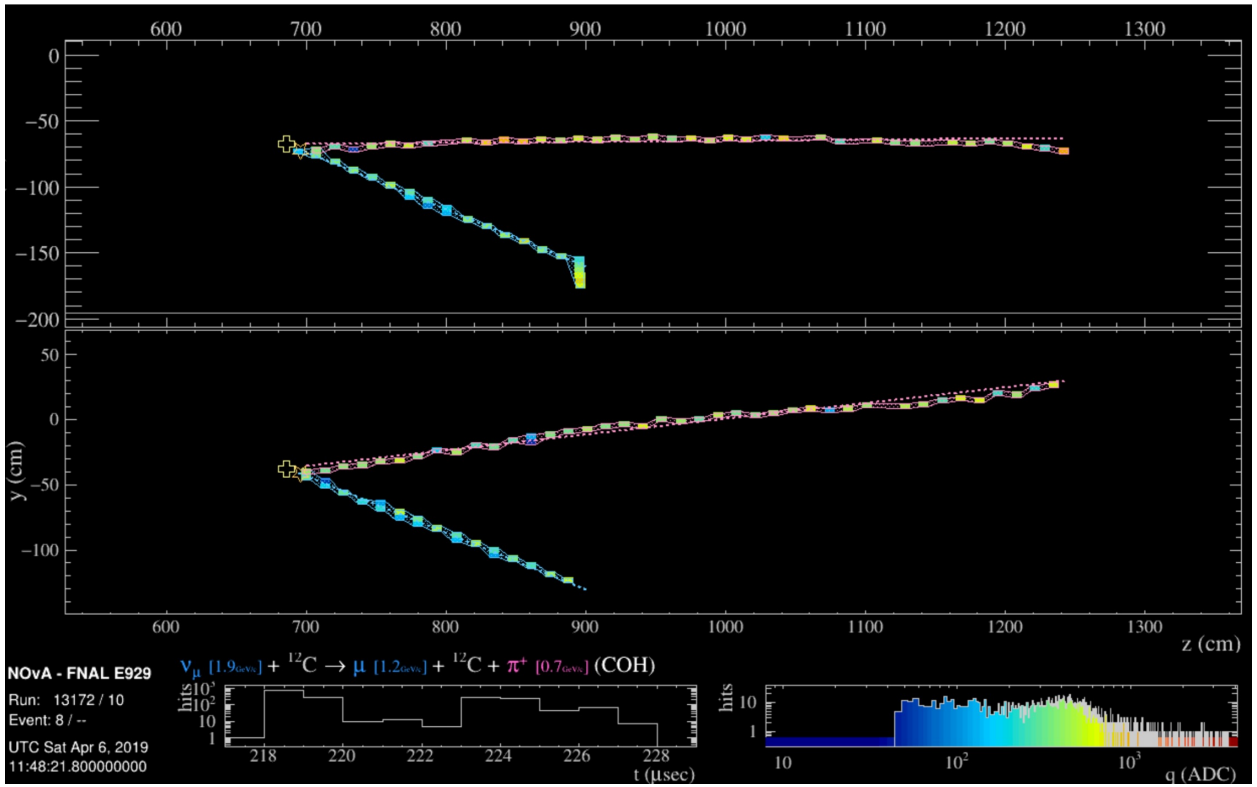
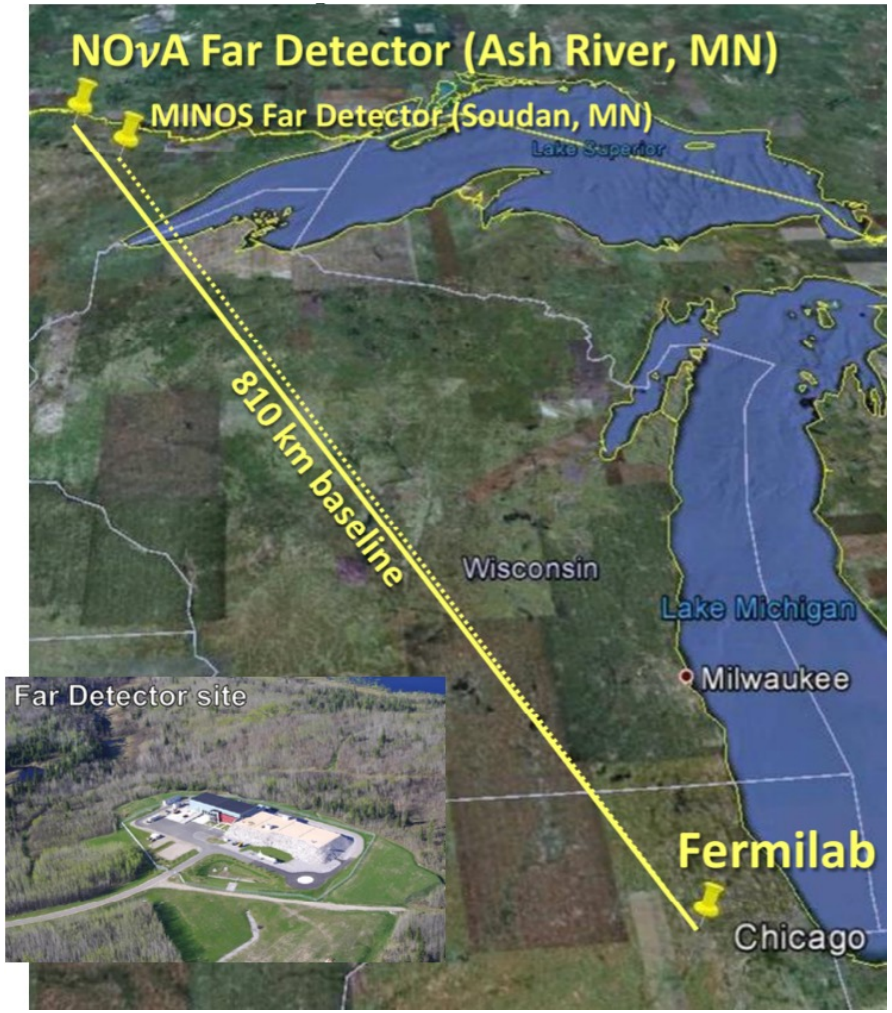
Status of the ν_μ CC Coherent π^+ Production in the NOvA Near Detector

On behalf of the NOvA collaboration



UNIVERSITY OF SOUTH CAROLINA

The NOvA Experiment

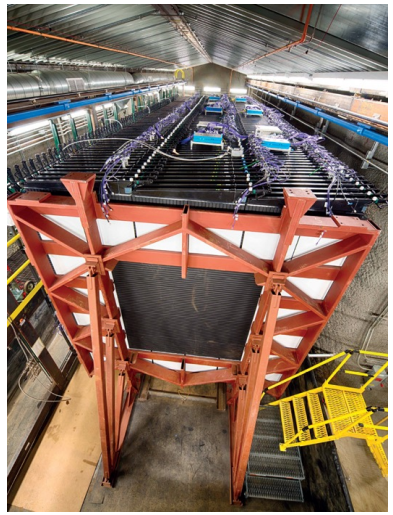


- A neutrino oscillation experiment with 810 km baseline, two structurally identical detectors, NuMI ν_μ 700 kW beam, off-axis

Main physics goals:

- $\nu_\mu \rightarrow \nu_e$ Oscillations
- Cross-section studies
- Sterile Neutrino studies
- Exotics
- More...

