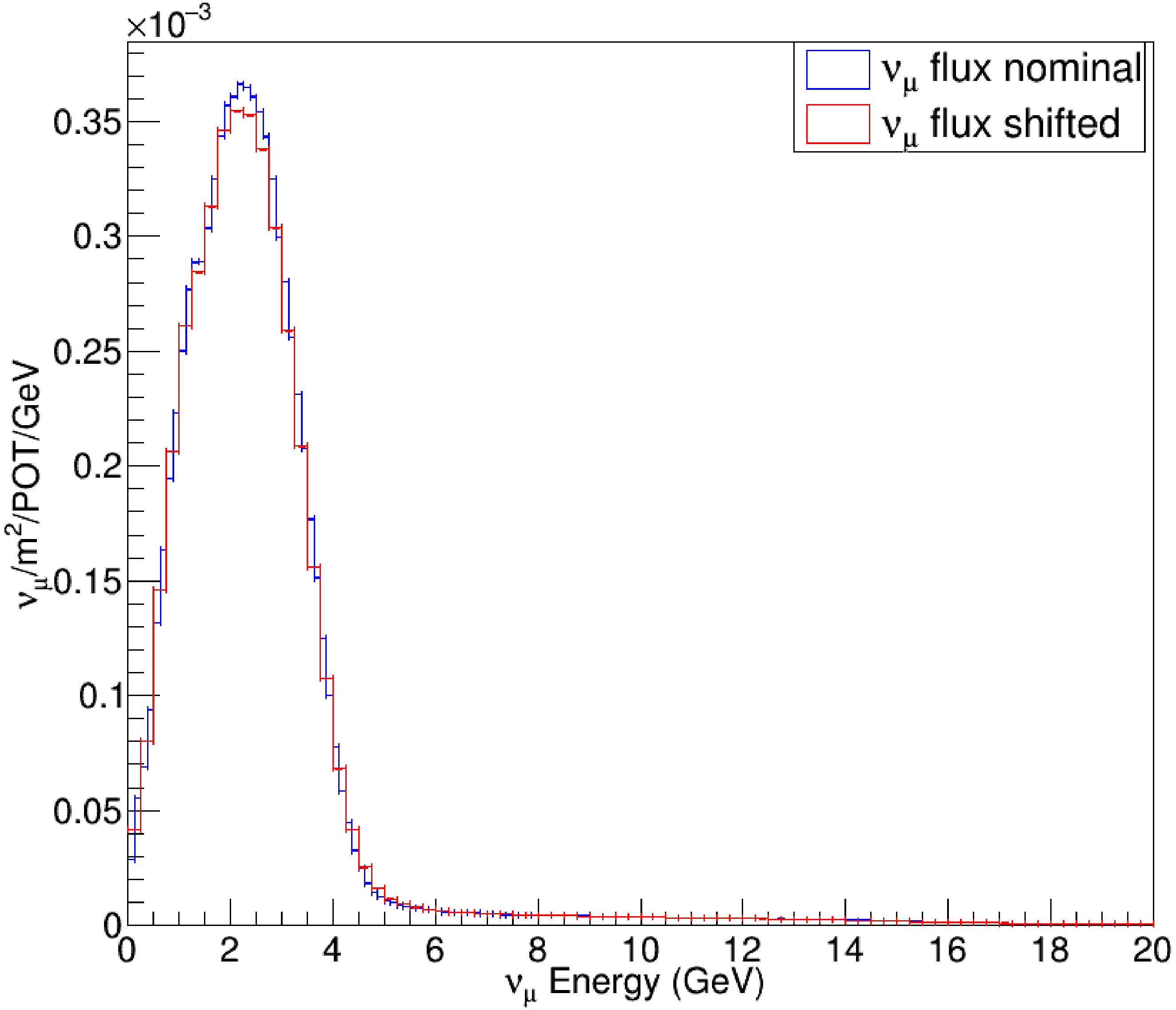
BEAM MONITORING WITH SAND

- My thesis studied the beam monitoring capabilities of the SAND detector, via the comparison of the distribution of an observable sensitive to beam anomalies
- **Observable:** reconstructed muon momentum
- **First systematic:** horn-1 0.5 mm Y shift
- **Test statistics:** $T \sim \chi^2$

SIMULATED SAMPLES

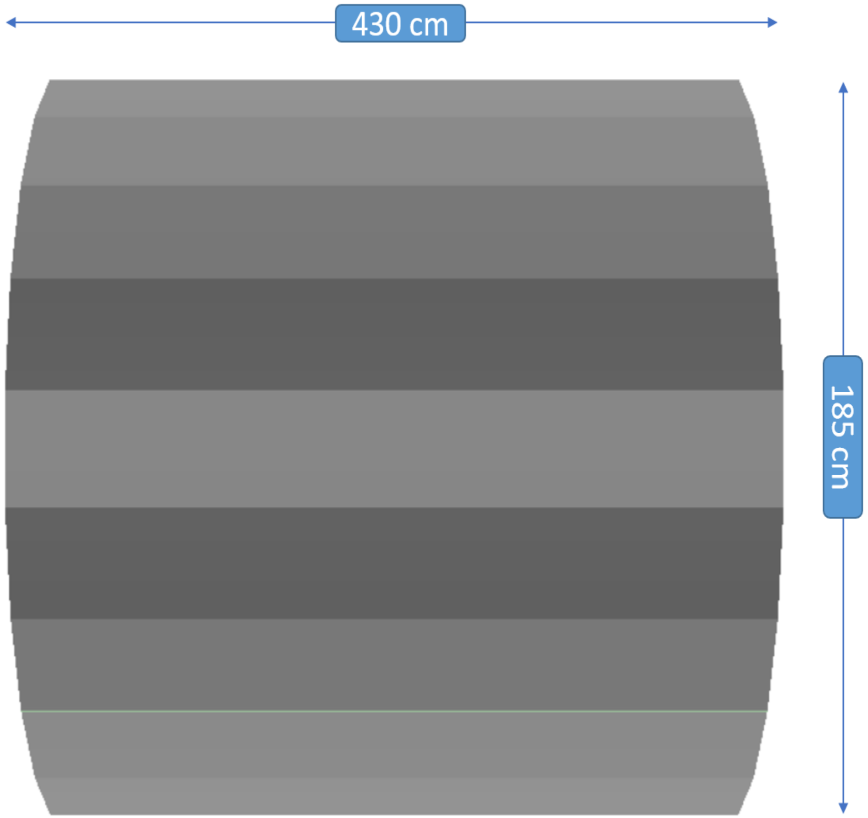


Simulated samples from :

- **Nominal** neutrino flux
- **Shifted** neutrino flux (Y +0.5mm in the first beam horn)

Note : Histograms retrieved from https://home.fnal.gov/~ljf26/DUNEFluxes

TARGET: FRONT CALORIMETERS



- *Dunendggd* simulated geometry
- Target: 9 front calorimeter barrel modules

$$N_{week} = r_{CC} \times f_{CC}^{-1} \times m_{mod} \times n_{mod}$$
$$= \left(4.865 \times 10^5 ev\left[\nu_\mu(CC)\right]/ton/week\,\right) \times (2/3)^{-1} \times (2.75\ ton) \times (9)$$
$$\simeq 1.75 \times 10^6$$

