Status and Plans for the DUNE Near Detector

Xinchun Tian
for the DUNE Collaboration

Department of Physics and Astronomy
University of South Carolina

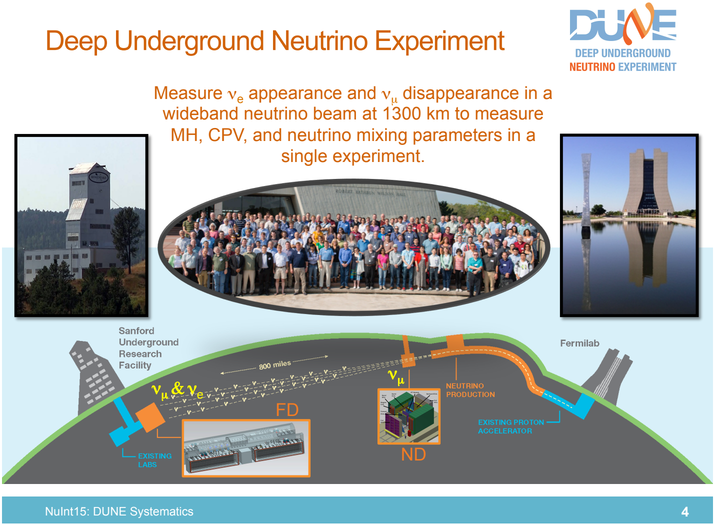
NuInt 2015 @ Osaka, Japan, Nov. 16-21, 2015

Outline

1. Introduction
2. Reference Design (FGT) and Physics Sensitivities
   - High Resolution Fine-Grain Tracker (Reference Design)
   - Measure Absolute Flux
   - QE and Resonance Processes
   - Constrain Nuclear Effects
3. Alternative Designs
   - Liquid Argon TPC
   - High Pressure Argon Gaseous TPC
   - NuPRISM
4. Outlook

Deep Underground Neutrino Experiment

See Elizabeth Worcester's talk: Link

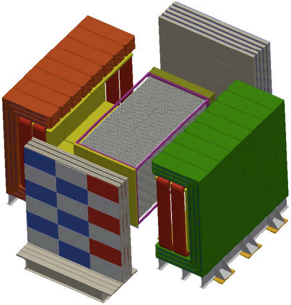


Goals of the ND in DUNE

- Constrain the systematic uncertainties in the oscillation measurements/searches
  - Neutrino source : ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ in "PMNS oscillation ($0.5 \leq E_\nu \leq 10$ GeV)" and "Control and New Physics ($0.10 \leq E_\nu \leq 50$ GeV) regions"
  - Neutrino and Anti-neutrino energy-scale / topologies
  - Backgrounds to the oscillation signals: $\pi^0/\pi^\pm$
- A generational advance in the precision neutrino physics
  - Cross sections: QE, Resonance, Coherent meson and DIS
  - Neutrino-nucleus (Ar) interactions and nucleon structure
  - Electroweak and isospin physics
- Search for New Physics
  - Heavy neutrinos, including "Light Dark Matter" search
  - Large Δm^2 oscillation
  - *etc.*

High Resolution Fine-Grain Tracker (Reference Design)

- $\sim$ 3.5 m $\times$ 3.5 m $\times$ 6.5 m STT ($\rho \simeq 0.1$ g/cm^3)
- 4π ECAL in a dipole magnetic field ($B = 0.4$ T)
- 4π MuID (RPC) in dipole and up/downstream
- Pressurized ^{40}Ar target $\simeq \times 10$ FD statistics and ^{40}Ca target



- Trasition Radiation : $e^{\pm}$
- dE/dx : $\pi^{\pm}$, $K^{\pm}$ and proton
- Magnet : + .vs. -
- MuID : μ

