# Generator Comparisons: The Oscillation Perspective

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# Purpose

- The organizers asked the oscillation experiments to propose useful plots for comparisons of neutrino generator performance.
- The most interesting, and useful plots were produced in an identical manner to facilitate direct comparisons.
- Not all generators could be used for all the plots
- Requested plots from NOvA, MINOS+, LBNE, MiniBooNE, T2K.

# Outline

- Pion (particularly neutral pion) production.
- Neutrino Energy Reconstruction
- Proton Multiplicities
- Neutrino Cross Section
- Neutrino Double Differential Cross Section in muon energy and scattering angle.

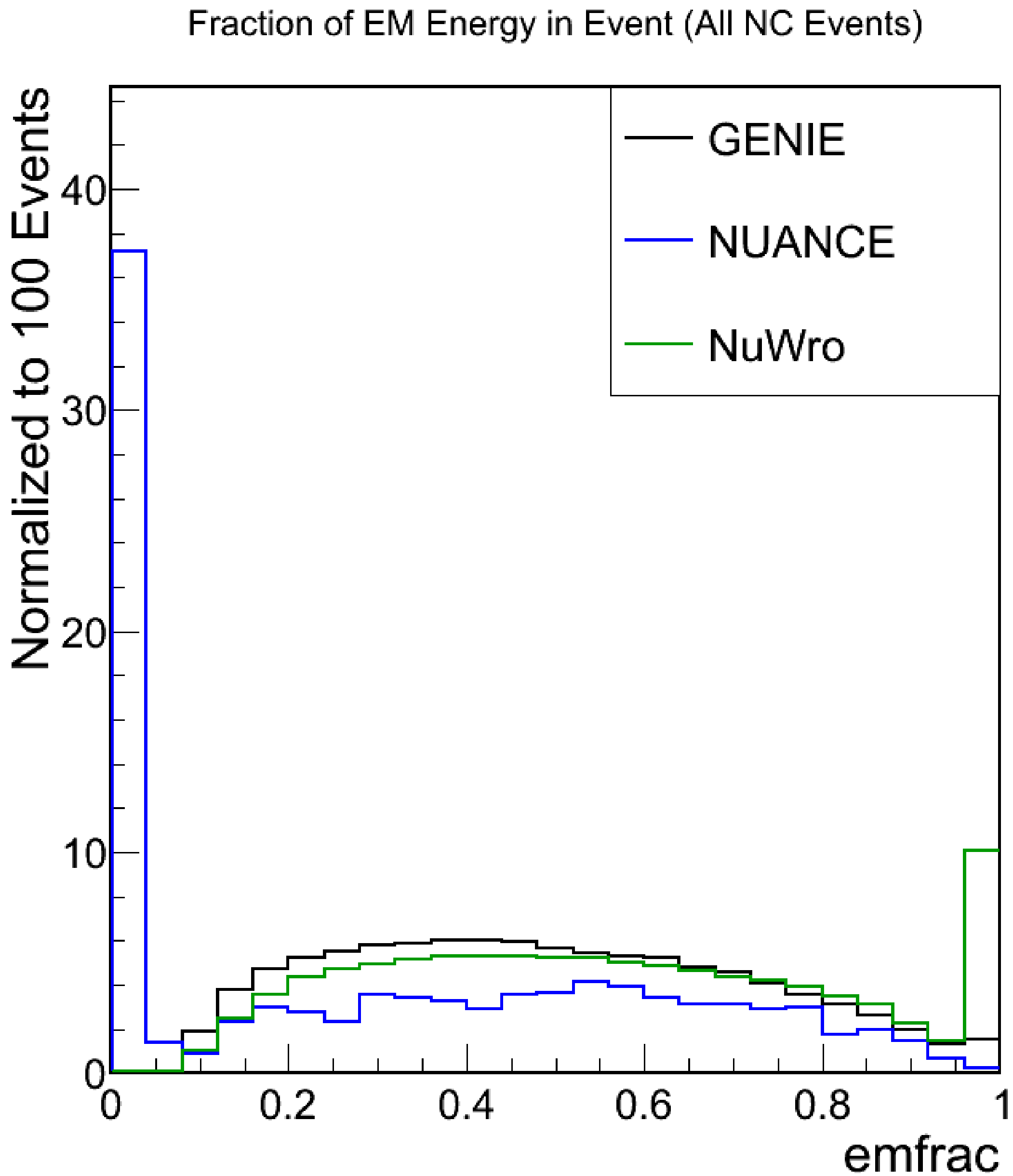
# EM Energy Fraction

- Fraction of energy in the event that Electro-Magnetic in origin.
  - This includes $e^{\pm}$, $\pi^0$, and $\gamma$
- Plots are for NC events, so EM energy is primarily due to $\pi^0$ production.
- Because we are looking at NC Events this distribution becomes a measure of background "fake" rate for $\nu_e$ appearance.

# NOvA Requested Plots

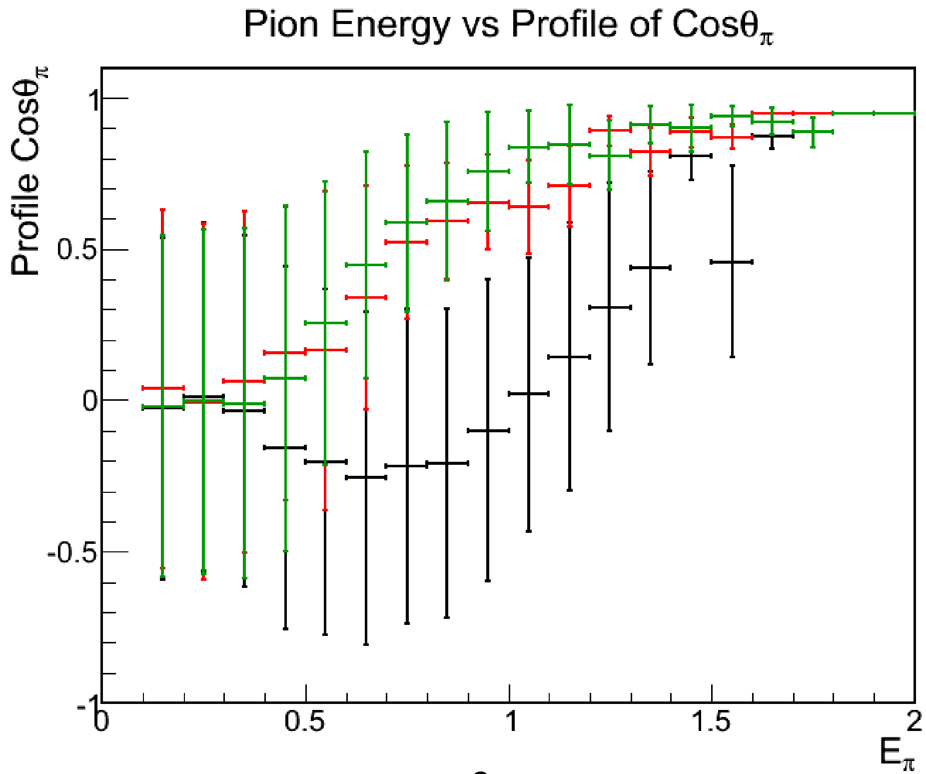
- NOvA interested in systematics that effect electron neutrino appearance.
- Generated at neutrino energies of 2 GeV.
- Using a carbon target.