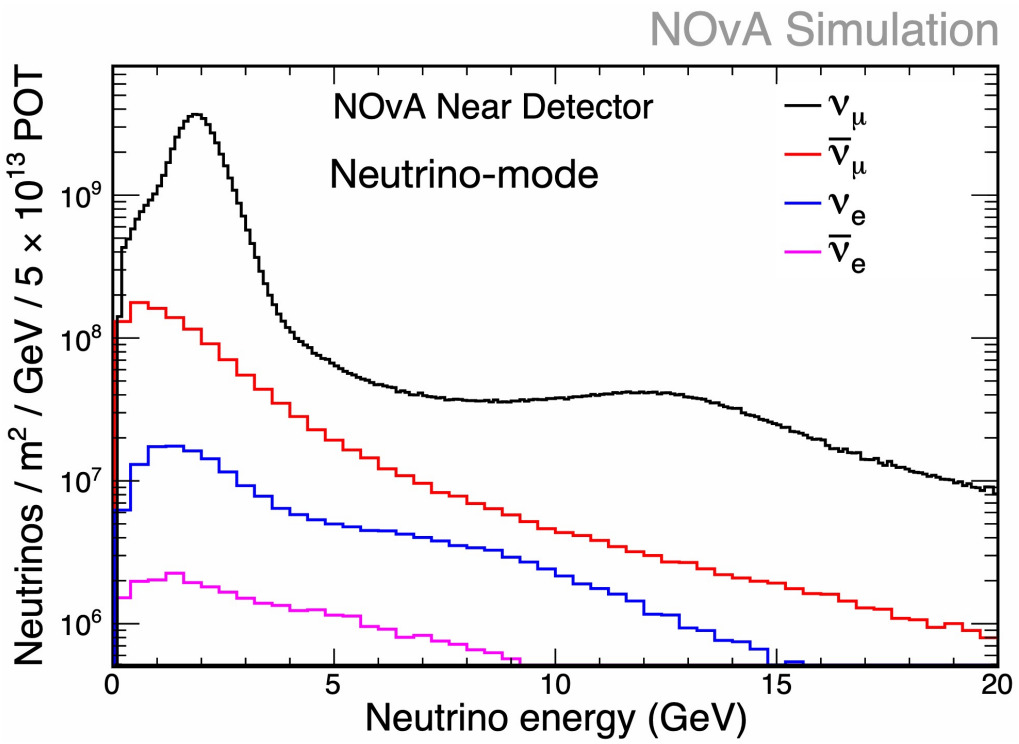
Far Detector

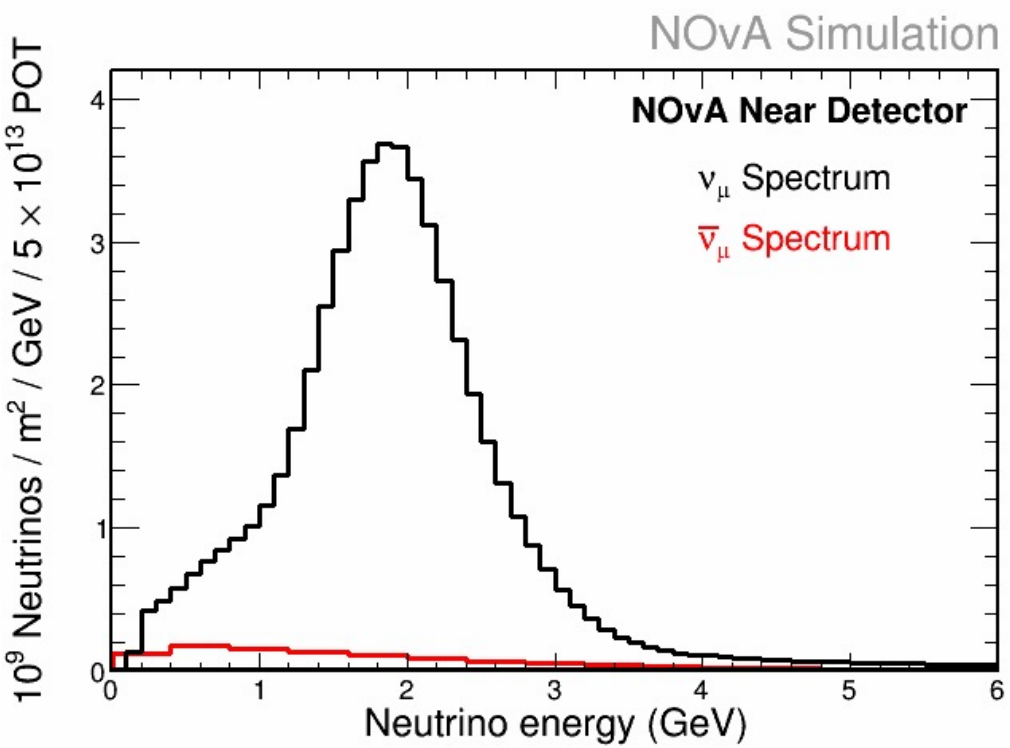


Near Detector

High statistics collected at the Near Detector can be used to study neutrino cross sections.!

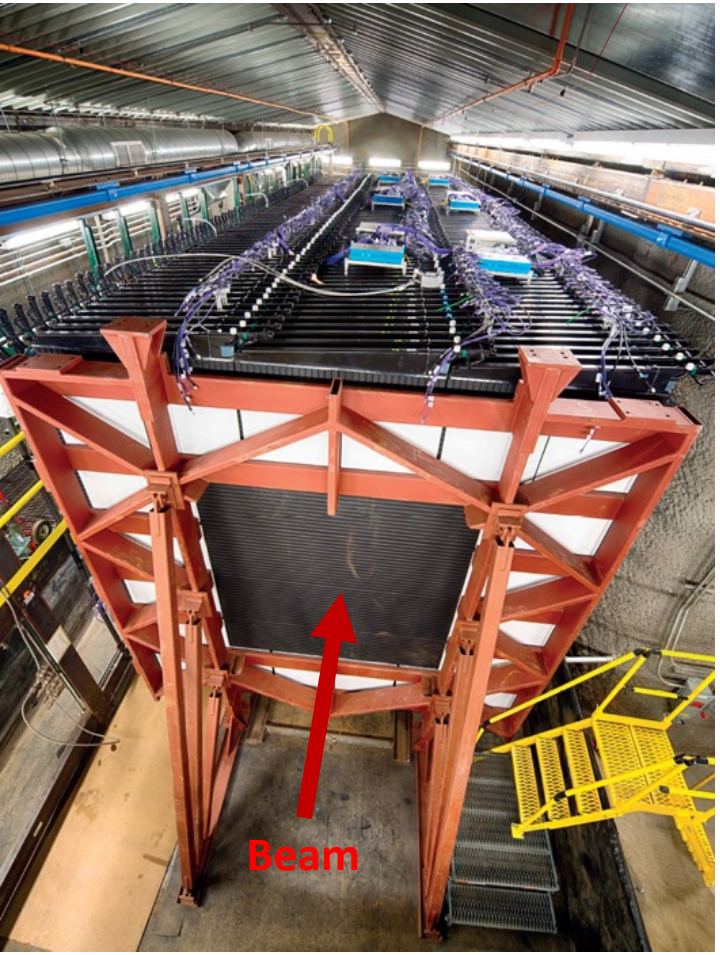
NOvA Beam Flux



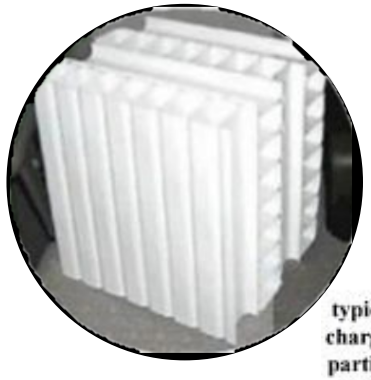


- flux has a peak between 1 and 5GeV
- receives high neutrino flux contains 96% pure ν_μ beam and 1% of ν_e and $\bar{\nu}_e$
- provides a rich data set for measuring cross-sections.

The NOvA Near Detector

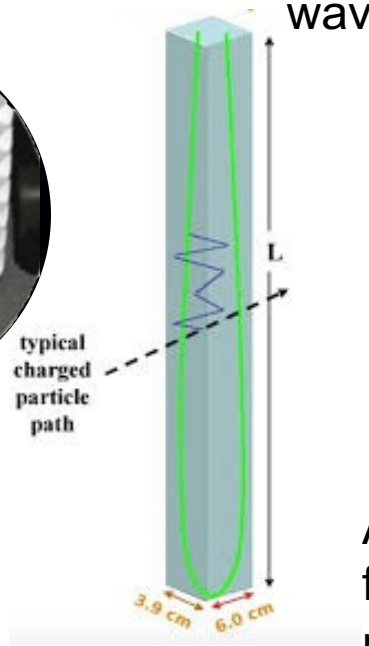


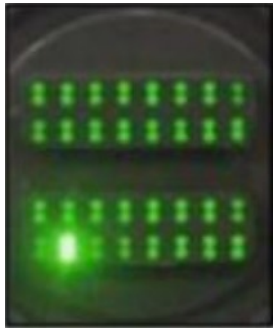
NOvA Near Detector located at the MINOS underground facility



Alternating horizontal and vertical planes for 3D reconstruction

A cell contains a single loop of wavelength shifting fiber



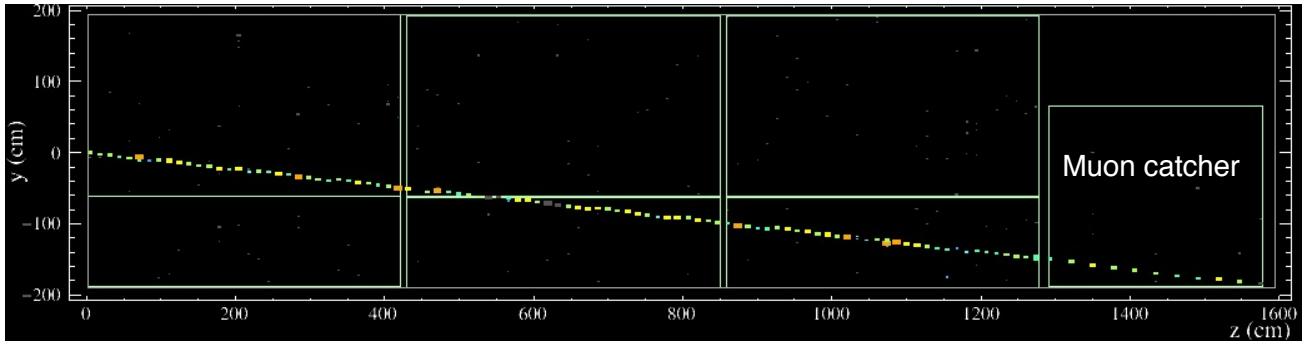


An array of wavelength shifting fibers ends that goes to avalanche photo diode interface

Wavelength shifting fibers read out by a single pixel on Avalanche Photodiode

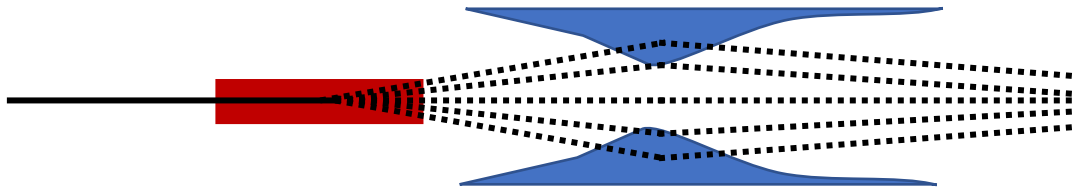
C-H	77%
Cl	16%
TiO_2	6%

Detector Composition



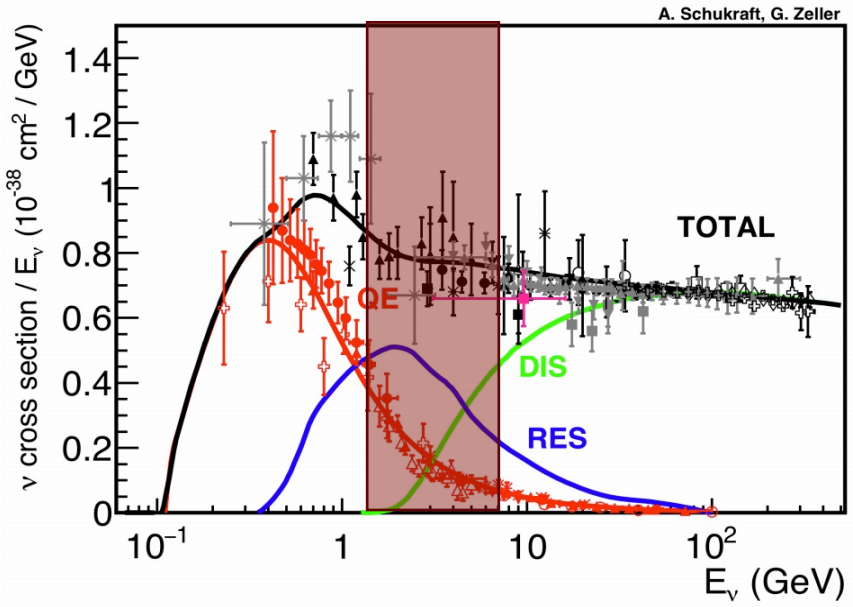
Side view of the NOvA Near Detector and Muon catcher