One week's worth of statistics

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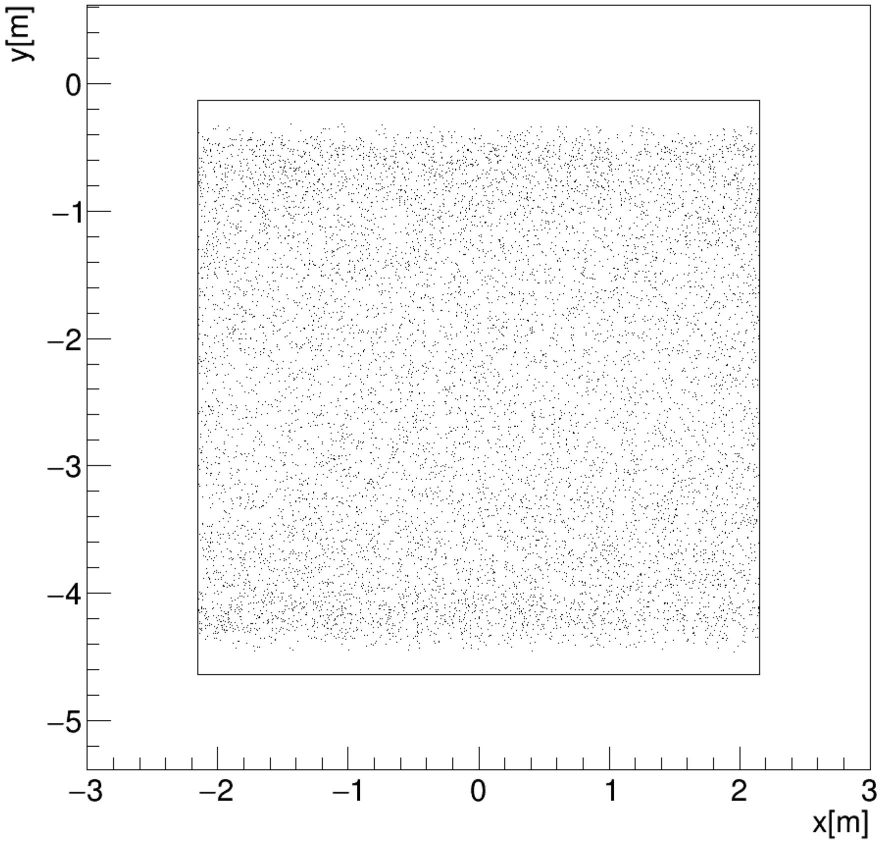

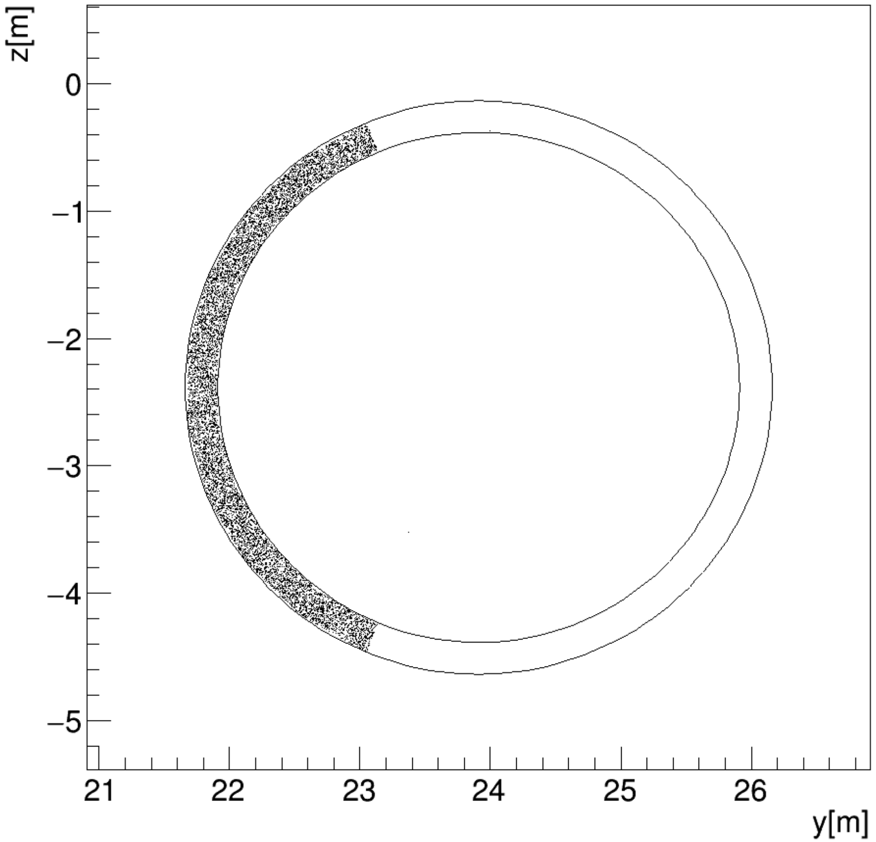

- Interaction vertex distributions on the *xy* and *yz* planes

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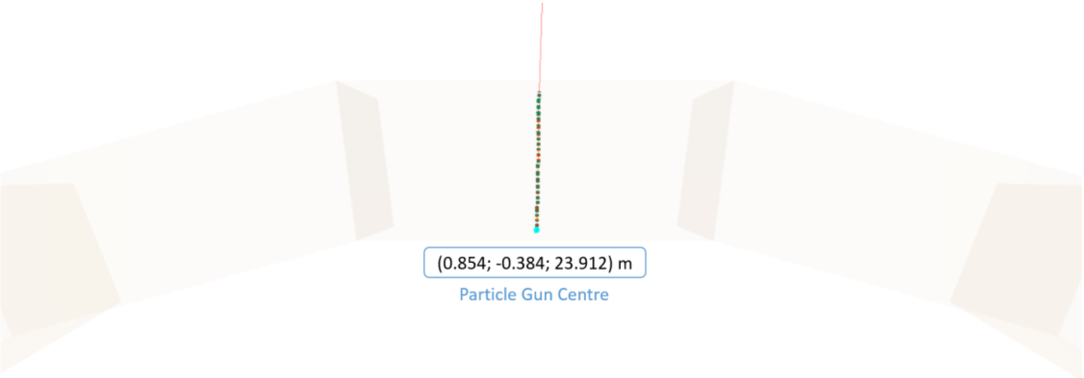
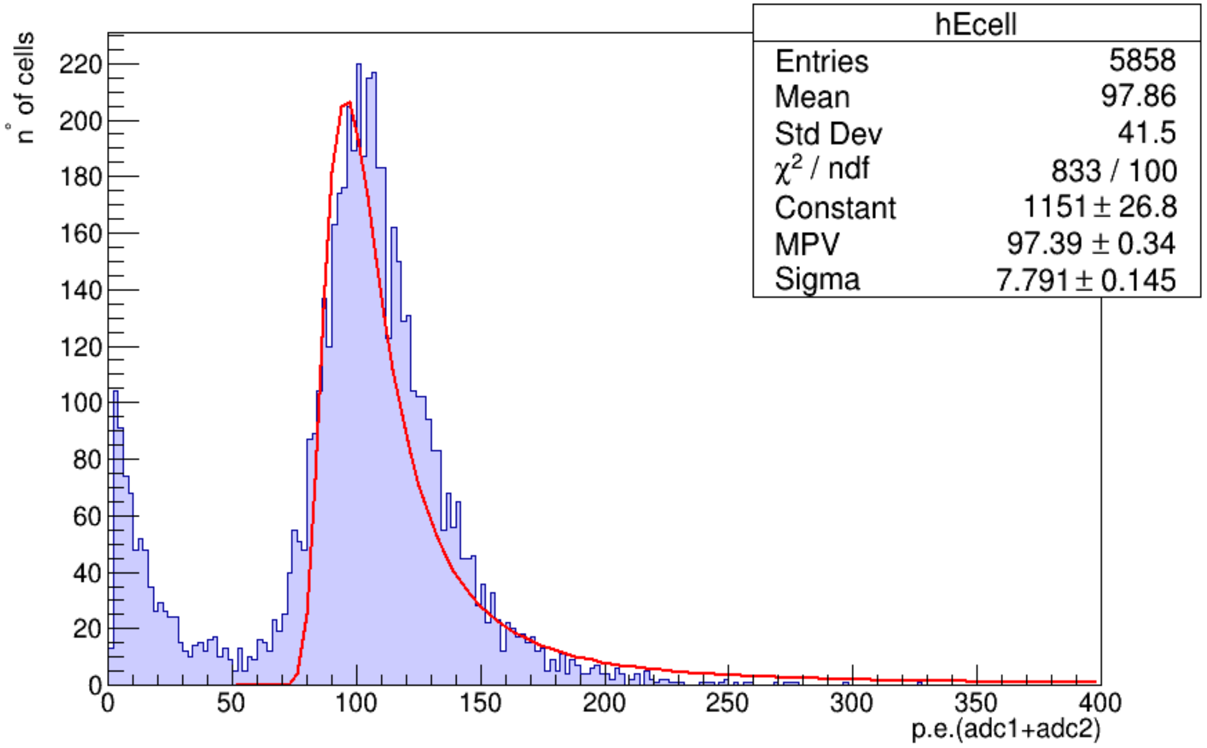
PRELIMINARY MEASUREMENT: LIGHT YIELD