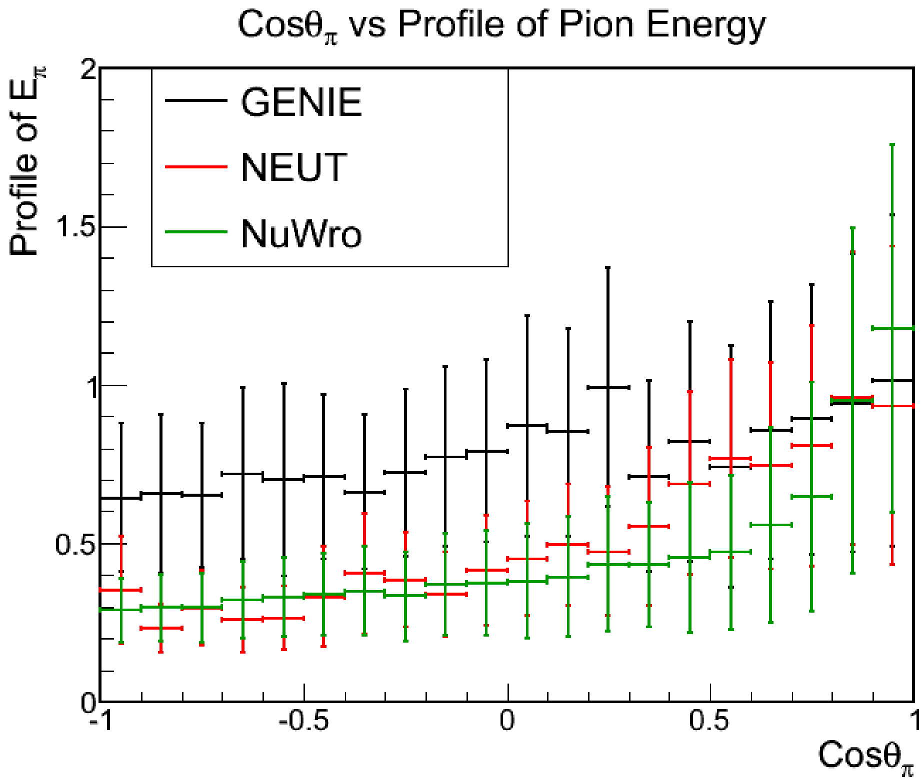
# EM Energy Fraction




- Events with 0 EM Energy excluded.
- Spike at 0 from NUANCE due to large number of de-excitation photons.

# Pion Energy vs. Scattering Angle



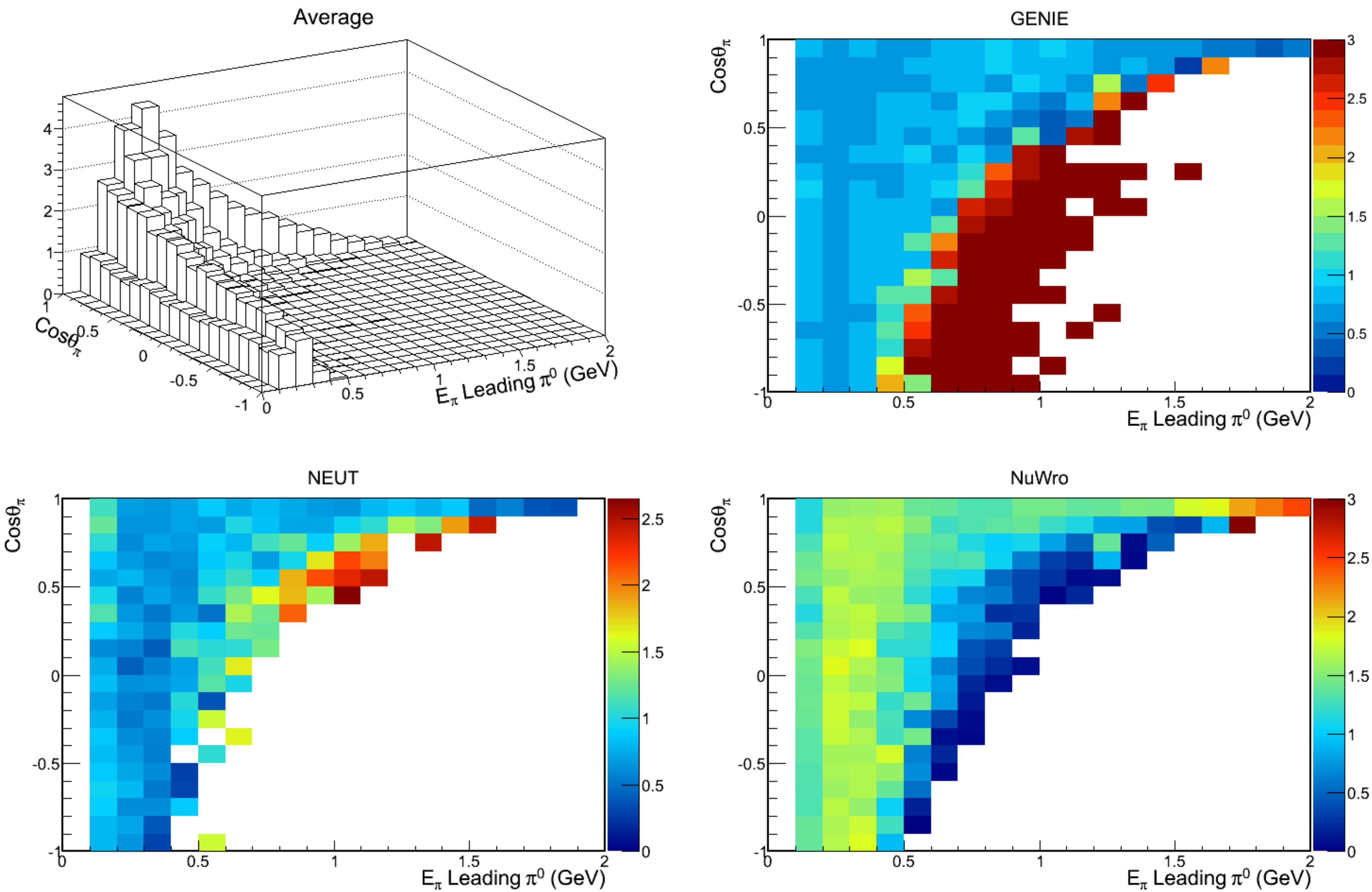




- For leading $\pi^0$ in NC events only.
- Difficult to overlay 2D histograms.
  - Profiles: data point is mean, error bar is RMS.
- Shape only comparison.
- Large differences in shape between all three generators.
- Next 2D comparisons.

# Pion Energy vs. Scattering Angle

- 2D distribution
- Calculate the average of the histograms.
- Divide each 2D distribution by the average.
- Looking at the distributions this way differences become clear.