$\Rightarrow$ Absolute flux measurement

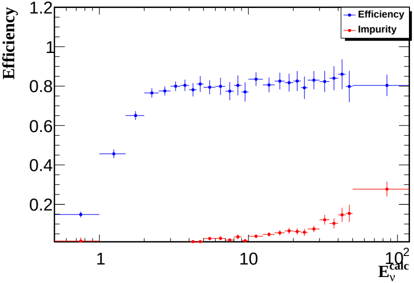
Radiator (Target) Mass	7 tons
Other Nuclear Target Mass	1–2 tons
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	$6\%/\sqrt{E}$ (4% at 3 GeV)
E_μ Resolution	3.5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
π^- .vs. π^+ ID	Yes
π^+ .vs. *proton* .vs. K^+	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

Constrain Absolute/Relative Flux

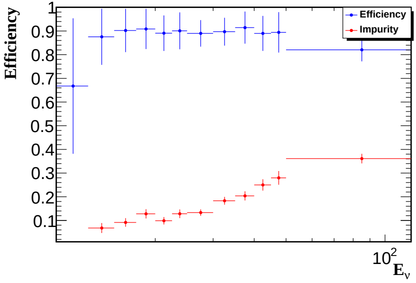
Absolute Flux: Neutrino electron NC/CC scattering

- Cross section is extremely small, but assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
  - 10 k $\nu e^- \to \nu e^-$ events, 78 k $\nu_\mu e$, 1.7 k $\bar{\nu}_\mu$, 1 k $\overset{(-)}{\nu}_e e$
  - 5.4 k $\sigma(\nu_\mu e^- \to \mu^- \nu_e)$ events

- Single, forward e^-
- Absolute flux : $\sim$ 2% precision in 0.5$\leq E_\nu \leq$ 10 GeV range.

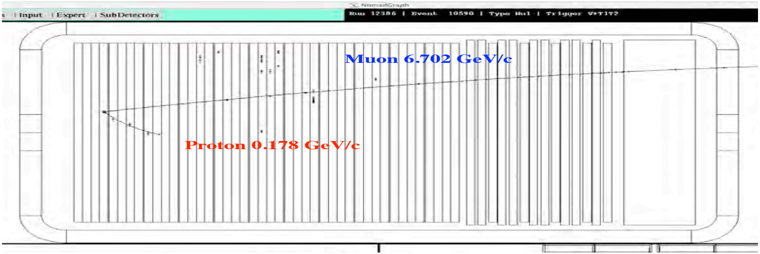


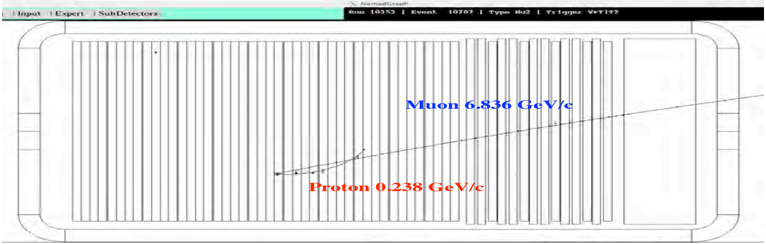
- Single, forward μ^-
- Absolute flux : $\sim$ 2.5% precision in 15$\leq E_\nu \leq$ 50 GeV range.



QE Candidates in NOMAD

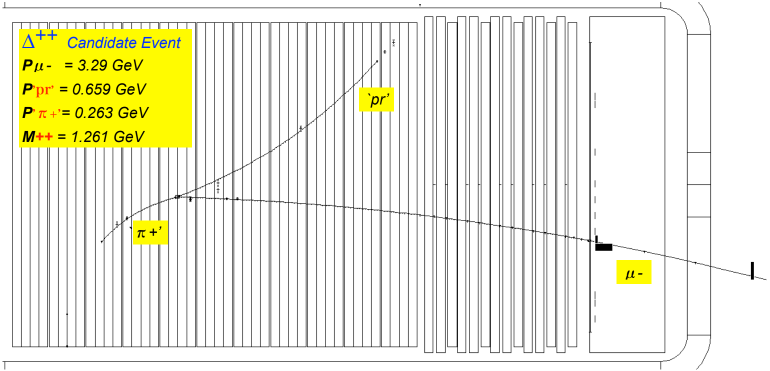
FGT will have $\sim \times$ 10 higher granularity vs NOMAD





