BEAM MONITORING FOR THE DUNE EXPERIMENT WITH THE SAND DETECTOR

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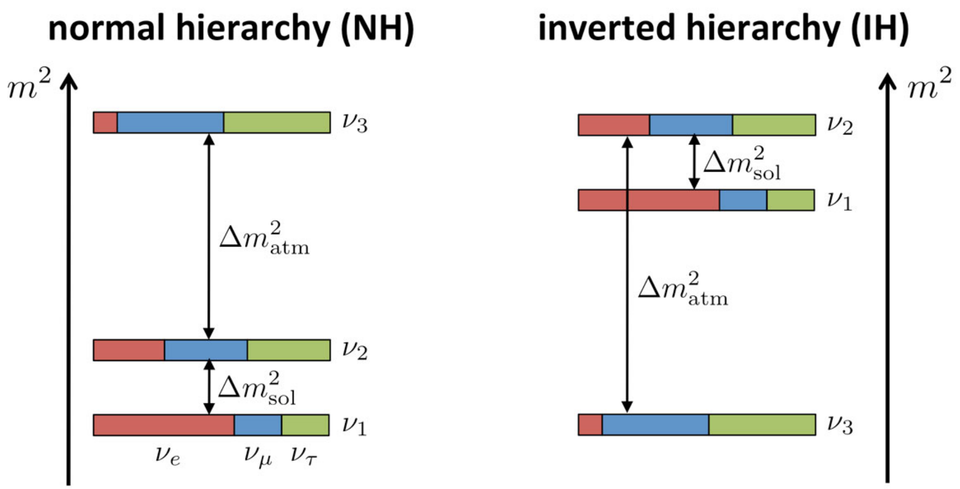
NEUTRINO OSCILLATIONS

- Neutrino mixing: three flavour eigenstates ν_α are connected to 3 mass eigenstates ν_i by unitary mixing matrix U
- Neutrino oscillation: in flight flavour change due to neutrino mixing and not degenerate mass eigenstates
- No right-handed neutrino in SM makes construction of neutrino Dirac mass term impossible

$$|\nu_\alpha\rangle = \sum_i U_{\alpha \mathrm{i}} |\nu_i\rangle$$

$$|\nu_i\rangle = \sum_\alpha U^*_{\alpha \mathrm{i}} |\nu_\alpha\rangle$$

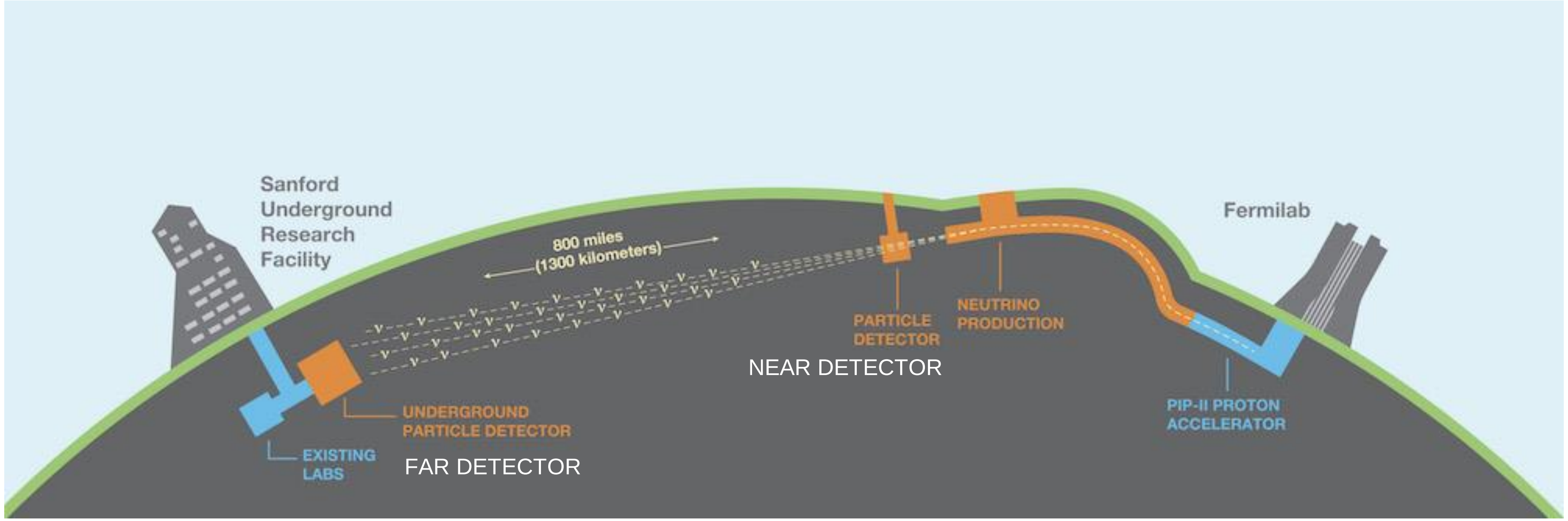
Neutrino oscillations require extension of the SM



Still major unknowns:

- Existence of CP violation in neutrino sector: δ_{CP}
- Neutrino mass ordering: $sign(\Delta m^2_{31})$

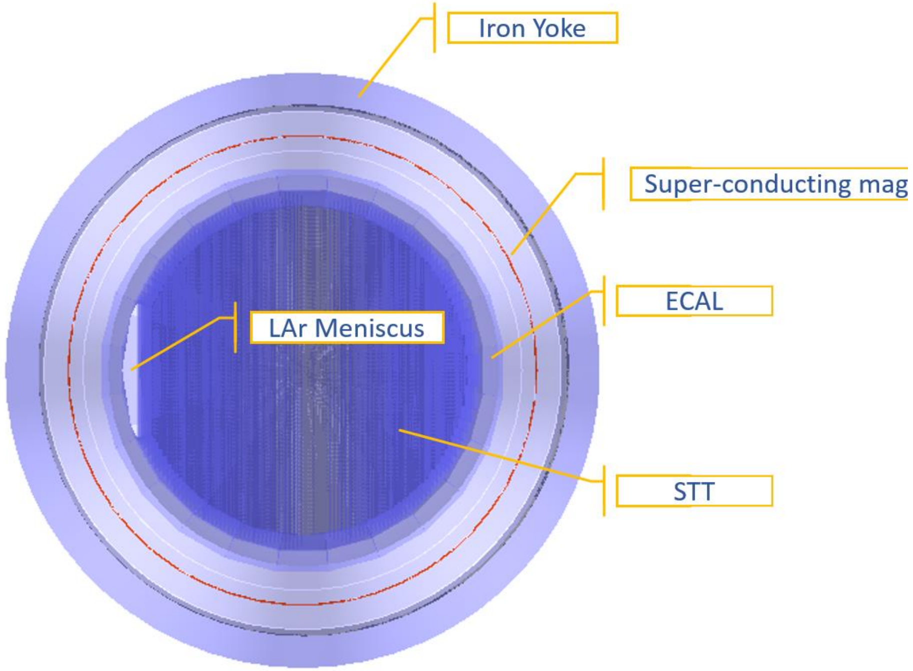
DUNE: DEEP UNDERGROUND NEUTRINO EXPERIMENT

