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

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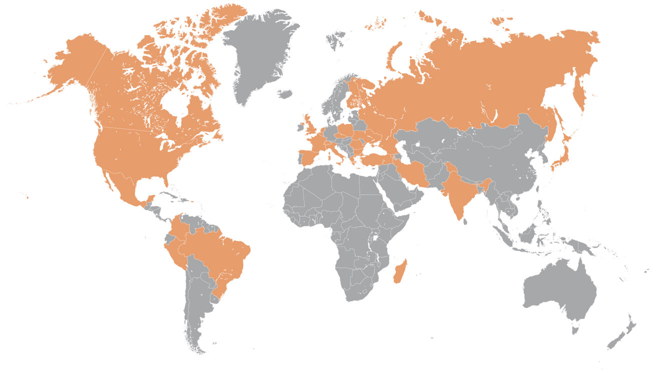
# Deep Underground Neutrino Experiment

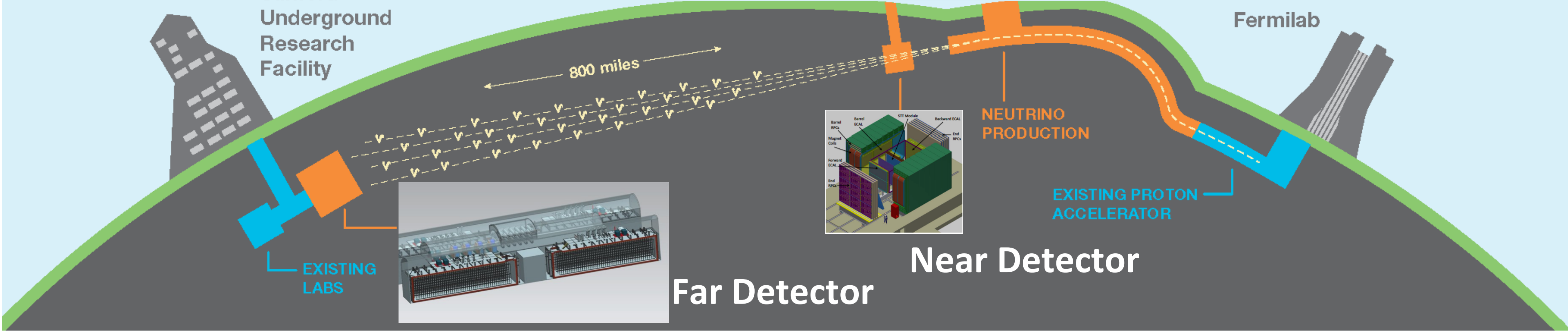
See Elizabeth Worcester's talk
Joint Neutrino Physics & Detector R & D session
August 5: 11 am - 1 pm

A strong International collaboration of about 882 physicists from more than 152 institutions in 28 countries

✓ Measure $\nu_e$ appearance and $\nu_\mu$ disappearance in a wideband neutrino beam at 1300 km to measure Mass Hierarchy, CP violation and precision measurements of neutrino mixing parameters in a single experiment.

- A large LArTPC far detector located deep underground.
- An advanced near detector for precision measurements of neutrino flux and neutrino interactions with matter.





# Near Detector Physics Motivation

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

  ✧ Prediction of FD/ND($E_\nu$) fluxes to ~ 1%

✧ Determination of the absolute $\nu_\mu$ 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 $\pi^0$ and $\gamma$ 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 $\nu - Ar$ processes: Quasi-elastic, single $\pi$, 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 $\nu$ vs $\bar{\nu}$ asymmetries in $E_\nu$ scale, flux and interactions cross-sections for $\delta_{CP}$

See Sanjib Mishra's talk
Joint Neutrino Physics & Detector R & D session
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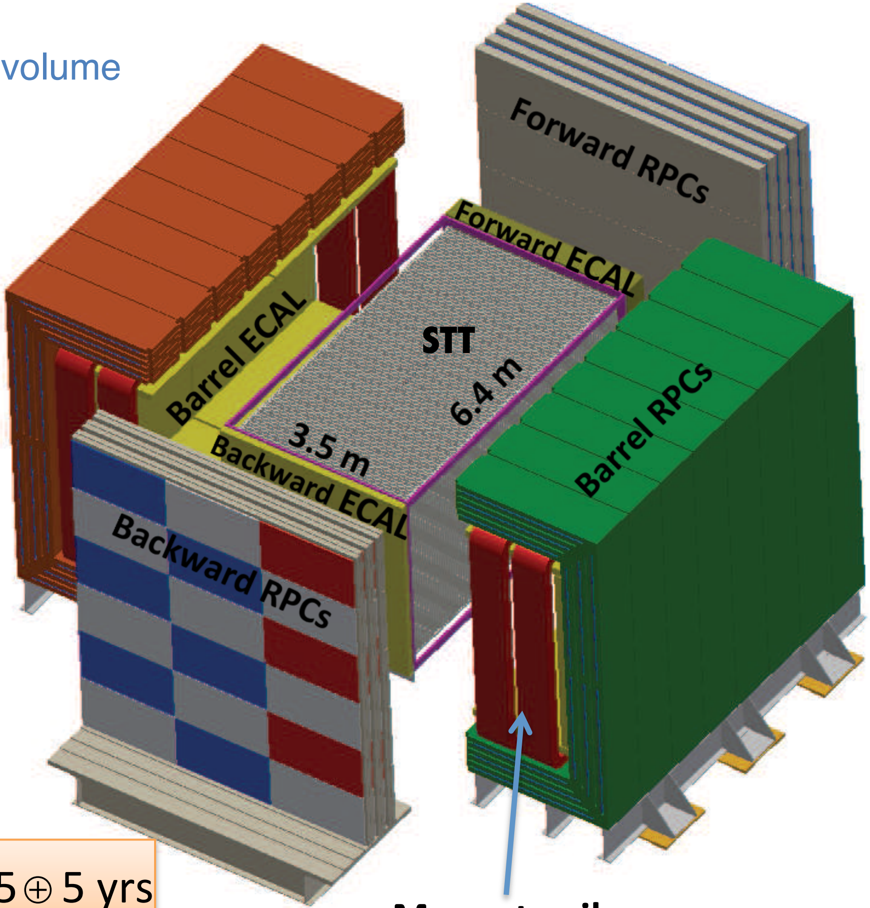
# DUNE Near Detector Concept

