How Neutrino Event Generator Works ? Ex : GENIE

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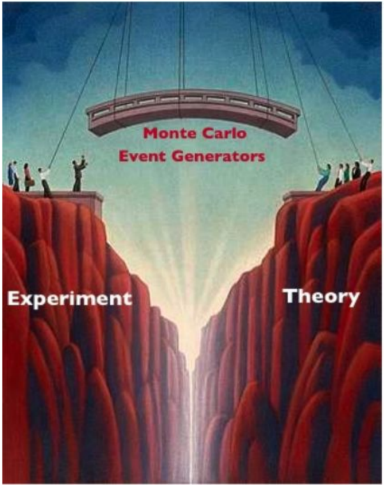
Understanding The Universe Through Neutrinos

Plan for the tutorials

- Gentle introduction to a complicated and highly technical field!
- Role of generators for experiments.
- Detaild information on neutrino-nucleous interaction is alreay discussed in the Prof Sajjad's lectures.
- See the parameters in the file "/opt/Gene......config/CommonParam.xml" , discussed in the morning lectures(Sajjad).
- Today, we will try to understand more basics simulation and perform more realistic simulation.
- Uncertainties, model tuning and detector effect will be discuss tomorrow.

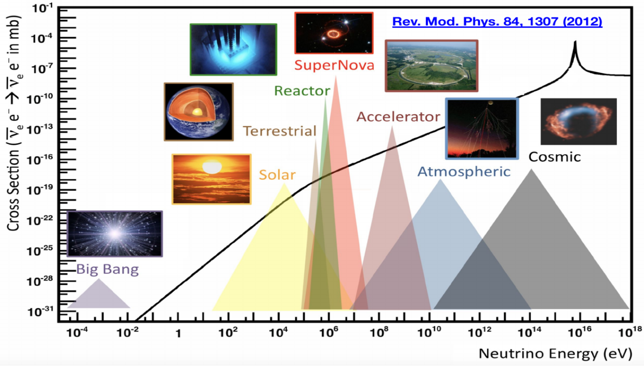
Role of the neutrino event generators

- "Bridge" between theory and experiment: model predictions are made easily usable.
- Essential for a variety of tasks needed for experimental analyses.
- Cross section data informs further theory improvements.



Neutrino physics across energy scales:

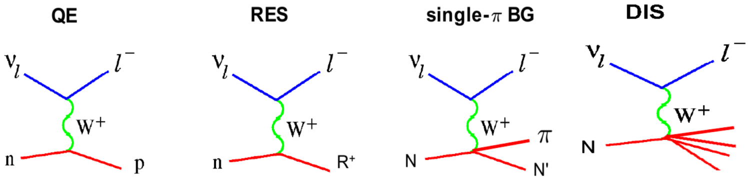
- Many orders of magnitude in energy!
- Most of NuInt looks almost at 100 MeV to 10 GeV region.
- I'll also talk a tiny bit about 1 MeV to 10 GeV.



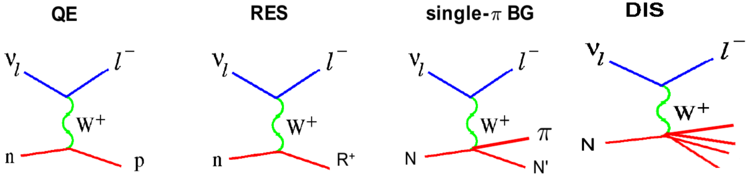
Neutrino-Nucleus Interactions

- A neutrino interacts via charged current and neutral current interactions.