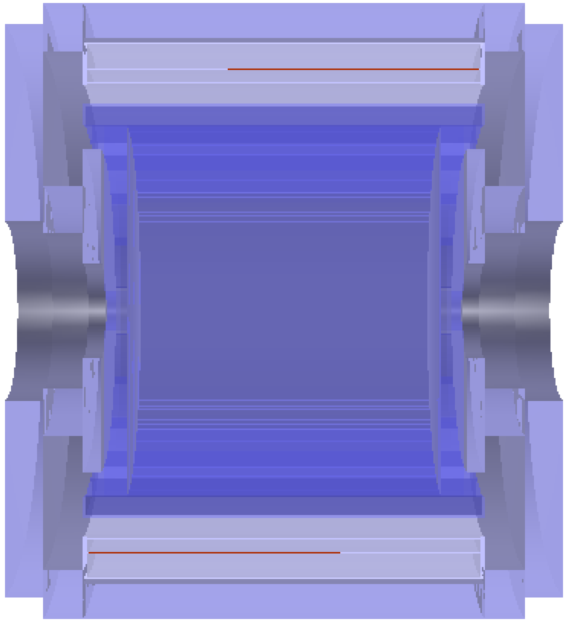


- DUNE will be a long baseline accelerator neutrino experiment aiming to measure CP violation and mass ordering
- Three main components:
  1. Conventional wide-band neutrino beam: Proton accelerator (60-120 GeV) + Target + Focusing magnets ($\nu/\ \bar{\nu}$ modes) $\rightarrow$ 1.2 MW
  2. Far Detector: 4-10kton LArTPC in South Dakota, 1300km from the source
  3. Near Detector:
     - 2 movable Argon based TPC : LArTPC (ArgonCube) and magnetized low density TPC (HPgTPC)
     - On-axis beam monitor (SAND)

SAND: SYSTEM FOR ON-AXIS NEUTRINO DETECTION

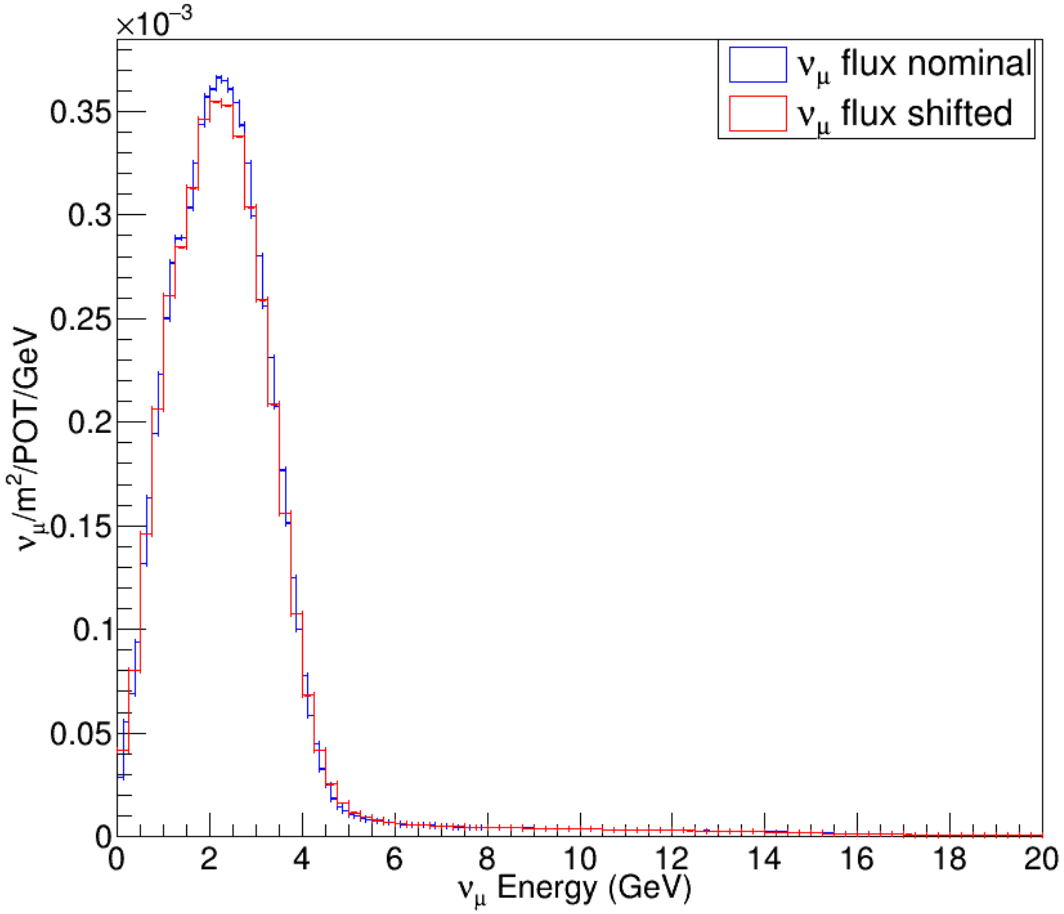
- Based on KLOE detector: iron structure, super-conducting magnet and electro-magnetic calorimeter (ECAL).
- Internal tracker yet to be defined: we considered STT (straw tube tracker)





$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) \times \phi^{near}_{\nu_\mu}(E_\nu) \times F_{far/near}(E_\nu) \times \sigma^{Ar}_{\nu_e}(E_\nu) \times D^{far}_{\nu_e}(E_\nu, E_{rec}) dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) \times \sigma^{Ar}_{\nu_\mu}(E_\nu) \times D^{near}_{\nu_\mu}(E_\nu, E_{rec}) dE_\nu}$$

