High Resolution Fine-Grained Tracker: Reference Near Detector for DUNE

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Near Detector Workshop
Fermi Lab

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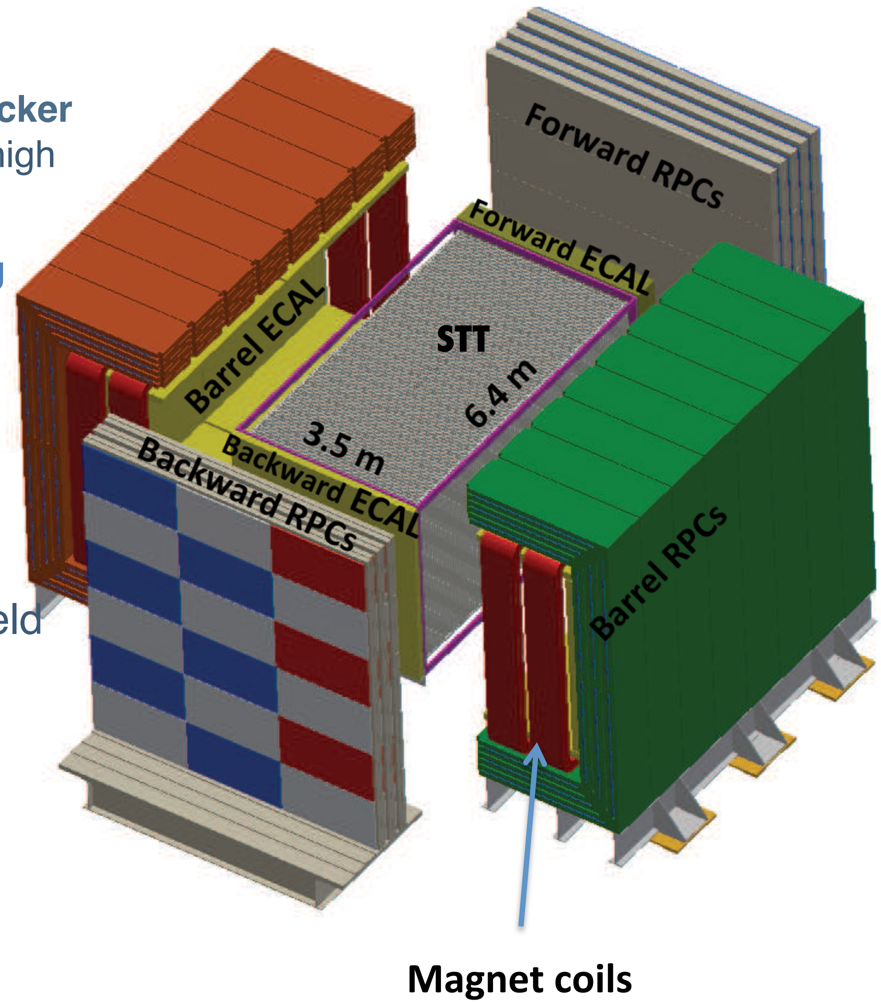
FGT Near Detector Concept

- **Four components detector**:
  - An active low density (0.1 g/cm^3) **straw tube tracker** (STT) in a **0.4 T magnetic field** with embedded high pressure argon gas targets.
  - Tunable thin target(s) spread over entire tracking volume: Target mass ~ 7 ton
  - Combined particle –ID and tracking for precise reconstruction and 4-momenta
    - dE/dx : Proton ID, $\pi^{\pm}, K^{\pm}$
    - Transition Radiation: e^{-}/e^{+} ID, γ
- 4π lead-plastic scintillator ECAL in dipole B field
  - Transverse and longitudinal segmentation.
  - Energy resolution: 6%/√E (GeV) for downstream ECAL; Time resolution: 1 ns for E > 100 MeV
- 4π RPC based muon detector
  - μ^{+} / μ^{-} identification.



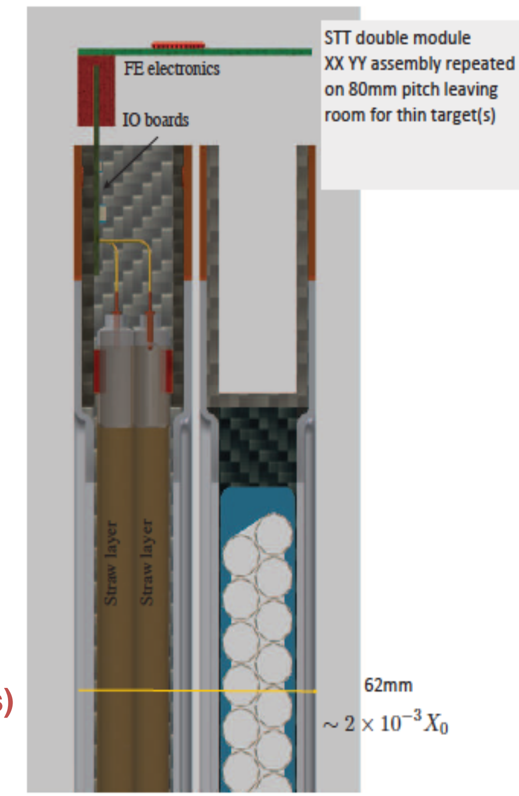
Straw Tube Tracker (STT)

✧ Proven Technology: Improve on NOMAD low density spectrometer

- ✓ Small cylindrical drift tubes insensitive to track angles.
- ✓ More sampling points along the track: x 6 perpendicular to beam axis and x2 along the beam axis.
  - Efficient proton reconstruction down to 250 MeV/c, particle identification via dE/dX and Transition Radiation. Proton and electron identification with little background.

✧ STT design parameters:

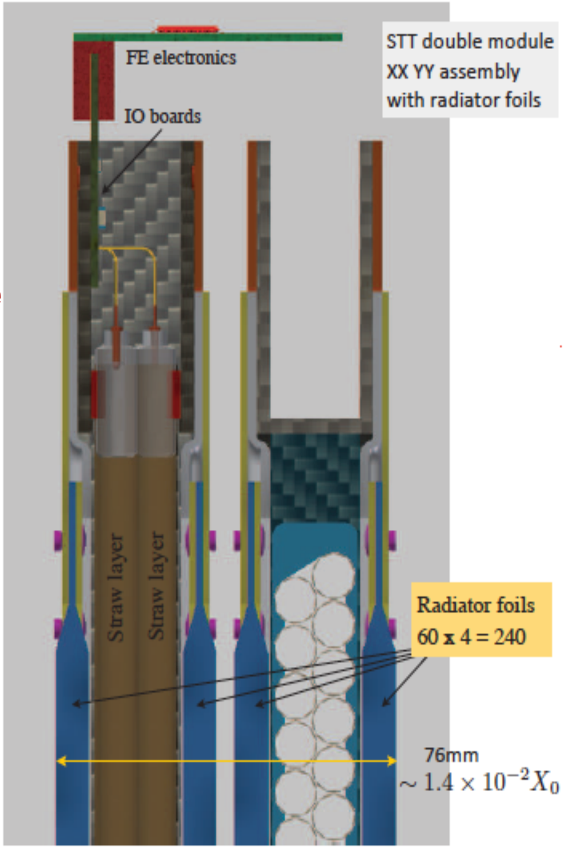
- ✓ Straw inner diameter: 9.530 ± 0.005 mm
- ✓ Straw walls 70 ± 5 μm Kapton 160XC370/100HN (ρ =1.42, x_0 = 28.6 cm, each straw < 5×10^{-4} X_0)
- ✓ Gold plated tungsten wire: 20 μm diameter; wire tension around 50 g.
- ✓ Straws are arranged in double layers of 336 straws glued together (epoxy glue) inserted in C-fiber composite frames.
- ✓ Each double module assembly will have (XX+YY) orientation with FE electronic (each XX+YY tracking module ~ 2×10^{-3} X_0)
- ✓ Operate with 70%/30% Xe/CO_2 gas mixture.
- ✓ Readout at both ends of straws (IO and FE boards on all sides of each XX + YY STT module)
- ✓ 160 modules arranged into 80 double modules over ~ 6.4 m (total 107,520 straws)
- ✓ Add dedicated thin targets, including pressurized Ar gas to each STT module keeping the average density same for required target mass.