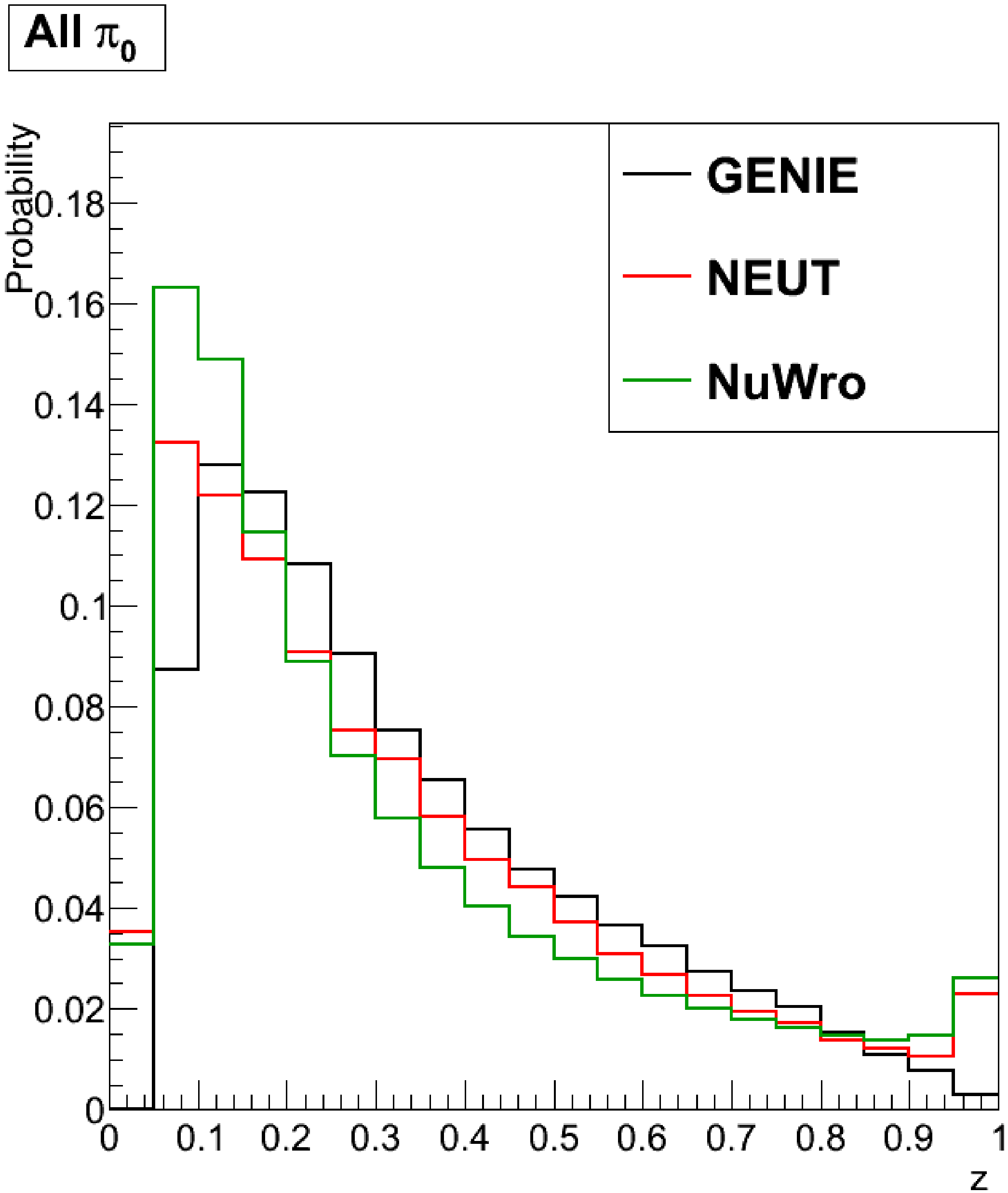
# Pion Energy vs. Scattering Angle



# MINOS Requested Plots

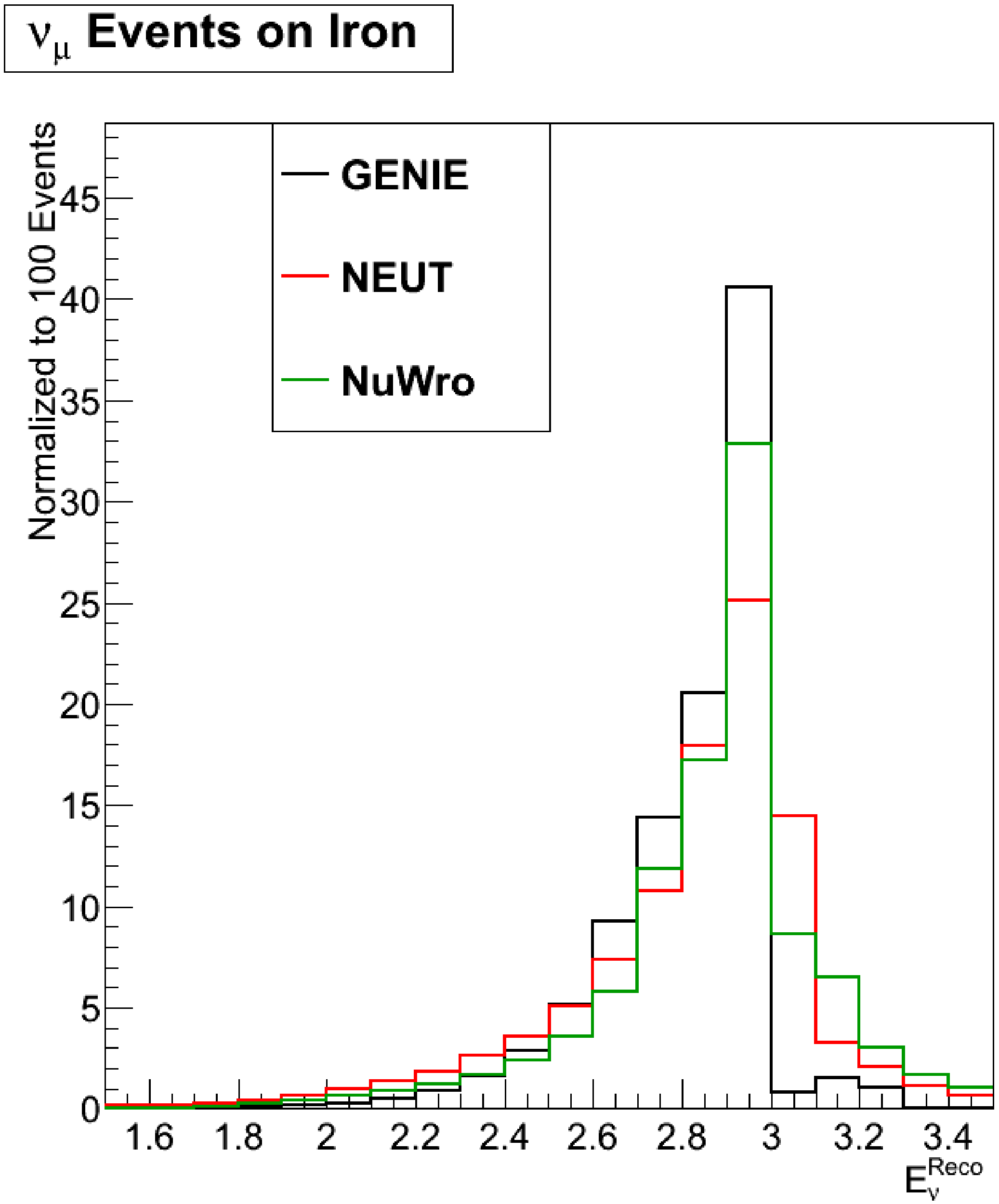
- Interested in systematics for electron neutrino appearance and muon neutrino disappearance.
- Generated at neutrino energies of 3 GeV.
- Iron target.

# $\pi^0$ Hadronic Z




- Fraction of hadron energy that is due to $\pi^0$.
- Another metric quantifying the electron appearance fake rate.
- More useful for experiments where individual particles can be identified.