BEAM MONITORING



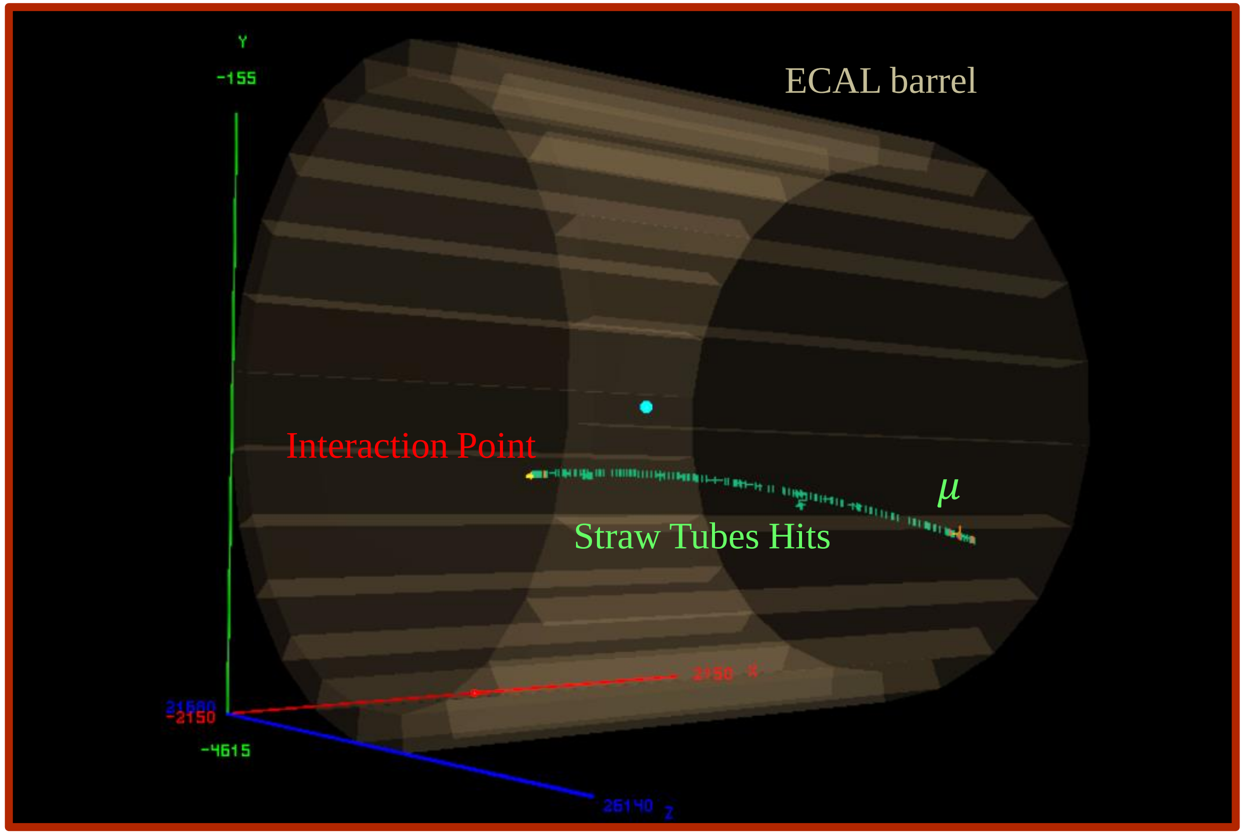
- My thesis studied the beam monitoring capabilities of the SAND detector, comparing on a weekly basis the distribution of an observable sensitive to beam anomalies
- **Target:** upstream calorimeter modules
- **Tracking System:** Straw Tube Tracker (STT)
- **Observable:** reconstructed muon momentum
- **Systematic under study:** horn-1 0.5 mm Y shift
- **Test statistic:** $T \sim \chi^2$

Note: we call nominal and shifted the results obtained with standard and horn-1 displaced neutrino beam respectively

GEOMETRY AND INTERACTION SIMULATION

- **Geometry:** *dunendggd* (Near Detector (ND) group specific software)
- **Neutrino interactions:** *GENIE* (neutrino Monte Carlo generator)
- **Particle propagation:** *edep-sim* (Geant4 based software)

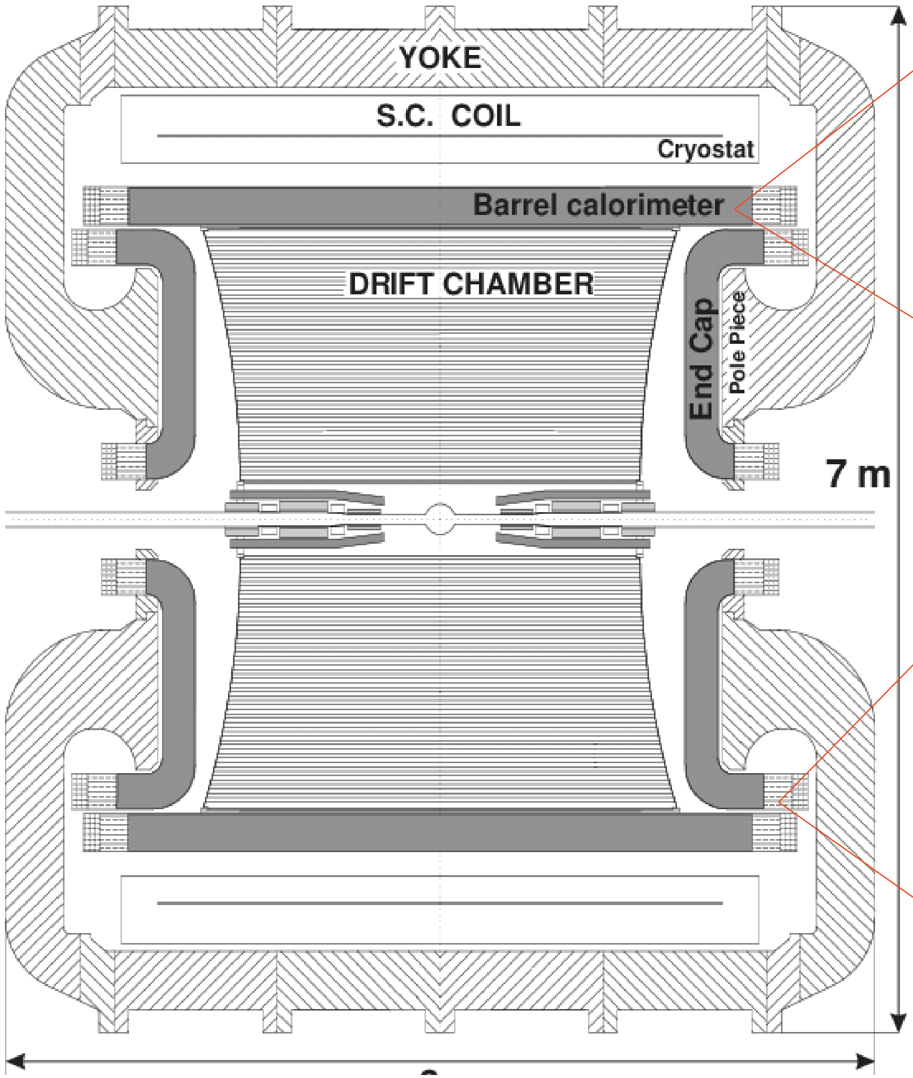
CC event ($E_\nu = 2.98 GeV$) *with interaction point on one of the front ECAL barrel modules*



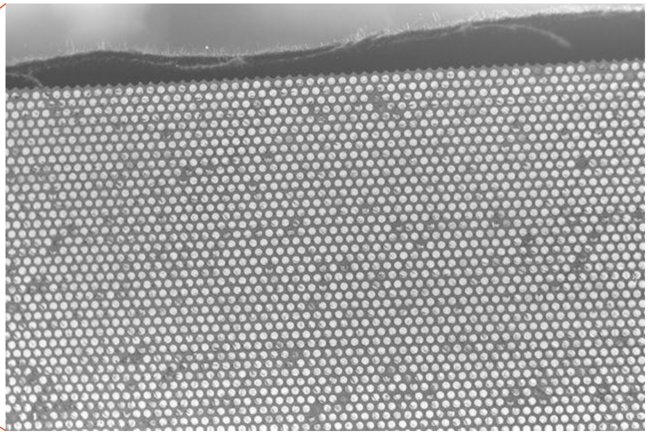
One week's worth of statistics on the 9 up-stream calorimeter barrel modules

