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Physics with NuMI beam in T600 detector

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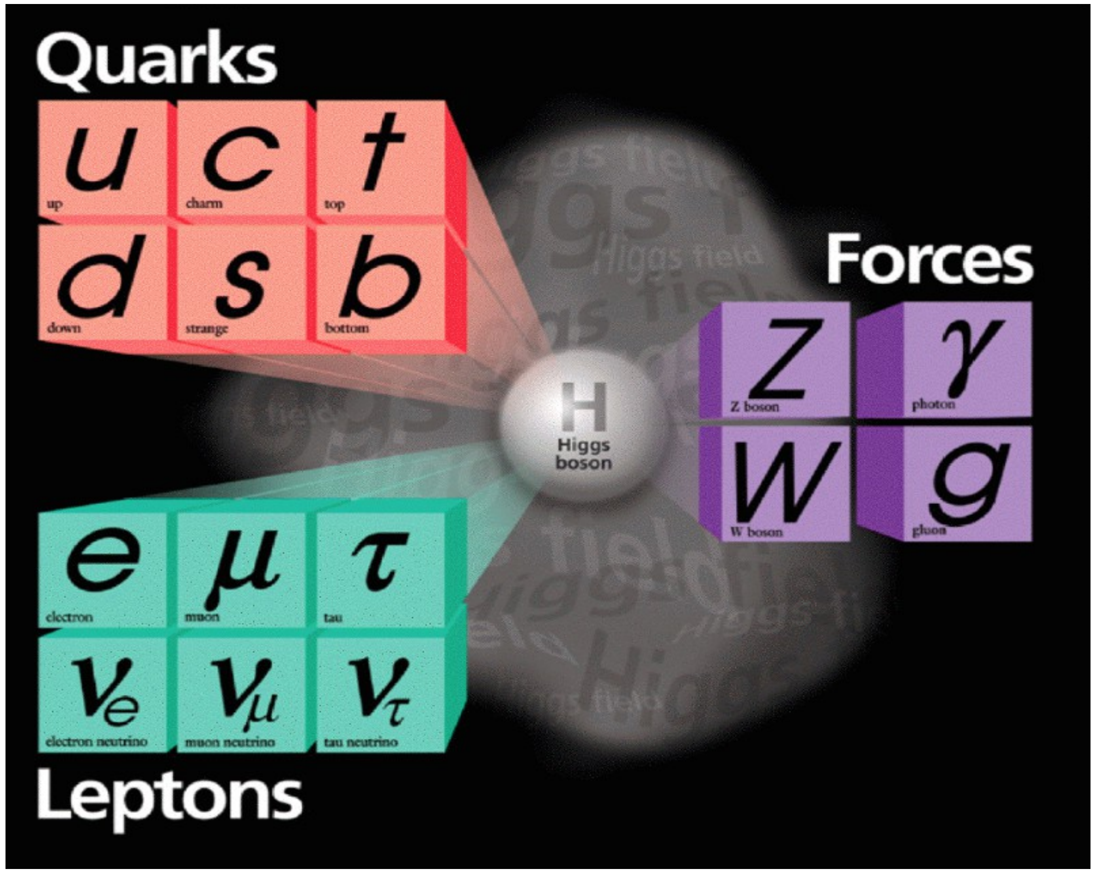
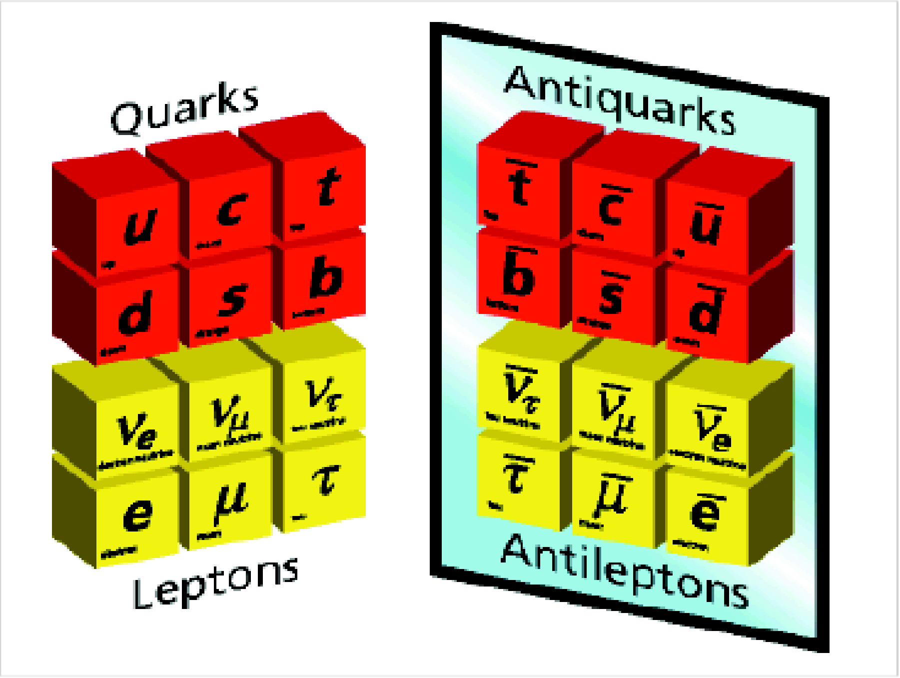
03 August 2021

The Standard Model of Elementary Particles

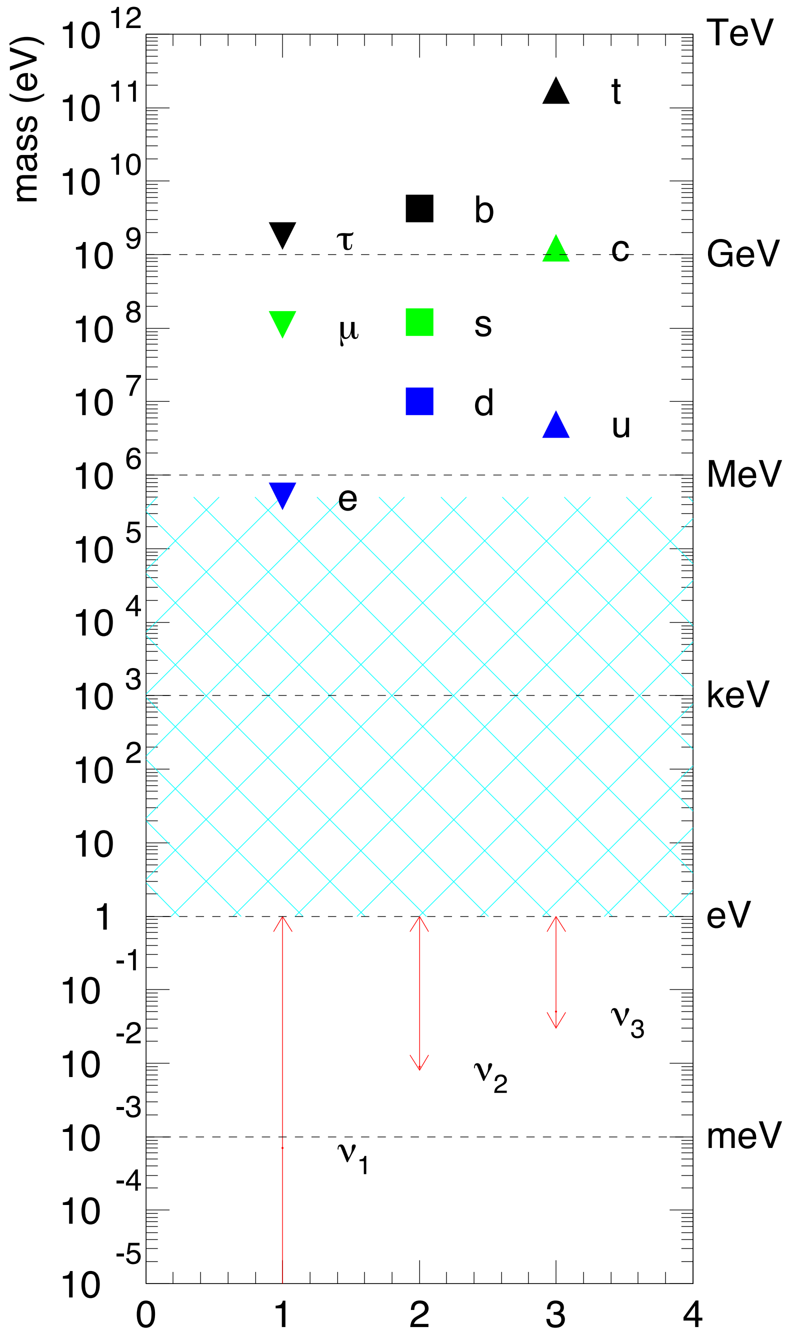


- Theory about fundamental ingredients of matter and how they interact with each other
- Everything known in this world is made of these (and the mirror images)

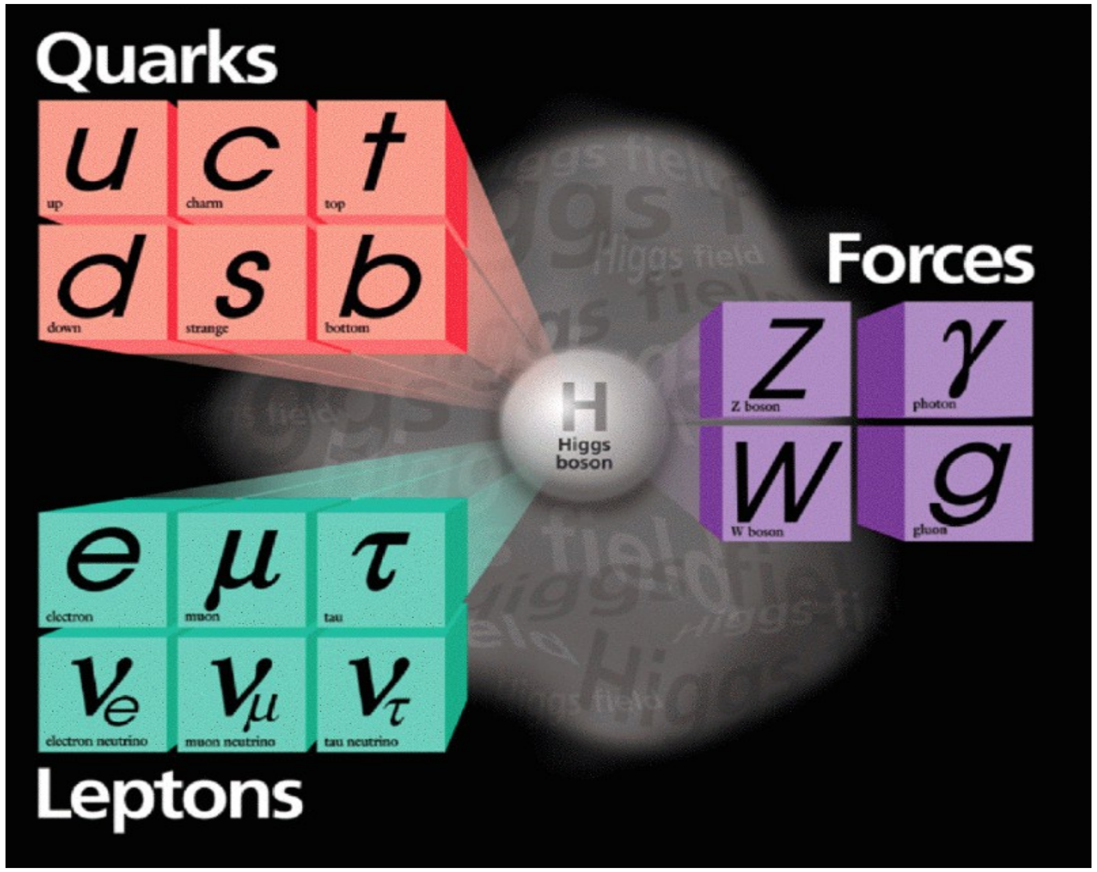


- Is the standard model complete?
  - Neutrino in the Standard Model has no mass
  - However neutrino mass has been observed, and it is much smaller than all other particles

Neutrinos have mass



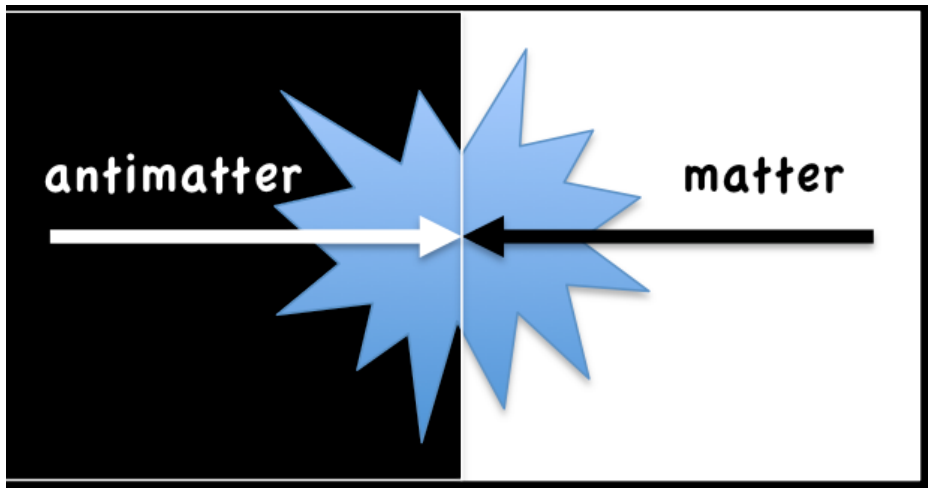
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^* \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