# Neutrino Energy

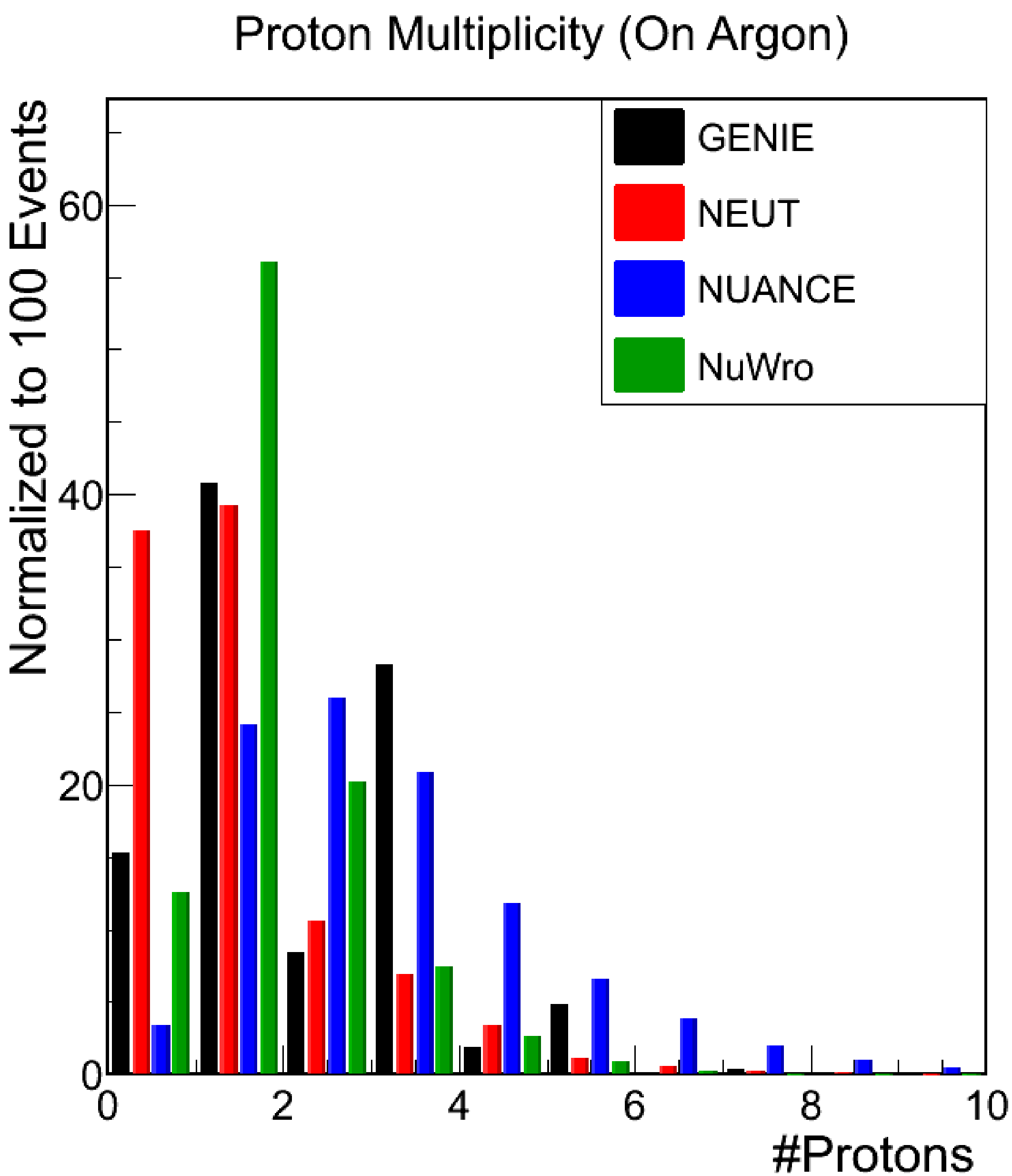



- “Reconstructed” Neutrino Energy.
- Smeared according to to: $E_{other}+1.3*E_{EM}+\alpha*T_{proton}+\beta*T_{neutron}$
  - $\alpha$=1 for (T>150MeV), $\alpha$=.5 (T<150MeV)
  - $\beta$=.5 for (T>300MeV), $\beta$=0 (T<300MeV)
- Simulates Energy uncertainties due to hadronization and intranuclear rescattering models.

# LBNE Requested Plots

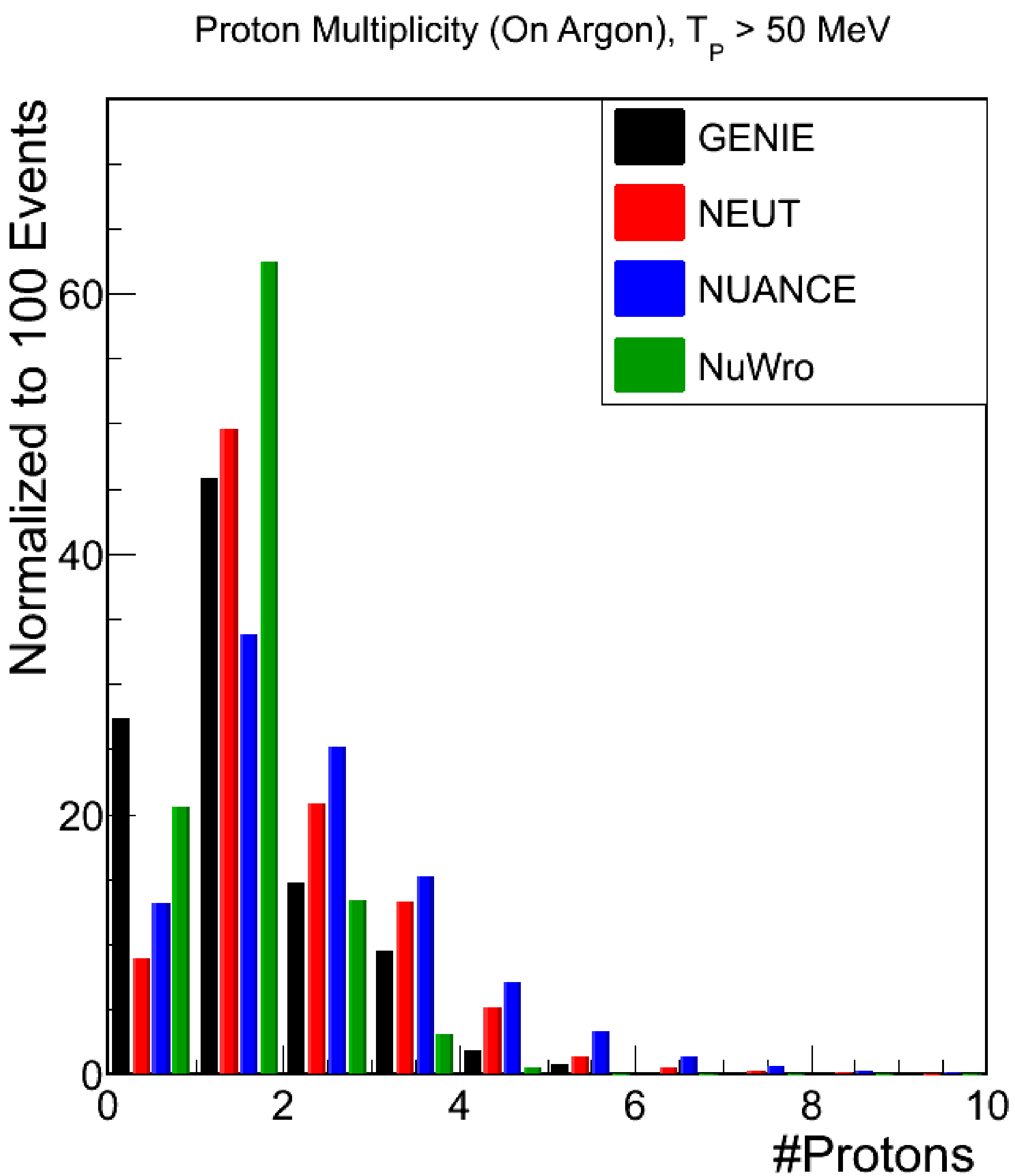
- Fine grained detector.
- Interested in single particle identification.
- Generated at neutrino energies of 2.5 GeV.
- Argon target.
- CC Events.

