GENIE: Neutrino Interaction Modeling and Tuning

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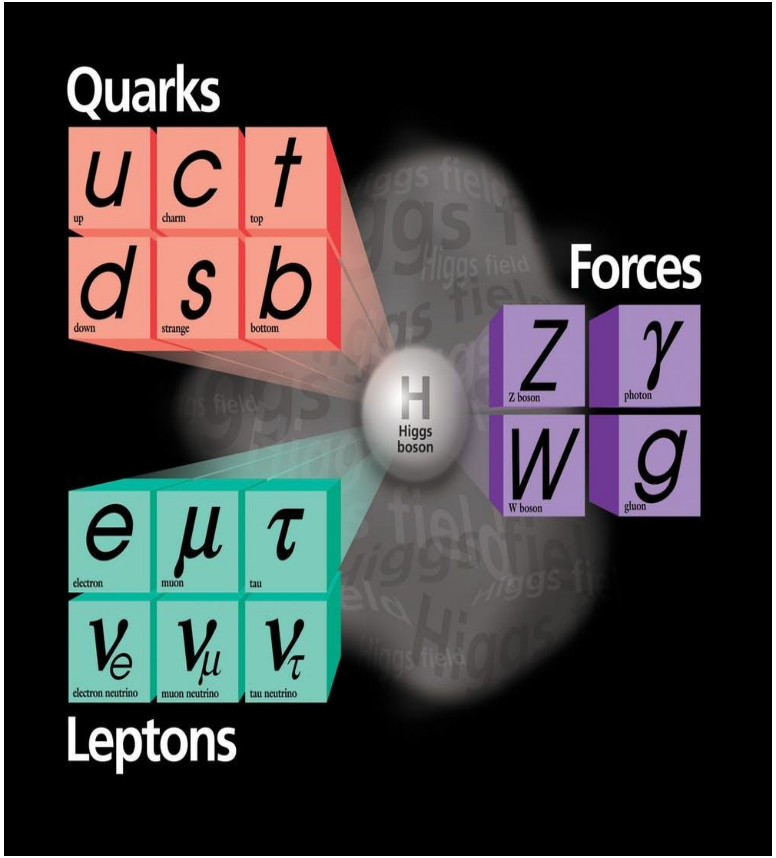
Outline

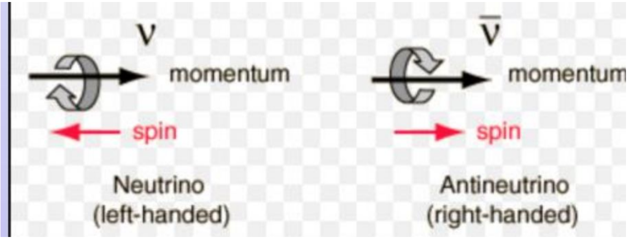
- Introductions to Neutrinos, Neutrino Interactions/Oscillations
- Why simulation?
- What is GENIE?
  - How does GENIE work
  - How does GENIE simulate neutrino interactions
- Models used in GENIE
  - Nuclear model, cross section model, final interaction model
- Comparing and Tuning against experimental data
- Summary

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Introduction to Neutrinos



Standard Model Assumes that:

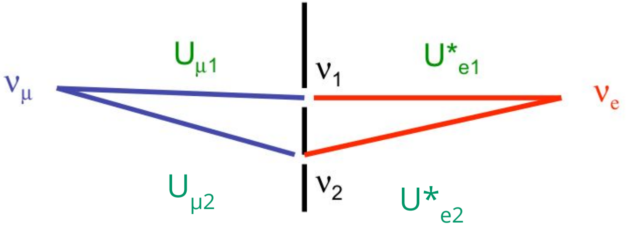
- Neutrinos are massless and chargeless particles
- No strong/electromagnetic interactions
- 

- Observation on contemporary experiments (neutrino oscillation) shows the neutrinos are **massive**
  - standard model needs to be extended
  - One of the frontiers of the standard model investigations

Introduction to Neutrinos: Oscillations

- Neutrino flavor states ν_α and mass eigenstates ν_i are related by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}\,|\nu_i\rangle \quad i = 1,2,3 \quad \alpha = e, \mu, \tau$$



Two flavor model:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

: θ is the mixing angle.

Oscillation: Given an initial flavor ν_α , observation some time later will yield a combination of ν_α and ν_β

Oscillation probability:

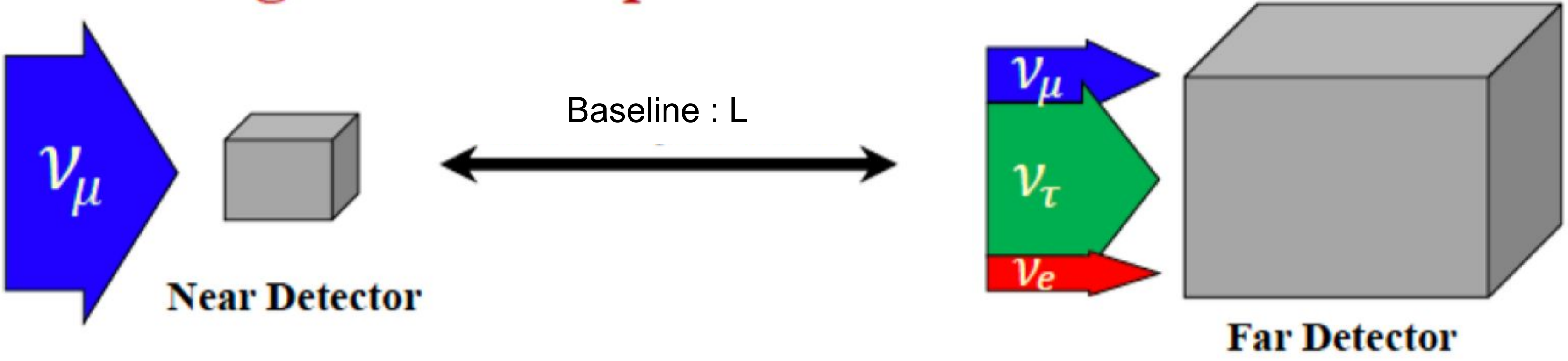
$$P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

L: Travel distance/Baseline

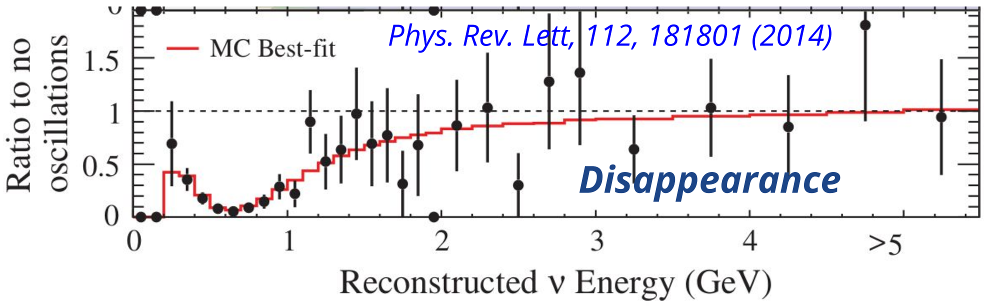
E: Neutrino Energy

Δm^2: Mass split/difference between two different mass eigenstates

Introduction to Neutrinos: Oscillations



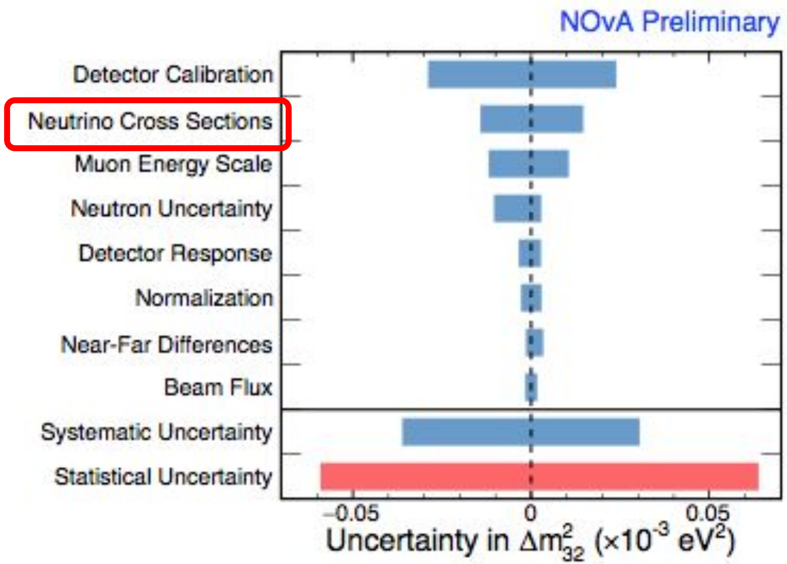
- **Signature of neutrino oscillation** is a distortion of the neutrino spectrum E(ν_μ)
    - Difference between measured Neutrino spectrum at Far detector and no-oscillation hypothesis
- Two types of oscillation searches
    - "***Appearance***" : Look for appearance of ν_e Or ν_τ in a pure ν_μ beam vs L and E
    - **"*Disappearance*"** : Look for a change in ν_μ flux



Example: The ratio of the observed spectrum (points) to the no-oscillation hypothesis, and the best oscillation fit (solid) of T2K in Japan.

Introduction to Neutrinos: Oscillations

- Neutrino Energy Spectrum: **Event Rate** $N(E_\nu)$
  - E_ν is not observable
  - Measured though neutrino target interaction from the final states
- **$N(E_\nu)$** = $\Phi(E)\times\sigma(E)\times\varepsilon(E)$
  - "Φ": the neutrino flux
  - **"σ" : cross section**
    - a measure of the probability of an interaction occurring
    - Relates neutrino energy to final state observables
    - Source of big uncertainty in oscillation measurement
  - ε: Efficiency

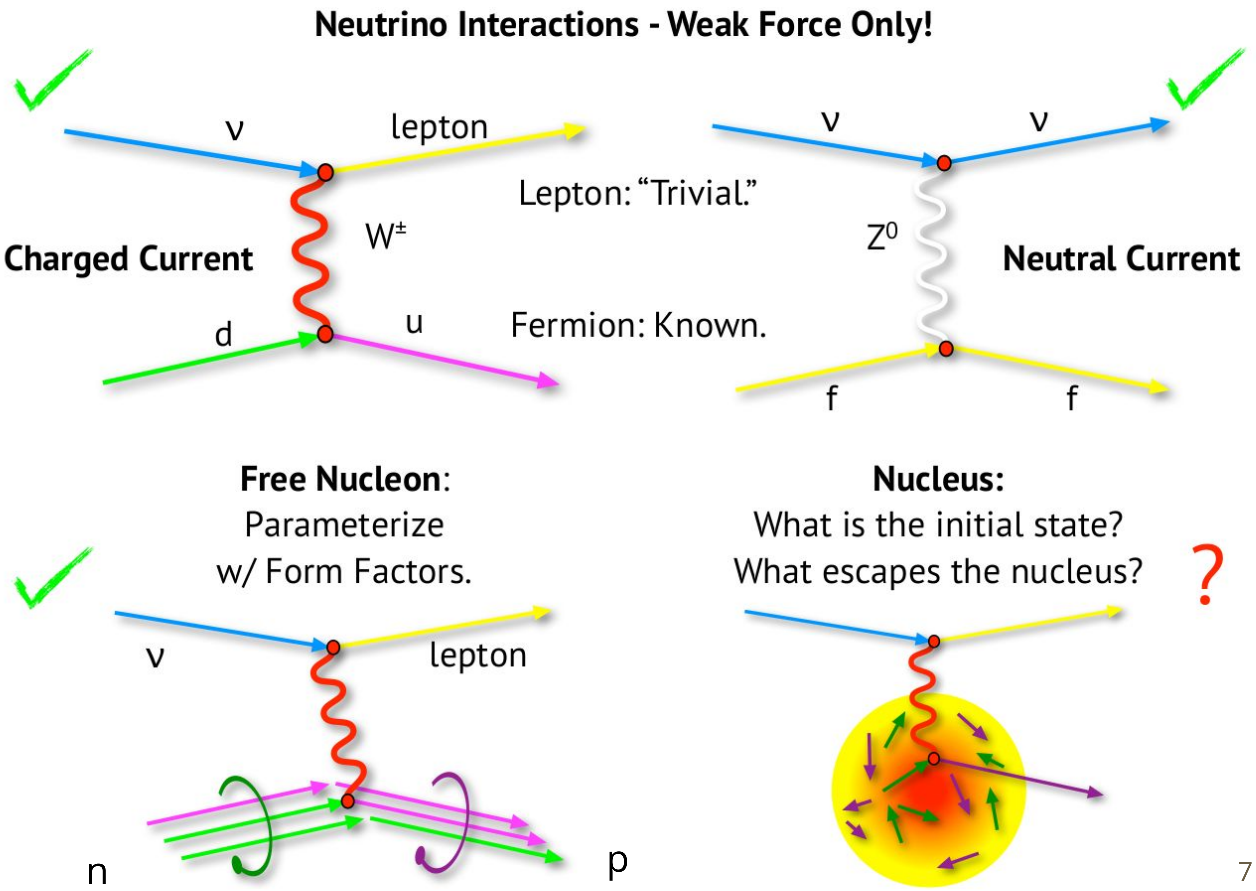


Alex Himmel's wine&cheese talk, NovA

- Big uncertainty from neutrino cross section measurement in the oscillation measurement.