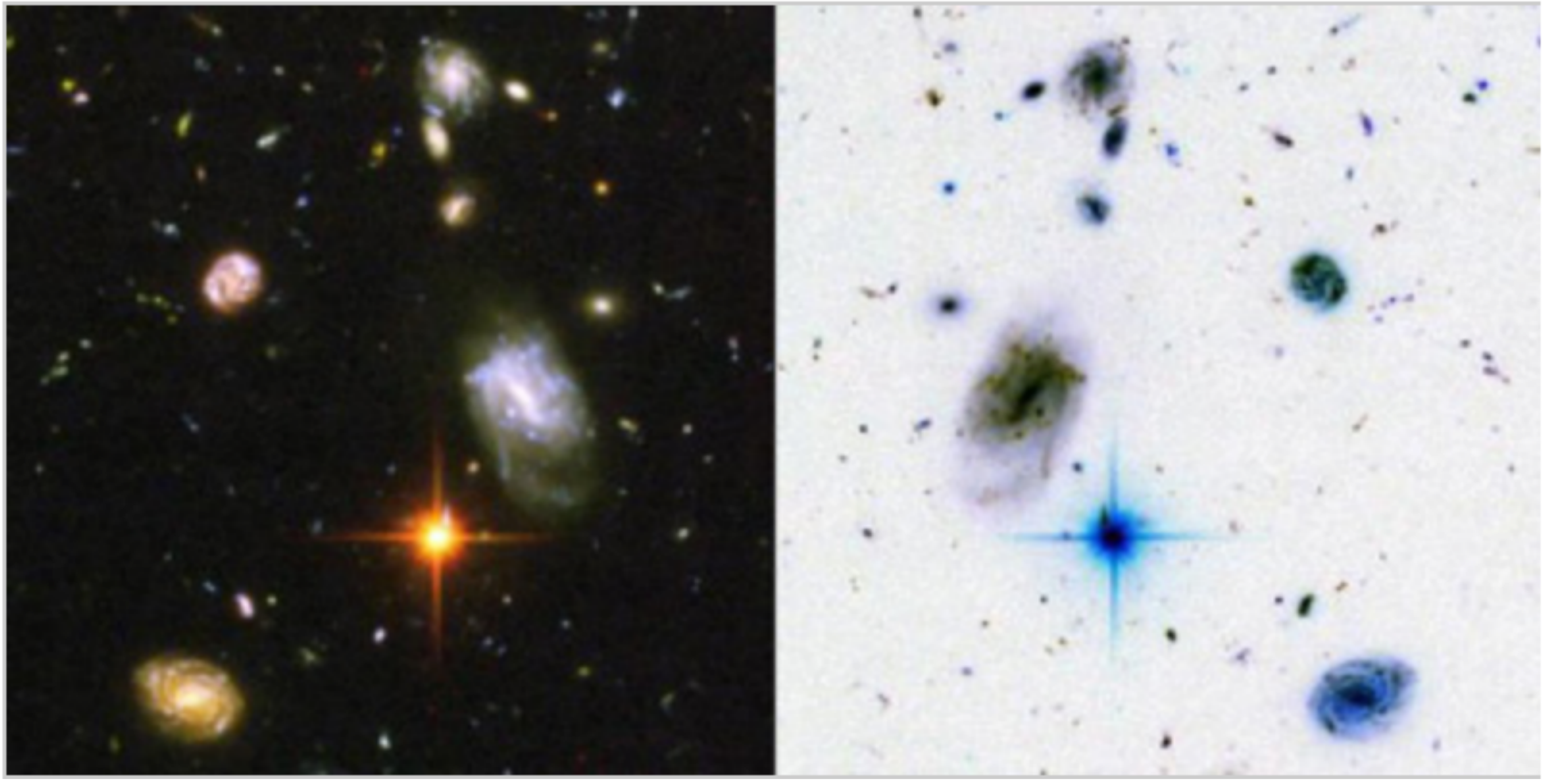


- Why is there such large gap between neutrino masses and quark masses?
- Why do quarks and leptons exhibit different behavior?
- What is the absolute mass of neutrino?

What is the symmetry between matter and antimatter?

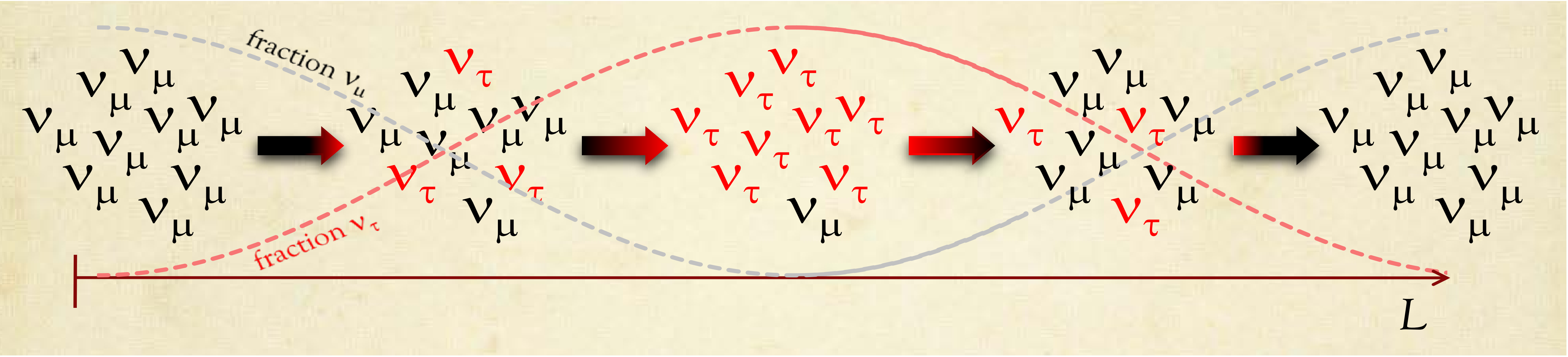
- Physics theorize that the big bang created equal amounts of matter and antimatter
- When corresponding particles of matter and antimatter meet, they annihilate one another





- But somehow we are still here and antimatter, for most part, has vanished
- How is that we exist?
- Neutrinos could help to explain why the universe has more matter than antimatter!

Neutrinos Oscillate!



- Neutrinos have mass and weak flavor states

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source

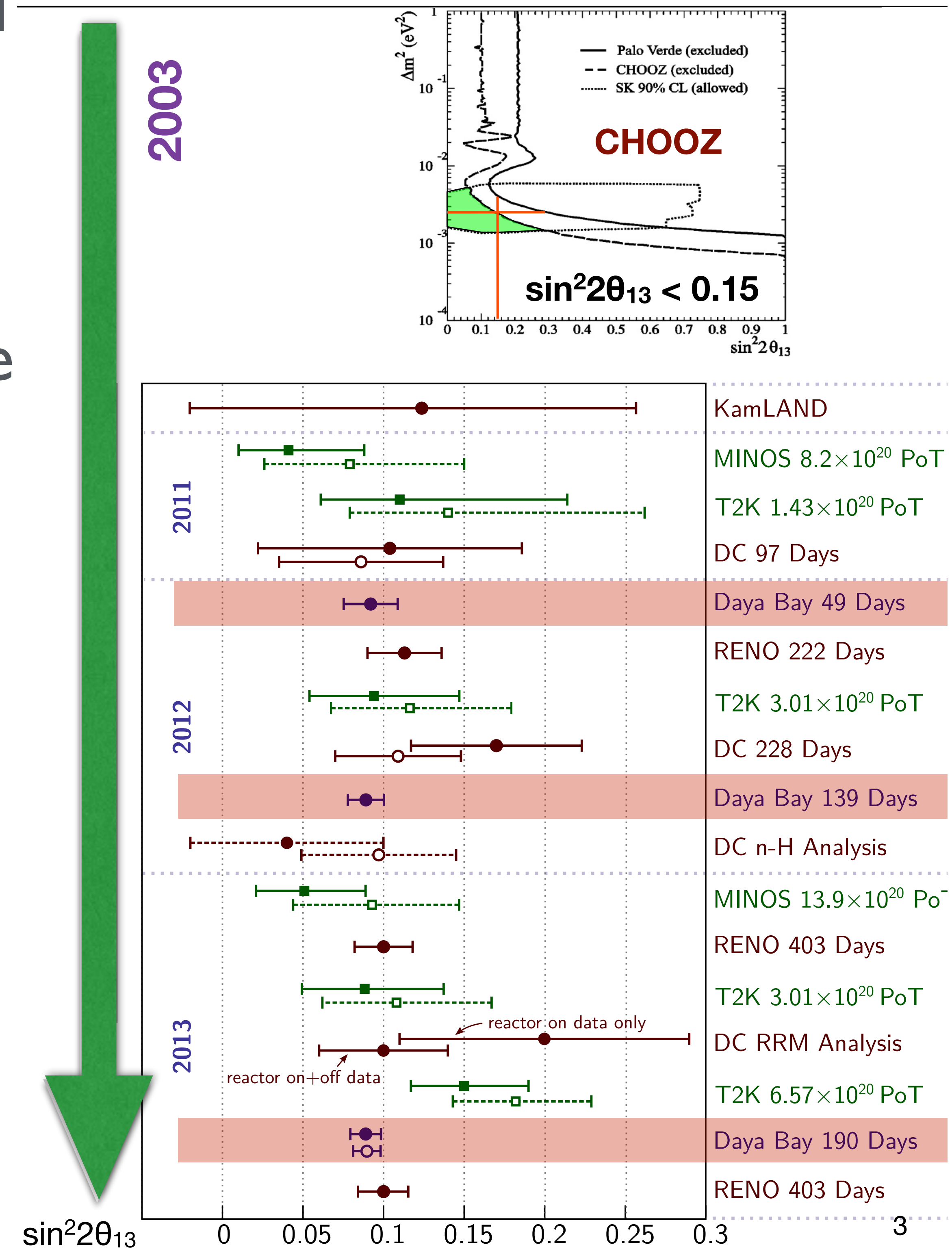
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m_{23}{}^2 L}{E_\nu}\right)$$

- The physics parameters are: the mixing angle and one mass squared difference

Field moves quickly

- Around 2003 neutrino physicists searched for the parameter $\sin^2\theta_{13}$
- The parameter $\sin^2\theta_{13}$ has now been measured
- In 2012 Daya Bay measured $\sin^2\theta_{13}$ for the first time
- Today is best known angle!

$$React. \rightarrow \sin^2\theta_{13}(4.7\%)$$



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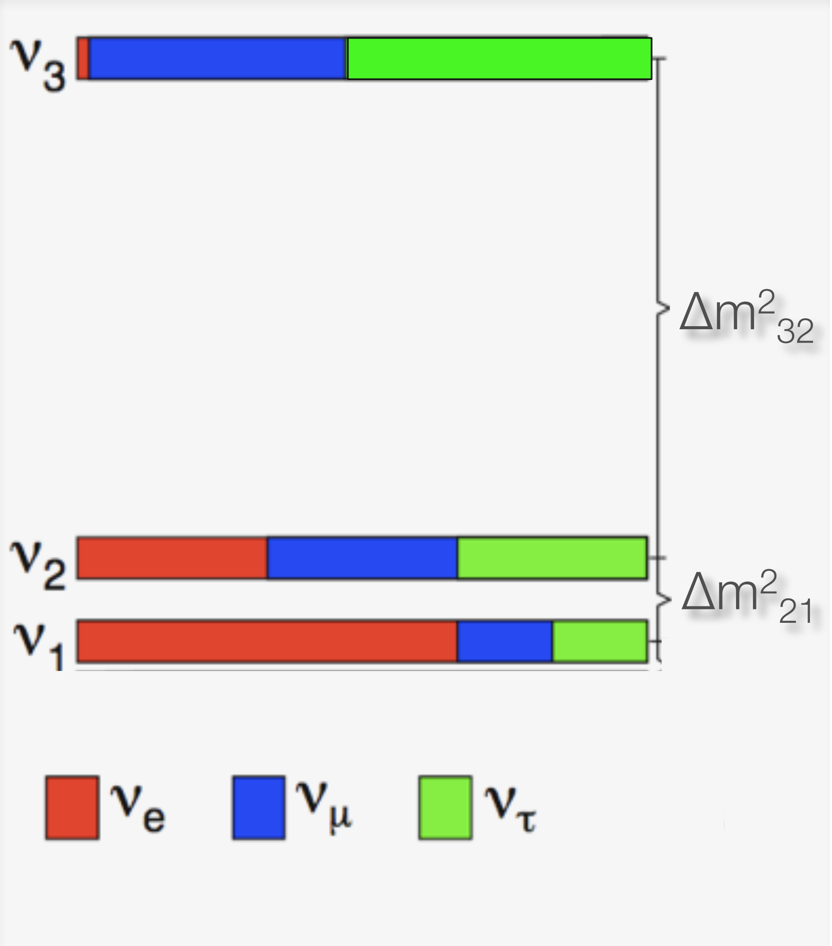
Remaining Questions

- Is there CP violation in the lepton sector?
  - May explain matter-antimatter asymmetry
- What is the mass hierarchy? (sign of Δm^2_{32})
  - Important to be able to understand the reach of experiments that study whether neutrinos are their own antiparticle or not
- Is θ_{23} maximal?
- Is there a fourth "sterile neutrino"?

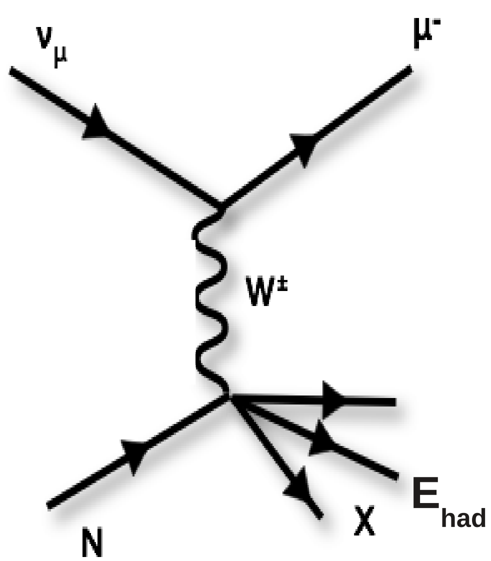


In More Detail

- Oscillation probability depends on neutrino energy E_ν
- We need to reconstruct the neutrino energy precisely

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{E_\nu})$$

- Neutrino energy reconstruction is obtained using the final state particles of neutrino-nucleus interaction
  - Fully active experiments reconstruct the energy using: $E_\nu = E_{lepton} + hadron$



- Nuclear effects modify the kinematics of the particles and the reconstruction of the neutrino energy

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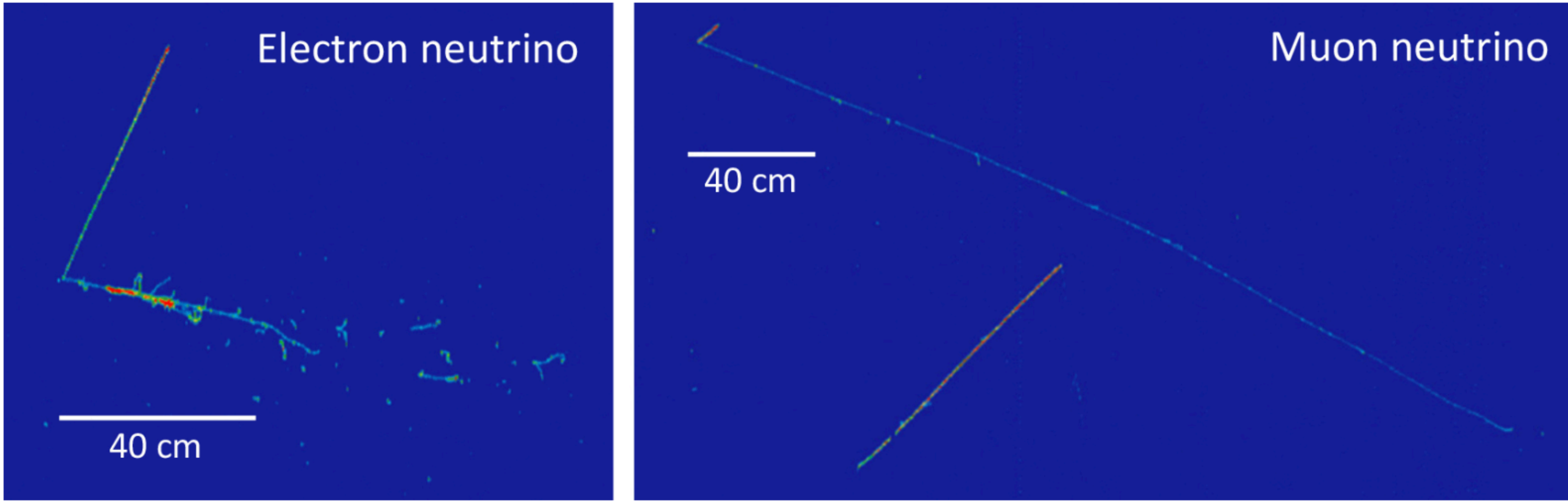
In More Detail