# Proton Multiplicities



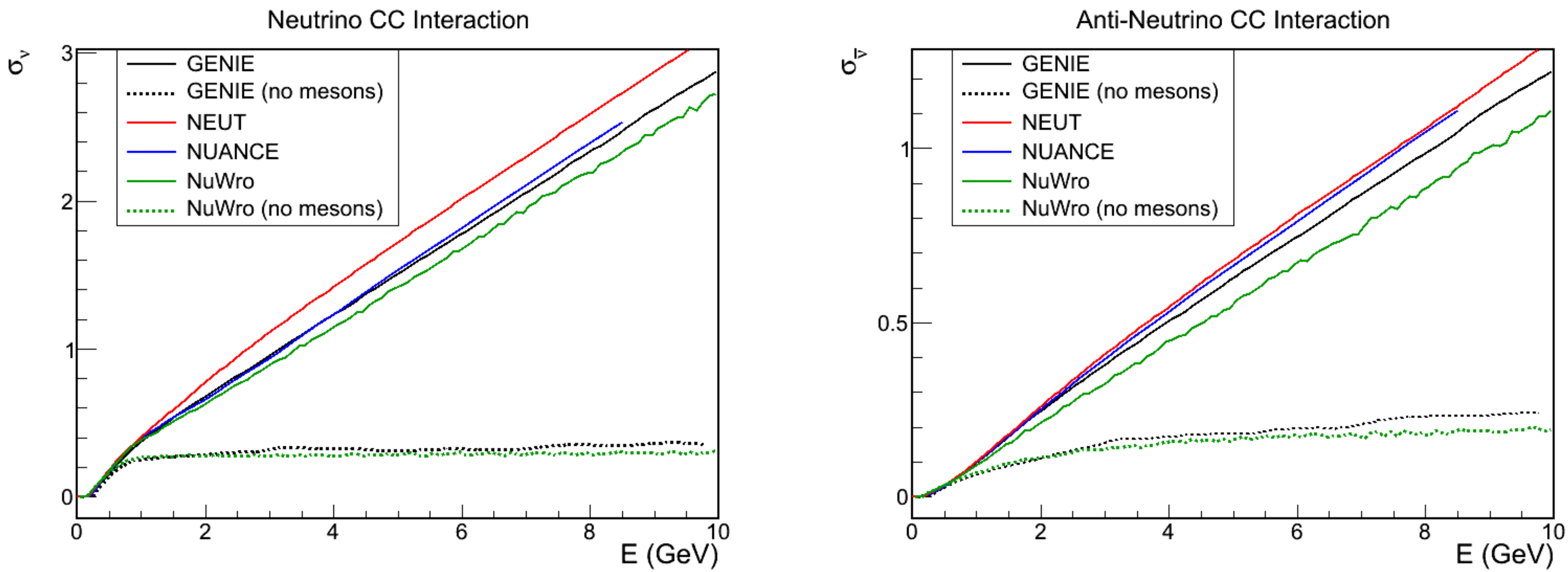

- This distribution shows the greatest differences between the generators out of all the generators I looked at.
- Differences are likely due to differences in the nuclear model used in the generators.

# Proton Multiplicities




- Exclude protons with kinetic energy less than 50 MeV.
- Removing the low energy protons also removes some of the differences.
- However, differences between the generators persist.
- 50 MeV "Detectable" proton
- Between the models 20-45% of CC events with detectable protons are multi-proton events.
- 9-27% of CC events with no detectable protons.

# Neutrino Cross Section (Argon)

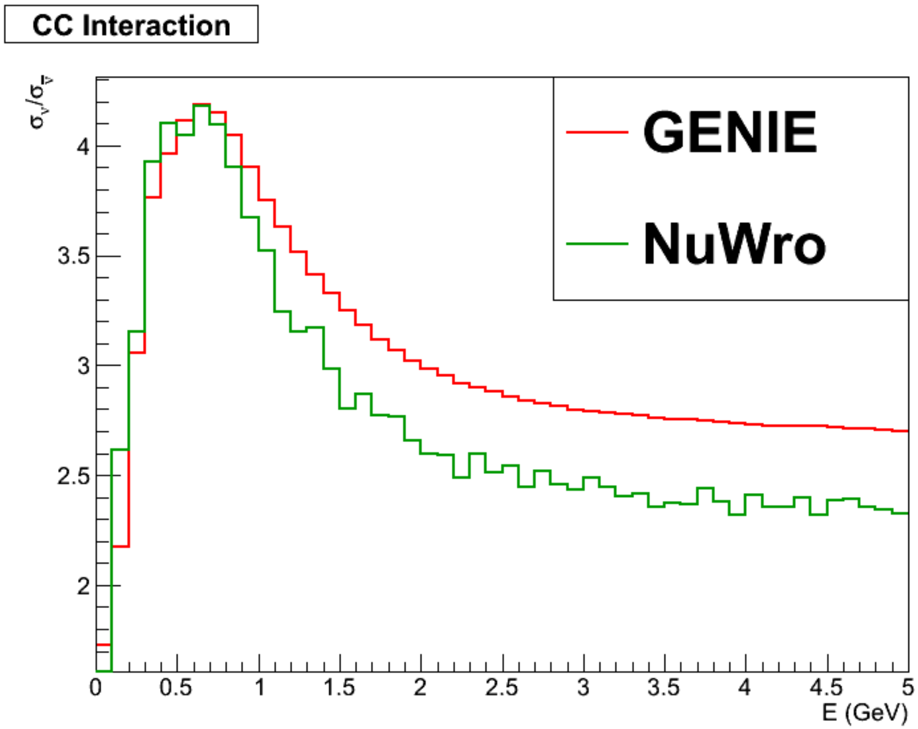


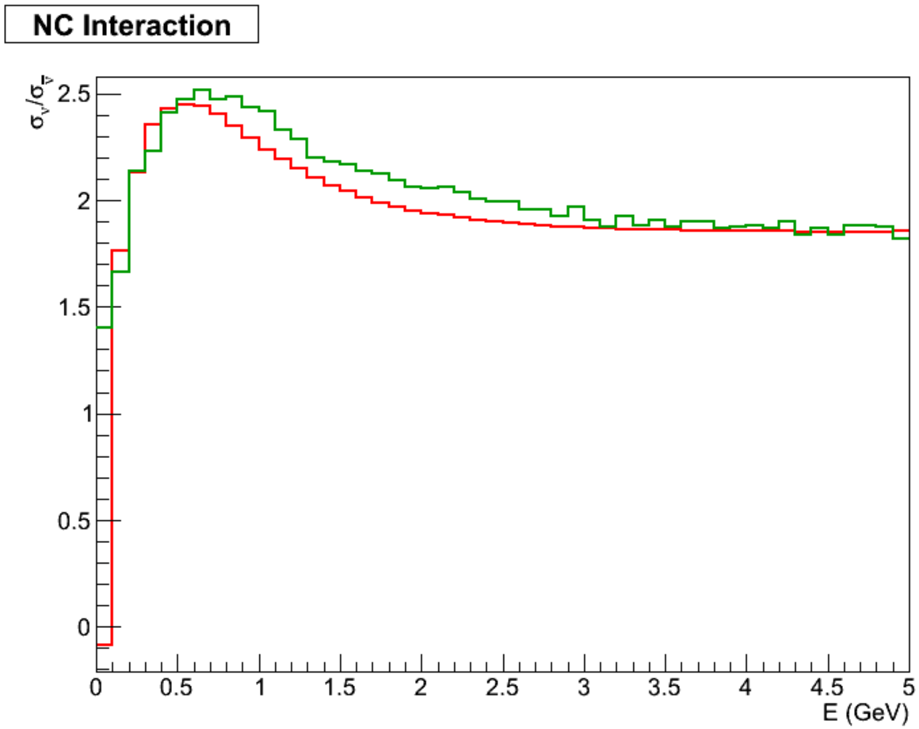

- Some small differences in the total cross section.
- Differences are smaller with out mesons.

# MiniBooNE Requested Plots

- CC and NC Cross section ratio
- 0-5 GeV neutrino energies.
- $CH_2$ target.

