DONUT : Neutrino Analysis techniques

Direct **O**bservation of the **NUT**au

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OUTLINE

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- **Neutrino Event Selection**
  - Goal - Method
  - Results
- **Neutrino Event Classification**
  - Goal - Method & Current Status
  - Preliminary Results
- **Scintillating Fiber System Clustering**
  - Method
  - Results
- **Vertex Prediction**
  - Method & Results
- **Conclusions - Ongoing Work**

-Direct Observation of the ν_τ-

- Weak Isospin Lepton Doublets:

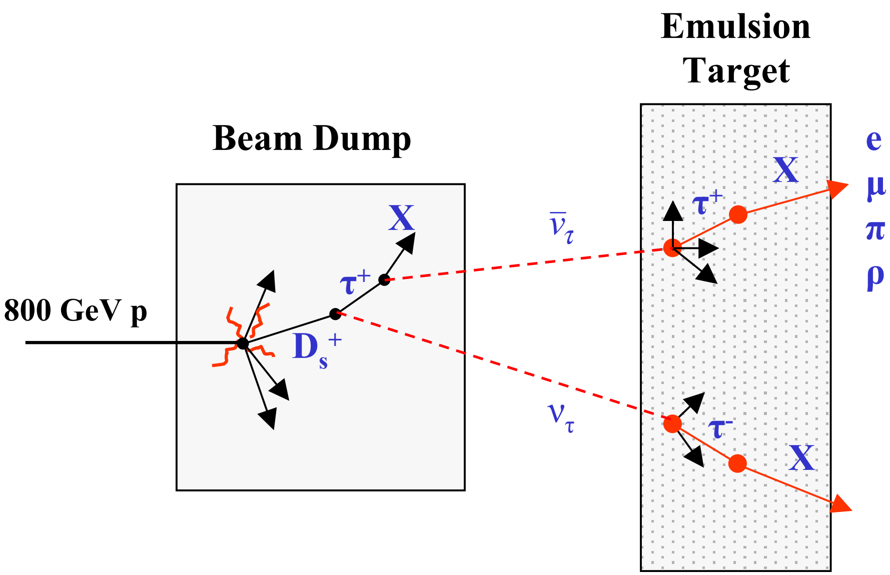
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

- The ν_τ was not directly observed, the way the other two neutrinos have, through its CC interactions although there was plenty of indirect evidence that the tau lepton has a neutral, spin 1/2 weak isospin partner.

- E872 Experiment : Direct Observation of the Tau Neutrino :

$$\nu_\tau + N \rightarrow \tau^- + X$$

-How the experiment is done-



- **Direct observation of the ν_τ :**

$$\nu_\tau + N \rightarrow \tau^- + X$$

- **Detection of the ν_τ- Tau decay topology :**
  - $\gamma c \tau \approx 2mm$ decay angle ≈ 50mrad
  - 86 % of its decays produce only one charged particle.

- **Production of the neutrino beam :**

$$p + N \rightarrow D^+{}_s + X$$
$$\hookrightarrow \tau^+ + \nu_\tau$$
$$\hookrightarrow \bar{\nu}_\tau + \ldots$$

neutrino beam : 5 % ν_τ - 95 % ν_μ, ν_e

-The DONUT Collaboration -

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- **University of Athens group :**
  - C.Andreopoulos, N.Saoulidou, P.Stamoulis, G.Tzanakos
- **Projects :**
  - Electromagnetic Calorimeter
  - Analysis of experimental data

-Analysis Flow for the Experiments Data-

6.6 M Triggers on Tapes

4 M Physics Triggers

50 K Stripped Events

898 Neutrino Events

(reconstructed vertex)

Emulsion Scanning

Vertex Location & Decay search

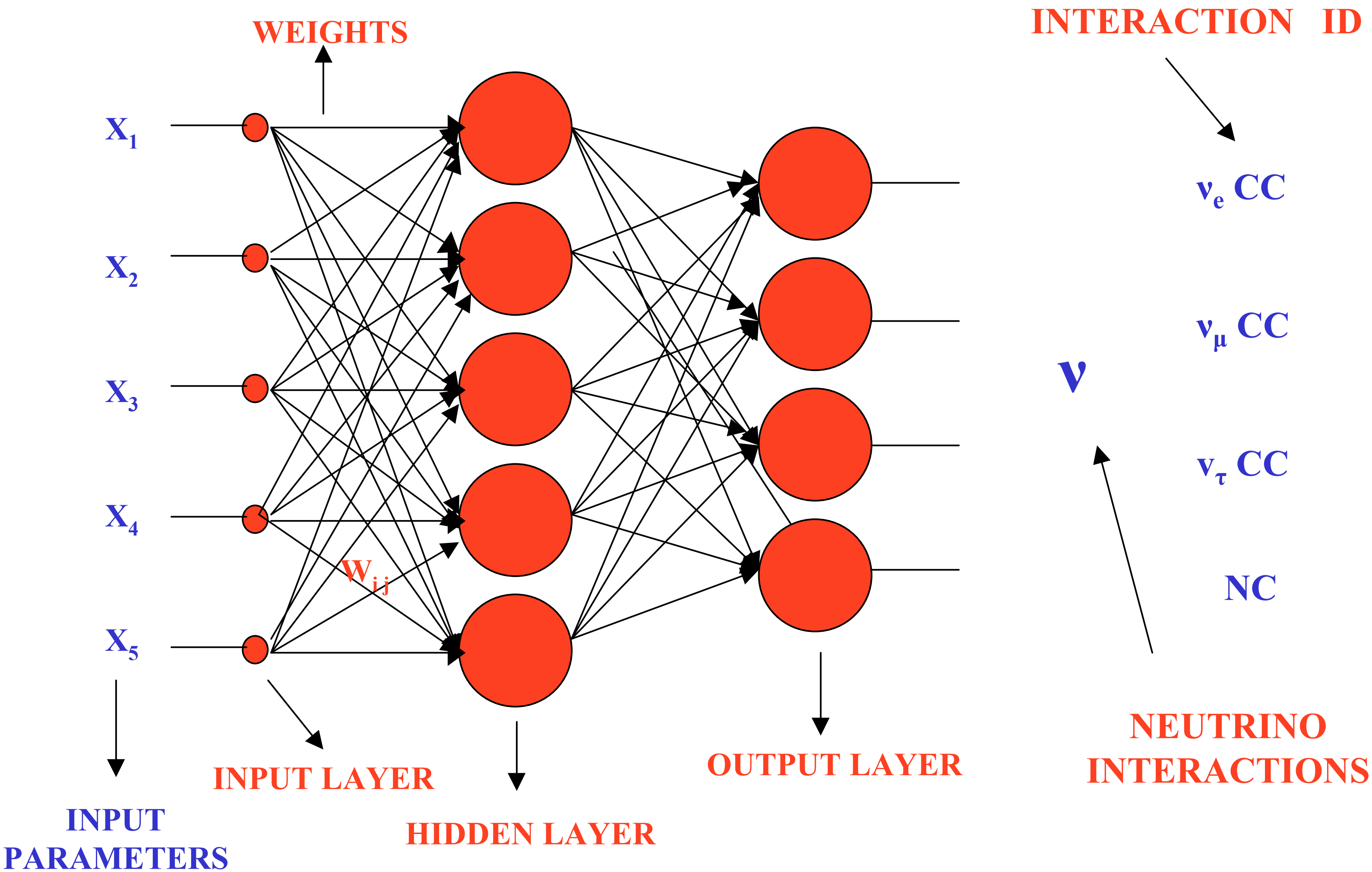
Spectrometer Analysis

Final Analysis for neutrino event characterization

-Goals-

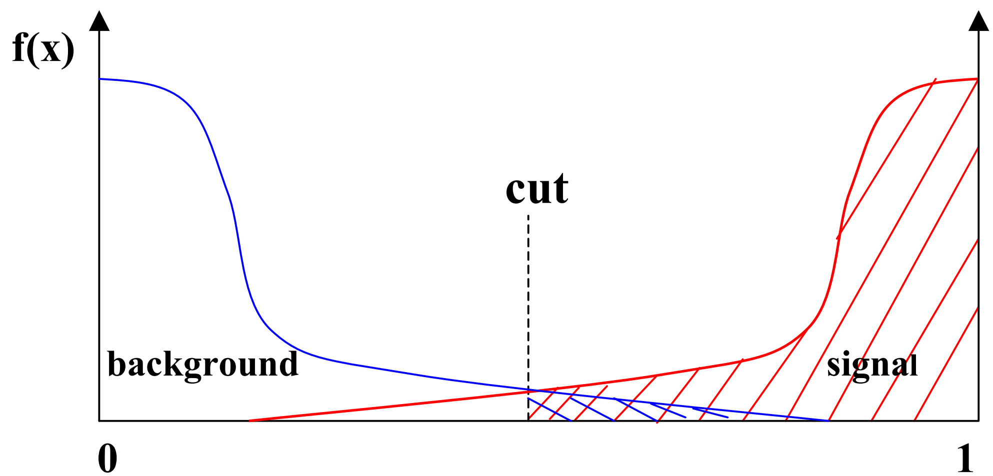
- Use **A**rtificial **N**eural **N**etworks
  - Select Neutrino Interactions
  - Classify Neutrino Interactions
- Use Graph Theory (**M**inimal **S**panning **T**rees)
  - Extract usefull Scintillating Fiber System information for neutrino event characterization
  - Possibly make more efficient Event Location.
- Use χ^2 **M**inimization **T**echniques
  - Obtain Vertex predictions for emulsion scanning.