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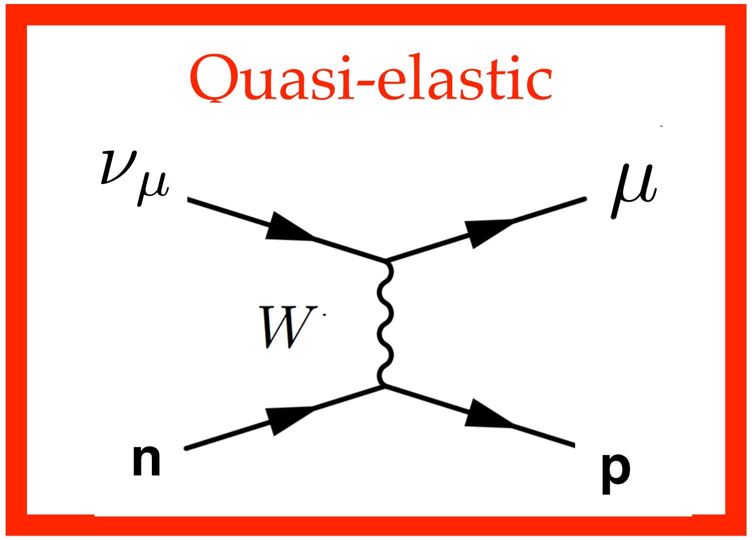
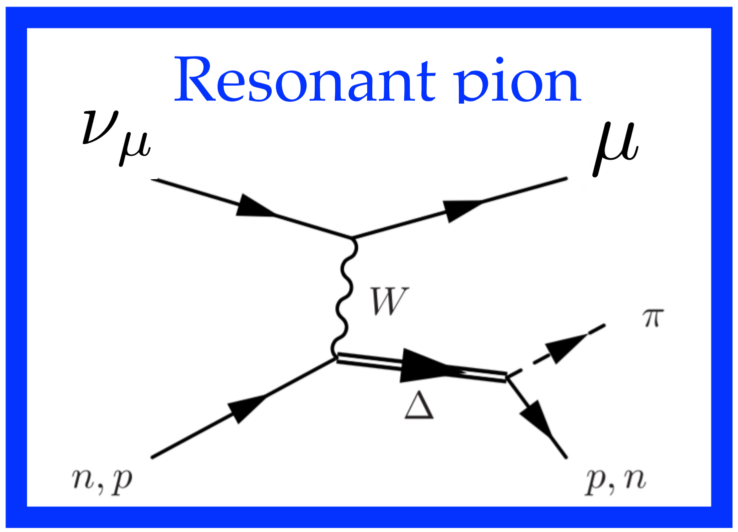
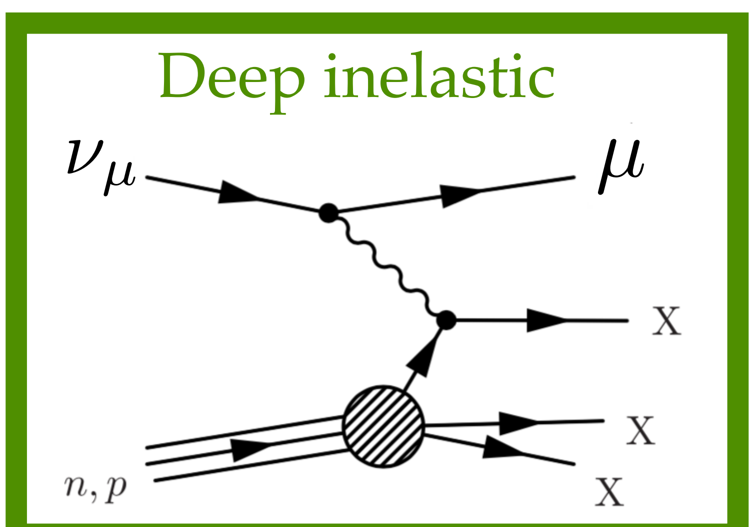
Charged Current Interactions



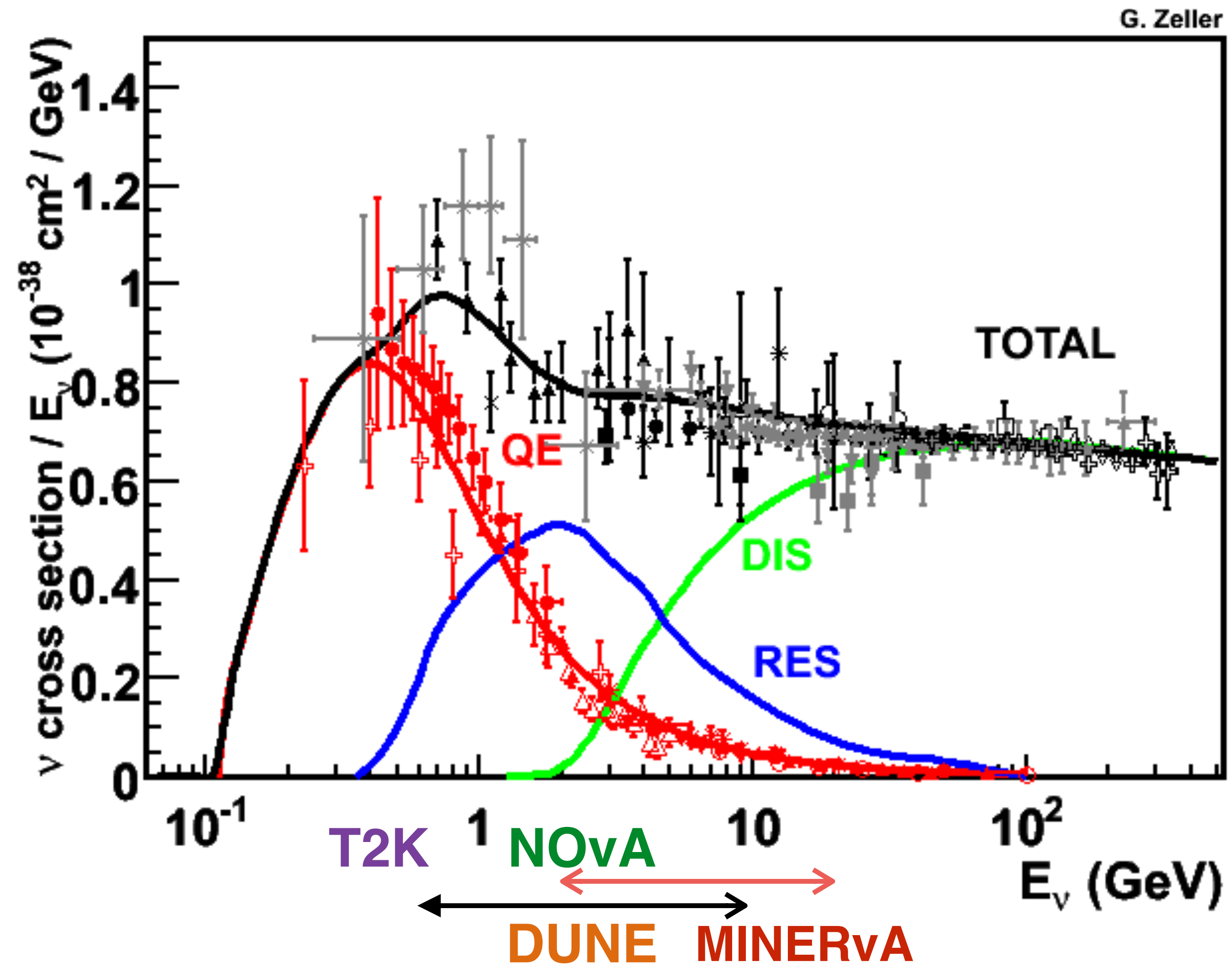
QE



RES



DIS

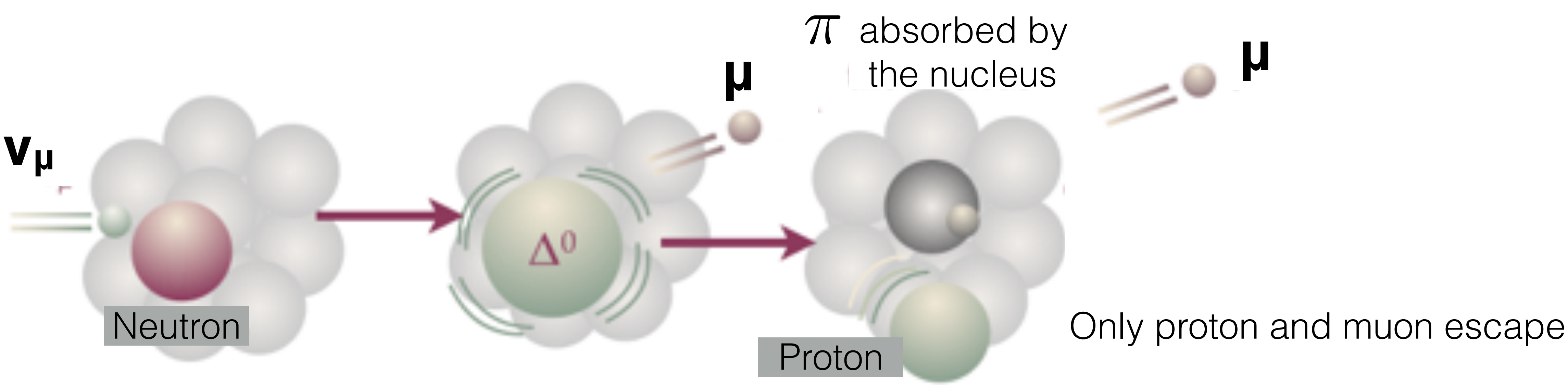


J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

Also, we have Neutral current interactions

Example of Nuclear Effects (Final State Interaction)

- Final state interaction (FSI):
  - Due to final state interactions, particles can interact with nucleons and pions can be absorbed before exiting the nucleus and other nucleons get knocked out

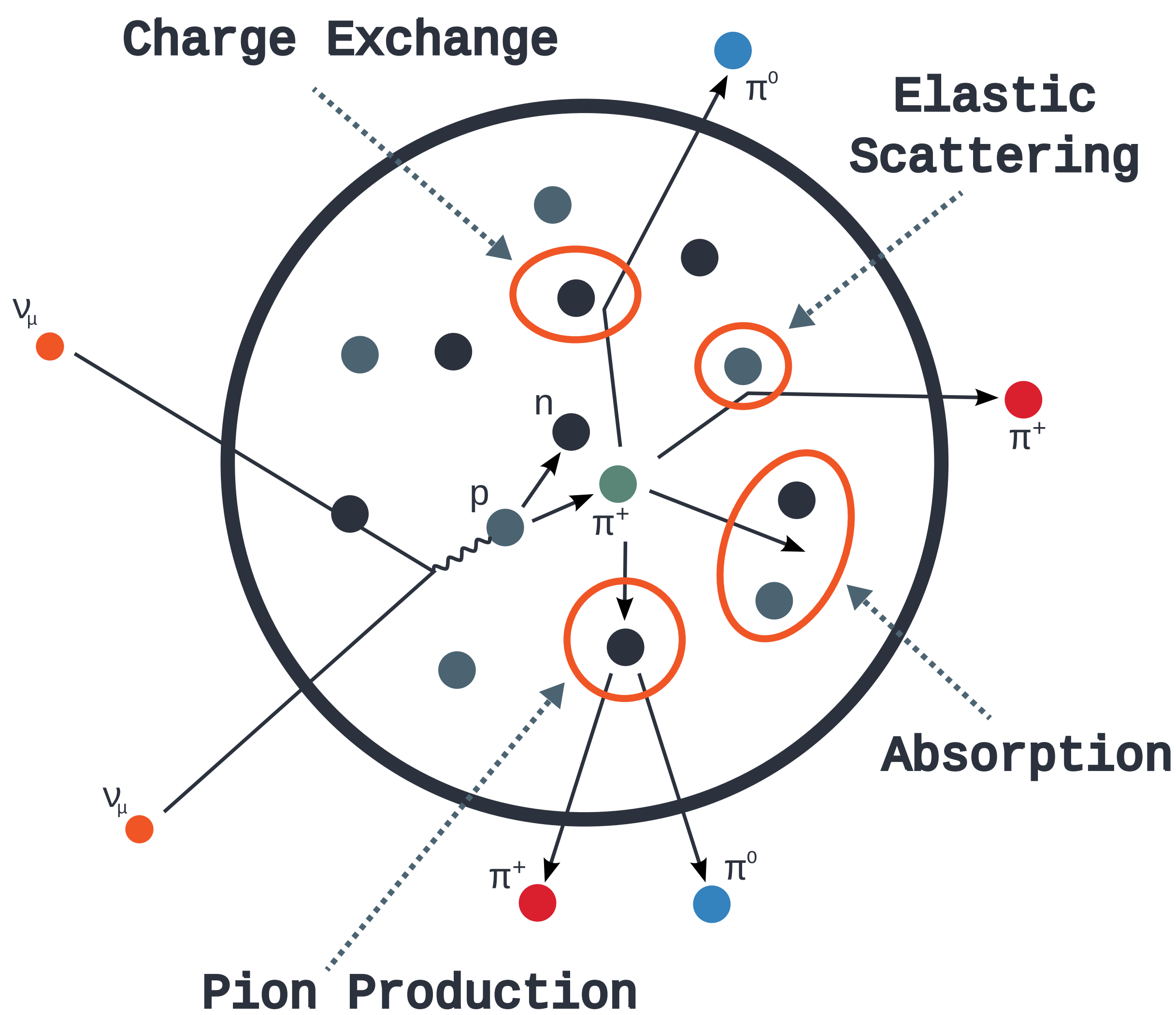


Start as a RES interaction, the pion is absorbed and the interaction looks QE like in our detector