Resonance Candidates in NOMAD

FGT will have $\sim \times$ 10 higher granularity vs NOMAD



Cross section

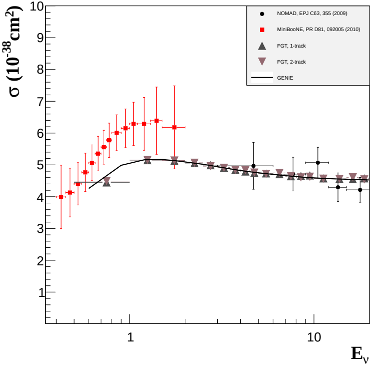


Figure: CCQE

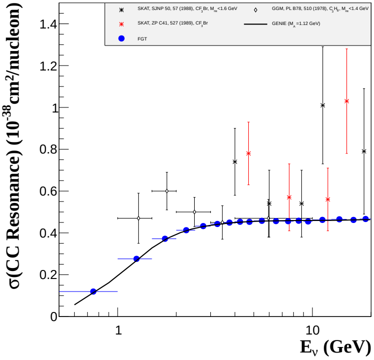


Figure: CC-Resonance

Constrain Nuclear Effects

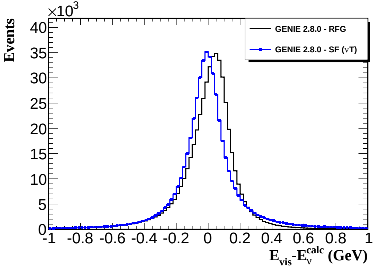
Compare $E_{\text{vis}} - E_\nu^{\text{calc}}$ using CCQE 2-track

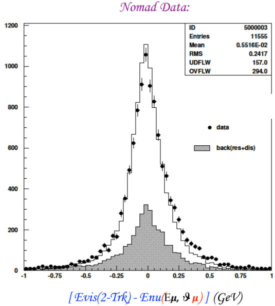
- Nuclear effects: initial state pair wise correlations & final state interactions

$$E_{\text{vis}} = E_\mu + E_{\text{had}}, \tag{1}$$

$$E_\nu^{\text{calc}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \delta M^2)}{2[(M_n - E_B) - E_\mu + p_\mu \cos\theta_\mu]}, \tag{2}$$

$$\delta M^2 = M_n^2 - M_p^2. \tag{3}$$





Alternative Designs

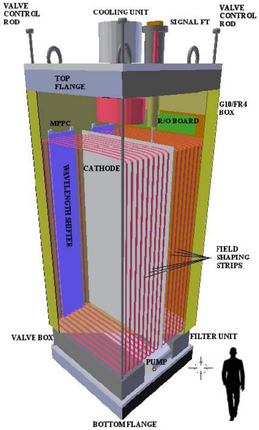
Alternative Designs

The DUNE collaboration has set up a task force that will be in place over the next 18 months and is charged with understanding the relative merits of the three detector options

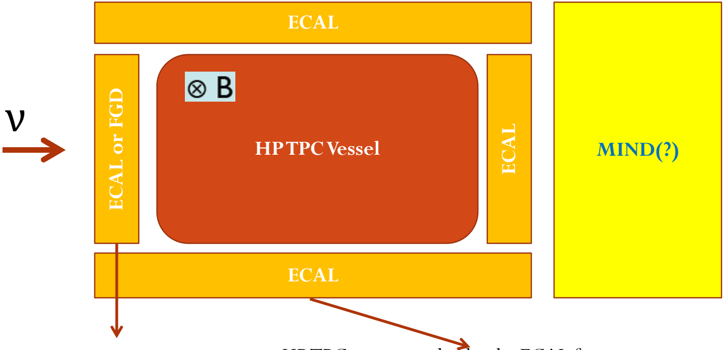
- Fine-Grained Tracker (Reference Design)
- Liquid Argon TPC
- High Pressure Argon Gas TPC