STT: Radiator Targets

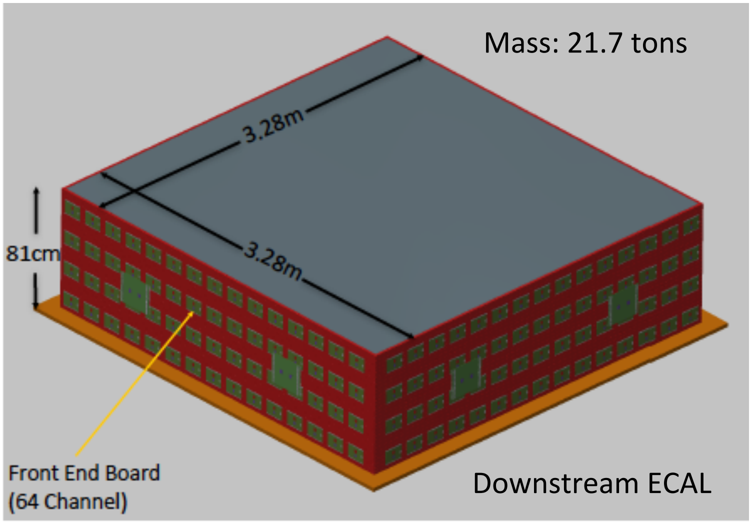
- Main $\nu(\bar{\nu})$ target in the form of multiple thin polypropylene foils (radiator targets)
  - ✓ Use target material for particle identification via Transition Radiation (TR)
- Radiator target is integrated at both sides of each STT (double layer) module to minimize the overall thickness (foils can be removed if needed)
  - ✓ Embossed radiator foils: 25 μm thick, 125 μm air gaps;
  - ✓ Total number of radiator foils: 240 per XXYY module arranged into 4 radiators composed of 60 foils each;
  - ✓ Total radiator mass in each XXYY module: 69.1 kg, 1.25×10^{-2} X_0.
    - Radiator represents 82.6% of the total mass of each STT module
    - Tunable for desired statistics and momentum resolution

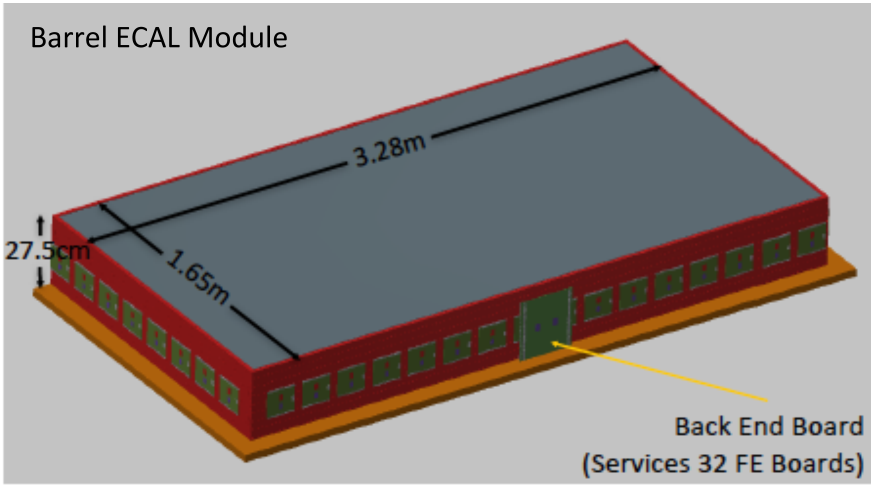
Performance Metric	Value
Vertex resolution	0.1 mm
Angular resolution	2 mrad
E_e resolution	5%
E_μ resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
NCπ^0/CCe rejection	0.1%
NCγ/CCe rejection	0.2%
NCμ/CCe rejection	0.01%



The Electromagnetic Calorimeter

- Reconstruction of e^+/e^-, γ with accuracy comparable to μ^+ / μ^- and FD
  - Containment of > 90% of shower energy; energy resolution < $6\% / \sqrt{E}$ (GeV)
- Sampling electromagnetic calorimeter with Pb absorbers and alternating horizontal and vertical (XYXYXY…) 3.2 m x 2.5 cm x 1 cm plastic scintillator bars readout at both ends by 1 mm diameter extruded WLS fibers and SiPMs.
  - Downstream ECAL: 60 layers with 1.75 mm Pb plates. **20 X_0** .
  - Barrel ECAL: Will surround the sides of the STT. 18 layers with 3.5 mm of Pb. **10 X_0**.
  - Upstream ECAL: 18 layers with 3.5 mm Pb.**10 X_0**.

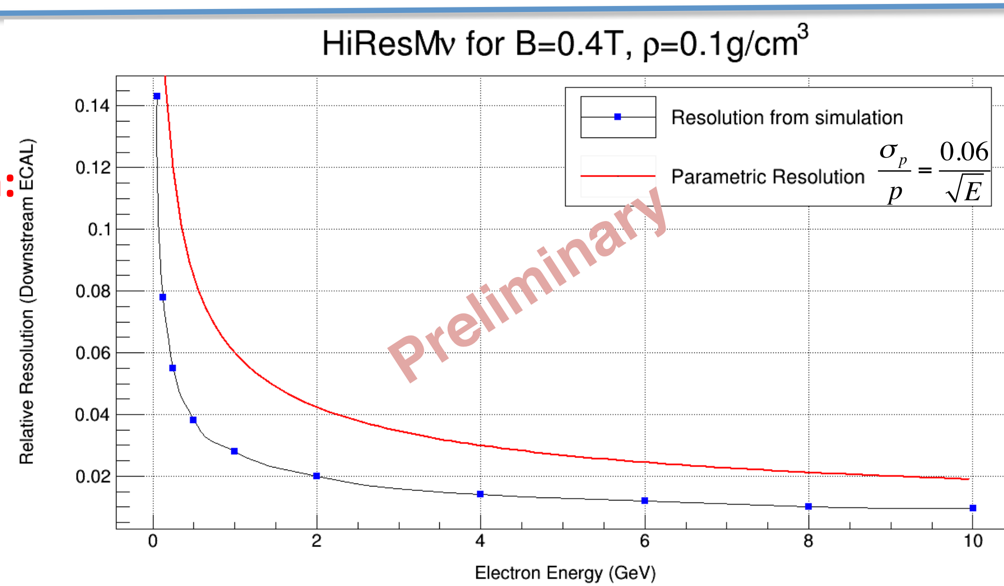


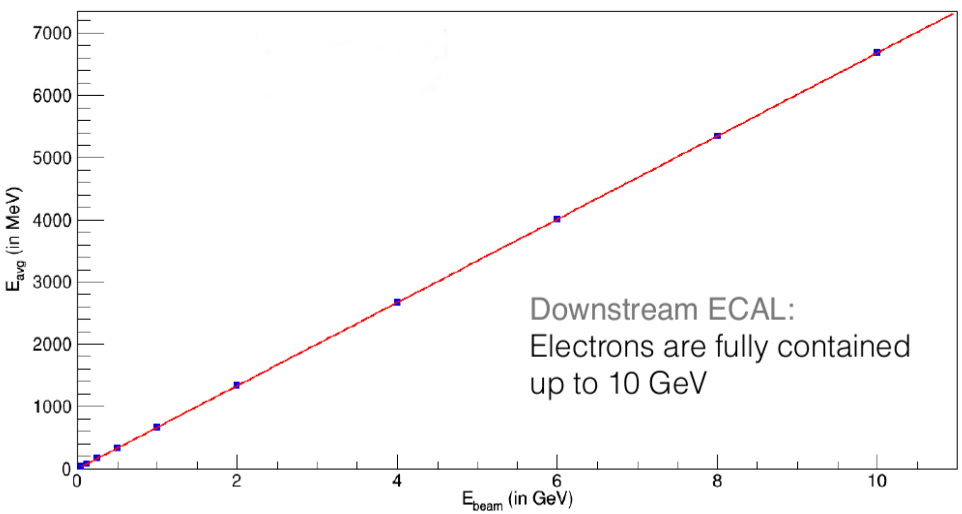


Detector Performance: ECAL

Downstream ECAL Energy Resolution:

6% could be conservative: simulation does not include electronics noise, detector inefficiency.



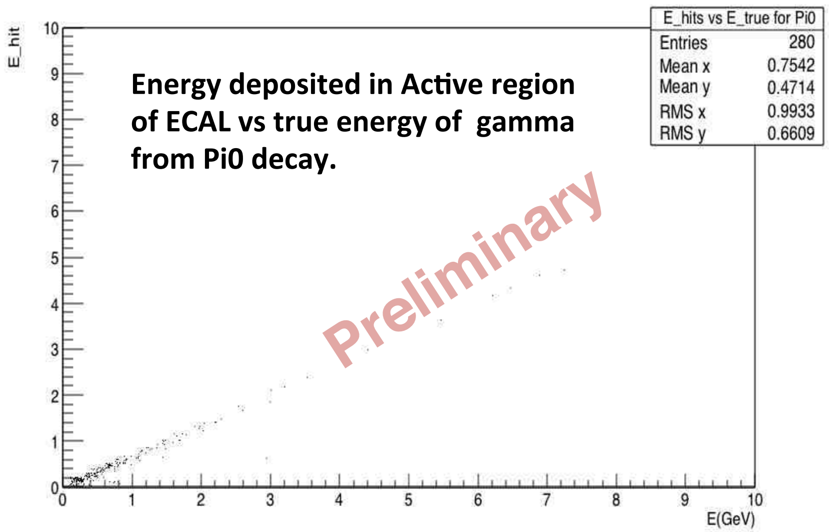


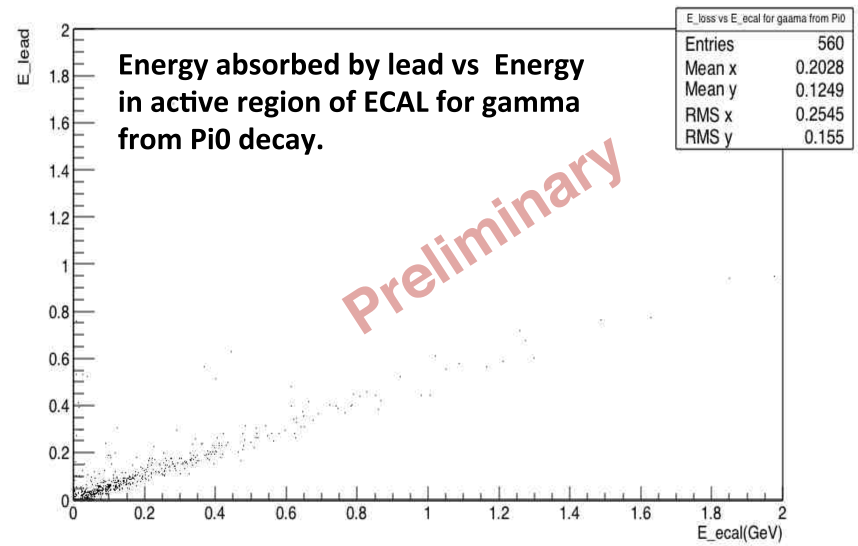
Downstream ECAL Linear Energy Response:

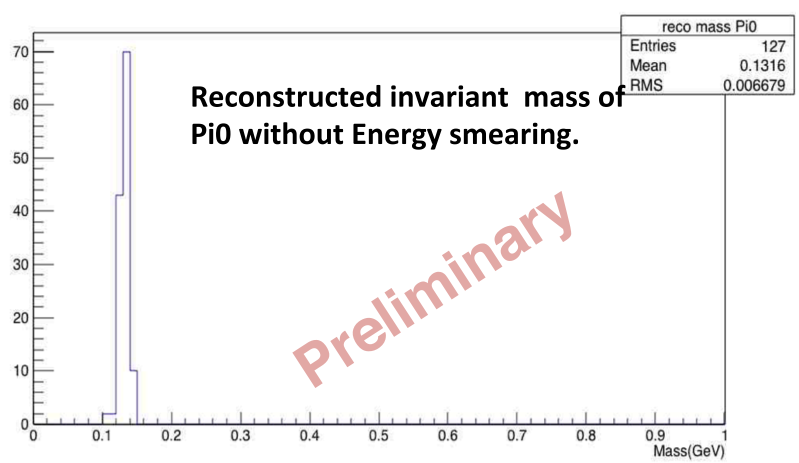
0.06/√E is valid at least up to 10 GeV

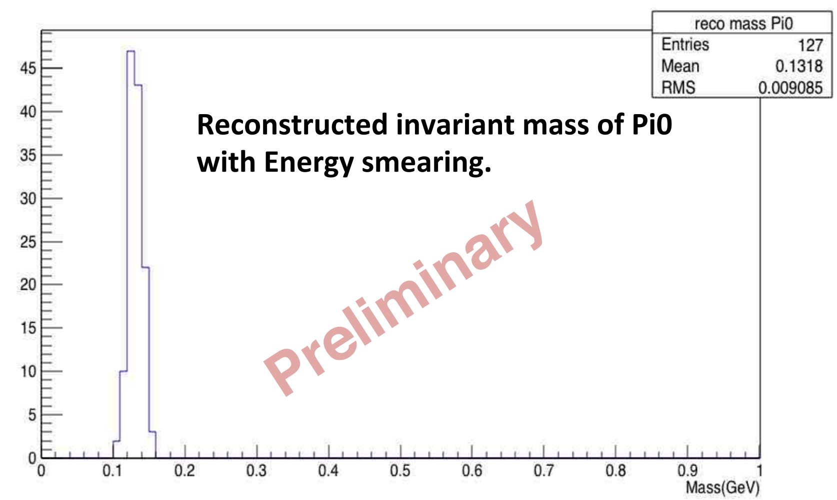
Pi0 Reconstruction in ECAL

Vikas Gupta, IIT Guwahati

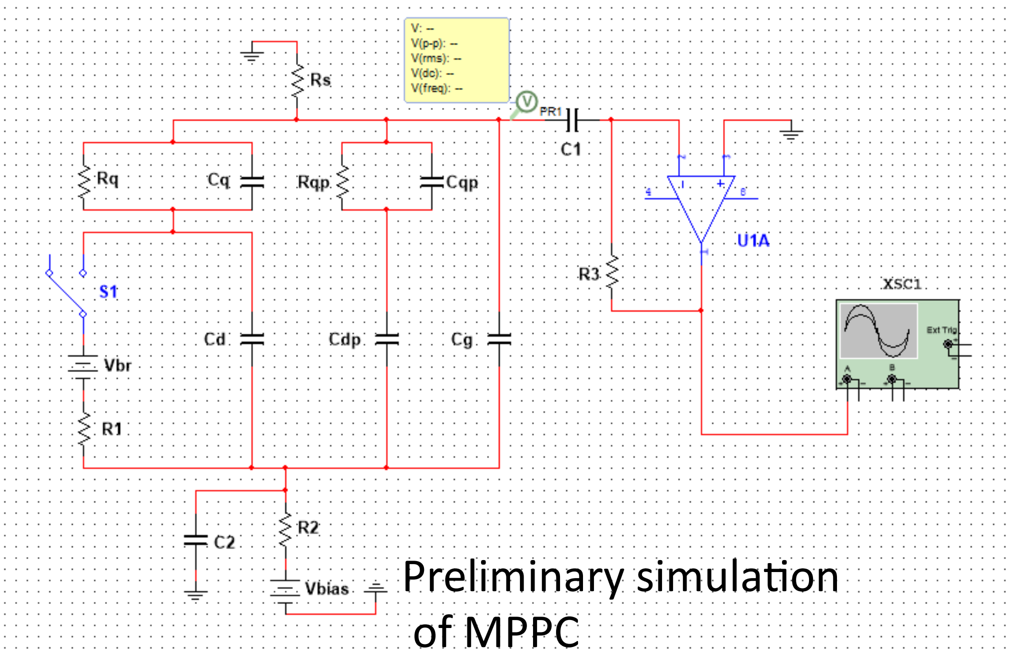




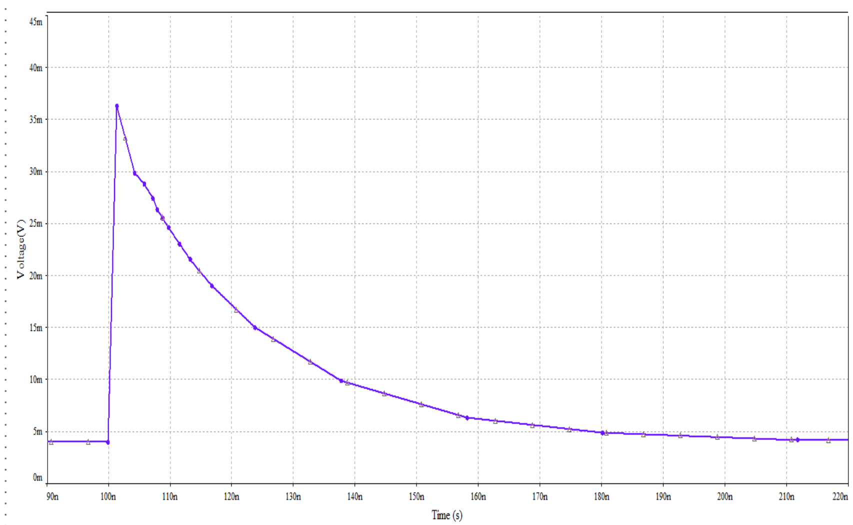




- ✧ Simulation and prototype construction of the ECAL readout electronics is progressing quite well.
  - Similar MPPCs as in ND280 of T2K is being considered.
    - ✓ Model S13360-1350CS by Hamamatsu
    - ✓ 667 pixels (with each pixel 50 x 50 μm^2) ceramic device
    - ✓ Small active area 1.3 x 1.3 mm^2
    - ✓ Lower operating voltage ~53 V, better PDE, lower noise



Preliminary simulation of MPPC

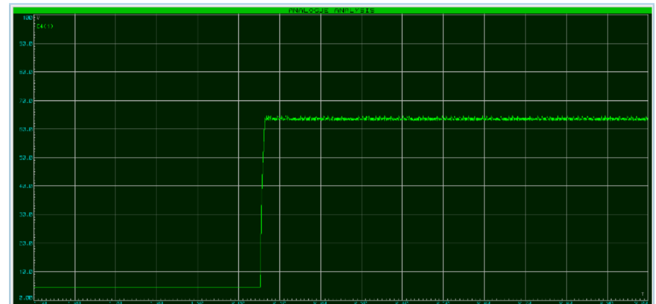


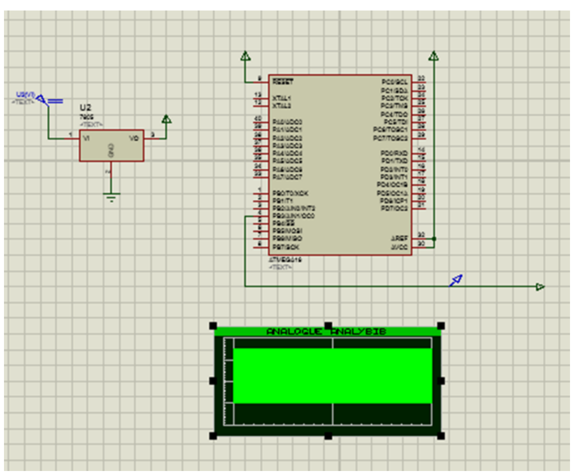
ECAL Readout

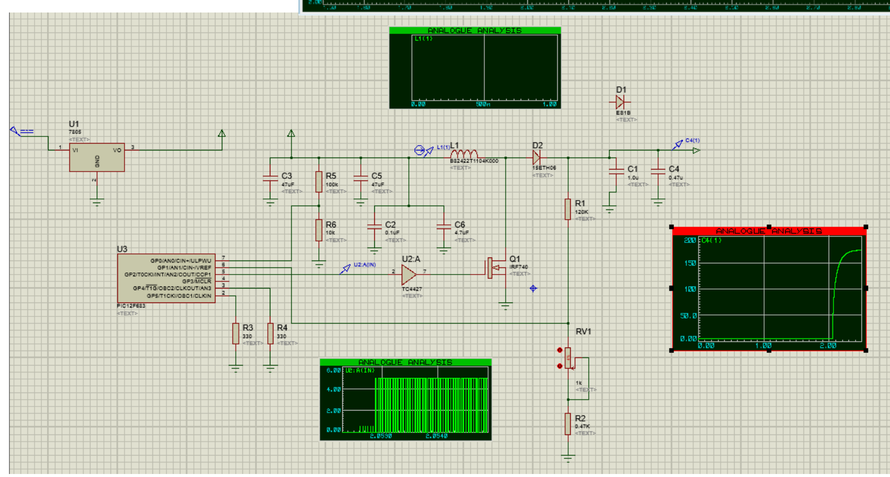
✧ Simulation and testing of each step of readout ASIC