# Cross Section off of $CH_2$



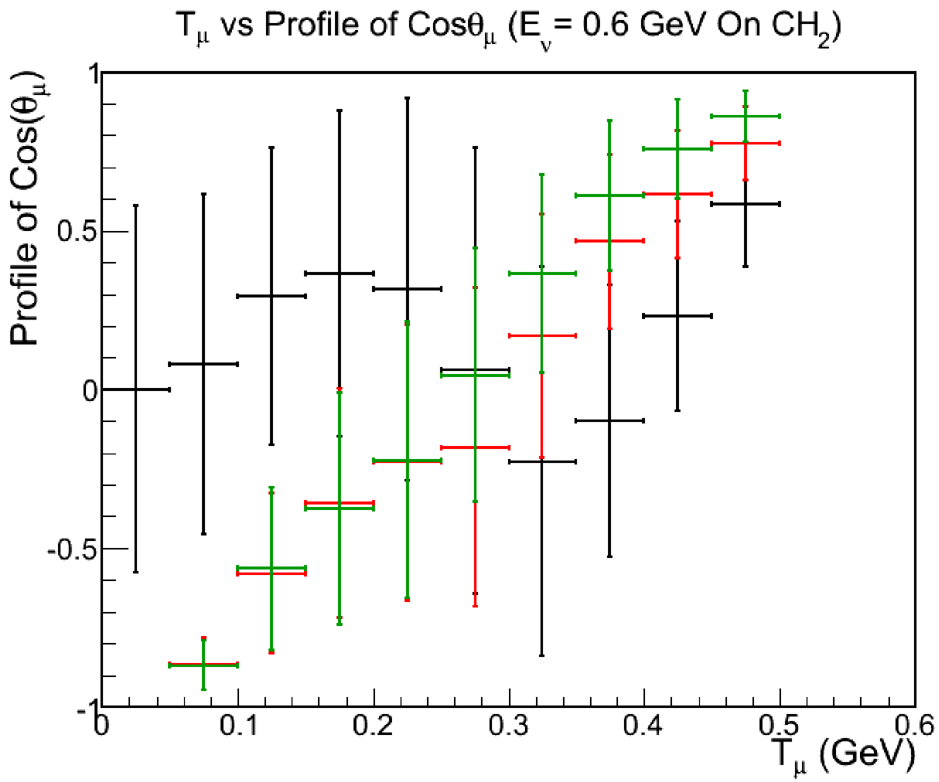



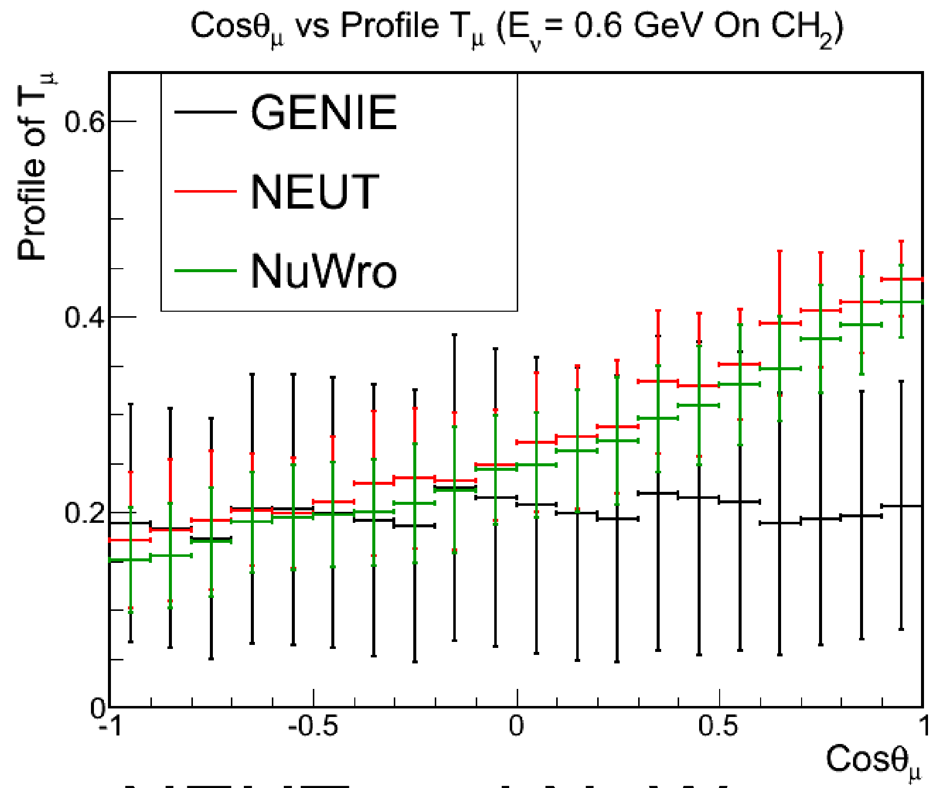

- Neutrino cross section normalized to number of neutrons (6), Anti-neutrino cross section normalized to number of protons (8).
- Larger than expected differences (~15%) in the CC cross section ratio between NuWro and GENIE 2-5 GeV.
- Smaller differences (~5%)in the NC cross section ratios between NuWro and GENIE.

# T2K Requested Plots

- Muon kinetic energy vs scattering angle plots
- Generated at 0.8 GeV and 1.2 GeV.
- $CH_2$ target.
- CCQE interactions only.
- First Profile Plots.
- Than 2D ratio to the average of the generators.

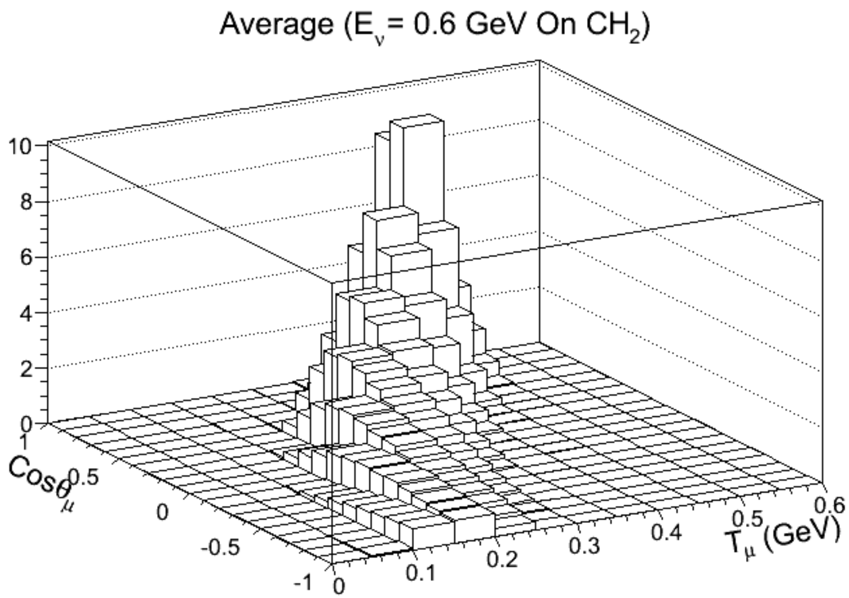
# $T_\mu$ vs $Cos\theta_\mu$ off of $CH_2$

