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CVN Studies for Neutral Current π_0 PID in NOvA

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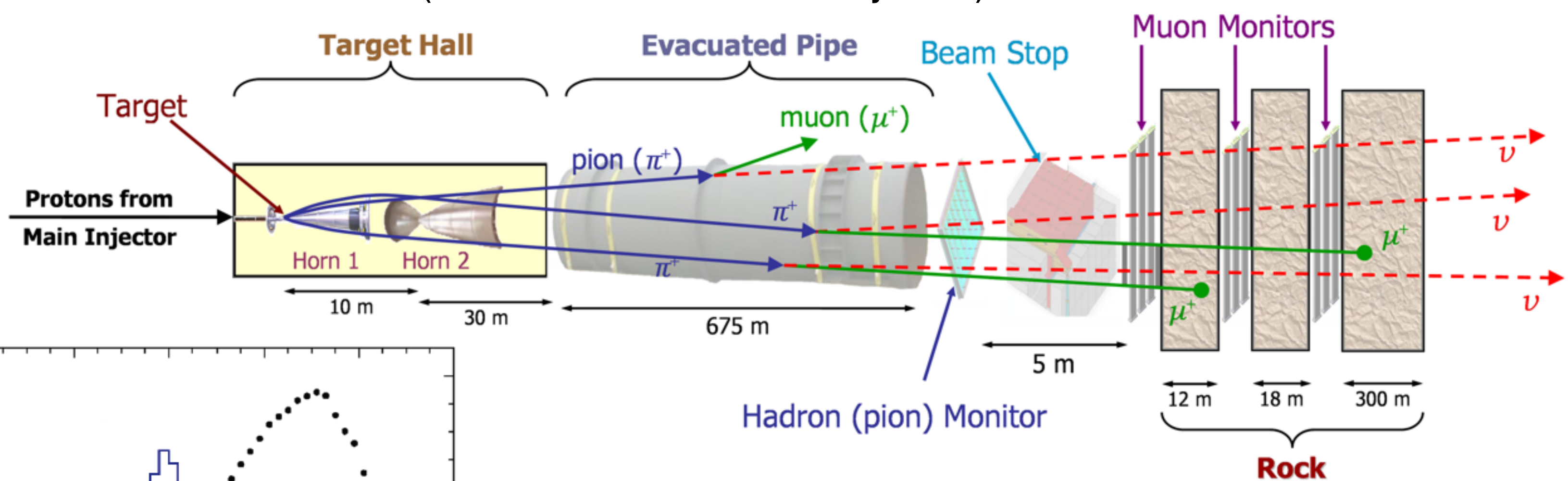
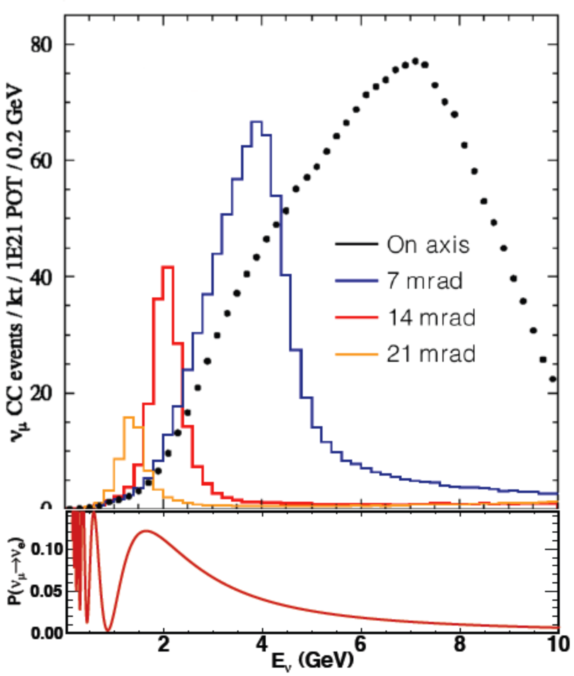
Outline

- NOvA Experiment:
  - NuMI Beam;
  - Near and Far Detectors;
  - Physics with NOvA.
- Neutral Current (NC) π_0 in NOvA:
  - Physics & Motivations;
  - NOvA Reconstruction;
  - Current Status.
- Convolutional Visual Network (CVN).
- CVN for π_0 in the Near Detector.
- Conclusions.

NOvA Experiment

NOvA (NuMI Off-axis ν_e Appearance) is an experiment which studies neutrino oscillations using the NuMI (Neutrinos at the Main Injector) beam at Fermilab.





NOvA detectors are located off-axis (14,6 mrad) —>
almost monochromatic neutrino flux that peaks at 2 GeV at the maximum of oscillations ν_μ —> ν_e