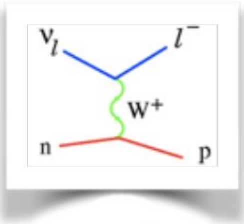
Introduction to Neutrinos: Interactions

- **The charged lepton in the final state identifies neutrino flavor**
- **Charge of leptons determines ν or ν-bar**
- **Can not determine the flavor in the Neutral Current interactions**

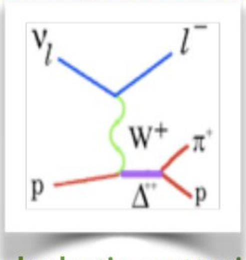


How does GENIE work? -Cross Section Model

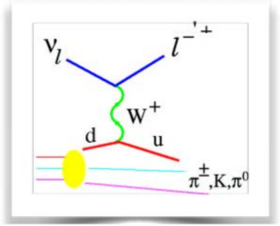
Quasi-elastic scattering (QE)

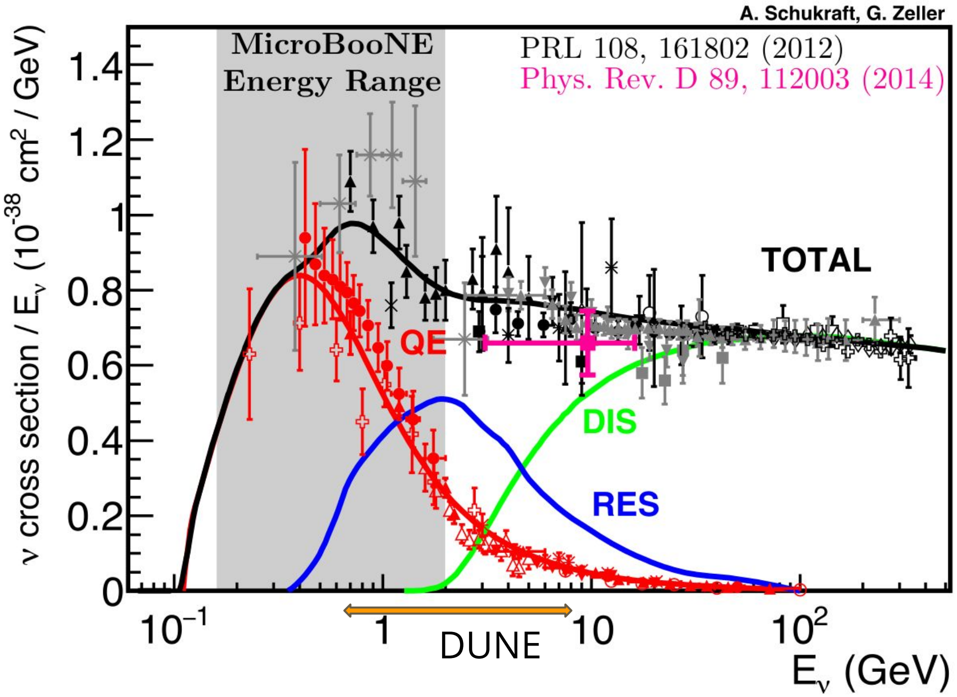


Resonance production (RES)



Deep Inelastic scattering (DIS)

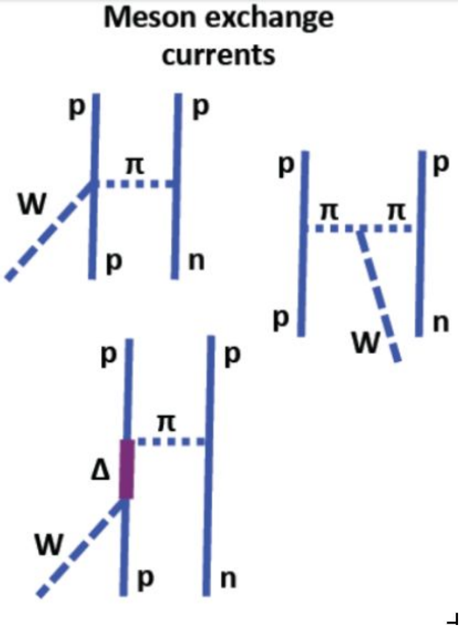




- Figure above shows the cross section distribution scale to neutrino nucleon scattering
- In case of target A>1 scattering one must consider COH(coherent pion production) and MEC(Meson Exchange Current).

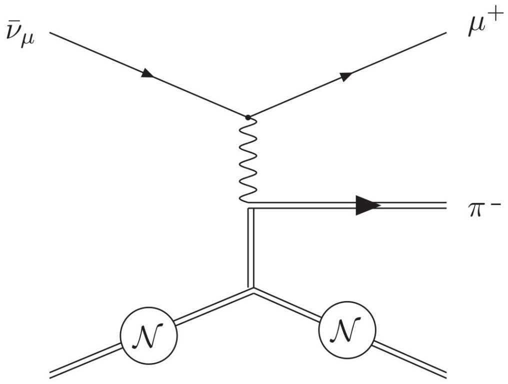
Introduction to Neutrinos: Other Channels

- **Meson Exchange Current** (MEC)
  - **Important background in QE measurements**
  - Many theoretical efforts
  - Need confirmation and further study!

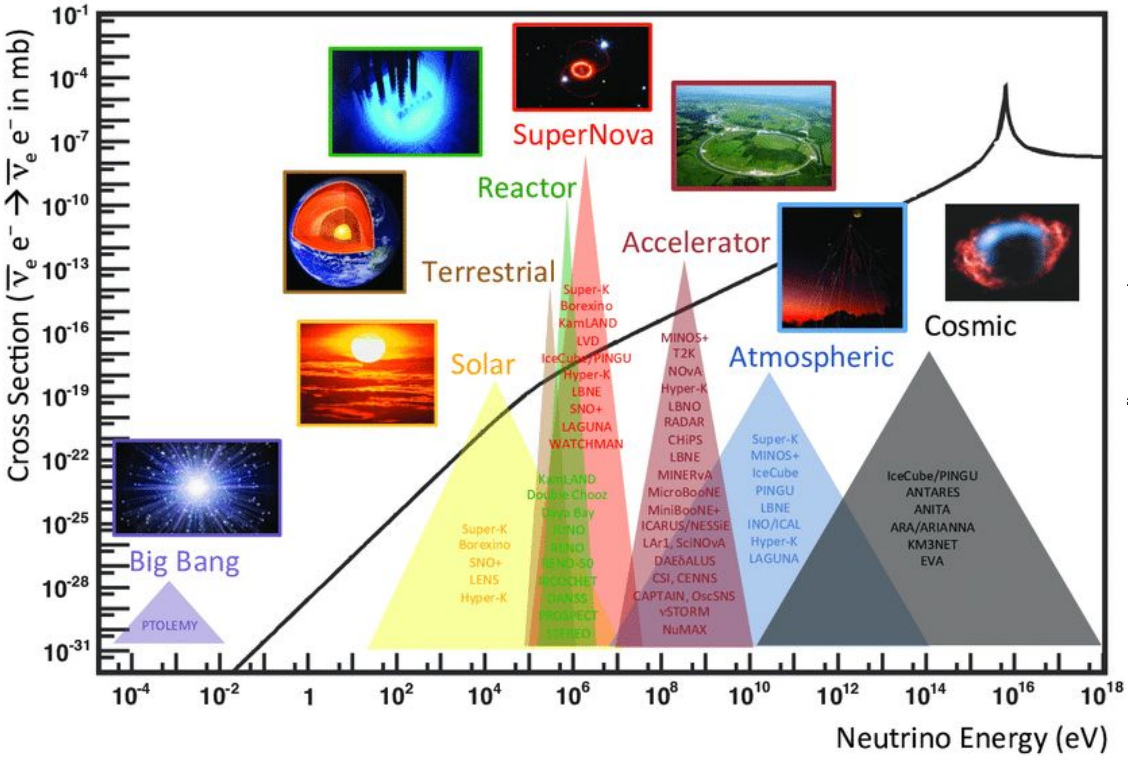


- Due to small cross sections of **coherent** process, not many measurements until now.

Coherent



Neutrino Sources & Experiments

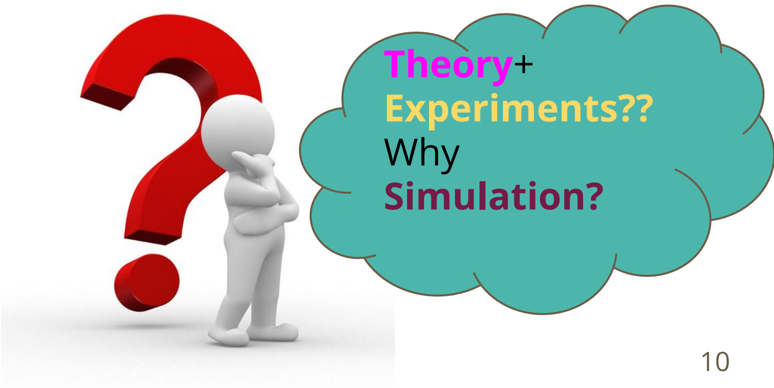


Reactor neutrino experiment: Daya Bay, Double Chooz, KamLAND, RENO, JUNO

Solar neutrino experiment: Borexino, Super-K, SNO

Atmospheric neutrino experiment: Super-K, IceCube

Accelerator neutrino experiment: NOMAD, Minos, MINERvA, T2K, MiniBooNE, NovA, MicroBooNE



Why Simulation?

- Theoretical models describes the cross sections in Ev, Q2, W, etc
- Detector efficiencies known in particle energies, angles, etc
- A Theory-Experiment Interface → **Simulation**
  - Connect truth and observables
    - Event topologies and kinematics
    - Cross section, nuclear effect
    - Optimal coverage of physical processes
- Good Generators should also be with
  - Systematic uncertainty analysis
  - Tune the physics models against experimental result

Several MC Generators in use: **GENIE**, GiBUU, NuWRO, NEUT ...

What is GENIE?

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

- **The software:**
  - **Simulates** a large variety of neutrino interactions
  - **Handles** all neutrinos and targets, and all processes relevant from MeV to PeV energy scales
  - Additionally run in **electron and hadron scattering** models
  - Many tools for studying systematics, comparison to data.
- The event generator used in almost all neutrino experiments.
  - **Interfaces** to HEP software frameworks (LArSoft ...) very well
  - Geometry
  - Reweighting - Propagating uncertainties/Systematic errors
- Needs have greatly increased as experiments become more advanced
  - New channels (coherent ρ ...)
  - Improved theoretical models

Overview of GENIE product

- **Generator** (open source)
  - State-of-the-art software framework
  - **Neutrino interaction + non-neutrino interaction physics module**
    - Nucleon decay, Neutron-antineutron oscillation. Boosted dark matter,
    - Electron/hadron Nucleus scattering
- **Comparisons (private)**
  - State-of-the-art framework and comparison plexus management
  - Vast collection of curated **data archives and implementation of data/MC comparison**
- **Tuning (private)**
  - Implements GENIE tuning strategy
- **Reweight (open source)**
  - **Propagating uncertainties** from parameters (e.g. M_A) to any observables (e.g. cross section)

How does GENIE work? - Flux & Geometry

- Many choices (including making your own):
  - User-specified histograms (no spatial variation, only energy and flavor)
    - Specify both the angles and energy of neutrinos
  - Simple, generic ntuple format (‘**GSimpleNtpFlux**’)
    - Neutrino flavor
    - Energy, momentum of neutrinos
    - Distance from source of the flux to flux window
    - Vertex position on flux window
- Wrap any of the above in a “flavor blender” adapter (‘GFlavorMixerI’) - this is how you handle far detector in oscillation experiment.

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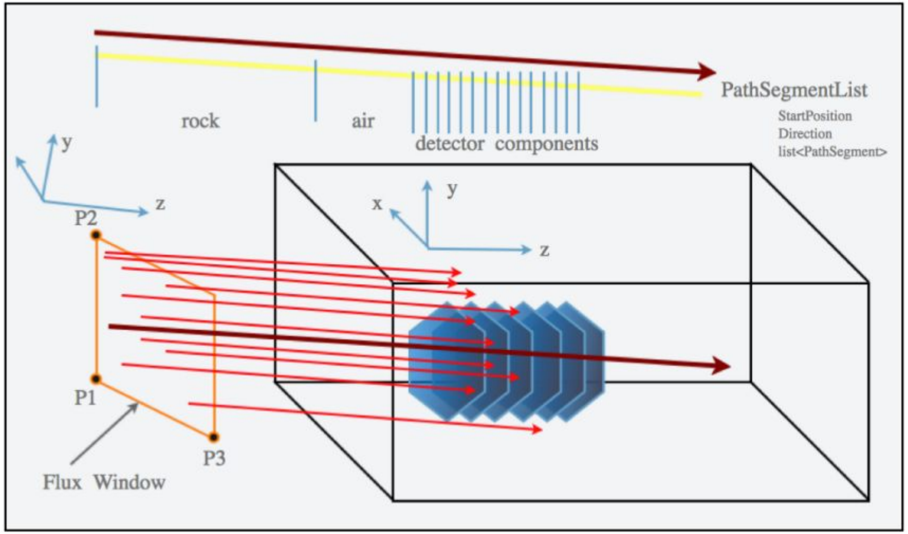
How does GENIE work? - Flux & Geometry

- Experiments need to generate interaction vertices in the correct locations
- Detectors have many elements(nuclei) and complicated geometries

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Example of Geometry File I made for SBND

How does GENIE work?