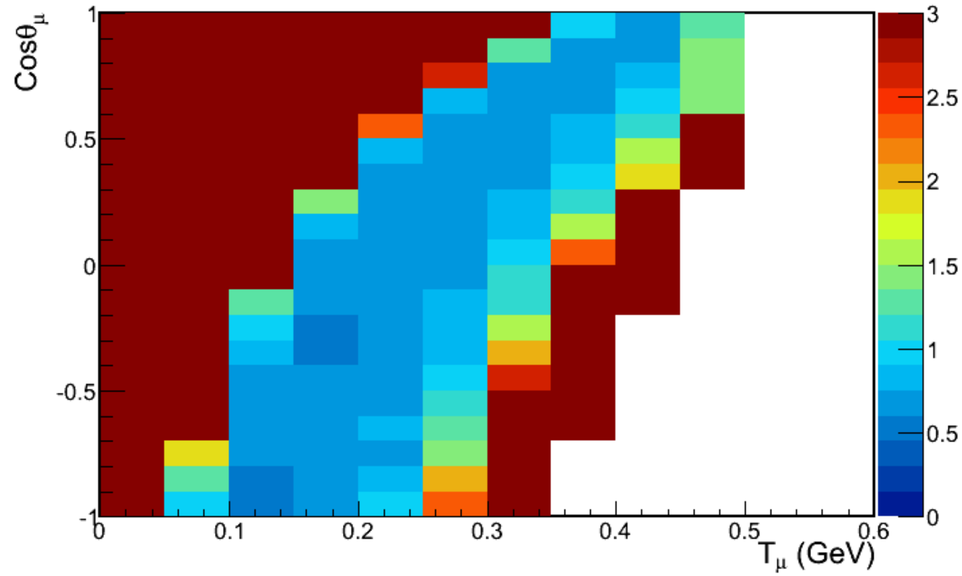


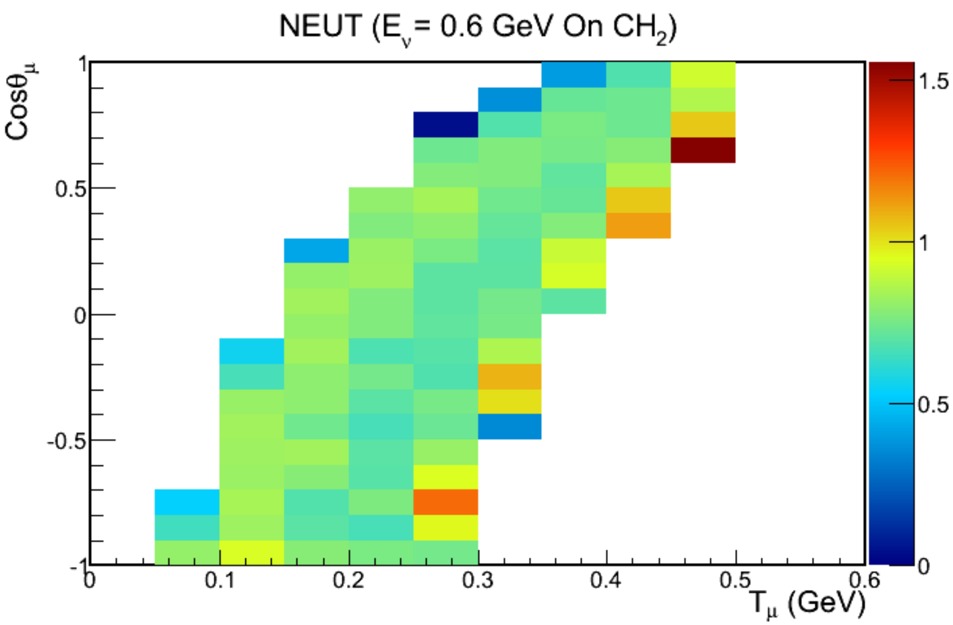



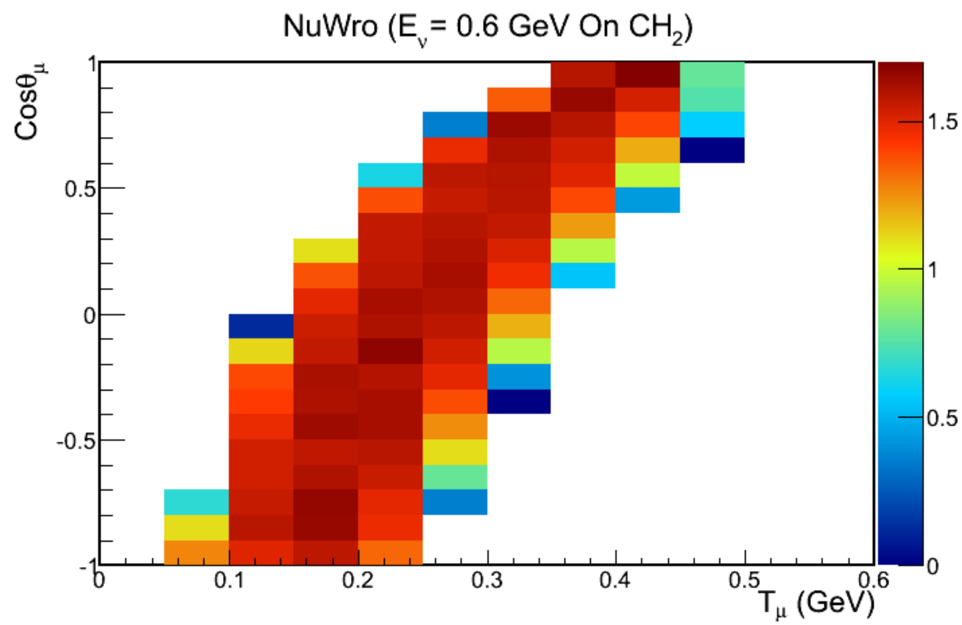

- Good agreement between NEUT and NuWro
- GENIE has a wider, flatter, scattering angle distribution.
- Now examine the 2D comparison.