Liquid Argon TPC : ArgonCube

- The international ArgonCube collaboration has submitted an LoI to CERN SPSC
- Novel implementation of LAR TPC technology
  - Modularity and scalability
  - Pixelized charge readout
- Potential applicability for DUNE ND
  - LAr
  - Modularity and pixels : high rate capability
  - Can be magnetized : compatible with 0.4 T field



Basic design of the HP TPC for DUNE



Could also be another target for neutrino interactions

HP TPC is surrounded by the ECAL for neutral particle containment
ECAL can provide additional target for neutrino interactions
ECAL inside the vessel is another (challenging) possibility

Conclusion

The ND complex, with a high resolution FGT, will:

- Determination of the relative abundance and of the energy spectrum of the four neutrino species in DUNE beam: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
  - Extrapolation to FD and predictions of FD/ND(E_ν) fluxes to $\sim 1\%$
- Determination of the absolute ν_μ and $\bar{\nu}_\mu$ fluxes to $\sim 2\%$ for oscillation measurements
- Measure cross sections and exclusive topologies of NC & CC interactions
- Calibration of the absolute neutrino energy scale in ν ($\bar{\nu}$)-Ar interactions
- Quantify asymmetries between ν and $\bar{\nu}$ (energy scale, flux, interactions) for $\delta_{\rm CP}$

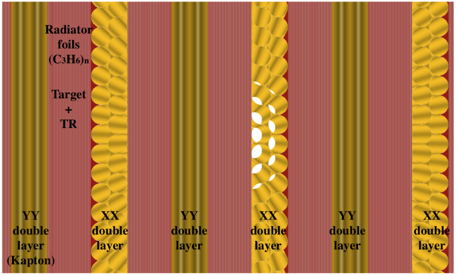
The DUNE collaboration has set up a task force that is charged with understanding the relative merits of the three detector options

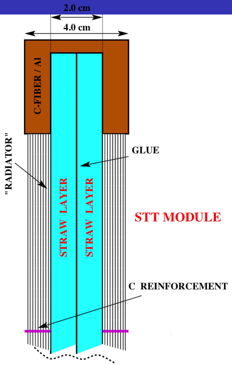
- Fine-Grained Tracker (Reference Design)
- Liquid Argon TPC
- High Pressure Argon Gas TPC

Backups

Straw Tube Tracker (Panjab Univ.)

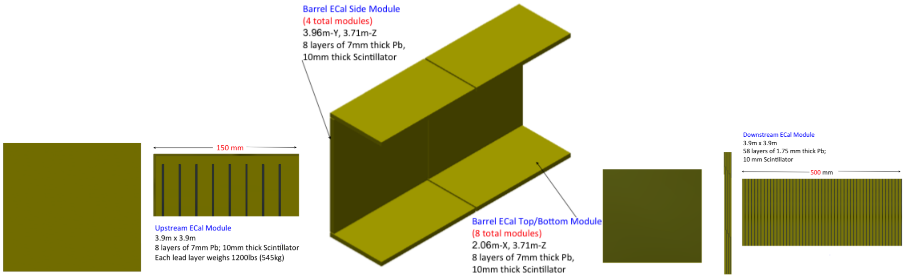
Geant4 schematic of STT with Radiator

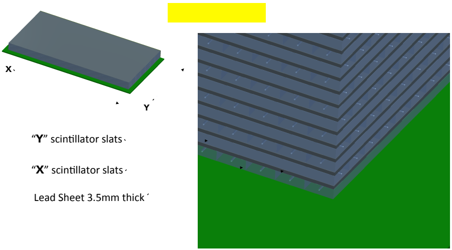




- Straw inner diameter: 9.530 ± 0.005 mm
- Operate with 70%/30% Xe/CO_2 gas mixture
- Raidator/target thickness ~ 20 mm with 75 $(C_3H_6)_n$ foils (40 μm) for transition radiation and tulle spacers
- Straws arranged in double layers glued together inserted with C-fiber/Al composite frames
- 166 modules arranged by alternating vertical and horizontal orientation with total length of 7 m
- Mass of the active target dominated by the radiators (82.6% of the total mass) can be tuned to achieve desired events and momentum resolution

Electromagnetic Calorimeter (IIT, Guwahati & Delhi Univ.)