- Currently implemented GENIE physics models rely heavily on a **factorization** assumption.

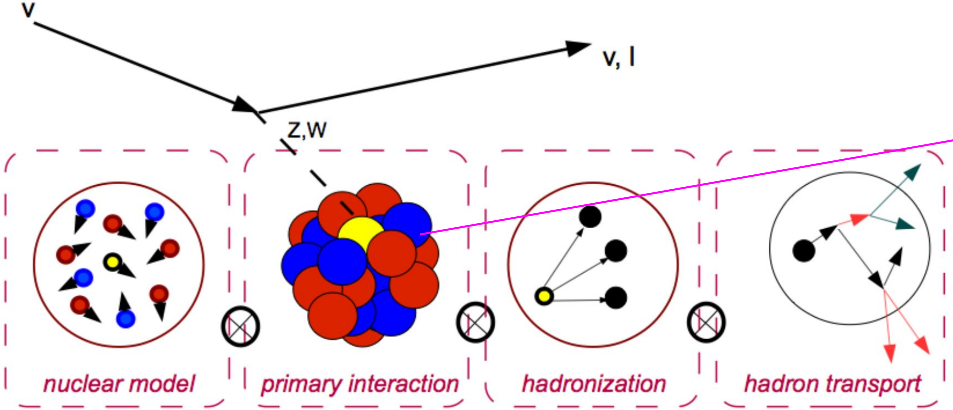
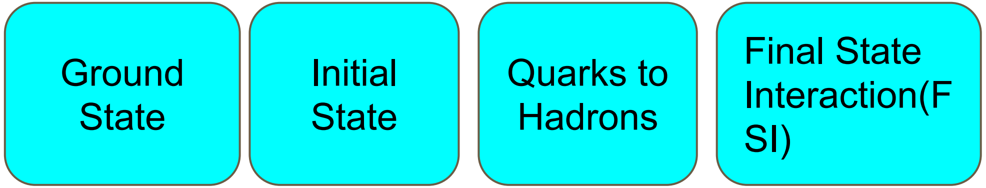
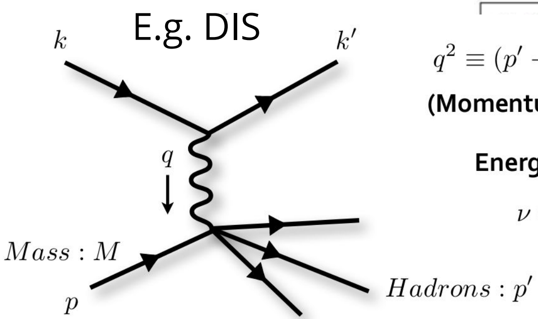


Figure by C. Andreopoulos



Primary interactions: using differential cross sections to get event kinematics: x, y, Q^2, W, t etc



$q^2 \equiv (p' - p)^2 = -Q^2$ **(Momentum Transfer)²**

Energy transfer. $\nu \equiv \frac{p \cdot q}{M}$

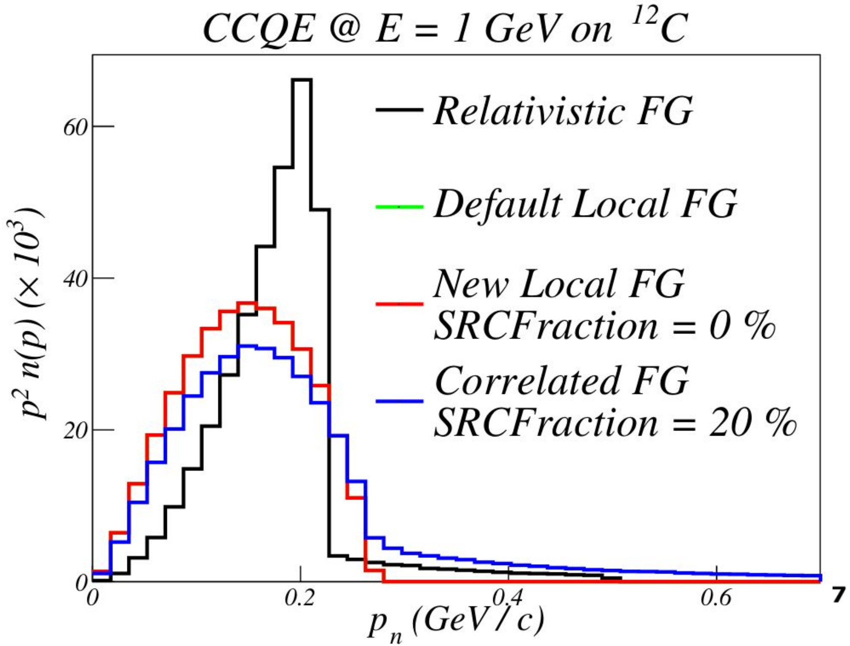
$W^2 \equiv (p+q)^2 = E_H^2 - \mathbf{p_H}^2$ **(Hadronic Invariant Mass)²**

$y = \frac{p \cdot q}{p \cdot k}$ **Inelasticity** $x = \frac{-q^2}{2p \cdot q} = \frac{-q^2}{2M\nu}$ **Parton Momentum Fraction**

How does GENIE work? - Nuclear Model

Model/generator	GENIE	NuWro	NEUT
Nuclear model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function

- Nuclear models come from proper descriptions of electron scattering (Data)
- RFG(Relativistic Fermi Gas) Model: is historical standard but not accurate
- New Models based on RFG model
  - Local Fermi Gas Model (LFG)
  - LFG with Short Range Correlations(SRC) implemented: ΔR<0.5fm
- **More modern models include Correlated Local Fermi Gas Model and Benhar-Fantoni spectral functions** are almost there



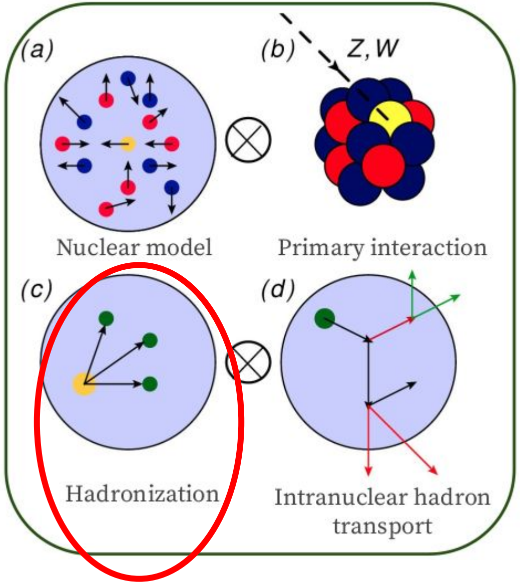
How does GENIE work? - Cross Section Models(2017)

Model/generator	GENIE (Version2)	NuWro	NEUT
QE	Lwlyn-Smith Nieves, Eff MA	Lwlyn-Smith RPA	Lwlyn-Smith Eff RPA
MEC	Valencia Empirical	Valencia Marteau	Valencia
Delta model (Resonance)	Rein-Sehgal (updated) Berger-Sehgal	Home-grown, great	Rein-Sehgal (update) Berger-Sehgal
Coherent	Rein-Sehgal(corrected) Berger-Sehgal	Rein-Sehgal Berger-Sehgal	Rein-Sehgal Berger-Sehgal

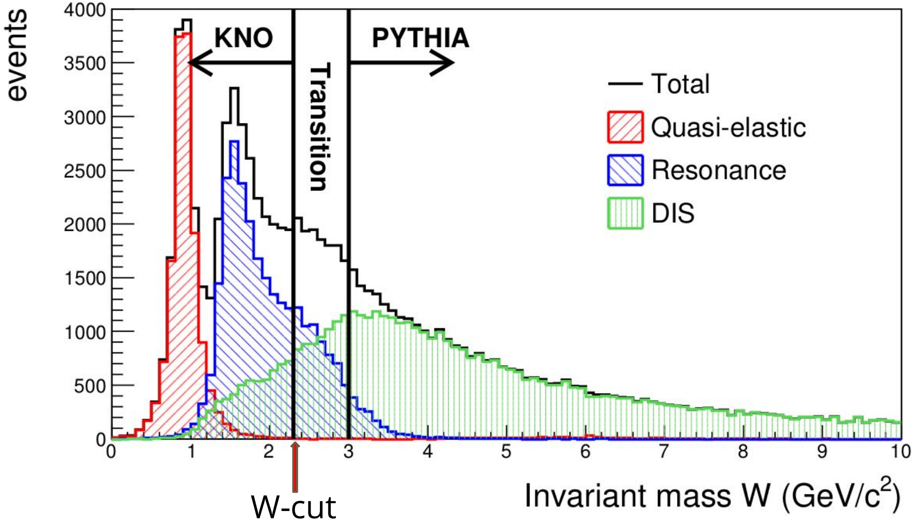
- All generators have largely the same models
- GENIE is advancing, taking more theoretical models and more channels simulated

Hadronization Modelling

- **Hadronization**: provides the hadrons coming out of **DIS** interaction
- Hadronization Modeling Impacts (also applies to other processes)
    - **Neutrino energy reconstruction**
        - Detectors are sensitive to different particles
        - Simulation must account for missing particles
    - Efficiency calculations for **event identification**
        - Hadronization determines neutral content that is hard to measure.
            - For example, hadronic showers (from NC or high - y ν_μCC events with large EM component could be misclassified as ν_eCC events, shower mismodeling can impact the estimation of backgrounds in neutrino oscillation.



How does GENIE work? - Hadronization Model

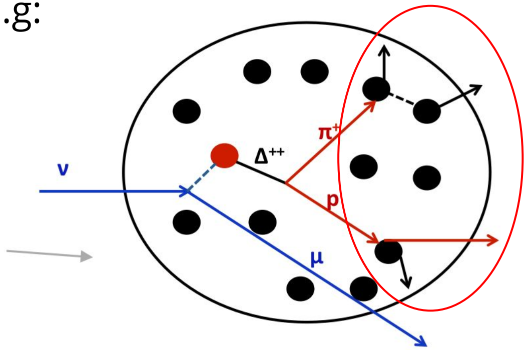


W distribution of ν_μ-water target interaction in GENIE, atmospheric neutrino flux

- Hadronization model in GENIE: **AGKY** model
  - 3.0 GeV/c^2<W, **PYTHIA** only region.
  - W<2.3 GeV/c^2, **KNO** Model.
    - PYTHIA hadronization models deteriorate at low energy region
  - 2.3 GeV/c^2 < W < 3.0 GeV/c^2 **Transition region**
    - Resonant + Non Resonant background(DIS)
    - Scale non resonance background(DIS) with different hadron multiplicities with a scaling factor (R(m) to match the data, m is the hadron multiplicity)

How does GENIE work? - FSI Models

E.g:



- Final state interactions describe particles interact with nucleons before exiting the nucleus

- Intranuclear Cascade model(INC) is commonly used in Generators, it is called “hN” in GENIE
  - Simulate rescattering of pions, nucleon in nucleus

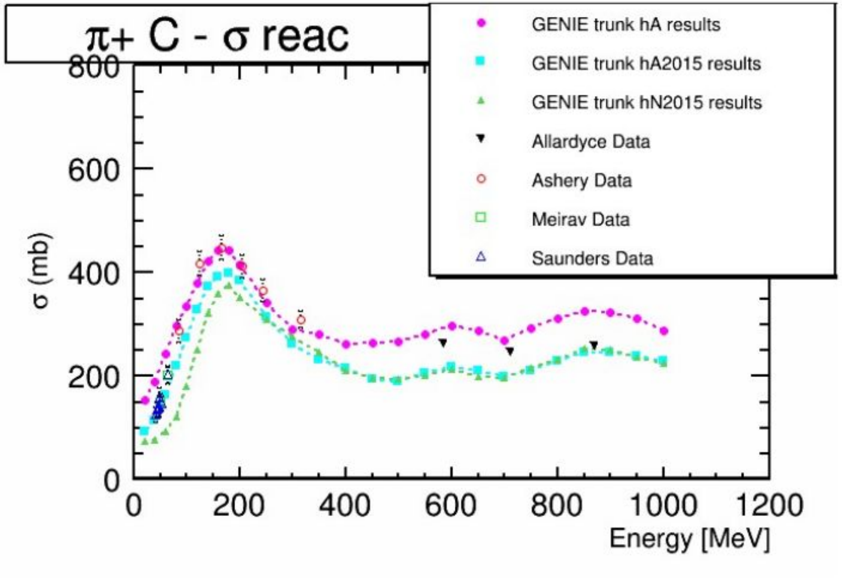
- Pions, K^+, p and n included in GENIE final state interaction model