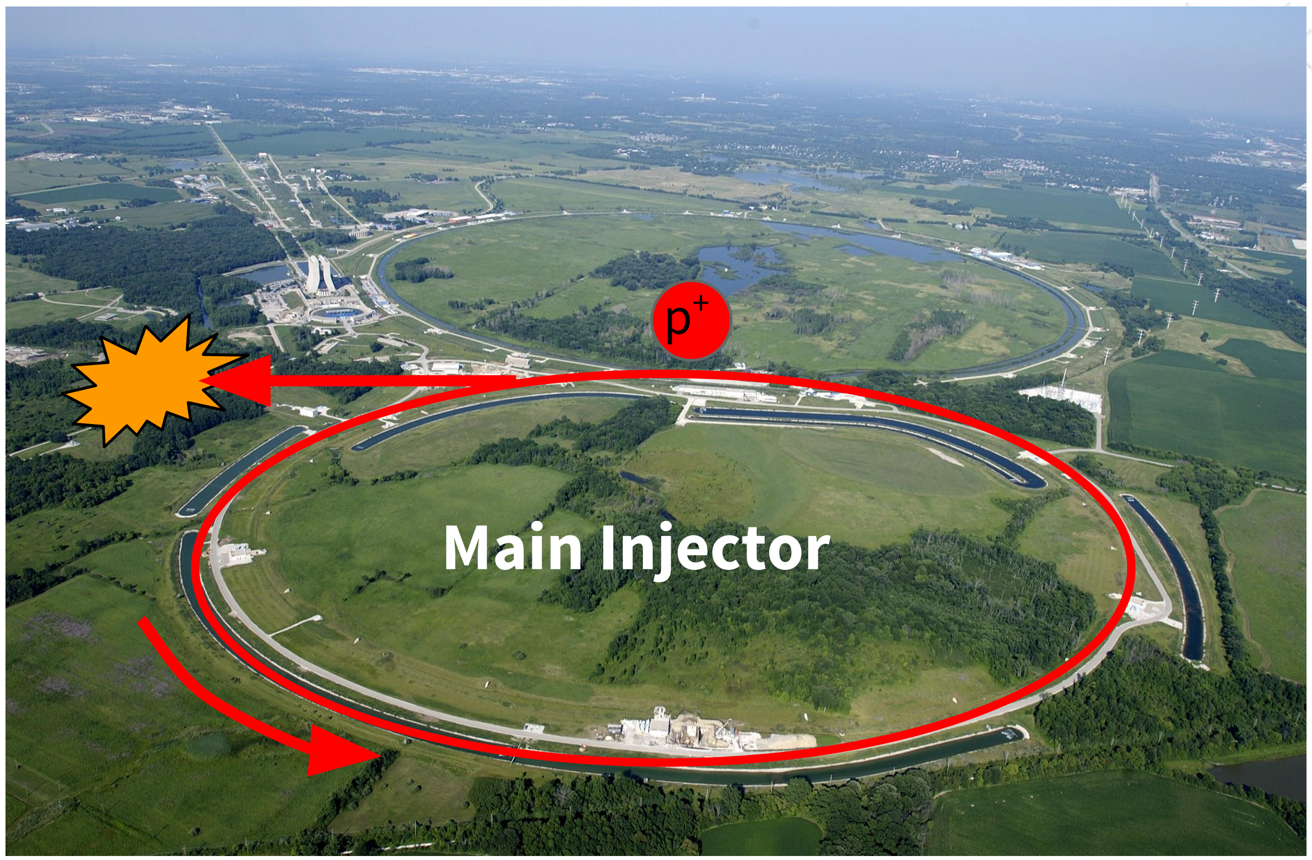
- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics
- Pion absorption is twice as big in Argon as it is in Carbon!

Example of Nuclear Effects (Final State Interactions)

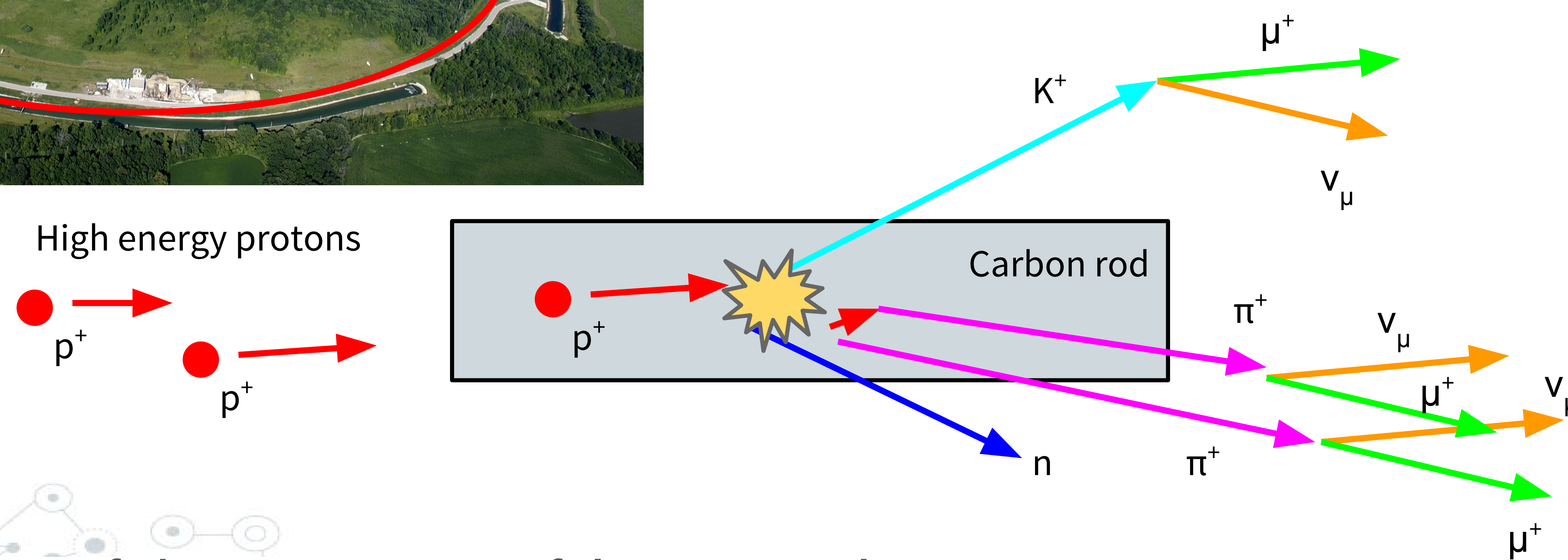
- Other examples of final state interactions:



How to make a neutrino beam



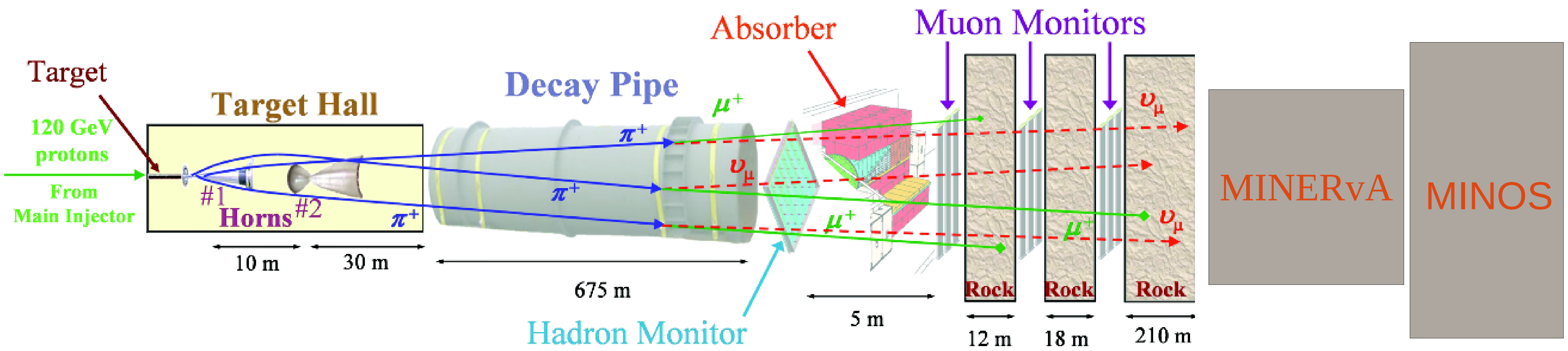
- Protons hit carbon
- Charged pions are produced
- Pions and kaons decay to neutrinos



Fermilab: home of the most powerful neutrino beams,
Two neutrino beams:NuMI and Booster

Neutrinos From Accelerators

- A beam of protons interact with a target and produce pions and kaons

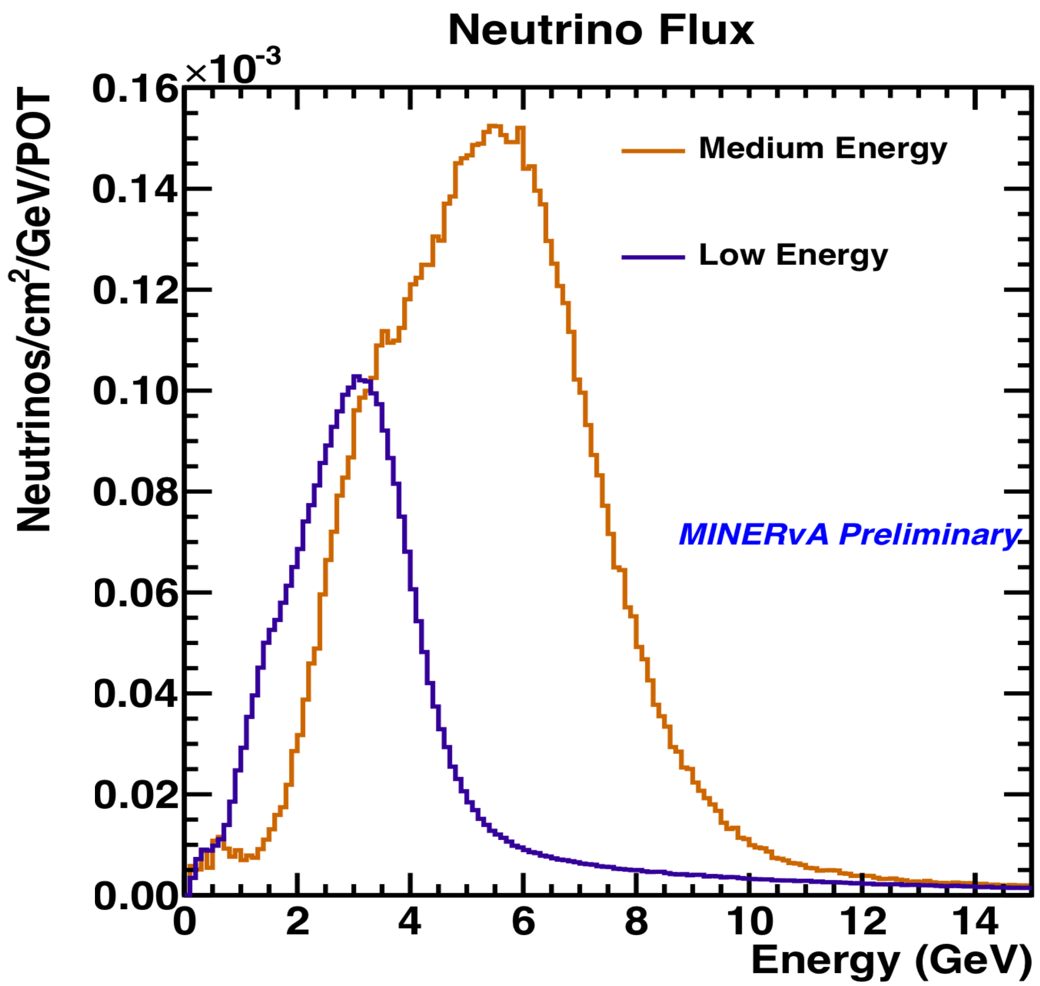


- Focusing system (2 horns, with current, emitting B field)
- Decay region (large pipe, filled with helium)
- Monitors and absorbers
- Neutrino beam produces mainly ν_μ and small component of ν_e

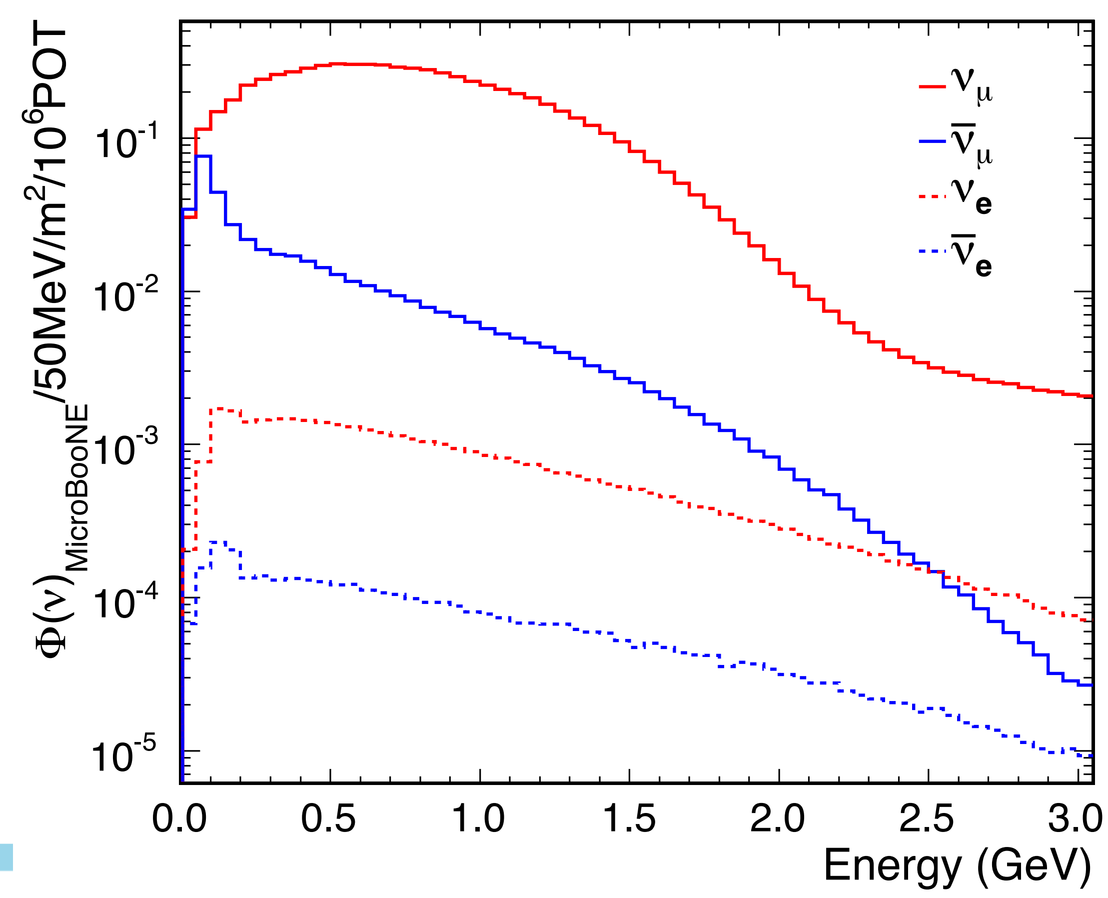
Neutrino Energy Spectrum

- The target and second magnetic horn can be moved relative to the first horn to produce different energy spectra
- This allows a study of neutrino interaction physics across a broad neutrino energy range
- Neutrino oscillation experiments use interactions in the near and far detectors to study oscillation physics