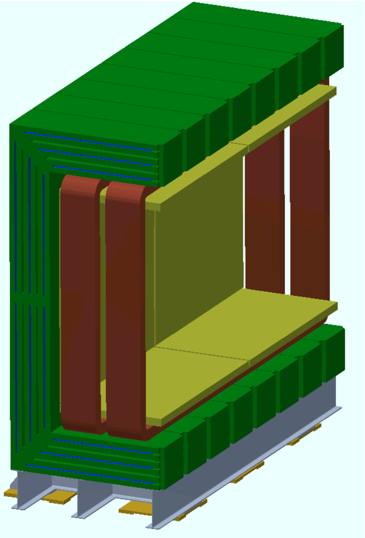




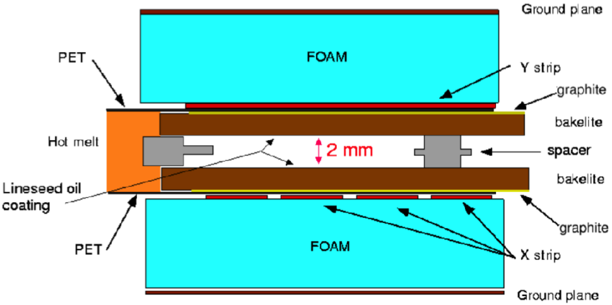
- Leadscintillator based on the T2K-ECAL, embedded inside the 0.4 T dipole magnet
- 58 layers of alternating horizontal/vertical scintillator strips per 1.75 mm Pb along the z-direction
- Plastic Scintillator bars: 4 m $\times$ 2.5 cm $\times$ 1.0 cm, 160 bars/layer, 9,280 bars in total
- Two sided readout

Magnet (Bhabha Atomic Research Center)

- 4.5 m $\times$ 4.5 m $\times$ 8 m inner dimensions
- 2.4 MW, 60 cm thick steel
- 0.4 T magnetic field
- $<$2% magnetic field variation over inner volumne



MuID - RPC (Variable Energy Cyclotron Center)



- Muon Range Detector - identify muons at low momenta exiting the sides of the detetor
  - 32 RPC planes interspersed between 20 cm thick layers of steel
- External Muon Identifier - identify high energy forward muons

Z position Radiography – NOMAD Tracker

Resolution of FGT will be much better

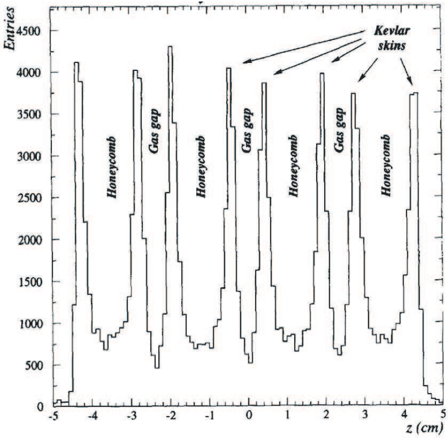


Figure: A neutrino radiograph of the NOMAD drift chambers shows the internal structure of the tracking volume. It illustrates the high resolution of the z-postion of the vertex.