- **CDR reference design**. 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, $\gamma$
- 4$\pi$ lead-plastic scintillator ECAL in dipole B field
  - Transverse and longitudinal segmentation.
  - Energy resolution: 6%/√E for downstream ECAL;  
    Time resolution: 1 ns for E > 100 MeV
- 4$\pi$ RPC based muon detector
  - $\mu^+ / \mu^-$ identification.



LBNF: Large statistics ~ $10^8$ $\nu$ Interactions in 5 $\oplus$ 5 yrs

# Straw Tube Tracker (STT)

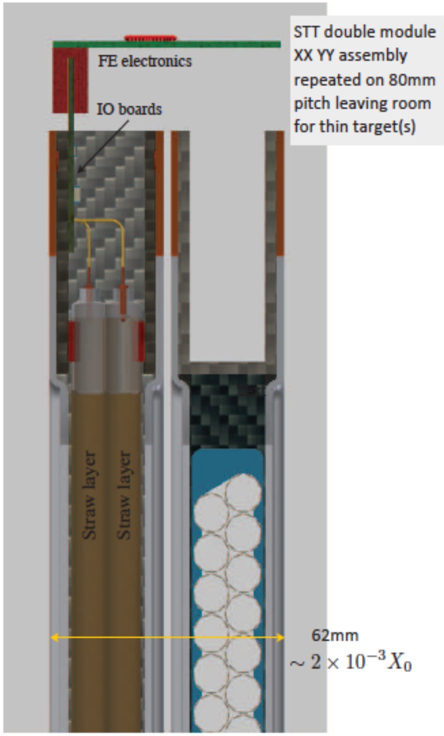
## ✧ Proven Technology: Improve on NOMAD low density spectrometer

- 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, dE/dX and Transition Radiation for particle identification. Proton and e identification with little background.

Total tracking length ~ $1.3X_0$
Vertex Resolution: 0.1 mm
Angular Resolution: 2 mrad

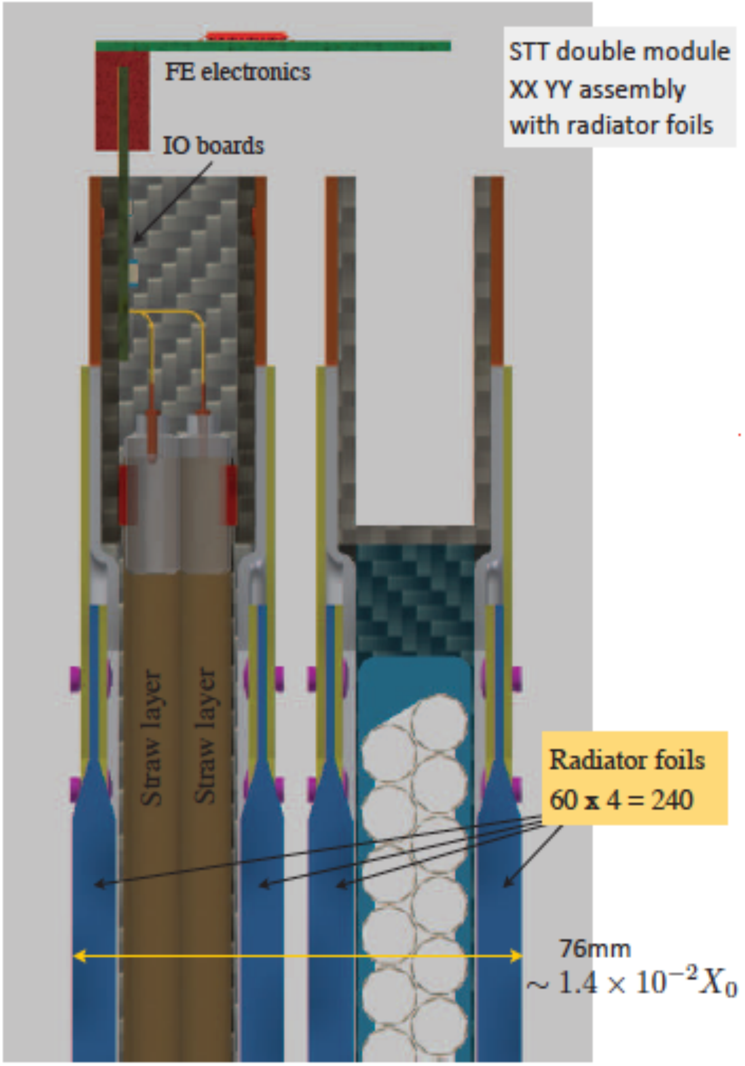
## ✧ STT design parameters:

- Straw inner diameter: 9.530 ±0.005 mm
- Straw walls $70 \pm 5\mu m$ Kapton 160XC370/100HN ( $\rho = 1.42, X_0 = 28.6cm,$ each straw $< 5 \times 10^{-4} X_0$ )
- Gold plated tungsten wire: $20\mu m$ 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.
- Double module assembly (XX+YY) with FE electronic (each XX+YY tracking module ~ $2 \times 10^{-3} X_0$ )
- Operate with 70%/30% Ar/$CO_2$ 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)