$$N_{week} \simeq 1.75 \times 10^6$$

ECAL: STRUCTURE



FIBERS

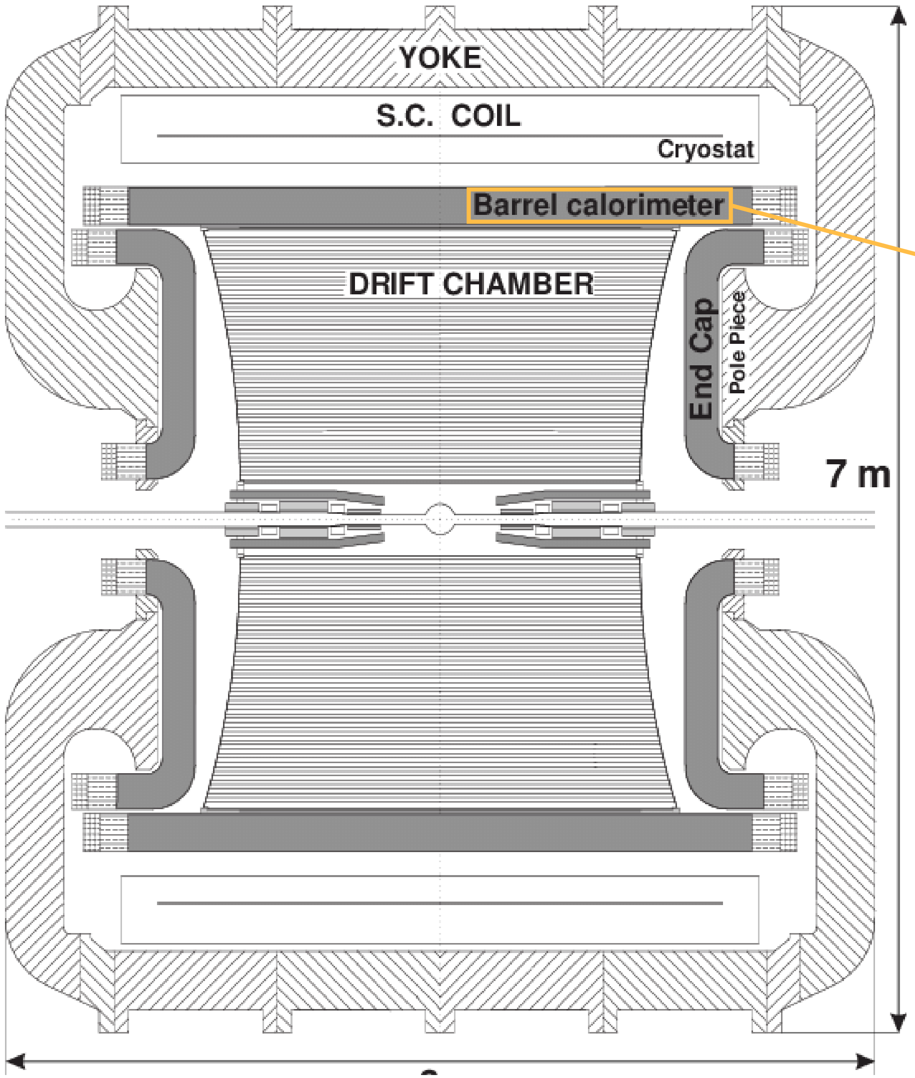


READ-OUT

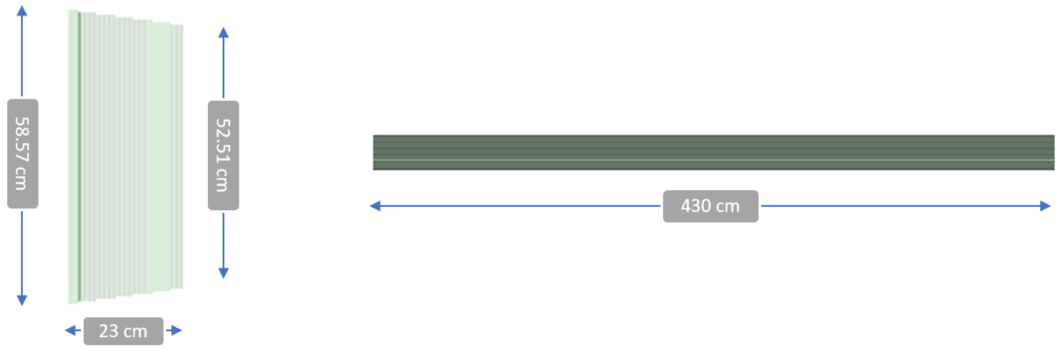
- Spaghetti calorimeter with lead and scintillating fibers

- Groups of scintillating fibers are read-out on both side by photo-multiplier tubes (PMT) through light guides