# $T_\mu$ vs $Cos\theta_\mu$ off of $CH_2$

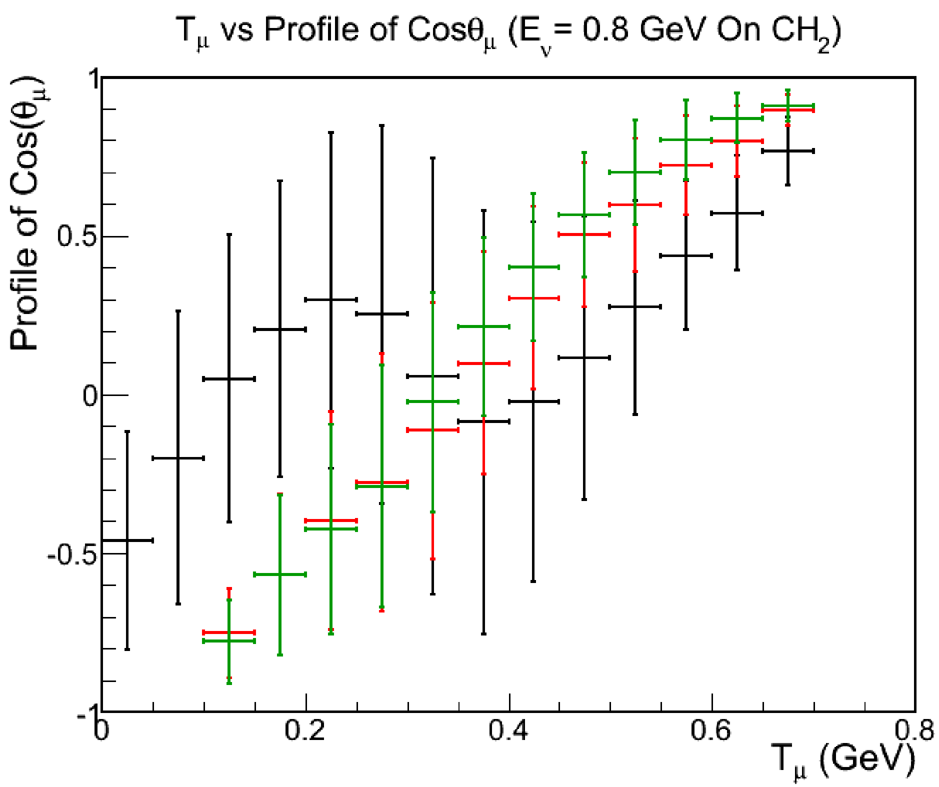


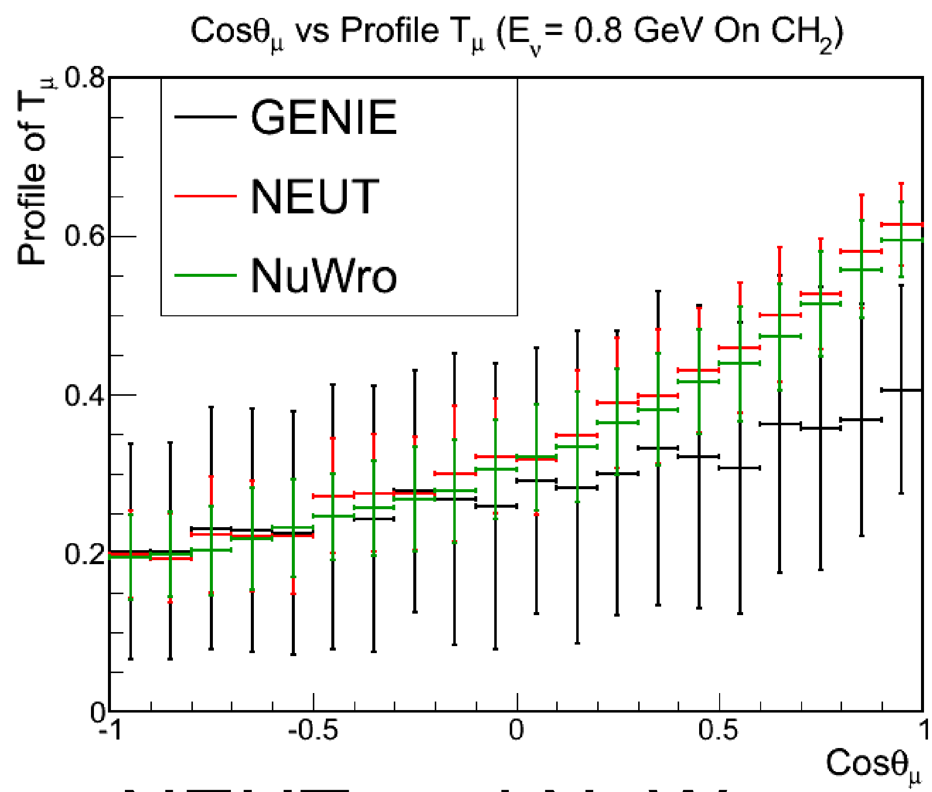



# $T_\mu$ vs $Cos\theta_\mu$ off of $CH_2$

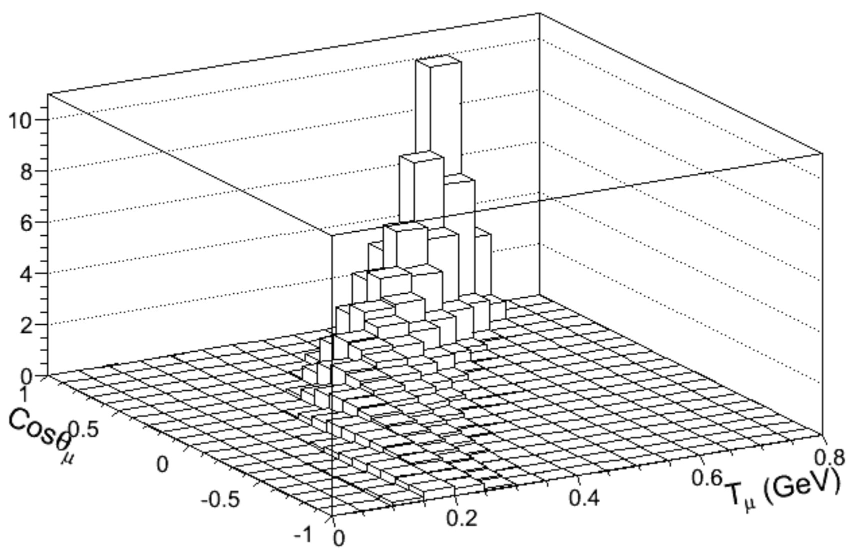


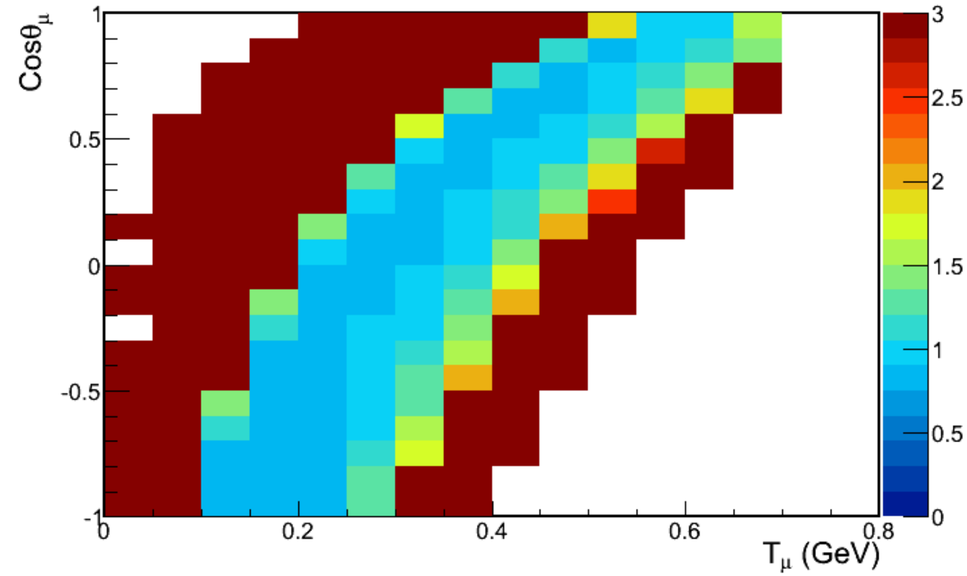




- Good agreement between NEUT and NuWro, GENIE is looks very different.
- Shape normalized.
- Now examine 2D comparisons.

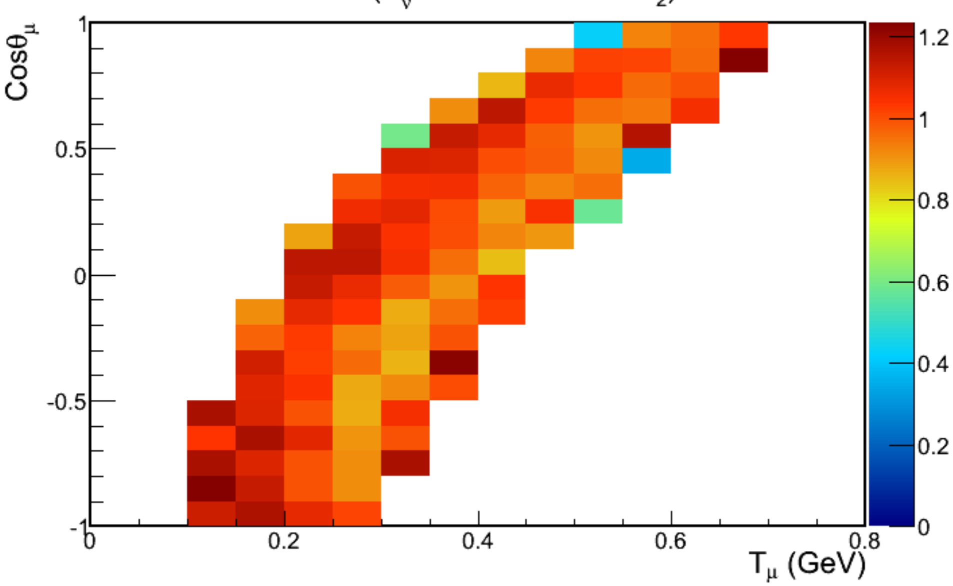
# $T_\mu$ vs $Cos\theta_\mu$ off of $CH_2$

Average ($E_\nu$= 0.8 GeV On $CH_2$)

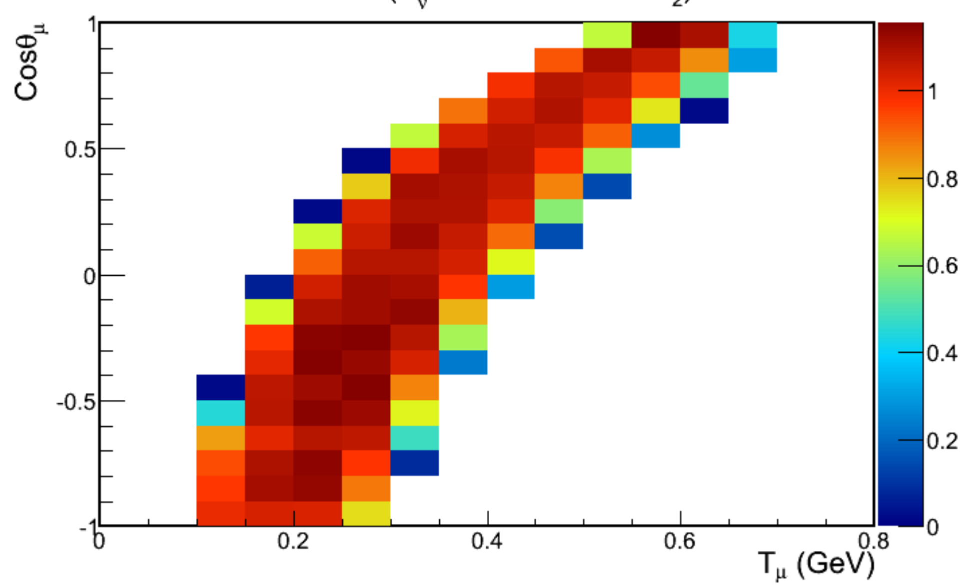



NEUT ($E_\nu$= 0.8 GeV On $CH_2$)




NuWro ($E_\nu$= 0.8 GeV On $CH_2$)



# Conclusion

- Neutrino generators are a necessary tool for neutrino collaborations.
- Generator/Model uncertainties are one of the major contributions to an experiments systematic uncertainties.
- Four different neutrino generators were examined today.
- Some similarities between generators
- Many more differences though.
- However differences our good, they allow us experimentalists to choose the “best tool for the job”
- Most importantly the generators should match measured data.