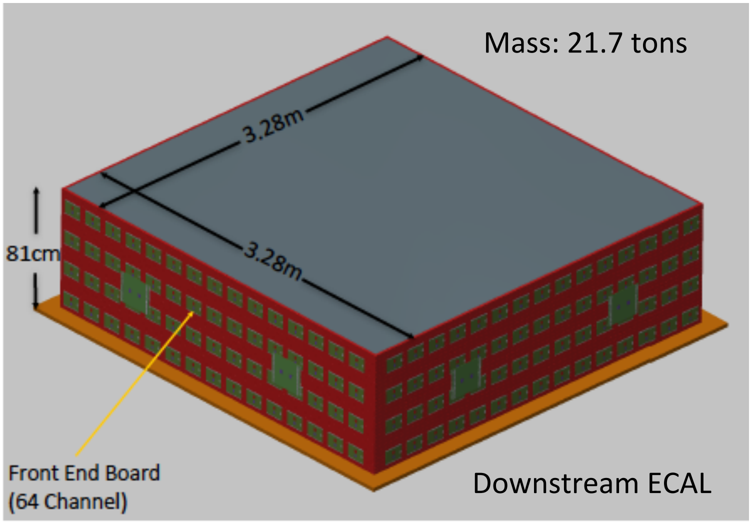
# STT: Radiator Targets

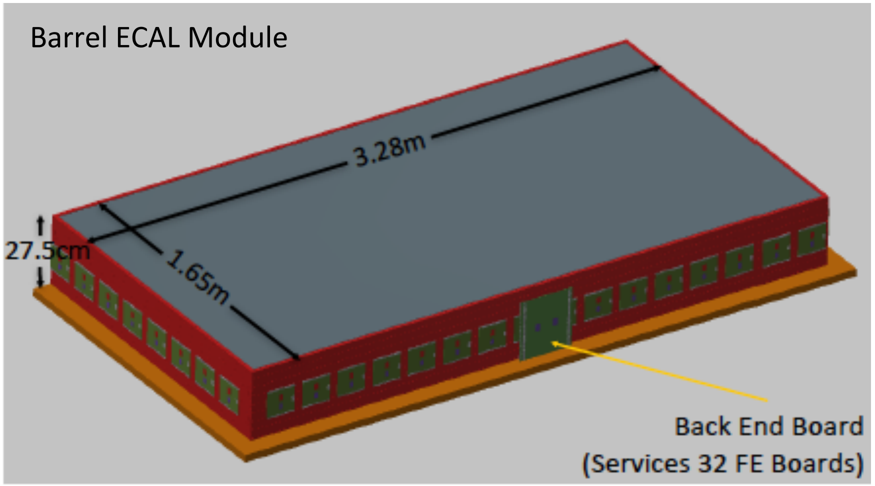
- STT design parameters:
  - **Main $\nu(\bar{\nu})$ target in the form of multiple thin polypropylene foils (radiators)**
    - **Use target material for particle identification via Transition Radiation (TR)**
- Radiator target integrated at both sides of each STT (double layer) module to minimize overall thickness (foils can be removed if needed)
  - **Embossed radiator foils: 25 $\mu m$ thick, 125 $\mu m$ 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,** $1.25\times10^{-2}X_0$
    - **The radiator represents 82.6% of the total mass of each STT module**
    - **Tunable for desired statistics and momentum resolution**


STT double module XX YY assembly with radiator foils

# The Electromagnetic Calorimeter

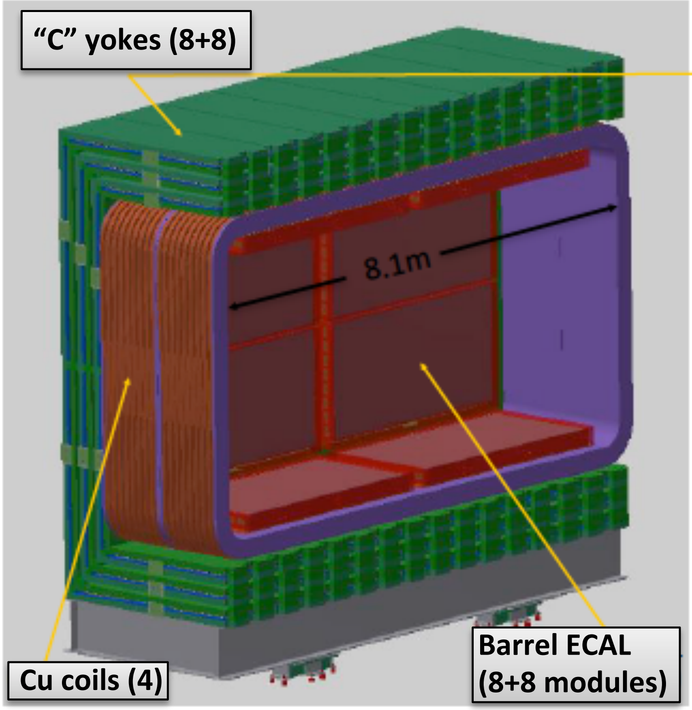
- ✧ Reconstruction of $e^+/e^-$, $\gamma$ with accuracy comparable to $\mu^+/\mu^-$ and FD
  - Containment of > 90% of shower energy; energy resolution < $\boxed{6\%/\sqrt{E}}$
- ✧ Sampling electromagnetic calorimeter with Pb absorbers and alternating horizontal and vertical (XYXYXY…) 3.2 m x 2.5 cm 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 $X_0$**.