Neutrinos from NuMI

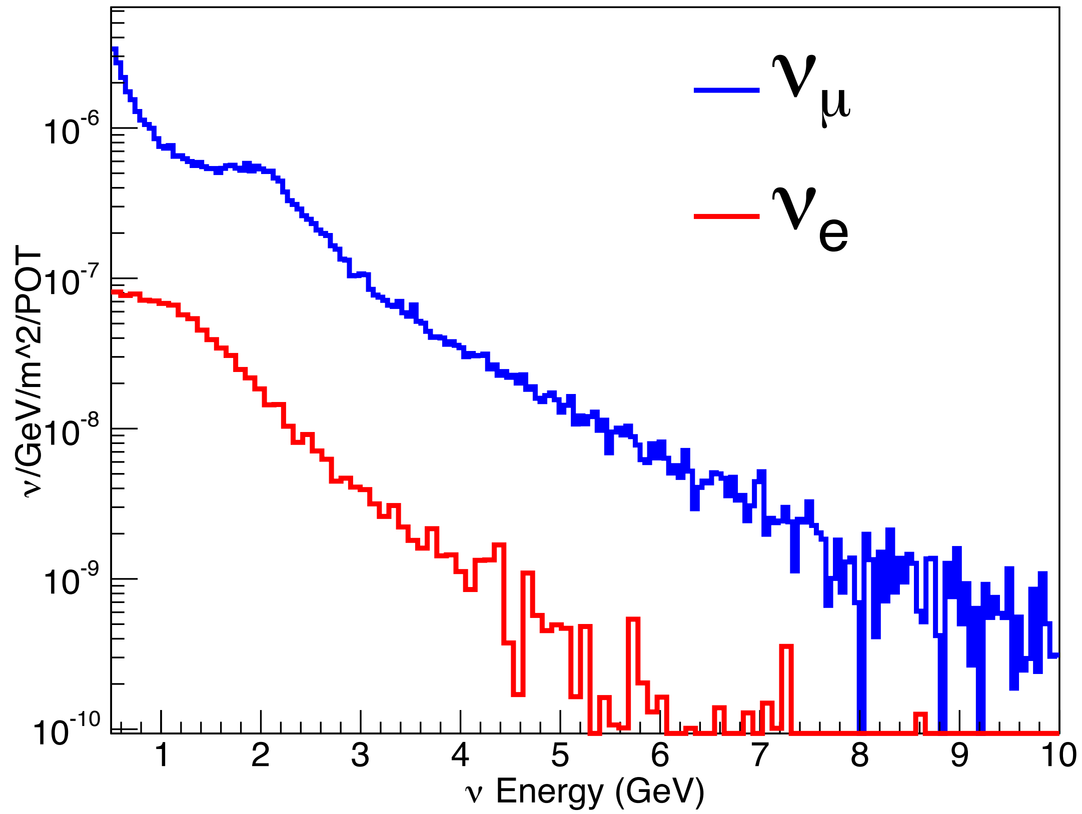


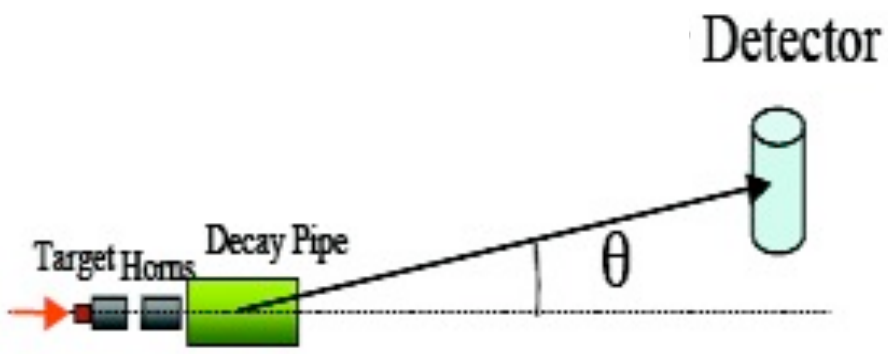
Neutrinos from Booster



Off axis NuMI beam at ICARUS

- ICARUS is located 103mrad off axis from the NuMI beam



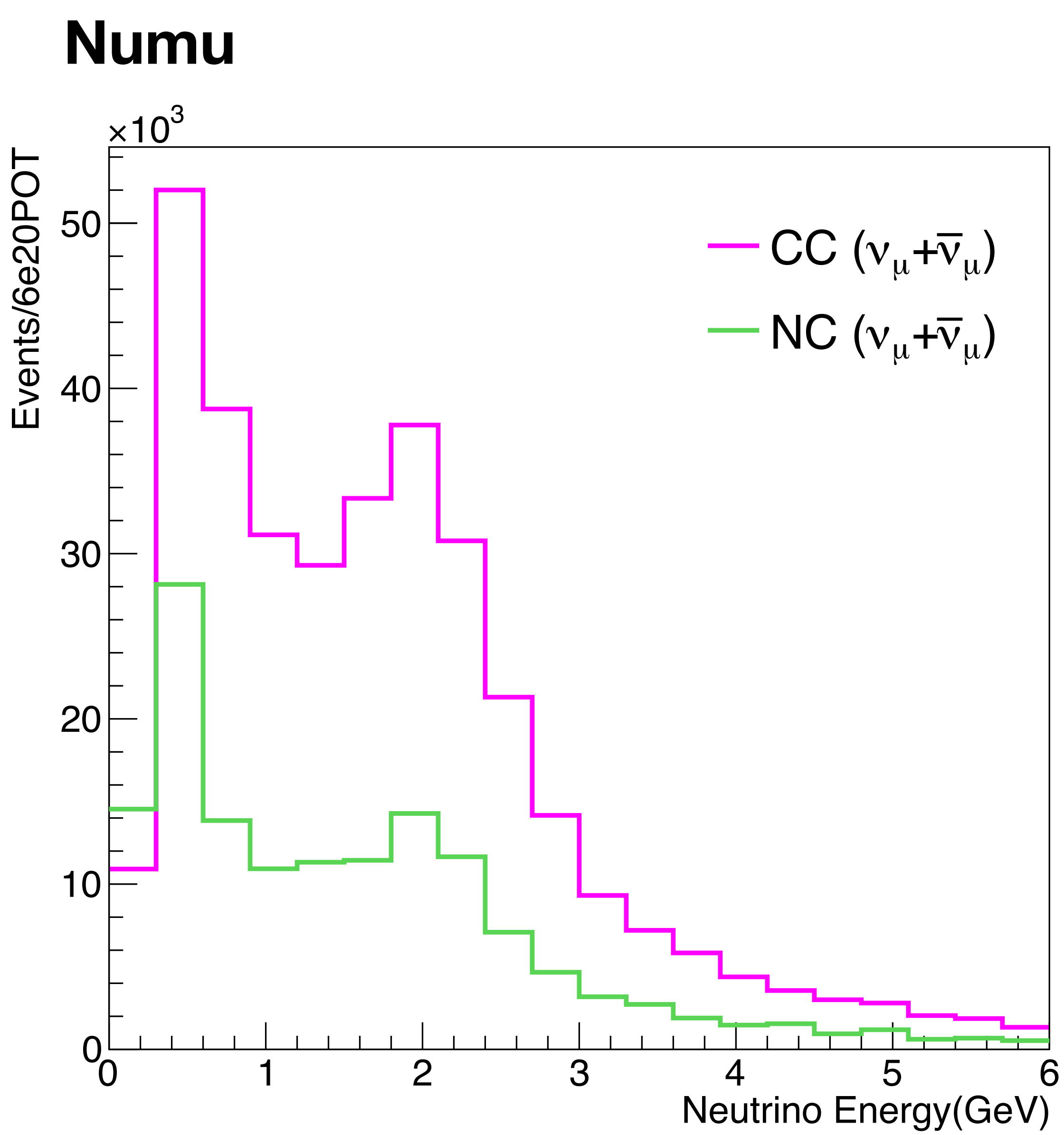


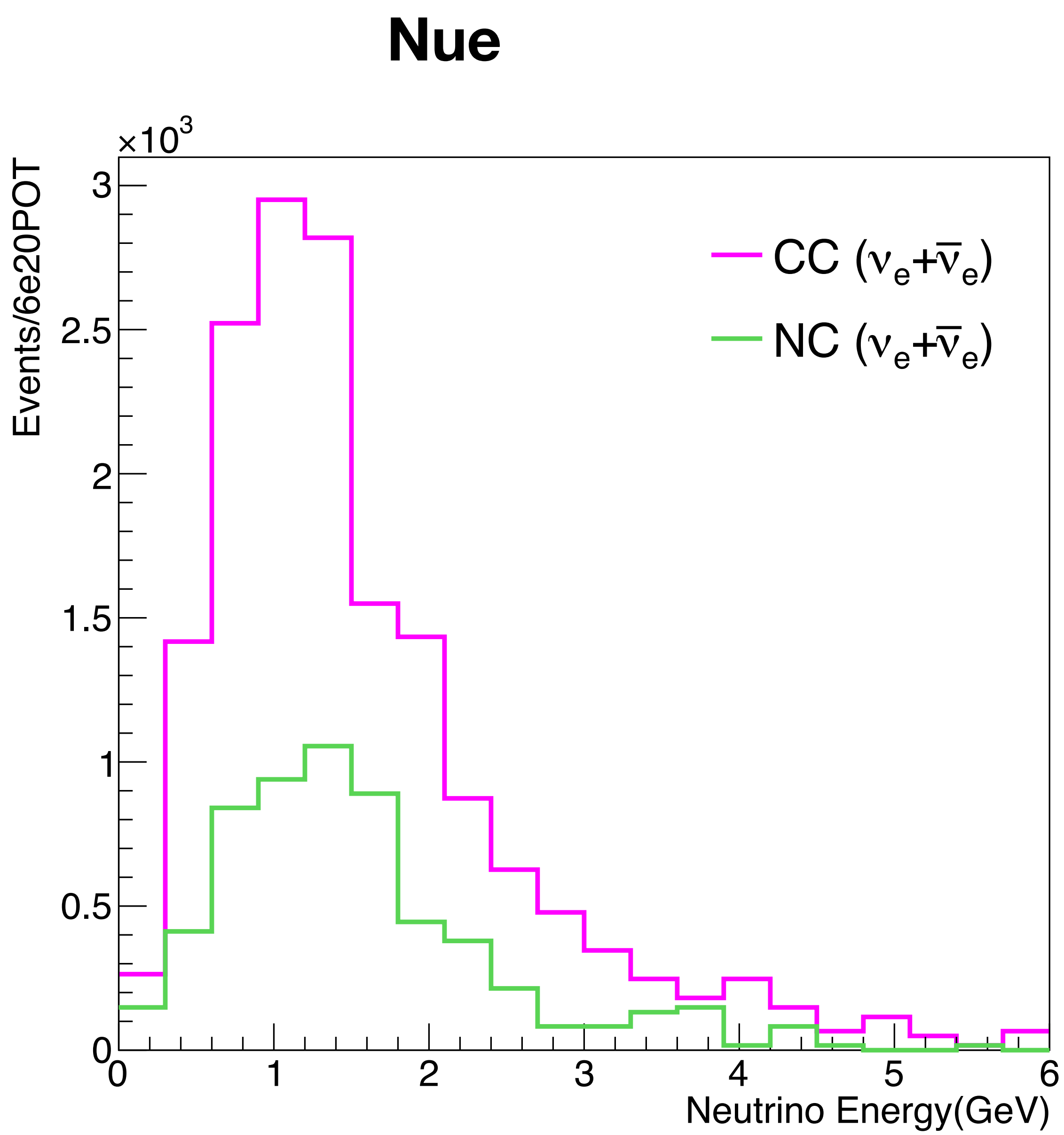
$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

- High statistics for muon and electron neutrinos at ICARUS from NuMI beam

Neutrino Interactions from NuMI off axis

- Vertex in LArTPC, making a cut on fiducial x, y and z coordinates in the active TPC
- Predicted events per year (6e20POT):
  - CC muon neutrino=433056, NC muon neutrino=191232
  - CC electron neutrino=20608, NC electron neutrino=7312