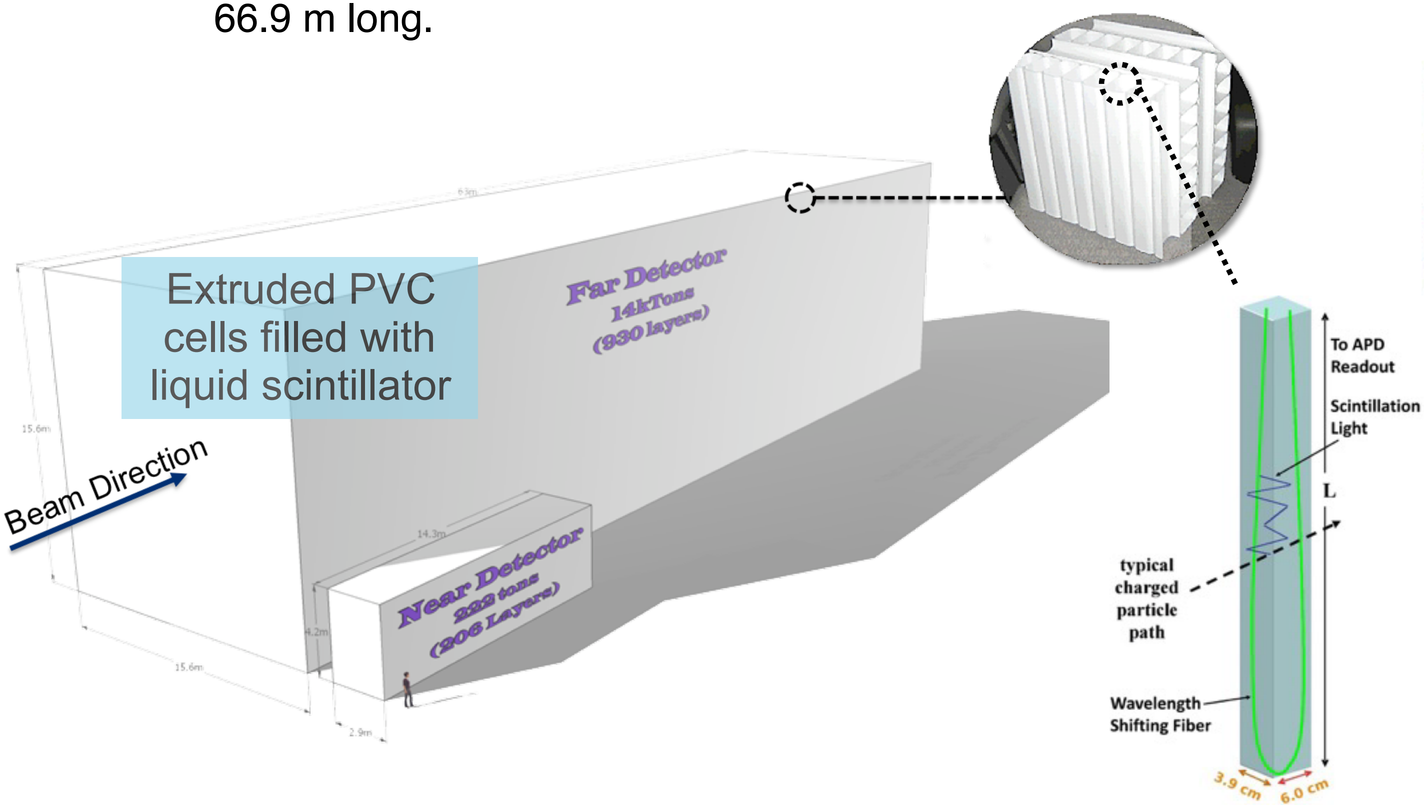
NOvA Experiment: The Near and Far Detectors

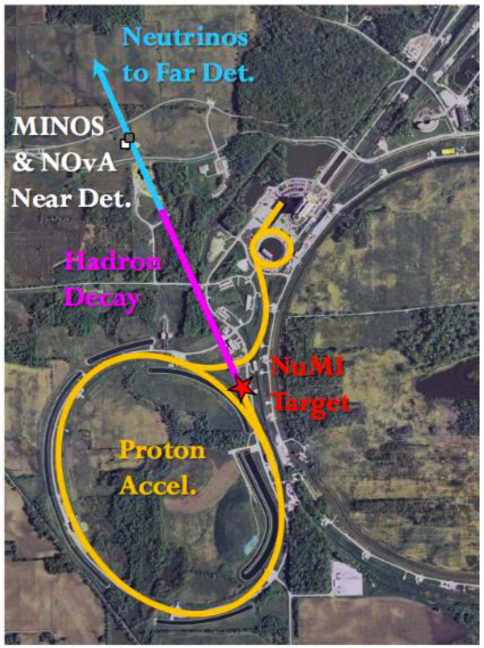
Far Detector (FD):

- fully active liquid scintillator;
- 810 km baseline (Ash River);
- 15.5 m wide, 15.5 m tall and 66.9 m long.

Near Detector (ND)

- ~1 km from NuMI target;
- 3.9 m wide, 3.9 m tall and 12.67 m long;
- smaller copy of the FD, used to predict flux in the FD.





NOvA Experiment: Physics with NOvA

Appearance

- With $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Mass hierarchy;
  - Determine the θ_{23} octant;
  - δ_{CP} ;

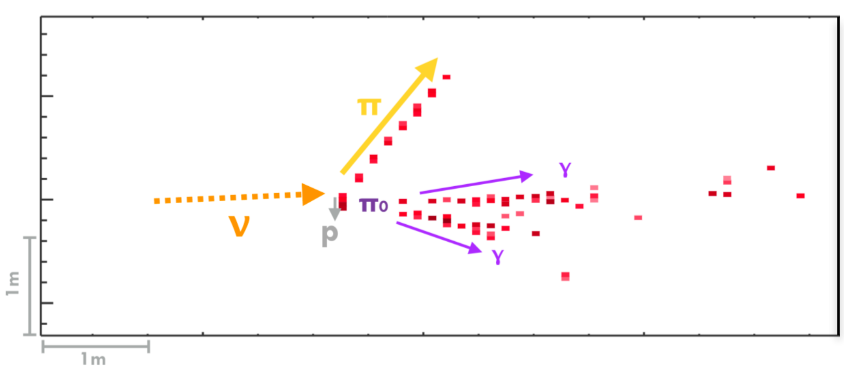
Disappearance

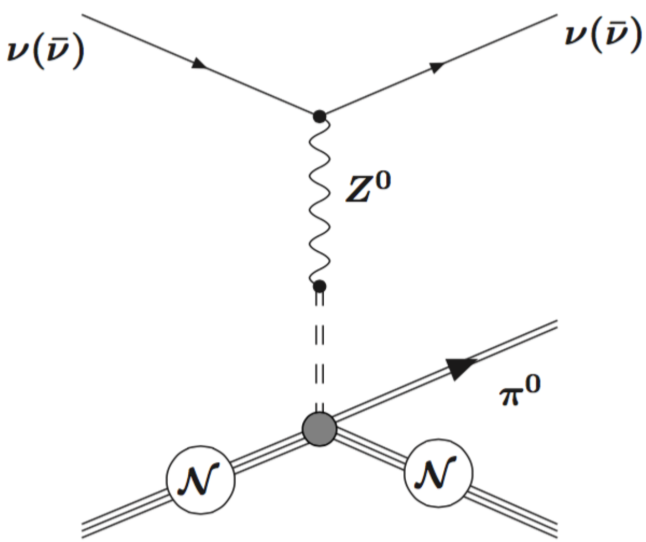
- With $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
  - $\text{Sin}^2(2\theta_{23})$;
  - Δm_{32}^2 .
- Also:
  - Neutrino cross-sections at the NOvA ND;
  - SN neutrinos;
  - Search for sterile neutrinos;
  - ….