HVPS → Detector → Biasing DAC + Preamplifier → Shaper → Analog Memory → ADC → …

- MPPC Power Supply Requirement:
  - Supply Voltage, $V_{IN(MIN)}$ & $V_{IN(MAX)}$ = 4.75 ≤ Vs ≤ 5.25V
  - Output Voltage, V_{OUT} = 50 to 90 V [40 to 80 V]
  - Current Consumption, $I_{IN(MAX)}$ = 20 mA
  - Output Current, I_{OUT} = 2 mA
  - Low Ripple Noise, $V_{p-p(MAX)}$ = 0.2 mV
  - Finely adjustable steps resolution= 1.8 mV
  - connectivity with PC/FPGA for setting BIAS voltage
  - based on Hamamatsu's C112014-01 PS



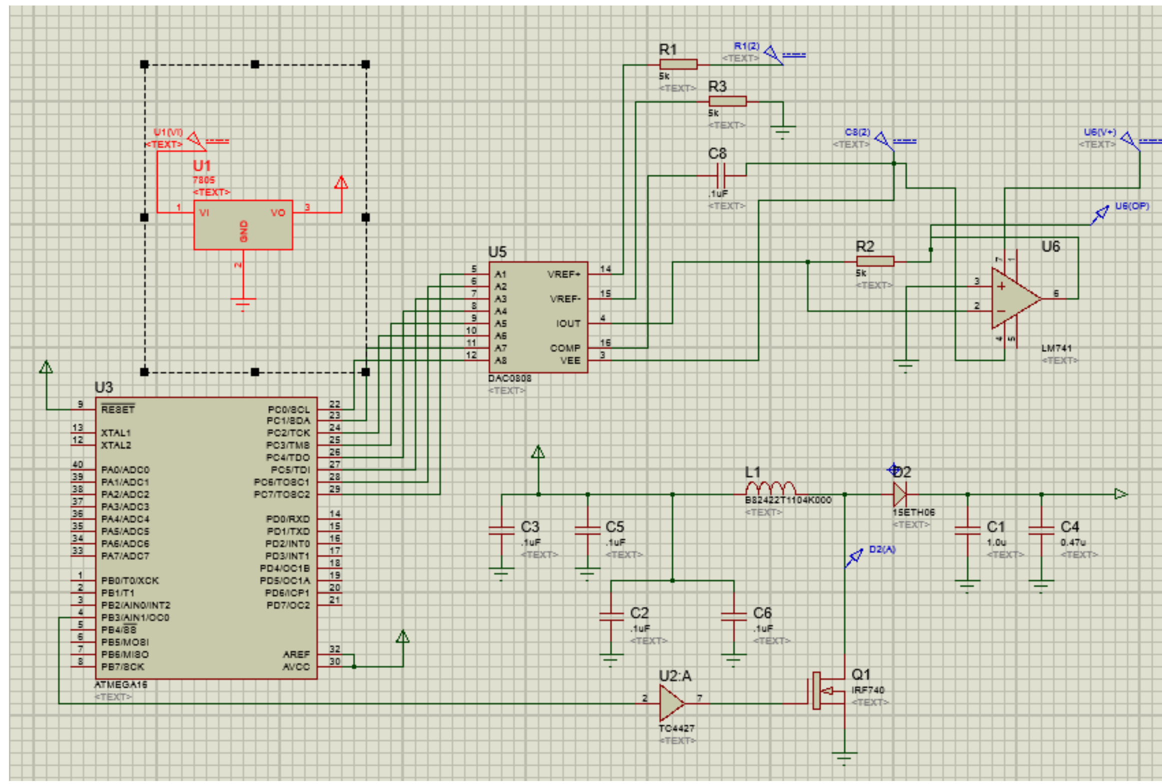




HVPS simulation using PWM drive for MOSFET; with different component (L, C,) and PWM driver selections

ECAL Readout

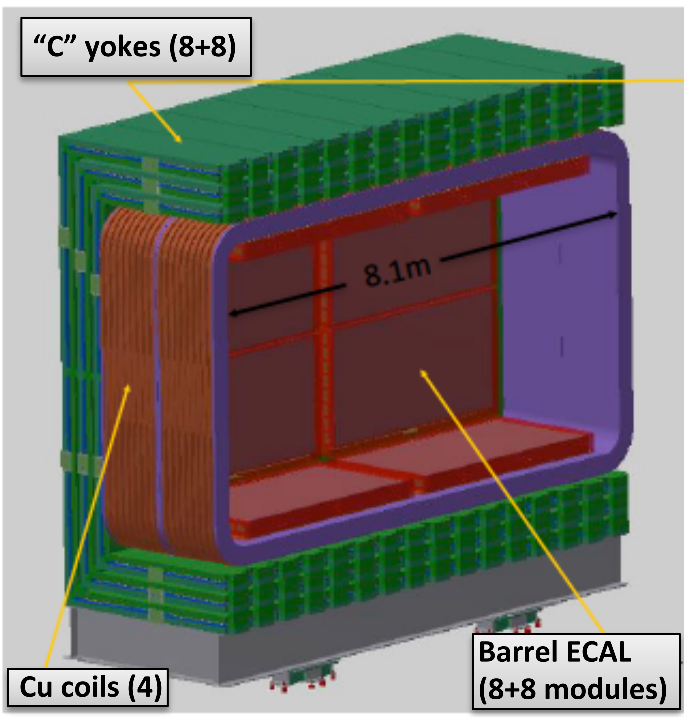
- ✓ Preliminary design of a prototype module with HVPS, HV DAC, pre-amplification stages with current/voltage monitors and temperature/humidity sensor circuits, each with 4 to 16 ch., having good signal-noise ratio.
- ✓ Adding amplification, memory stages (Shaper, analogue memory, ADC etc) to the prototype module soon.

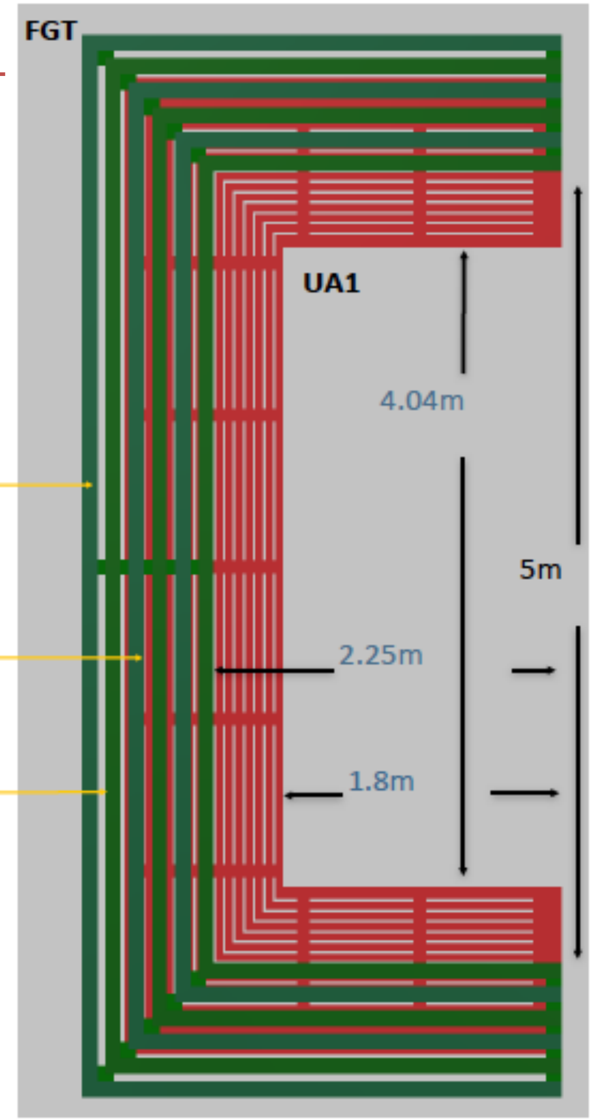


Development of the prototype board is under progress.