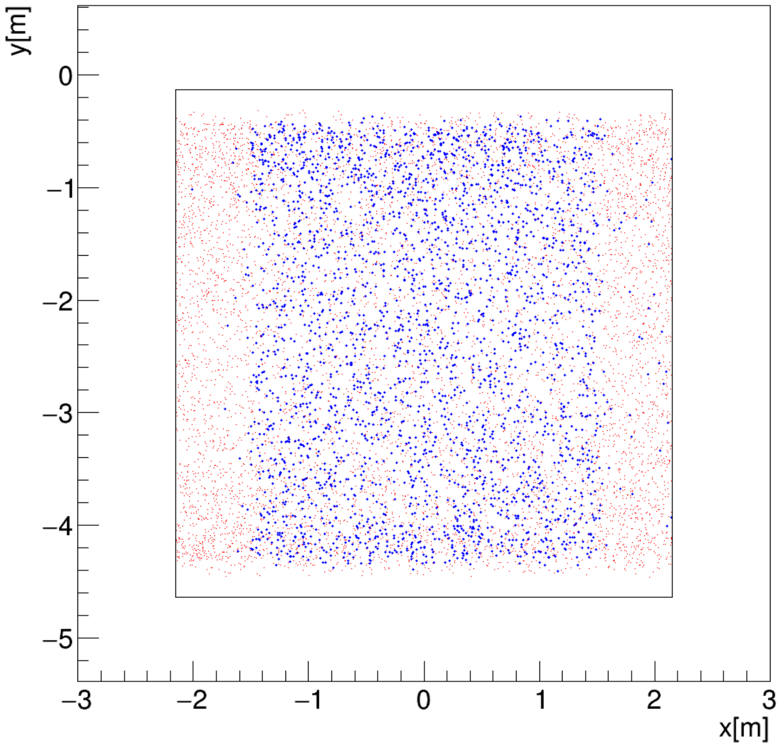
- Simulated 1000 muons at 10 GeV passing through an ECAL barrel module

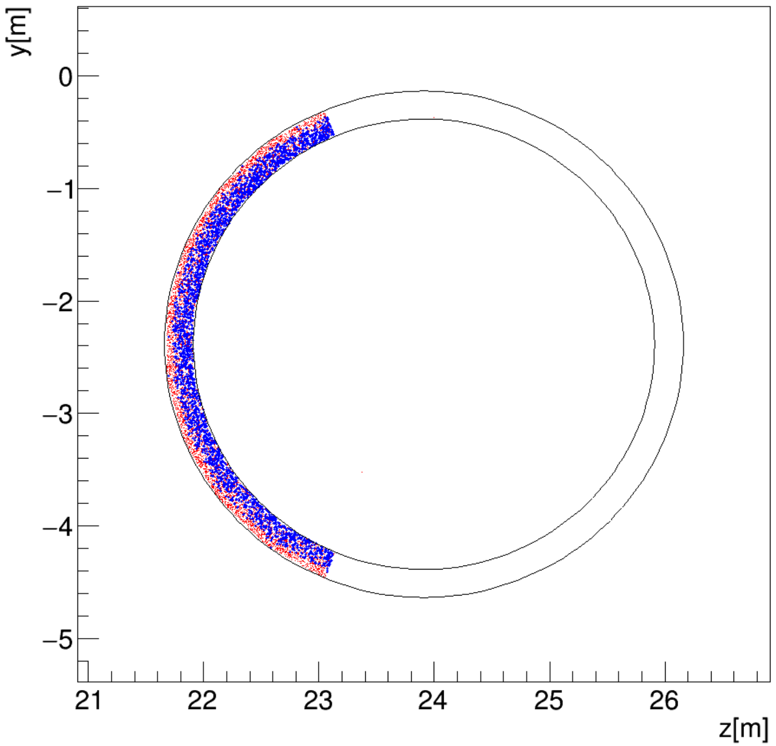
$$\Delta E_{cell} \simeq \left(\frac{dE}{dx}\right)^{MIP} \rho_{Pb}\Delta x_{Pb} + \left(\frac{dE}{dx}\right)^{MIP} \rho_{Sc}\Delta x_{Sc} \simeq 42.22 \text{ MeV}$$

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

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

FIDUCIAL CUTS





- Threshold on the energy deposition on the outer layer (E < 15MeV):

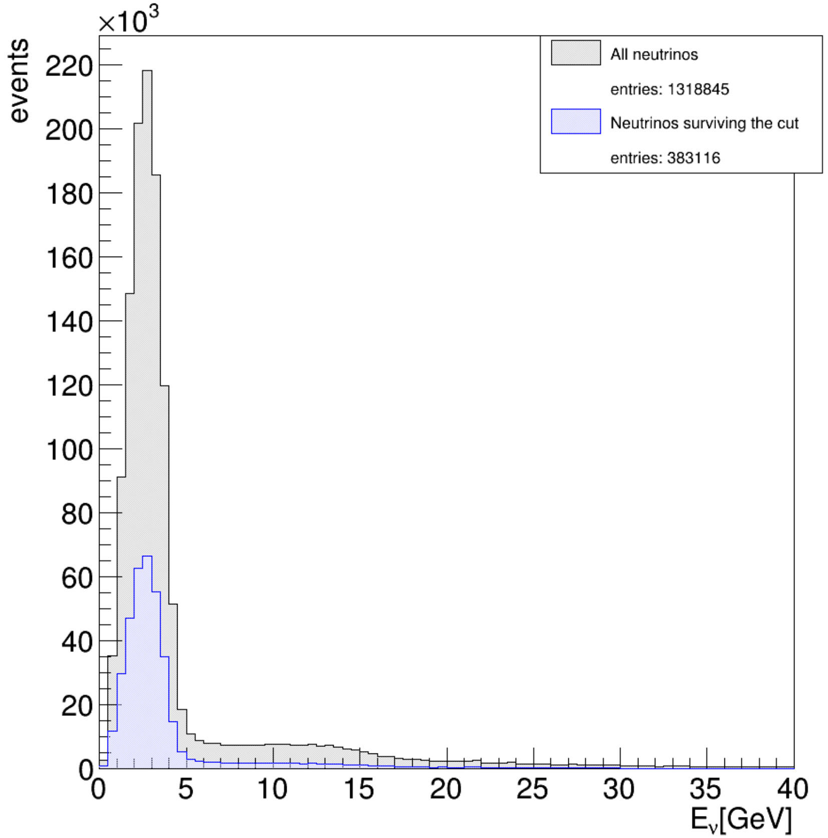
$$N_{p.e.}^{th} = c \times \Delta E_{th} \simeq 35 \text{ p.e.}$$