NOvA Simulation

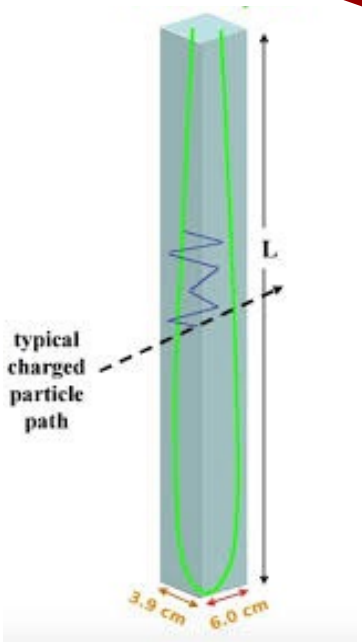


Beamline and flux: G4NuMI

ν-A modelling: GENIE



Detector response: GEANT4



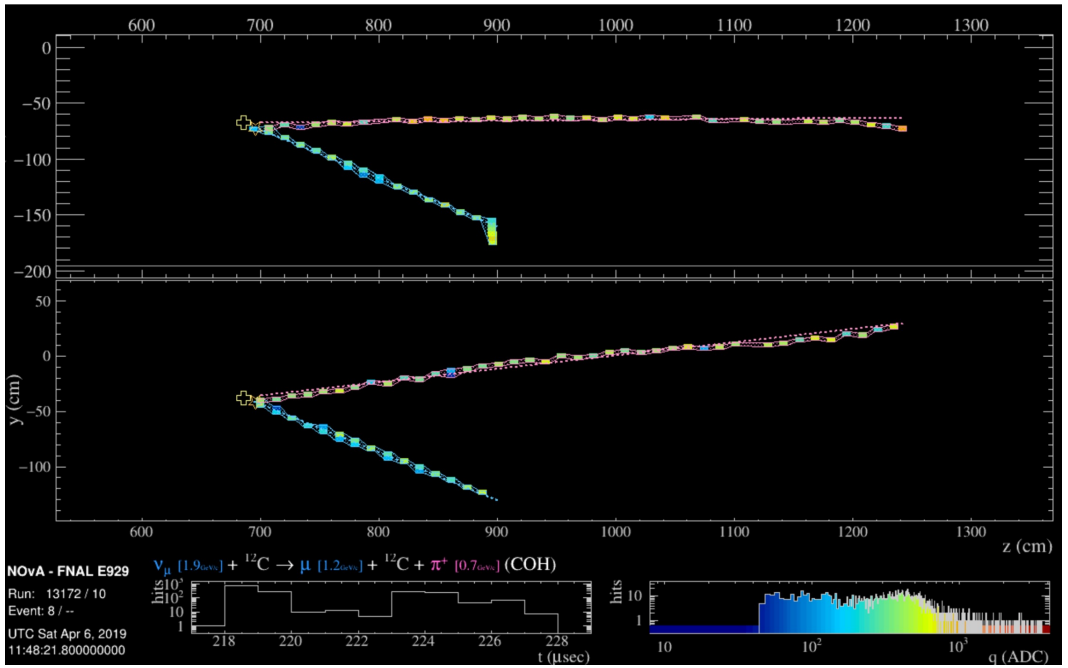
Readout electronics and DAQ: Custom simulation routines

Charged Current Coherent Interaction

- An inelastic interaction produces a lepton and a pion in the forward direction
- Nucleus (A) stays in its initial state.

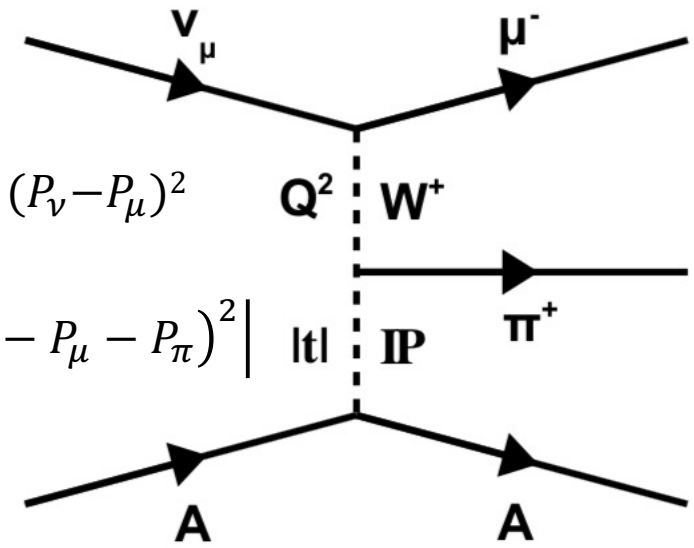
$$\nu_l + A \rightarrow l^- + \pi^+ + A$$

$$\bar{\nu}_l + A \rightarrow l^+ + \pi^- + A$$



$$Q^2 = (P_\nu - P_\mu)^2$$

$$|t| = \left|\left(P_\nu - P_\mu - P_\pi\right)^2\right|$$



- The square of the four-momentum exchanged with the nucleus, |t|, must be small.

Motivation

- **Theoretical Interests:**

Charged Current Coherent models are not very well understood.

Provides detailed tests for hypothesis such as:
- CVC
- PCAC
- HDM

- **Experimental Interests:**

Reconstructing E_ν is more accurate compared to other channels. (i.e. $E_\nu = E_\mu + E_\pi$)

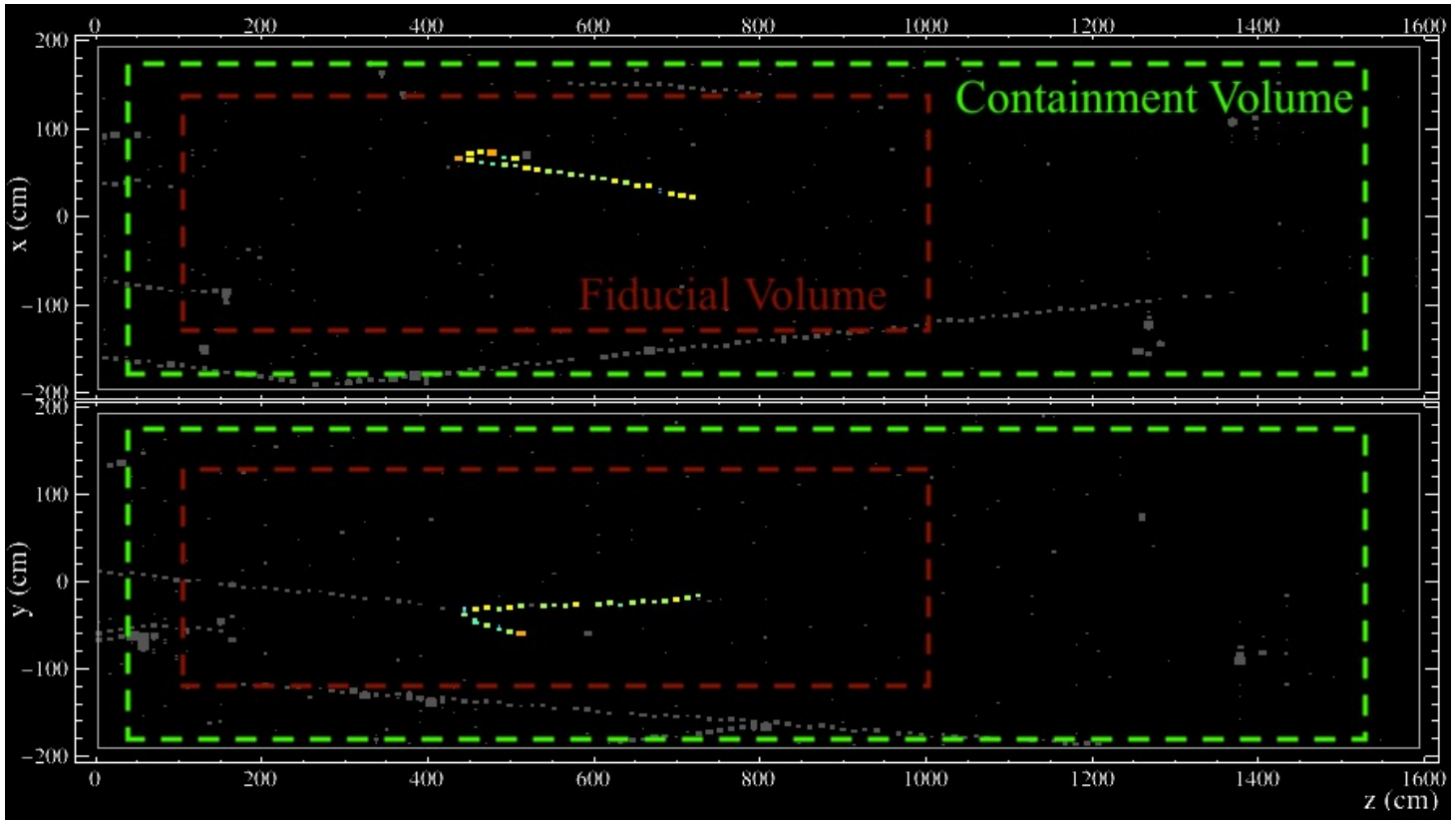
NOvA cross-section results will be useful for the upcoming DUNE experiment.

Coherent pion production can be mistaken for quasi-elastic scattering when the π^+ is misidentified as a proton or is not detected.

For isoscalar nuclei coherent π^+ and π^- cross sections are same.