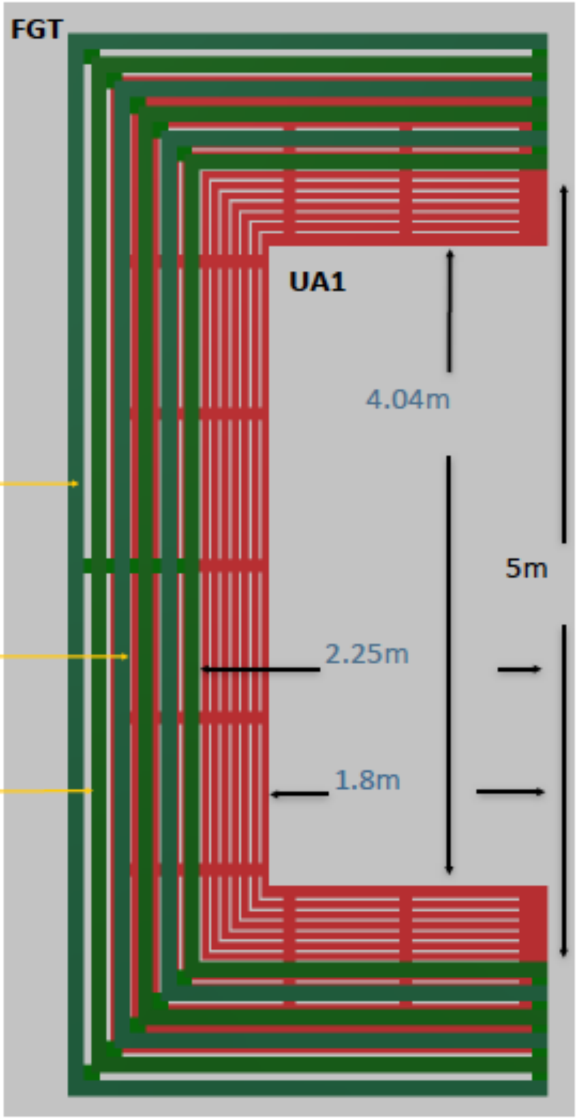




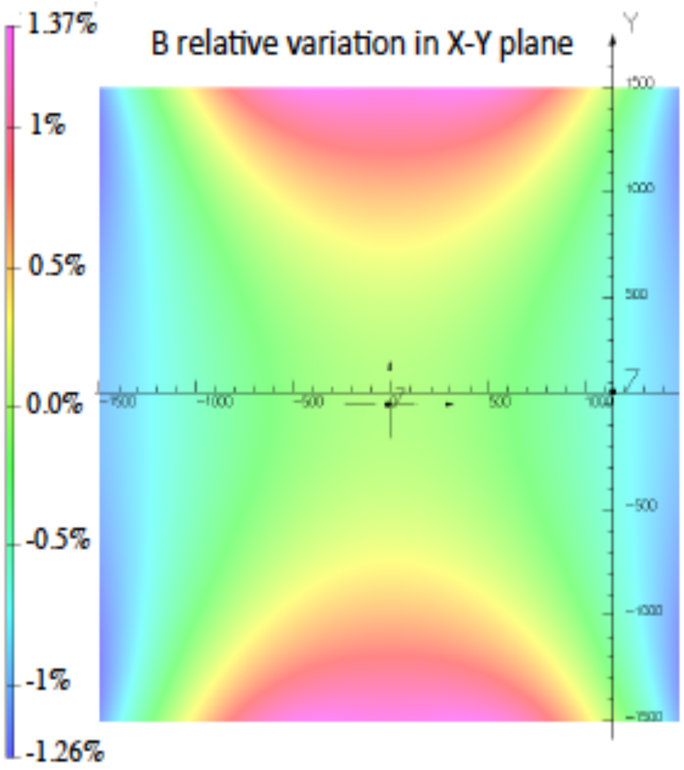
# The Dipole Magnet

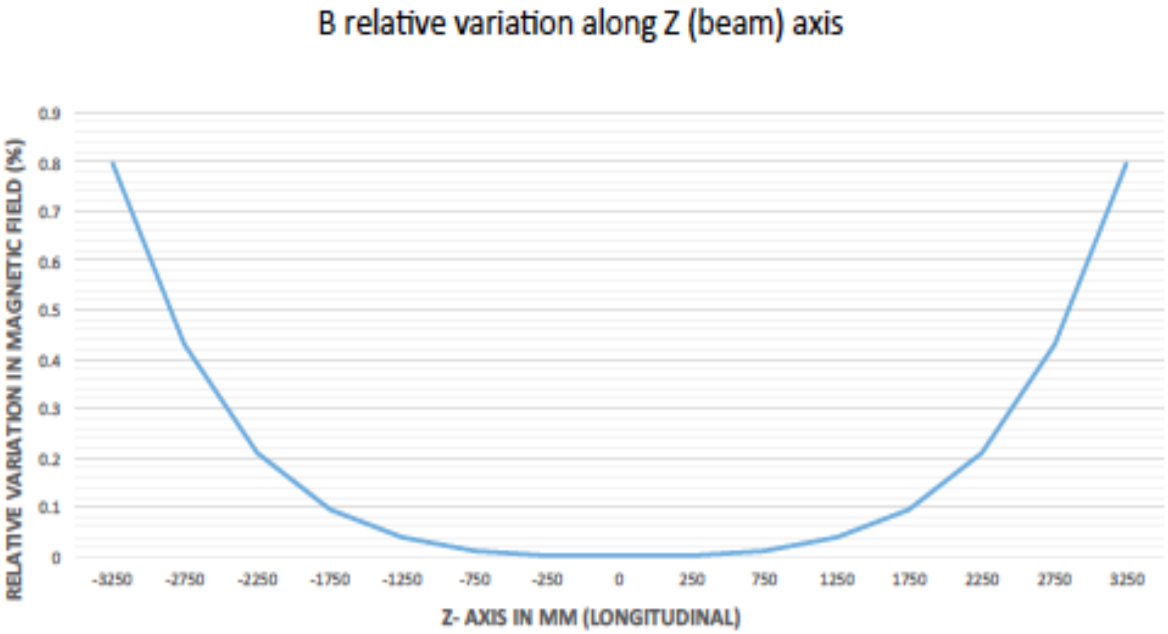
- Design based on UA1/NOMAD/T2K magnet
- Magnetic volume: 4.5 m x 4.5 m x 8.1 m, nominal B = 0.4T
- Return yoke with 8+8 "C" section:
  - 6 x 100 mm steel plates, 50 mm gaps (960 tons)
- 4 vertical Cu coils (168 tons) made of 8 double pancake
- Power requirement for nominal field 2.43 MW, water flow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