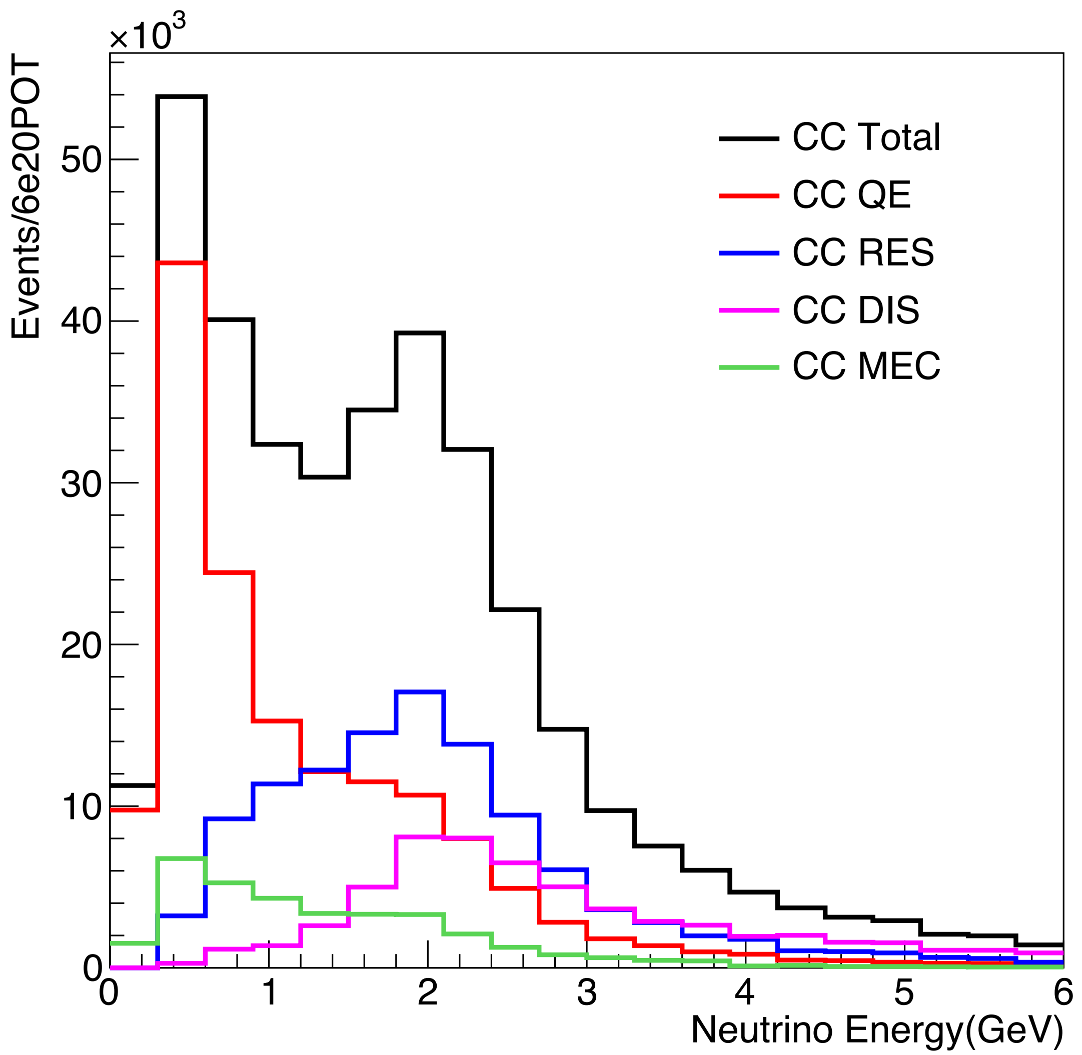




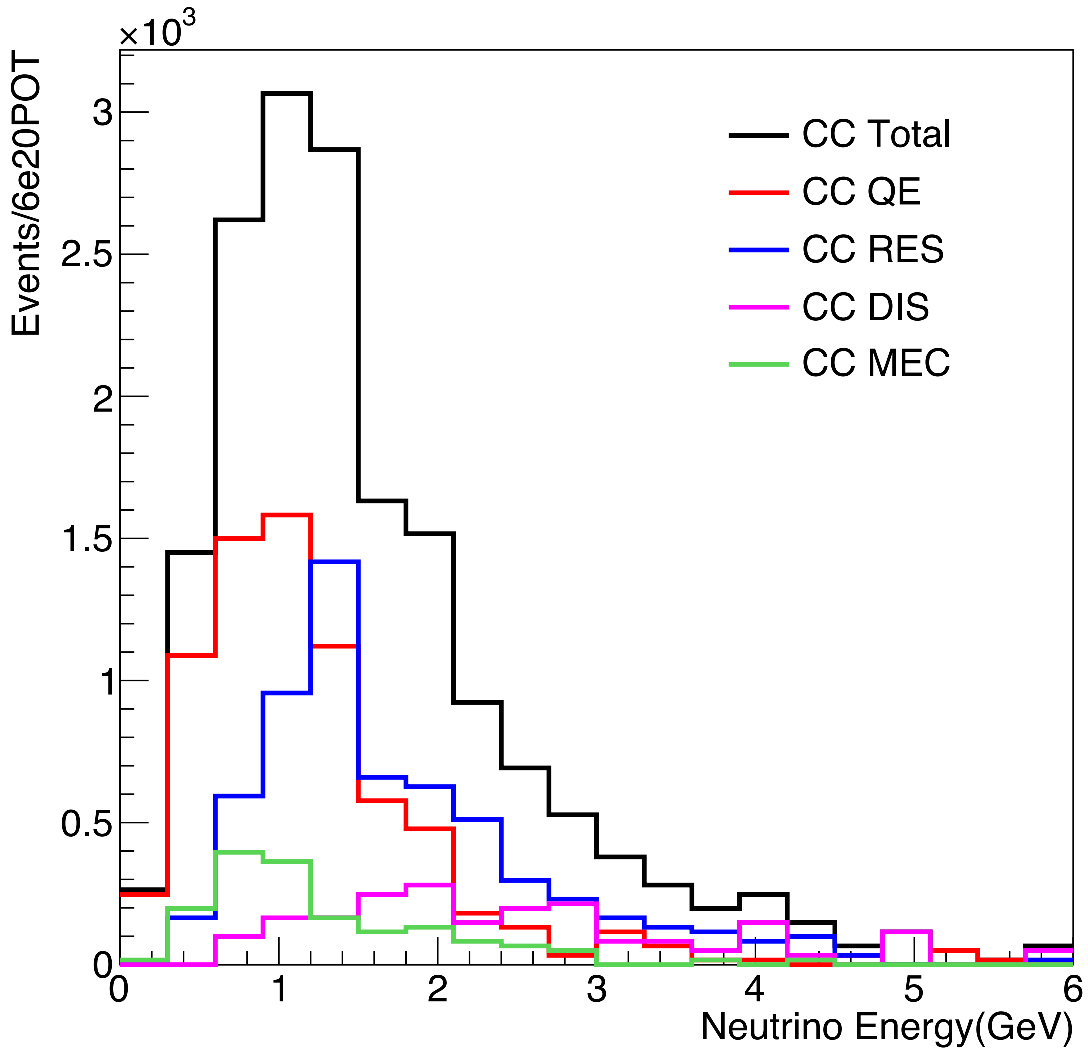
Neutrino Interactions from NuMI off axis

- Mainly channels are quasi-elastic and resonance interactions
- We could make cross section measurements for quasi-elastic and pion production scattering, for both electron and muon neutrinos

Numu

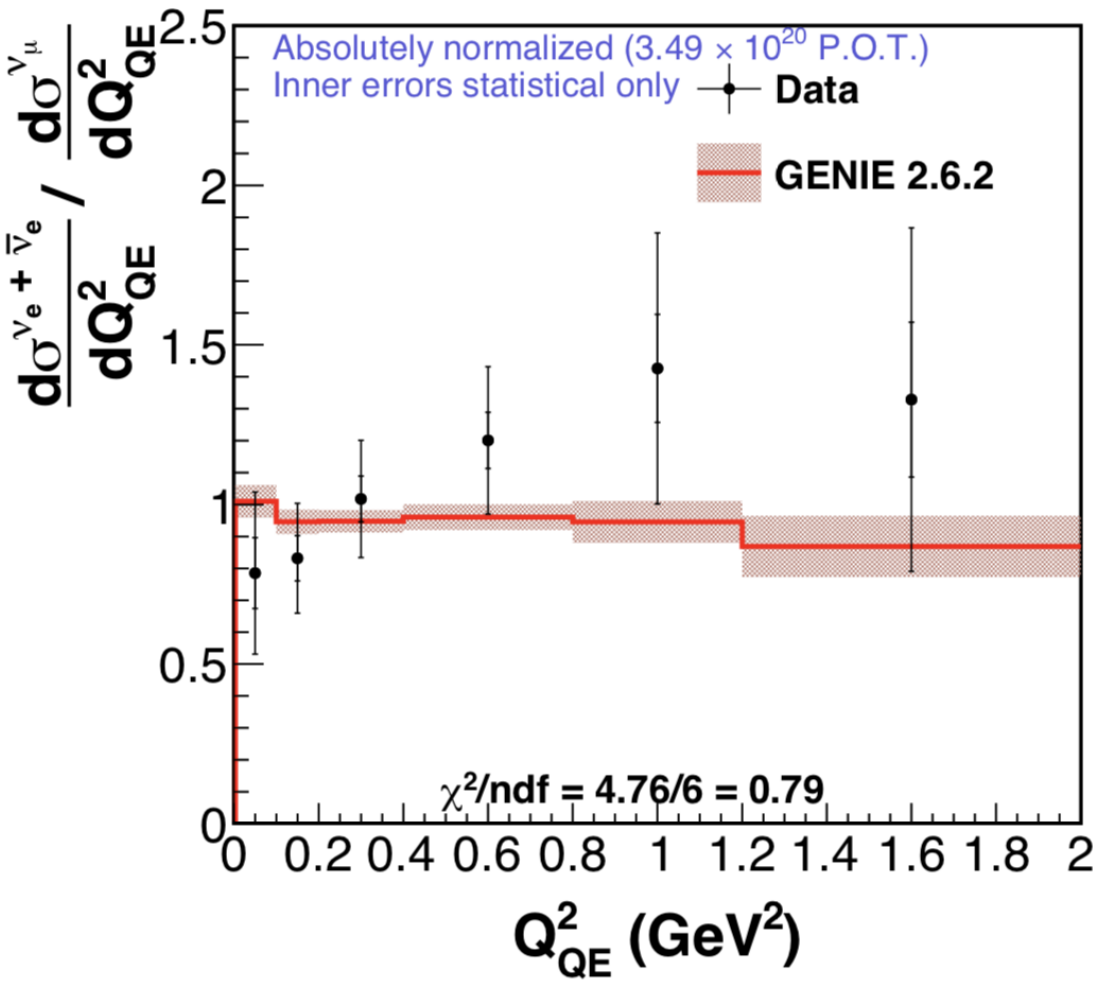


Nue



Neutrino Cross Section at ICARUS

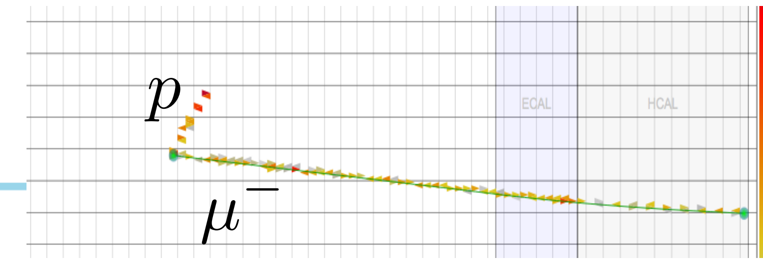
- Ratio of electron neutrino to muon cross section has been measured on carbon
  - Measurement of Electron to muon neutrino Quasielastic Scattering at MINERvA experiment

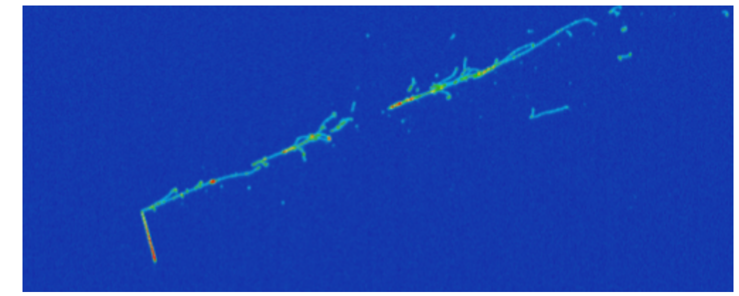


Phys.Rev.Lett. 116 (2016) no.8, 081802

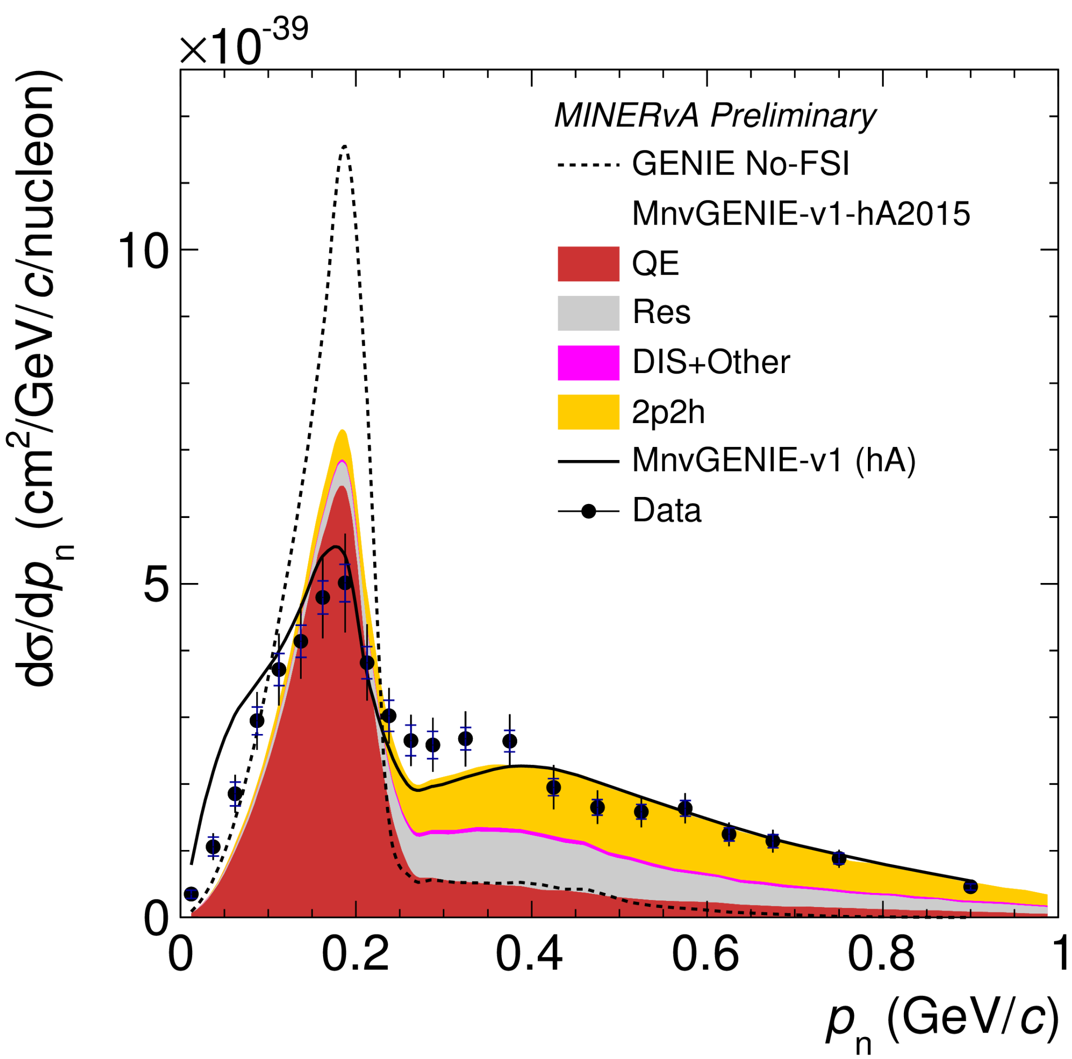
- There are no high statistic measurements of the electron neutrino cross-section and muon to electron neutrino ratio cross section on argon at DUNE high energies
- This is an example of the measurements we could do

Measurements with Quasi-Elastics Events

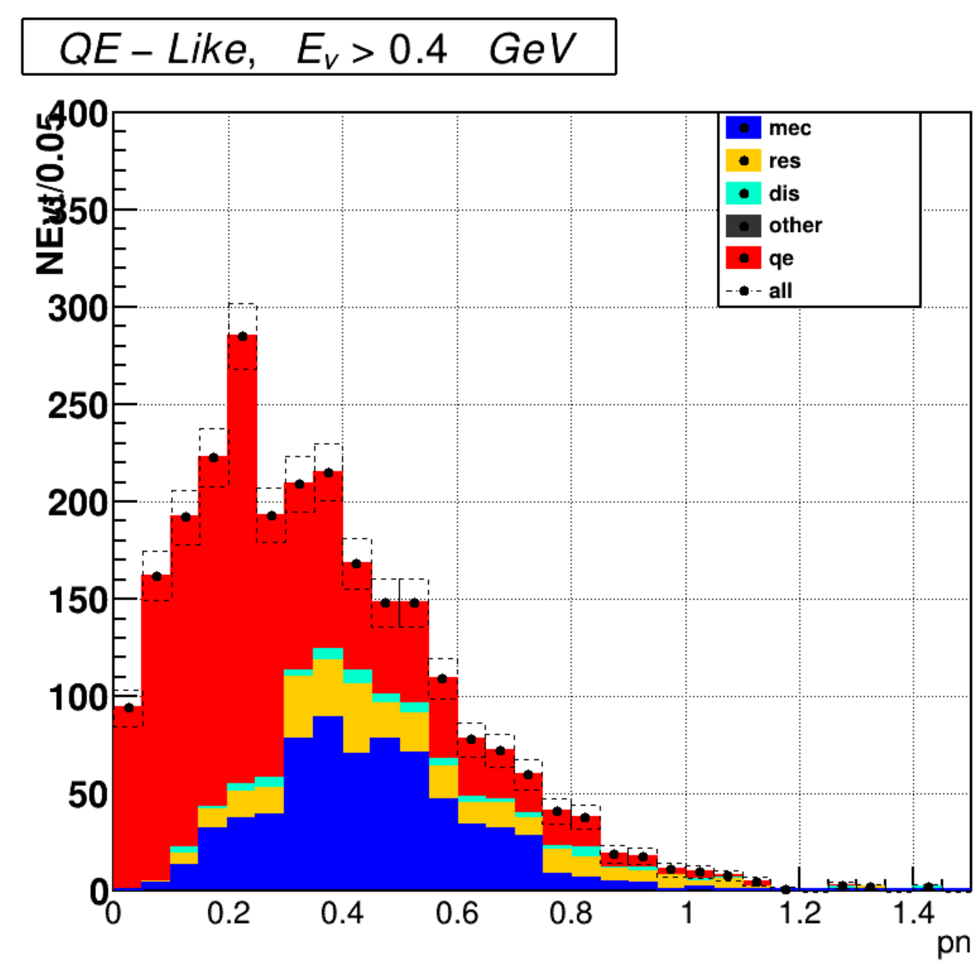




- Probing final state nuclear effects using the leading proton and the lepton
- Differential cross section in initial struck neutron momentum
  - Useful to constrain initial nuclear effects, deficiencies in the model at low and mid region of the neutron momentum