- ANN Structure-



-Quantities that characterize an ANN-

Network output (selection) function for "background "and "signal" events



S = Total # Signal events

$$\text{efficiency} = \frac{S_C}{S}$$

B = Total # Background events

$$\text{purity} = \frac{S_C}{S_C + B_C}$$

S_C = Signal events above Cut

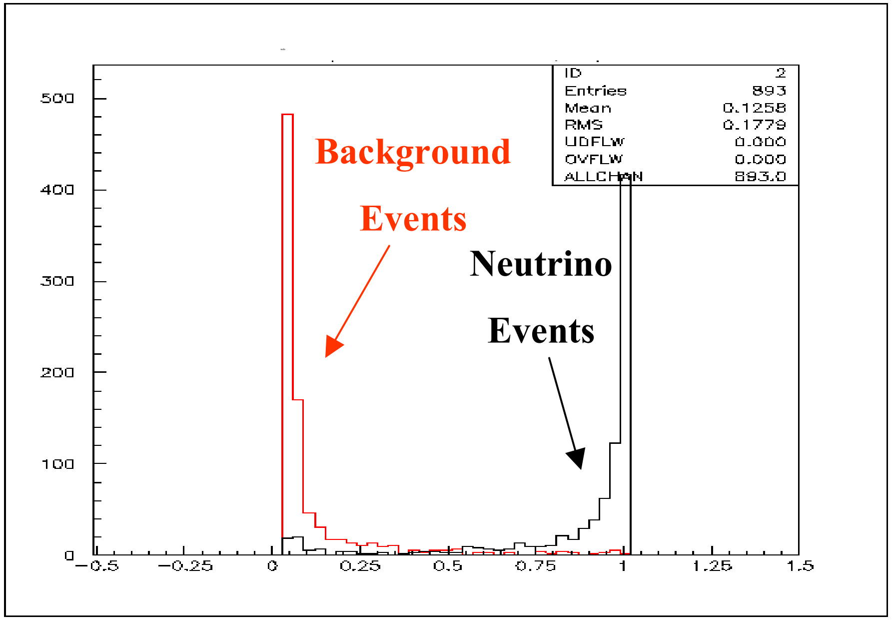
B_C = Background events above Cut

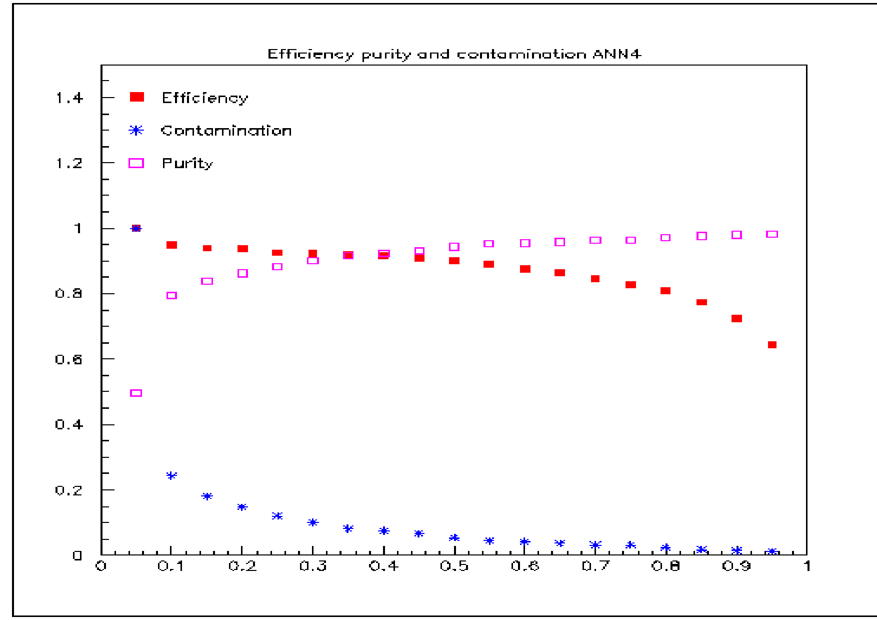
$$\text{contamination} = \frac{B_C}{B}$$

ANN Input Variables

- **Scintillating Fiber System :**
  - Total Number of SF hits (and Total number of “interaction” SF hits 500)
  - Total Pulse height (and Total “interaction” Pulse Height, Pulse height cut @ 500)
  - % of hits in Stations 1 2 3 4 & % of “Interaction hits “
  - Number of SF lines (UZ,VZ)
- **Vector Drift Chambers:**
  - Total Number of VDC hits
- **Drift Chambers:**
  - Total number of DC hits
  - Number of DC tracks
- **EMCAL :**
  - Total Energy Deposition & Total Energy Deposition along y = 0 and | x | > 100 cm
  - Number of clusters
  - Average cluster energy
  - Mean Cluster angle with respect to the z axis from the interaction point
- **Muon Identification System :**
  - Total number of MID hits
  - Total number of MID hits in the central tubes
- **Other Variables :**
  - Number of 3D final Tracks & Number of 3D final tracks that have SF and DC hits.
  - Trigger Timing Differences (T32,T21,T31)
  - Reconstructed Vertex in the Emulsion Module

-ANN Output Function-

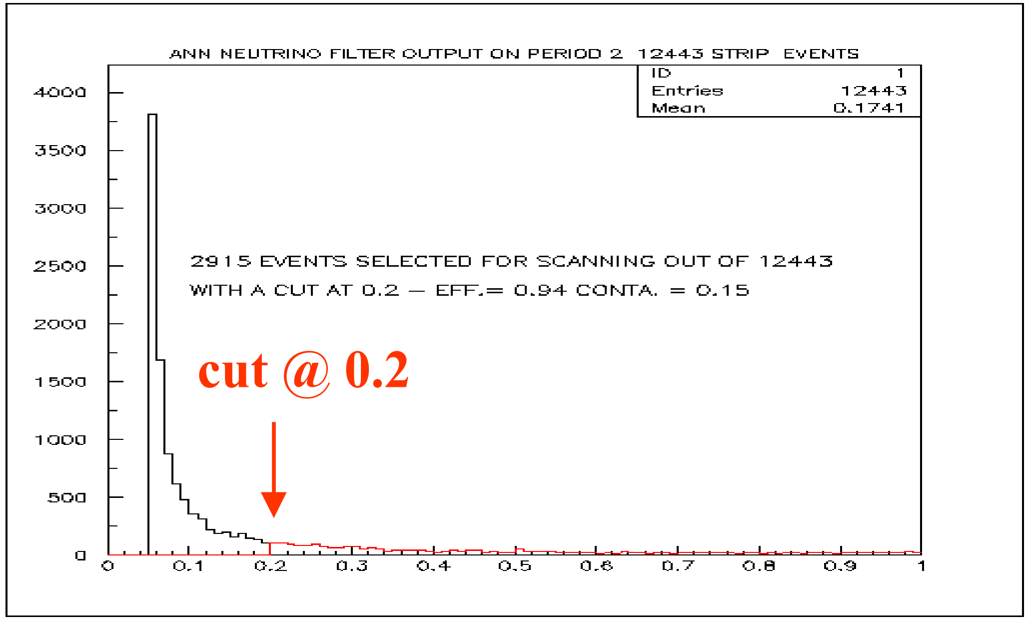




- The **performance** of the ANN is **good** and one can **select events** with **high efficiency** and **high purity (low contamination).**
- With a cut **@ 0.2** :

efficiency 0.94 - purity 0.86 - contamination 0.15

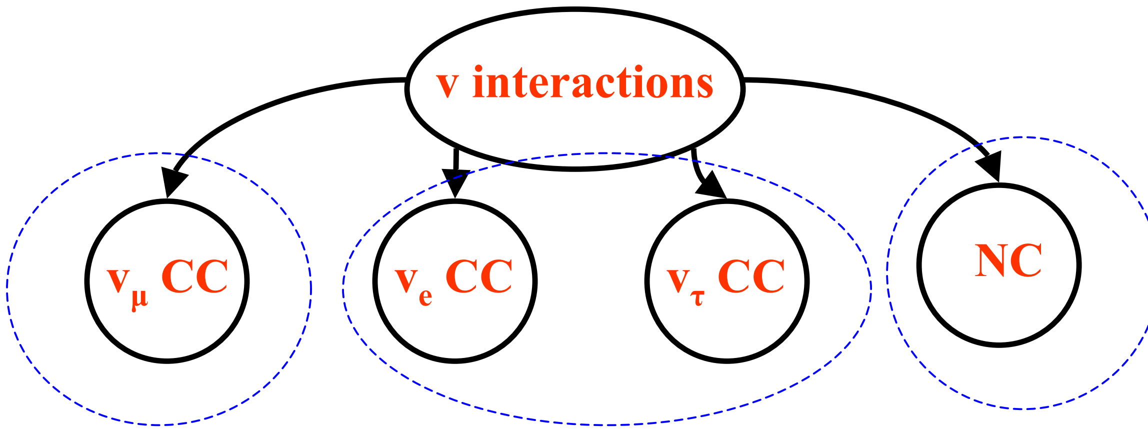
ANN Implementation & Results on a "raw" Data Sample



- With a **cut @ 0.2 2915 out of 12443** are **selected** as **"neutrino" interactions.**
- **Initial Signal/Background Ratio** ~ 100/12443 = **0.008**
- **Obtained Signal/Background Ratio** ~ 100/2915 = **0.034**

Goal

- Use **Artificial Neural Networks** to **classify neutrino interactions** on event by event basis using topological and physical characteristics of neutrino events derived from **MC generated interactions**.



- Since **till recently** only **spectrometer simulated information available**, present **preliminary results** on separation :
  - ν_μ CC -- (ν_e CC + ν_τ CC) -- NC

Method

- **Method :**
  - Construct **two sequential** Neural Networks (ANN1 & ANN2) that will be **applied in the whole data set** :

a) The first to distinguish **ν_μ CC** from **ν_e & ν_τ CC + NC**

b) The second to distinguish **NC** from **ν_e CC & ν_τ CC**

Training Set & Input Variables

- For **every period** we construct a **separate set of (2) ANN's** since every period has **different target configuration** and thus **different event characteristics**.

- For every period we use **5000 MC** events as a **training set.**

INPUT VARIABLES

HITS Total number of DC hits
(Total number of MID hits in the Central tubes)

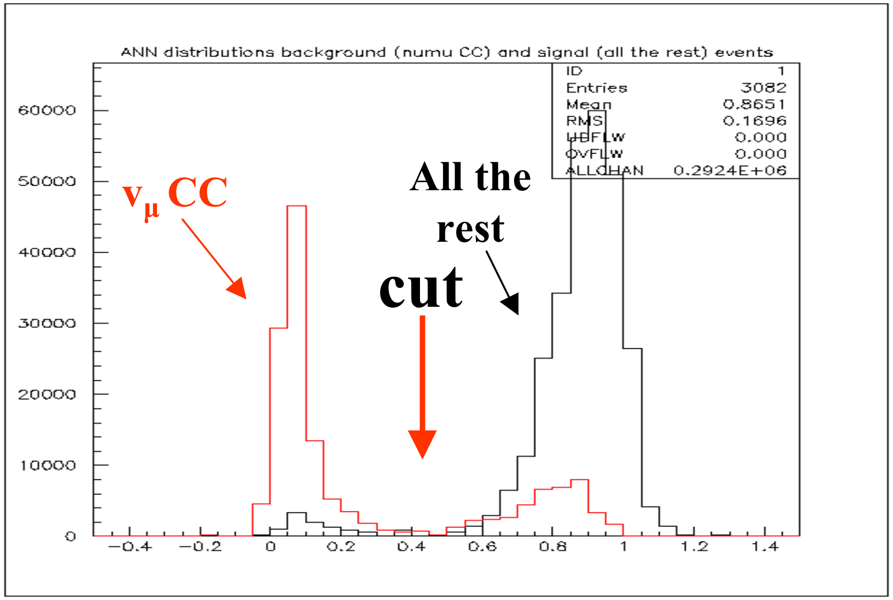
EMCAL Total energy deposition
Number of clusters
Average Cluster energy
Mean value of the Clusters angle from the vertex with respect to the z - axis
Standard deviation of the Clusters angle
Mean Absolute deviation of the of the Clusters angle
Higher Moments of the Clusters angle : a) Skewness b) Curtosis
(Percentage of tracks with E/P < 0.3 (Muons))