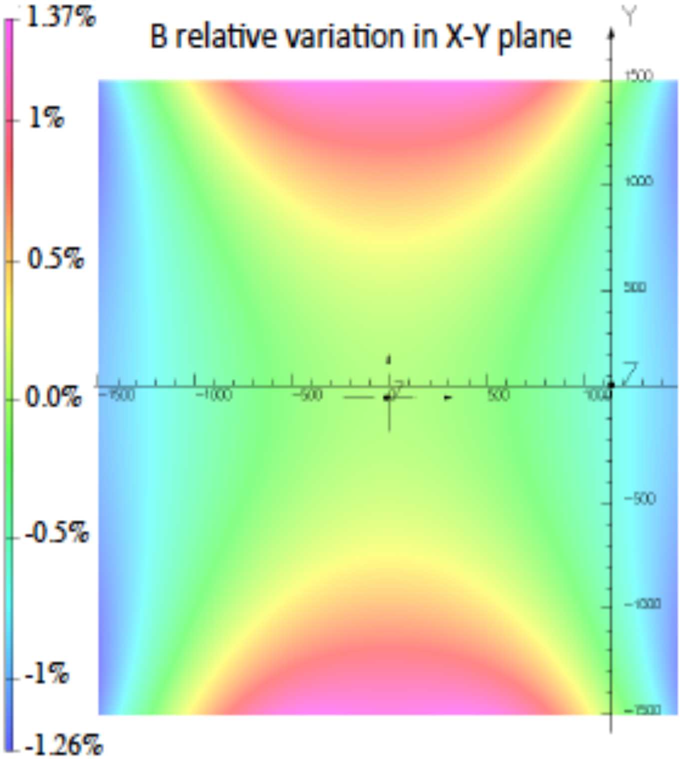
The Dipole Magnet

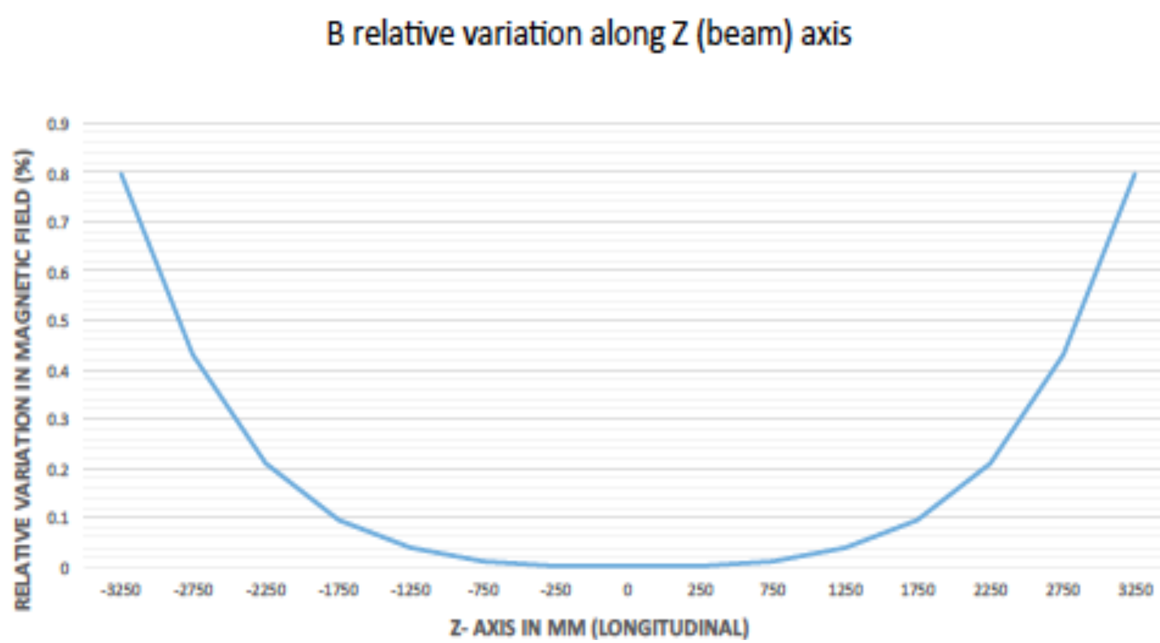
- Design based on UA1/NOMAD/T2K magnet
- Magnetic volume: 4.5 m x 4.5 m x 8.1 m, nominal B = 0.4T
- Return yoke with 8+8 "C" section:
  - 6 x 100 mm steel plates, 50 mm gaps (960 tons)
- 4 vertical Cu coils (168 tons) made of 8 double pancake
- Power requirement for nominal field 2.43 MW, water flow for coil cooling: 20 l/s



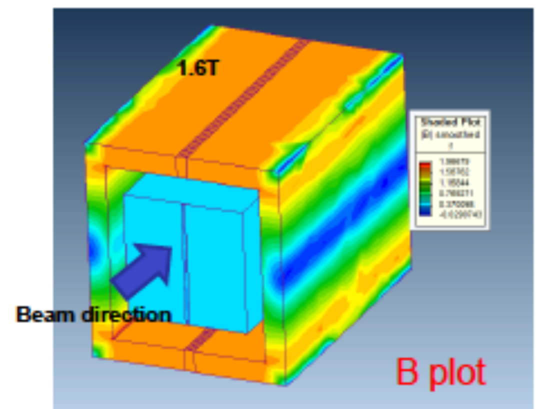


Dipole Magnet Simulation





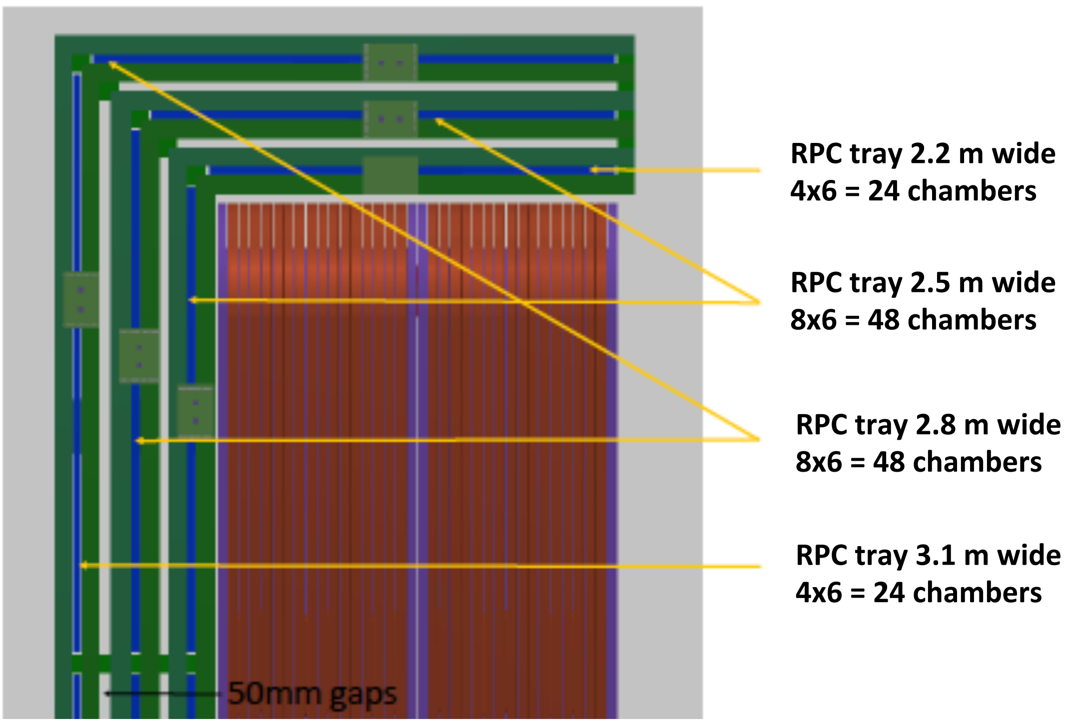
BARC, India

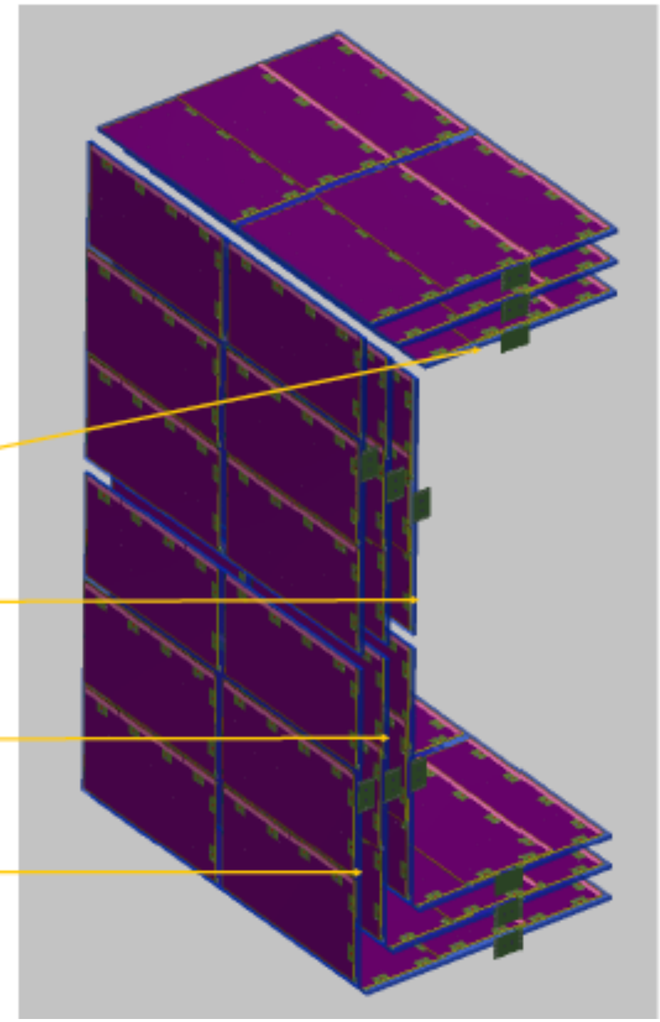


✧ *B uniformity* in 3.5 m x 3.5 m x 7 m tracking volume is better than 2% (field simulations)