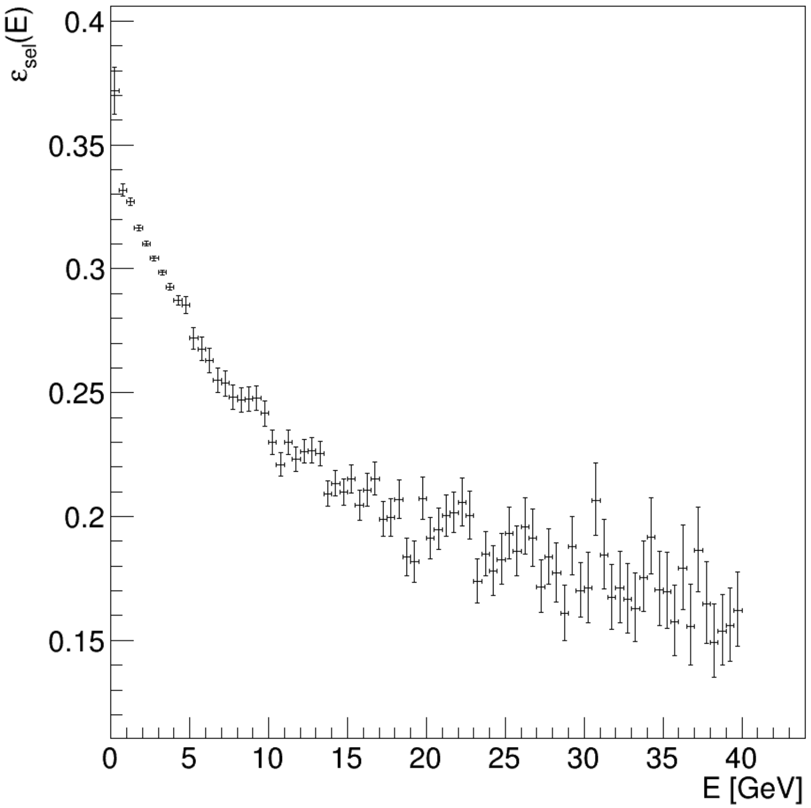
- X vertex, estimated as a weighted average on the energy deposition on the cells, is selected as:

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

Spatial distribution in ND hall global coordinates of the true neutrino interaction vertexes of the events that survive the fiducial cut (blue) and those that don’t (red).

FIDUCIAL CUT





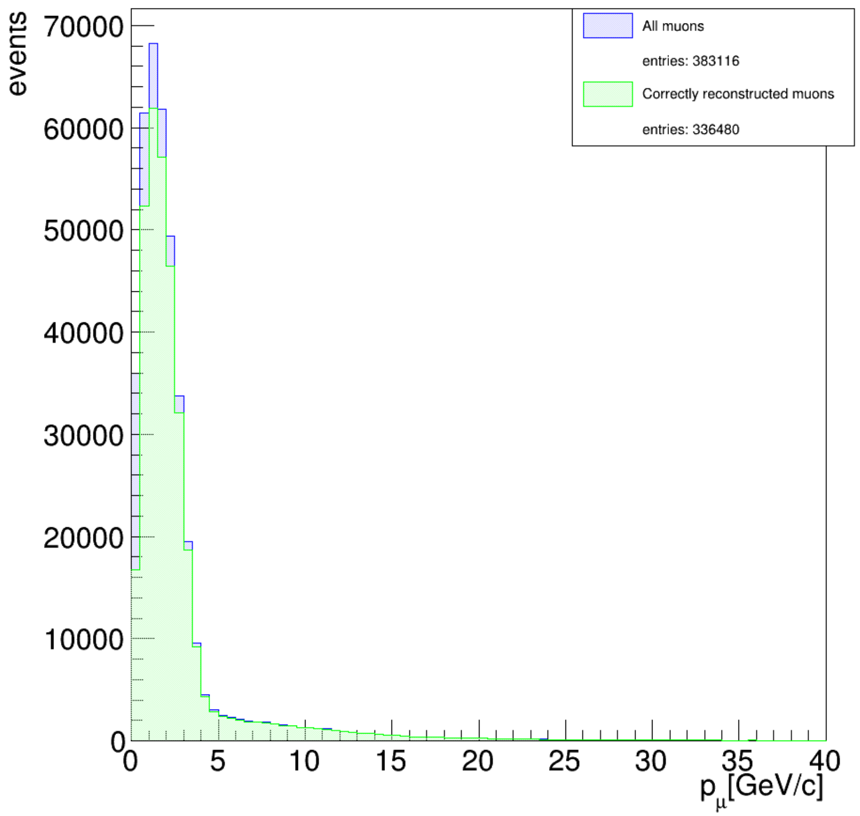
- Selection efficiency:

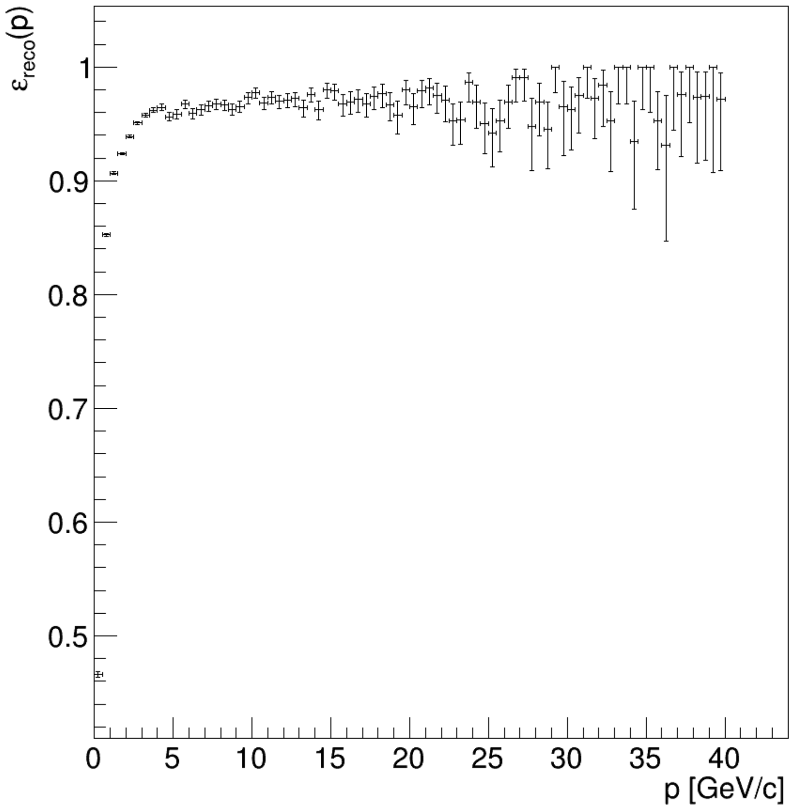
$$\varepsilon_{cut} = \frac{N_{fid}}{N_{CC}} = 0.2905 \pm 0.0004$$

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

(*Left*) Energy (Monte Carlo truth) distribution of neutrinos from the CC nominal sample (grey); distribution surviving the fiducial cut (blue).
(*Right*) Selection efficiency as a function of neutrino energy from the Monte Carlo truth.