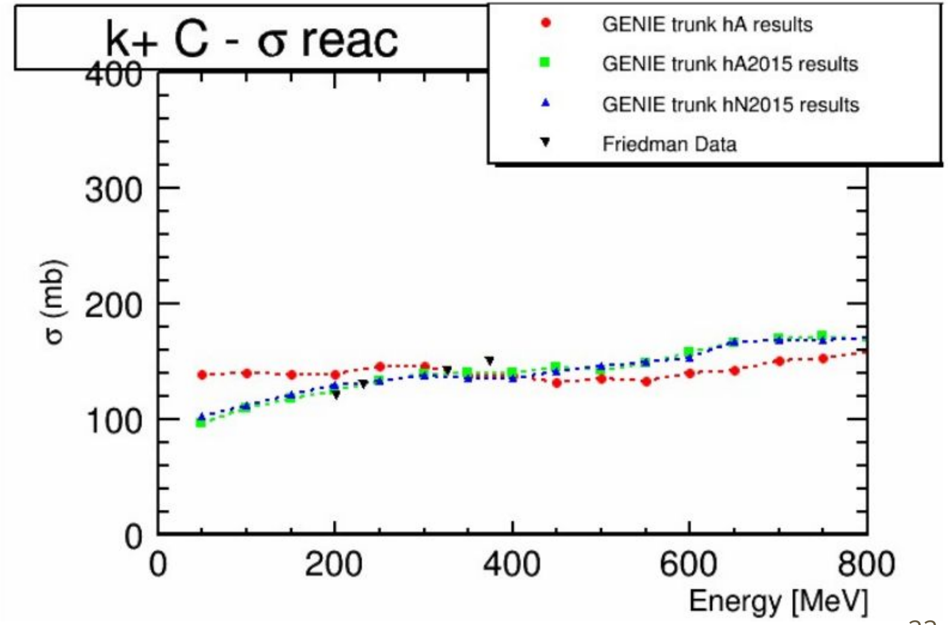
Model/generator	GENIE	NuWro	NEUT
FSI	Schematic Cascade (med corr)	Cascade(med corr)	Cascade(med corr)

- Schematic Model(hA): simulate the cascade model in a data -driven way (total cross section, and inclusive cross section); → Reweightable
- Medium Correlations: Low energy nucleons (describe the correlation between the nucleons as the final state being produced)

How does GENIE work? - FSI Model

- π+ has significant peak for Δ excitation, none for K+
  - Very few kaon data
- Both hA2015 and hN2015 underpredict pion peak cross section





GENIE Version 3

- Many new models introduced in GENIE version 2
  - Some groups developed modified tunes with these new models, but often in inconsistent ways
- GENIE v3
  - Put most compatible physics models into model sets, e.g. QE+MEC
  - Provide Comprehensive Model Configurations(CMC) for different “Model Sets” for users
    - Can be called by a parameter --tune G**_**
  - Presents new tunes
    - Only deuterium data for now, more later
    - Expanded resonance region (larger Wcut)
    - Provide full error analysis for each

GENIE Version 3

- G00_00 series: Historical default configuration.

G00_00a	G00_00b
No MEC	with (empirical) MEC

- From G00_00 to G18_01 series: adiabatic evolution of old default.

	G00_00	G18_01
Hadron Transport Model	HAIntranuke/HNIntronuke	HAIntranuke2018/HNIntranuke2018 Added diffractive and Lambda production

- From G18_01 to G18_02 series:

	G18_01	G18_02
RES	Rein-Sehgal	Berger-Sehgal
COH	Rein-Sehgal	Berger-Sehgal

- From G18_01 to G18_10 series: theory driven configuration.

	G18_01	G18_10
Nuclear Model	FGM BodekRitchie	Local Fermi Gas (LFG)
QEL	LwlynSmitch	Nieves
MEC	Empirical	Nieves
RES	Rein-Sehgal	Berger-Sehgal

Additional new models now in v3.0.0

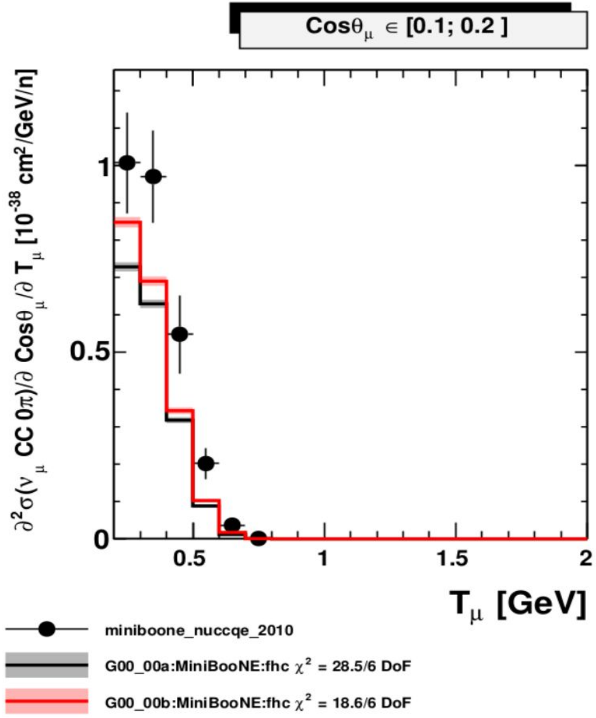
- Single K+ production
- Diffractive pion production with neutrinos
- Quasielastic hyperon production(Pais)
- Alvarez-Ruso Coherent Model (Low energy only)
- Smith-Moniz QE model

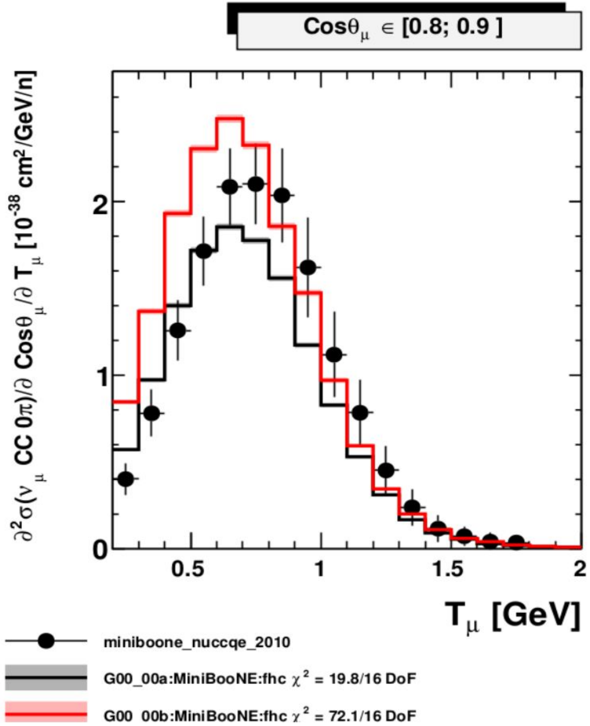
Database and Validation

- "Comparison" Comparing GENIE predictions against public datasets
    - Modern Neutrino **Cross Section Measurements**
        - Nuclear targets
        - MiniBooNE, T2K, MINERvA
    - Historical Neutrino Cross Section Measurement
    - Measurements of neutrino-induced **hadronic system characteristics**
        - E.g. Forward/backward hadronic multiplicity distributions
    - Measurements of hadron-nucleon and hadron-nucleus event characteristics
        - FSI tuning
        - For pion, kaons, nucleons and several nuclear targets
        - Spanning hadron kinetic energies from few tens MeV to few GeV
    - Semi-inclusive **electron scattering data**
        - Electron-nucleus QE data
        - Electron-nucleus Resonance Data

MiniBooNE CC0π (2010) need for MEC (E_ν~1GeV)

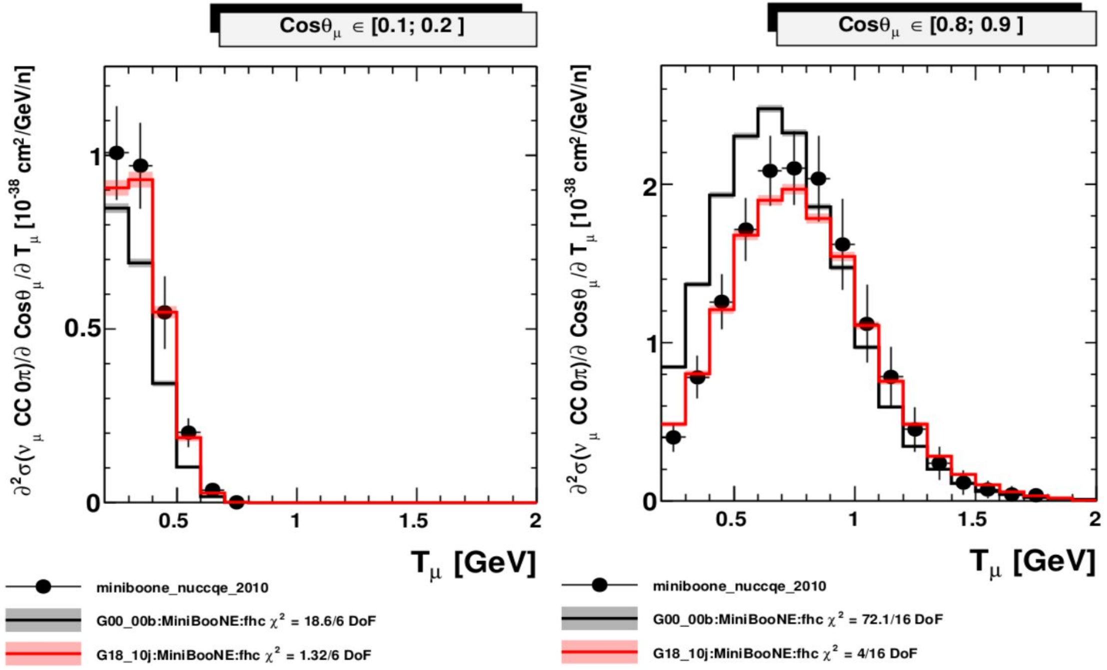
- Miniboone published both true CCQE and CC0pi, we use latter
- **G00_00b (LS, with MEC)** vs **G00_00a(LS, no MEC)**
- MEC process increases cross section of CC0π at all angles





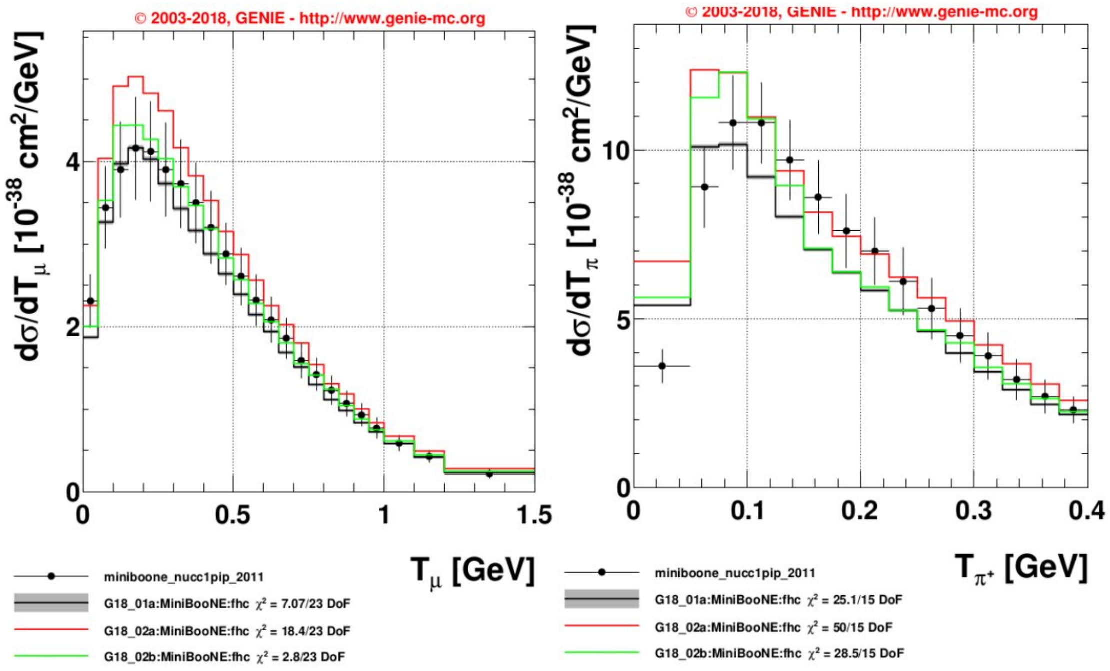
Modern Calculation has better agreement

- **G18_10j** has **full valencia CCQE** with RPA/Coulomb, MEC with local Fermi Gas (LFG) nuclear model. Much better theoretical model compared to **L-S model** with empirical MEC **(MiniBooNE CC0π Data)**