ECAL: STRUCTURE

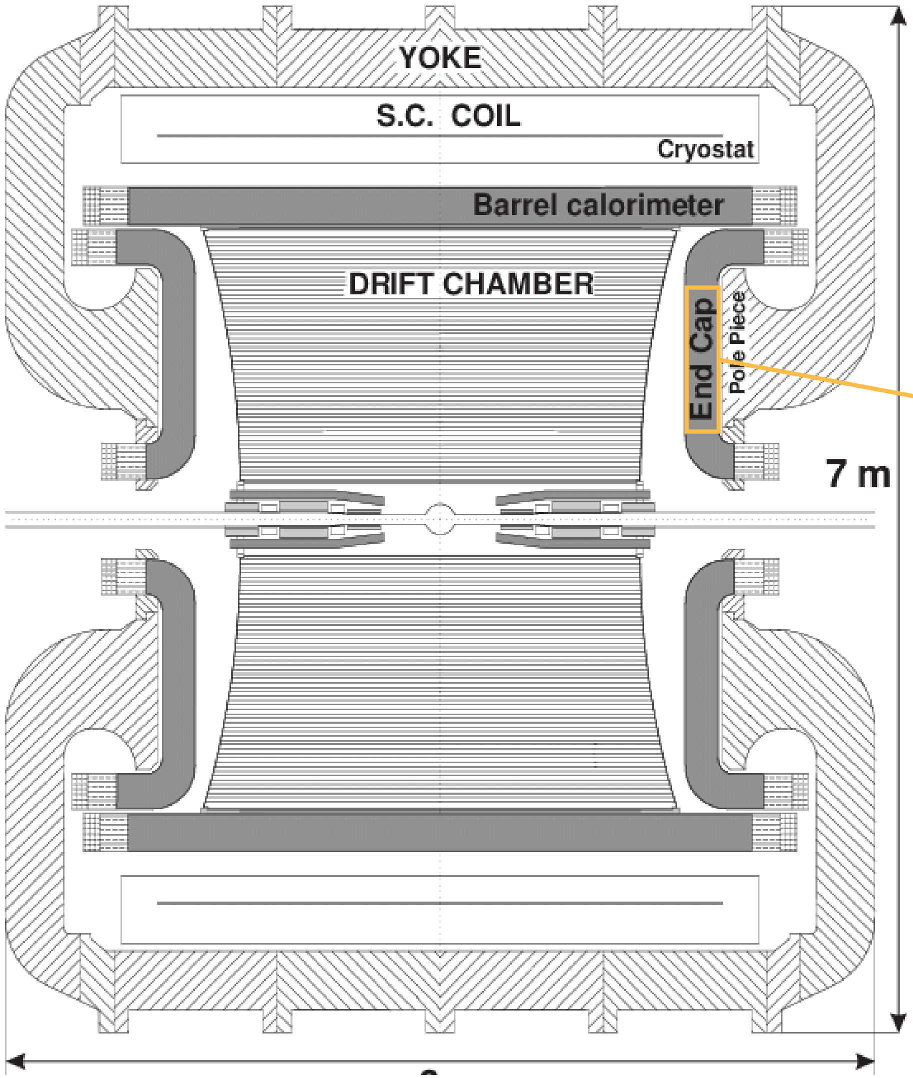


BARREL

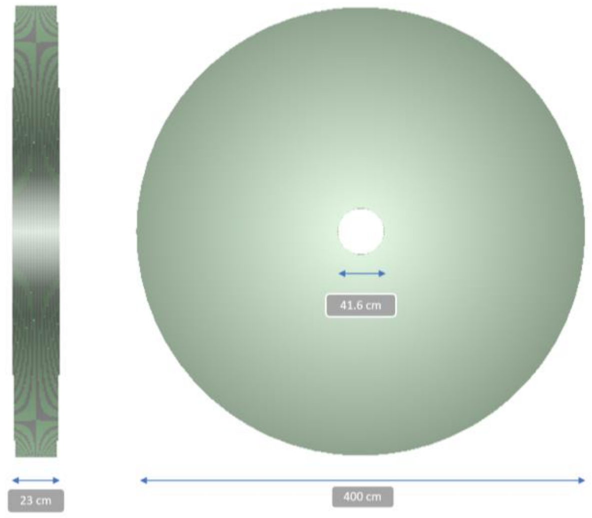


- Calorimeter Barrel: segmented into twenty-four trapezoidal modules 4.3 m long, 23 cm thick and bases of 52 and 59 cm.
- Approximation: 209 alternating slabs of plastic scintillator (0.07cm) and lead (0.04cm)

ECAL: STRUCTURE



END-CAPS



- Calorimeter End-caps: complex geometry with vertical modules bent horizontally to fit PMs
- Approximation: hollow cylinders of inner diameter 41.6 cm and outer diameter 400 cm

ECAL: DIGITIZATION AND RECONSTRUCTION

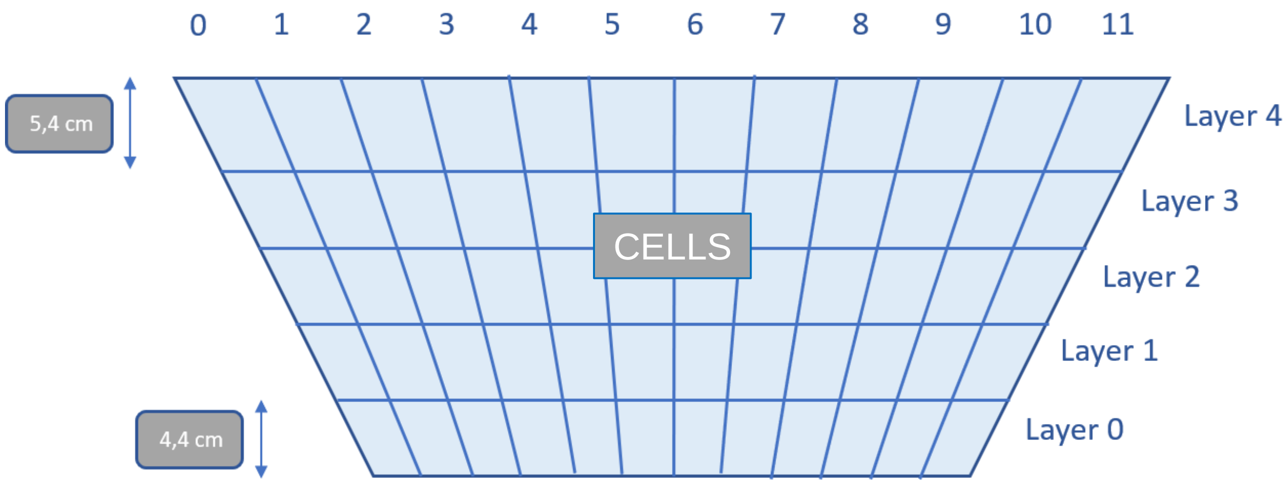
DIGITIZATION

- Calorimeter read-out is segmented in cells ($\sim 4.5 \times 4.5$ cm^2) and hits are assigned to them
- Hits are converted into number of photo-electrons and their arrival time at PMT on each side

$$N_{p.e.} = 25 \times E_A \times dE$$

$$t_{p.e.} = t_{part} + t_{decay} + d \cdot u_{ph} + Gauss(1\text{ns})$$

- For each PMT:
  - ADC: signal is proportional to $N_{p.e.}$
  - TDC: t_{TDC} is evaluated as constant fraction (15%) discriminator



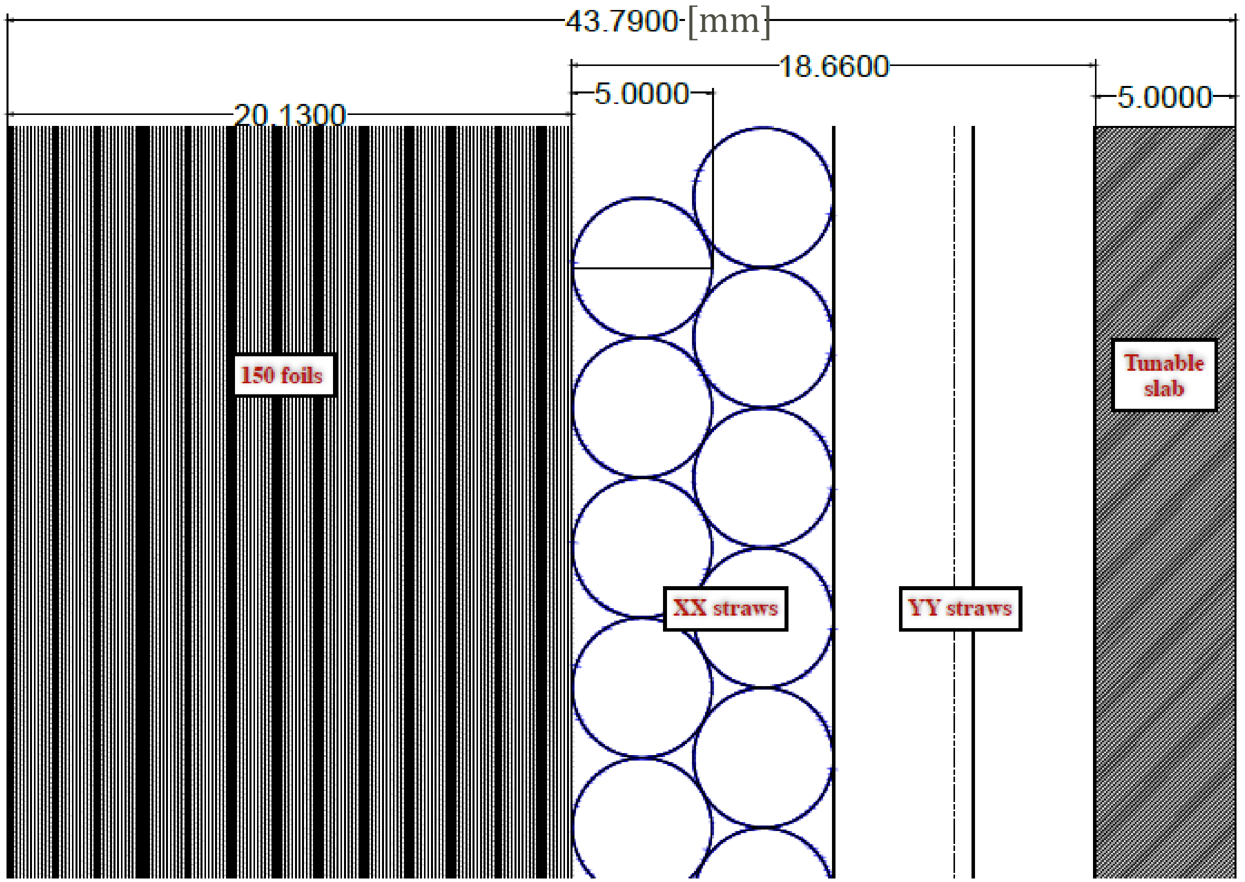
RECONSTRUCTION

- The particle arrival time t and its coordinate x along the fiber direction are evaluated as:

$$x = \frac{t_{TDC1} - t_{TDC2}}{2u_{p.e.}} + x_{cell};$$

$$t = (t_{TDC1} + t_{TDC2} - u_{p.e.} \times L);$$

STT: STRUCTURE



MODULE

Main components:

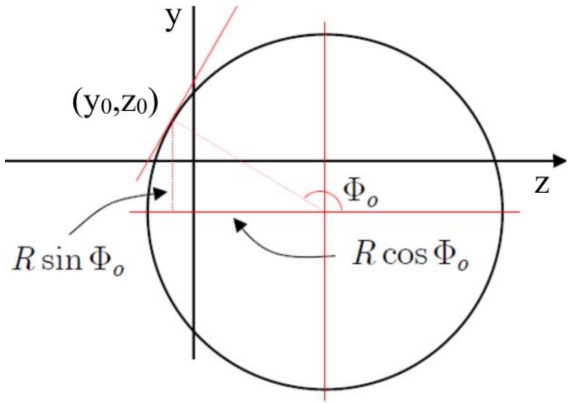
1. Transition Radiation (TR) radiator made of 150 foils of polypropylene;
2. Straw tube layers in a XXYY disposition;
3. Tunable target slab:
   - Polypropylene C_3H_6
   - Graphite C
   - No slab

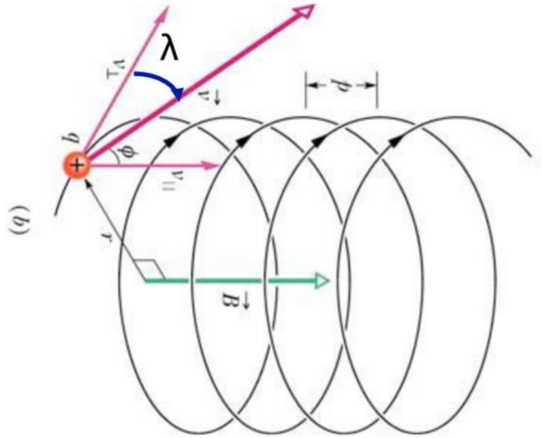
- 90 total modules. Proceeding downstream: 85 modules alternated between the 78 polypropylene ones and the 7 graphite ones + 5 slabless

STT: DIGITIZATION AND RECONSTRUCTION

DIGITIZATION

- Straw tubes provide:
  - Transversal position and time of the passage of the particles
  - Their energy deposit





RECONSTRUCTION

- Elicoidal motion due to the magnetic fieldis split into:
  - Circular: fit on the *yz* plane perpendicular to the magnetic field to obtain radius R and angle Φ_0
  - Linear: fit on $x\rho$ plane to find dip angle λ:

$$x = x_0 + \rho\tan\lambda$$

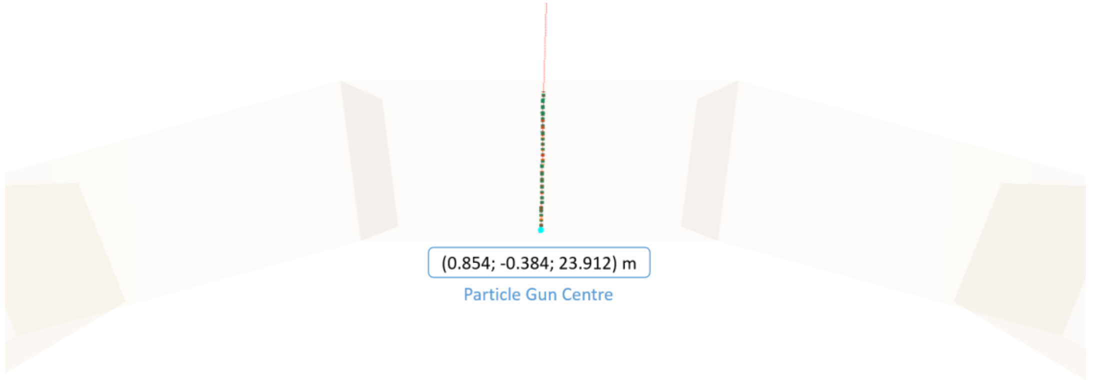
- Transverse momentum:

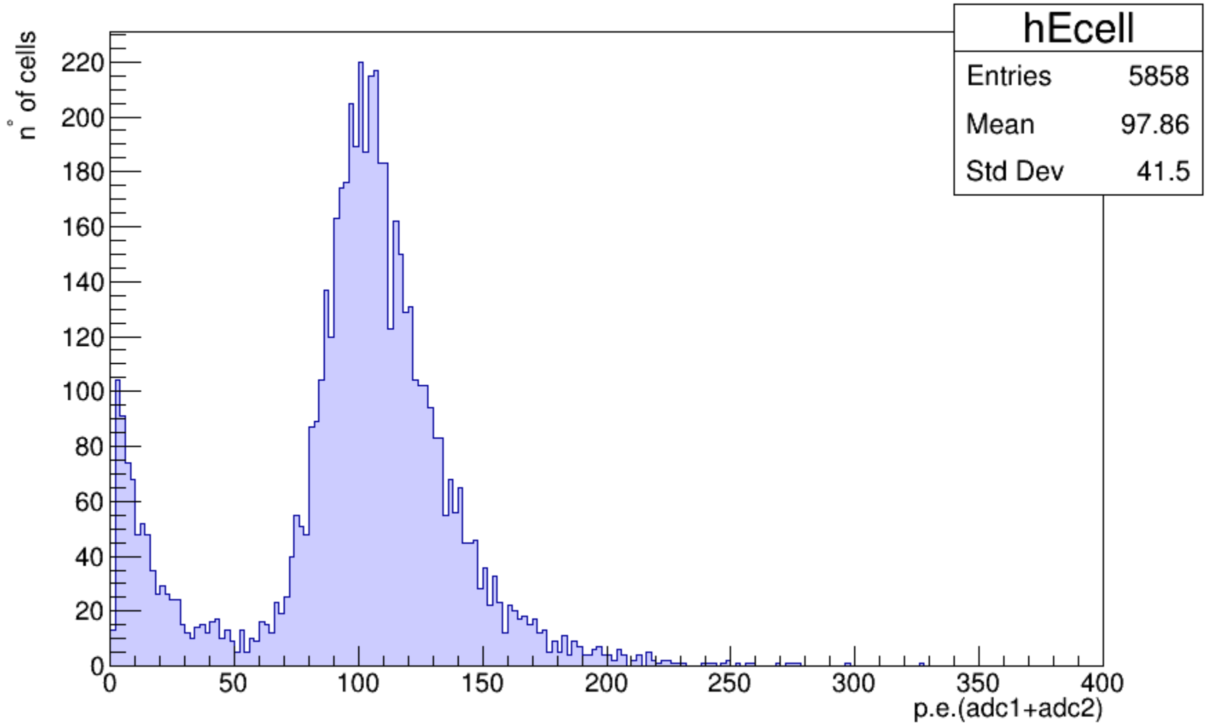
$$p_T[\mathrm{GeV}] = 0.3B[\mathrm{T}]R[\mathrm{m}]$$