MOMENTUM RECONSTRUCTION SELECTION



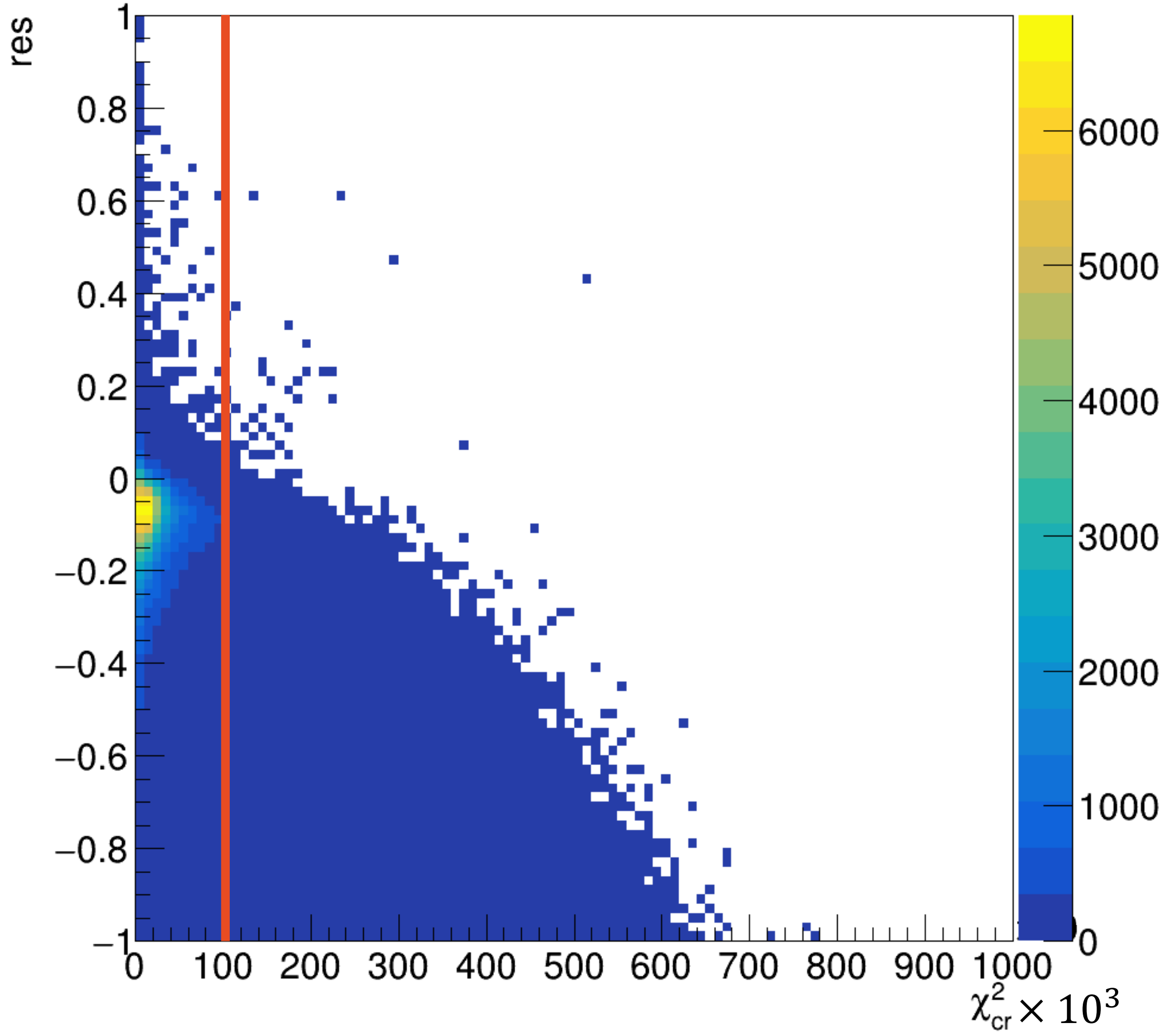


- Momentum reconstruction efficiency:

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

(*Left*) Distributions of the true Monte Carlo momenta of the muons from the fiducial sample (blue) and only the ones correctly reconstructed (green).
(*Right*) Reconstruction algorithm efficiency as a function of the true Monte Carlo muon momentum

MOMENTUM RECONSTRUCTION QUALITY SELECTION



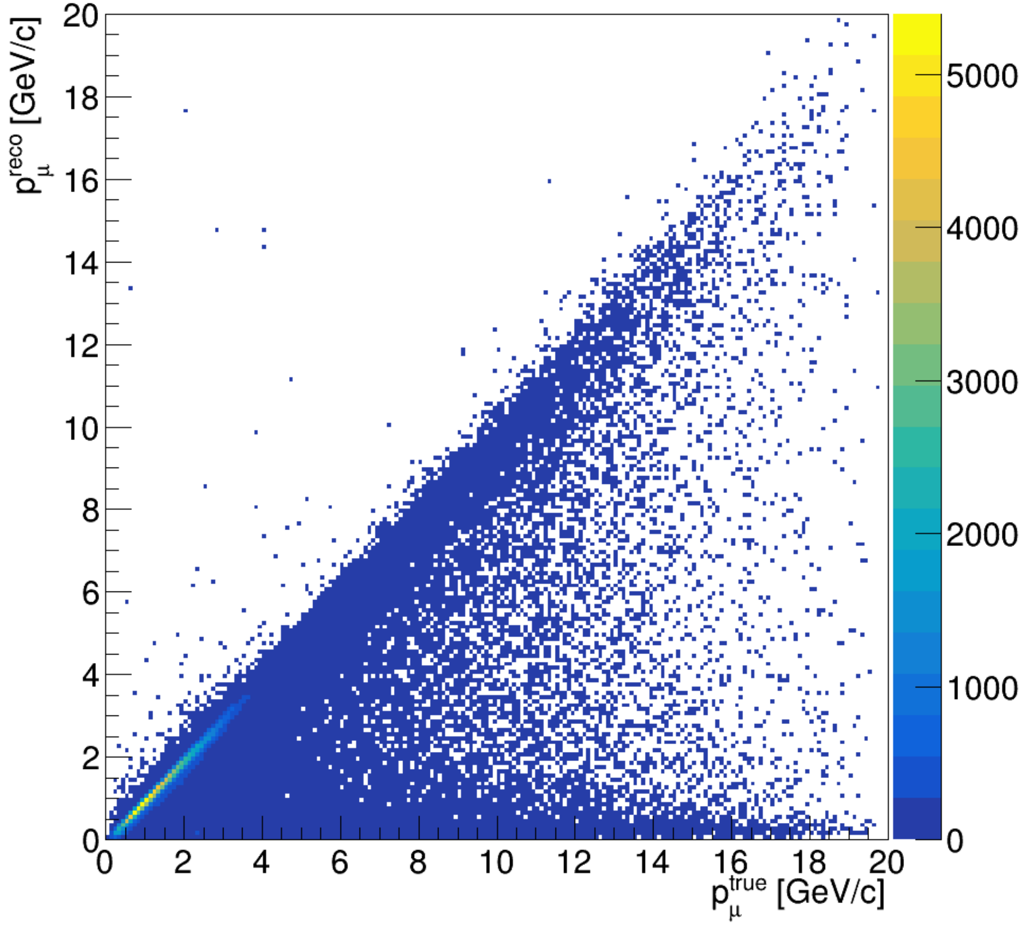
$$\chi^2_{cr} = \frac{1}{N_{hits}} \sum_{i=1}^{N_{hits}} |(y_i - y_C)^2 + (z_i - z_C)^2 - R^2|$$

