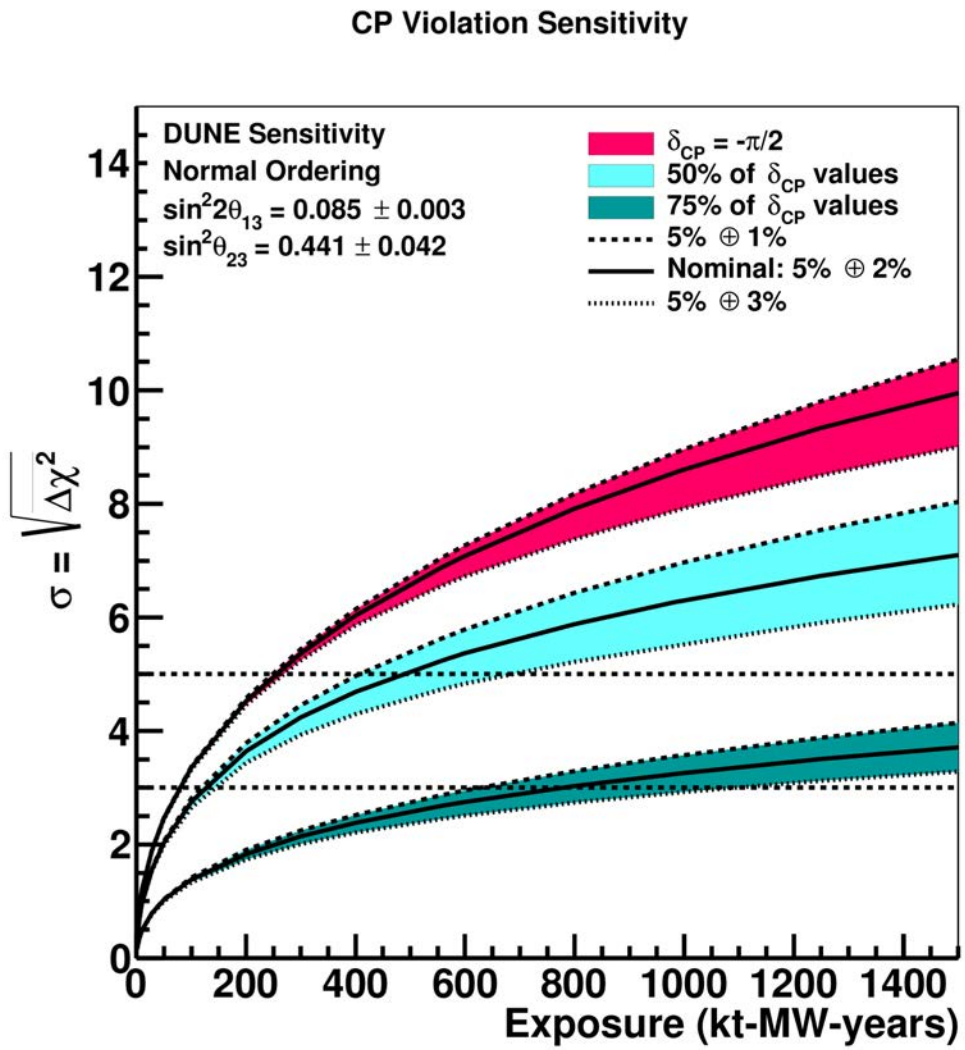
Details in the talks that follow

Why do we need near detector(s)

Primary purpose

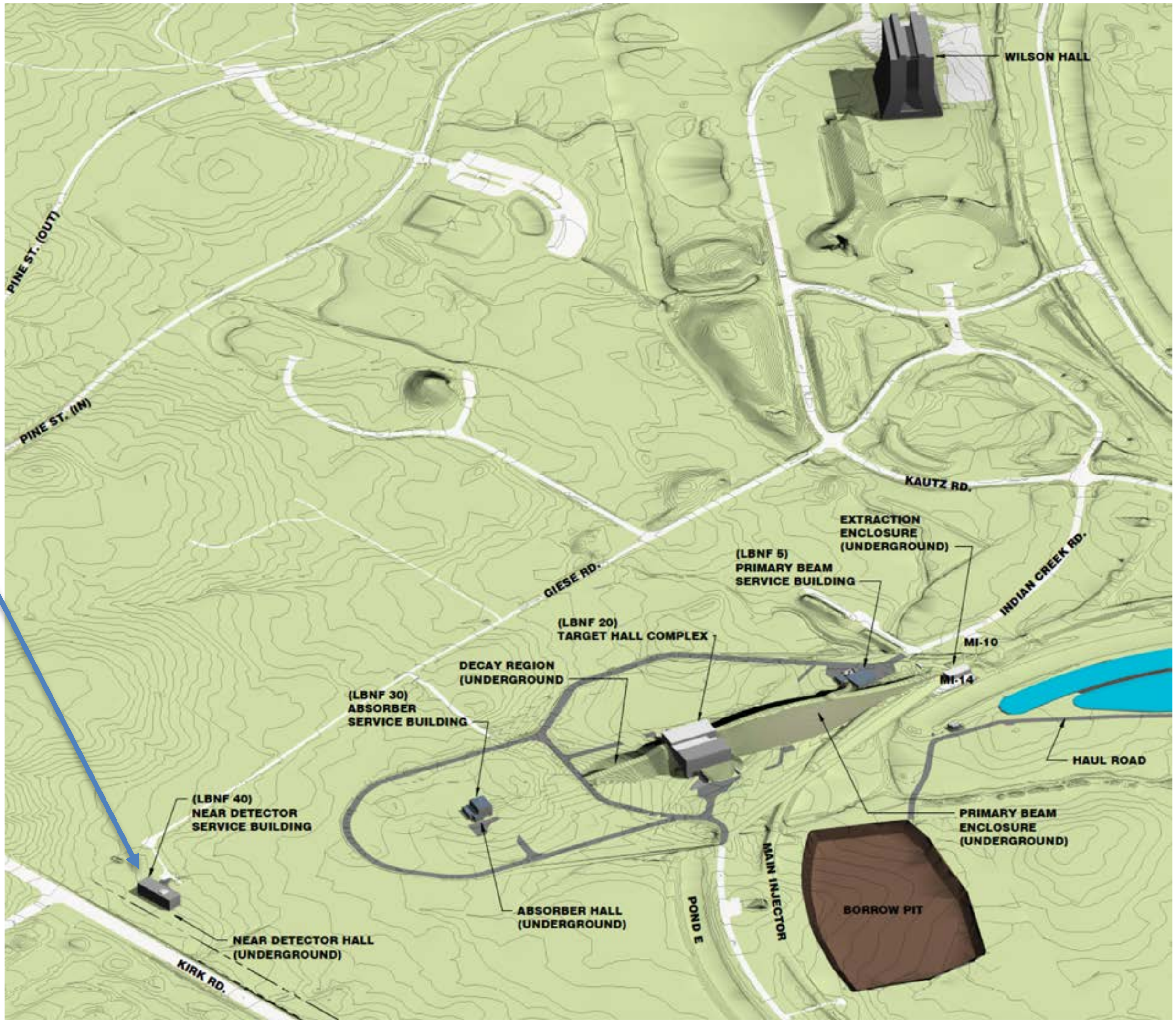
The significance with which CP violation, defined as δCP not equal to zero or π, as a function of exposure in kt-MW-years, for equal running in FHC and RHC mode. True normal ordering is assumed. The width of the band corresponds to the difference in sensitivity between ν_e signal normalization uncertainty of 1% and 3% with 5% uncertainty on the ν_μ disappearance mode.