NC neutrino interactions with π_0s in the final state
Physics & Motivation

NC π_0 events are the Main Background for NOvA $\nu_\mu \rightarrow \nu_e$ as the π_0 can fake ν_e appearance

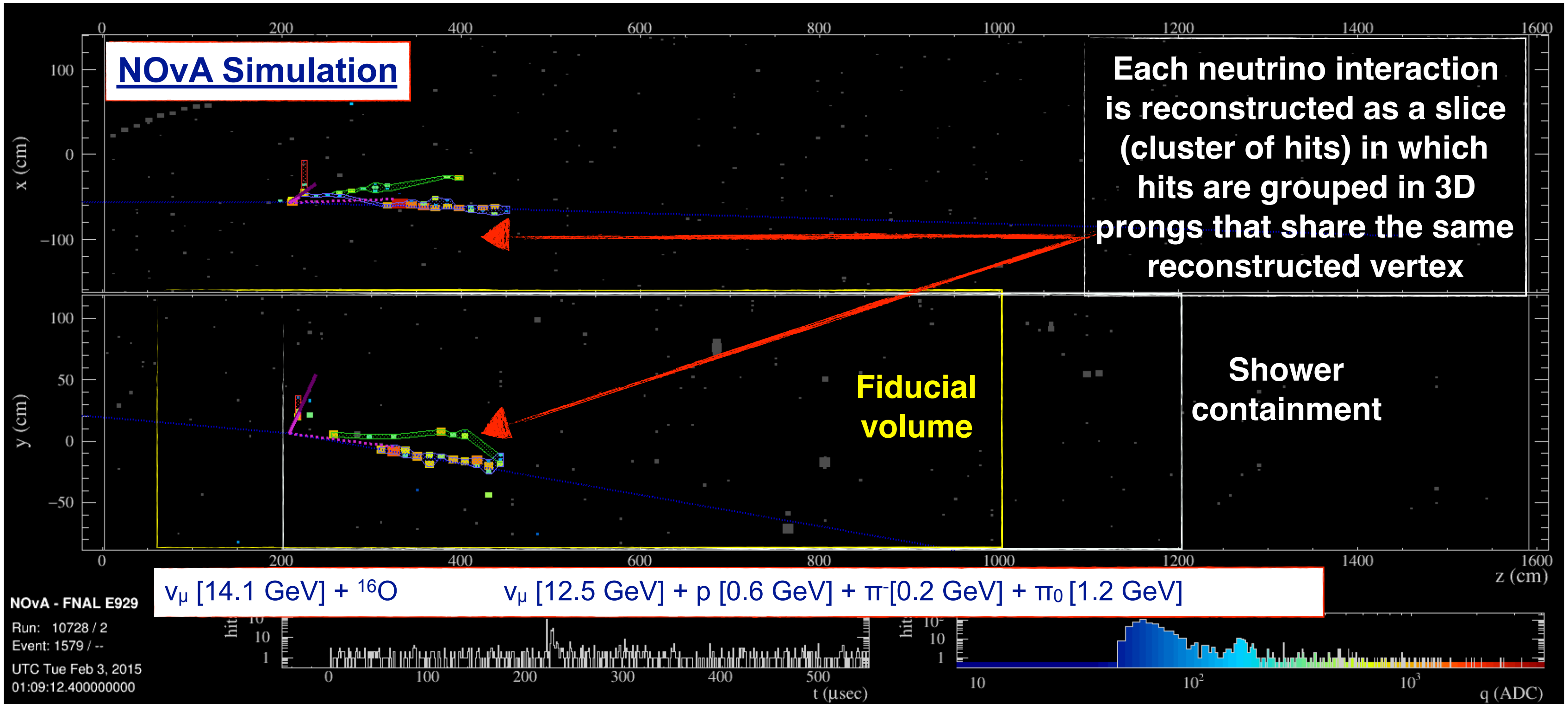
The signature for ν_e appearance is a single electron shower.
e showers can be faked by $\pi_0 \rightarrow \gamma\gamma$ showers, where the 2γ showers are reconstructed as one or one is not identified at all





NC π_0 Inclusive in the NOvA ND: NOvA Reconstruction

Reconstructed vertex in the fiducial volume and showers contained in the ND



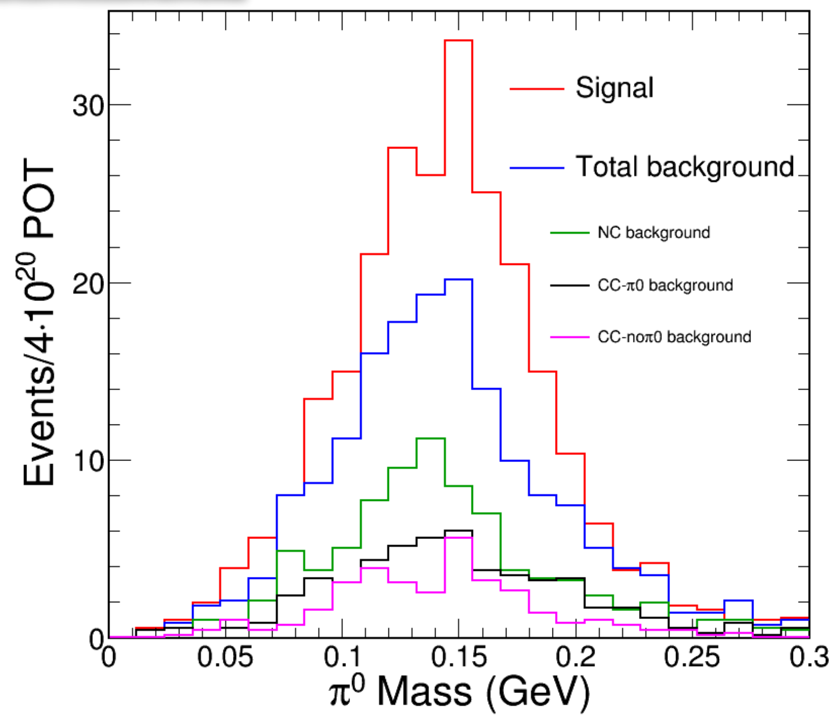
NC π_0 Inclusive in the NOvA ND: Current Status

Our Signal:

- ν_μ NC interactions;
- at least one π_0 with KE π_0 > 0.5 GeV.