# Dipole Magnet Simulation


B relative variation in X-Y plane

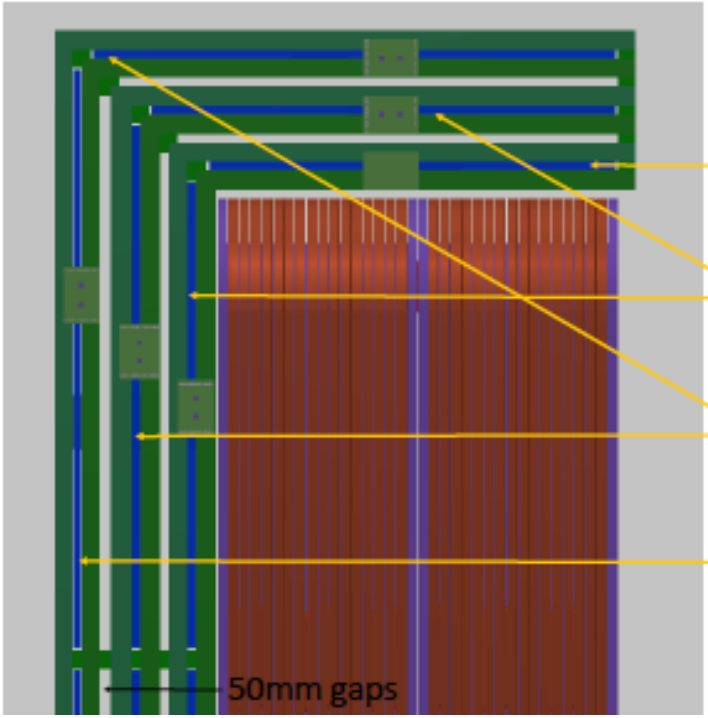

B relative variation along Z (beam) axis

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 $\nu_\mu$ and $\bar{\nu}_\mu$ spectra separately
  - Identify muons exiting the tracking volume
  - $4\pi$ 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

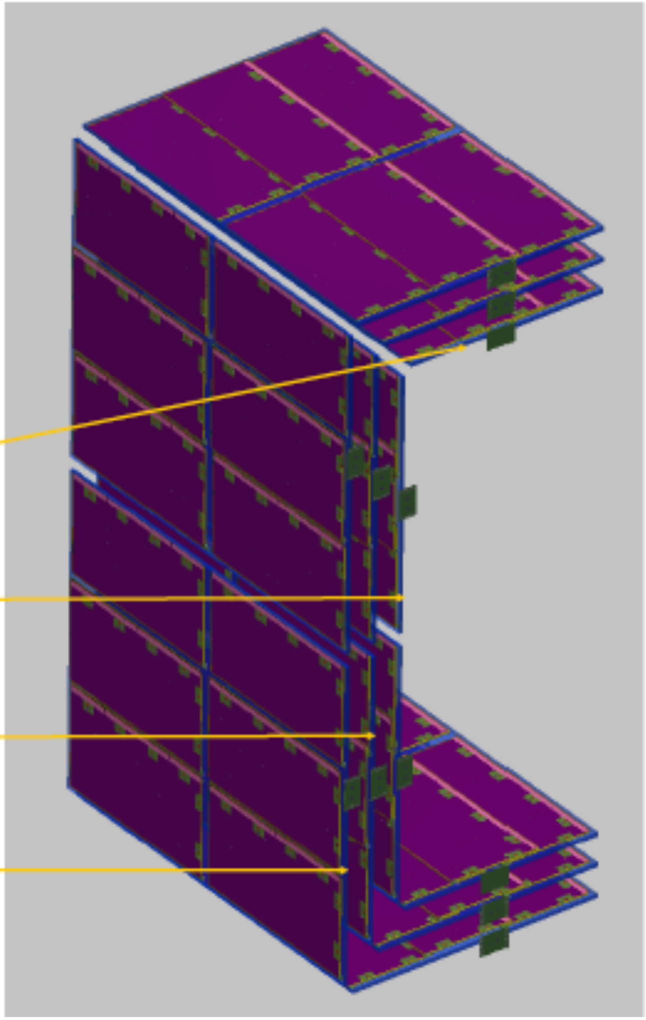


**RPC tray 2.2 m wide**
**4x6 = 24 chambers**

**RPC tray 2.5 m wide**
**8x6 = 48 chambers**

**RPC tray 2.8 m wide**
**8x6 = 48 chambers**

**RPC tray 3.1 m wide**
**4x6 = 24 chambers**



# Readout Electronics

- Near Detector should cater pulse structure of the beam (~ 9.6 $\mu s$ spill) and provide GPS time stamp to identify origin and nature of events.