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

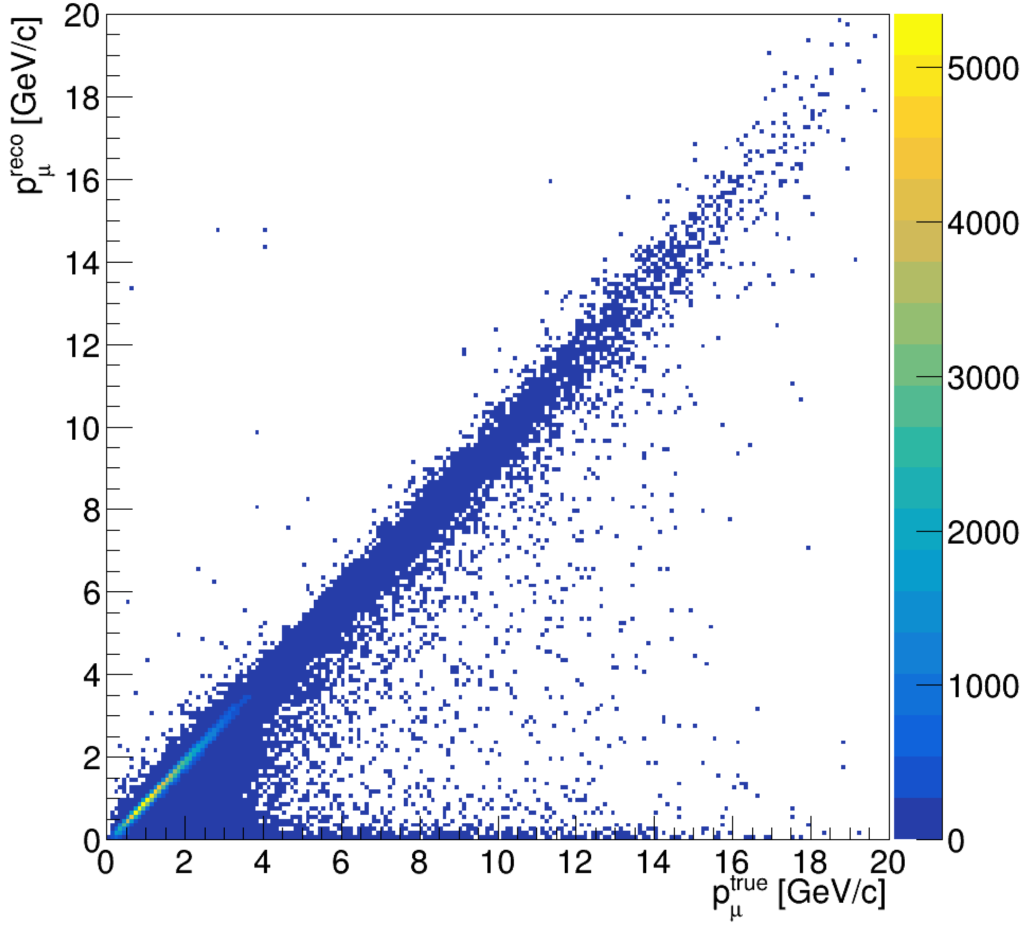
$$\chi^2_{cr} < 10^5$$

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

MOMENTUM RECONSTRUCTION QUALITY SELECTION



BEFORE CUT



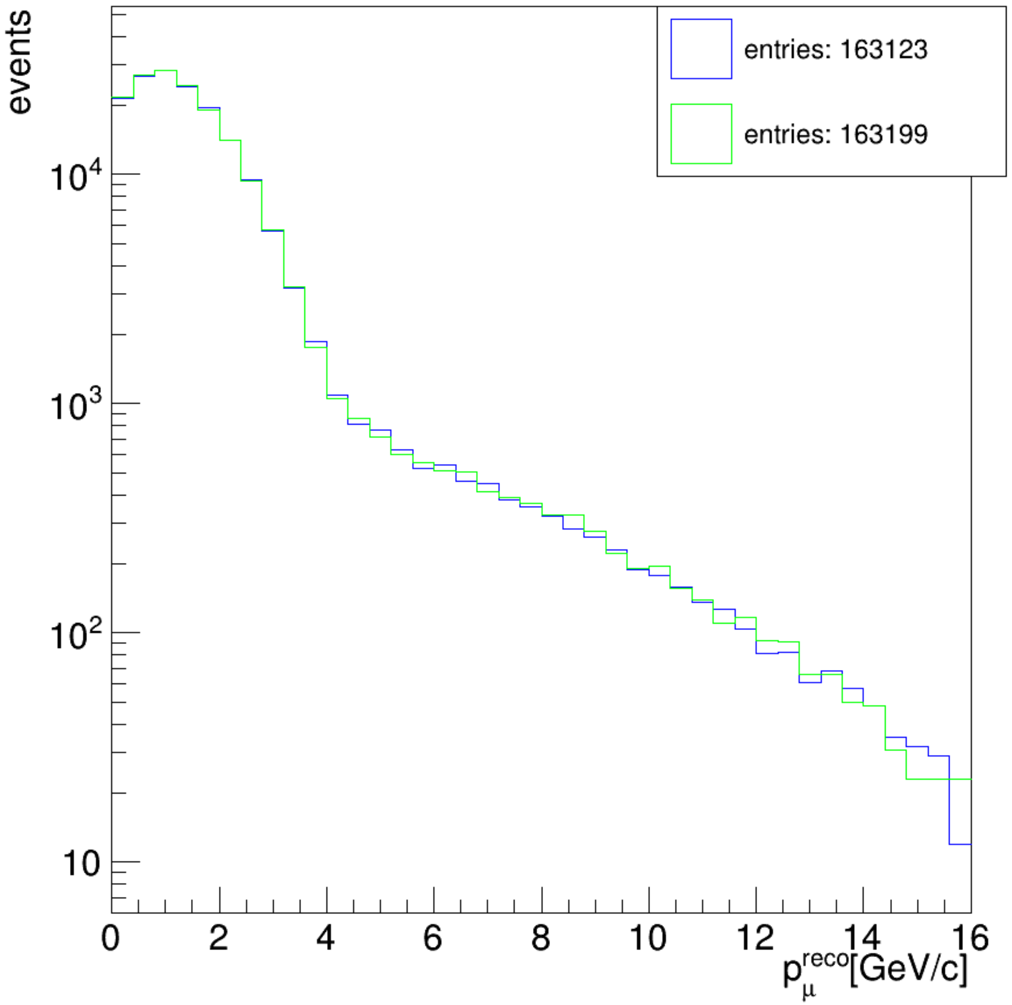
AFTER CUT

CHI-SQUARED TWO-SAMPLE TEST STATISTICS

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

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

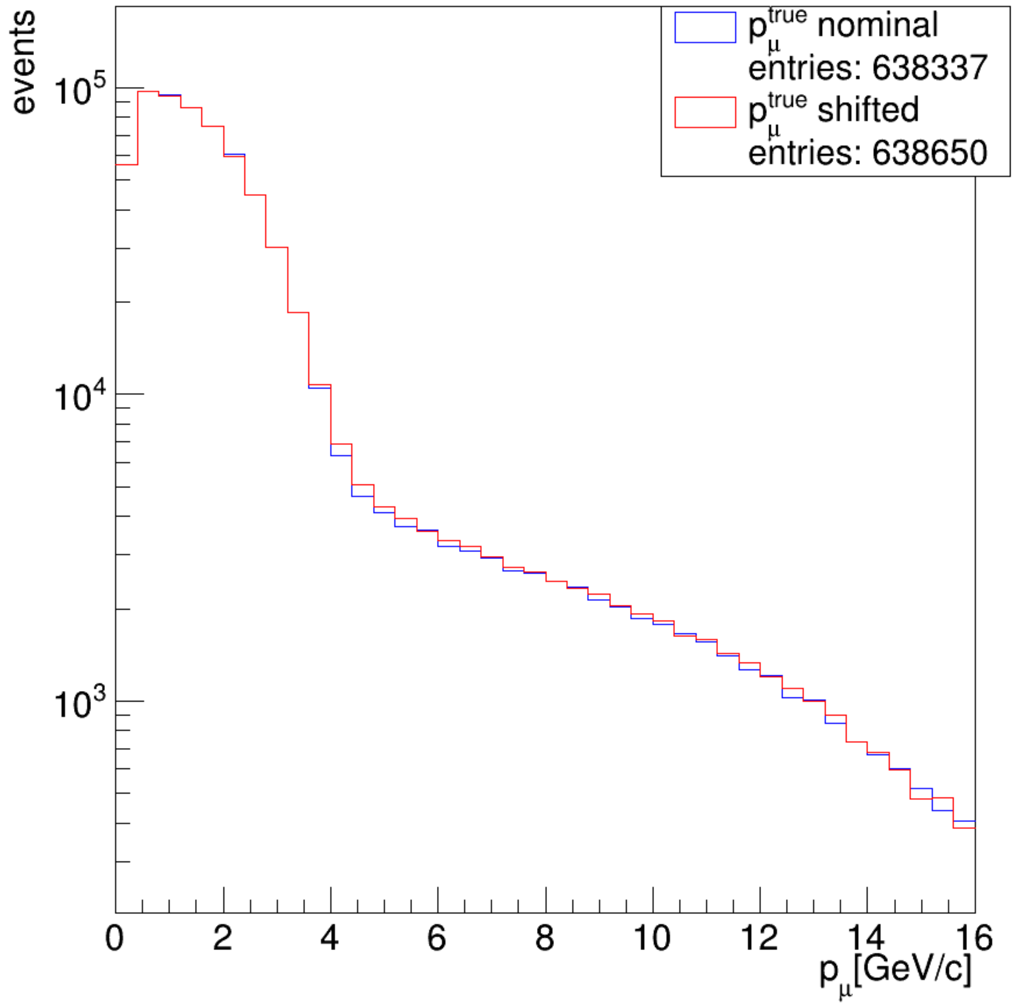
CONSISTENCY CHECK: TWO NOMINAL SAMPES



- We apply the T two equally large nominal samples ($\sim 0.8 \times 10^6$ events):