- Various energy dependent neutrino interaction processes

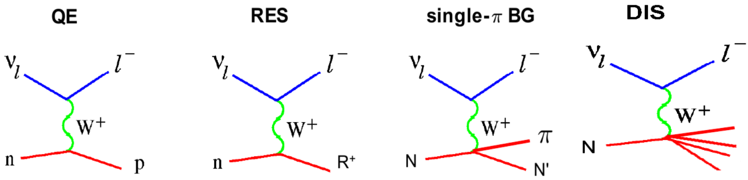


Pre-school example (Yesterday):

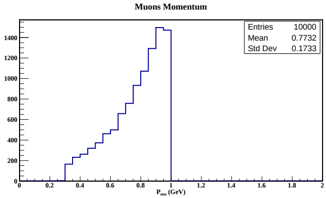


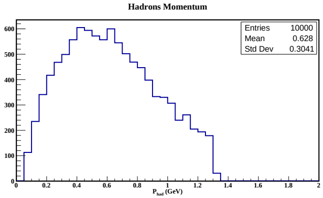
- What is the muon and hadrons momentum for 1 GeV neutrino beam for CCQE ?

Pre-school example (Yesterday):

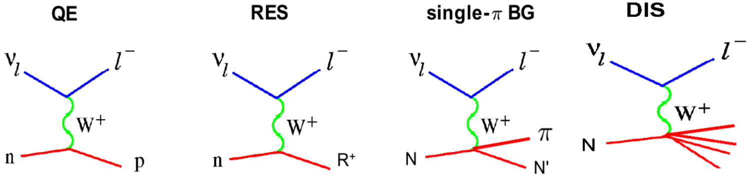


- What is the muon and hadrons momentum for 1 GeV neutrino beam for CCQE ?



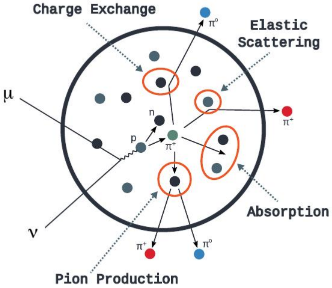


Questions..??(Example contnue ..)



- Is that will be same for anti-neutrino; $\bar{\nu_\mu}$, 1 GeV neutrino beam for CCQE prcess ?
- Is there any other process at 1 GeV neutrino events, like : RES, MEC and DIS process ?
- Is it same for other nuclear targer material Ar, Ca, C, Fe, H ?
- What are the list of parameters that can affect this final states particles kinematics ?

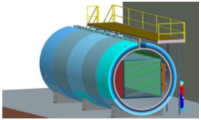
- **Initial State Interactions**
  - Nuclear Binding
  - Fermi motion
  - Pauli blocking
- **Final State Interactions**
  - absorption of outgoing particles
  - rescattering, charge exchange
  - production of new particles
- A model must include realistic description of nuclear effects including both ISI and FSI



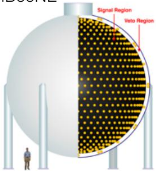
Nuclei as Targets

- Neutrino experiments use heavy nuclear targets with high atomic mass numbers like Ar(A=40), C(A=6), Ca(A=40).
- Why they are using Heavy nuclear target ?

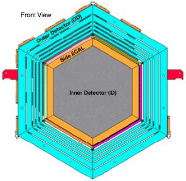
MicroBooNE

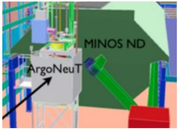


MiniBooNE



MINERvA

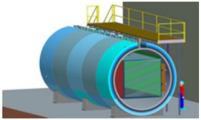




Nuclei as Targets

- To increase neutrino interaction rates: experiments use heavy nuclear targets with high atomic mass numbers like Ar(A=40), C(A=6), Ca(A=40).
- Heavy nuclear targets gives a boost to the event statistics in turn reducing the statistical uncertainties but at the same gives rise to the systematic uncertainties which are ultimately required to be tuned.