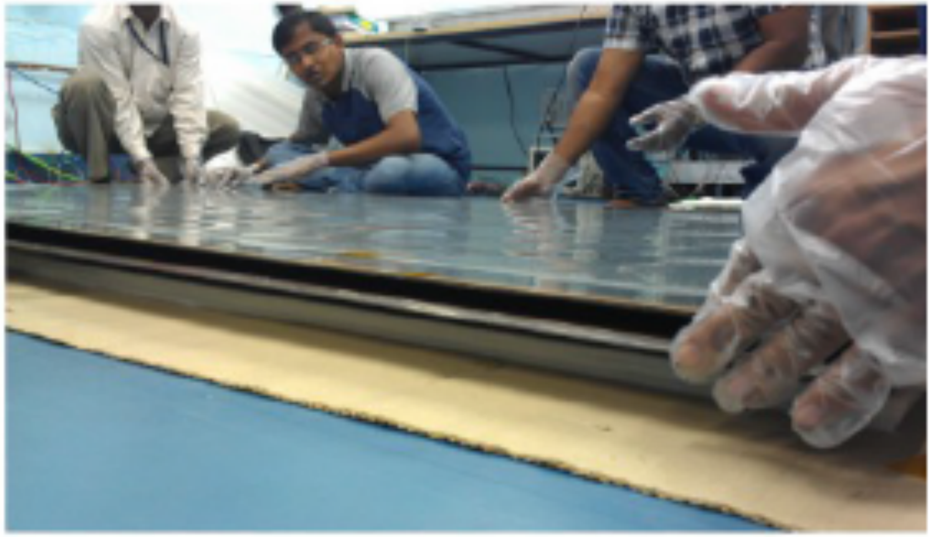
The Muon Detector

- Require to measure absolute and relative ν_μ and $\bar{\nu}_\mu$ spectra separately
  - Identify muons exiting the tracking volume
  - 4π muon detector with < 1 mm space resolution
- Bakelite RPC chambers 2m x 1m (432 in total) with 7.65 (7.5) mm X(Y) strips in avalanche or streamer mode
- Instrument magnet yoke (3 planes) and downstream (5 planes) and upstream (3 planes) stations





The Muon Detector



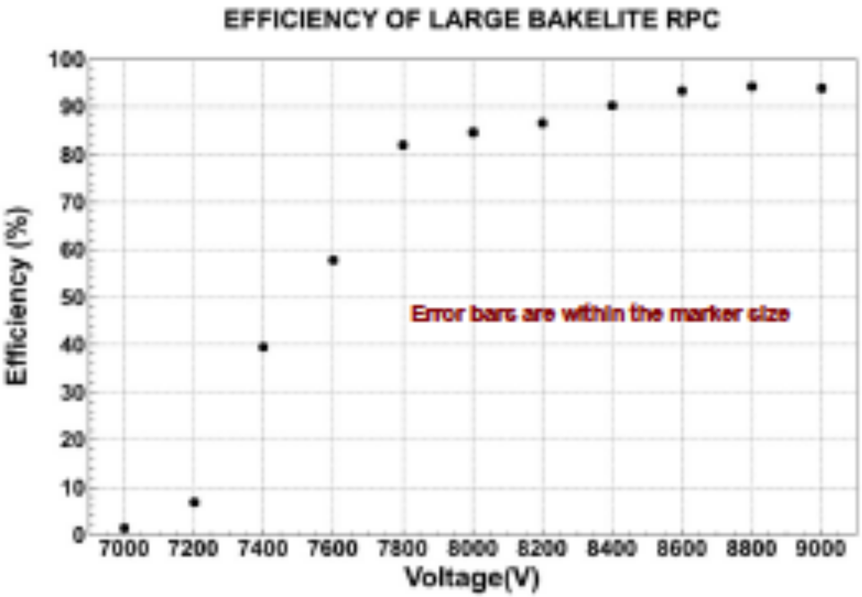


Figure 7.6: Fabrication of a large (2.4 m × 1.2 m) RPC prototype at the Variable Energy Cyclotron Centre (VECC) in India (left) and corresponding efficiency tests (right).

FGT Readout Electronics

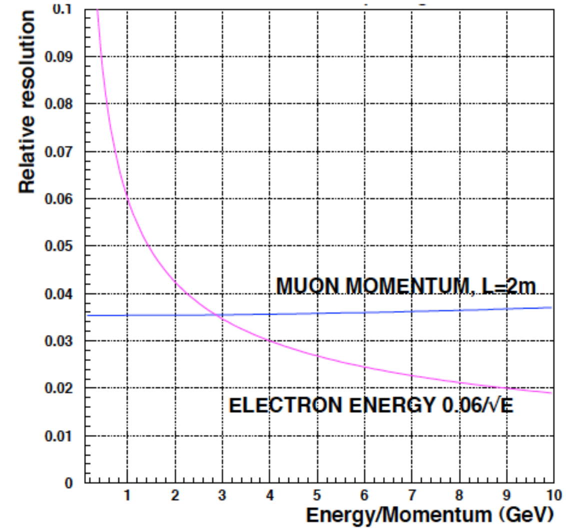
- Near Detector should cater pulse structure of the beam (~ 9.6 μs spill) and provide GPS time stamp to identify origin and nature of events.
- Fast readout electronics for STT, ECAL and muon detector (rise time a few ns) with time stamping (resolution ~ 1 ns) and charge measurements.
  - STT and ECAL: total charge and time associated with a given hit, in-sync with beam spill triggers.
  - MuID RPCs: provide the position and time associated with a traversing track.
- Expected rates per spill are ~0.2 events/ton.
  - Negligible pile-up due to size ~ 160 m^3 and timing resolution ~ 1 ns
- STT, ECAL and the backward RPC can define various triggers
  - Hits stored in pipelines for a later decision

Detector	# of Channels
STT	215,040
ECAL	52,224
MuID	165,888

FGT Detector Performance

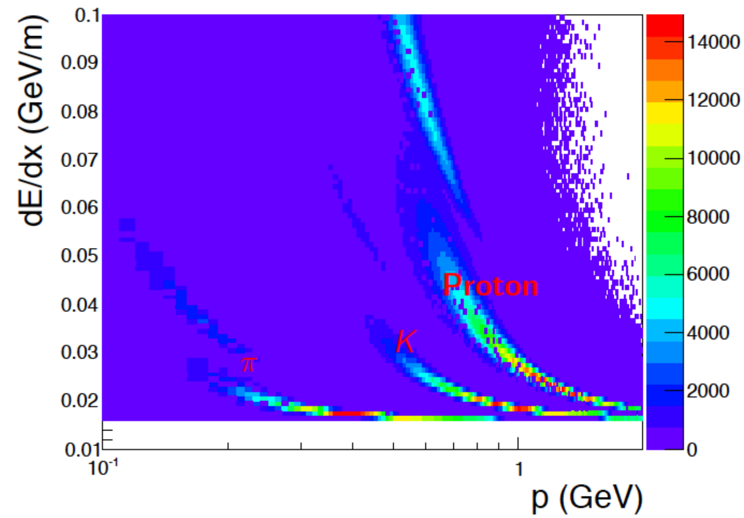
Expectation

Value	*Res.*
Muon p	3.5%
Electron p	12%
Pion p	7.5%
Proton p	5.5%
ECAL E	6%/√E (GeV)
Muon angle	1 mrad
Electron angle	2 mrad
Charge Separation	~100%
Spatial (radial)	<200μm
Vertex (2+ trk)	within 100μm



FGT has good dE/dx particle-ID: π^{+-} / K^{+-} / p

PID Performance



Event rates at FGT (5 years ν run)

Interaction	Events	Cuts
Inclusive ν_μ-CC	38.2×10^6	FV
ν_μ-QE-CC	8.1×10^6	FV
ν_μ-Res-CC	11.0×10^6	FV
ν_μ Coherent-π^+	0.63×10^6	FV
Inclusive ν_μ-NC	4.1×10^6	FV & $E_{Had} \geq 3$ GeV
Coherent-π^0	0.32×10^6	FV
IMD	1944	FV ($E_\nu \geq 11$ GeV)
ν_μ-e NC	4700	FV
Contaminant CC's		
ν_e-CC	4.2×10^5	FV
$\bar{\nu}_e$-CC	4.2×10^4	FV
$\bar{\nu}_\mu$-CC	2.5×10^6	FV

Assumption:
ND is at a distance of 459 m from the primary target.

CC events induced by the Inherent "contaminant" neutrinos in the beam: ν_e, $\bar{\nu}_e$, and $\bar{\nu}_\mu$.

- *Assuming 1.8 x 10^7 seconds/year as a the operational duration of the LBNF beam with 120 GeV protons from the Main Injector with 700 kW*
  - **A 5-year run will yield 3.2 x 10^{21} protons-on-target (POT)**

Summary

✧ The FGT Provides:

✧Very good charged particle tracking via the STT, good charged separation since the detector is magnetized.

✧Good momentum/energy resolution via STT/ECAL.

✧Good hadron discrimination, muon-ID via RPC based muon detectors

✧Possibility of measuring neutral pions and their energies: important for controlling NC background.

Backup slides

DUNE ND: Capability of FGT

✧ Determine the relative abundance and energy spectrum of the four ν species in LBNF beam: $\nu_\mu, \bar{\nu}_\mu, \nu_e,$ and $\bar{\nu}_e$ through CC-interactions.