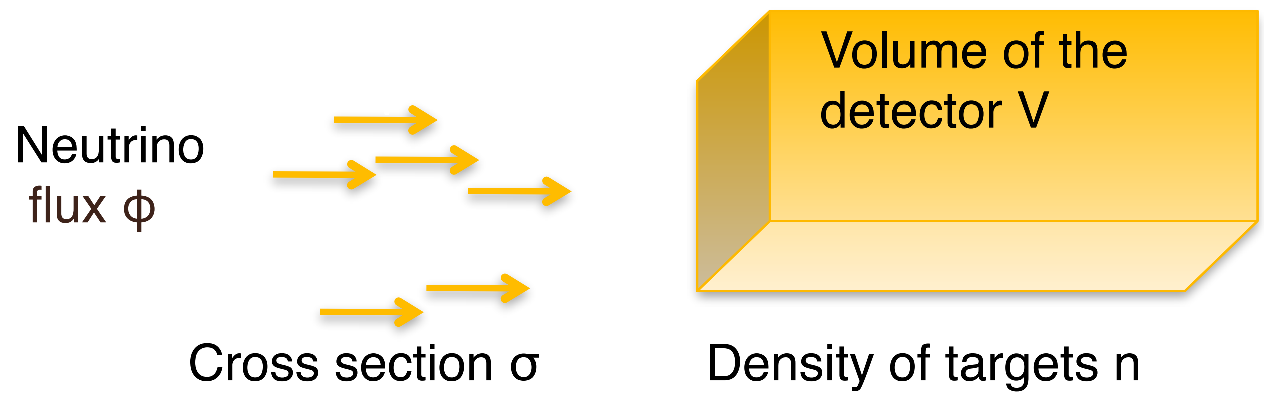
Using ICARUS simulation for electron neutrinos



Phys.Rev.Lett. 121 (2018) no.2, 022504

Neutrino Cross Section

- A measure of the probability of an interaction occurring



Number of interactions per second

Cross Section

$$\sigma = \frac{N}{\Phi T}$$

Number of interactions that occurred

Total flux of incident neutrinos per unit area

Number of targets

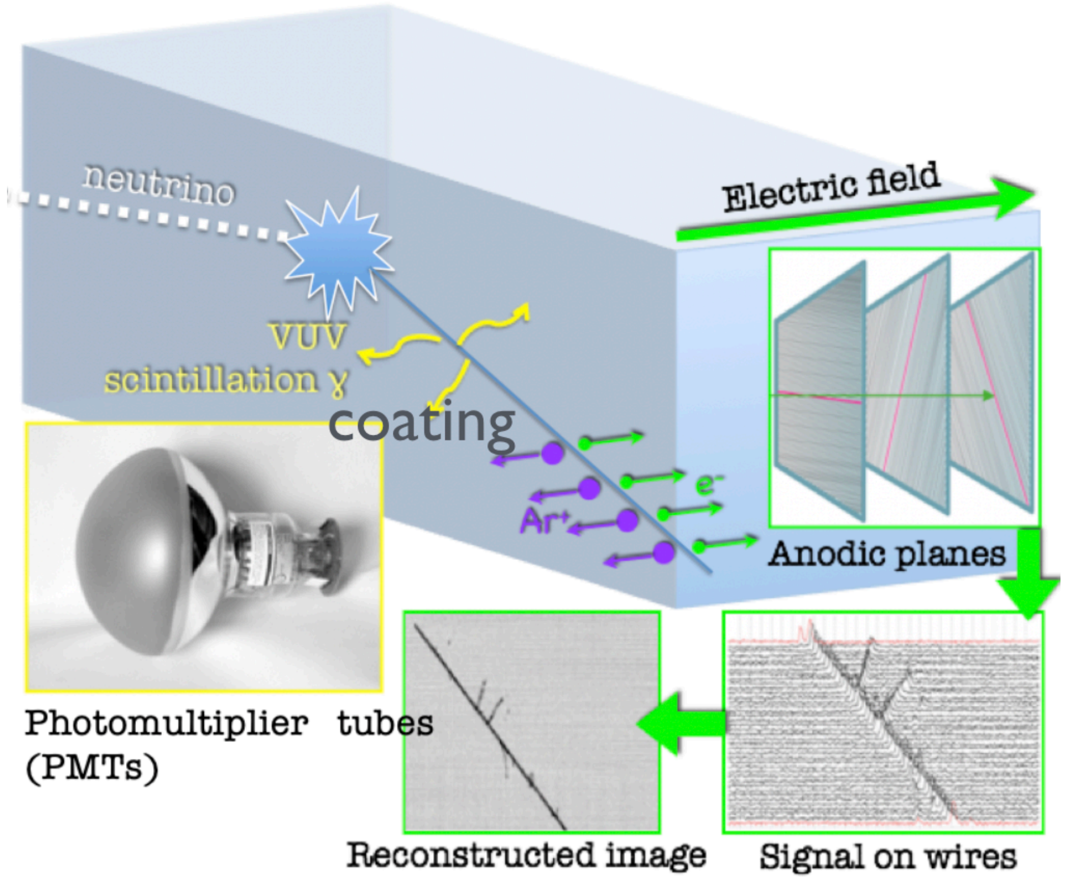
For a neutrino that has 1 GeV of energy the cross section $\sigma(\nu N) \sim 10^{-38} cm^2 \longrightarrow$ tiny

compare with $\sigma(pp) \sim 10^{-26} cm^2$

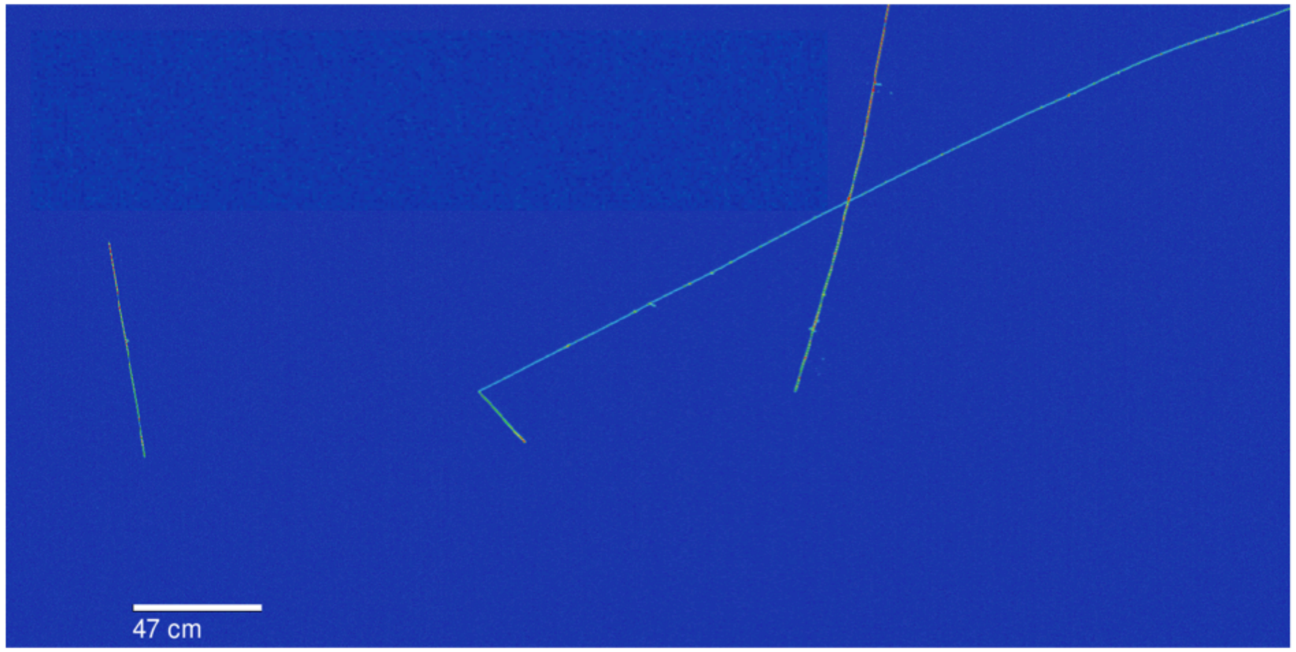
Detector

Cosmic Ray Tagger (CRT)

Time Projection chamber (TPC)



Photomultipliers (PMT)



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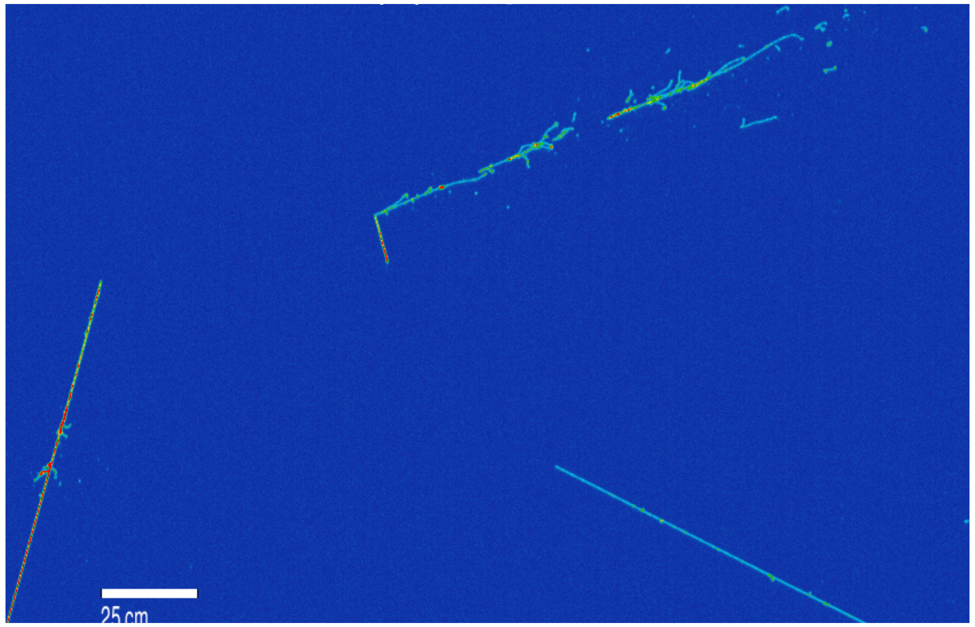
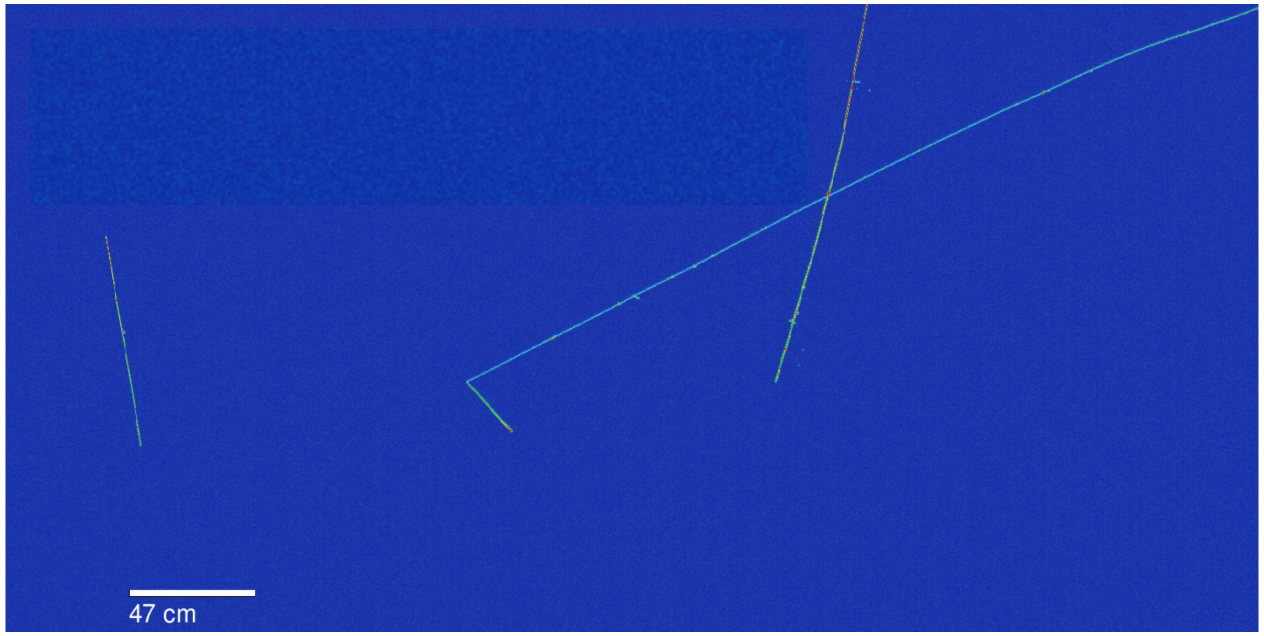
Building a Cross Section

- All cross section analyses need to use reconstructed tracks or showers
- We need calibration of the charge and energy response in the TPCs
  - Calorimetry and particle ID
- We need reconstruction from the PMT and CRT systems to reject the cosmic background
  - TPC-PMT matching and CRT-PMT matching
- Measurements will be done as function of neutrino energy, four momentum transfer, muon/electron momentum and angle
  - Need to reconstruct muon momentum and angle, neutrino energy, four momentum
  - $E_\nu = E_{lepton}$+hadron $Q^2 = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos\theta\mu)$