MicroBooNE



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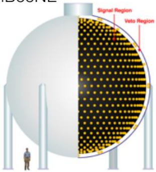

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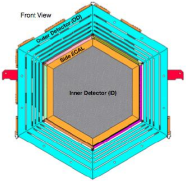
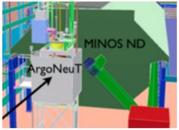
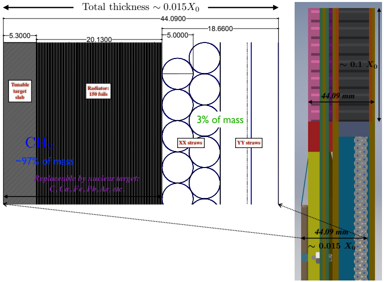




Hydrogen Target

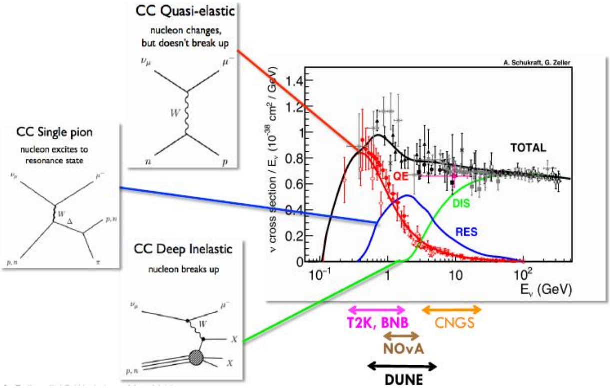
- Control sample free from nuclear effects to calibrate (anti)neutrino energy scale.
- Direct constraints on nuclear effects required to reduce systematics from nuclear targets.
- Straw Tube Tracker designed for a control of ν - target(s), proposed to build at ND hall.
- Separation from excellent vertex, angular and timing resolutions[1].
- Thin targets replaceable during data taking CH_2, C, Ca, Fe, Pb, etc.



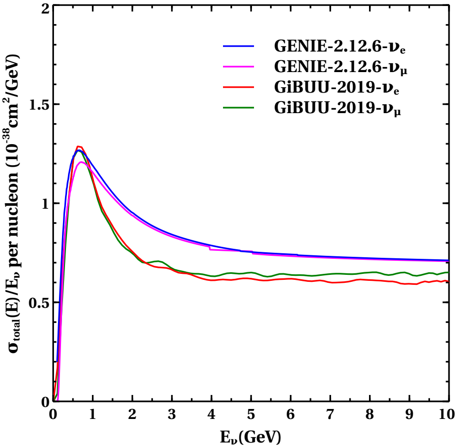
[7]R. Petti (South Carolina), (NDNN(nustec2021))

Uncertainties in the ν-nucleus cross-section:

- poor knowledge of neutrino flux
- Neutrino experiments measure a convolution of energy dependent neutrino flux $\otimes$ energy dependent cross-section $\otimes$ energy dependent nuclear effects.
- Interacting neutrino energy is evaluated based on kinematics of particles in the final state, taking into account detector acceptance.



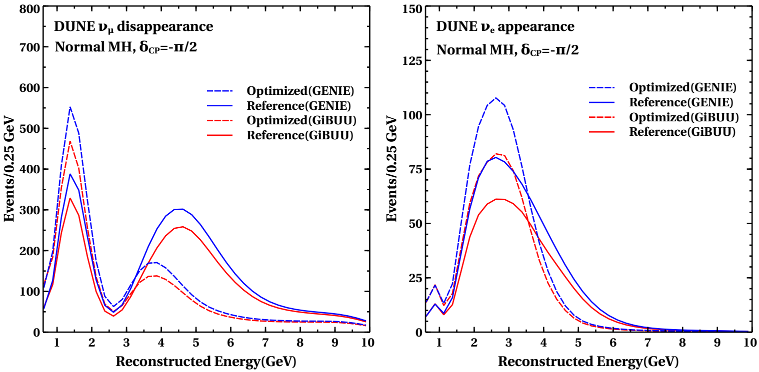
ν-Ar cross-sections : GENIE and GiBUU



- We have considered the QE, RES from Δ resonant decay and contribution from higher resonances, 2p2h/MEC and DIS interaction processes.