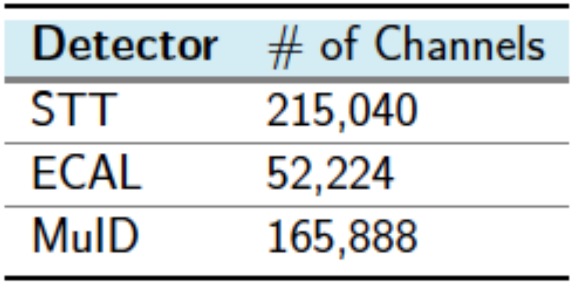
- Fast readout electronics for STT, ECAL and muon detector (rise time a few ns) with time stamping (resolution ~ 1 ns) and charge measurements.
  - STT and ECAL: total charge and time associated with a given hit, in-sync with beam spill triggers.
  - MuID RPCs: provide the position and time associated with a traversing track.
  - In STT, desirable waveforms are digitized to enhance the capability to detect transition radiation.

- Expected rates per spill are ~0.2 events/ton: 1.5 events in STT, 22 events in ECAL, 222 in magnet/coil, 57(34) events in downstream (upstream) steel planes.
  - **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

- For STT FE , consider VMM2 chip (ASICS) developed for ATLAS upgrades, with fast ADC and TDC

- For ECAL FE consider options: TRIP-T, SPIROC by OMEGA



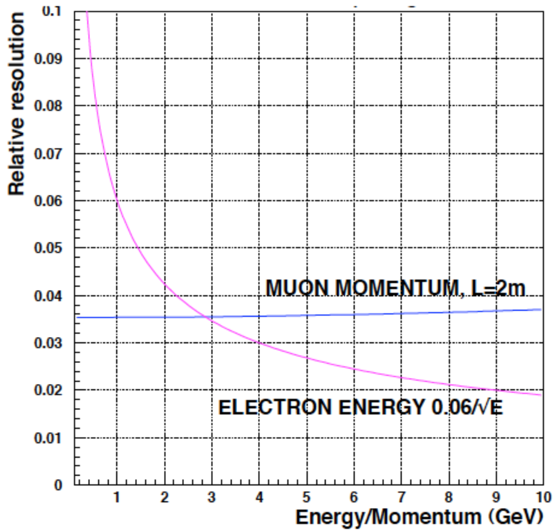
| Detector | # of Channels |
|---|---|
| STT | 215,040 |
| ECAL | 52,224 |
| MuID | 165,888 |