- Momentum components:

$$p_x = p_T\tan\lambda$$
$$p_y = p_T\cos\Phi_0$$
$$p_z = p_T\sin\Phi_0$$

PRELIMINARY MEASUREMENT: LIGHT YIELD





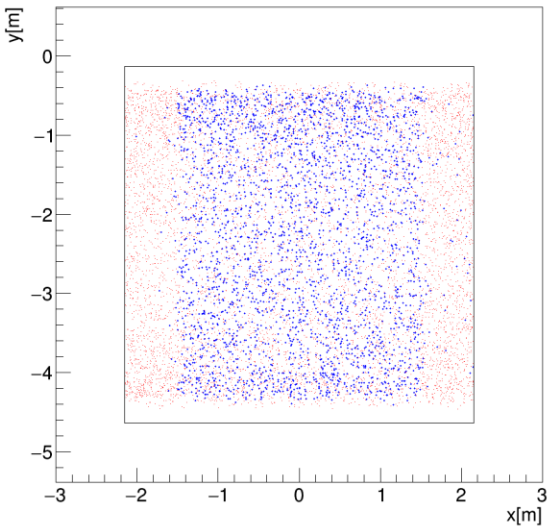
- Simulated 1000 muons at 10 GeV passing through an ECAL barrel module

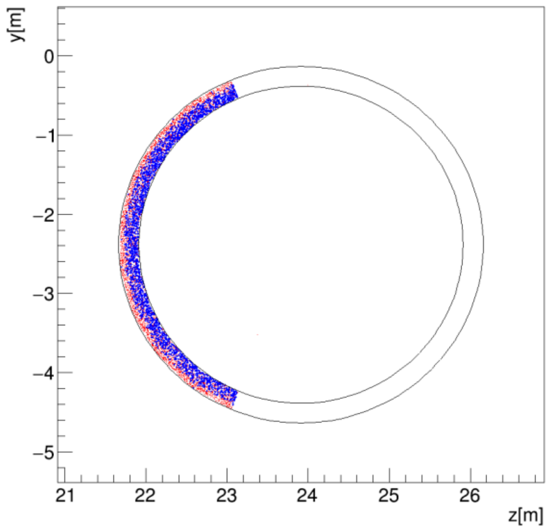
$$\Delta E_{cell} \simeq \left(\frac{dE}{dx}\right)^{MIP} \rho_{Pb} \Delta x_{Pb} + \left(\frac{dE}{dx}\right)^{MIP} \rho_{Sc} \Delta x_{Sc} \simeq 42.22 \text{ MeV}$$

$$N_{p.e.}^{cell} = (97.4 \pm 0.3) \text{ p.e.}$$

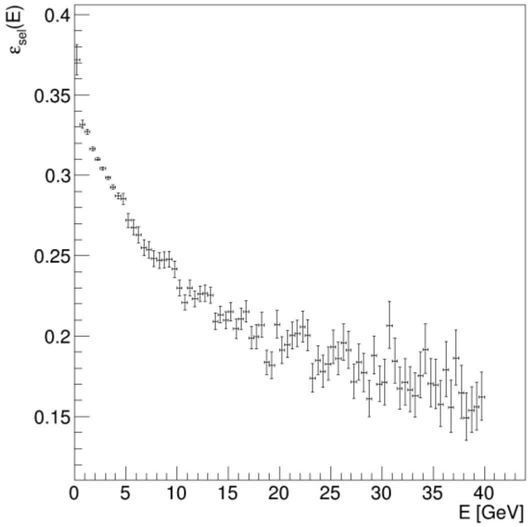
$$c = \frac{N_{p.e.}^{cell}}{\Delta E_{cell}} \simeq 2.31 \; [\text{p.e./MeV}]$$

FIDUCIAL CUT





Note: efficiency decreases at higher energy; might be due to nuclei fragmentation in DIS



FIDUCIAL CUT: eliminate interactions outside SAND + muons not crossing the tracking system

- Threshold on the ADC total on the outer layer for energy deposition $\Delta E_{th} > 15$ MeV:

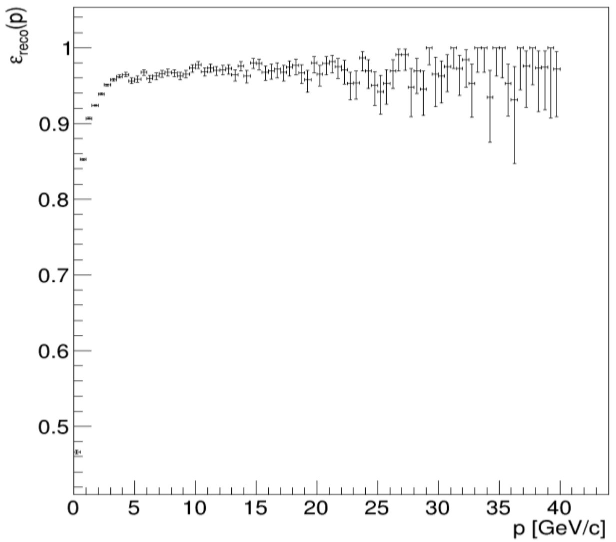
$$N_{p.e.}^{th} = c \times \Delta E_{th} \simeq 35 \text{ p.e.}$$

- X interaction point, estimated as a weighted average on the energy deposition on the cells, is selected as:

$$|x_V| \leq 1.5 \text{ m}$$

$$\varepsilon_{cut} = \frac{N_{fid}}{N_{CC}} = 0.2905 \pm 0.0004$$

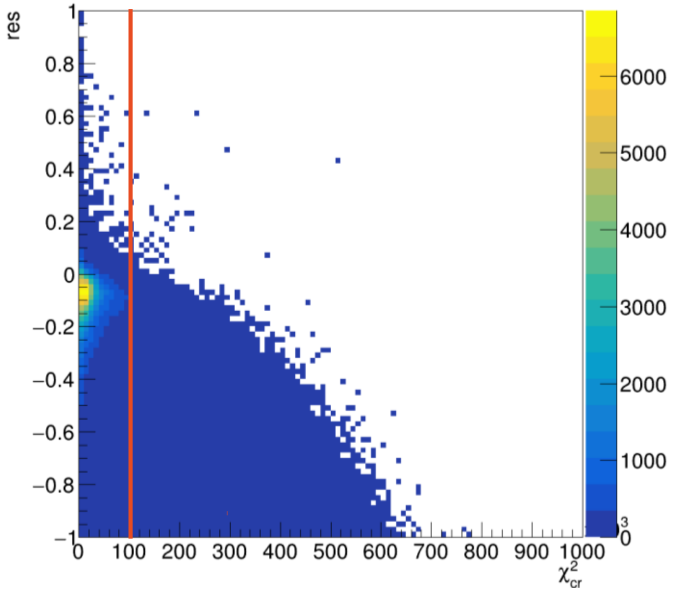
MUON MOMENTUM RECONSTRUCTION AND QUALITY CUT