+ many topics on physics beyond νSM *(I think that is why we are here)*

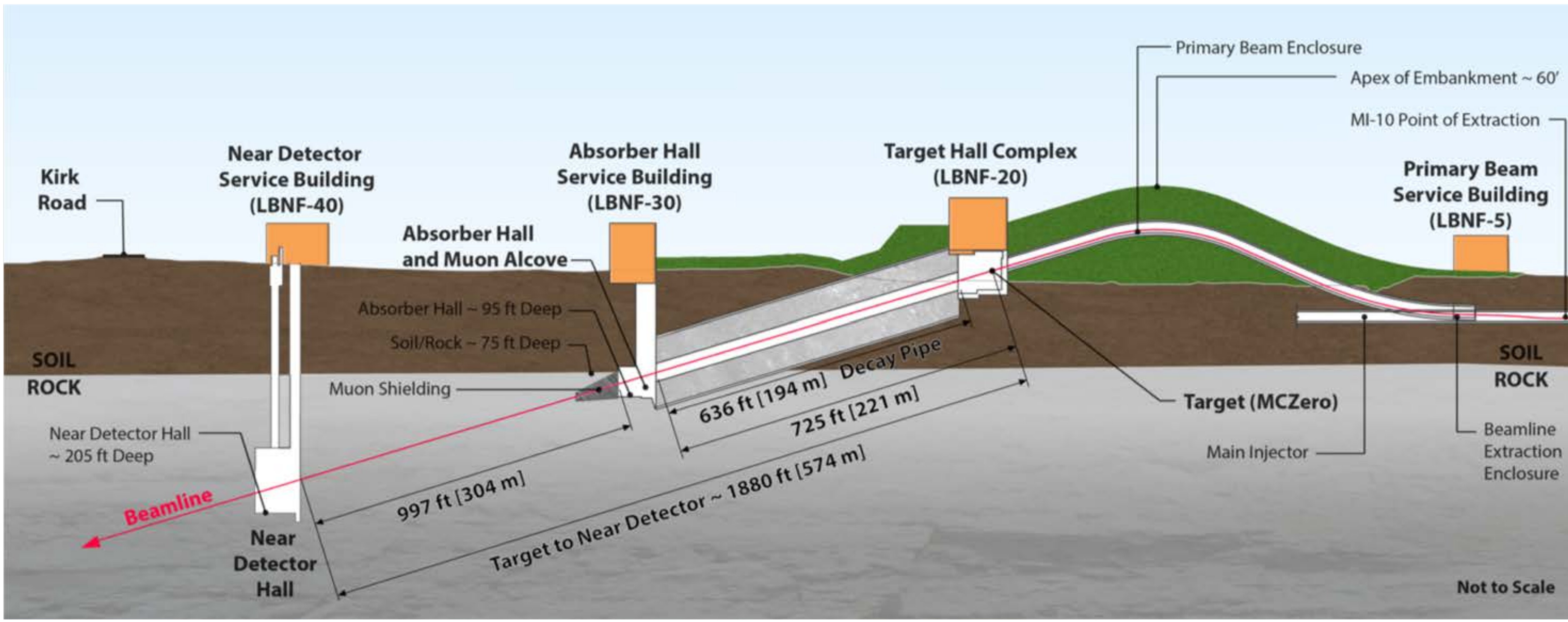


Facility: Bird's-Eye View

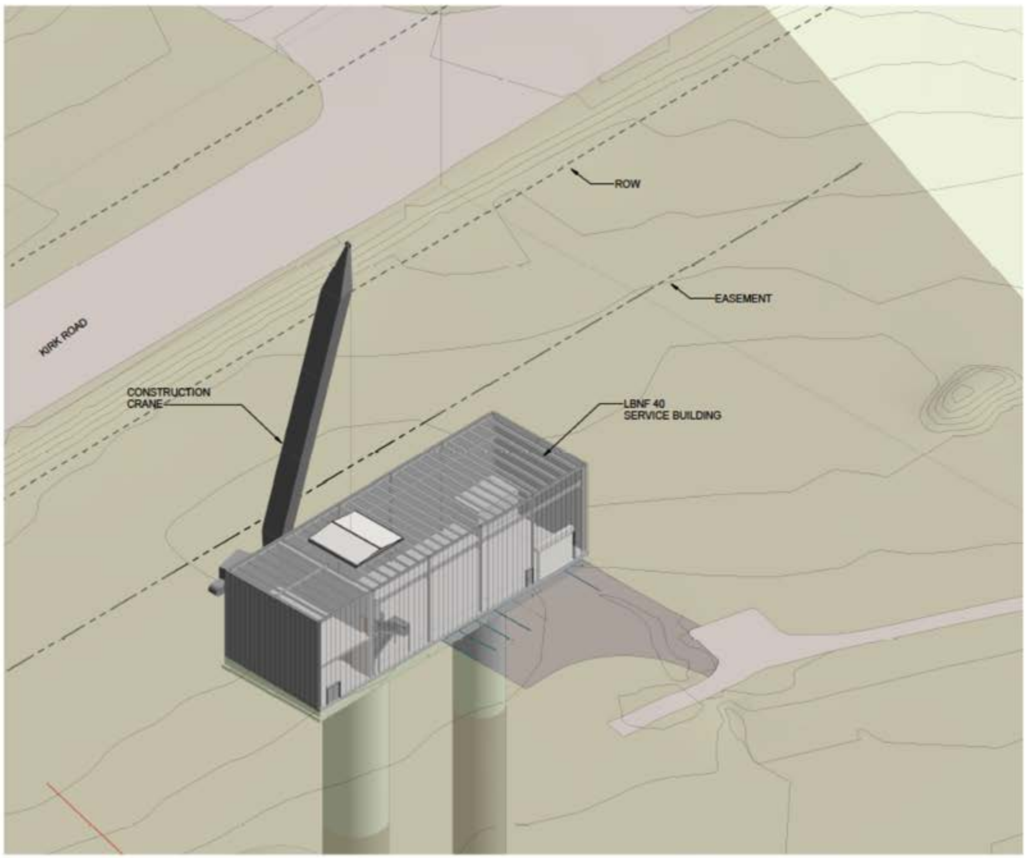
You are here



Looking underground

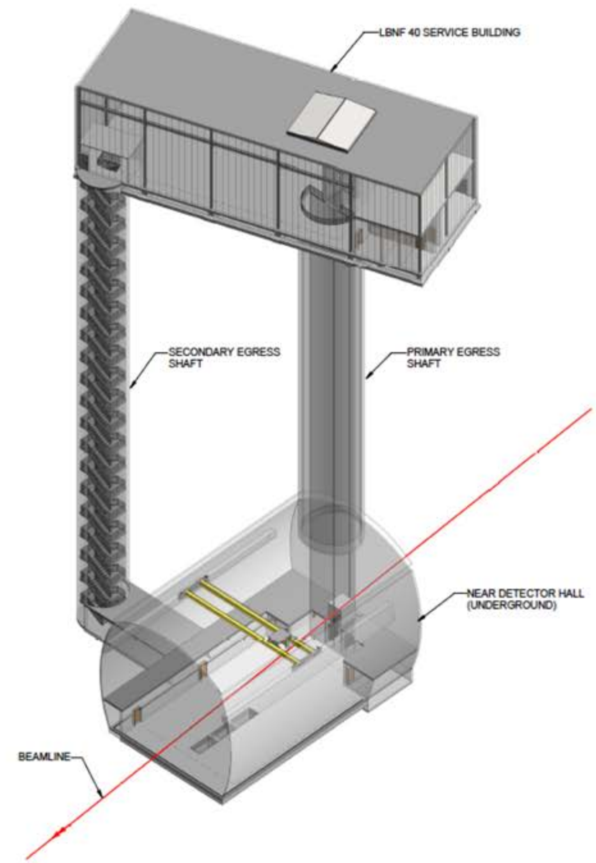


Service building: Reference design



3D PRESENTATION AT GRADE LEVEL

SCALE:

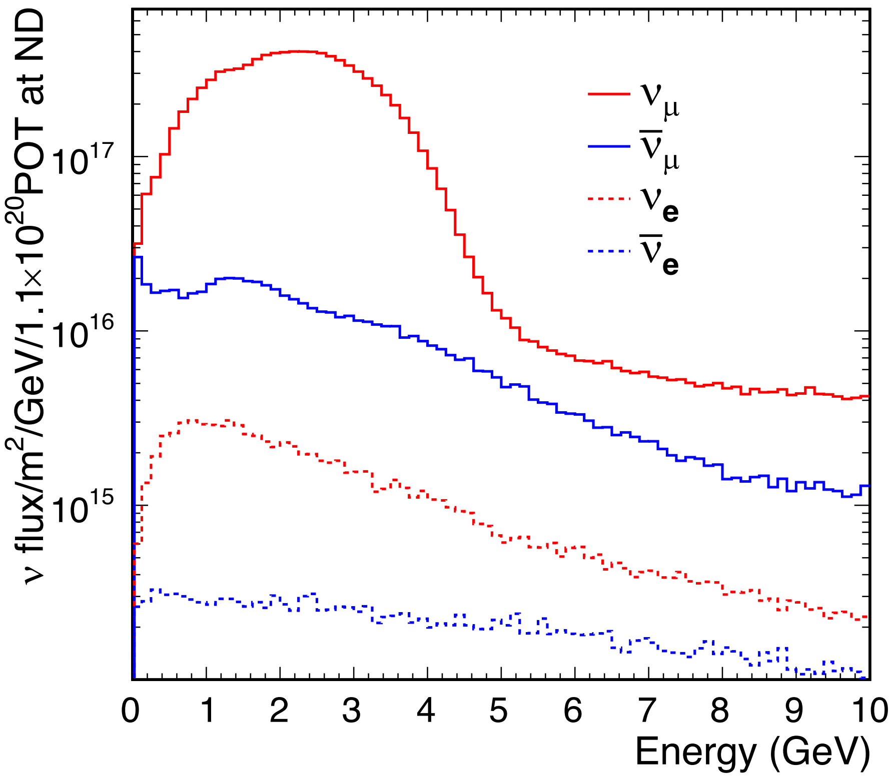


3D PRESENTATION

SCALE:

Flux, event rates @ ND570

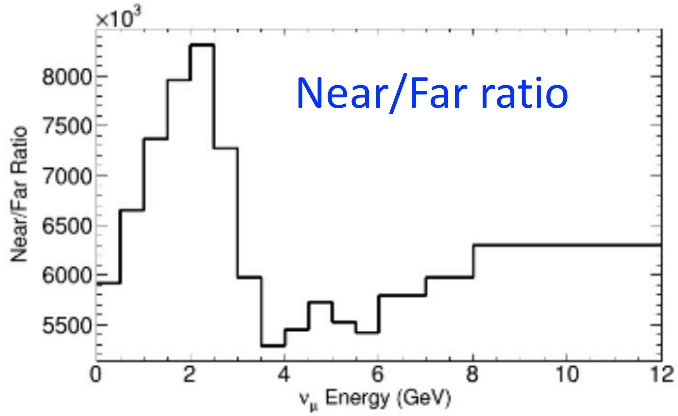
Optimized CPV tune



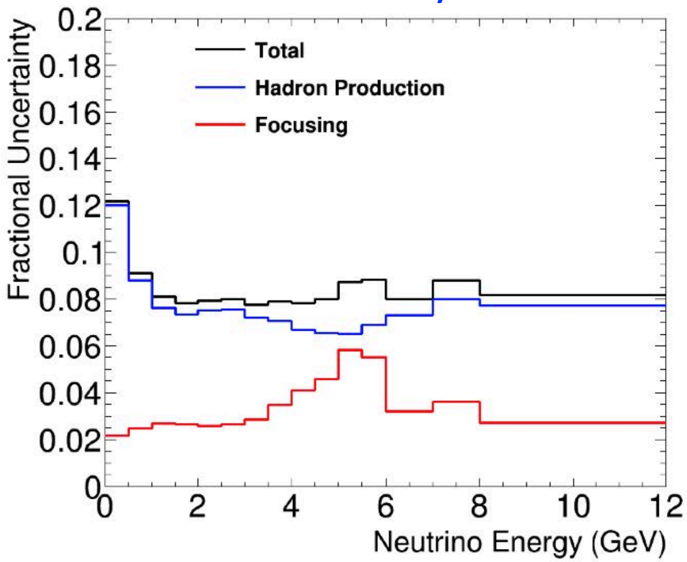
FHC, Events/ton_Ar-year

Event class	Number of events per ton-year
ν_μ CC Total	1.64×10^6
ν_μ NC Total	5.17×10^5
ν_μ CC Coherent	8.35×10^3
ν_μ NC Coherent	4.8×10^3
ν_μ - electron elastic	135
ν_μ CC π^0 inclusive	4.47×10^5
ν_μ NC π^0 inclusive	1.96×10^5
ν_μ Low ν (250 MeV)	2.16×10^5
ν_μ Low ν (100 MeV)	7.93×10^4
$\bar{\nu}_\mu$ CC Coherent ($\bar{\nu}$ mode)	6.90×10^3
ν_e CC Total	1.89×10^4
ν_e NC Total	5.98×10^3
ν_e CC Coherent	93
ν_e NC Coherent	52

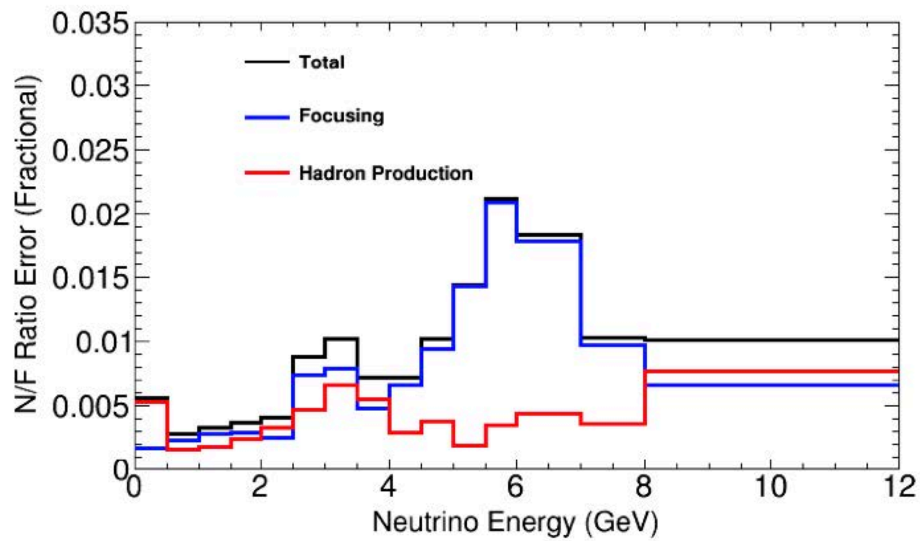
Beam systematics



Flux uncertainty at ND



Near/Far ratio uncertainty



Beam systematics II: Instrumentation

- Work continues on understanding beam
- Hadron production measurements
  - Flux spectrometer
    - Exact mock up of LBNF target horn system with multiparticle spectrometer, PID, etc.
  - EMPAHTIC
    - Uses the FNAL Test Beam Facility (FTBF), either MTest or Mcenter
- Beam line instrumentation
  - Muon monitors
    - Conventional
    - Diamond
    - Muon total absorption
  - Transition radiation detector
  - RF-based hadron monitor

Measuring the # of events, near & far

- Oscillation probabilities

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}\ (E_\nu)}$$

- Number of events/energy spectrum

$$\frac{dN_\nu^{det}}{dE_\nu} = \phi_{\nu_\mu}^{det}(E_\nu) * \sigma_{\nu_\mu}^{Ar}\ (E_\nu)$$

- In reality

$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}\ (E_\nu) * T_{\nu_\mu}^{det}(E_\nu, E_{rec})\ dE_\nu$$

- Folding of detector effects
  - Prevents (easy) cancellations of many systematic effects
  - Needs unfolding

Details

- Oscillation signal

$$\frac{dN^{far}_{\nu_e}}{dE_\nu} \Bigg/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * F_{far/near}(E_\nu)$$

- Near muon/electron ratio

$$\frac{dN^{near}_{\nu_e}}{dE_\nu} \Bigg/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * \frac{\phi^{near}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu)}$$

Uncertainty

- Need to know
  - Flux & cross section ratios
  - Far/near extrapolation

Details II

- Since E_ν^{rec} is not equal to E_ν
- Need to understand
  - Detector effects in near and far detector
  - Relation of visible to neutrino energy
    - **NEUTRONS**
  - Cross section ratios
  - Near to far flux extrapolation
- Flux normalisation provides some cancellation
  - Shape is important, however

Near Detector needs to measure:

- ND Fluxes

  $\phi_{\nu_x}^{near}(E_\nu)$

  - Prior constrained 5-10%
- Total and differential cross sections on Argon

  $\frac{d^n \sigma_{\nu_x}^{Ar}}{da\ db\ dc\ \ldots}(E_\nu)$ (Largely unknown)
- True to reconstruction "matrix"

  $T_{\nu_x}^{far}(E_\nu, E_{rec})$ and $T_{\nu_x}^{near}(E_\nu, E_{rec})$

  - Depends on: Detector effects, xsections, nuclear effects
- Approach
  - Measure as many exclusive differential cross sections with as much precision as possible

$$\frac{dN}{dX_{rec}} = \int \phi_{\nu_\mu}^{near}(E_\nu) \frac{d\sigma_{\nu_\mu}^{Ar}}{dX}(E_\nu)\, T_{\nu_\mu}^{near}(E_\nu, X, X_{rec})\ dE_\nu dX$$

Flux measurements

- Primary thrust within DUNE near detector suite is to do measurements on Ar (Liquid and gas)
- Proposed measurements
  - Neutrino-electron scattering (LAr)
  - Low-$\boldsymbol{\nu}$ method (liquid and gas)
  - Coherent Scattering(liquid and gas)
    - $\upsilon_l + N \rightarrow l^- + N + \pi^+$
    - $\bar{\upsilon}_l + N \rightarrow l^+ + N + \pi^-$
- Measurements on hydrogen (CH and gas)
    - $\upsilon_l + p \rightarrow l^- + \Delta^{++} \rightarrow l^- + p + \pi^+$
    - $\bar{\upsilon}_l + p \rightarrow l^+ + \Delta^0 \rightarrow l^+ + p + \pi^-$

DUNE Near Detector Concept Study

- The Near Detector Concept Study explored the requirements, technology and physics performance of a number of options for the near detector.
  - It was an approximately 2 year effort which included workshops at Fermilab and CERN and targeted study by 6 working groups
- The final report, providing recommendations for the near detector complex, was submitted to the DUNE Executive Board in July 2018.
- At the end of August, the Executive Board approved the recommendations that were proposed.