# FGT Detector Performance

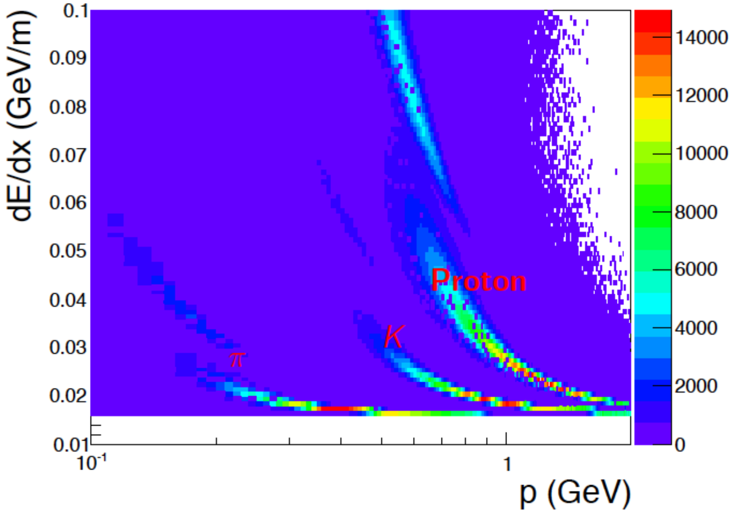
**Expectation**

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

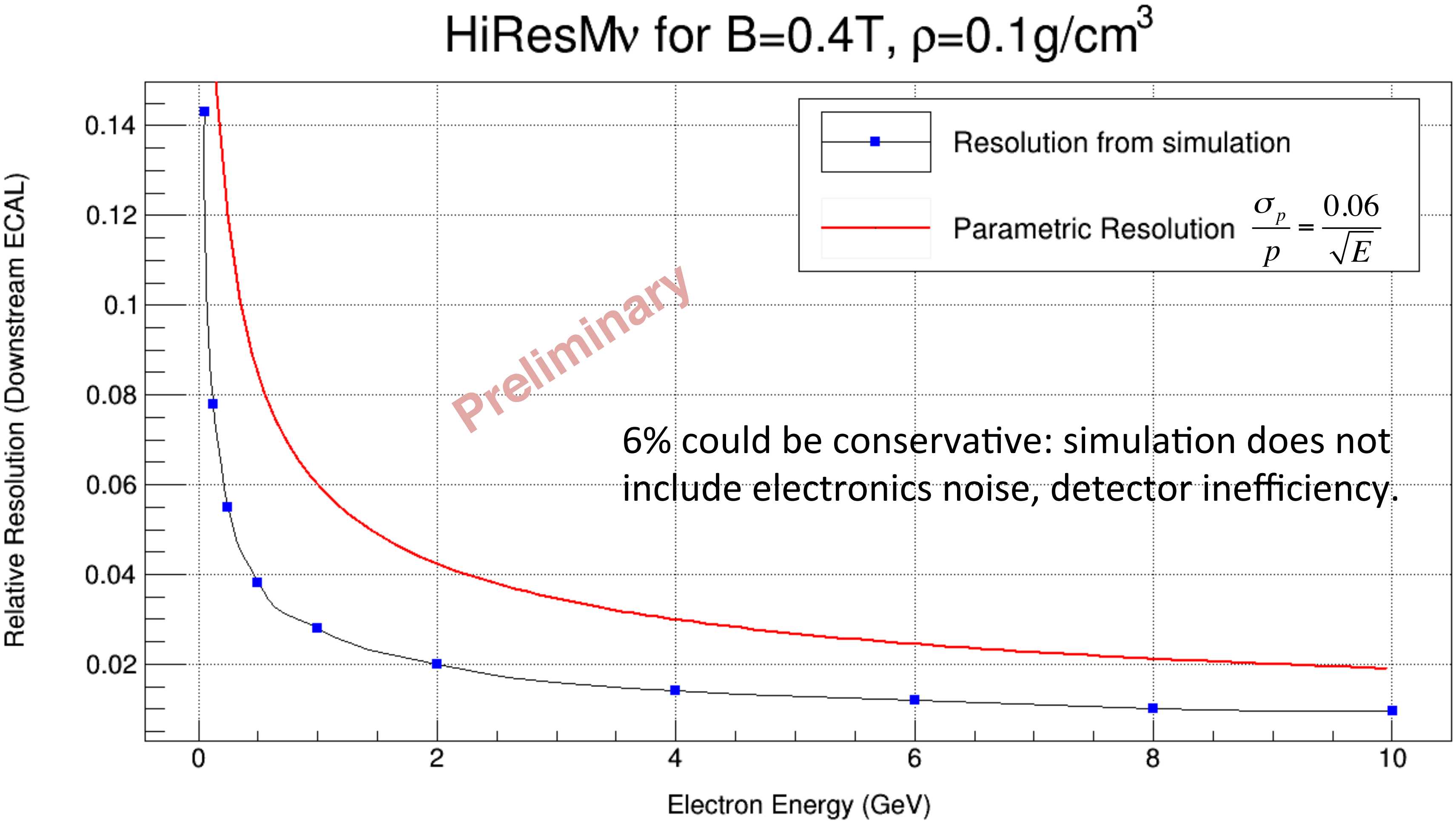
**PID Performance**



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

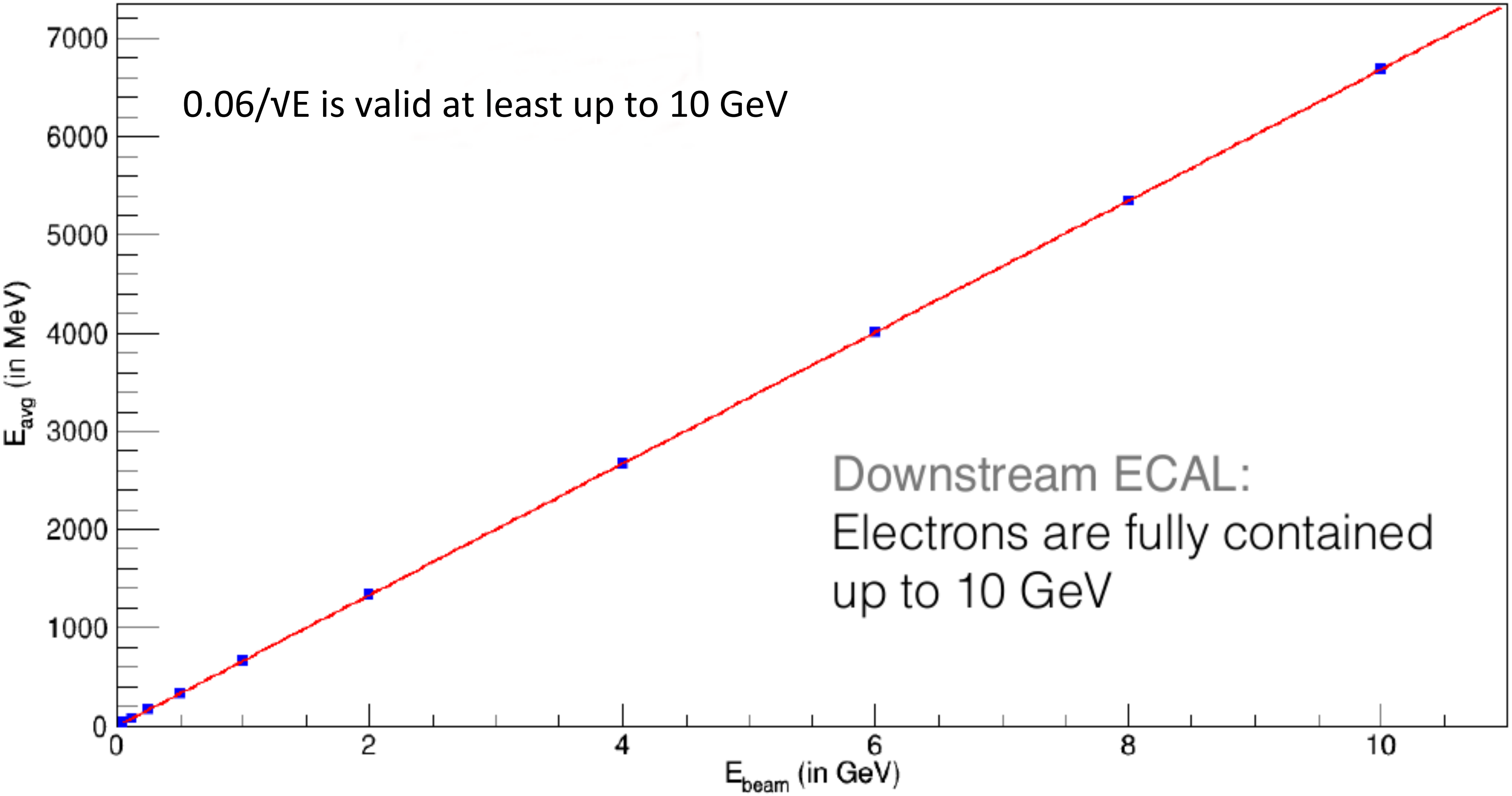


# Detector Performance-ECAL Energy Resolution



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

# Detector Performance- Linear Energy Response

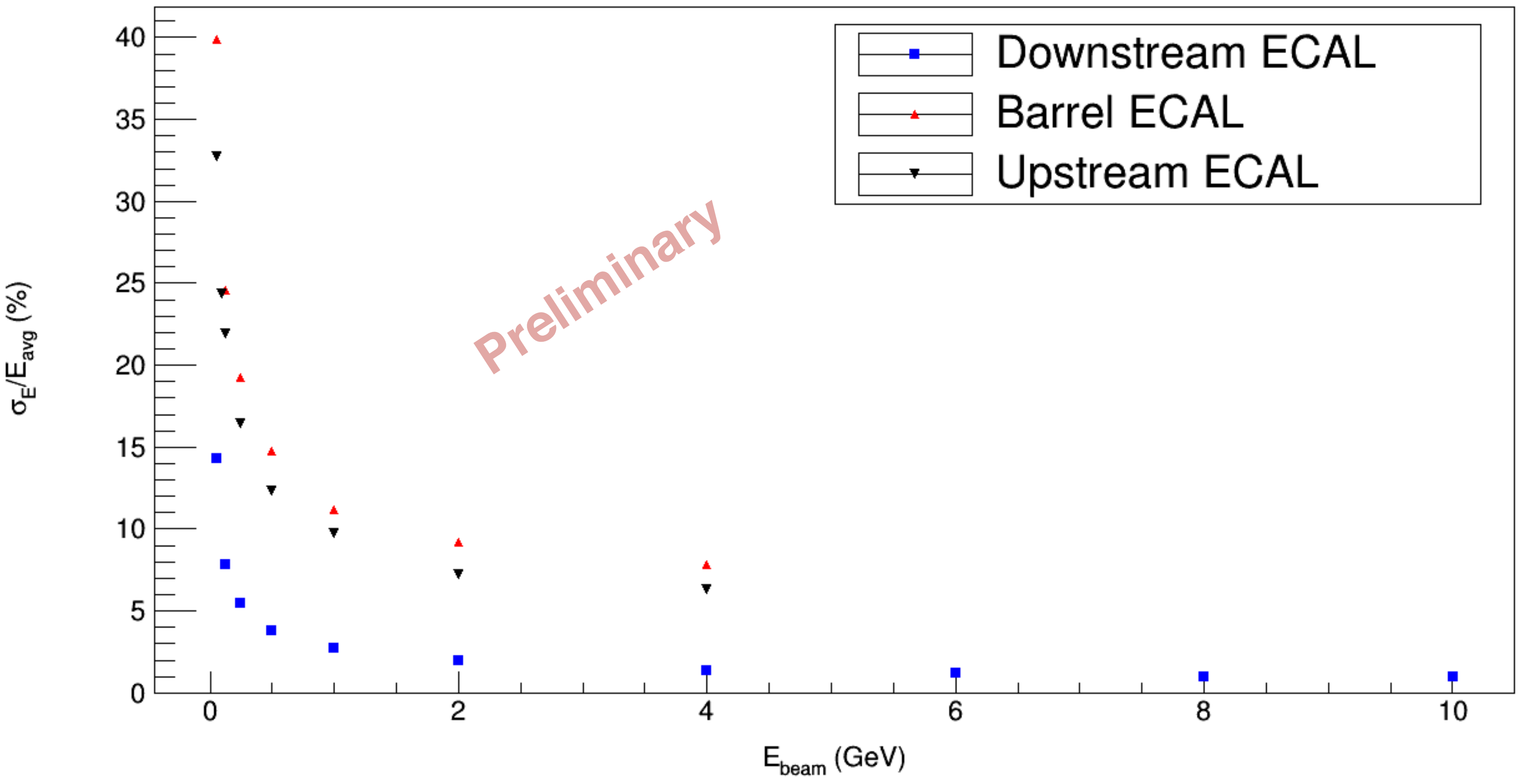


0.06/√E is valid at least up to 10 GeV

Downstream ECAL:
Electrons are fully contained up to 10 GeV

# Detector Performance- Energy Resolution in the Full ECAL

Energy resolution vs input energy of electrons incident normally on each ECAL



# Summary

✧ FGT design is based upon successful experience of NOMAD and T2K: proven technologies.

- STT design is based on ATLAS and COMPASS straw trackers.
- ECAL design after T2K ND280 EM calorimeter
- Magnet design following the UA1/NOMAD/T2K dipole magnet.

✧ The reference FGT conceptual and mechanical design matches the global science requirement of the Near Detector for DUNE

- ✧ Very good charged particle tracking via the STT, good charged separation.
- ✧ 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.
- ✧ FGT provides redundancy in absolute flux measurements via
  - ✧ NC elastic scattering off electrons: $\nu e^- \rightarrow \nu e^-$
  - ✧ Inverse Muon Decay (IMD) interactions: $\nu_\mu e^- \rightarrow \mu^- \nu_e$
  - ✧ Quasi-elastic (QE) CC interactions in the limit $Q^2 \rightarrow 0 : \nu_\mu n \rightarrow \mu^- p$