- First studies: cut-based selection of some significant variables for 2-prongs and 3-prongs events brought to a quite good S/B separation, but the efficiency can be improved.
- New approaches currently under studies:
  - multivariate analysis;
  - **CVN prong based particle identification.**

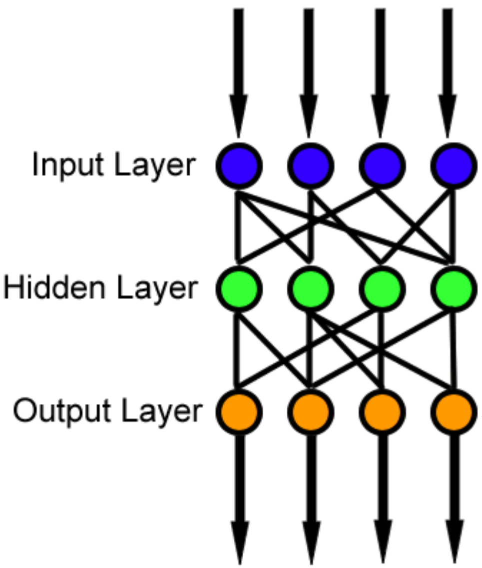
NOvA Simulation



Convolutional Visual Network (CVN)

Convolutional neural network (CNN), based on modern image recognition technology

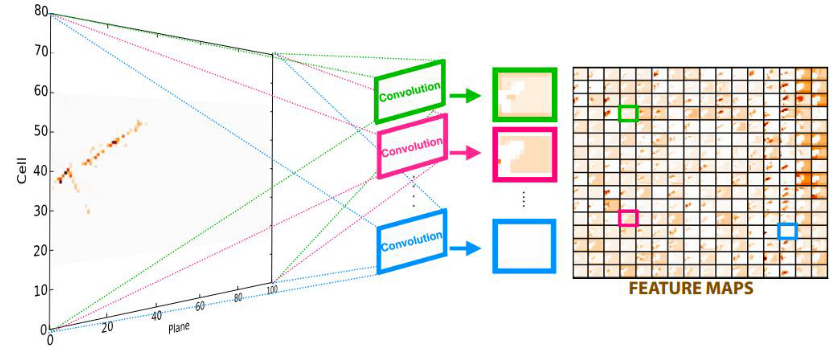
Feed-forward artificial neural network in which the connectivity pattern is inspired by the animal visual cortex

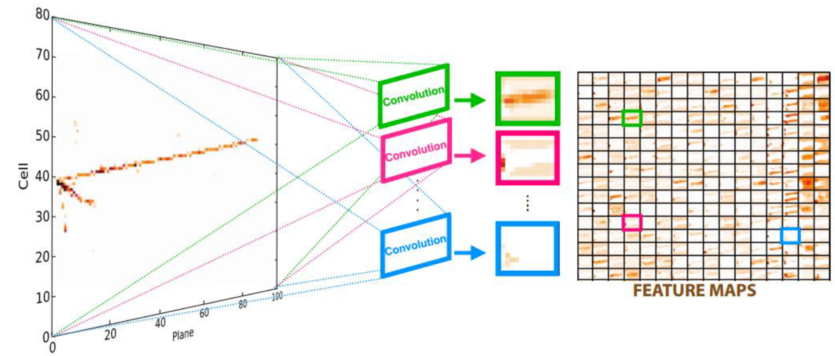


Calibrated hit maps
("Pixel Maps")

Convolution filters

Abstract features to be used as inputs to a CNN to classify the event





Already used as a PID with high performances for $\boldsymbol{\nu_\mu \rightarrow \nu_e}$, sterile neutrinos and ν_μ disappearance

Statistical power equivalent to 30% more exposure ($\nu_\mu \rightarrow \nu_e$)

CVN NC π_0 in the ND (1)

- CVN in NOvA trained mainly for ν_μ , ν_e and *NC* ID;
- Training was based on pixel maps for entire slices. In NC π_0 events most of the info comes from the γ prongs;

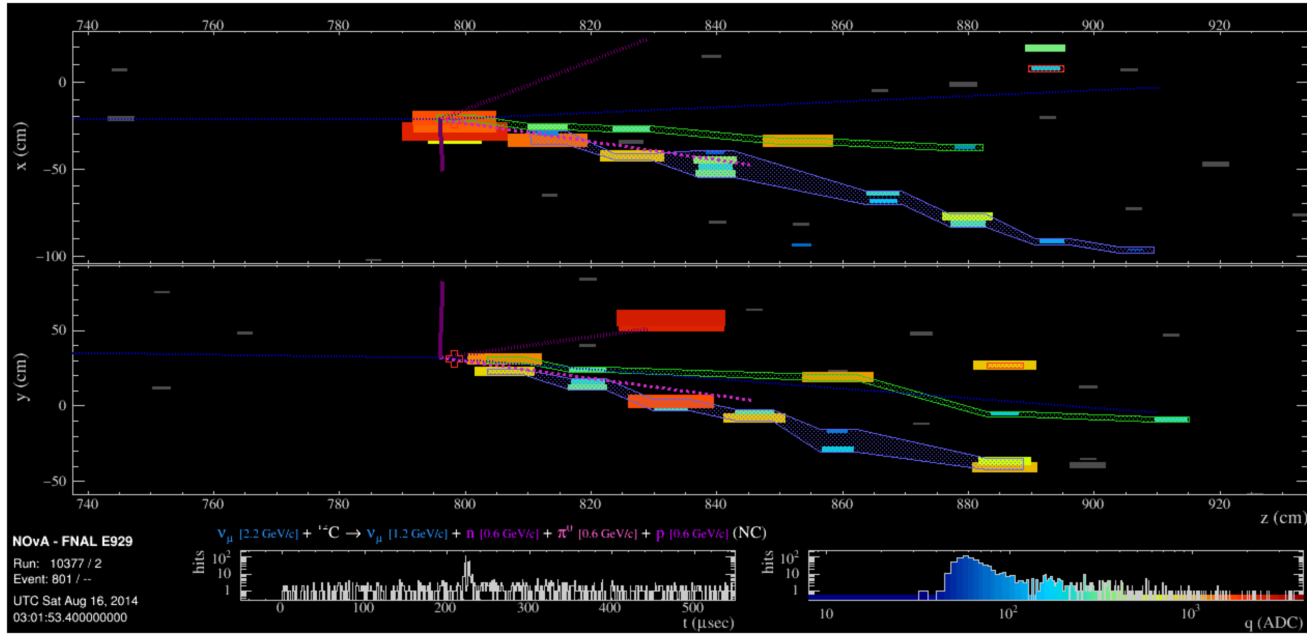
➡ Prong based CVN study for NC π_0 in the ND;

- The first checks are on the γ-purity of the prongs: identification of the reconstructed prongs in the signal events that are given by the γ from π_0 decay and study of their purity by matching reconstructed prongs with MC truth information;
- Purity = % of the contribution of a particle to that prong;
- Let's take a look at some event display →

CVN NC π_0 in the ND: Example of a Lucky Event

ν_μ [2.2 GeV] + ^{12}C ⟶ ν_μ [1.2 GeV] + n [0.6 GeV] + p [0.6 GeV] + π_0 [0.6 GeV]

- Res Interaction;
- E (ν_μ) = 2.2 GeV;
- 3 Primaries:
  - p;
  - n;
  - π_0.