Main Near Detector Recommendations

- The recommended concept is a near detector suite consisting of a LArTPC (not in a magnetic field), a HPgTPC in a magnet, and a 3DST.
- The design of a mobile LAr detector that can make measurements at one or more off-axis positions should go forward (DUNE-PRISM). Study option of moving HPgTPC also
- The experimental floor area should be at least 42.5m x 17m and the hook height must be at least 13m, measured from the floor. The minimum lateral dimension of hall needs further study, and will ultimately be settled in EFIG.
- The option of filling the HPgTPC with hydrogen should also be investigated.

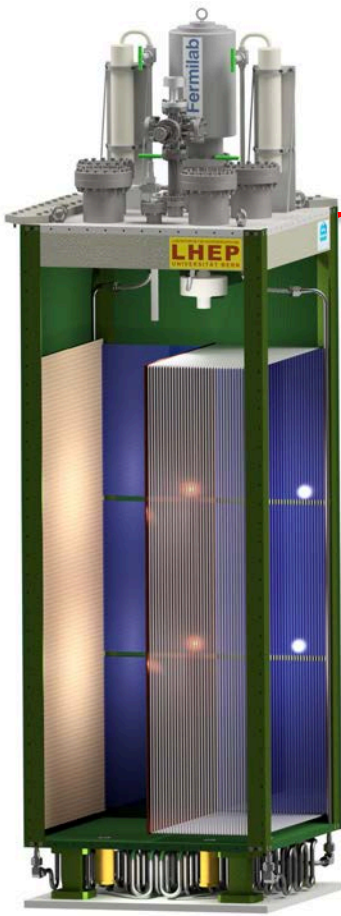
Multi-pronged approach

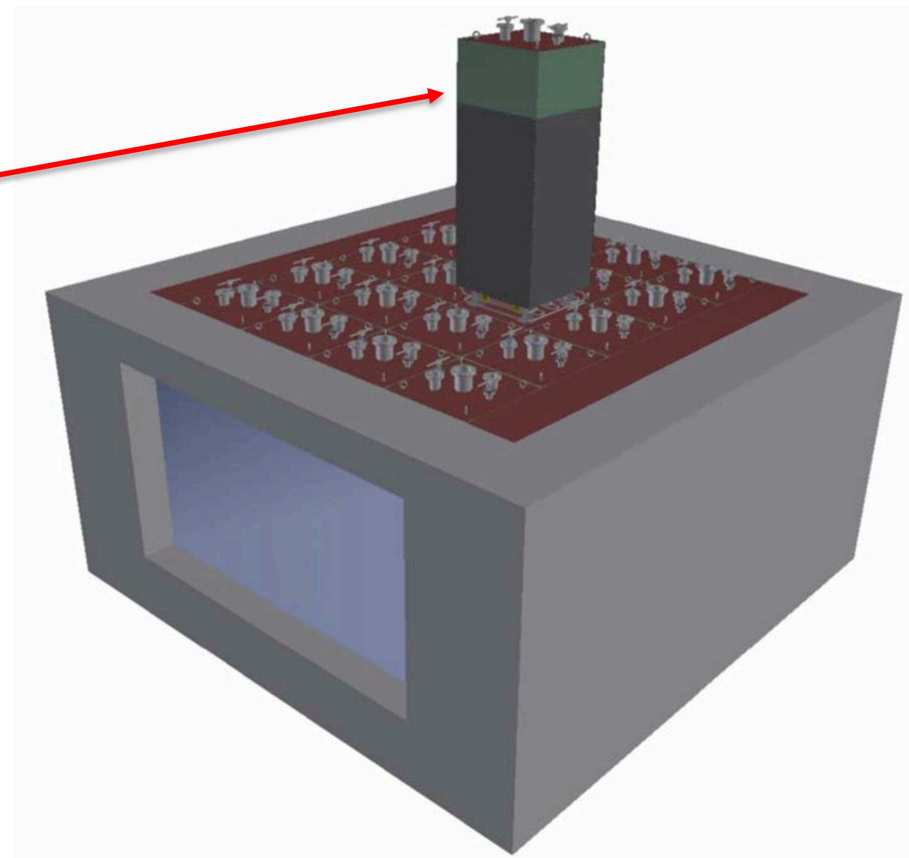
- Prong I: State-of-the-art Ar detectors:
  - LAr (~75t fiducial target mass), non-magnetized
    - Pixelated (raw 3D data)
    - Optically segmented
      - Neutron tagging
  - Multi-purpose Detector (MPD)
    - High-Pressure (10ATM) gas TPC (HPgTPC) (1t fiducial target mass)
    - In ~0.5T field (magnetic spectrometer)
    - Surrounded by high-performance ECAL and muon tagger
- Prong II: DUNE-PRISM
  - Move LAr and possible MPD off axis
- Prong III: 3 dimensional scintillator (CH) tracker (3DST) (4t)
  - Interactions on protons and carbon
  - Magnetized
  - With external tracking and ECAL

LAr: ArgonCube

- Underlying principles
  - True Raw 3D readout – in a sense, the first true LArTPC
    - Pad readout, no wires
    - S/N >> than in conventional LAr TPCs
    - Better energy resolution and better pointing resolution
  - Modular, highly segmented
    - Short drift ⇒ little diffusion, low high voltage, less sensitive to impurities
    - Optically isolated modules ⇒ more effective use of scintillation light

LAr: ArgonCube design





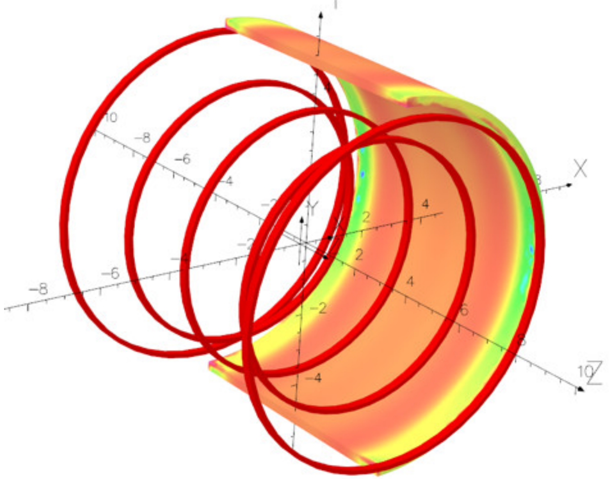
James will provide the details

Multi-purpose detector

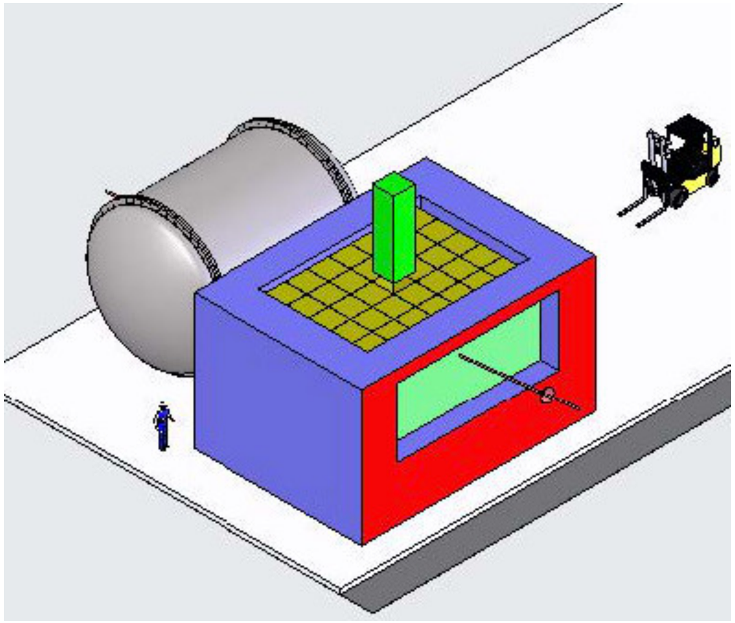
- Central component is a large gas TPC operating at 10 Atm (HPgTPC)
  - Copy of ALICE TPC (5m in diameter X 5m long active)
  - Re-use the ALICE readout chambers were are being replaced during the current long shutdown (& engineering)
- HPgTPC surrounded by high-performance ECAL following designs developed in the CALICE program
- ~0.5T B field
  - Superconducting design looks most promising
  - Open geometry
- Muon tagger outside coils
- MPD is essentially a Collider Detector design