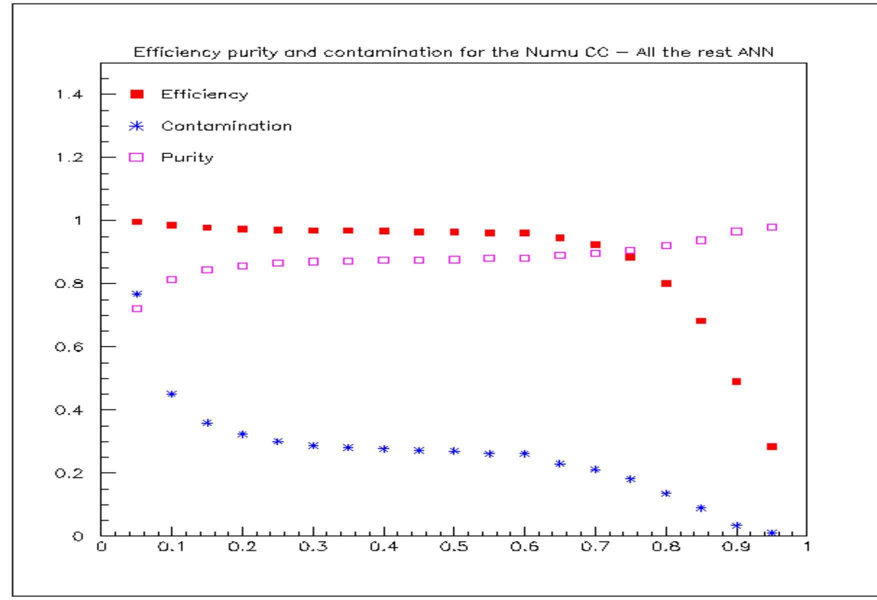
TRACKS Number of final tracks
Number of DC tracks
(Number of tracks that have more than 3 hits in the MID system (Muons))

OTHER Total Pulse Height in the SF system

**** Comparing the MC distributions of these variables with REAL data we found that with the **0.001 criterion** they are considered **compatible** according to the **Kolmogorov Test***

-Output of ANN1 (ν_μCC - All the rest)-

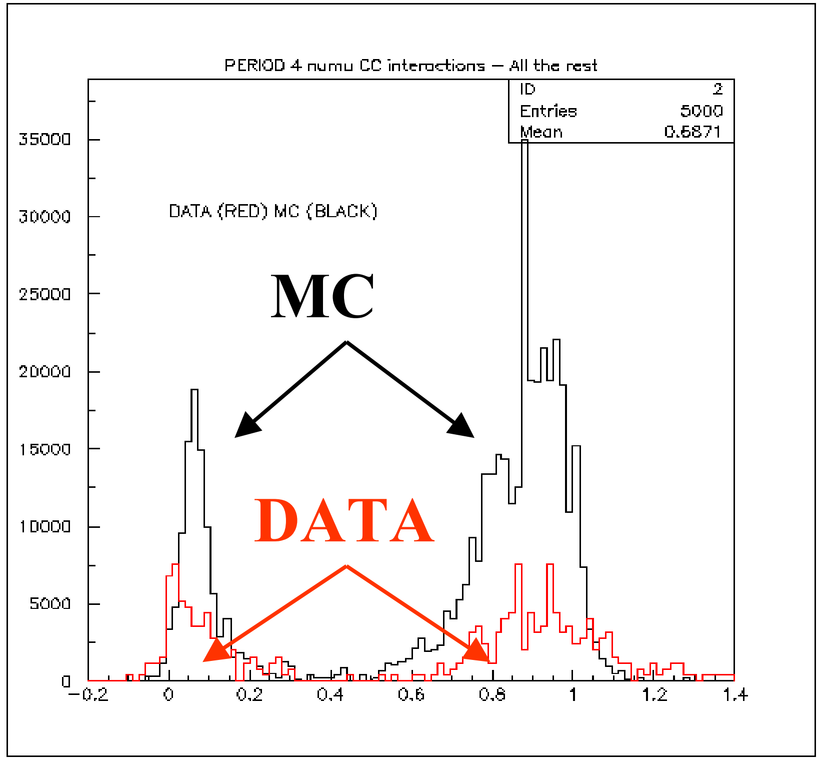




- The **performance** of that network is **satisfactory.**
- With a **cut @ 0.5** in the network output function we select **"signal"** events and on the same time **"background"** events with :

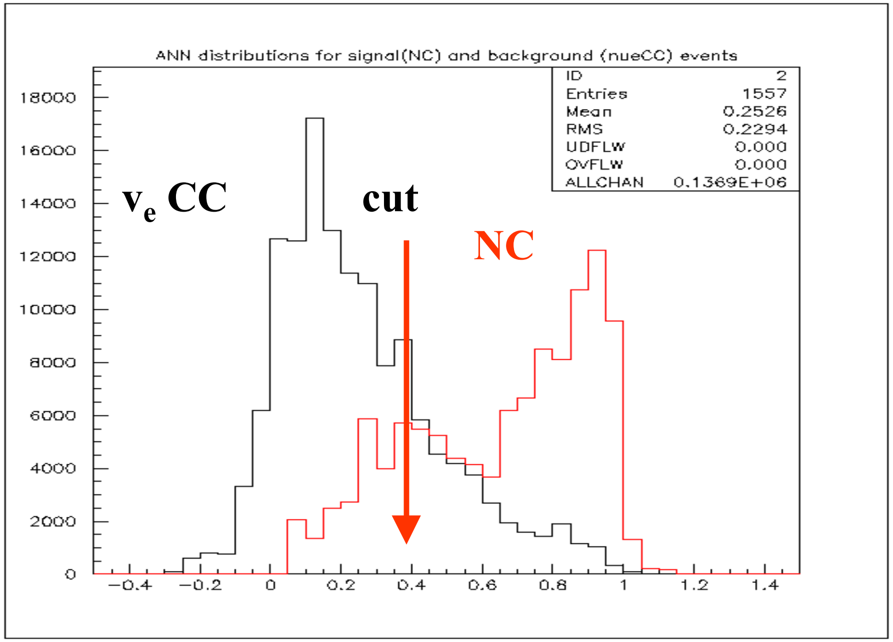
All the rest	**efficiency 96 % - purity 88 %**
ν_μ CC	**efficiency 73 % - purity 96 %**

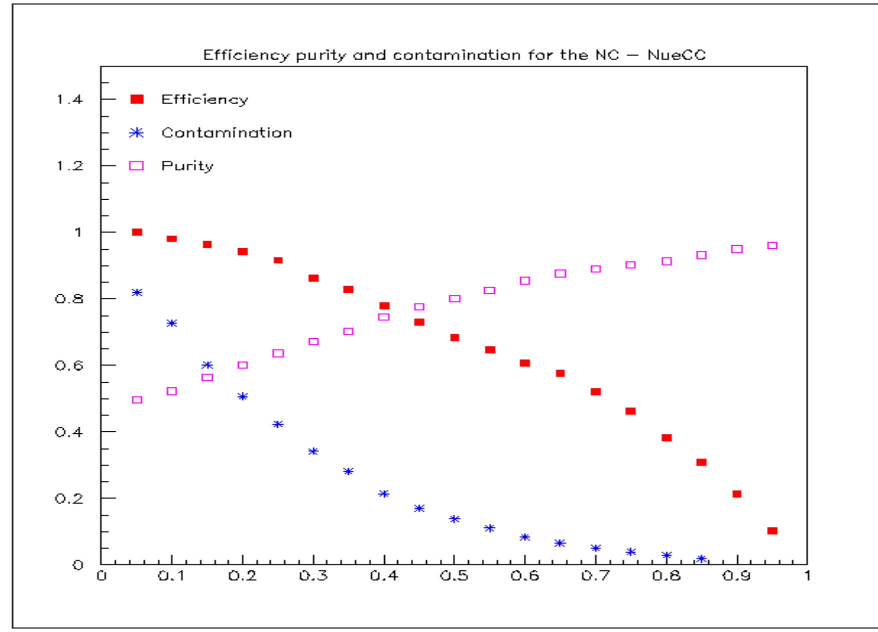
ANN1 (ν_μCC - All the rest) performance on MC & Real Data



- The performance of the **output function** of **ANN1** in **MC** events and in the **Real data set** is **very similar**.
- That indicates that the **results from ANN1** implementation in the **experimental data** set are **quite reliable.**

Output of ANN2 (NC - ν_e CC)

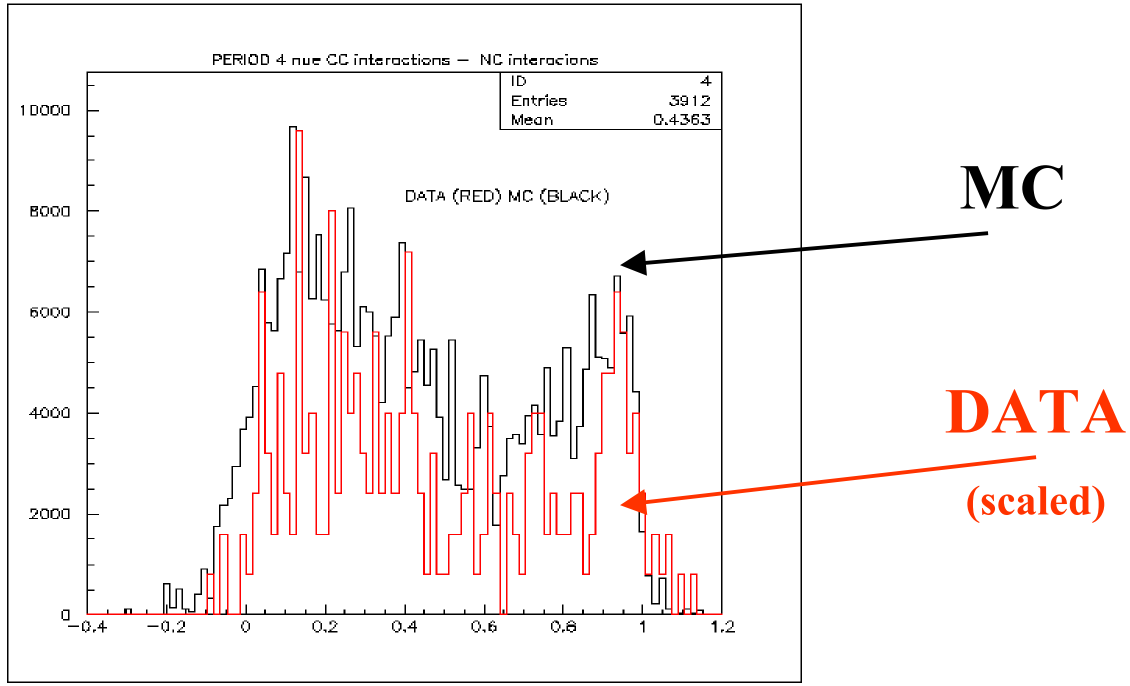




- This network shows a quite good behavior and by choosing a **cut @ 0.5** we select **signal (NC)** and at the same time **background** events **(ν_e CC)** with :