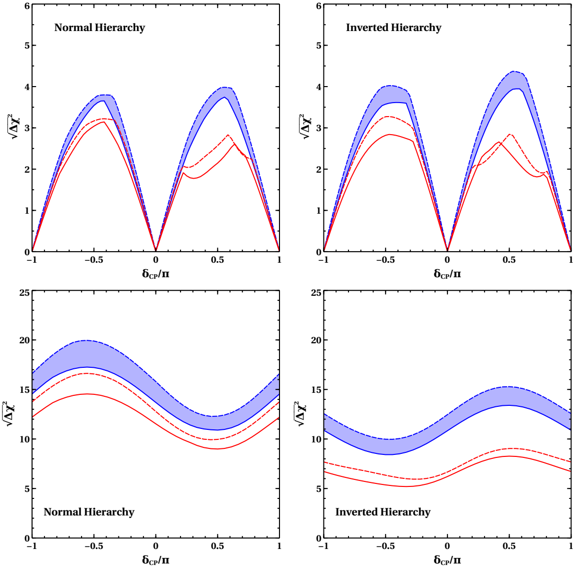
Event distributions

$$Event = \sigma \times \phi(E) \times N_T \times t$$

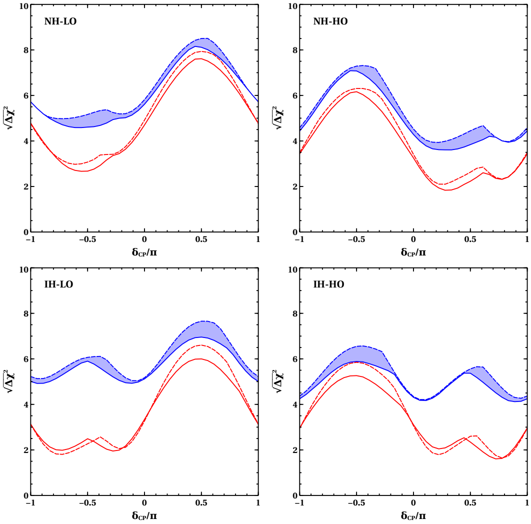


- ν_μ disappearance and ν_e appearance event distributions as a function of reconstructed neutrino energy for both reference and optimized beamline designs in the energy regime 1-10 GeV.

CP and Mass Hierarchy Sensitivity



Octant sensitivity(NH/IH)



Energy Reconstruction: Calorimetric technique

- Applying the calorimetric approach i.e. summing up all the outgoing particles, E_ν^{Calor} (reconstructed neutrino energy), can be calculated as-

$$E_\nu^{Calor} = E_{lep} + \sum_i T_i^{nuc} + \epsilon_{nuc} + \sum_m E_m \tag{1}$$

- where E_{lep} is the outgoing final state charged lepton's energy, T_i^{nuc} is the kinetic energies of the outgoing nucleons(i.e. the protons and/or neutrons), their corresponding separation energies represented as ϵ_{nuc} and total energy of any other particle produced represented as E_m.
- We can also write Equation(1) as- $E_\nu^{Calor} = E_{lep} + E_{had}$, where,

$$E_{had} = \sum_i T_i^{nuc} + \epsilon_{nuc} + \sum_m E_m \tag{2}$$

Energy Reconstruction: Kinematics technique

- For incoming neutrino with an energy < 1 GeV, CCQE interaction is the dominant interaction mode.
- The two-body kinematics of this interaction offers a simplified calculation of neutrino energy by using the kinematics of the outgoing lepton only i.e. the angle and energy of the outgoing muon.

$$E^{\nu}_{rec} = \frac{2(M - E_b)E_{\mu} - (E_b^2 - 2ME_b + m_{\mu}^2 + \Delta M^2)}{2(M - E_b - E_{\mu} + |\vec{p_{\mu}}|cos\theta_{\mu})} \tag{3}$$

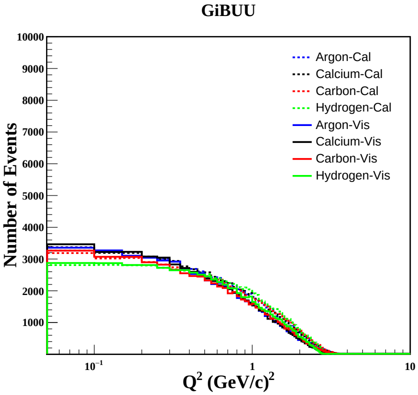
- Here E_{μ}, m_{μ}, p_{μ} is the energy, mass and momentum of the outgoing muon and θ_{μ} is the angle between the direction of outgoing muon and incoming neutrino. M is the mass and E_b is the binding energy of the struck neutron.
- $\Delta M^2 = M_n^2 - M_p^2$.