Energy Scale of Neutrino and Antineutrino

- Problem: simplest of interactions, *e.g.* QE, Resonance, are obfuscated by nuclear effects (2-particle correlation, FSI). Furthermore, these effects could affect the antineutrino differently from neutrino.
- The key is: the measurement of the hadron-vector
  - ν-QE: 2-track events
  - $\overset{(-)}{\nu}$-Resonance : 2/3-track events
  - Coherent $\pi^{\pm}$
    - With missing $p_t < 300$ MeV ($\sqrt{t} < 5$ MeV)
    - Identical topology in ν_μ .vs. $\bar{\nu}_\mu$ (to the first order little nuclear-effect)

Coherent π/ρ Production – Constraining Absolute Flux

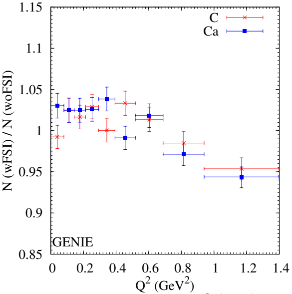
$$\nu_\mu + \mathcal{A} \rightarrow \mu^- \mathcal{A} + \pi^+(\rho^+)\ (CC) \quad (4)$$

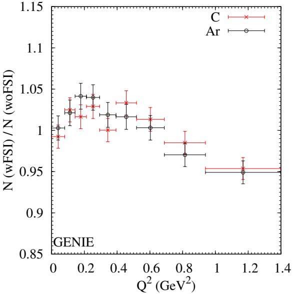
$$\nu_\mu + \mathcal{A} \rightarrow \nu_\mu \mathcal{A} + \pi^0(\rho^0)\ (NC) \quad (5)$$

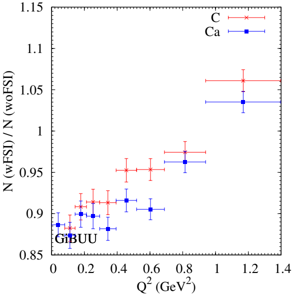
- Measure coherent ρ with $\sim 2\%$ precision
- Tie the neutrino measurement to photo-production and extract flux – to determine the absolute flux $\sim 5\%$ precision
  - Dominated by systematics in relating neutrino to electron (CVC)
- Critical measureables
  - $\pi^{0,\pm}$ momentum vectors
  - Veto additional particles : secondary tracks in STT and calorimeter
  - MuID : RPC

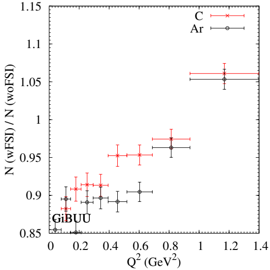
QE FSI Effects : C .vs. Ca .vs. Ar using GENIE & GiBUU

HRI with Carolina Group





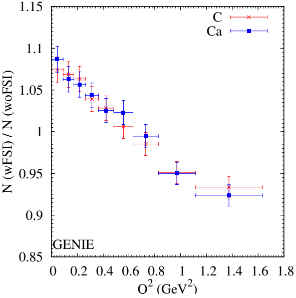


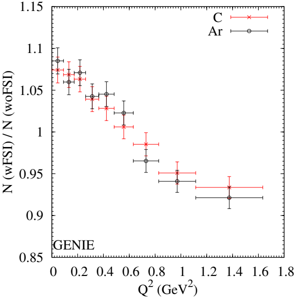


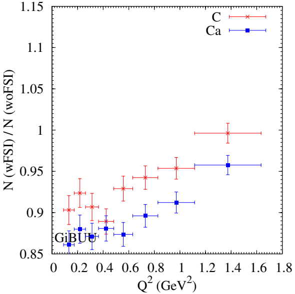
- FSI effects at $\pm \sim 10\%$
- Different in GENIE .vs. GiBUU
- Similar in Ca/C & Ar/C

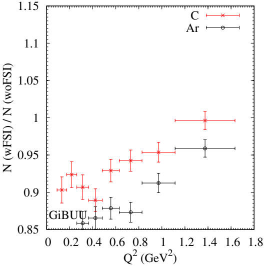
Res FSI Effects : C .vs. Ca .vs. Ar using GENIE & GiBUU

HRI with Carolina Group









- FSI effects at $\pm \sim 10\%$
- Different in GENIE .vs. GiBUU
- Similar in Ca/C & Ar/C