- 3 prongs:
  - 2 EM-like;
  - 1 from an *α* particle (classified as a *nucleon* prong).

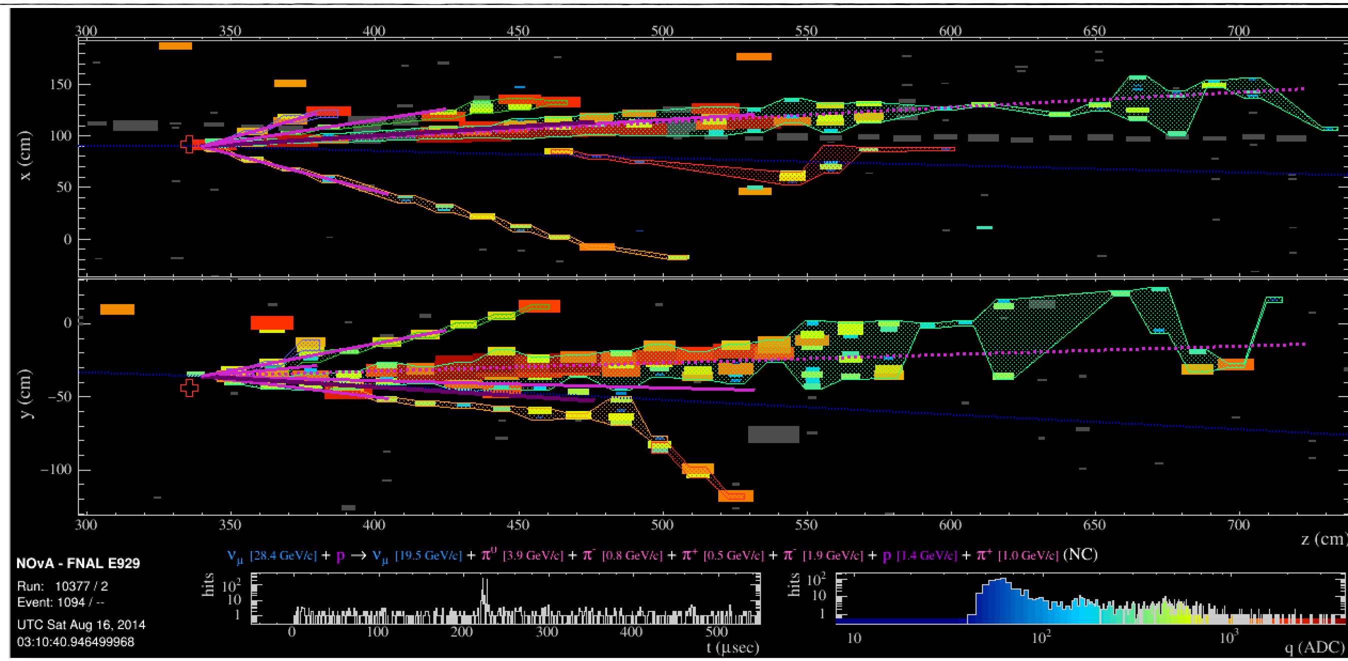
They come from the two π_0's γ:

- One has 100 % purity;
- The other 91 % (9 % comes from *p*).

CVN NC π_0 in the ND: Example of a Common Event

ν_μ [28.4 GeV] + p $\longrightarrow$ ν_μ [19.5 GeV] + π^- [0.8 GeV] + p [1.4 GeV] + π_0 [3.9 GeV] + π^+ [0.5 GeV] + π^- [1.9 GeV] + π^+ [1.0 GeV]

- DIS Interaction;
- E (ν_μ) = 28.4 GeV;
- 6 Primaries:
  - p;
  - 2 π^+;
  - 2 π^-;
  - π_0.



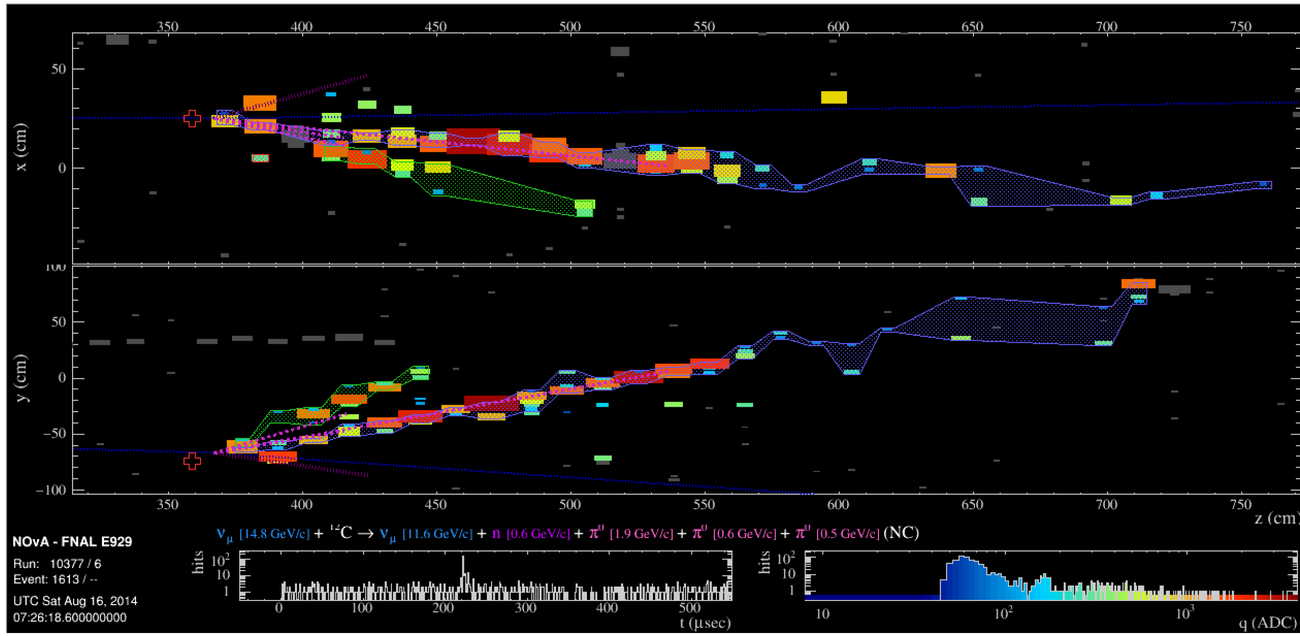
- 5 prongs:
  - 1 EM-like;
  - 2 from one π^-;
  - 2 from *p*.