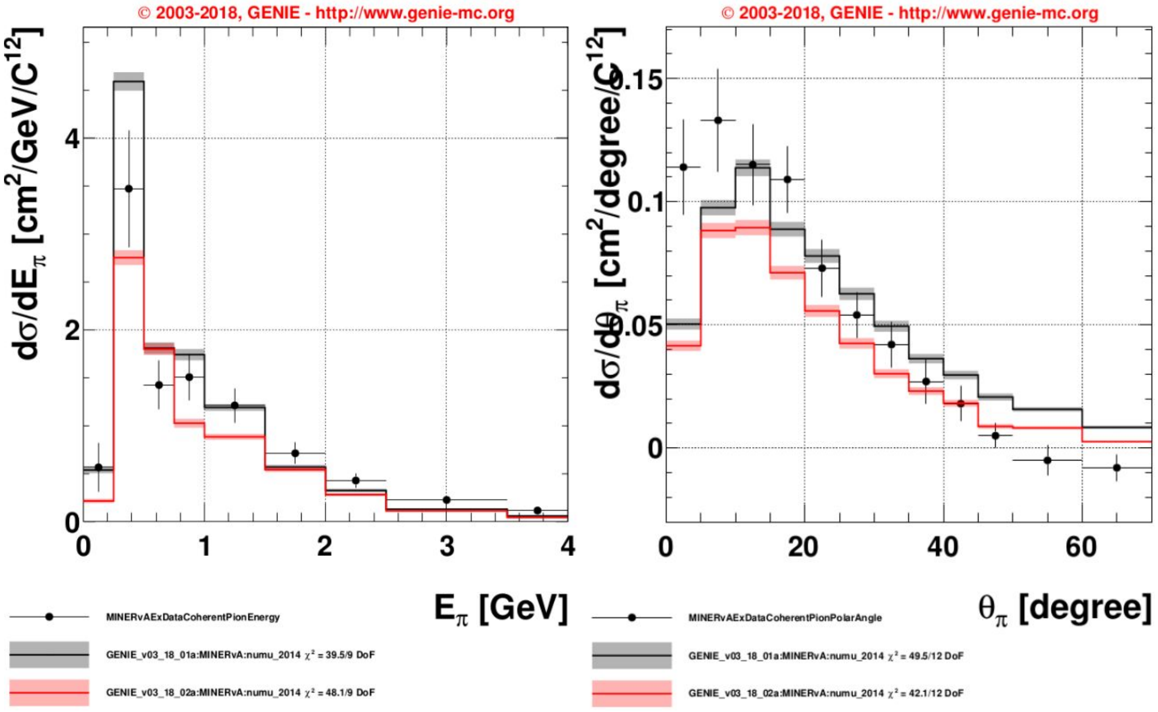
MiniBooNE ν_μ CC1π^+ <E_ν>~1GeV

- **G18_01a(Rein-Sehgal, hA)** vs **02a(Berger-Sehgal with new Form Factors, hA)** vs **02b(Berger-Sehgal with new Form Factors, hN)**
- **G18_02b** most advanced theory, gets details best



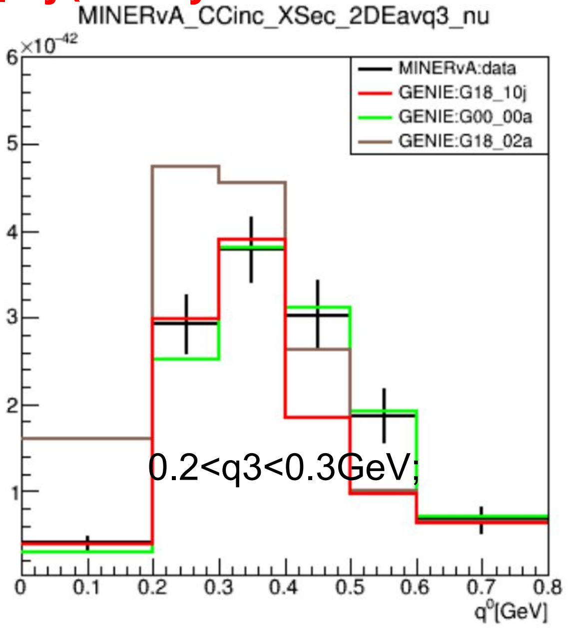
MINERvA Coherent 2015 (<E_ν>=4.0 GeV)

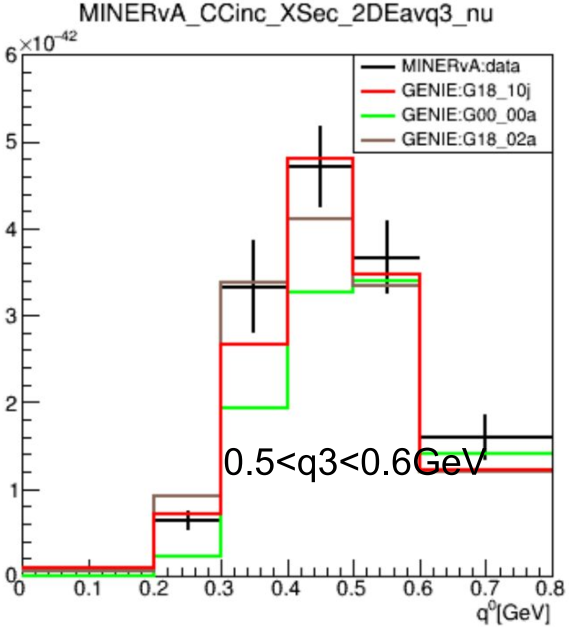
- Compares Berger-Sehgal **(G18_02a)** with updated Rein-Sehgal**(G18_01a)**
- Better agreement with the Berger-Sehgal model



MINERvA CC Inclusive (2016) [NUISANCE]

- **CCinclusive cross section in different q3 bins**
- **G18_10j (Theory-driven model: Valencia QE, Berger-Sehgal)** has best agreement





Tuning

- Why Tuning?
  - Constrain parameters (some parameters from old experimental data)
  - Provide specific GENIE tuning version for experiments with new parameters
    - **Deuterium** Tuning, working on others
- What kind of Minimizer used?
  - Old problems in high energy physics
  - CPU demanding
  - Multiple parameter fitting
  - Solution found in the **Professor** suite

→ Trying to get it working with Fermilab Computing grid

Tuning against data

- GENIE Comparisons and Tuning products have built-in interfaces to professor
- Professor is a tool developed for a general purpose MC tuning at the LHC
  - Andy Buckley, Holger Schulz and collaborators.
  - https://professor.hepforge.org
- GENIE / Professor integration was supported by an IPPP Associateship award.

"Fundamentally, the idea of Professor is to reduce the exponentially expensive process of brute-force tuning to a scaling closer to a power law in the number of parameters, while allowing for massive parallelisation and systematically improving the scan results by use of a deterministic parameterisation of the generator's response to changes in the steering parameters. "[Professor web page]]

Global Fit

- Use only ν & ν-bar deuterium data including Wikinson et al.
- Goal is to maintain CCQE fit and emphasize CCRES exclusive data

Parameter	Default value	Best tune value
M_A^{RES} [GeV/c^2]	1.12	1.065 ± 0.025
M_A^{QE} [GeV/c^2]	0.99	0.961 ± 0.031
R-vp-m2	0.1	0.008 ± 0.00
R-vp-m3	1	0.788 ± 0.20
R-vn-m2	0.3	0.128 ± 0.021
R-vn-m3	1	2.115 ± 0.57
RES-XSecScale	1	0.878 ± 0.031
DIS-XSecScale	1.032	1.019 ± 0.055
W_{cut} [GeV]	1.7	1.928 ± 0.091

Multiplicity parameters (R-vp-m2 to R-vn-m3), e,g, R-vp-m2 is for νp, 1 pions

Relative normalization, RES vs. NONRES (RES-XSecScale, DIS-XSecScale)

Boundary – RES vs. DIS (W_{cut})

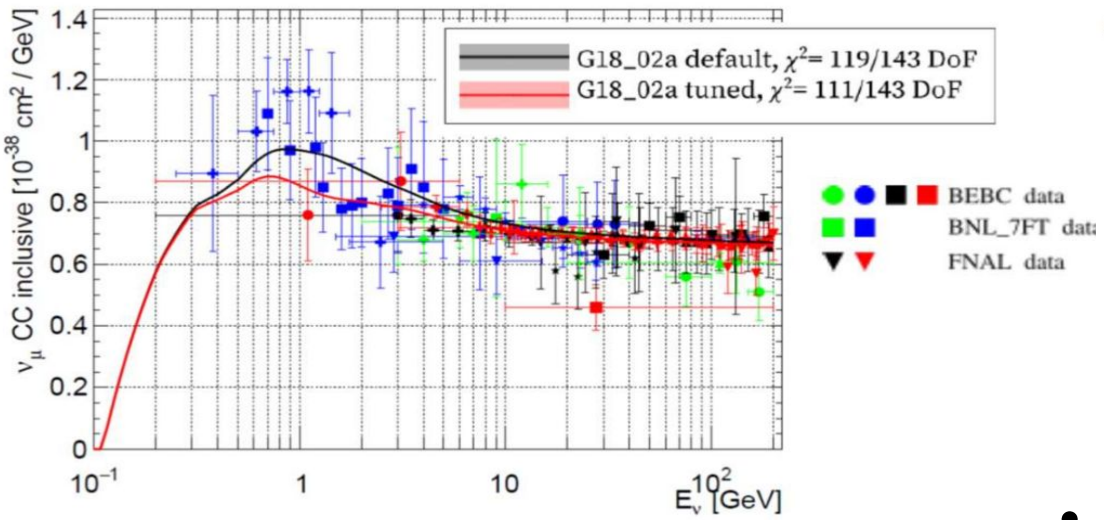
Priors applied

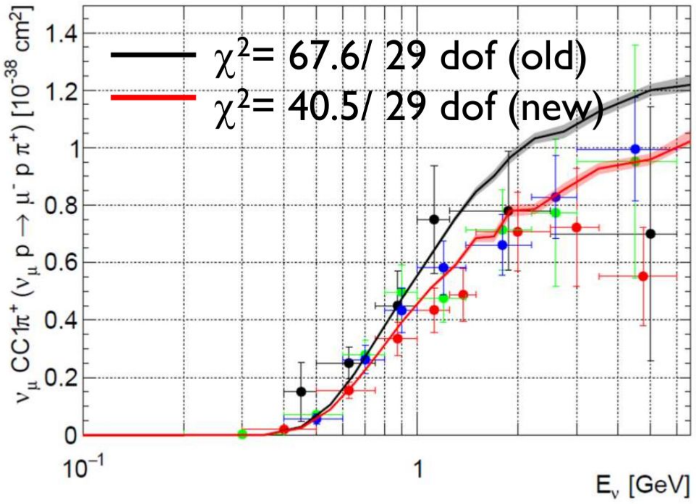
$M_A^{QE} = 0.89 \pm 0.044$ GeV/c^2, fit to just BEBC data [Eur. Phys. J. C (2008) 54]

$M_A^{RES} = 1.12 \pm 0.03$ GeV/c^2, [ArXiv:0606184]

DIS-XSecScale$= 1 \pm 0.05 \rightarrow$ Motivated by DIS high energy cross section values

Compare previous with new fits





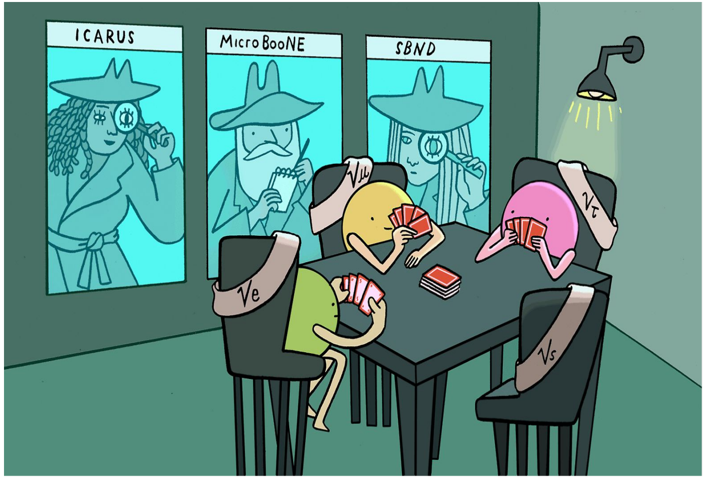
- CC inclusive cross sections before and after tuning.
- ν_μCC1π Cross section decrease ~30% by tuning.