Relative Flux: Low-ν_0 method

- Relative ν_μ, $\bar{\nu}_\mu$ flux .vs. energy from low-ν_0 method

$$N(E_\nu, E_{\rm Had} < \nu_0) = k\Phi(E_\nu) f(\frac{\nu_0}{E_\nu}) \quad (6)$$

  - The correction factor $f(\frac{\nu_0}{E_\nu}) \to 1$ for $\nu_0 \to 0$

$$f(\frac{\nu_0}{E_\nu}) = 1 + (\frac{\nu_0}{E_\nu})\frac{\mathcal{B}}{\mathcal{A}} + (\frac{\nu_0}{E_\nu})^2 \frac{\mathcal{C}}{2\mathcal{A}} + ... \quad (7)$$

  - In practice use MC to calculate the correction factor normalized at high E_ν

$$f(E_\nu) = \frac{\sigma(E_\nu, E_{\rm Had} < \nu_0)}{\sigma(E_\nu \to \infty, E_{\rm Had} < \nu_0)} \quad (8)$$

- Need precise muon energy scale and good resolution at low ν values
- Main systematic uncertainties
  - Muon (Hadronic) energy scale
  - Detector smearing and effects of ν_0 cut
  - Cross sections (anti)neutrino-nucleus (QE, Res, DIS) and FSI
  - Backgrounds and selection cuts

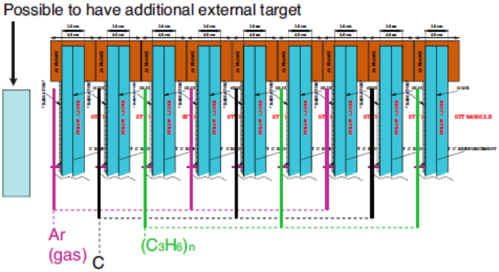
Questions for the FGT during the 3 Reviews in the summer of 2015

- Energy scale of neutrino and antineutrino
- Constraint/measurement on the beam diversion
- Signal characterization: ν_e & $\bar{\nu}_e$
- Backgrounds from the outsize: γ, neutrons (dirt events)
- Pileup in the ECAL
- Nuclear Effect: Ar vs Ca
- Quantify how to “translate” ND measurements to FD: full simulation and reconstruction on physics sensitivities

Minimal set of Questions for any given ND option

- Sensitivity (precision) to the absolute flux measurement of ν_μ : neutrino source
- Precision on the un-oscillated relative flux, FD/ND (E_ν), for ν_μ, $\bar{\nu}_\mu$: neutrino source
- Precision on ν_e/ν_μ ($\bar{\nu}_e/\bar{\nu}_\mu$) at the FD : signal
  Efficiency and purity of π^0 from NC .vs. CC : background
- Precision on the "wrong-sign" contaimination
- Efficiency and purity for ν_e-CC : interaction model
- Efficiency nad purity for ν_μ-induced QE and resonance: interaction model
- Error on the energy-scale of neutrino and antineutrino: interaction model (In-situ constraints on the initial and final state interactions in Ar)

Neutrino-Nuclear Interactions



- Main target polypropylene $(C_3H_6)_n$ foils in radiators: mass ~ 5 t
- Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, Ar gas ($\times 10$ statistics of FD), H_2O, D_2O, Ca, Fe, Pb
  - Separation from excellent vertex ($\sim 100\ \mu$m) and angular < 2 mrad resolutions
- Pressurized Ar Gas target (~ 140 atm) inside C tubes and solid Ca target provide detailed understanding of the Far Detector A=40 target

Benefits of HP gas TPC

- Magnetized and 4π coverage
- Same target as the DUNE Far Detector
- Pressure and target flexibility
  - He, Ne, Ar, CF_4 can be used to study A-dependence and FSI
- Excellent PID
- Low density and low thresholds
  - Sensitivity to < 100 MeV/c protons and < 25 MeV/c muons and pions
  - Model testing and generator tuning
    - 2p2h, spectral functions, FSI
    - 1π high mass resonance