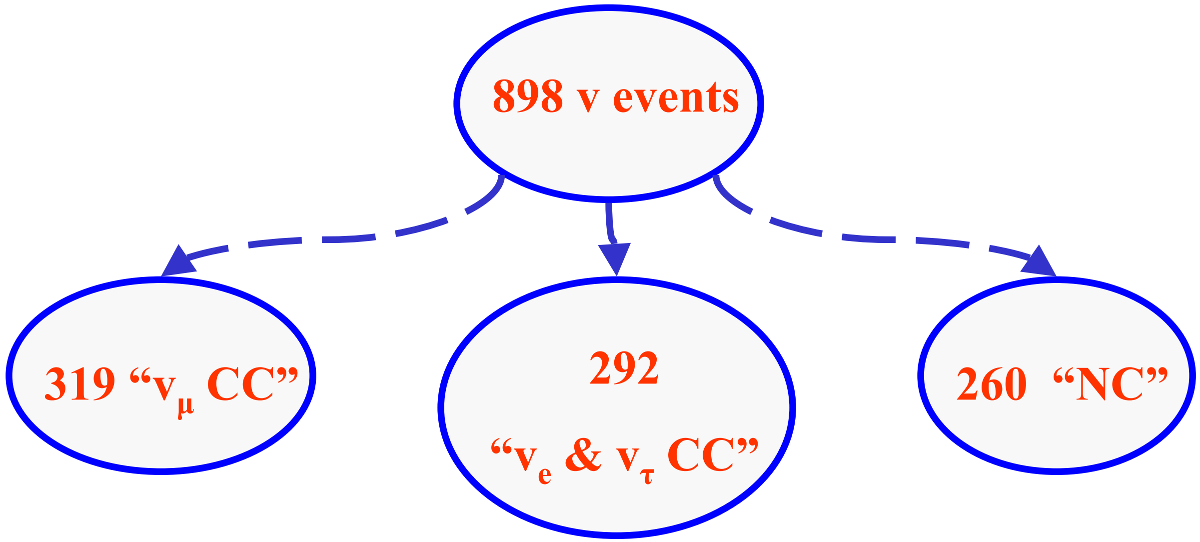
NC	**efficiency 68 % - purity 80 %**
ν_e CC	**efficiency 86% - purity 76 %**

ANN2 (NC - ν_e CC) performance on MC & Real Data



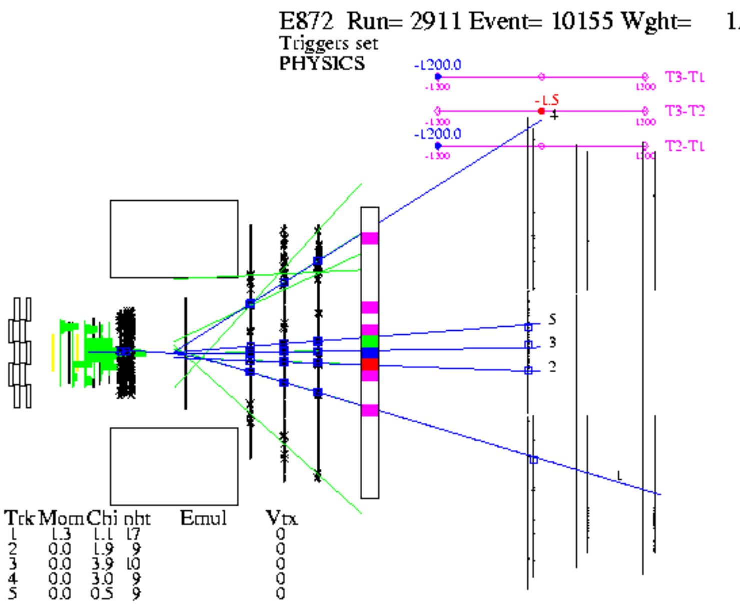
- The **performance** of the **output function** of **ANN2** in **MC** and in the **Experimental data** set is **very similar**.
- That permits us to consider the **results** of **ANN2** quite **reliable.**

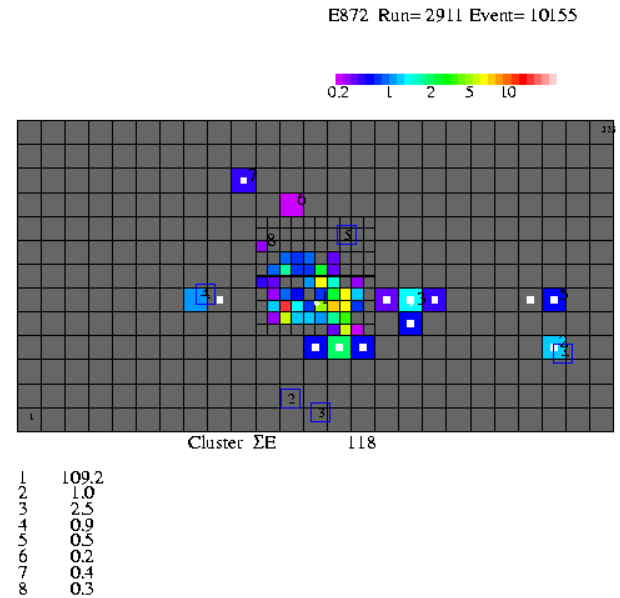
Results from the Implementation of ANNs in Data (~ 898 neutrino events)

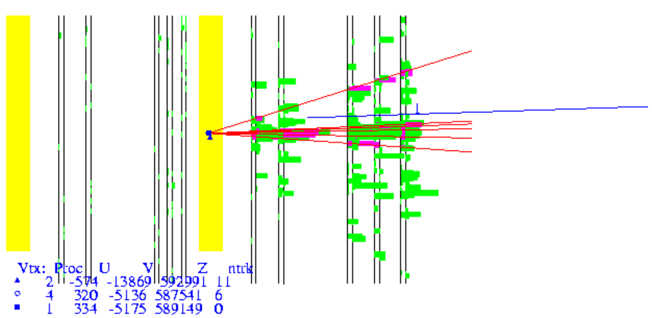


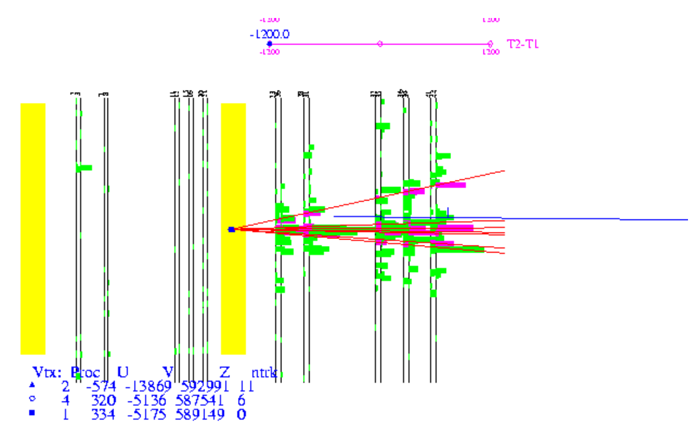
Categories	ν_μ CC	ν_e CC	NC
ANN ratios	35.5 ± 1.6 %	32.5 ± 1.5 %	28.9 ± 1.5 %
Expected ratios	38 %	31 %	25 %

EM shower recognition & reconstruction in SF with Minimal Spanning Trees





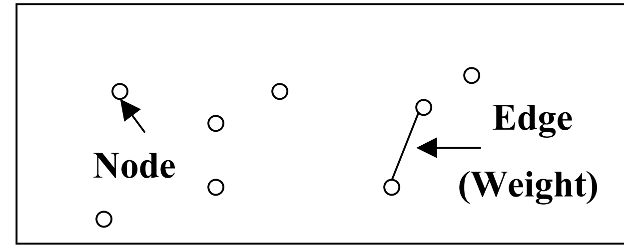




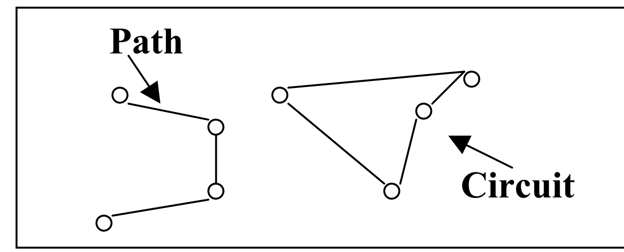
-Minimal Spanning Trees Basics-

- An **edge weighted Linear Graph** is composed of a set of points called **nodes** and a set of node pairs called **edges** with a number called **weight** assigned to each edge.

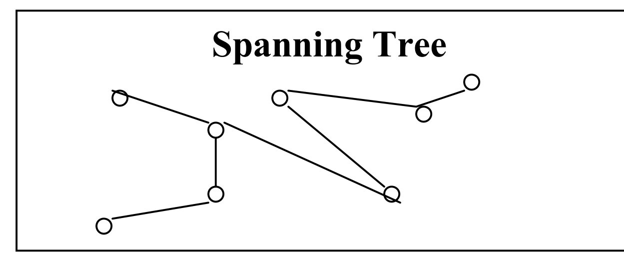
Graph



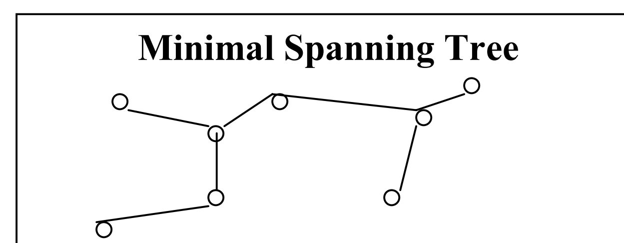
- A **path** in a graph is a sequence of edges joining two nodes. A **circuit** is a closed path.