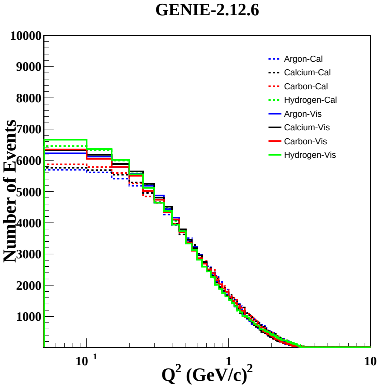
Q^2 Estimation

- Q^2 is calculated as-

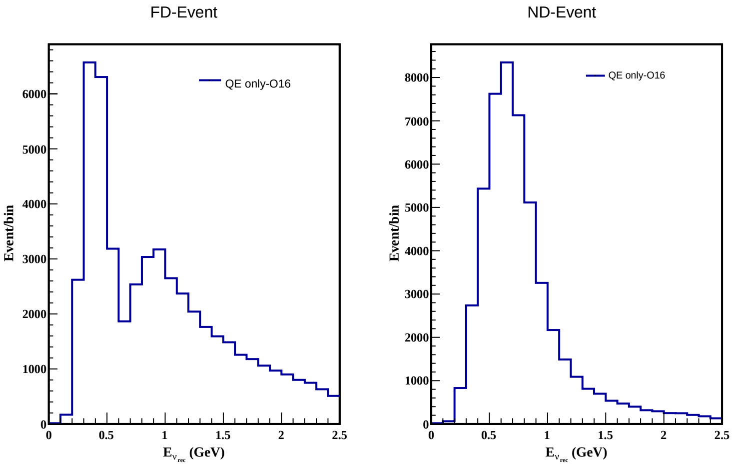
$$Q^2 = 2E^{\nu}_{rec}(E_\mu - p_\mu cos\theta_\mu) - M^2_\mu \tag{4}$$

where M_μ, p_μ, E_μ and θ_μ are the mass, momentum, energy and angle of the outgoing muon.