$$p_{control} = 0.527; \quad \sigma_{control} = 0.633 \ (\chi^2)$$

CONSISTENCY CHECK: IDEAL DETECTOR

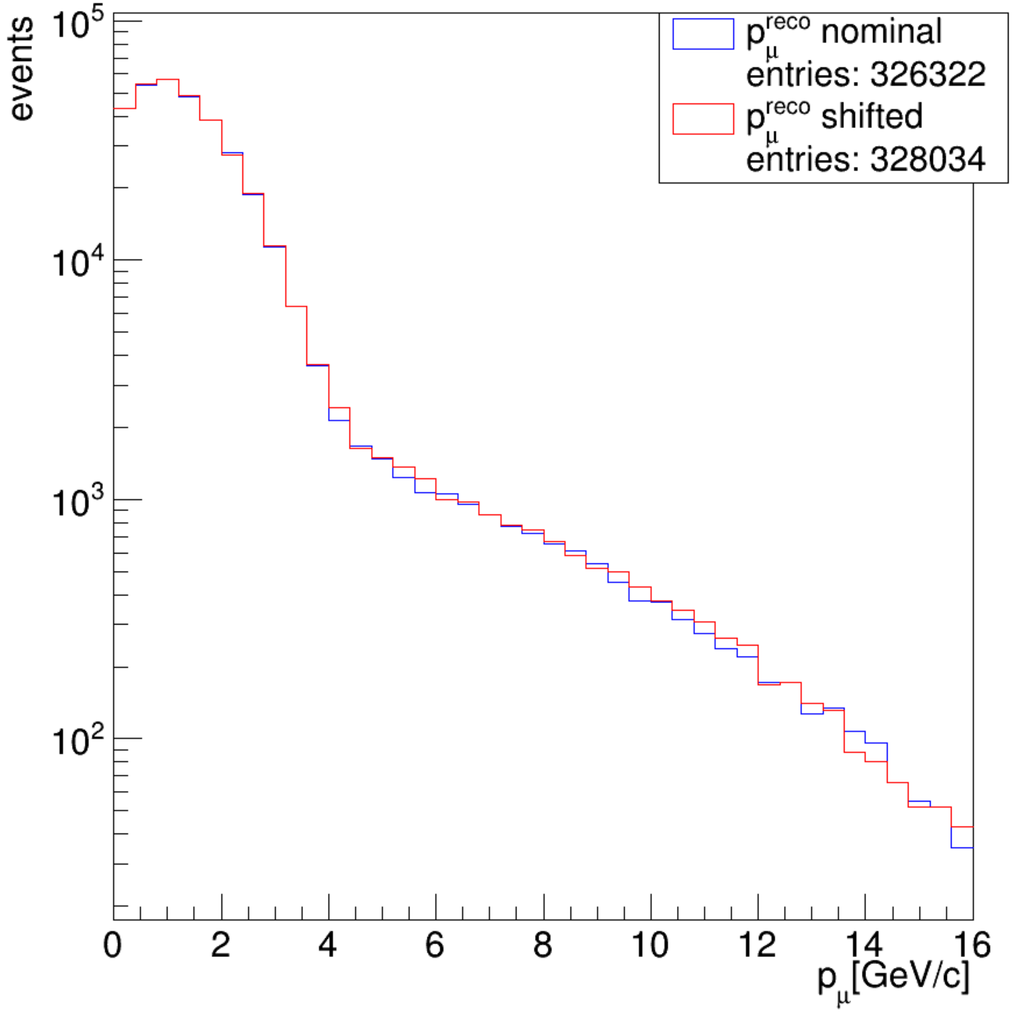


- We applied T the test to the true Monte Carlo momenta from the nominal and shifted samples.
- A fiducial cut was applied by selecting events whose true interaction position was in the fiducial volume
- This was done in order to gauge what the best possible p-value (i.e. the smallest and most decisive) might be:

$$p_{truth} = 5.15 \times 10^{-7}; \quad \sigma_{truth} = 5.02\ (\chi^2)$$

Note: in principle no p-value should be smaller than p_{truth}

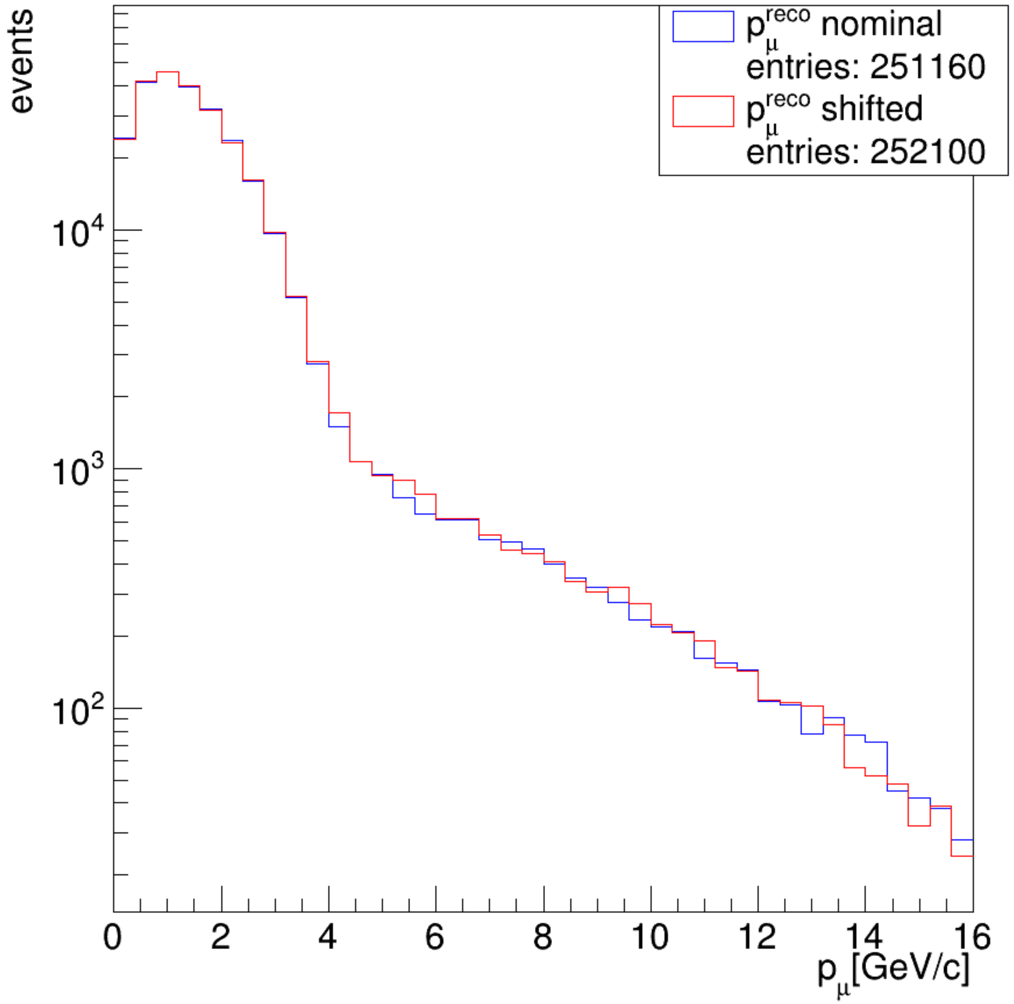
RESULTS: FIDUCIAL + RECONSTRUCTION



$$p_{reco} = 1.55 \times 10^{-3};$$

$$\sigma_{reco} = 3.17$$

RESULTS: FIDUCIAL + RECONSTRUCTION + QUALITY

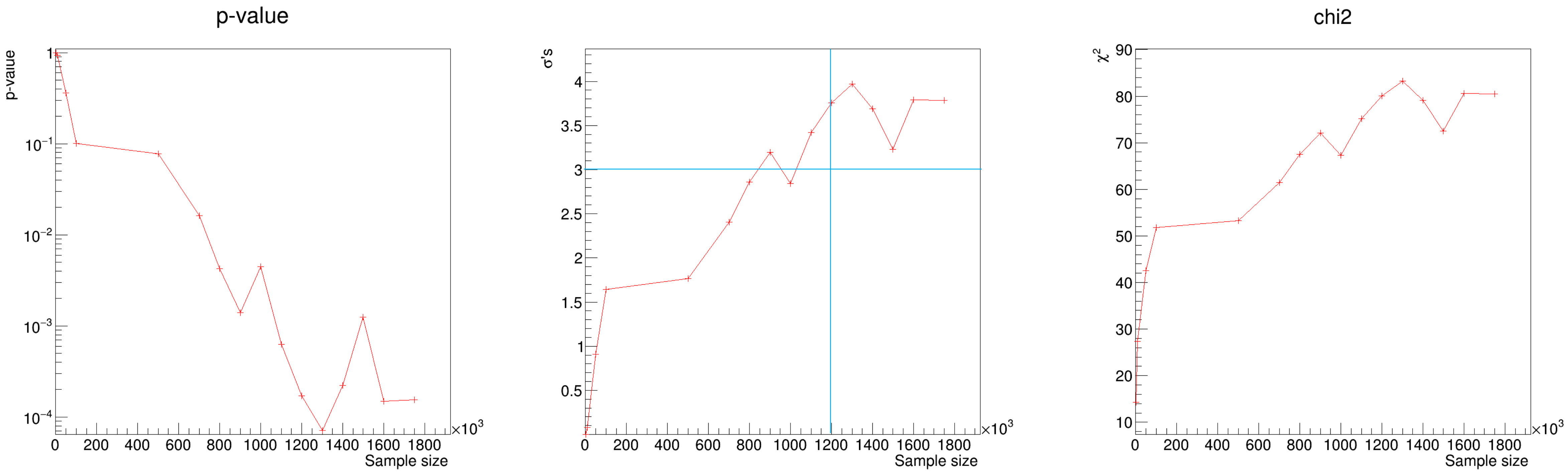


We repeat the procedure by applying the quality cut to both samples:

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

$$\sigma_{reco} = 3.78$$

P-VALUE EVOLUTION WITH THE SAMPLE



- As we should expect, as the samples become larger the χ^2 and number of σ's increase, while the p-value decreases.
- With a sample grater than 1.2 million events, comparable to (even if smaller) that the one expected during a week of data taking, is possible to identify the beam anomaly with a confidence level corresponding to more than 3σ

CONCLUSIONS

- 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)
- We observed that in the case of a perfect detector with a perfect reconstruction, (i.e. using the Monte Carlo “truth”), the significance of the difference among the nominal and shifted samples is around 5σ
- Using reconstructed quantities, fiducial volume and quality selection we reach $\sim 3.8\sigma$ confidence level
- The result can be improved: for example include neutrinos with interactions in the STT, or consider the reconstructed position on the *xy* plane of the interaction vertexes, both in the front calorimeters and the STT.

EXTRA

ECAL: DIGITIZATION AND RECONSTRUCTION

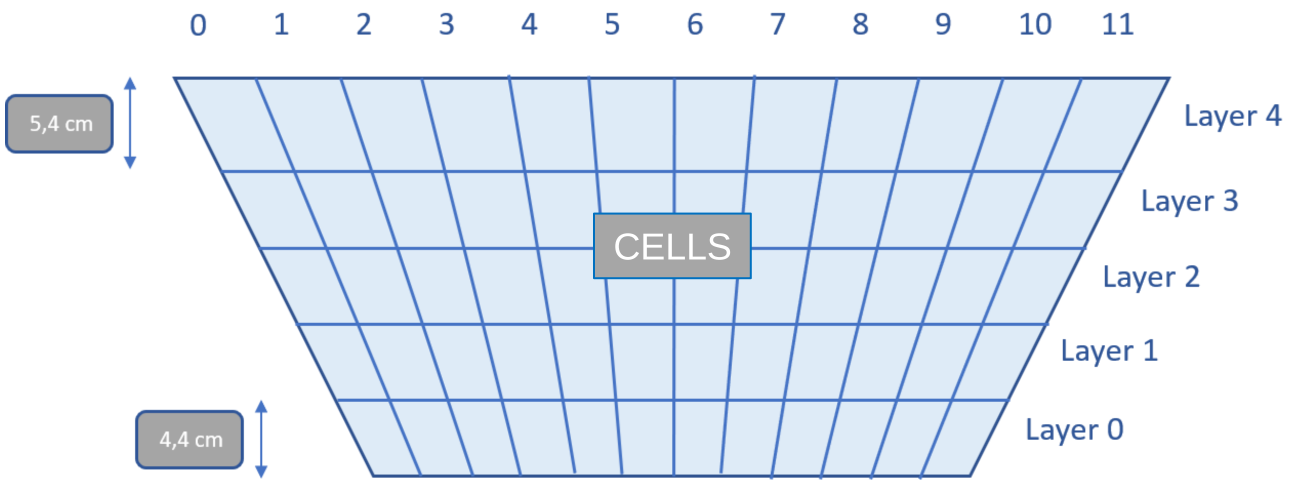
DIGITIZATION

- Calorimeter read-out is segmented in cells (~ $4.5 \times 4.5\ \text{cm}^2$) 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:

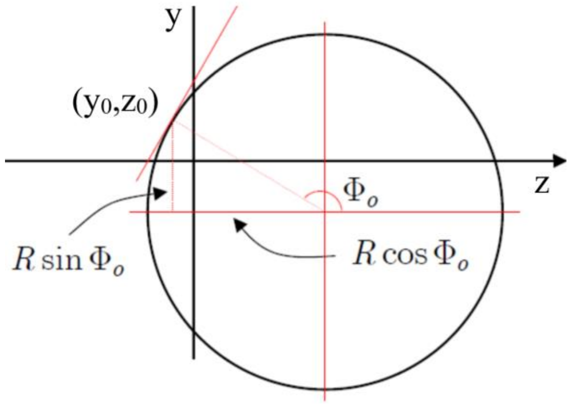
$$x = \frac{t_{TDC1} - t_{TDC2}}{2u_{p.e.}} + x_{cell};$$

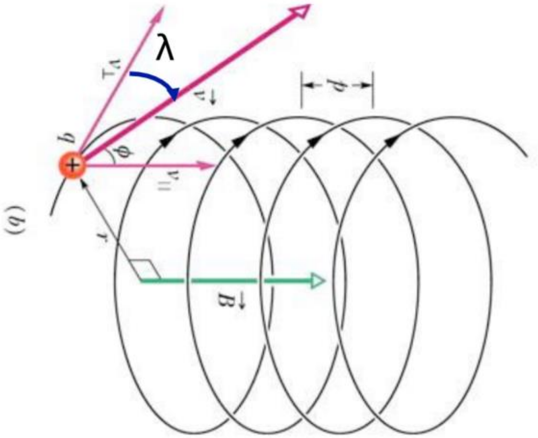
$$t = (t_{TDC1} + t_{TDC2} - u_{p.e.} \times L);$$

STT: 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:

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

- Momentum components:

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