- A **spanning tree** is a connected graph with no circuits which contains all nodes.

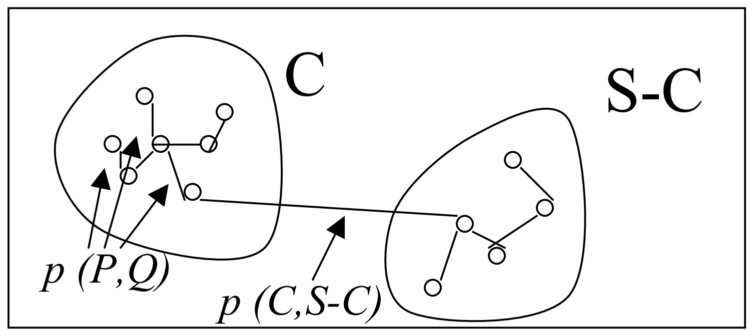


- A **minimal spanning tree** is the spanning tree whose weight (= sum of weights of its constituent edges) is minimum among all spanning trees in this set of nodes.



- MST Theorem 1 -

- Theorem 1 : " *If S denotes the nodes of G and C is a nonempty subset of S with the property that p (P,Q) < p (C,S-C) for all partitions (P,Q) of C then the restriction of any MST to the nodes of C forms a connected subtree of the MST* ". The significance of this theorem for cluster detection can be illustrated if the following figure which depicts the MST for a point set containing two clusters C and S-C :

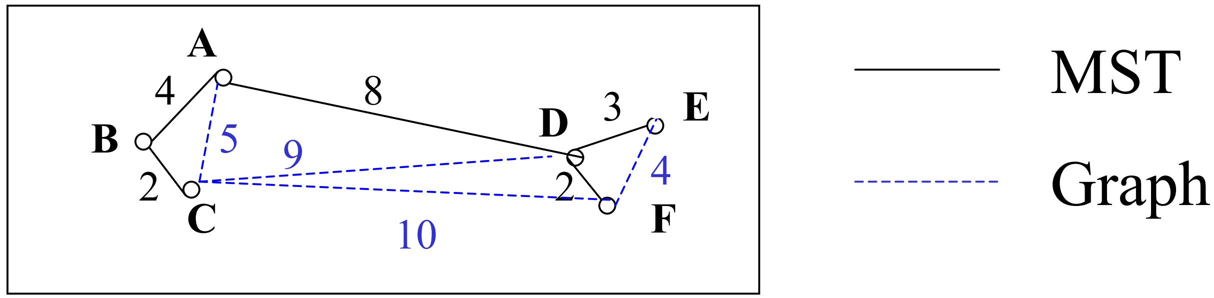


- This theorem assures us that **the subgraph of an MST** does **not break up the real clusters in S**, but on the other hand neither does it force breaks where real gaps exist in the geometry of the point set.

- A spanning tree is forced by its very nature to span all the points but at least **the MST jumps across the smaller gaps first**.

- MST Theorem 2-

- Theorem 2 : *" If T is an MST for graph G and X,Y are two nodes of G, then the unique path in T from X to Y is a minimax path from X to Y"*.[1]



- Cost : maximum edge weight of the path e.g the path (CBADE) has a cost of 8.
- Minimax path : The path between a pair of nodes that has the least cost e.g there are four minimax paths from C to F all of cost 8.
- The minimax path each of whose subpaths are also minimax lies within the MST and that is not a coincidence as shown in the previous theorem.
- So the preference of minimax paths in the **MST** forces it to **connect** two **nodes X and Y** belonging to a **tight cluster** without straying outside the cluster.

- MST properties-

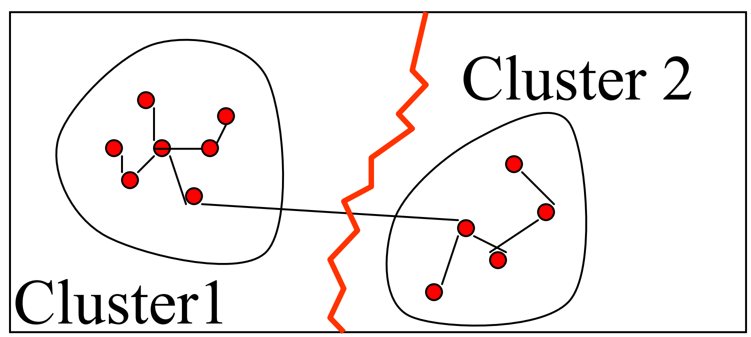
- **The MST is deterministic**. It does not depend on random choices in the algorithm or on the order in which nodes and edges are selected and examined but only on the given set of nodes.

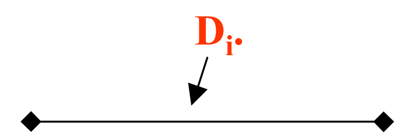
- **The MST is invariant under similarity transformations**, that is under all transformations that preserve the monotony of the metric (rotations, translations changes of the scale and even some nonlinear distortions) .

- **The metric** for the **weight assignment** can be defined in many ways and does not have to be the **Euclidean Distance between 2 nodes** .

-MST & Cluster Analysis-

- Main Idea : *After forming the MST of a set of points group the points into disjoint sets by joining all edges of weights D_i or less. Each set is then said to form a cluster at level D_i.Thus all segments joining two clusters defined at level D_i will have lengths greater than D_i.*





-Implementation in the SF 's-

- STEPS :

  A **Construct the MST in each view U V X**
  - Determine the metric for weight assignment.

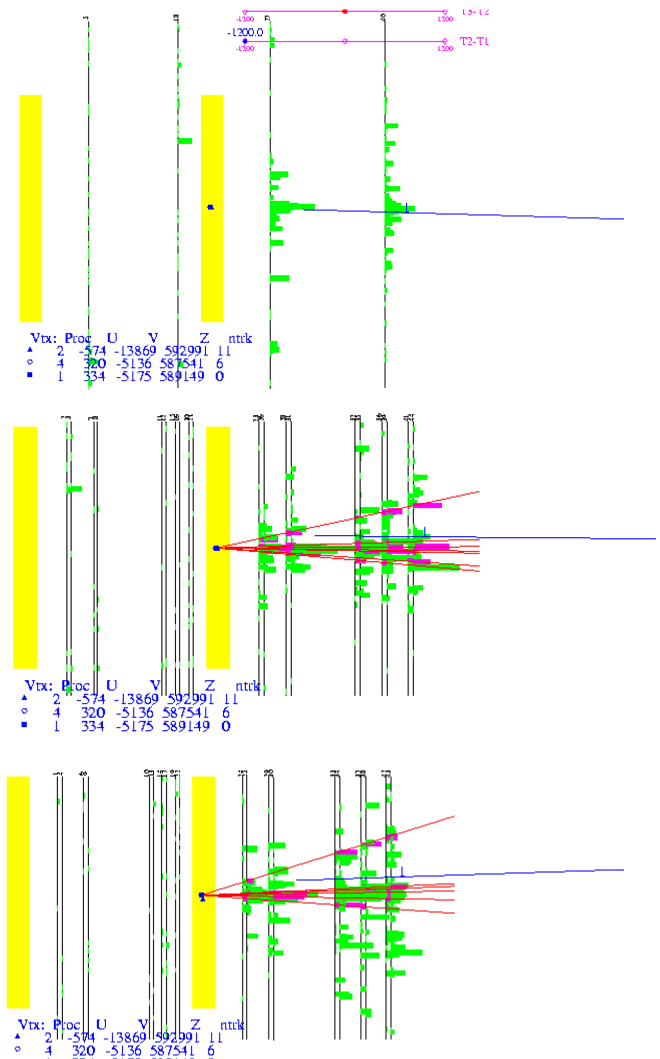
  B **Form the clusters at level D_i in each view.**

  C **Extract the cluster's characteristics in each view**
  - Cluster direction
  - Number of hits
  - Total pulse height
  - Start position

  D **Combine clusters in U V X to form 3D clusters**

-2D CLUSTERS IN EVENT DISPLAY-

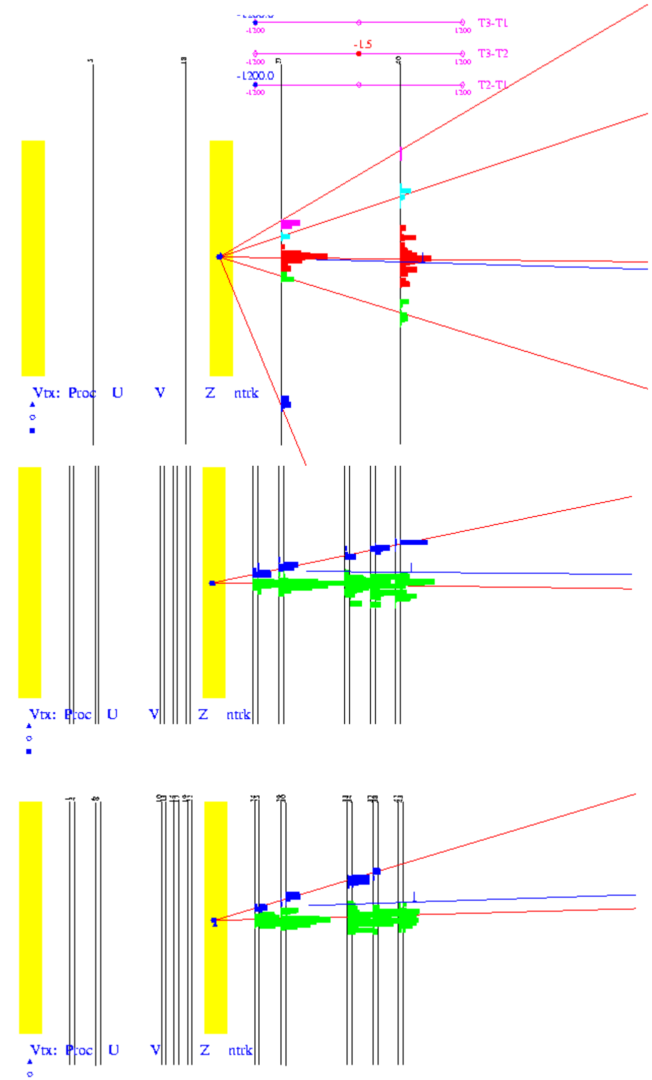
BEFORE CLUSTERING | **AFTER CLUSTERING**