Purity 36 %, the rest comes from a mixture of other particles.

CVN NC π_0 in the ND: Example of a Multi-π_0 Event

- DIS Interaction;
- E (ν_μ) = 14.8 GeV;
- 4 Primaries:
  - n;
  - 3 π_0 —> one below Kin. En. threshold
- 3 prongs:
  - 2 EM-like;
  - 1 from an α particle classified as a *nucleon* prong).

ν_μ [14.8 GeV] + ^{12}C ⟶ ν_μ [11.6 GeV] + n [0.6 GeV] + π_0 [1.9 GeV] + π_0 [0.6 GeV] + π_0 [0.5 GeV]



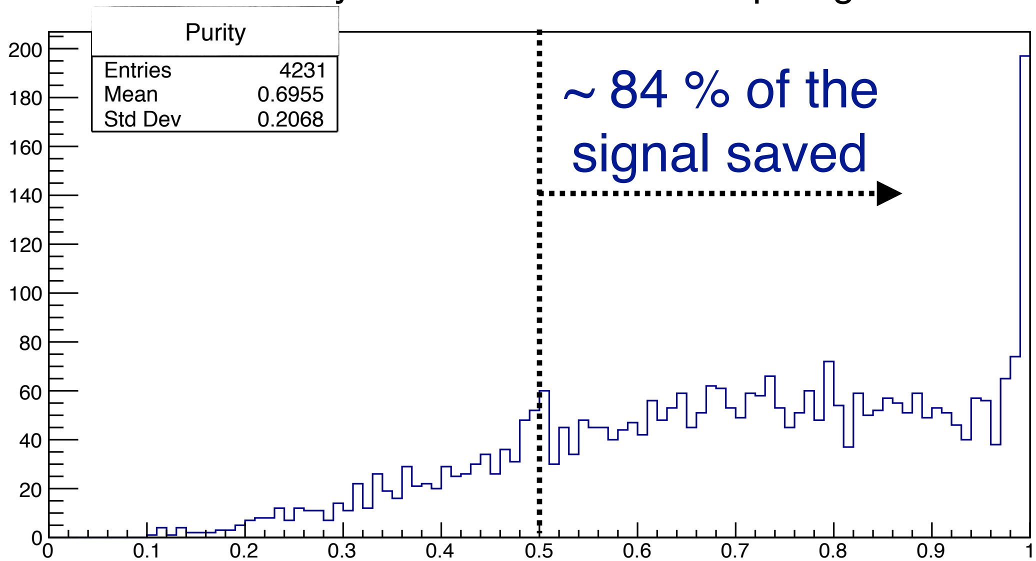
- π_0^1—> γ^4 (Png0 16 %) γ^5 (Png2 80 %)
- π_0^2—> γ^6 (Png2 13 %) γ^7 (Png1 74 %)
- π_0^3—> γ^8 γ^9 (Png1 & Png2) —> Below Threshold

They don't both come from one of the two π_0's γ:

- One has a purity of 74 %;
- The other 80 %;
- The missing 26 % and 20 % are a mixture of the other γ (from the π_0 below threshold too).

Prong Purity Distributions

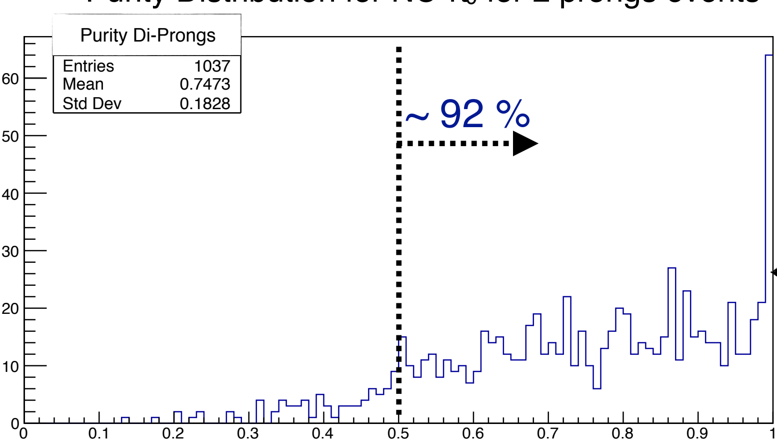
Purity Distribution for NC-π_0 prongs



What if we require a prong to be at least 50% pure in a π_0's γ?

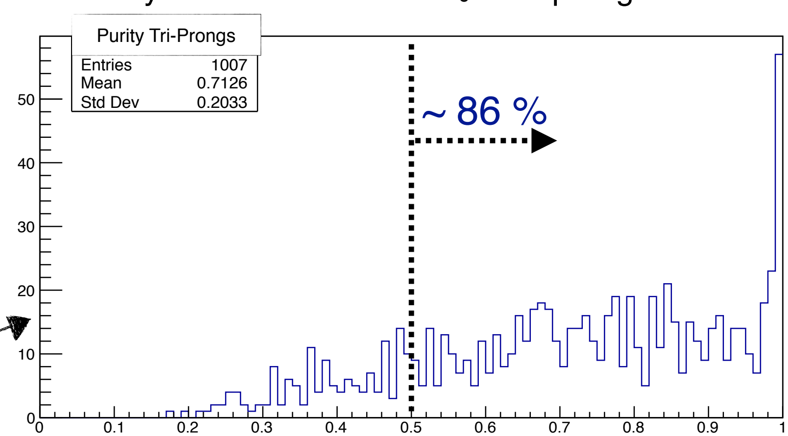
Prong purity for all of the signal events