EFFICIENCY

- Momentum reconstruction efficiency:

$$\varepsilon_{reco} = \frac{N_{reco}}{N_{fid}} = 0.9168 \pm 0.0004$$



QUALITY

$$\chi^2_{cr} = \frac{1}{N_{hits}} \sum_{i=1}^{N_{hits}} |(y_i - y_C)^2 + (z_i - z_C)^2 - R^2|$$

$$res = 1 - p_\mu^{true}/p_\mu^{reco}$$

$$\chi^2_{cr} < 10^5$$

$$\varepsilon_{qual} = \frac{N_{qual}}{N_{reco}} = 0.9290 \pm 0.0004$$

CHI-SQUARED TWO-SAMPLE TEST STATISTICS

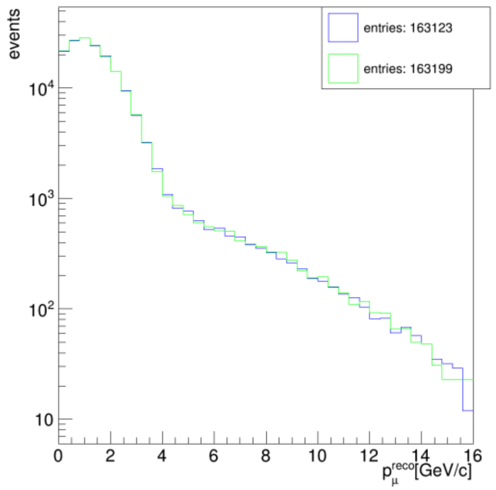
- To compare the distributions obtained from the nominal and shifted sample we use the test statistic:

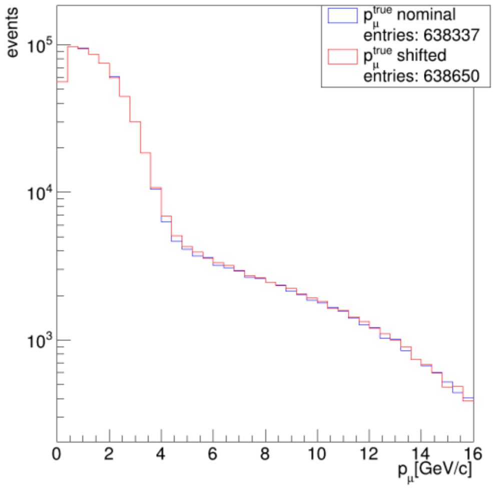
$$\boxed{T = \sum_{i=1}^{k} \frac{(u_i - v_i)^2}{u_i + v_i}}$$

- Where k is the number of bins in the histograms and u_i and v_i are their contents
- T approximately follows a χ^2 distribution

Note: we call nominal and shifted the results obtained with standard and horn-1 displaced neutrino beam respectively

PRELIMINARY ANALYSIS





CHECK

- T applied to the reconstructed momenta from two equal-size samples obtained from nominal beam.

$$p_{control} = 0.527 \qquad \sigma_{control} = 0.633$$

REFERENCE

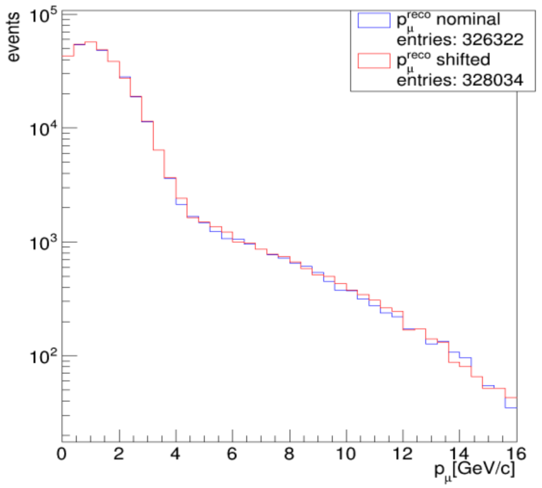
- T applied to the true Monte Carlo momenta from the nominal and shifted samples:

$$p_{truth} = 5.15 \times 10^{-7} \qquad \sigma_{truth} = 5.02$$

RESULTS

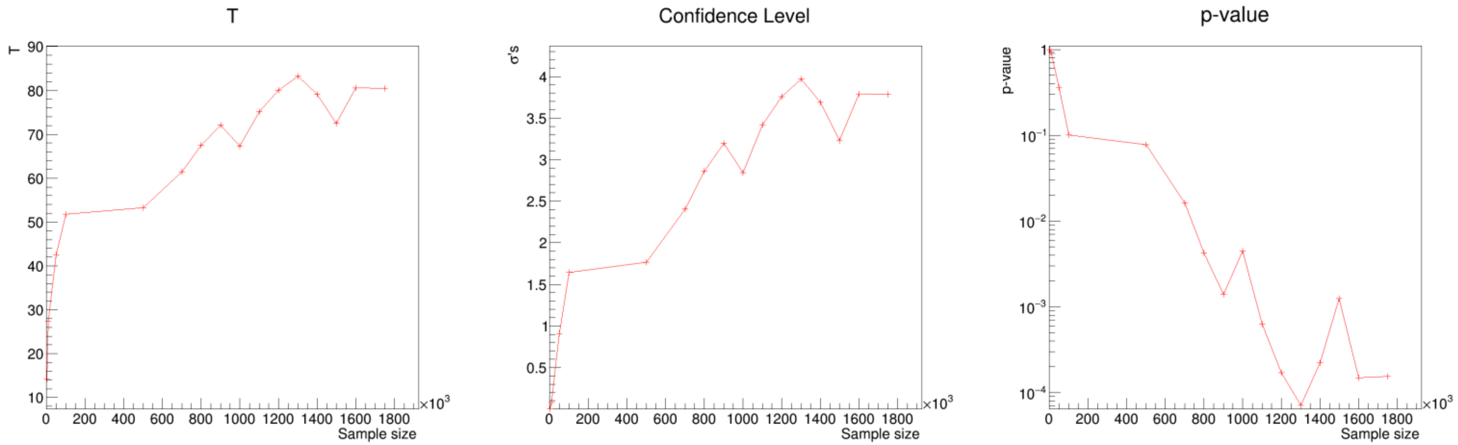
- T applied to nominal and shifted muon momenta samples after all cuts are applied:

$$p_{reco} = 1.55 \times 10^{-4};$$
$$\sigma_{reco} = 3.78$$



- Evolution of p-value with sample size

With a sample $> 1.2 \times 10^6$ we identify the beam anomaly with a confidence level $\geq 3\sigma$



CONCLUSIONS

- DUNE will be a next generation neutrino oscillation Long Baseline accelerator experiment aiming at measuring CP violation and mass ordering
- One essential component will be the beam monitoring (SAND) which will exploit KLOE's magnet and e.m. calorimeter
- In this thesis, I studied the beam monitoring capabilities of the SAND detector, comparing on a weekly basis the muon momentum distribution, from a sample in standard conditions (nominal) and one where an anomaly was introduced (shifted)
- After defining a fiducial volume and quality selection SAND will be able to exclude the nominal beam hypothesis with a confidence level corresponding to $\sim 3.8\sigma$
- With a sample $> 1.2 \times 10^6$ we identify the beam anomaly with a confidence level $\geq 3\sigma$
- The result can be improved:
  - Include neutrino interactions in the STT;
  - Optimize fiducial and quality cuts;
  - Consider also the possible modification of the shape of the beam studying the geometric distribution of interaction points;