X view

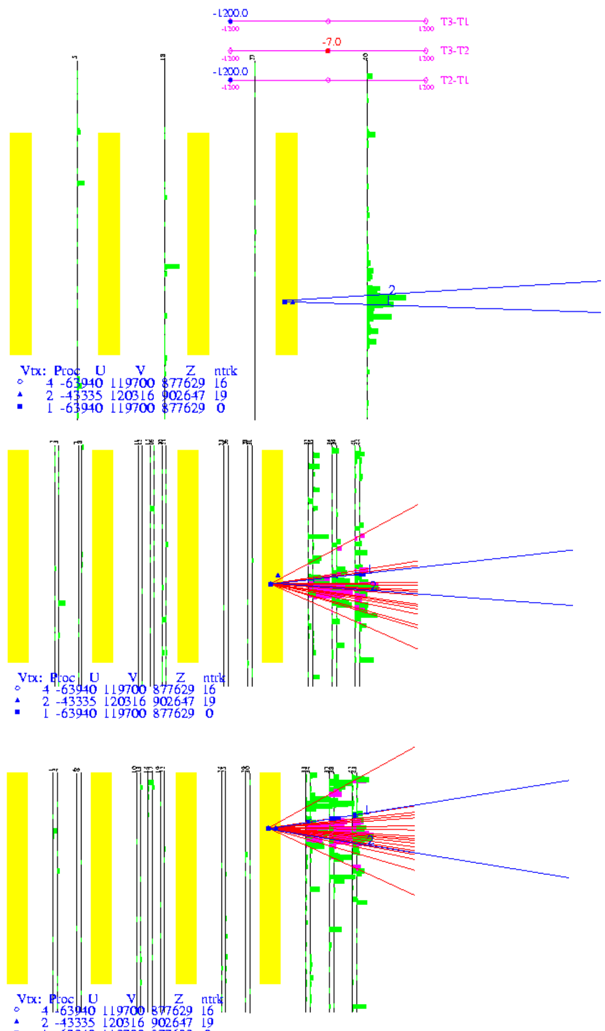
U view

V view



2D CLUSTERS IN EVENT DISPLAY

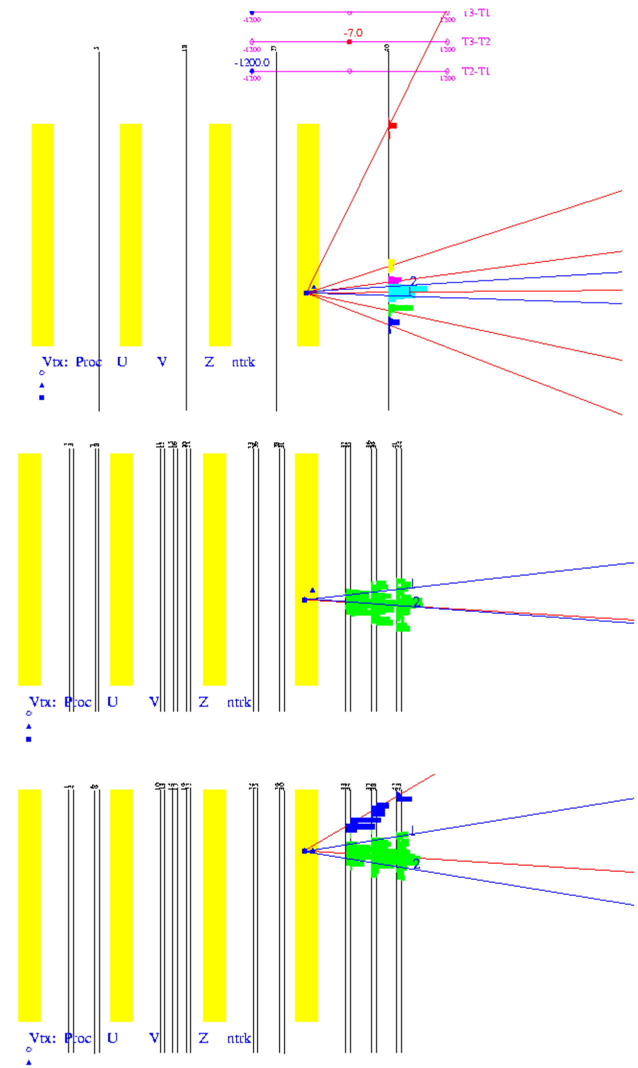
BEFORE CLUSTERING **AFTER CLUSTERING**



X view

U view

V view



3D CLUSTER RECONSTRUCTION

- Steps :
  - Use all possible combinations of UZ VZ XZ lines (2D Clusters) to create a set of points in the SF planes.
  - For **each combination** use **χ^2 minimization** method to compute 3D cluster parameters :

$$\mathbf{x = a_x + b_x \cdot z}$$

$$\mathbf{y = a_y + b_y \cdot z}$$

and χ^2.

  - Set a **χ^2 / ndf cut** @ 1.8 and consider combinations **satisfying** this **cut** as **valid 3D clusters**

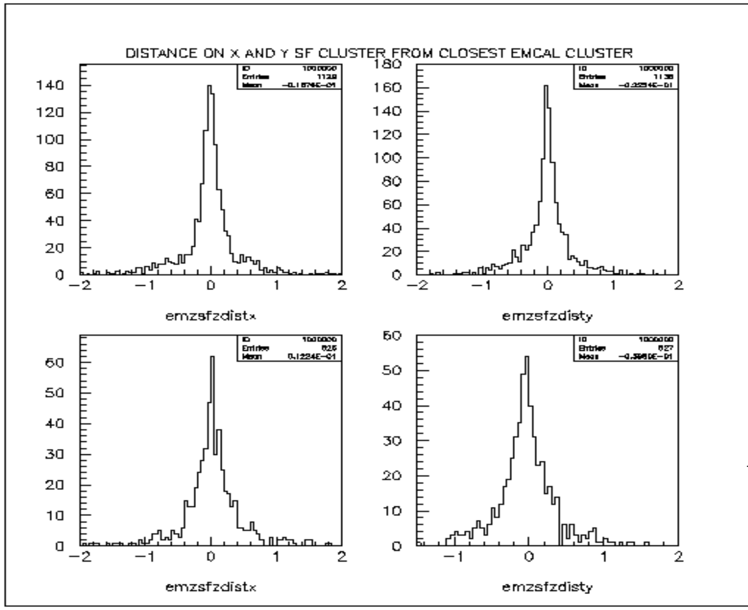
SF CLUSTERS - EMCAL CLUSTERS

- We examine **correlation** of **SF clusters** with **Electromagnetic Calorimeter clusters**.

- Such a **correlation** could be **useful** in:
  - **Neutrino event classification** &
  - **Electron identification**

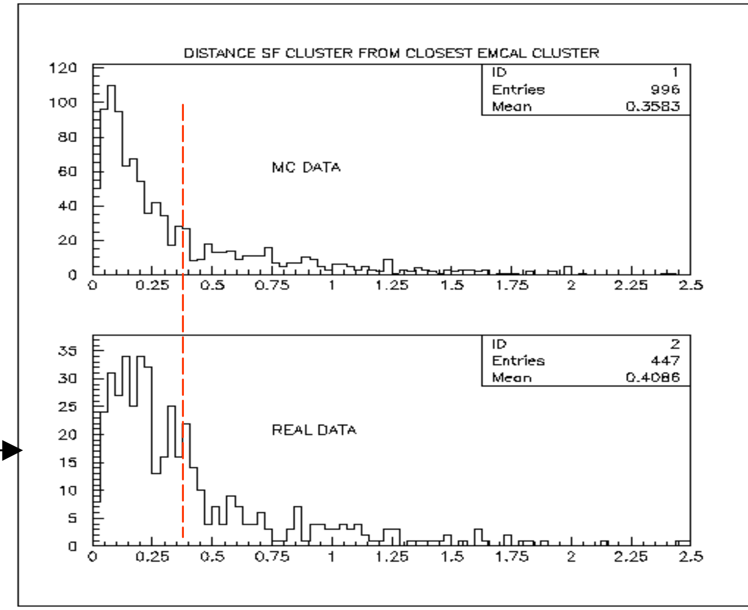
- So we **project 3D SF clusters** to the **Calorimeter** and **study** various **parameters** for both MC & Experimental data

SF - EMCAL cluster matching



←MC→

←DATA→

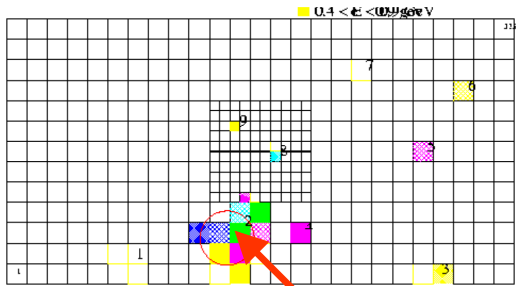


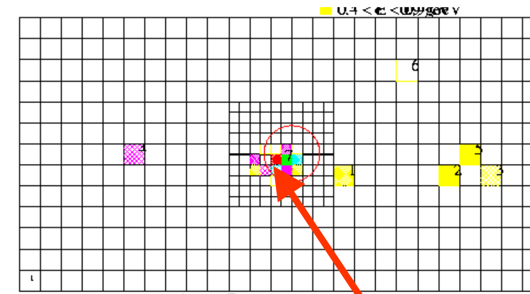
Distance in X &Y of SF cluster from EMCAL closest cluster

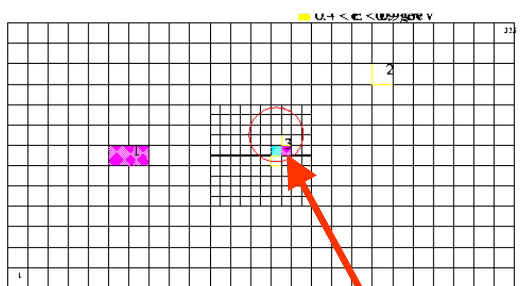
Distance of SF cluster from EMCAL closest cluster

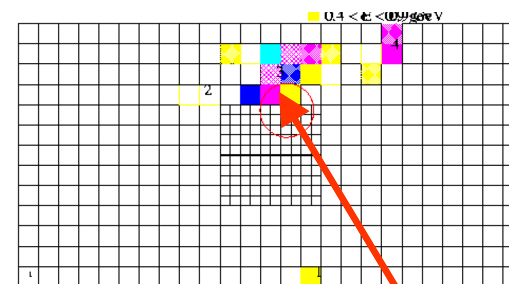
- **Most SF** clusters are **matching within 0.35 m** with one **EMCAL cluster** *(EMCAL block size = 0.15 m)*

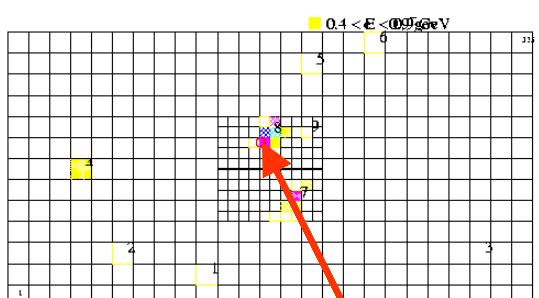
-SF - EMCAL cluster matching in Event Display-











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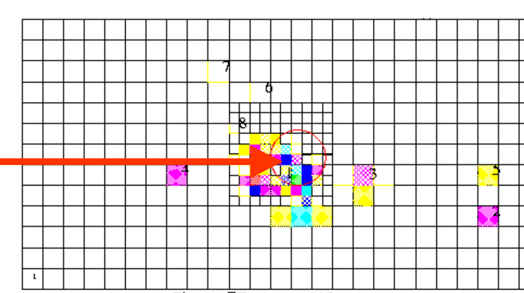


Goal - Main Idea

> **Goal** : To **predict** the vertex position with the desired accuracy (~ 2.5 mm in u & v and ~ 5 mm in z) with **minimal manual intervention**.