Signal and Background Definitions

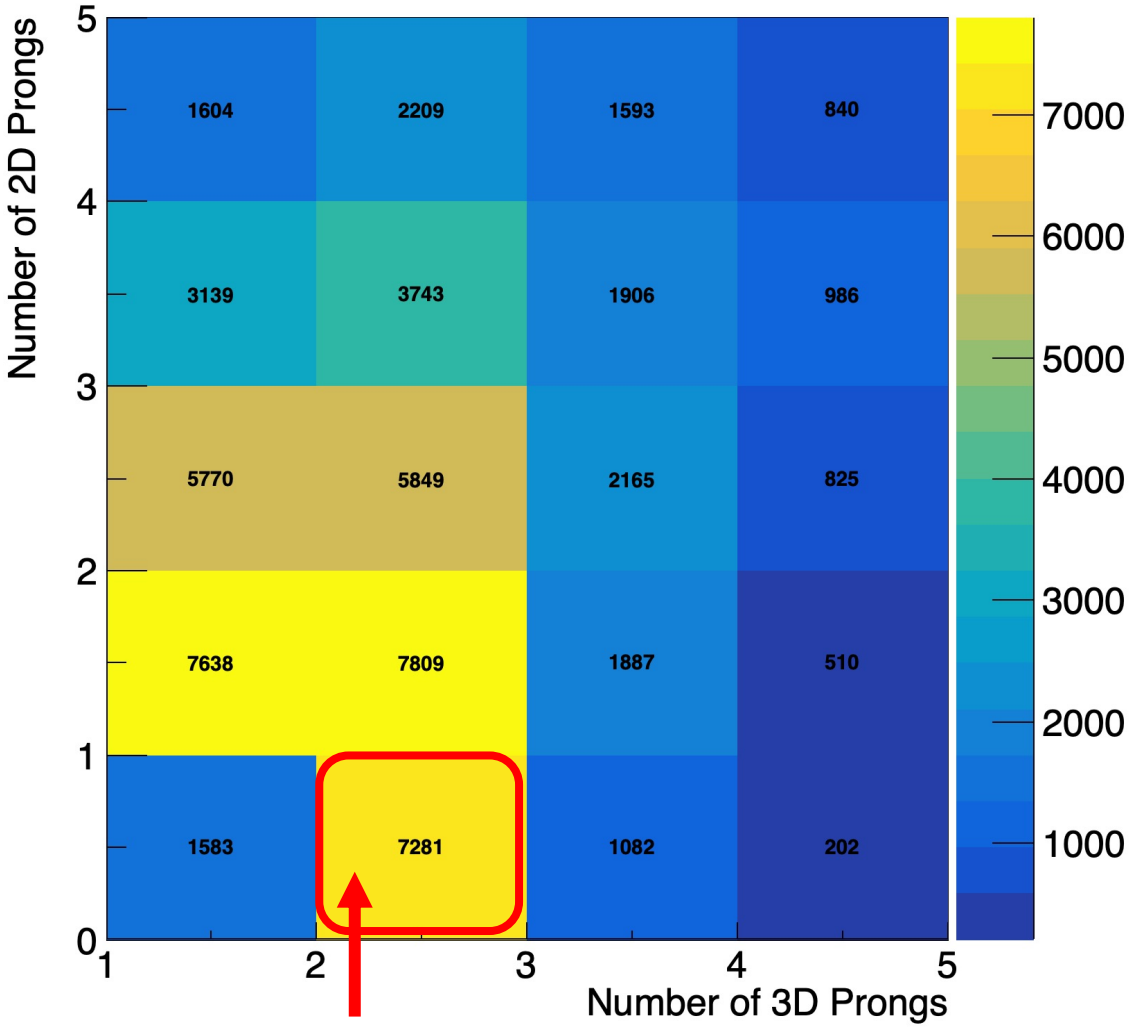
- Scaled down to POT 1.42e21



- Signal definition:
  ν_μ CC coherent interactions formed within the fiducial volume. (Currently using same fiducial volume defined in NuMi CC inclusive analysis.)
- Background definition:
  Interactions other than signal will be treated as Background. (!signal)

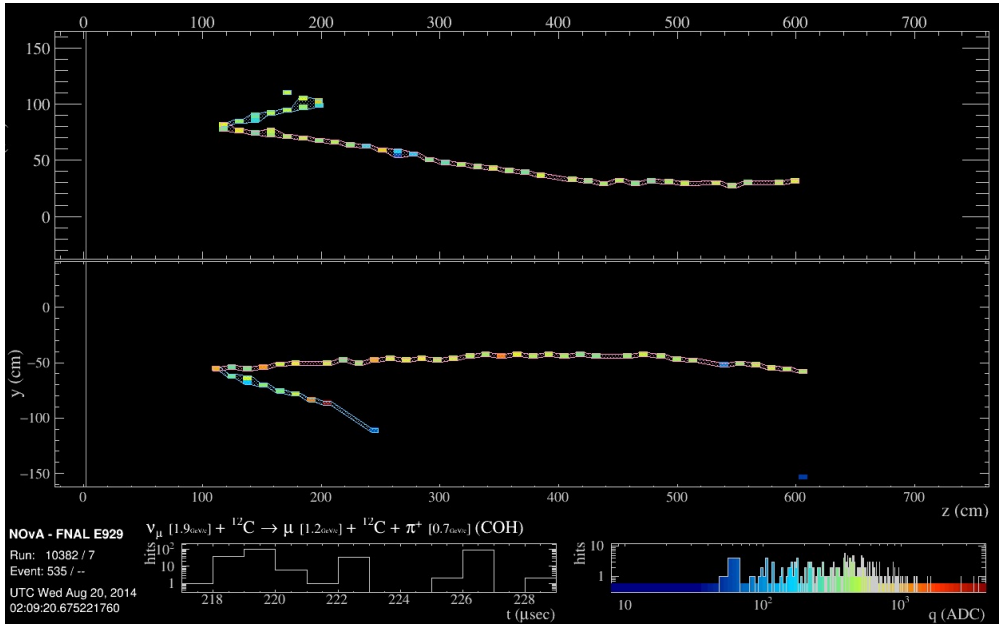
Current Topology

Topology Study

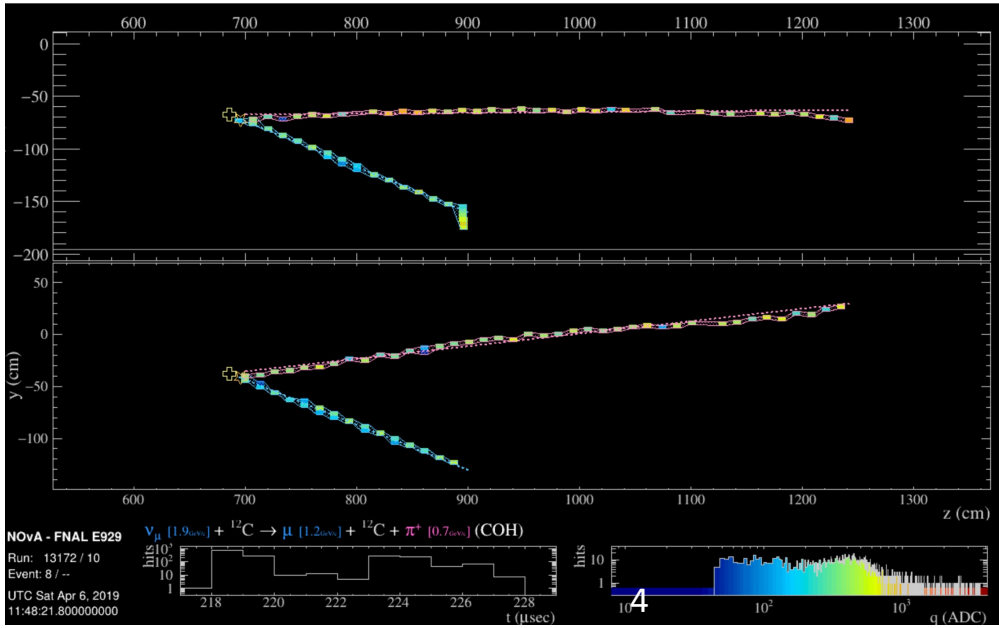


Currently analyzing golden event sample

Charged Current Coherent event reconstructed as two 3D prongs and one 2D prong



Charged Current Coherent event reconstructed as two 3D prongs



Note: Prong is a reconstructed particle candidate that has directional and reconstructed information

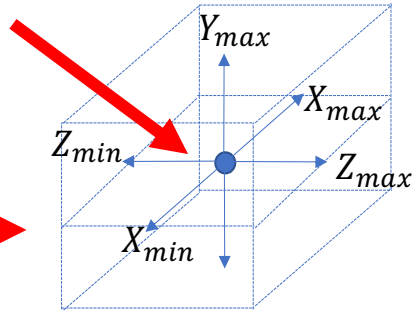
Event Selection

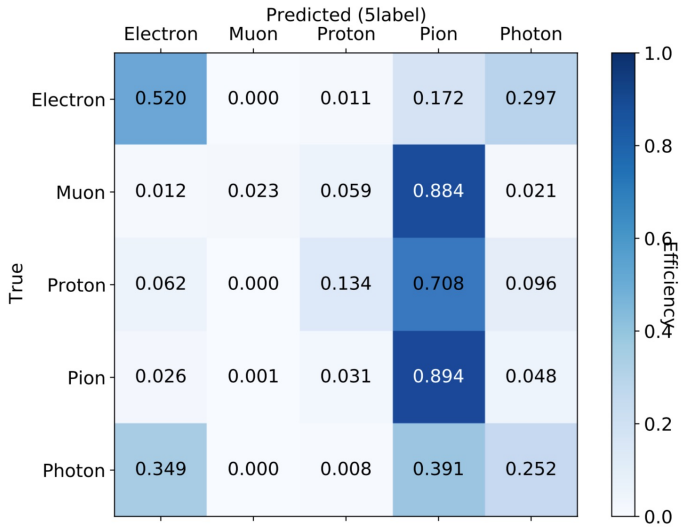
- Created following cuts to separate Signal and the Background
  - Data Quality Cut ✓
  - Fiducial Cut ✓
  - Containment Cut ✓

  From NuMu CC Inclusive analysis
  - Muon ID Cut (optimized muonID > 0.615) ✓
  - Two Prong Cut (Only use clean events) ✓
  - Pion ID Cut (PionID > 0.7) (using single particle cvn) ✓
  - Vertex Energy Cut (Extra VertexE10 > -0.079) ✓
  - Loose |t| Cut <= 0.2GeV ✓