MPD

Magnet concept



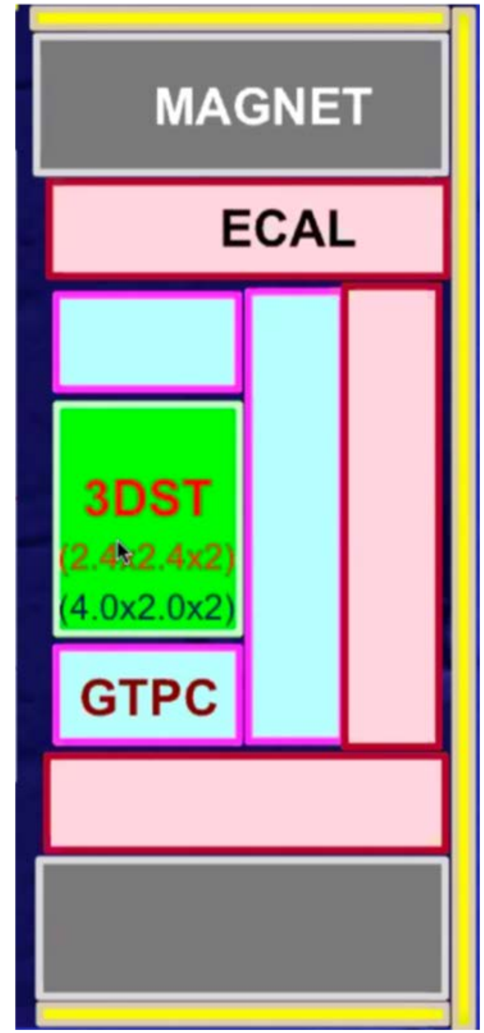
ALICE being lowered into Hall



Tanaz will go into the details

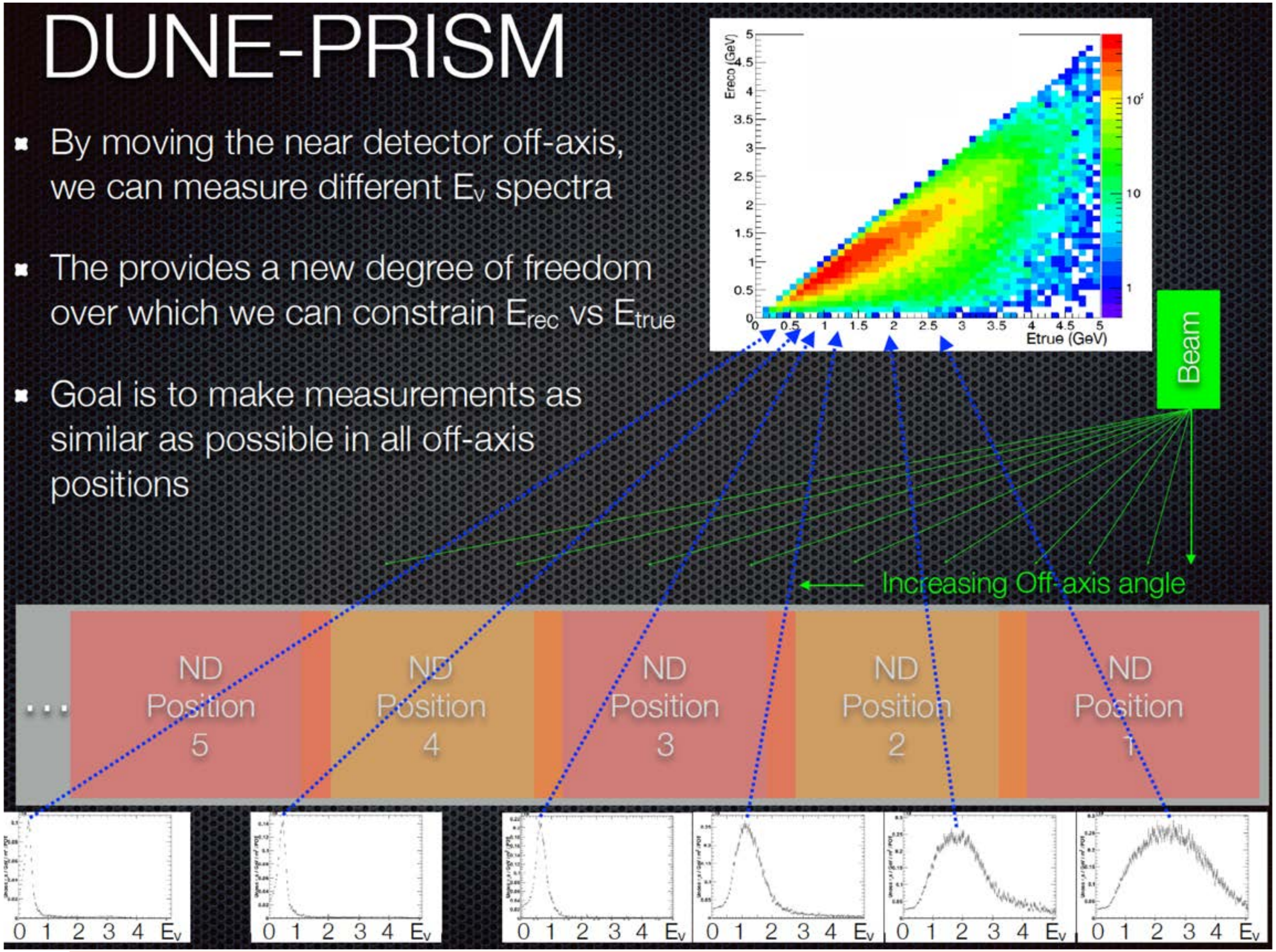
3DST

- Magnetized system complementary to MPD/HPgTPC
  - Different target nucleus
  - High statistics tests of neutrino models
  - Connection to the existing catalog of cross section measurements on scintillator (K2K, MiniBooNE, SciBooNEne, MINERvA, T2K, NOVA)
- Can remain on-axis when other detectors move off-axis
  - Accurate determination of the flux
  - High statistics measurement of the beam electron neutrino component



Clark will give the details

DUNE-PRISM

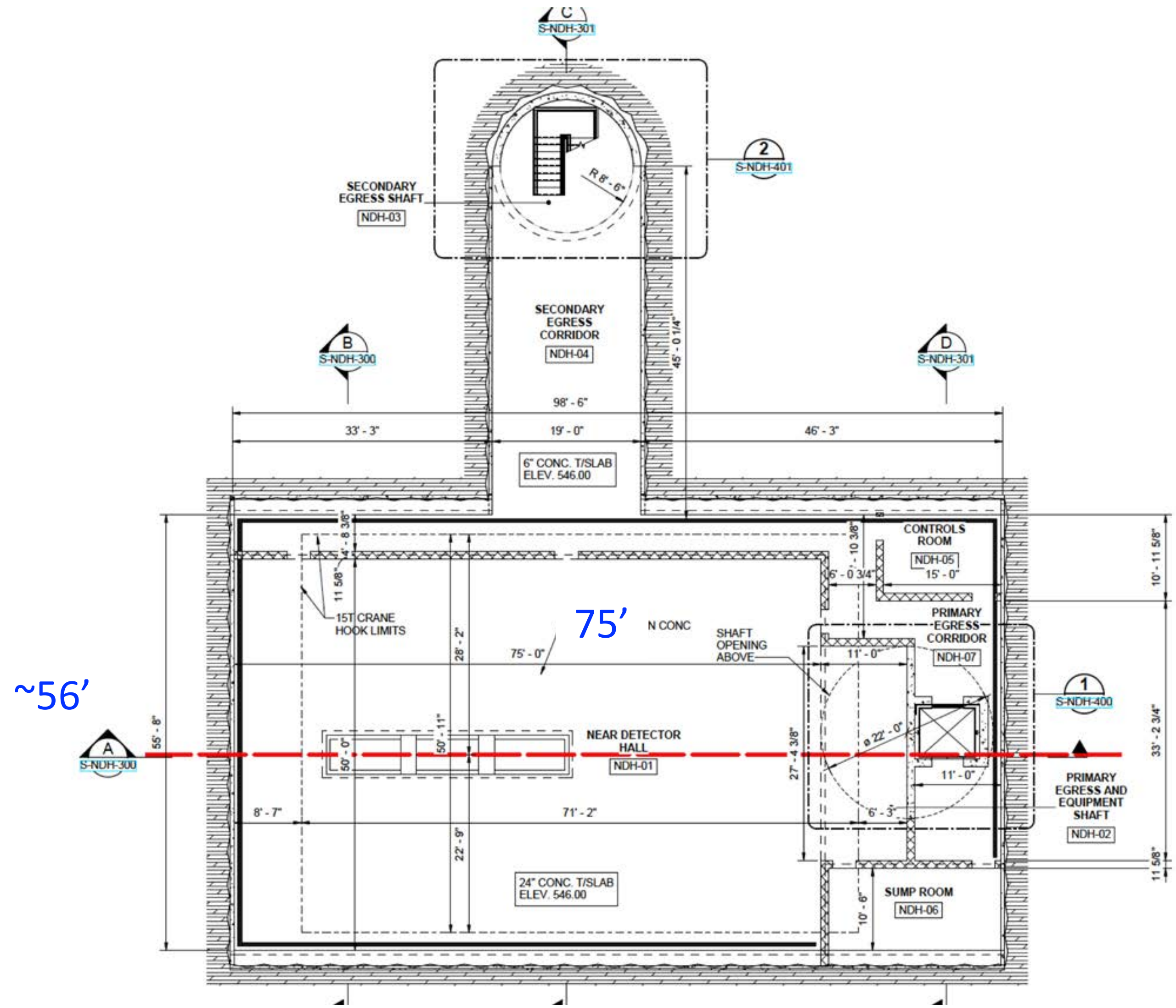


Use linear combinations to disentangle flux and x-section effects using different fluxes.