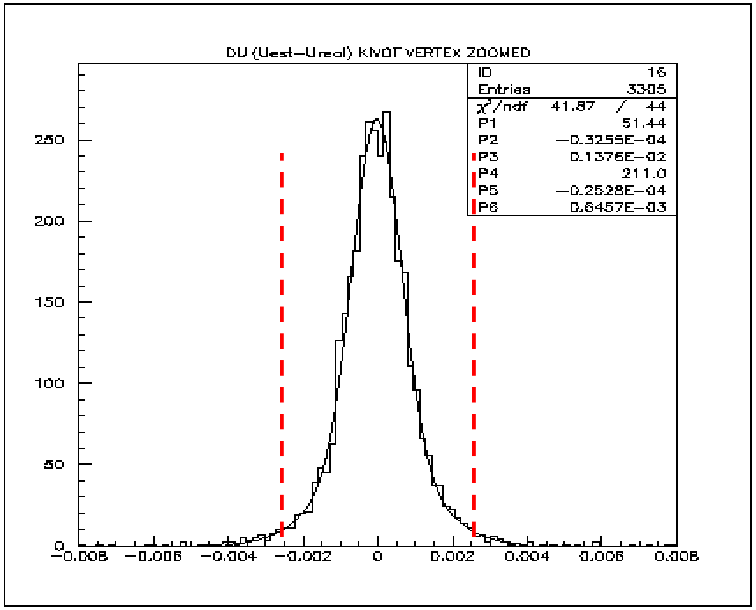
> **Main idea** : Use confidently reconstructed SF tracks and **minimize** the quantity :

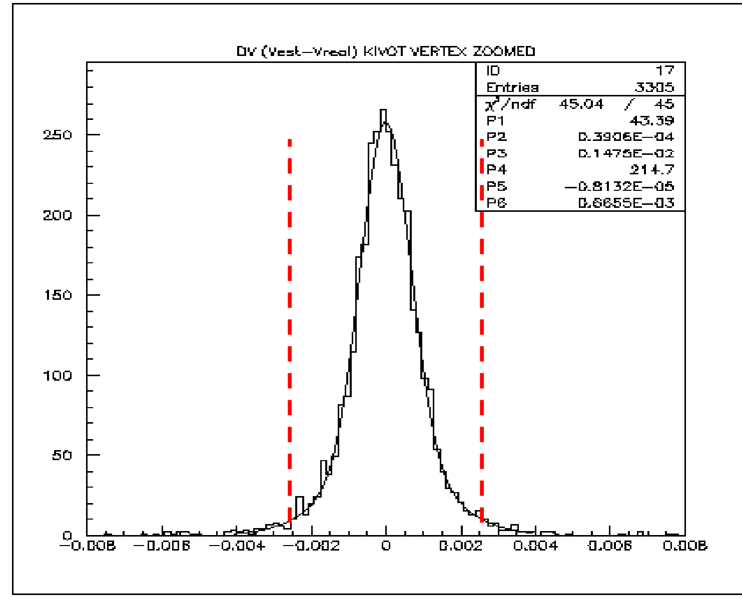
$$\chi^2 = \sum \frac{\mathbf{d}^2{}_{\mathbf{i}}}{\sigma^2{}_{\mathbf{i}}}$$

where d_i = *distance of SF track i from the vertex*

σ_i = *error of* d_i

χ^2 Minimization (MC Events)



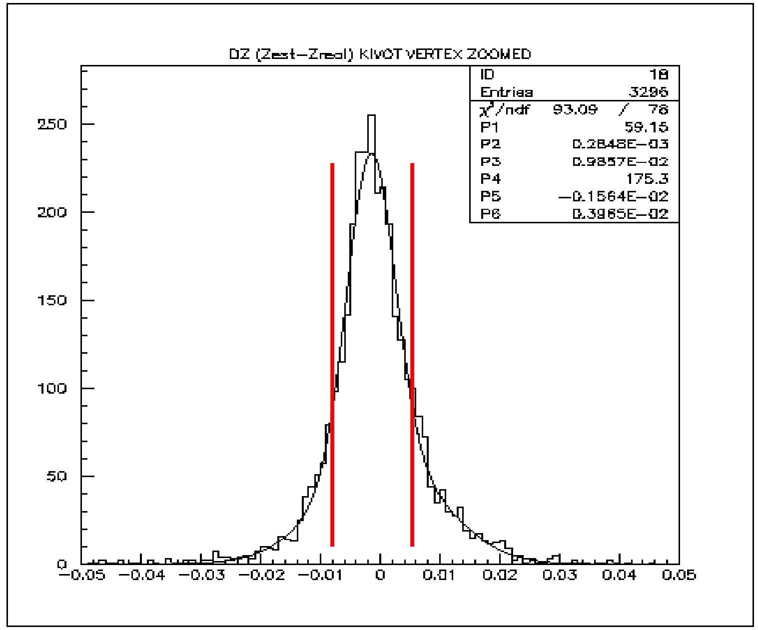


U_{est} - U_{real} 2 gaussian fit V_{est} - V_{real}

- In 16.5 % of Events u-vertex is estimated with 1.40 mm sigma
- In 83.5 % of Events u-vertex is estimated with 0.64 mm sigma

χ^2 Minimization (MC Events)

2 gaussian fit

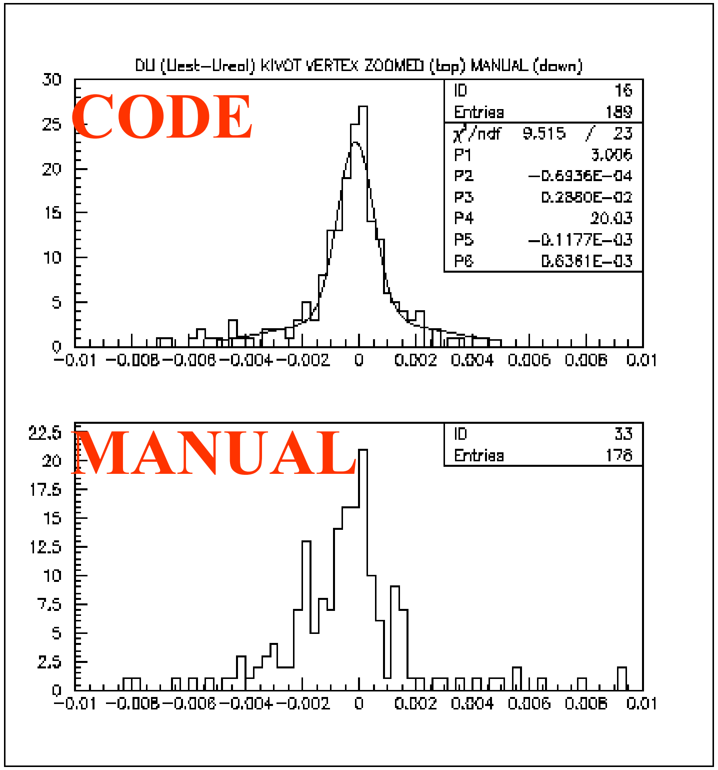


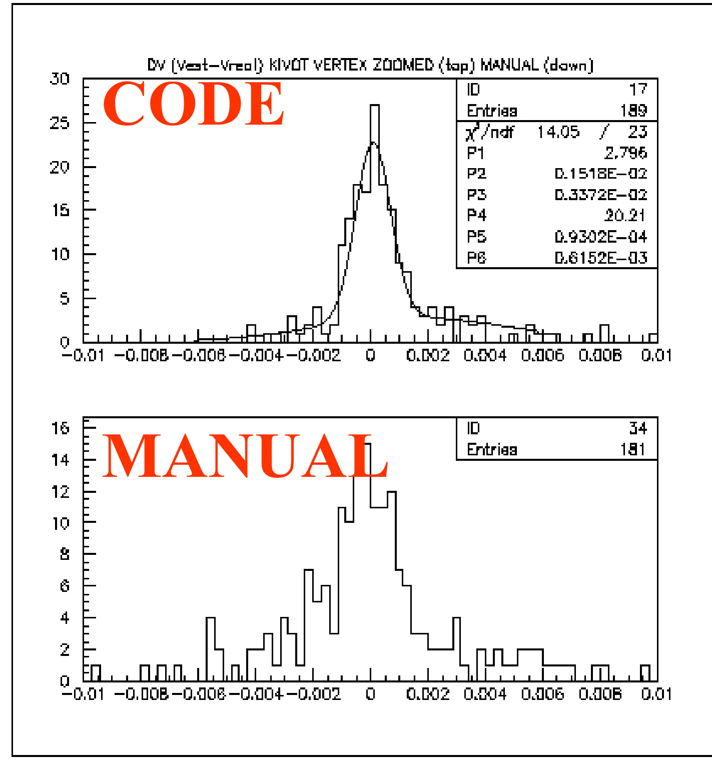
$Z_{est} - Z_{real}$

- In 25 % of Events u-vertex is estimated with 9.8 mm sigma
- In 75 % of Events u-vertex is estimated with 4.0 mm sigma

Vertex predictions (203 Events)