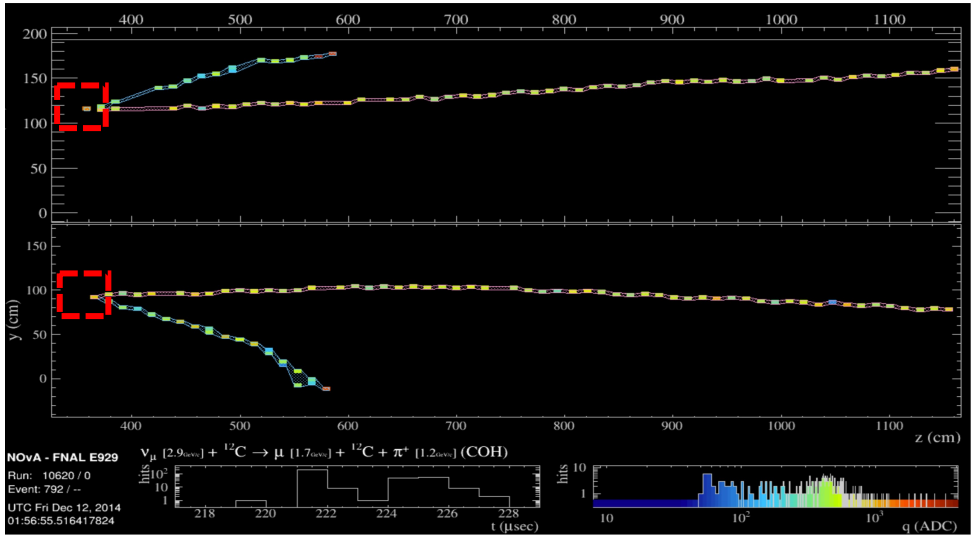
Primary Vertex

Volume drawn around interaction vertex to enclose reconstructed hits

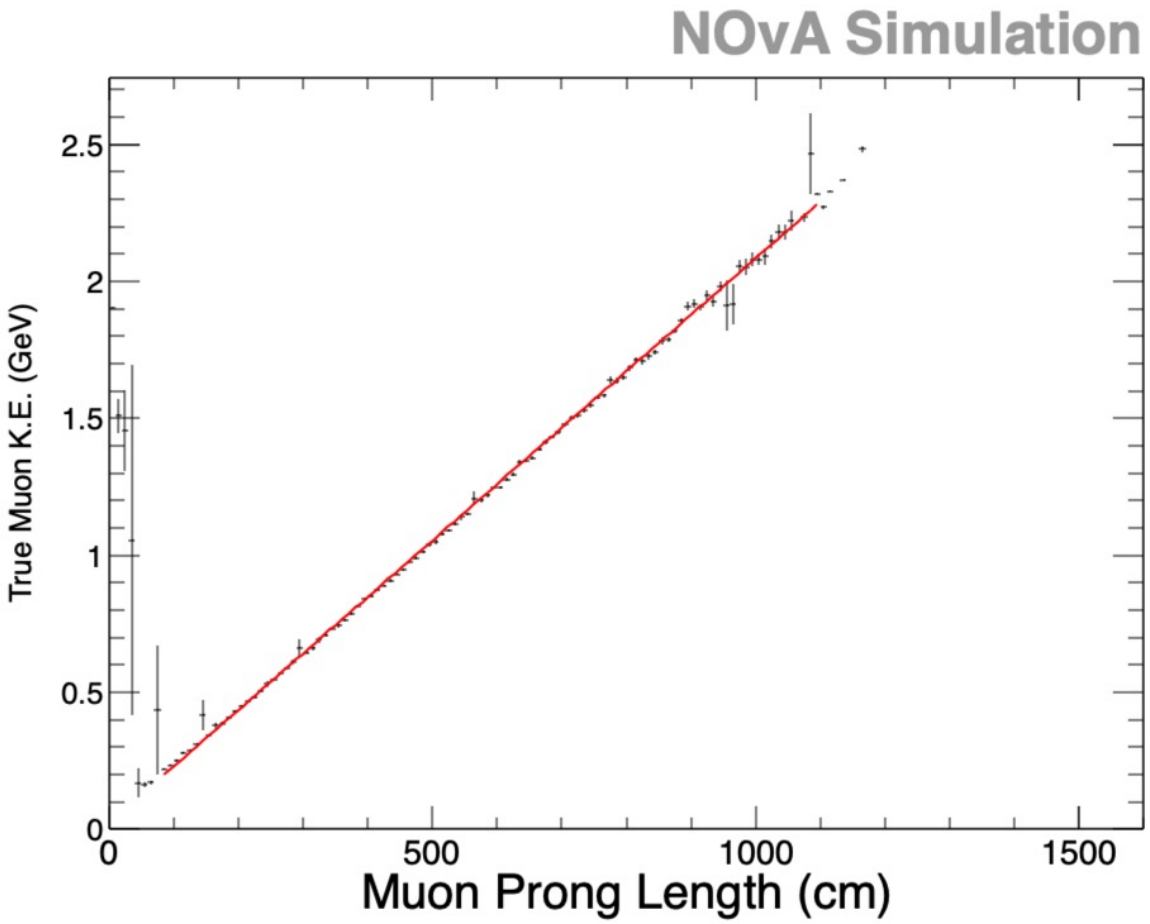


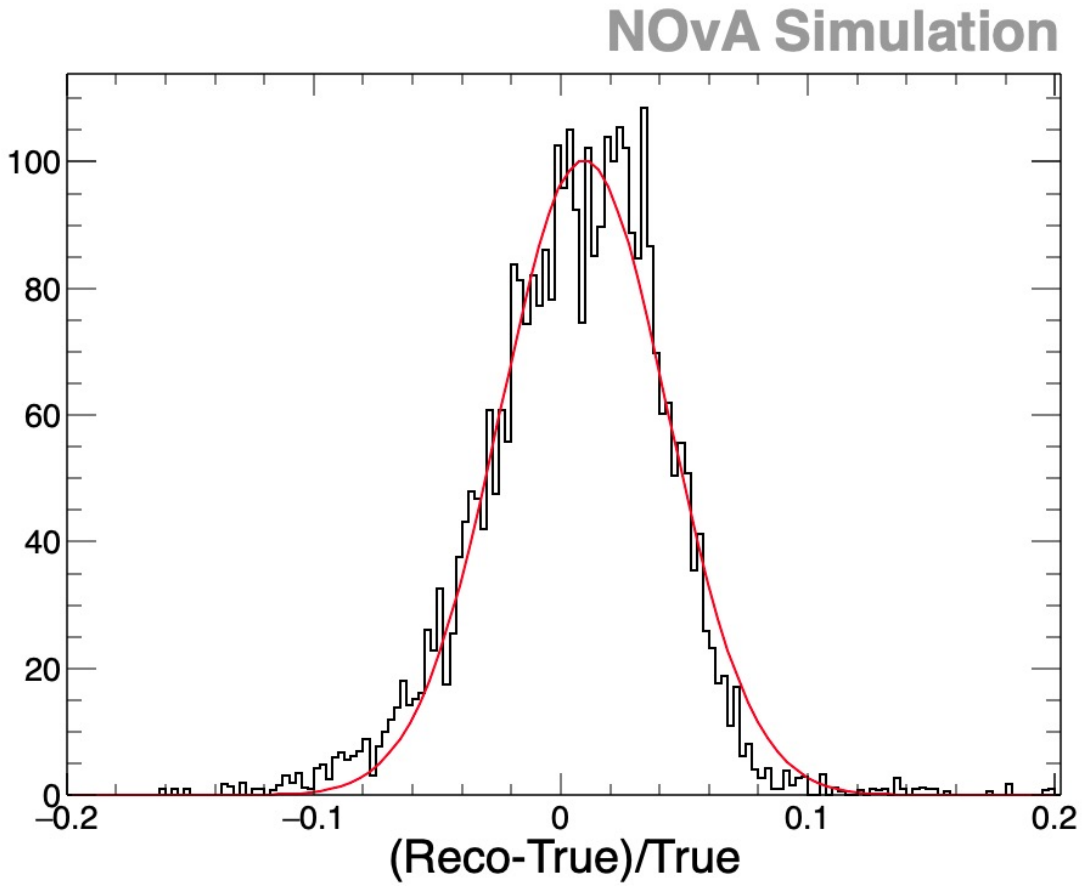


Efficiency confusion matrix for the 5label network evaluated on FHC genie prongs



Estimating Muon K.E.