- ✧ **Prediction of FD/ND (E_ν) fluxes to ~ 1%**

✧ Determination of the absolute ν_μ and $\bar{\nu}_\mu$ fluxes to ~ 3%

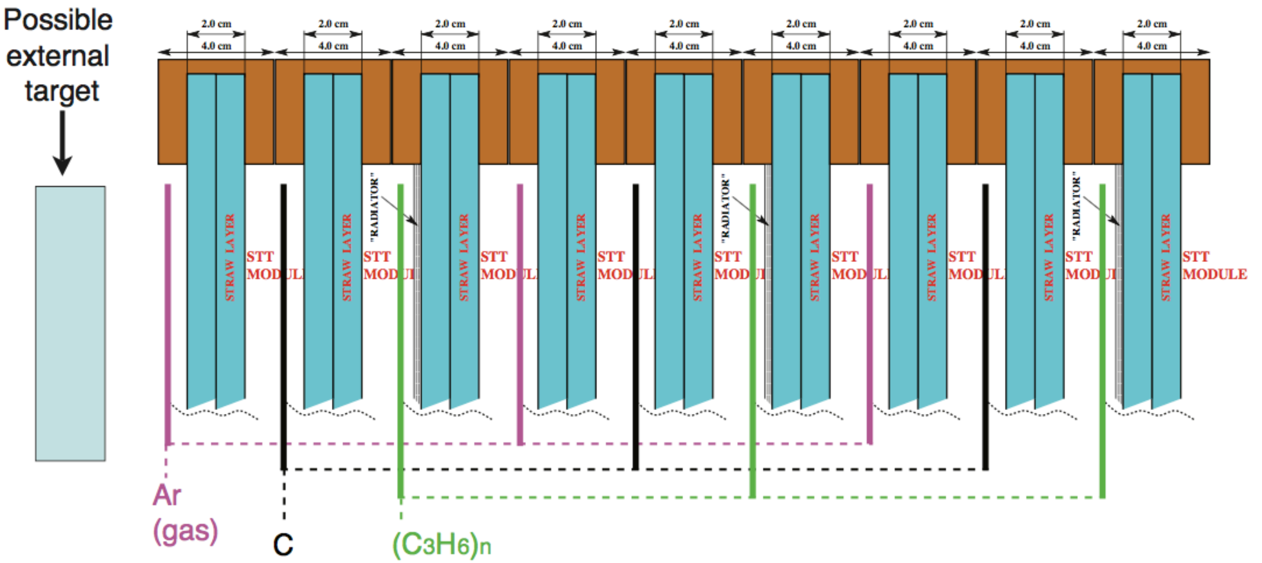
✧ Measure cross-sections and exclusive topologies of NC and CC interactions

- ✧ Event by event NC/CC separation as a function of hadronic energy E_{had}
- ✧ Measurement of π^0 and γ yields in both NC and CC to better than 5%
- ✧ Measurement of $\pi^\pm / K^\pm$ in CC and NC to constrain $\pi^\pm / K^\pm \rightarrow \mu^\pm$ decays.
- ✧ Measure exclusive and semi-exclusive NC and CC ν-Ar interactions: Quasi-elastic, single π , Deep Inelastic Scattering (DIS) and coherent pion production.
  - ✧ *Backgrounds to appearance and disappearance channels.*

✧ Calibration of the absolute energy scale in $\nu - Ar$ and $\bar{\nu} - Ar$ interactions.

✧ Quantify ν vs $\bar{\nu}$ asymmetries in E_ν scale, flux and interactions cross-sections for δ_{CP}

NUCLEAR TARGETS



MAIN target $(C_3H_6)_n$ radiators: mass $\sim 5t$

- *Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, H_2O, D_2O, etc.*
  $\Longrightarrow$ *Separation from excellent vertex ($\sim 100\mu m$) and angular (< 2 mrad) resolutions*

- *Subtraction of* C TARGET *(0.5 tons) from polypropylene* $(C_3H_6)_n$ RADIATORS
  provides $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)$ $\nu(\bar{\nu})$ *CC interactions on free proton*
  $\Longrightarrow$ *Absolute $\bar{\nu}_\mu$ flux from QE*
  $\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*

- *Pressurized* Ar GAS *target ($\sim$ 140 atm) inside SS/C tubes and solid* Ca TARGET
  provide detailed understanding of the FD $A = 40$ target
  $\Longrightarrow$ *Collect $\times 10$ unoscillated FD statistics on Ar target*
  $\Longrightarrow$ *Study of flavor dependence & isospin physics*

LONGITUDINAL PROFILE OF STT

- *Placeholder composition of STT planes (from downstream to upstream):*
  - *Total of 75 STT XXYY modules with 4 straw layers and integrated radiators*
    $\Longrightarrow$ *Overall length of 600 cm* $\longrightarrow \sim 1.09 X_0$ *and mass* $\sim$ *5.18 tons*
  - *Total of 2 STT XXYY modules with radiators replaced by graphite targets (total 18 mm C)*
    $\Longrightarrow$ *Overall length 16 cm* $\longrightarrow \sim 0.093 X_0$ *(*$\rho = 1.74$ *g/cm*^{3}*,* $X_0 = 19.41$ *cm) and C mass* $\sim$ *384 kg*
  - *One plane with 7 mm thick Ca target with C-fiber/composite enclosure, followed by one STT XXYY module without radiators*
    $\Longrightarrow$ *Overall length 8 cm* $\longrightarrow \sim 0.067 X_0$ *(*$\rho = 1.54$ *g/cm*^{3}*,* $X_0 = 10.41$ *cm) and mass 132 kg*
  - *One plane with 68 2-in inner diameter (0.04-in wall) C-composite tubes filled with pressurized Ar gas at 140 atm, followed by one STT XXYY module without radiators*
    $\Longrightarrow$ *Overall length 12 cm* $\longrightarrow \sim 0.02 X_0$ *and Ar (C) mass* $\sim$ *112 (66) kg*
  - *One plane with 1 mm steel (Fe) target followed by one STT XXYY module without radiators*
    $\Longrightarrow$ *Overall length 8 cm* $\longrightarrow \sim 0.057 X_0$ *(*$\rho = 7.874$ *g/cm*^{3}*,* $X_0 = 1.76$ *cm) and mass 96.5 kg*

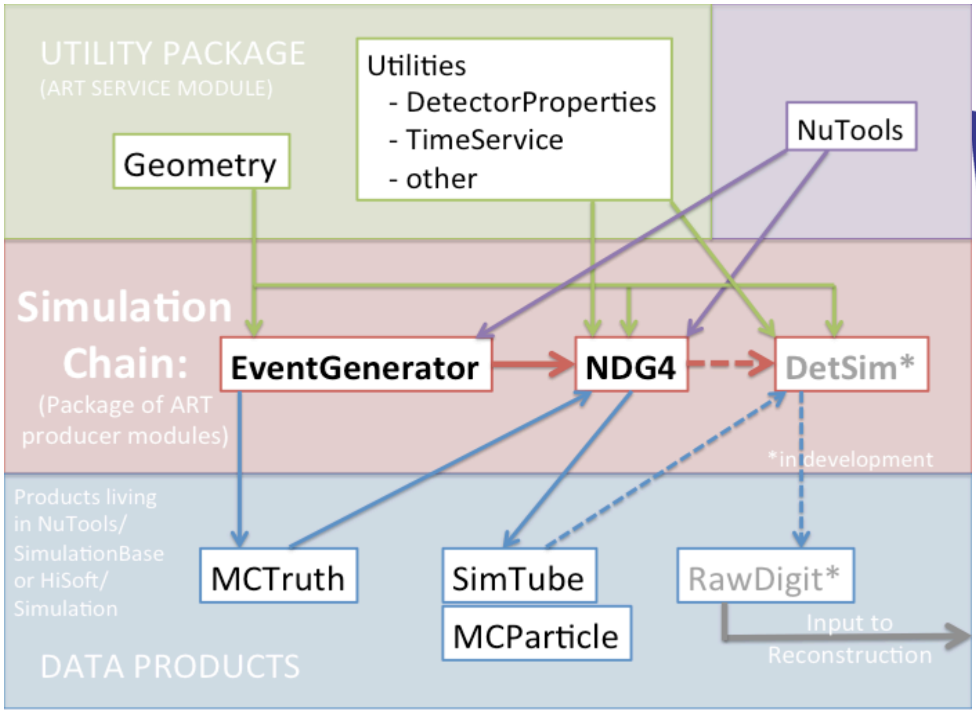
  $\Longrightarrow$ *Total longitudinal STT length 644 cm equivalent to* $\sim 1.3\ X_0$ *and* $\sim$ *7.1 tons*

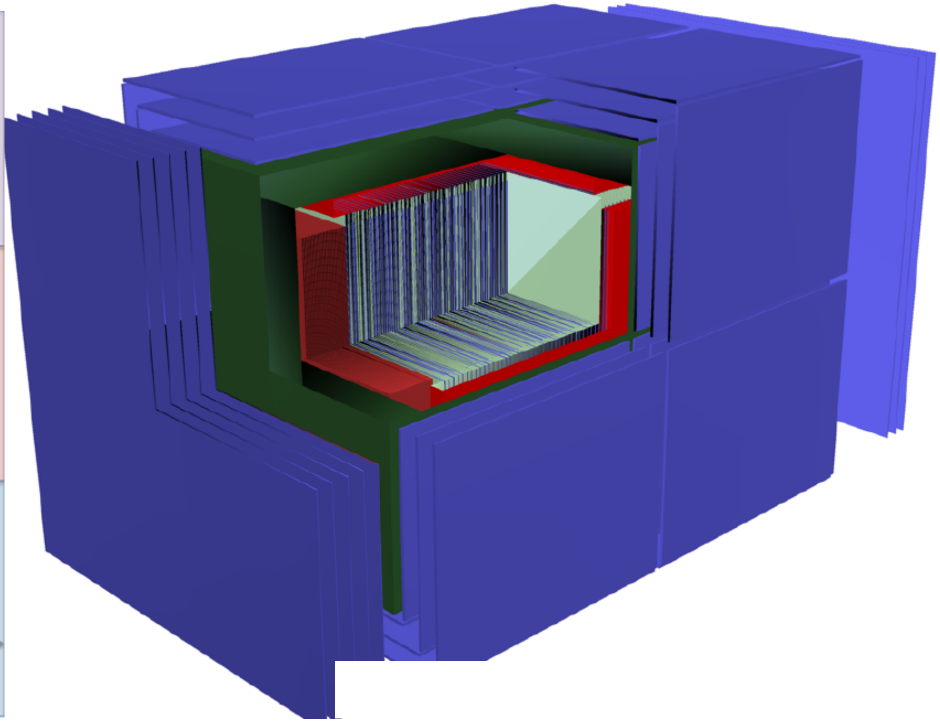
- *Need to optimize the nuclear targets with complete GEANT4 simulations of the detector performance and corresponding physics sensitivity studies.*