$U_{est} - U_{real}$ $V_{est} - V_{real}$

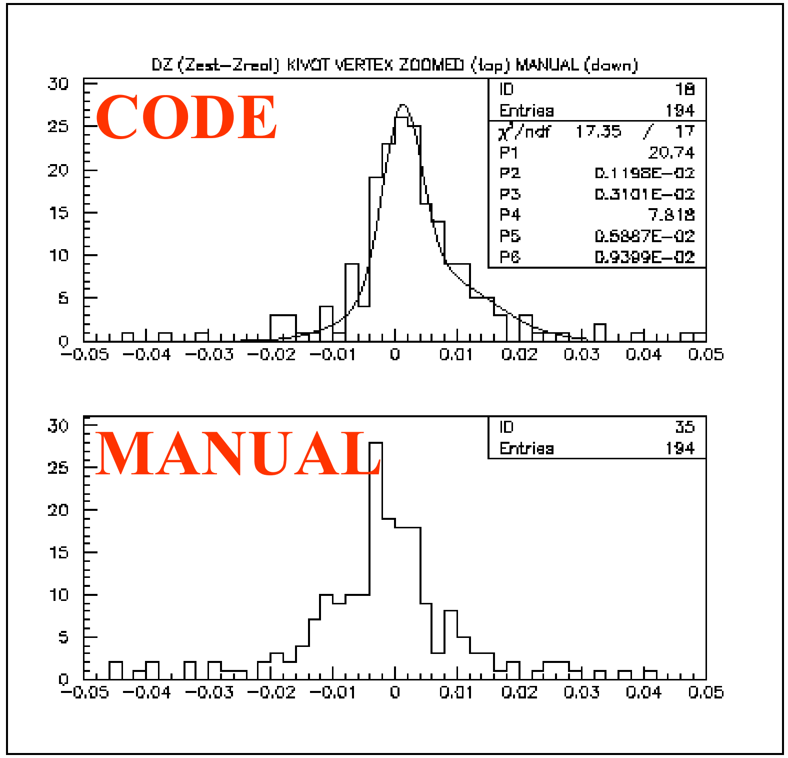




- In 13 % of Events u-vertex is estimated with 3.00 mm sigma
- In 87 % of Events u-vertex is estimated with 0.63 mm sigma

Vertex predictions (203 Events)

$Z_{est} - Z_{real}$



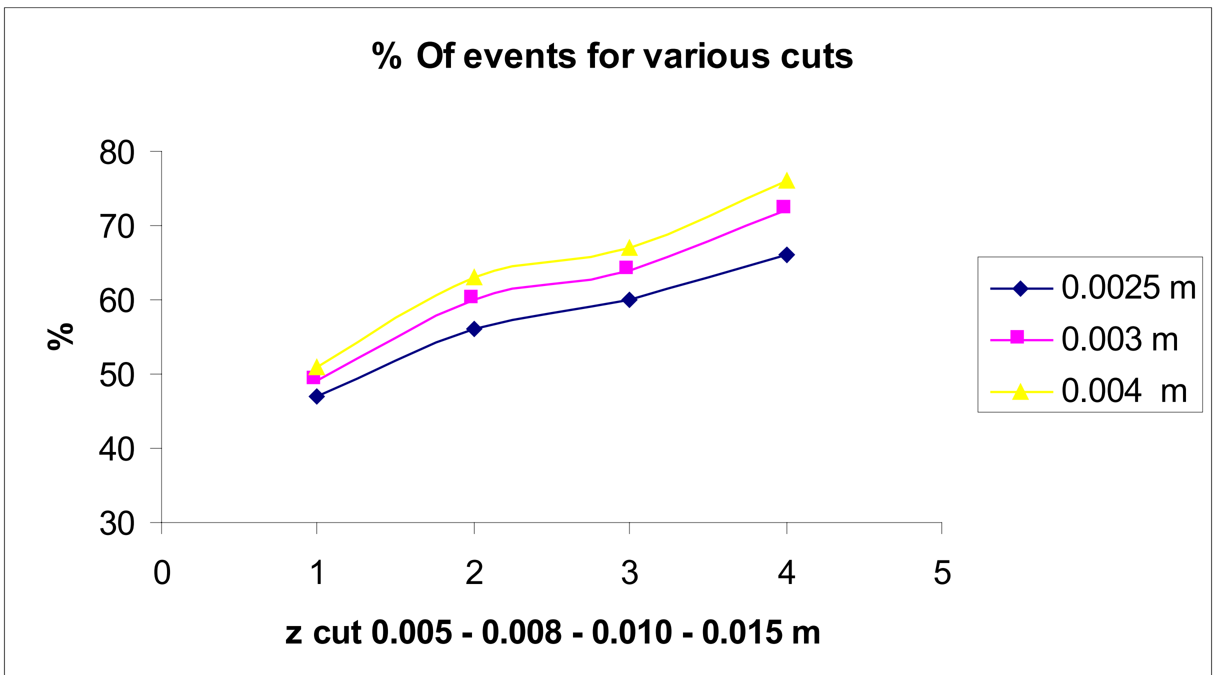
- In 26 % of Events Z-vertex is estimated with 9 mm sigma
- In 74 % of Events Z-vertex is estimated with 3 mm sigma

Comparison Data - MC

MC	DELTA U (V)	DATA
16.5 % 1.40 mm sigma		13 % 3.00 mm sigma
83.5 % 0.64 mm sigma		87 % 0.63 mm sigma
	DELTA Z	
25 % 9.8 mm sigma		26 % 9.0 mm sigma
75 % 4.0 mm sigma		74 % 3.0 mm sigma

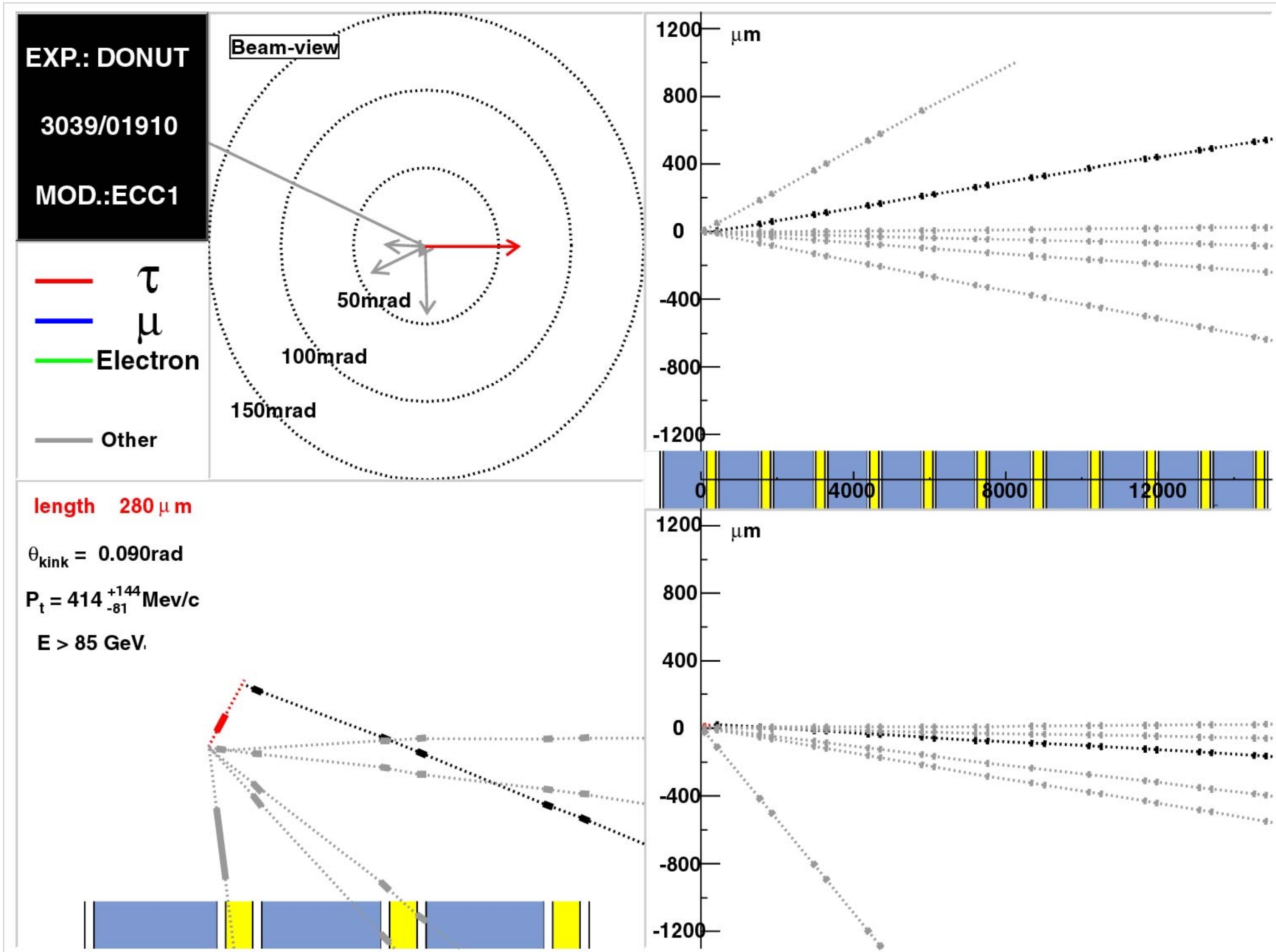
Timing & Results

- In **2 days** we produced **manual vertex** predictions for 203 events
- In **1 hour** we produced the **final predictions** with the **code.**



-Spectrometer & Emulsion Analysis-

- So far we have discussed **aspects** of the **spectrometer analysis** of **neutrino data**.
- We are planning of **extending** our **spectrometer analysis** to include **emulsion information.**
- **Emulsion analysis** is going on **in parallel** and has so far **produced** the **4 ν_τ events**


EXP.: DONUT
3039/01910
MOD.:ECC1
Beam-view
τ
μ
Electron
Other
50mrad
100mrad
150mrad
length 280 μ m
θkink = 0.090rad
Pt = 414 +144 -81 Mev/c
E > 85 GeV.
μm
1200
800
400
0
-400
-800
-1200
0
4000
8000
12000

-Conclusions - Ongoing Work-

- The **ANN neutrino filter** achieves a **reduction of ~ 76 %** on the number of **events** that are **rescanned** (<=> **improvement** of **Signal/Background** Ratio by a **factor of ~ 4.25**) and is the standard procedure the Collaboration is using.
- The **results** of the **ANNs** for **neutrino event classification** are very **close** to what **expected**.
- Including **emulsion information** in the input ANN variable set can **possibly lead** us to **more accurate results.**
- SF **shower recognition & reconstruction could help** in **event location.**
- From **EMCAL - SF cluster matching** useful **information** can be **obtained** for **event characterization** and **electron identification.**
- The procedure for **vertex predictions** gives quite **accurate results very quickly** & we are using it to **obtain vertex predictions** for the **new "neutrino" events**.
- **The first phase of the DONUT analysis has produced 4 ν_τ events. The phase 2 analysis just started and we hope to have more results within a year.**