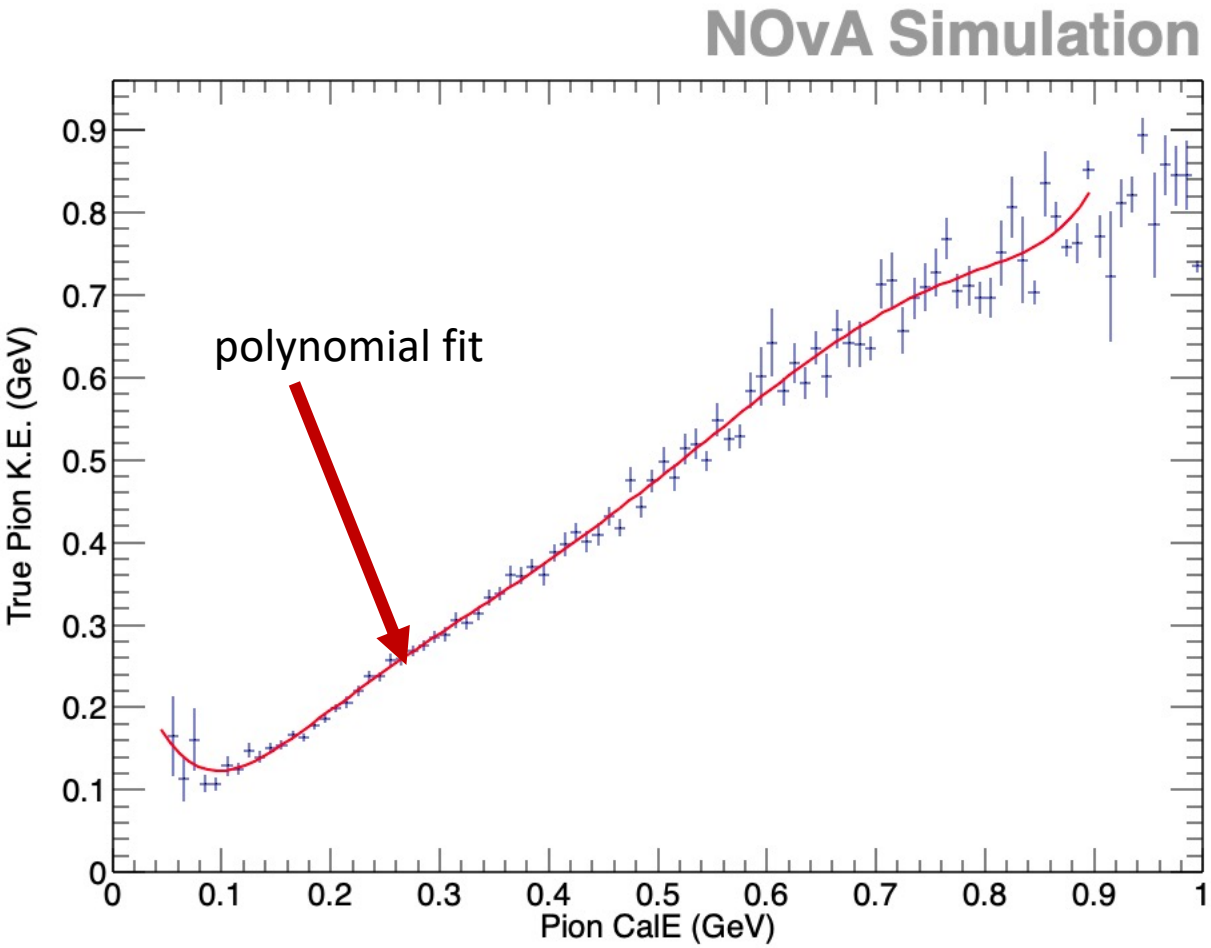


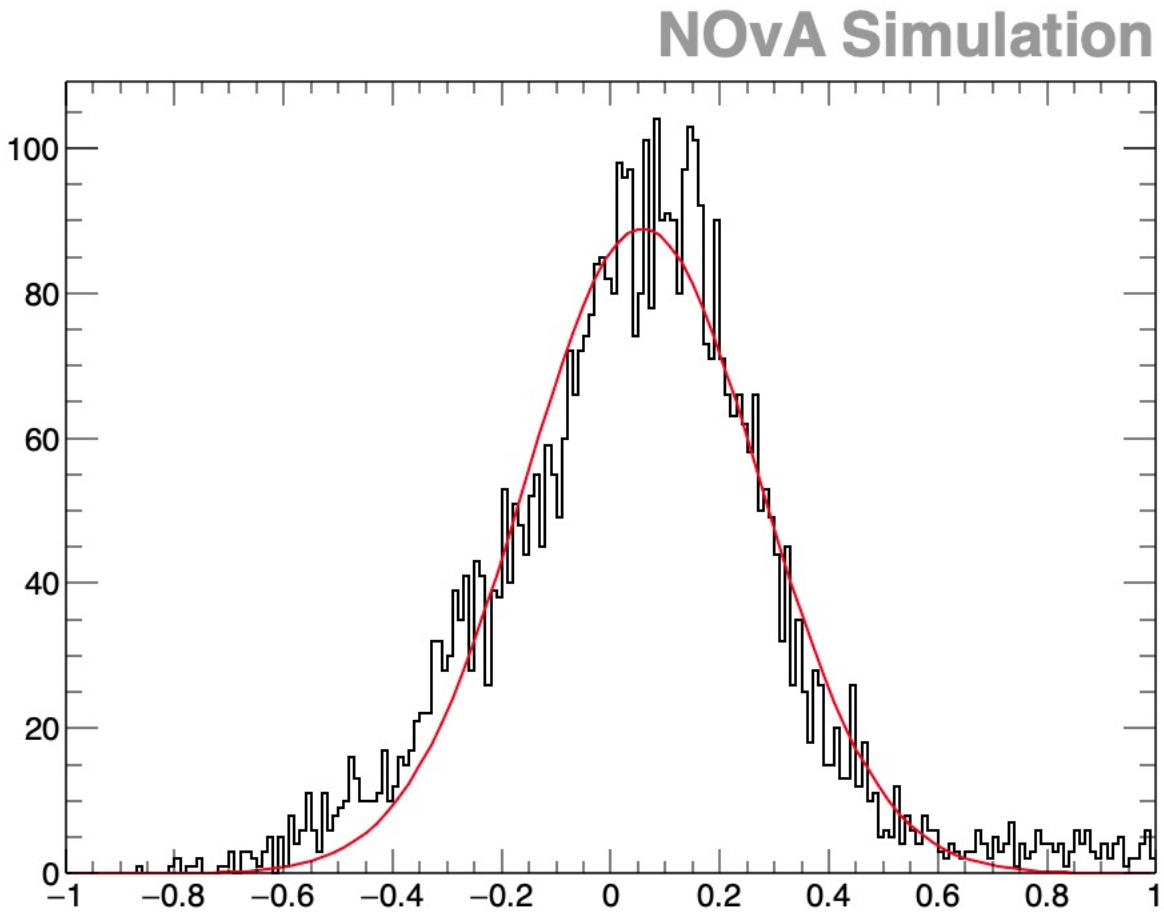


$$\mu^- K.E = 0.00206646 \times (\mu^- \, Prong \, Length) + 0.0201737$$

Mean	5.87918e-03
Sigma	3.22632e-02

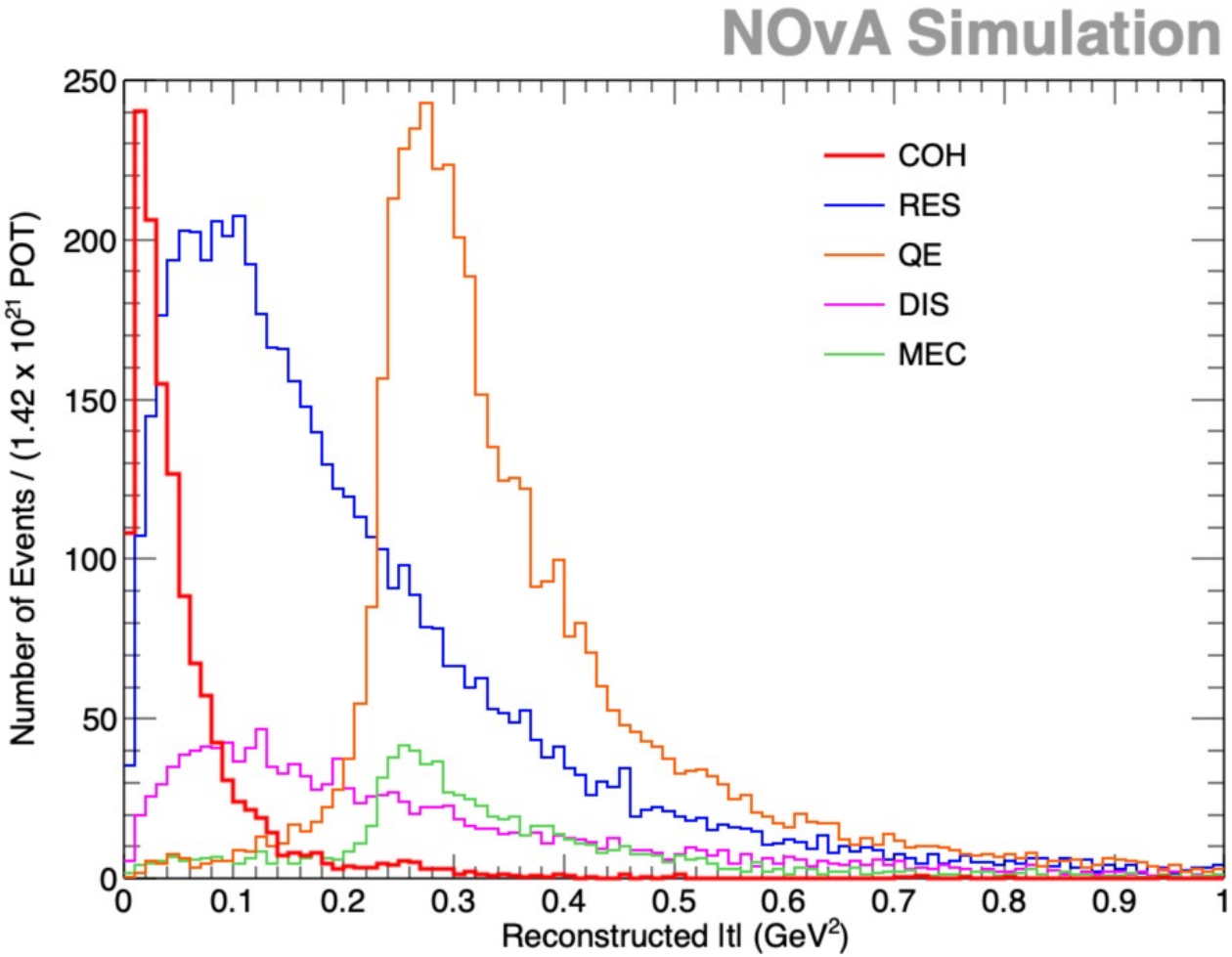
Estimating Pion K.E.

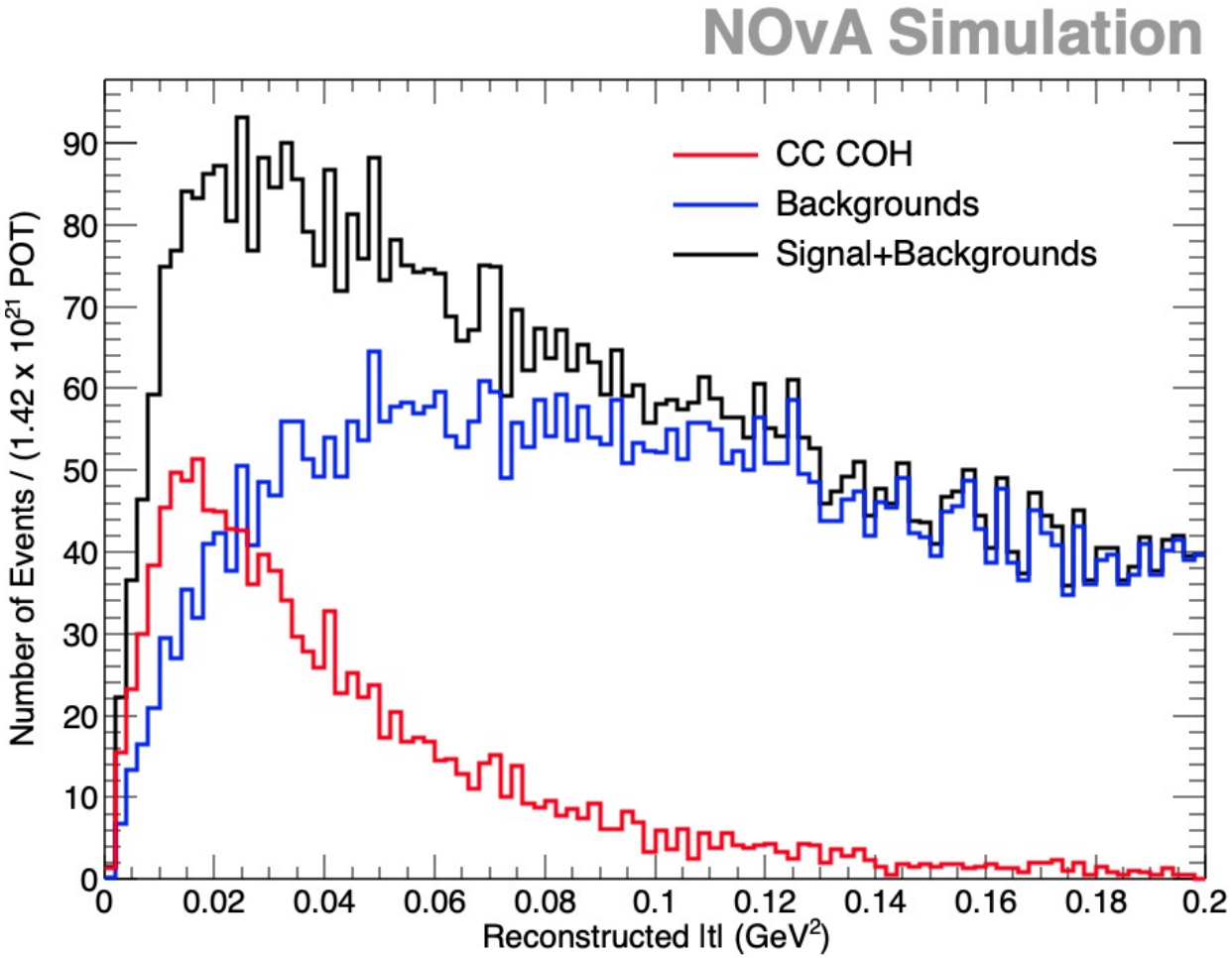




Mean = 0.0585206
Sigma = 0.215871

Reconstructed |t| (Signal Vs Background)