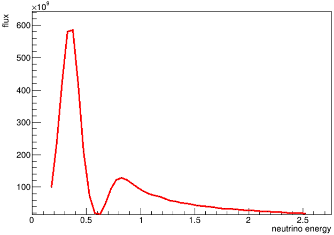


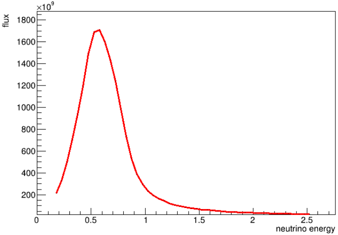


Event distribution for CCQE : Assignment-1



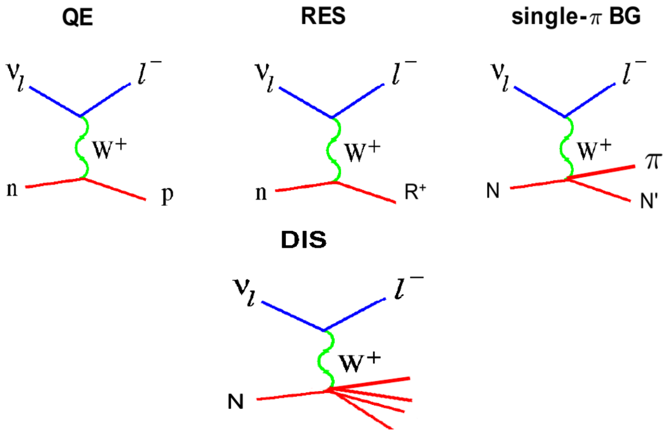
T2K Flux used : Assignment-1





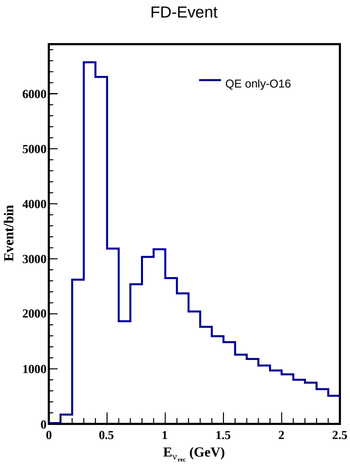
Assignment-2:

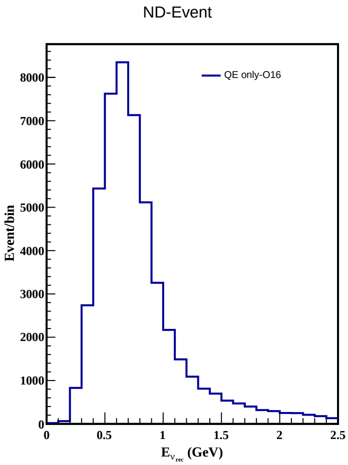
- Generate the 10000 event using argon target for 3 GeV neutrino energy and count the number of interaction process RES, QE and DIS.



Event distribution for CC : Assignment-3

- Repeat the simulation for liquid argon target (1000180400) and includes all the CC process (QE, RES, DIS, COH, MEC...).
- See the list of process defined for your simulation in the file "/opt/Gene....../config/EventGeneratorListAssembler.xml".

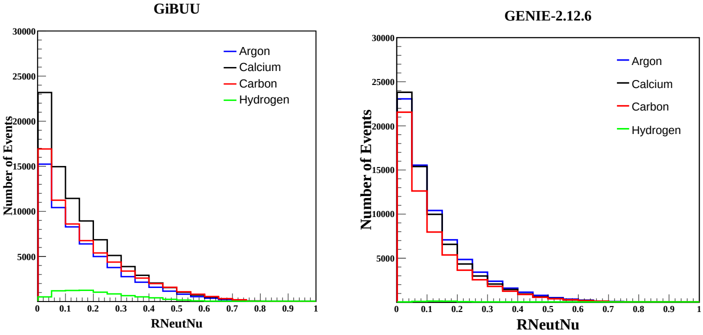


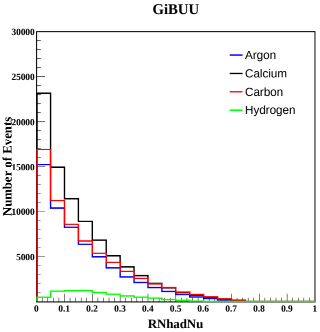


Plan for tomorrow

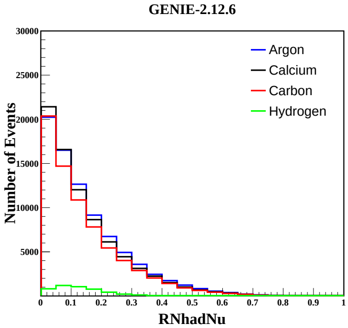
- Model tuning , parameters setting and the detector effect will be discuss tomorrow.
- Use the real detector geometry for realistic simulation, also neede for your Geant4 simulation.
- Define your own flux spectrum: Ex : Dark-matter flux, Supernova-flux, Solar-Neutrino flux and some new physics flux?

- **RNeutNu** = KE-Neutron/EnuTrue
  This ratio defines the fraction of kinetic energy of neutrons with respect to the true neutrino energy.
- **RNHadNu** = KE-NeutralHadrons/EnuTrue
  This ratio defines kinetic energy of neutral hadrons with respect to the true neutrino energy.





GiBUU
Argon
Calcium
Carbon
Hydrogen
Number of Events
RNhadNu



GENIE-2.12.6
Argon
Calcium
Carbon
Hydrogen
Number of Events
RNhadNu