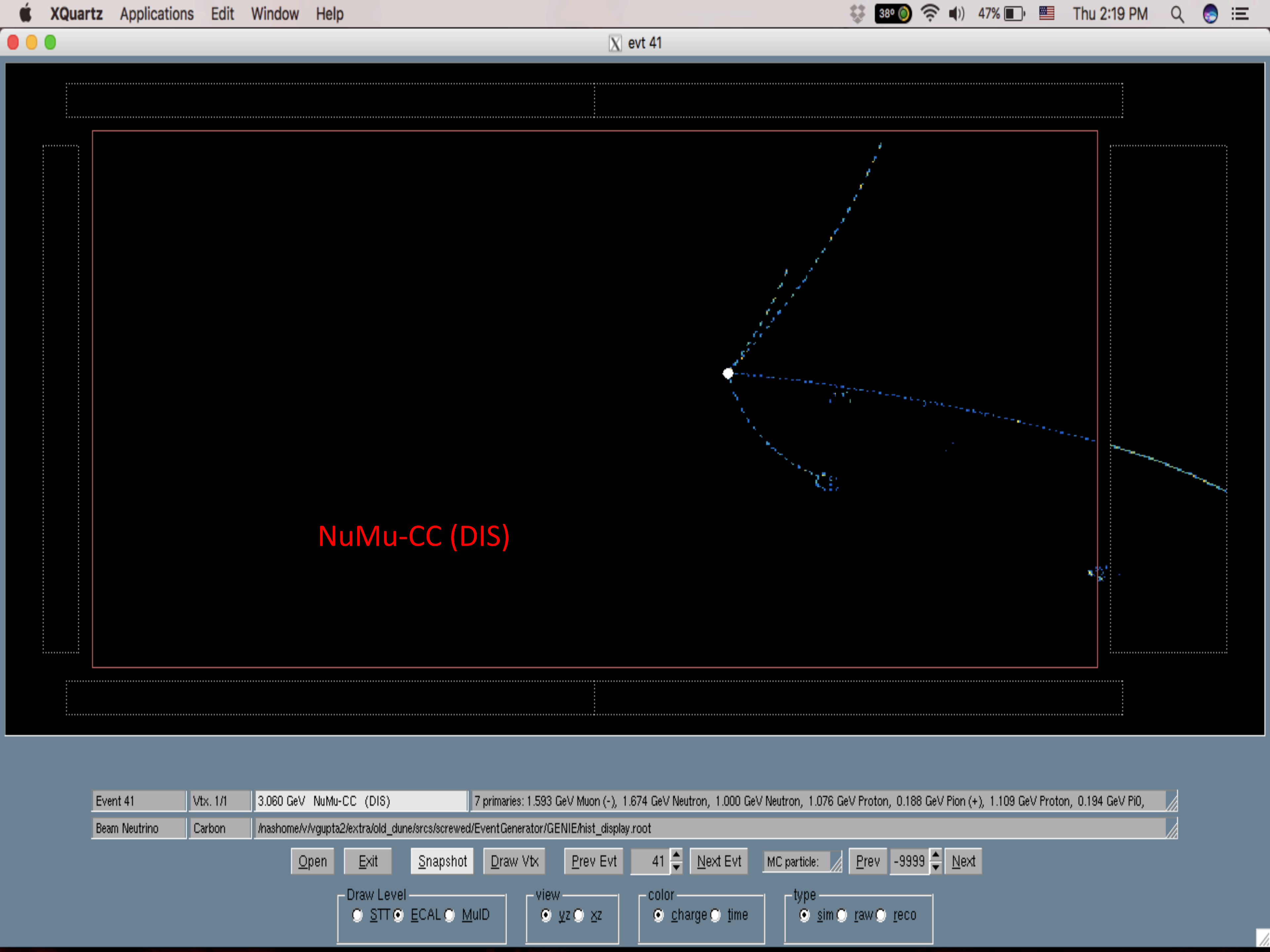
FGT Geant Simulation

- FGT ND G4 Simulation already exists: *HiSoft* Framework
  - Based on the ART framework (following LArSoft)
  - Uses MRB (Multi-Repository-Build) for building, versioned by GIT, interfaced with Geant4 through NuTools.

- Complete STT, ECAL, MuID, Magnet: GDML files generated with a python script.
- The FGT Software Repository: https://cdcvs.fnal.gov/redmine/projects/dunefgt/repository






XQuartz Applications Edit Window Help
Thu 2:19 PM
evt 41
NuMu-CC (DIS)
Event 41
Vtx. 1/1
3.060 GeV NuMu-CC (DIS)
7 primaries: 1.593 GeV Muon (-), 1.674 GeV Neutron, 1.000 GeV Neutron, 1.076 GeV Proton, 0.188 GeV Pion (+), 1.109 GeV Proton, 0.194 GeV Pi0,
Beam Neutrino
Carbon
/nashome/v/vgupta2/extra/old_dune/srcs/screwed/EventGenerator/GENIE/hist_display.root
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Prev Evt
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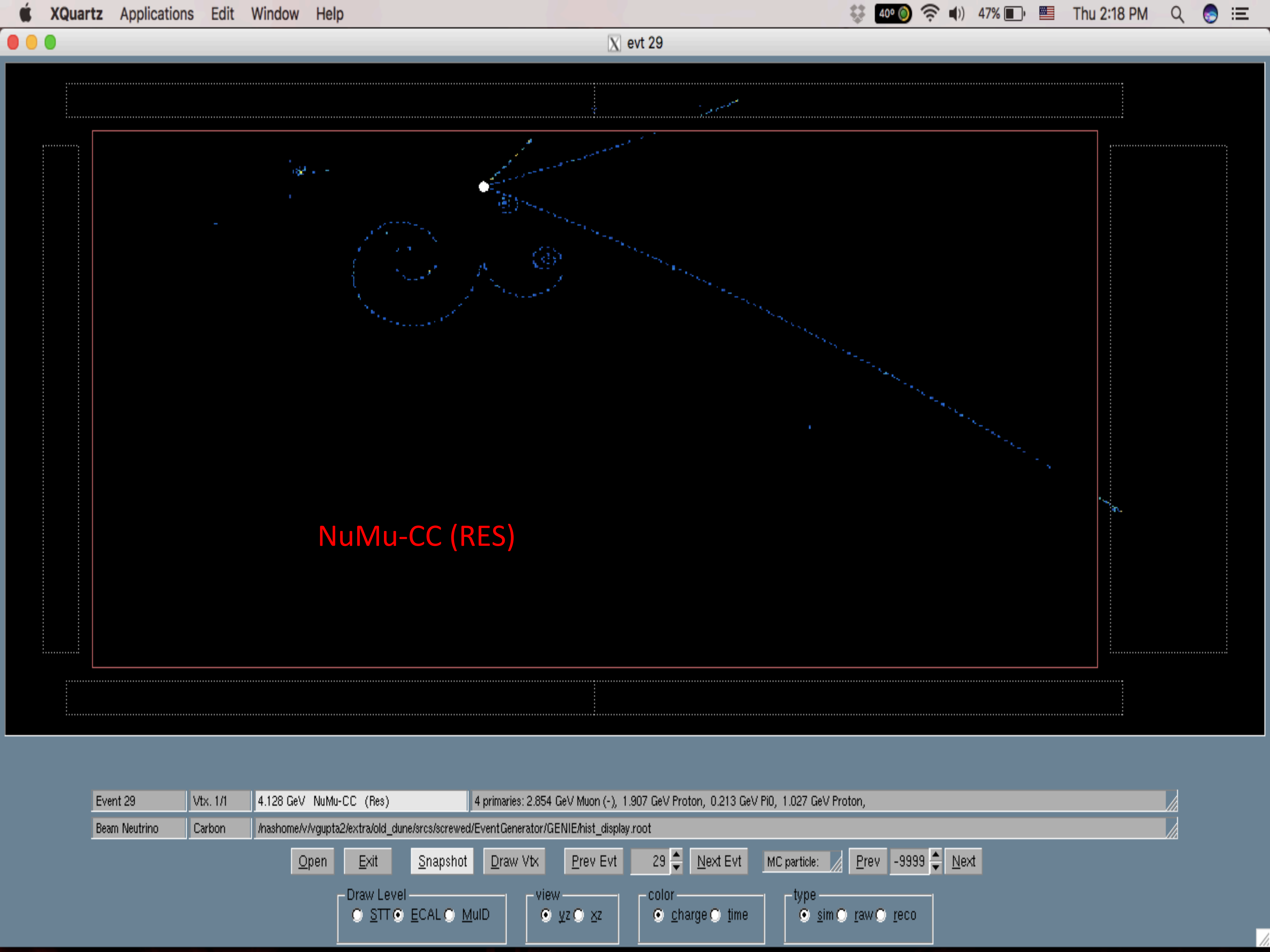
XQuartz Applications Edit Window Help
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evt 29
NuMu-CC (RES)
Event 29
Vtx. 1/1
4.128 GeV NuMu-CC (Res)
4 primaries: 2.854 GeV Muon (-), 1.907 GeV Proton, 0.213 GeV Pi0, 1.027 GeV Proton,
Beam Neutrino
Carbon
/nashome/v/vgupta2/extra/old_dune/srcs/screwed/EventGenerator/GENIE/hist_display.root
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