Summary

- Energy of the Muon can be successfully estimated by using Muon prong length.
- Energy of the Pion can be estimated by using Pion CalE but, requires more improvements.
- Reconstructed |t| can be used to separate Coherent events from dominating backgrounds.
- After implementing loose |t| cut (i.e |t| < 0.2 GeV^2) the cut table (POT Normalized) can be summarized as follows:

Cut Name	CC COH	CC RES	CC QE	CC MEC	CC DIS	NC	TOTAL Bkg.	Eff %	Relative Eff.	Purity %
Data Quality	29312.4	3644007.8	1214097.2	1004434.4	3266009.6	2625084.3	9305263.6	99.8	99.8	0.31
Fiducial	28645.1	1971807.1	630035.9	529390.7	1672683.7	1443259.8	4885034.2	97.72	97.7	0.58
Containment	19966.1	1753343.8	434417.2	331591.3	1611071.3	1438900.8	4206645.8	68.11	69.7	0.47
Muon ID	17713.5	777508.6	291175.5	279690.4	405887.6	123259.1	1766796.5	60.43	88.7	0.99
Two Prong	2066.7	32327.4	60441.2	12786.6	5475.0	3033.6	112382.3	7.05	11.7	1.81
Pion ID	1421.4	9695.0	5821.1	1325.7	2006.6	887.0	19486.9	4.8	68.8	6.8
Vertex Energy	1388.6	6243.0	5610.4	1040.4	1633.1	797.5	14981.7	4.7	97.7	8.5
Loose |t|	1239.8	3266.5	197.1	115.8	673.9	361.1	4628.8	4.2	89.3	21.1

Next Steps

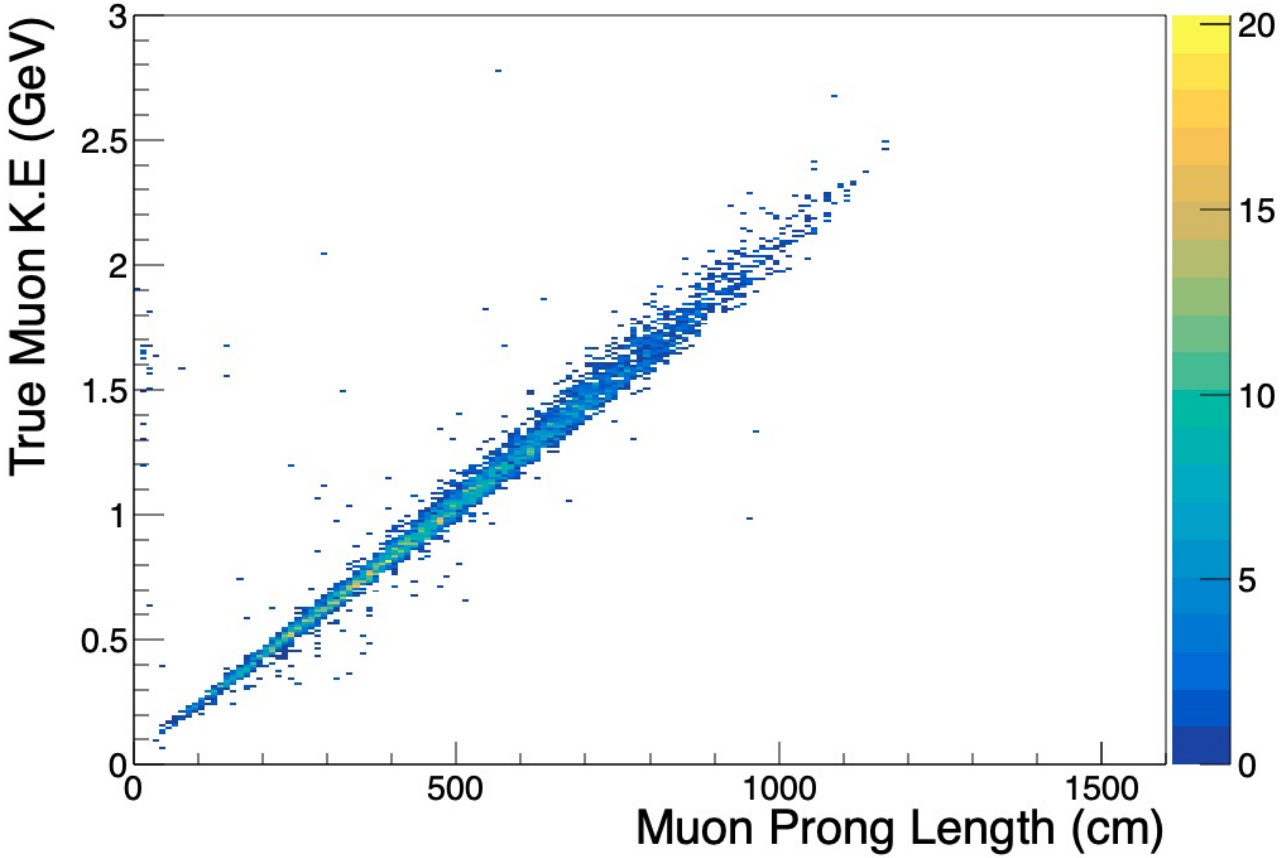
- Finalizing Pion energy estimator by using multivariate method trained by single pions
- Finalizing event selection by adding final cut based on multivariate event classifier
- Hand scanning event display views to find out ways to further separate dominating background: RES from signal events
- Creating an enhanced sample and considering signal events other than golden event sample to address low efficiency

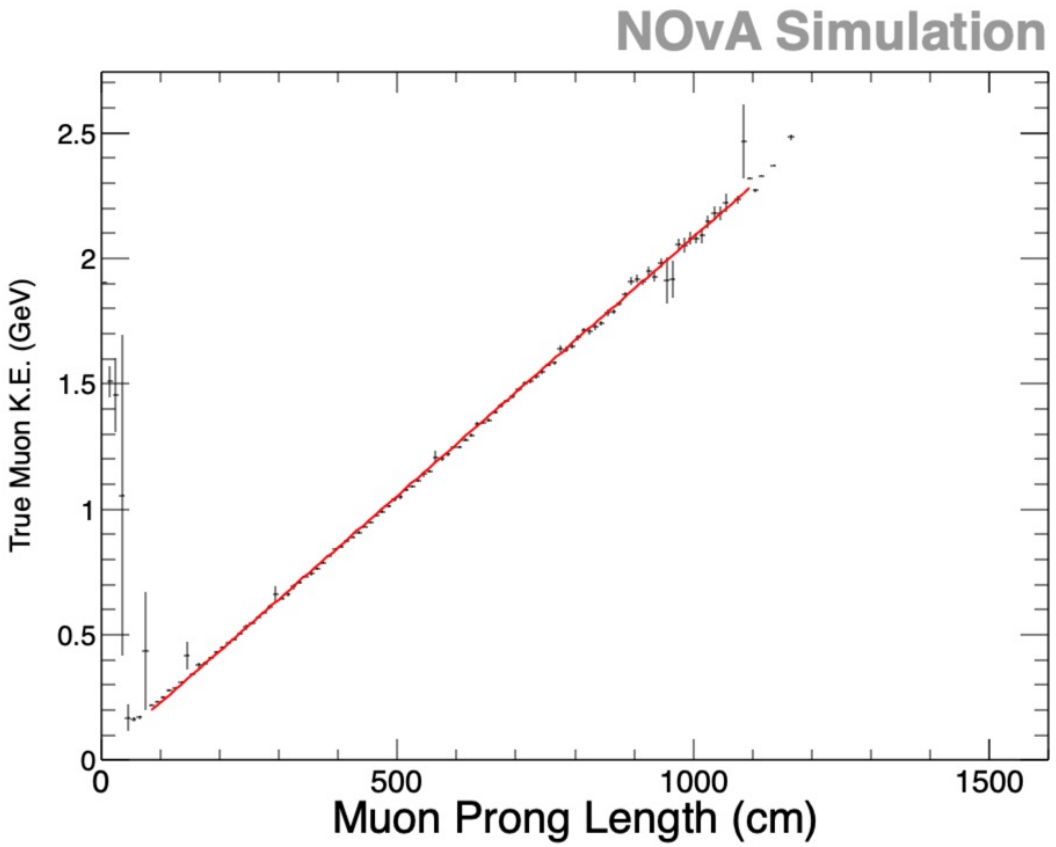
Thank you.!