- Smaller Chi2, better agreement with the parameters tuned against data
- GENIE version 3 also provide the model sets with the parameters tuned against data

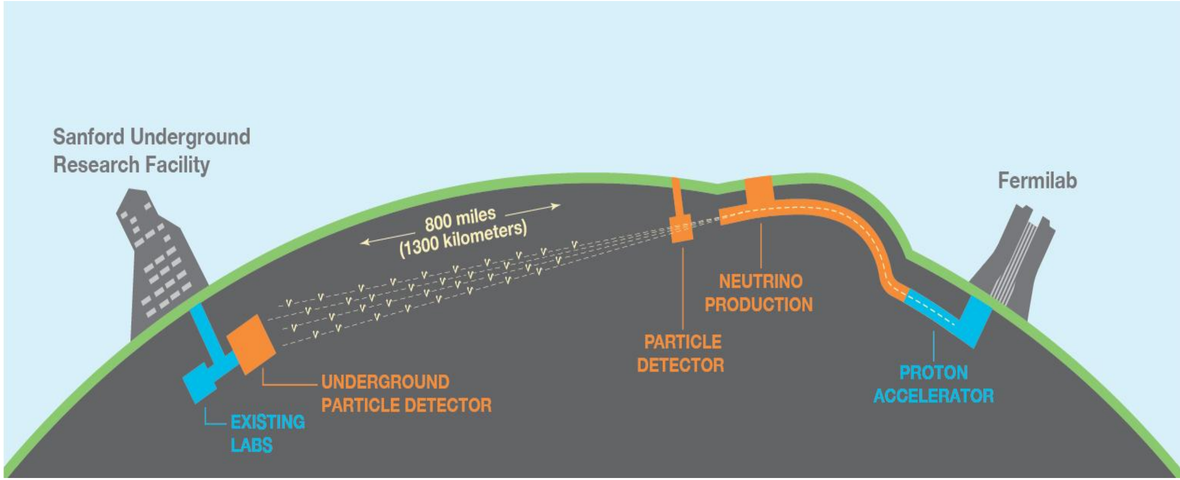
Data on heavier nuclei

- Short Baseline Neutrino Program(SBN) and DUNE uses argon as a target
- How do we know our tune works for argon?
- We need data on argon!
  - New challenges/opportunities to study nuclear effects
  - Needs increasing for the simulator

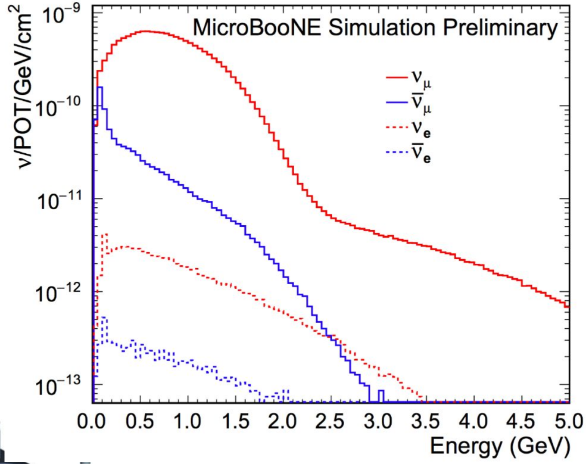
Short Baseline Neutrino Program(SBN)



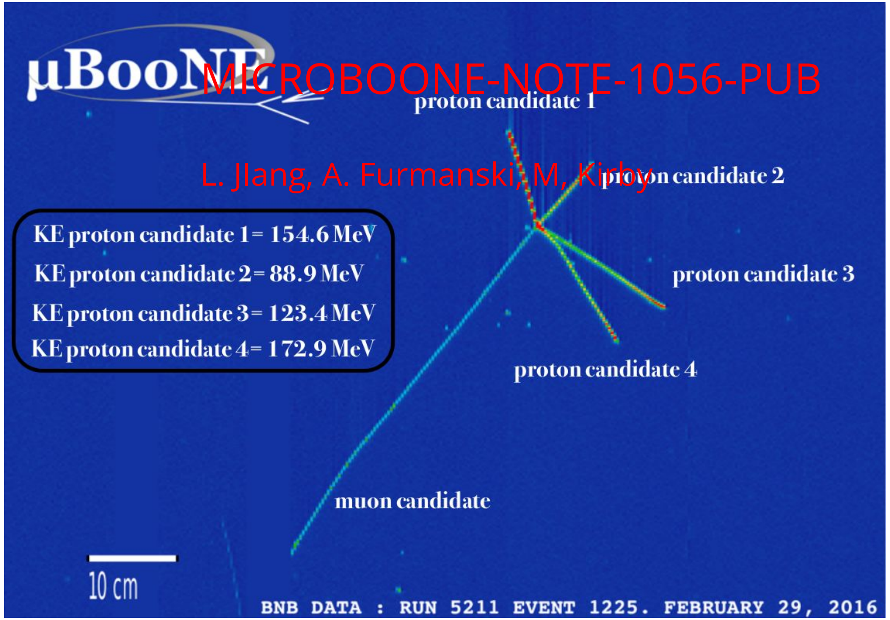
Deep Underground Neutrino Experiment (DUNE)

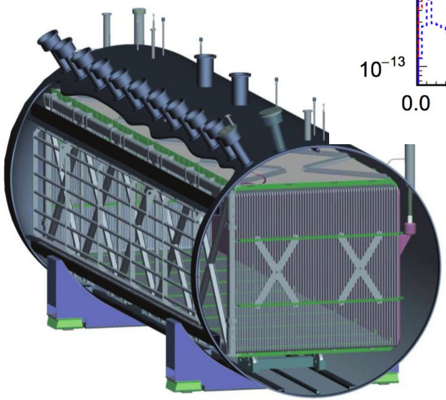


Charged Current One Muon N proton Analysis in MicroBooNE (Liquid Argon TPC)



Booster Neutrino Beam



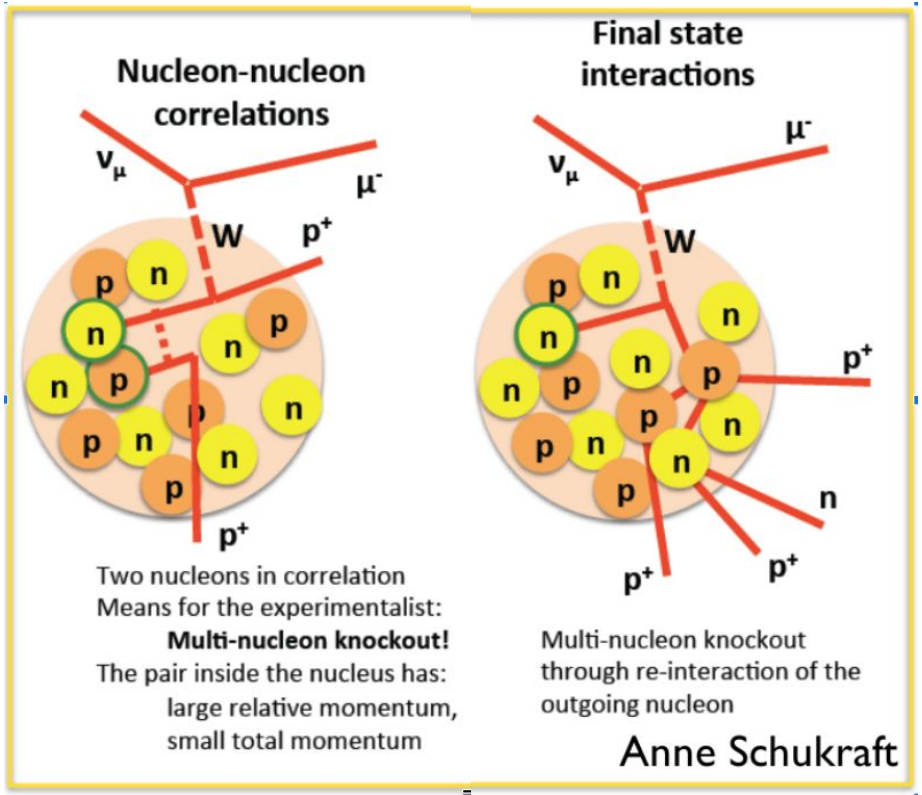


MicroBooNE Detector

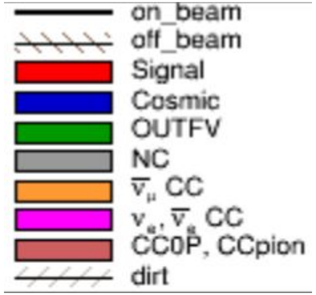
- Multiple proton events from MicroBooNE
- Proton momentum threshold measured down to 300 MeV (Kinetic Energy ~45 MeV)

Challenges in ν-Ar Interaction

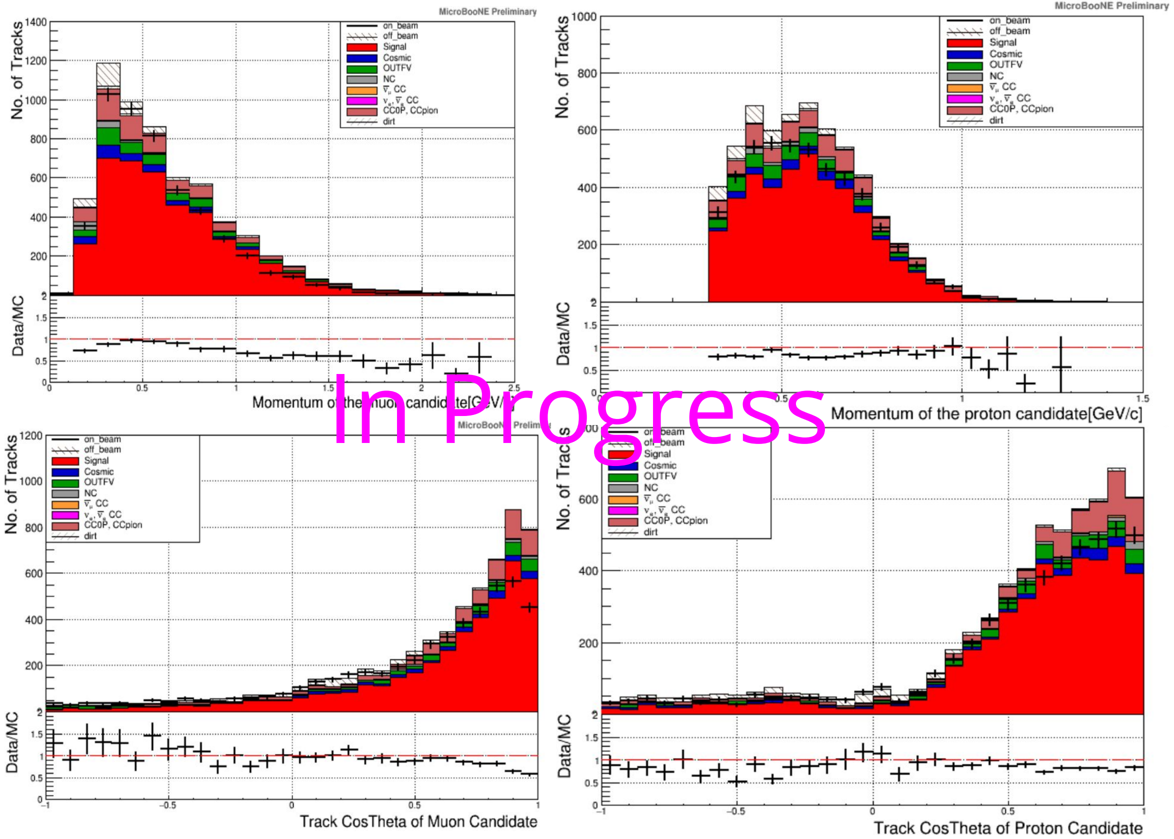
- Heavy Nucleus means complicated nuclear effects
  - Charged Current 1μ0π (CC1u0π) data tells us about **nuclear physics** with the heavy nucleus (Ar):
    - Final and initial state interactions
    - Nucleon correlations
- Neutrons carry part of the energy without being detected in LArTPC
- Charged particles with low momentum can not be reconstructed
  - Lower proton momentum threshold in LArTPC (300 MeV/c)



Charged Current One Muon N proton Analysis in MicroBooNE (Liquid Argon TPC)



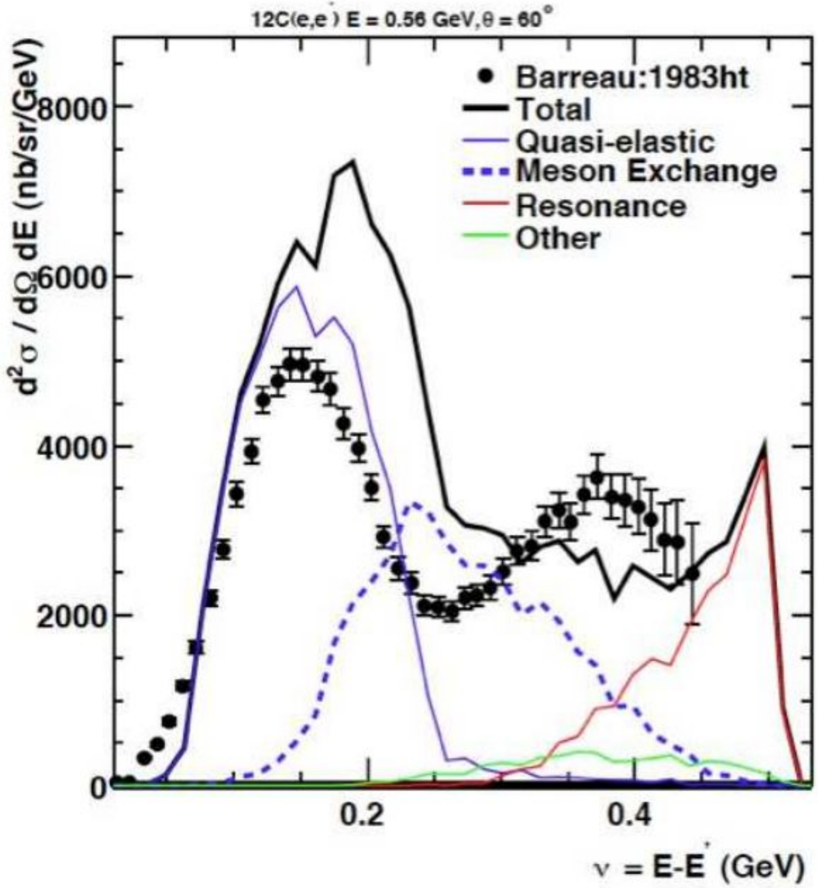
- Better cosmic background suppression
- Both backward and forward going particle reconstruction
- First results targeted for publication