Purity Distribution for NC-π_0 for 2 prongs events



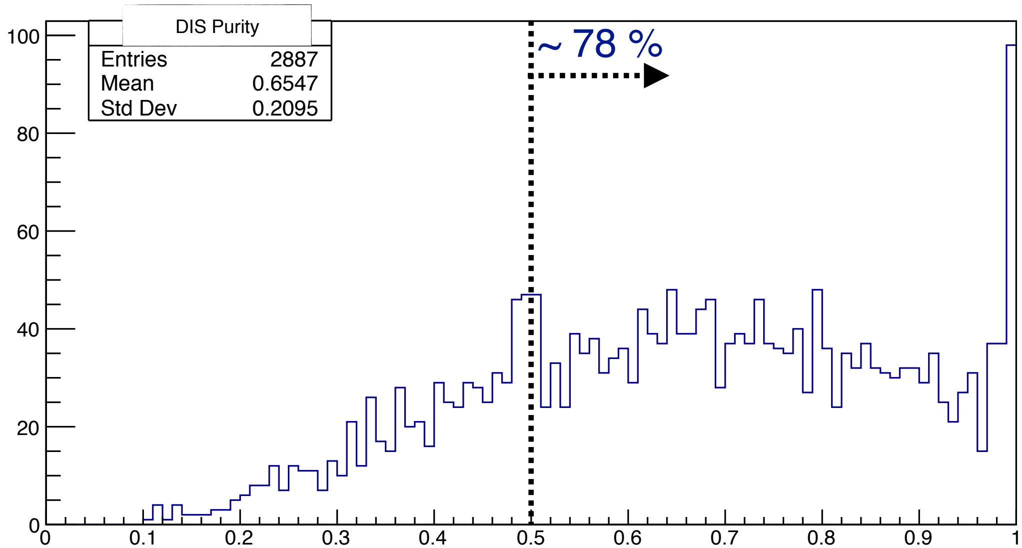
Sub categories: events with 2-prongs and 3-prongs

Purity Distribution for NC-π_0 for 3 prongs events



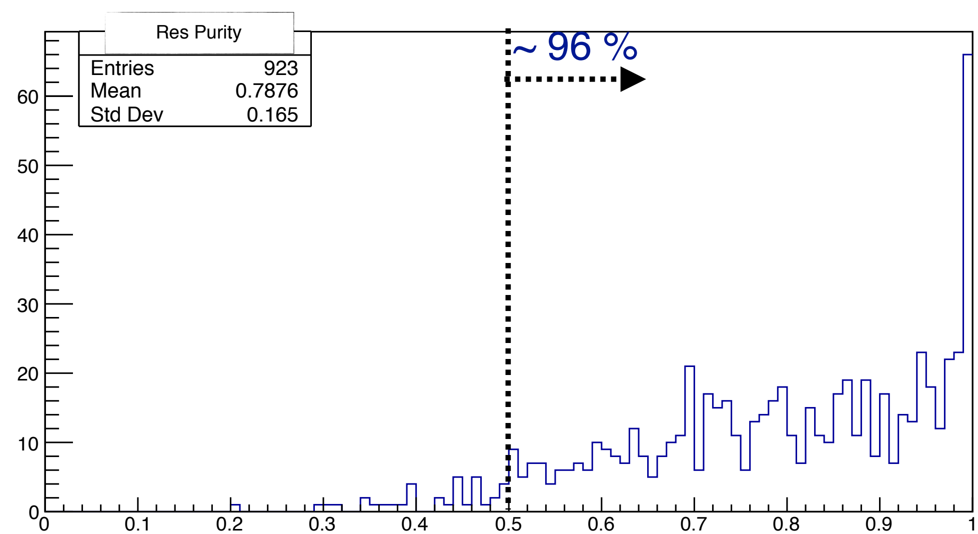
Purity Distributions —> Breakdown by Interaction Types

Purity Distribution for NCDIS-π_0



I also studied the prong purity making distinctions between the different kind of NC interactions (DIS, Res, Coh, QE);

Purity Distribution for NCRes-π_0



CVN NC π_0 in the ND (2)

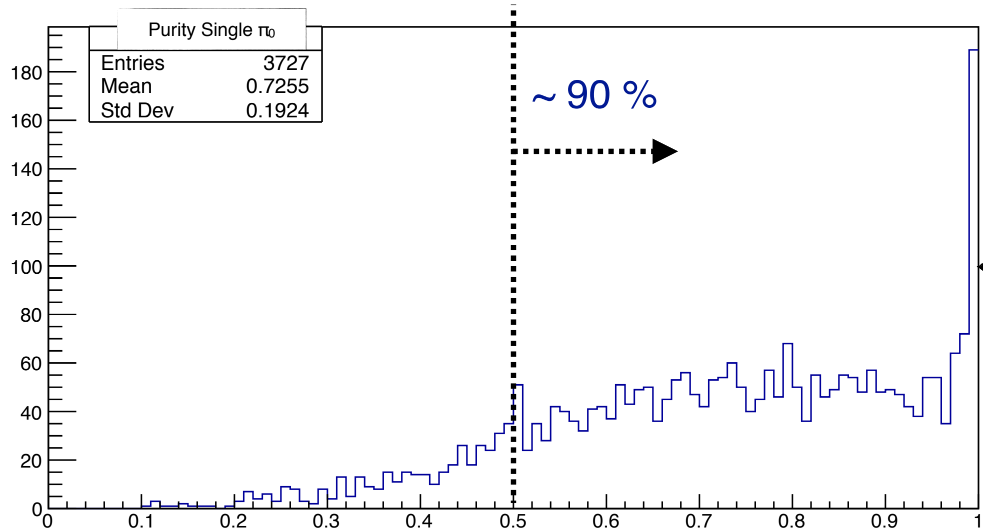
- There's a number of possibility for a new training to build a π_0 ID Prong Based: one can consider just the prong by prong information or include also the slice (to keep informations such the distance from the vertex);

- Prong by prong or EM-like coupled prongs (from the same π_0)?