4

Backups

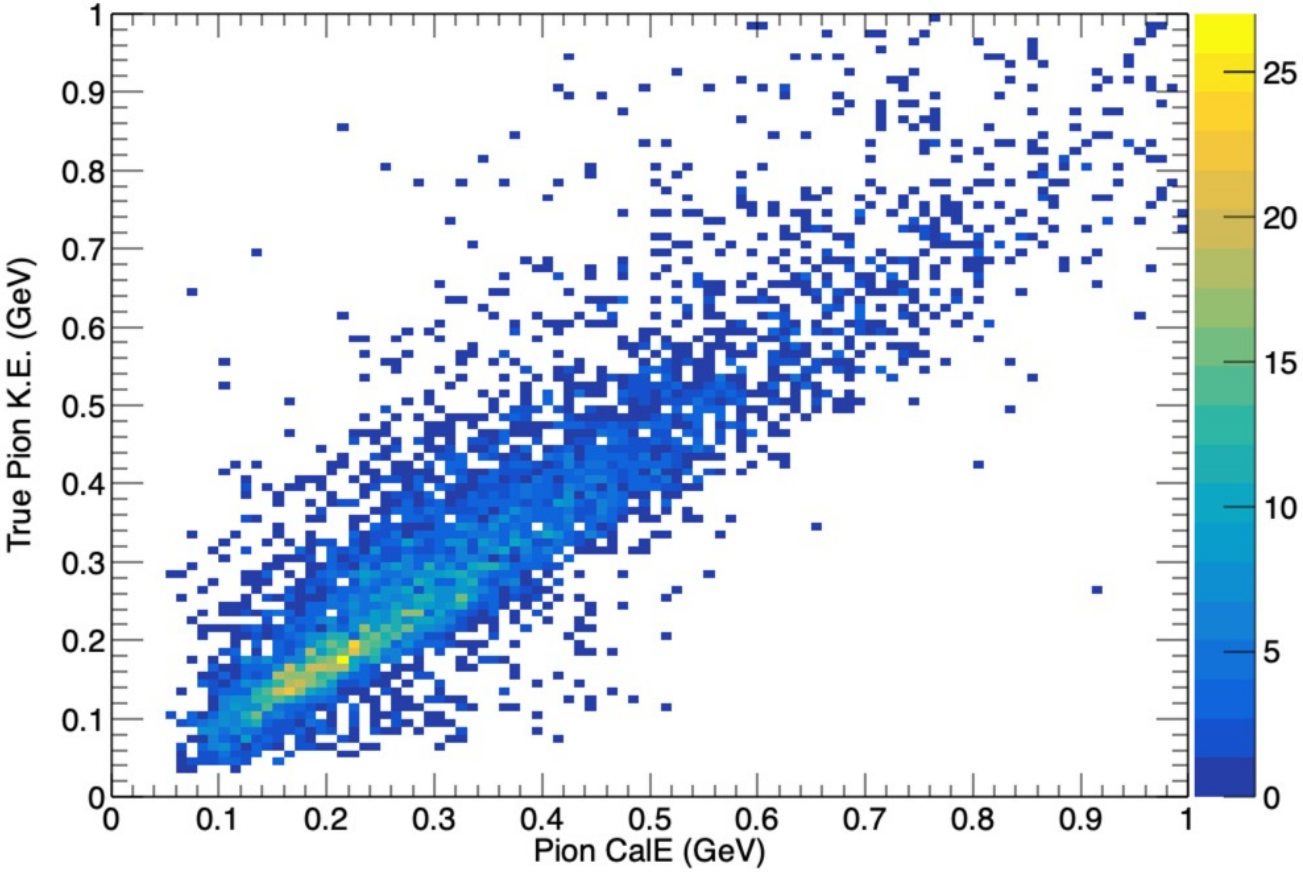
Estimating Muon K.E.

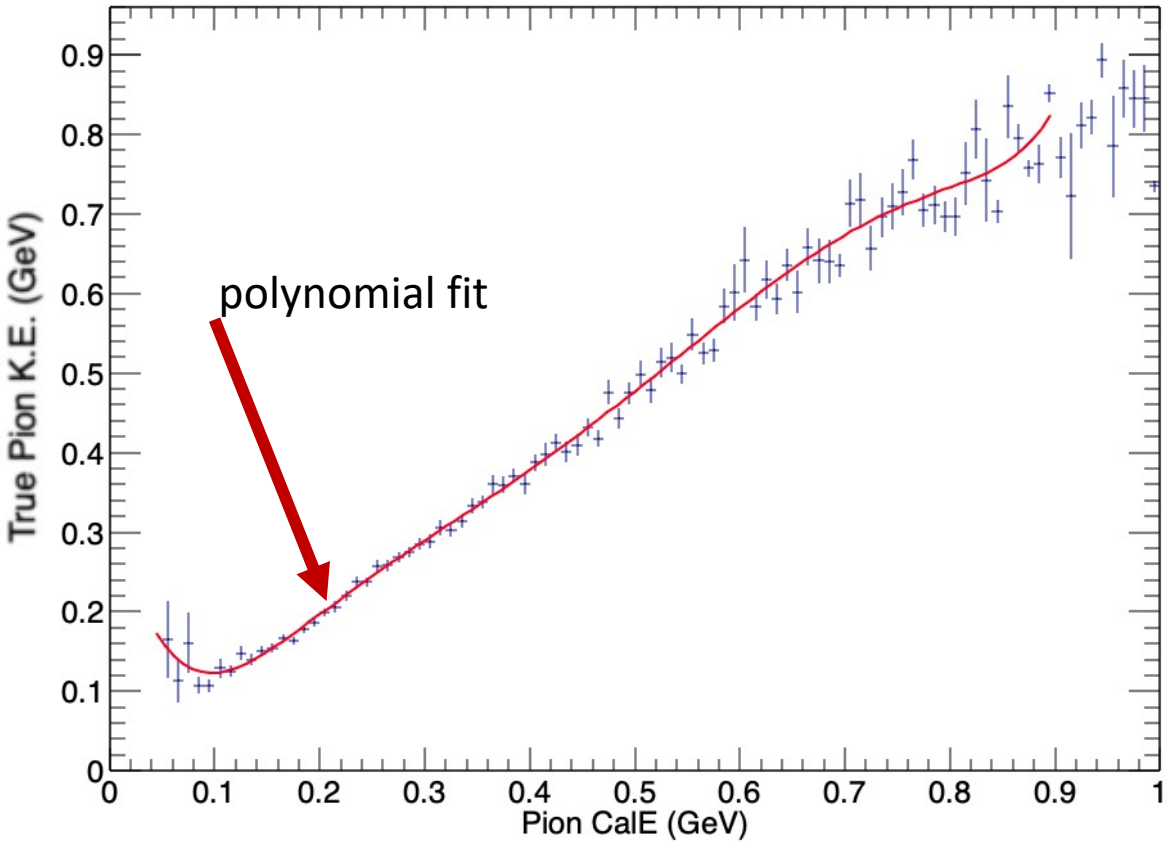




$$\mu^- K.E = 0.00206646 \times (\mu^- \, Prong \, Length) + 0.0201737$$

Estimating Pion K.E.





Reconstructing |t|

$$|t| = \left|(p_\nu - p_\mu - p_\pi)^2\right|$$
$$\approx \left(\sum_{i=\mu,\pi} E_i - p_{i,L}\right)^2 + \left|\sum_{i=\mu,\pi} \vec{p}_{i,T}\right|^2,$$

(Measurement of Total and Differential Cross Sections of Neutrino and Antineutrino Coherent pion Production on Carbon by MINERVA Collaboration [arXiv:1409.3835])

- Assumptions:
  - The recoiling nucleus only takes momentum and no energy (infinitely heavy nucleus)
  - The transverse momentum of the incoming neutrino is zero (w.r.t. beam coordinates system)

$$\therefore p_\nu = \begin{pmatrix} E_\mu + E_\pi \\ 0 \\ 0 \\ E_\mu + E_\pi \end{pmatrix}, p_\mu = \begin{pmatrix} E_\mu \\ p_{\mu_x} \\ p_{\mu_y} \\ p_{\mu_z} \end{pmatrix} \text{ and } p_\pi = \begin{pmatrix} E_\pi \\ p_{\pi_x} \\ p_{\pi_y} \\ p_{\pi_z} \end{pmatrix}$$

Determining P_t and P_l

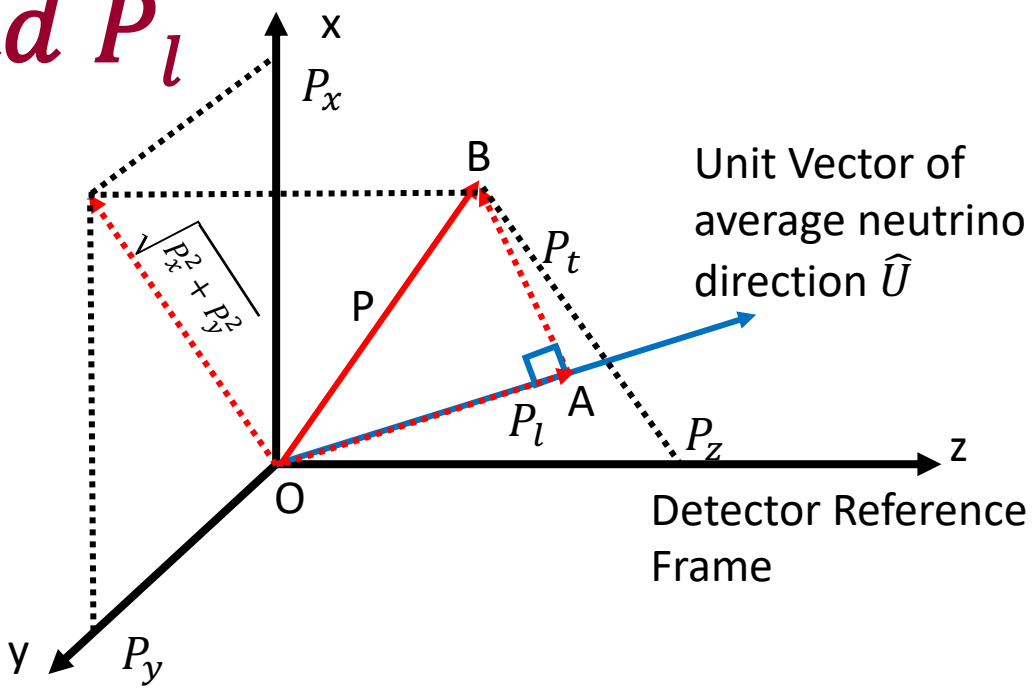
$$\vec{P}.\hat{U} = P_l$$

$$P^2 = P_x^2 + P_y^2 + P_z^2$$

$P^2 = P_t^2 + P_l^2$ (By considering OAB Right Angle Triangle)

$$P_t^2 = P^2 - P_l^2$$

$$\therefore P_t = \sqrt{P_x^2 + P_y^2 + P_z^2 - P_l^2}$$



Here, P_t and P_l are transverse and longitudinal momenta calculated w.r.t. the beam direction

Here, P_x, P_y and P_z are momentum components of the neutrino observed w.r.t. the detector coordinate system

Here, $\hat{U} = (0.0011401229, -0.06190152, 0.99807253)\ i.e\ Average\ Beam\ Direction()$