Summary

- With the development of detector and analysis methods, **more attentions** are paid on neutrino interaction simulation.
- GENIE provides **a framework** handles all neutrinos and targets, and almost all processes relevant from MeV to PeV energy scales. Softwares for comparison and tuning also provided.
- Both Short Baseline Neutrino Program (SBN) and DUNE use LArTPC as the detector, **new challenges**
  - Nuclear effect understanding, models improved
  - More efforts on cross section modeling and new channel needed

MEC(Meson Exchange Current)



- **Empirical Model** is motivated by the lightbody model.
- In the lightbody model, QE and Delta peaks are give by Gaussian distributions, then MEC part is modeled as a Cauchy distribution between those 2 distributions
- **Valencia Model:**

Fermions are particles that obey Fermi–Dirac statistics, like electrons, protons, and neutrons, and, in general, particles with half-integer spin. An ideal Fermi gas or free Fermi gas is a physical model assuming a collection of non-interacting fermions in a constant potential well. It is the quantum mechanical version of an ideal gas, for the case of fermionic particles.

Fermi Gas Model

- Free electron gas: protons and neutrons moving quasi-freely within the nuclear volume
- 2 different potentials wells for protons and neutrons.
- Spherical square well potentials with the same radius

Statistics of the Fermi distribution

Given a volume V the numer of states dn goes like:

$$dn = \frac{4\pi p^2 dp V}{(2\pi\hbar)^3}$$

$$n = \int_0^{p_F} \frac{4\pi p^2 dp V}{(2\pi\hbar)^3} = \frac{V p_F^3}{6\pi^2\hbar^3}$$

If T=0 the nucleus is in the ground state and p_F (Fermi Momentum) is the maximum possible momentum of the ground state.

$$N = 2n = \frac{V p_{F,n}^3}{3\pi^2\hbar^3} \qquad Z = \frac{V p_{F,p}^3}{3\pi^2\hbar^3}$$

N= number of neutrons

Z= number of protons

↓

Spin 1/2 particles

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A \quad R_0 = 1.21\,fm$$

$$Z = N = A/2 \quad \frac{A}{2} = \frac{4}{3}\frac{\pi R_o^3 A p_F^3}{3\pi^2\hbar^3} \Rightarrow p_F = p_{F,n} = p_{F,p} = \frac{\hbar}{R_0}\left(\frac{9\pi}{8}\right)^{\frac{1}{3}} \approx 250\,MeV/c$$

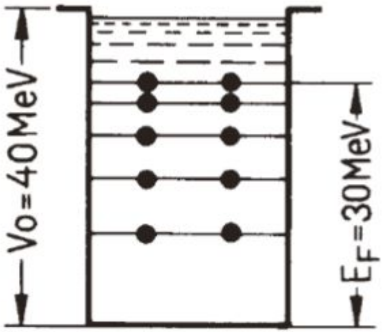
The nucleon moves in the nucleus with a large momentum

Fermi Energy $E_F = \frac{p_F^2}{2m_N} \approx 33\ MeV$

Binding Energy: BE/A= 7-8 MeV

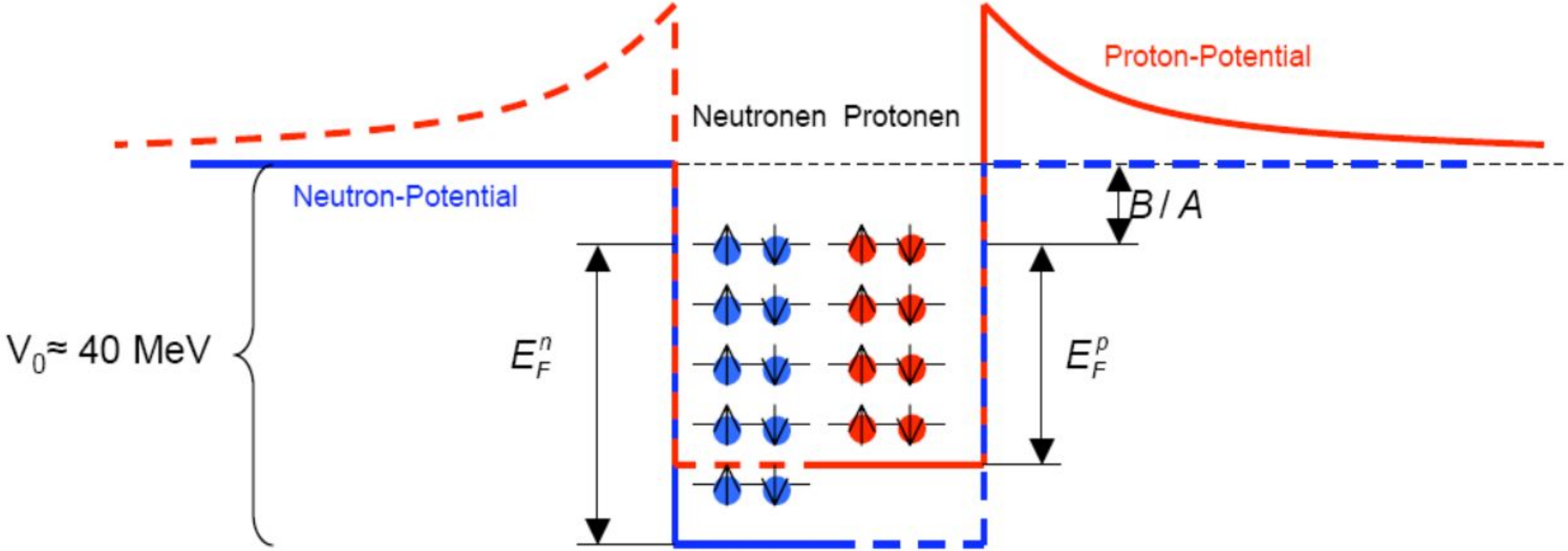
$V_0 = E_F + B/A \sim 40 MeV$

➔Nucleons are rather weakly bound in the nucleus



Potential well in the Fermi-gas model

The neutron potential well is deeper that the proton well because of the missing Coulomb repulsion. The Fermi Energy is the same, otherwise the p-->n decay would happen spontaneously. This implies that they are more neutrons states available and hence N>Z the heavier the nuclei become.

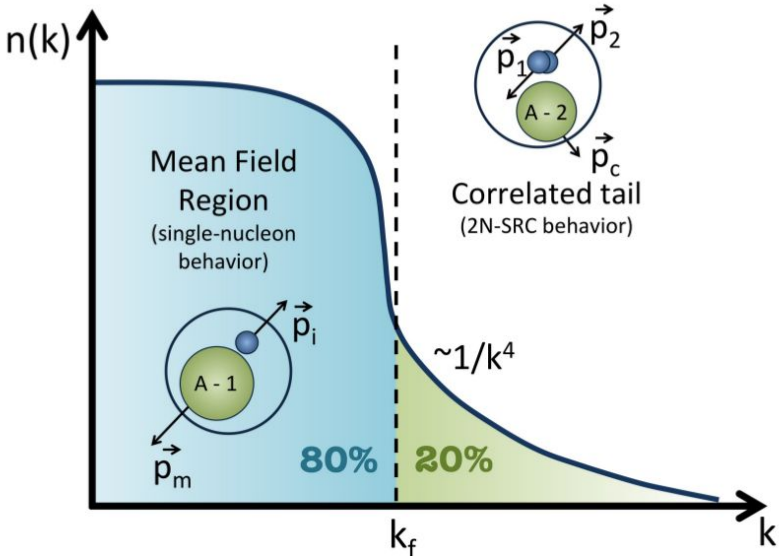


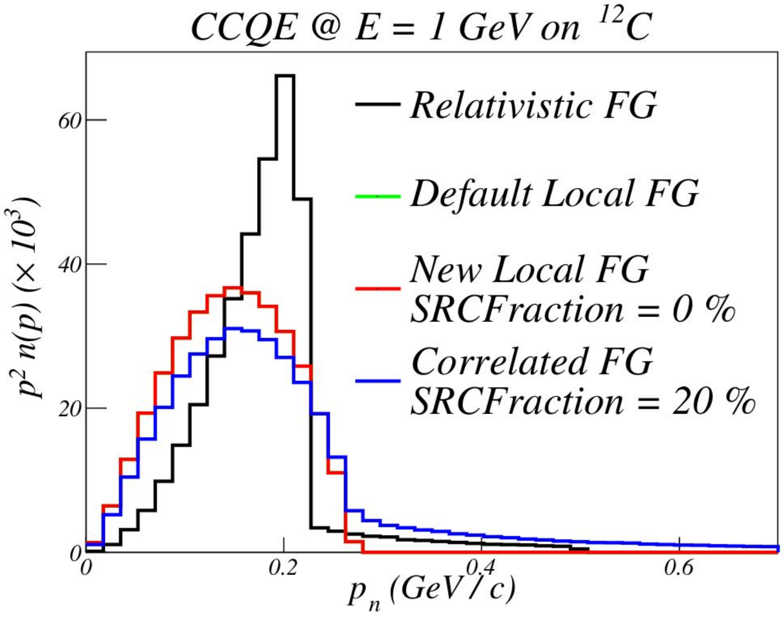
The relativistic Fermi gas model is also used for the description of large white dwarfs which are close to the Chandrasekhar limit.

How does GENIE work? - Nuclear Model

Model/generator	GENIE	NuWro	NEUT
Nuclear model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function

RFG(Relative Fermi Gas) Model: is the default model in GENIE v2 with Bodek-Ritchie high momentum tails





KNO: Hadronization models at low W where pythia is not applicable. Describe details of the GENIE NIM paper.

How does GENIE work? - Simulation Chain

GROUND STATE

- Vertex selection
  - Simple nuclear density model
- Initial state nuclear model
  - Removal energy and momentum
    - RFG with Bodek-Ritchie tails.
    - New: Local Fermi Gas
    - New: Effective Spectral Function
    - Almost there: "Benhar" spectral function
    - Just started: Correlated Fermi Gas (MIT)

INITIAL STATE

- Hard scattering process
  - Differential cross section formula to get event kinematics (x, y, Q2, W, t, etc.)
- Lepton kinematics
- Hadronic system

FINAL STATE

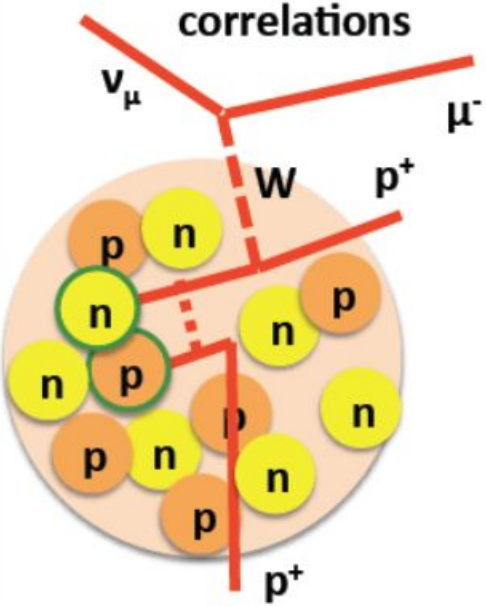
  - Propagation/transport (default is an "effective cascade")
    - Fast and re-weightable