  Selection of good single-π_0 events →

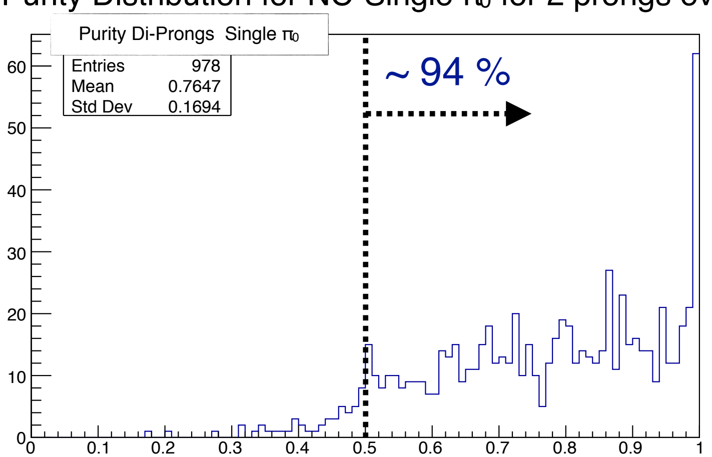
Single π_0 Purity Distributions

Purity Distribution for NC-Single π_0 prongs



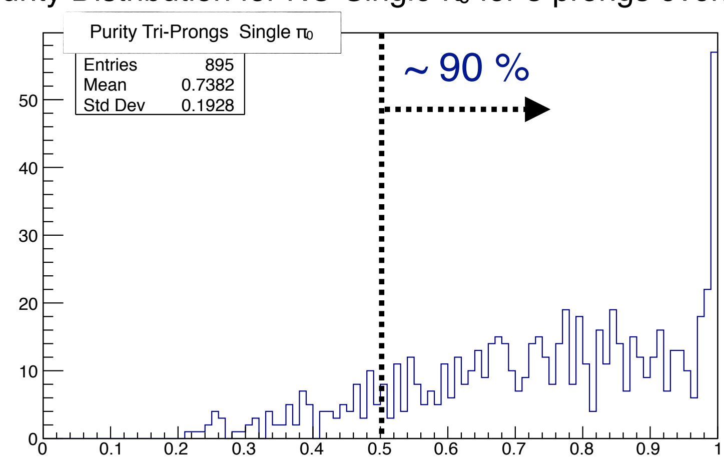
Prong purity for all of the signal events

Purity Distribution for NC-Single π_0 for 2 prongs events



Sub categories: events with 2-prongs and 3-prongs

Purity Distribution for NC-Single π_0 for 3 prongs events



CVN NC π_0 in the ND (3)

- Training developed focusing on EM-like coupled prongs (from the same π_0) maintaining the slice information;
- So some changes were necessary to create Pixel Maps containing the aforementioned infos and new labels needed;
- Pixel Maps are normally created starting from the hit info (# of hit cells and planes and energy deposited) of each prong, in our case we merge together two prongs to create a map;
- Then from Pixel Maps to two datasets: test (20%) and training (80%).

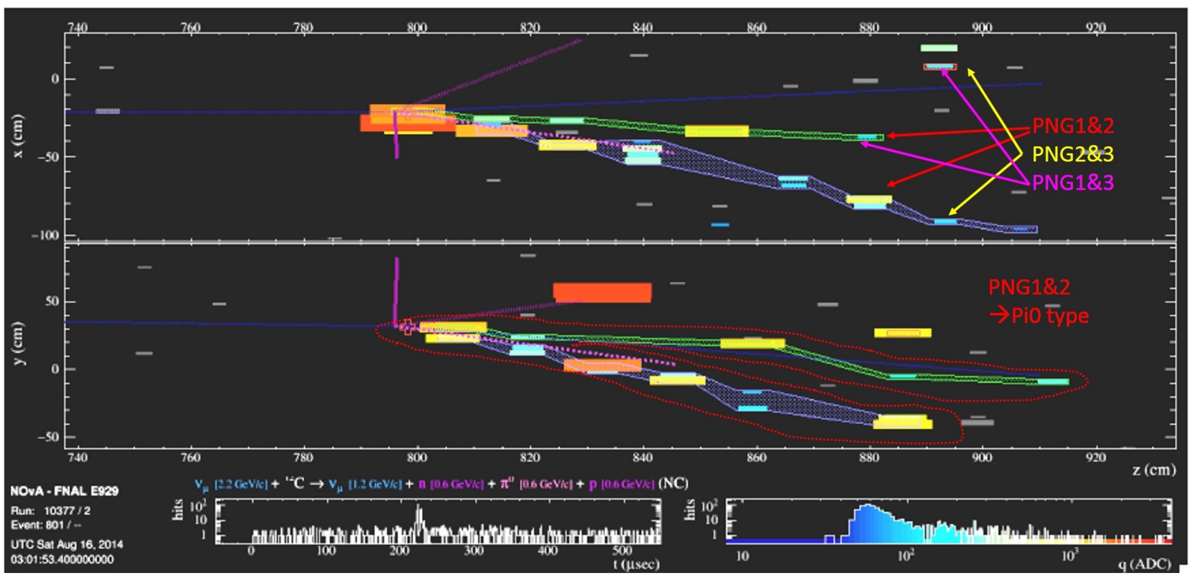
CVN NC π_0 in the ND: The Labels

- CVN takes as input both the labels and the Pixel Map and associate them;
- Considering the Pixel Maps were different, different labels were needed; ·····→
- **I wrote, tested and implemented this new part of the code for the NOvA software.**

Prong Type
e o μ = Leptons
p o n = Hadrons
π^{+-} = Mesons
π^{0} = Pi0
OtherPDG
Unkwn
Empty

All the possible couples are taken into account

Prong 1	Prong 2	Couple Type
Lep	Lep	LepLep
Lep	Had	LepHad
Lep	Gamma	LepGamma
Lep	Mes	LepMes
Lep	Pi0	LepPi0
Lep	Oth	LepOth
Had	Had	HadHad
Had	Gamma	HadGamma
Had	Mes	HadMes
Had	Pi0	HadPi0
Had	Oth	HadOth
Gamma	Gamma	GammaGamma
Gamma	Mes	GammaMes
Gamma	Pi0	GammaPi0
Gamma	Oth	GammaOth
Mes	Mes	MesMes
Mes	Pi0	MesPi0
Mes	Oth	MesOth
Pi0	**Pi0**	**Pi0Pi0**
Pi0	Oth	Pi0Oth
Couple	Unknwon	Unknwon



Conclusions

- CVN is a new and still developing PID and used by NOvA experiment for the very latest results;
- Training CVN specifically for π_0 ID in the NOvA ND requires a detailed prong study;
- It's extremely useful for background study and cross sections measurements in the ND;
- I created a new mapping based on EM-like couples;
- Next step will be to start the training (almost there!);
- Then further studies for the FoMs, the efficiency, etc …;
- Stay tuned!