Cristovao will give the details

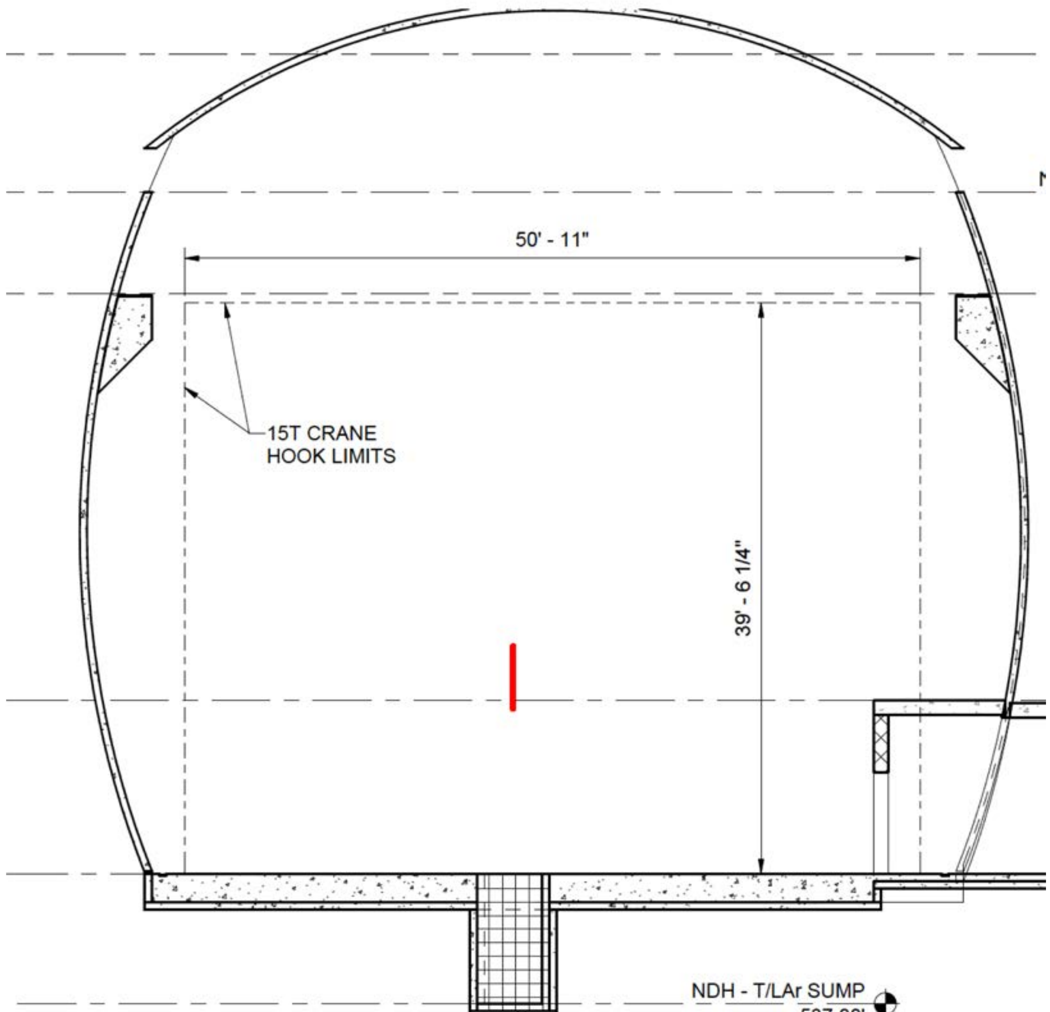
Where we house all this stuff

Hall: Reference design (2015 CDR)



Hall: Reference design II

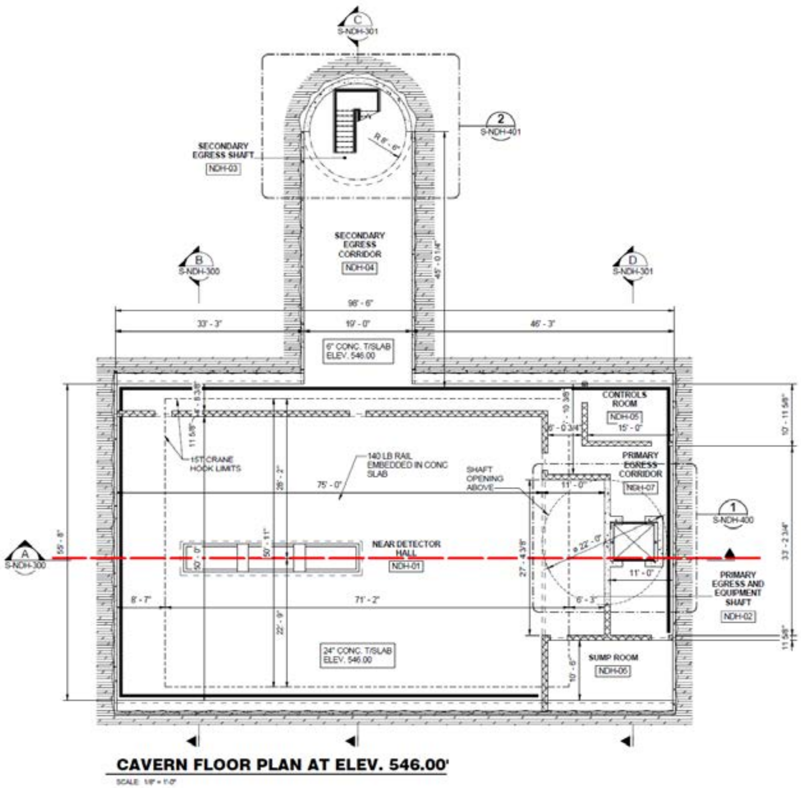
Beam's-eye view

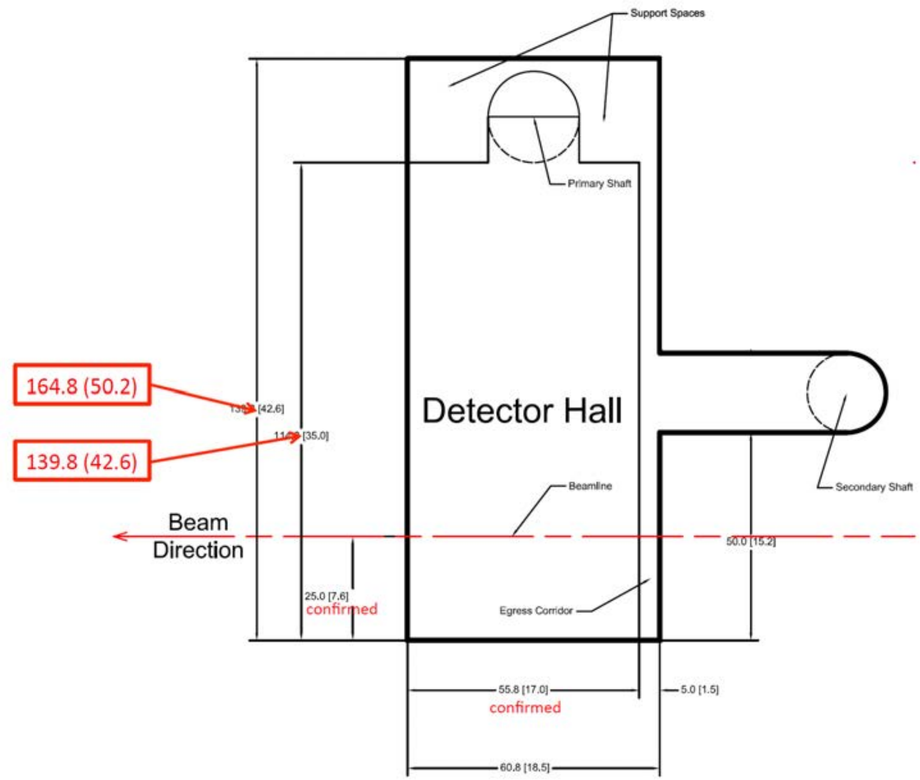


Hall: Reference design III

- It becomes obvious rather quickly that the hall reference design does not accommodate our current detector designs and run plan

Near Detector Hall: June 2018 Update





Reference ND Detector Cavern Concept:

100ft x 56ft Cavern with

75ft x 50ft Detector Hall

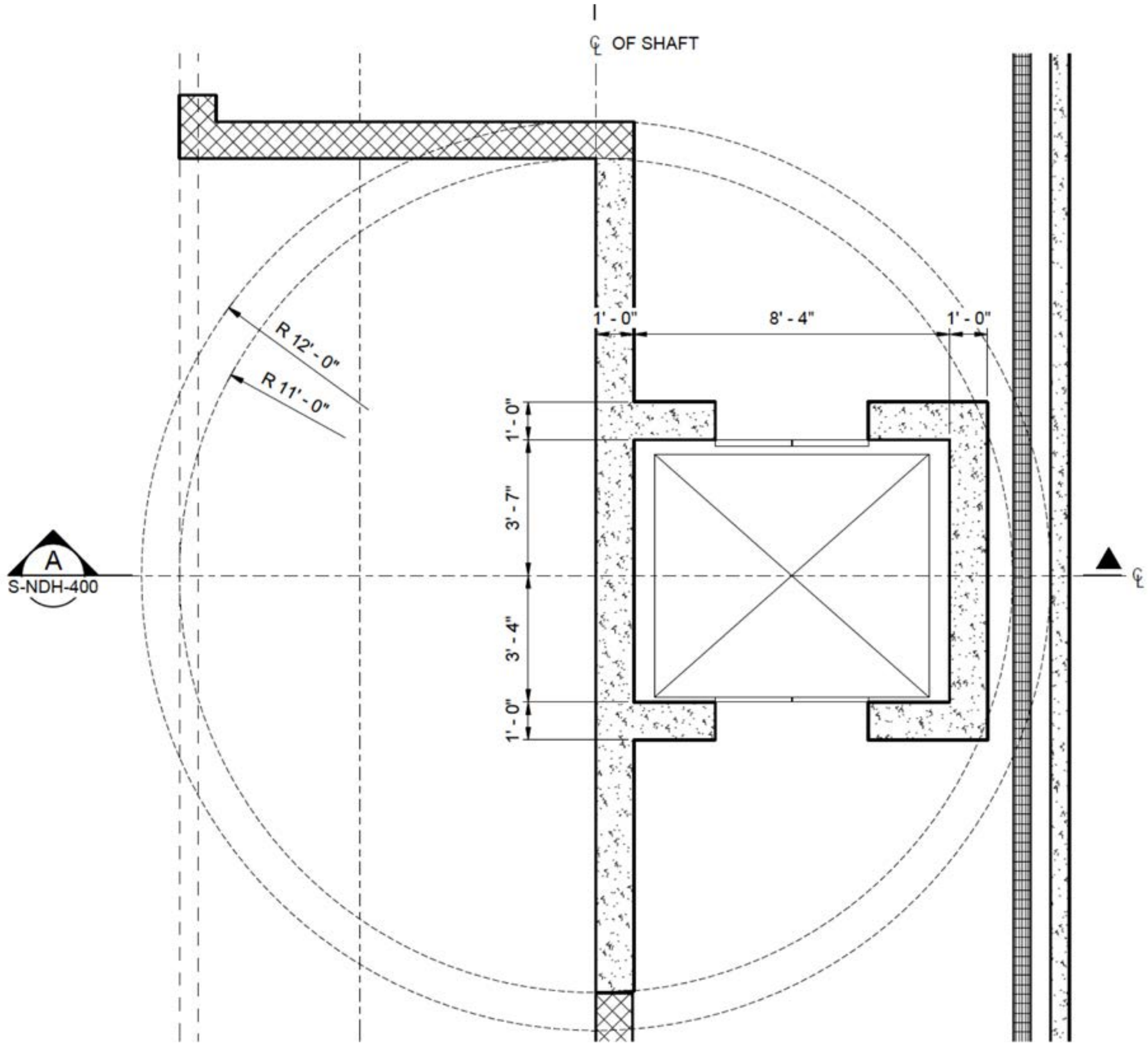
June 2018 ND Collaboration Proposal:

165ft x 61ft Cavern with

140ft x 56ft Detector Hall

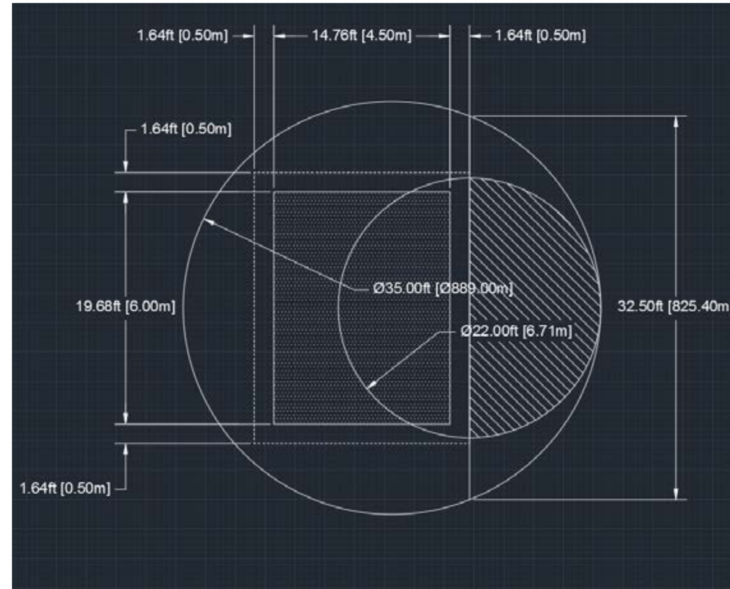
Primary access shaft: Reference design

22’ Ø

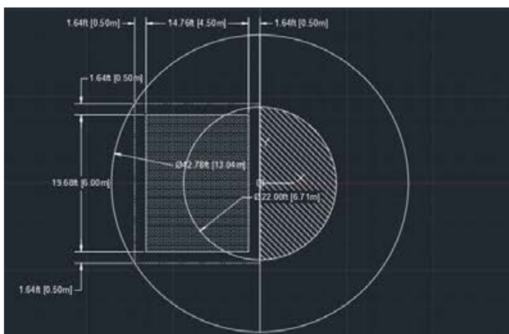


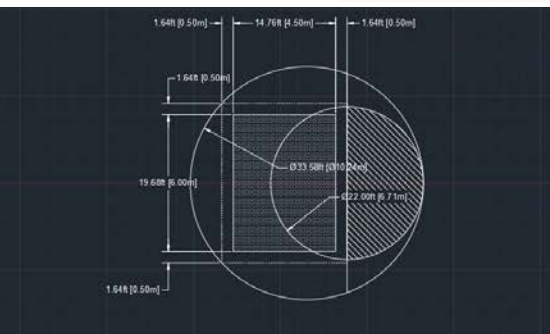
Larger Shaft – Size

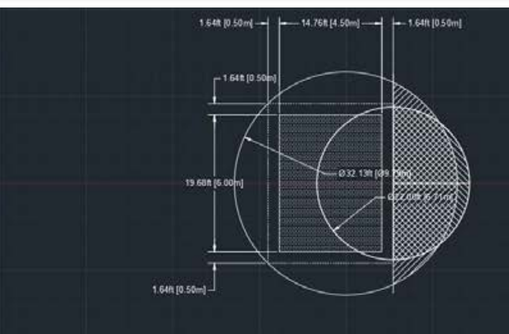
- Reference shaft is 22ft ID
- Considered shaft diameters ranging from 32ft to 43ft ID
- Now looks like a 38ft ID shaft provides a minimum of 0.5m clearance around HPgTPC and preserves lift/utility segment



35ft diameter

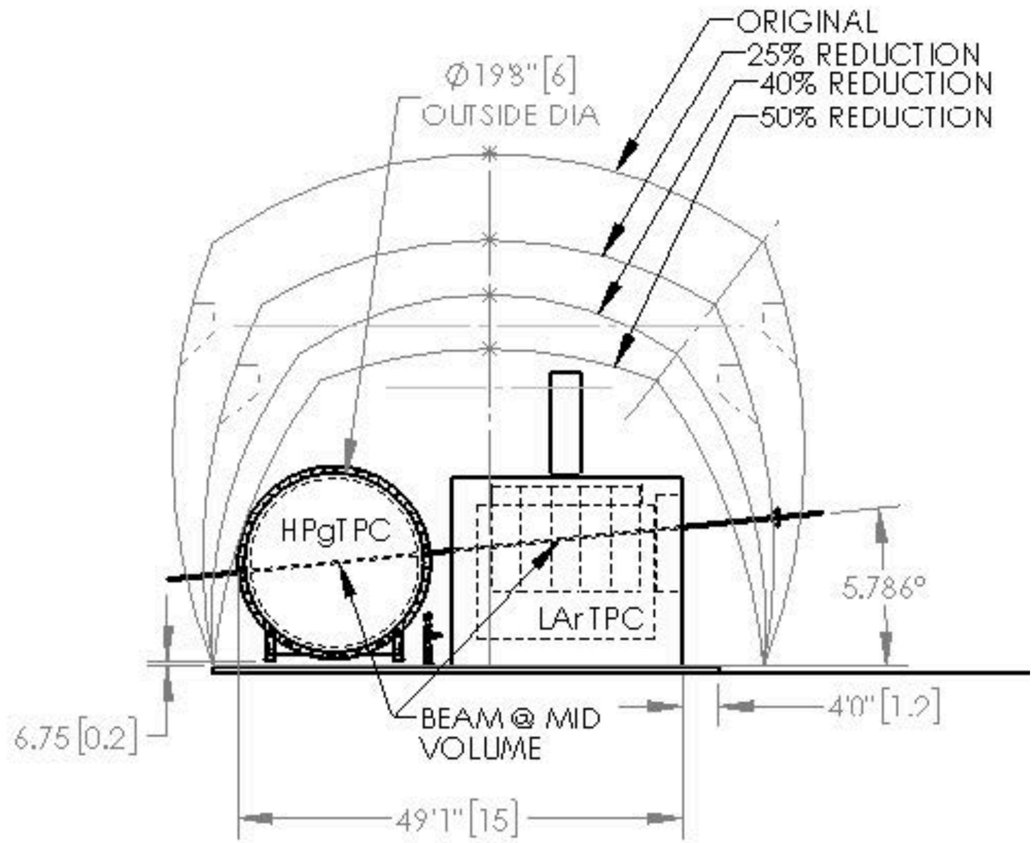

Shaft sized to keep septum wall centered in shaft - 43ft diameter


Shaft sized to preserve the cross-sectional shape of the 22ft diameter shaft's lift and utility segment - 34ft diameter