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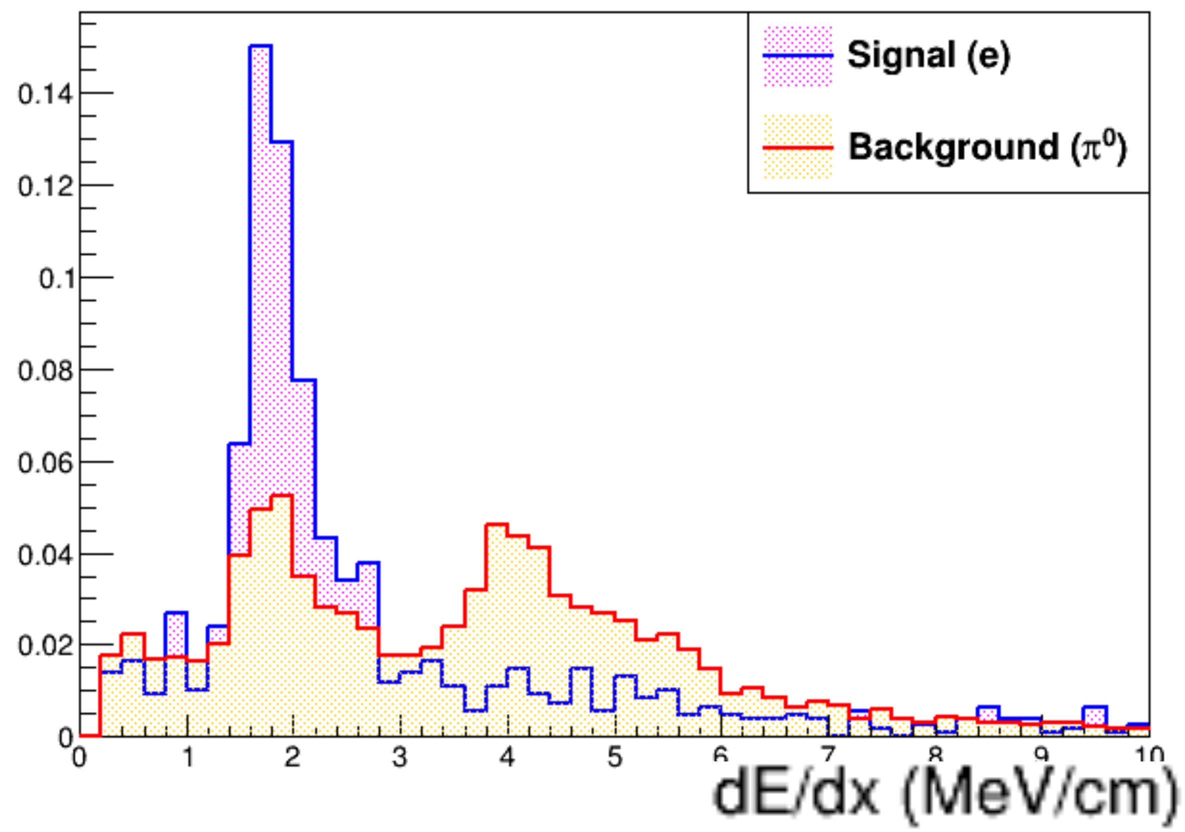
Electron Neutrino Event Selection

- Working with the electron neutrino event selection using the simulation
  - Initial studies used the following cuts:
    - Longest track length
    - Shower start position
    - One shower with energy greater than 250 MeV and initial dE/dx cut
- Recently there has been a lot development with the SBN event selection and we have started to look other variables and cuts using the analysis framework from SBN and starting to look into optimization



More details at SBN-docs 21651 and 21426

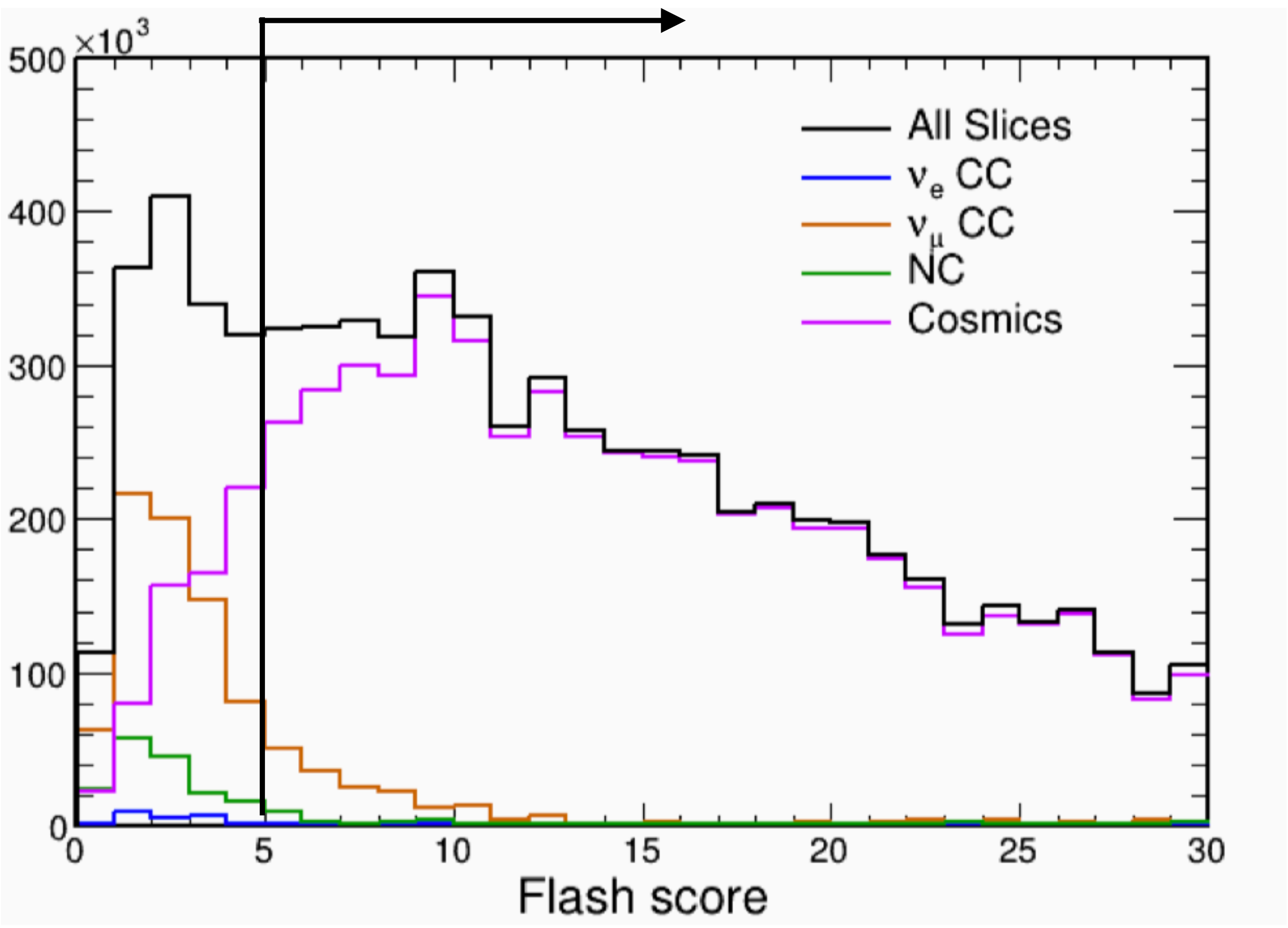
Electron Neutrino Event Selection

- Initial work explored comics background rejection
  - Preliminary studies using containment cuts on tracks/showers

$$(-180, -885)\text{cm} < \text{Shower } (y, z) < (130, 870)\text{cm}$$
$$(-175, -885)\text{cm} < \text{Track } (y, z) < (130, 880)\text{cm}$$

  - PMT flash matching using the PMT information

Cut to reject the cosmic



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    (-175,-885)cm < Track (y, z) < (130, 880)cm

  - PMT flash matching using the PMT information
  - CRT cuts using hits from CRT

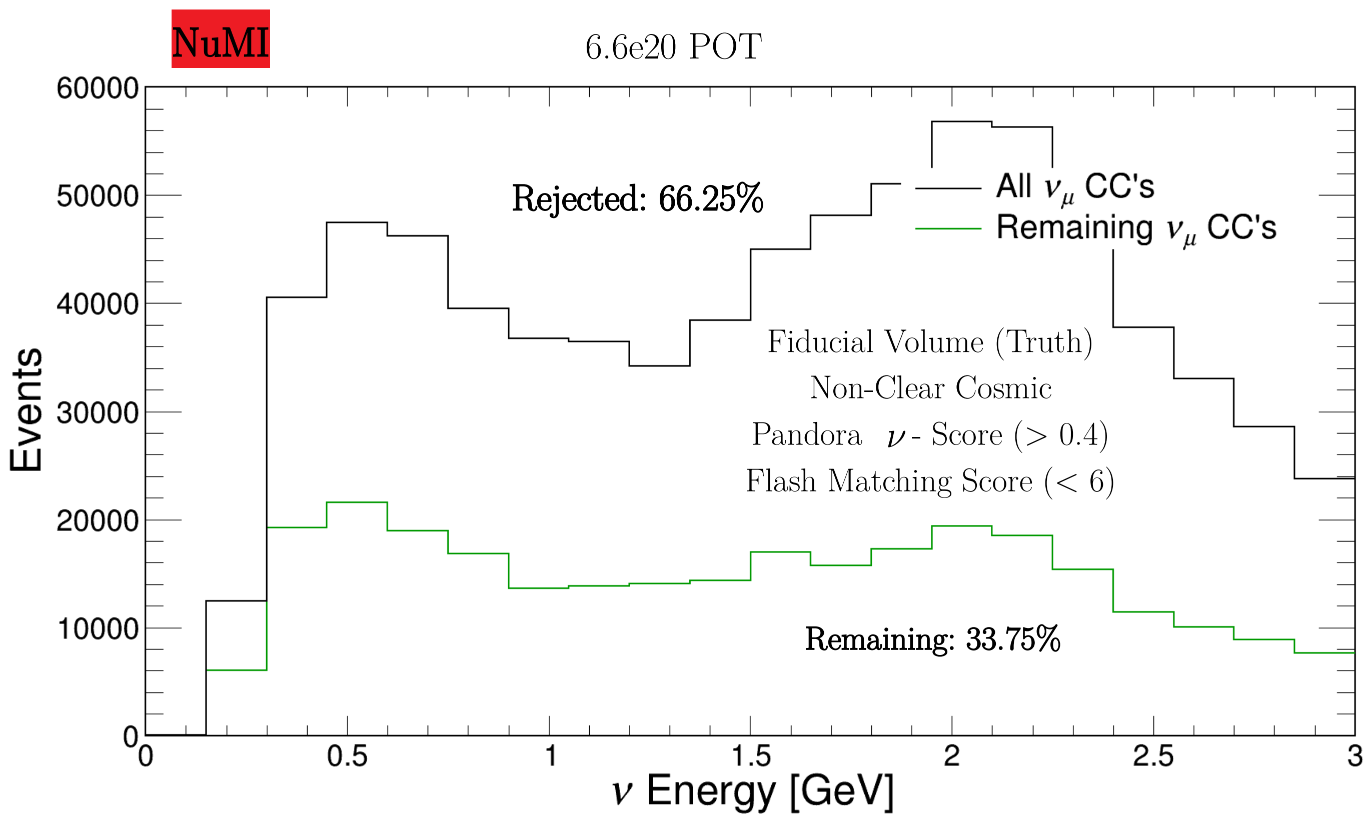
Cut	Background (Cosmics)		Signal (Nue with e)	
Pre-Selection*	5674		1085	
Containment	2683	**52.71 %**	951	**12.35 %**
Flash Score	2350	**58.58 %**	1078	**0.65 %**
CRT hits	1690	**70.21 %**	1081	**0.37 %**

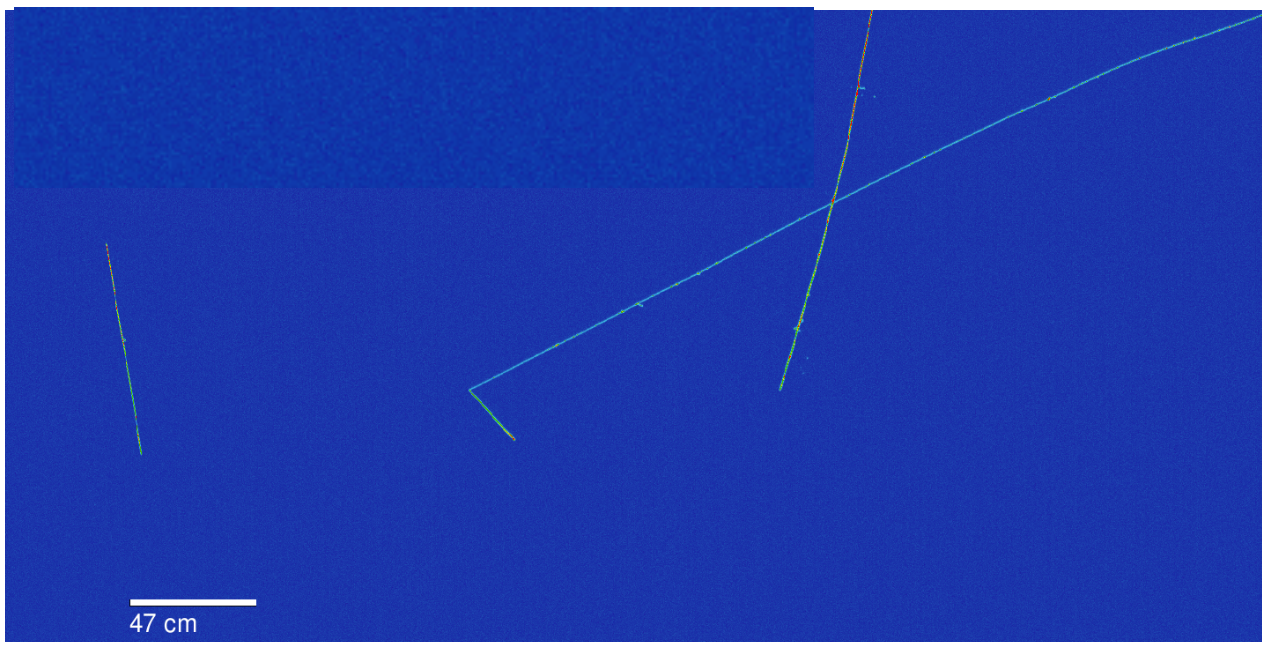
- More information from CRT could be used to reduce further the cosmic background

Muon Neutrino Event Selection

- Starting the analysis with MC simulations
  - Using different cuts to reject the cosmic background

- Energy spectrum before and after the cuts





Summary

- Neutrinos are great probes to answer fundamental questions about the nature of matter and the evolution of the universe
- Several discoveries since the first experimental evidence of neutrinos
- Oscillation experiments depend on modeling nuclear effects correctly and knowledge of cross sections to a few percent for precision oscillation measurements
- Rich physics program of neutrino-argon scattering measurements at ICARUS
- We have been commissioning the ICARUS detector at FNAL
- Working with the event selection in MC simulations and data
- Exciting times, we will be working to produce electron and muon neutrino cross sections
- ICARUS data taking for physics expected in fall

25 cm