Shaft sized so that the cross-sectional area of the lift and utility segment matches that of the 22ft diameter shaft - 32ft diameter

Larger cavern – cost savings?

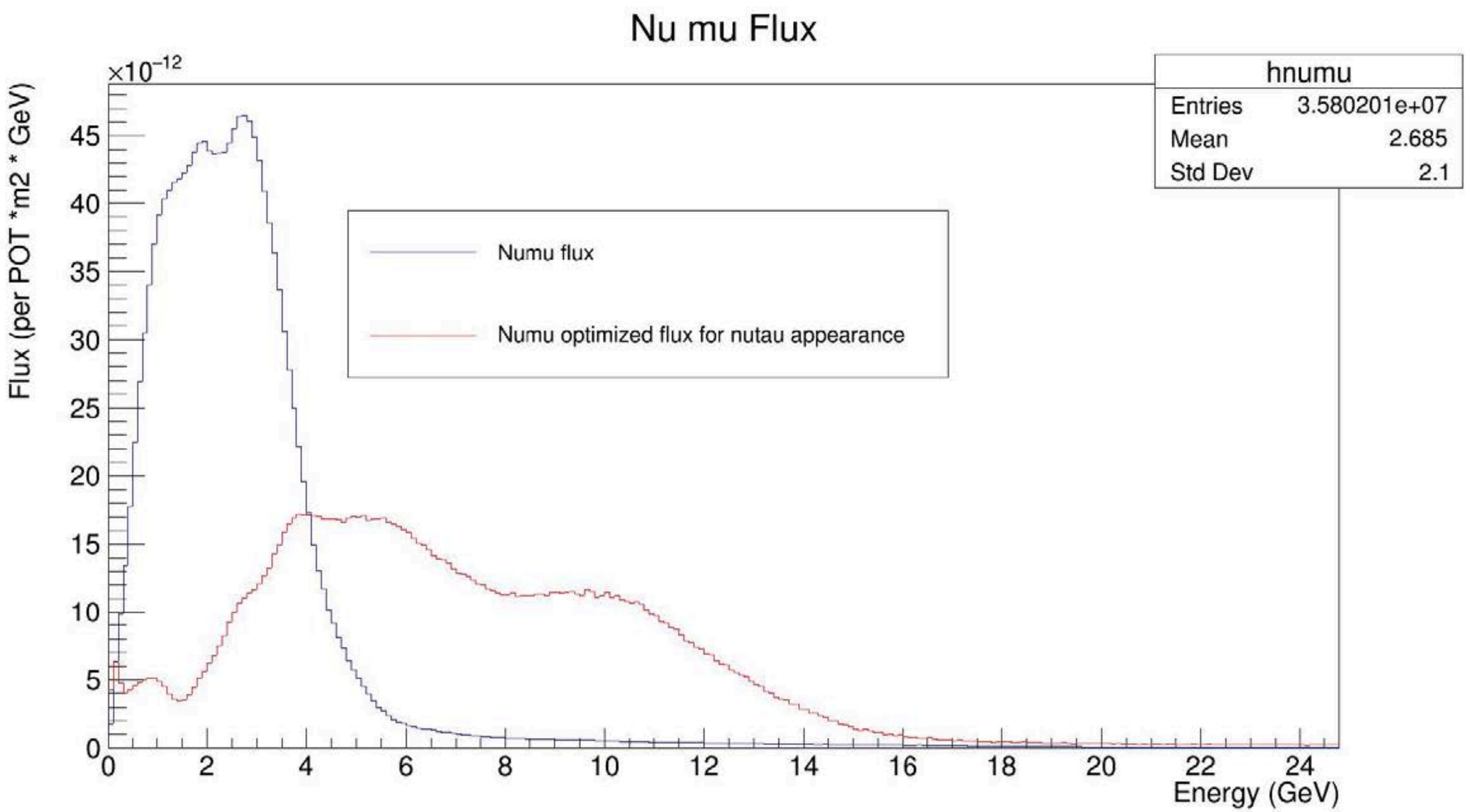
- Although LBNF, DUNE and Fermilab management understands the benefits of the larger cavern and access shaft for the DUNE physics program
- Trying to see if some costs can be saved while keeping the larger hall footprint and larger access shaft
- Bring Down the Roof



One More Thing

Unique capabilities of LBNF beam

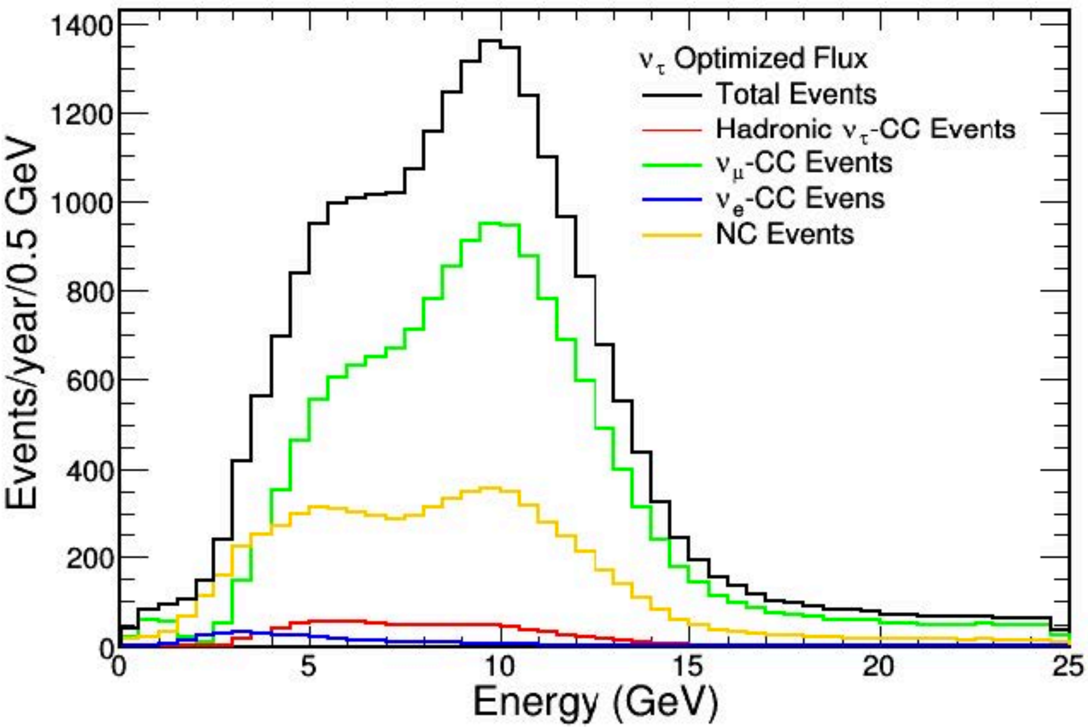
High energy tune



ν_τ Appearance

- No other planned experiment/facility can study tau neutrino appearance in a neutrino beam
- What physics topics can be studied with this beam at the near site?

~10X increase in ν_τ evts in Far detector



Conclusions and outlook

- The DUNE Near Detector Design Group (NDDG) has been formed to deliver a CDR for near detectors & the facility
  - I have outlined the basic approach that is being studied and which will form the bases of the CDR to a large extent
- Powerful, high-precision, full capability (calorimetric, spectrometer, PID, multiple target nuclei, off-axis measurements) detector systems
  - LAr, MPD (HPgTPC+ECAL+Magnet+μ tagger), 3DST
- With these detectors and the LBNF beam we will accumulate enormous statistics in all channels, including neutrino-electron elastic scattering.
  - **~1.5M ν_μCC events/yr-ton (FHC)**
- Aggressive 3-pronged approach to CPV
- Opportunities to study physics beyond the νSM are extensive

THANK YOU