How does GENIE work? Simulation Chain

REMNANT STATE

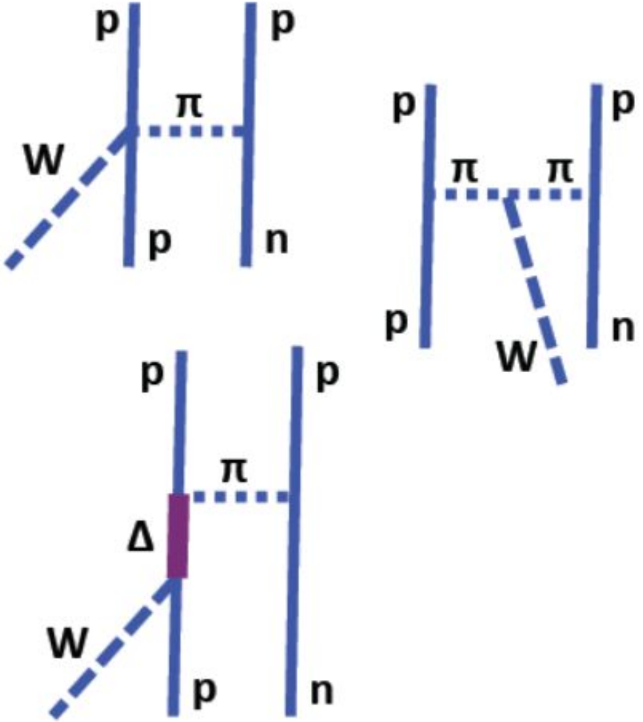
- Decays before and after propagation
- Remnant decay
  - Just started caring about this, really...
  - Current model is very simple
    - Working on adopting other codes (Geant4, INCL++, possibly GiBUU) to handle clustering, de-excitation, evaporation
    - May be a bridge to more sophisticated transport codes

Nucleon-nucleon correlations



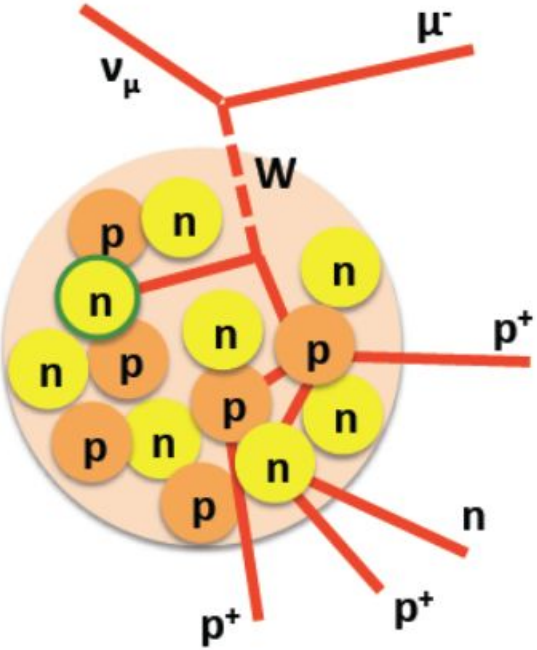
Two nucleons in correlation
Means for the experimentalist:
Multi-nucleon knockout!
The pair inside the nucleus has:
large relative momentum,
small total momentum

Meson exchange currents



The observed state looks
like QE but it was not!

Final state interactions



Multi-nucleon knockout
through re-interaction of the
outgoing nucleon

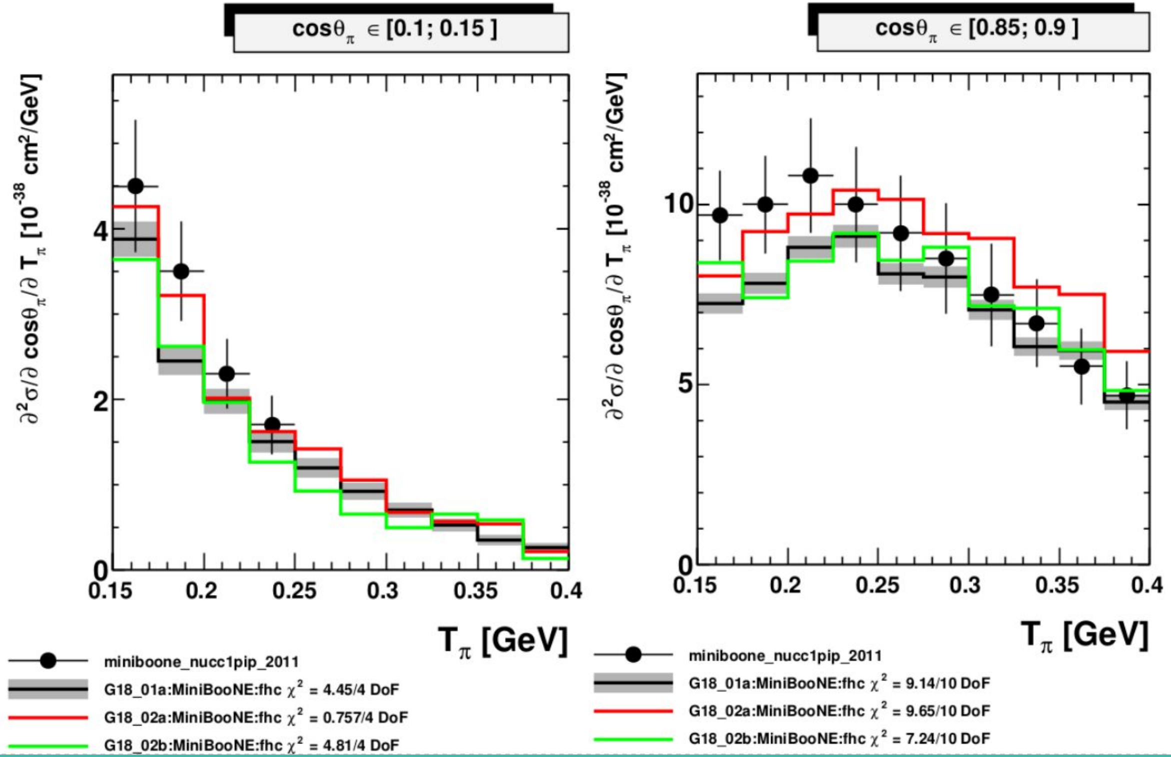
Anne Schukraft

How does GENIE work? - KNO Model

- Averaged charged hadron multiplicity data are fit to a function of invariant mass squared, W^2
  $<n_{ch}>=a_{ch}+b_{ch}*\log W^2$

- The total averaged hadron multiplicity if deduced to be
  $<n_{tot}> = 1.5*<n_{ch}>$
- Used KNO scaling law to simulate the actual hadron multiplicity
- KNO scaling law relates the dispersion of hadron multiplicity at different invariant masses with a universal scaling function f(n/<n>)
  $<n>*P(n)=f(n/<n>)$
  Where <n> is the averaged hadron multiplicity and P(n) is the probability of generating hadrons
- The scaling function is parameterized by the Levy function
-

$$L(z,c) = \frac{2e^{-c}c^{cz+1}}{\Gamma(cz+1)}$$



cosθπ ∈ [0.1; 0.15]
cosθπ ∈ [0.85; 0.9]
∂²σ/∂ cosθπ/∂ Tπ [10⁻³⁸ cm²/GeV]
Tπ [GeV]
miniboone_nucc1pip_2011
G18_01a:MiniBooNE:fhc χ² = 4.45/4 DoF
G18_02a:MiniBooNE:fhc χ² = 0.757/4 DoF
G18_02b:MiniBooNE:fhc χ² = 4.81/4 DoF
G18_01a:MiniBooNE:fhc χ² = 9.14/10 DoF
G18_02a:MiniBooNE:fhc χ² = 9.65/10 DoF
G18_02b:MiniBooNE:fhc χ² = 7.24/10 DoF

What is GENIE?

- Dedicated webpage: www.genie-mc.org

GENIE Collaboration

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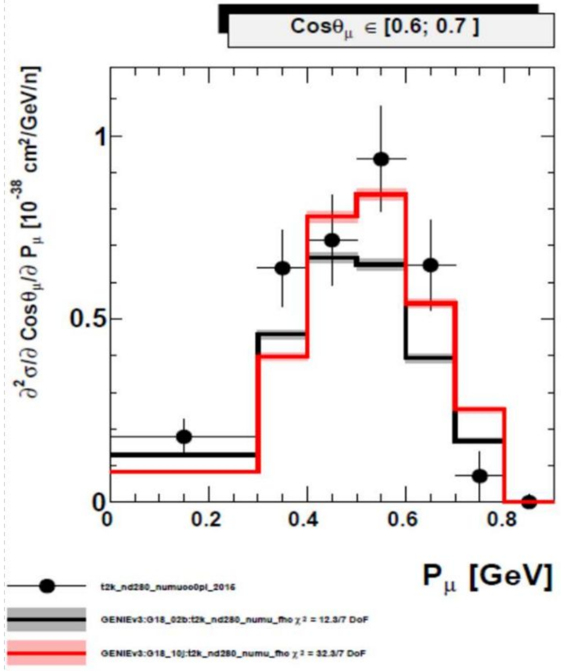
Core GENIE mission - from GENIE by-law

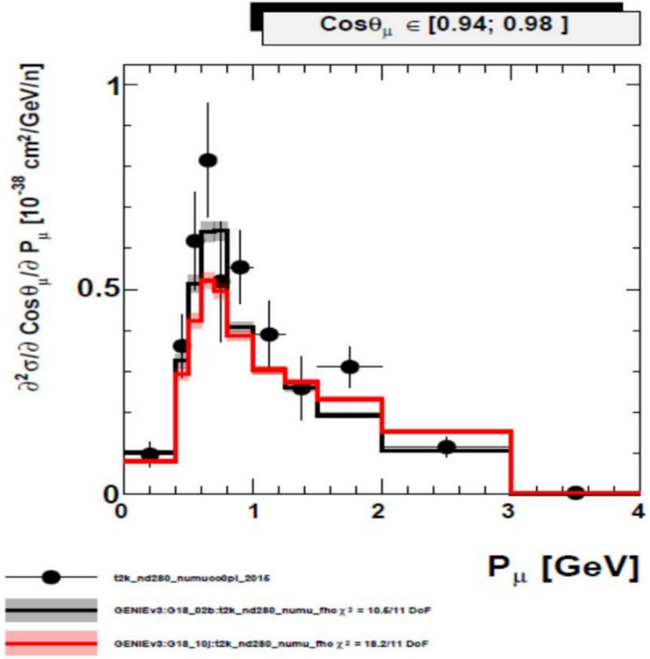
Framework "... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community ..."

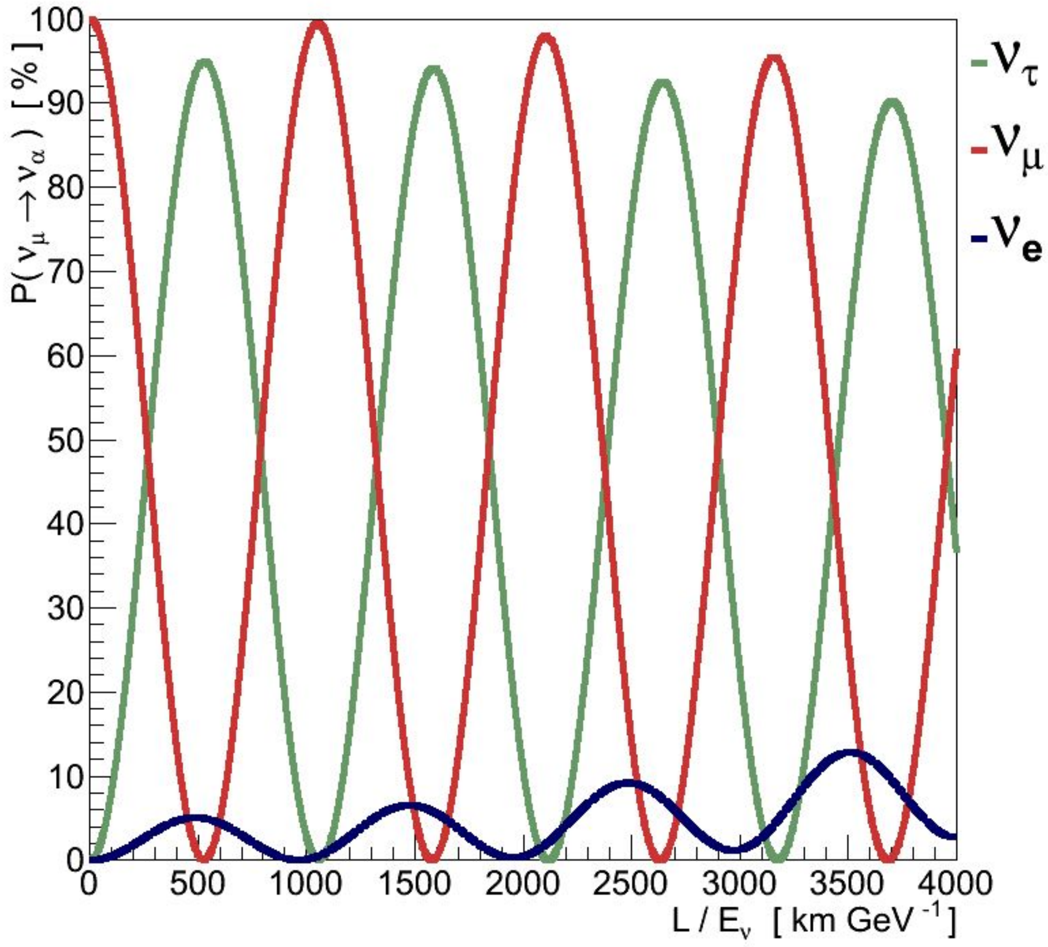
Universality "... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales ..."

Global fit "... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes ..."

T2K CC0π (2015)

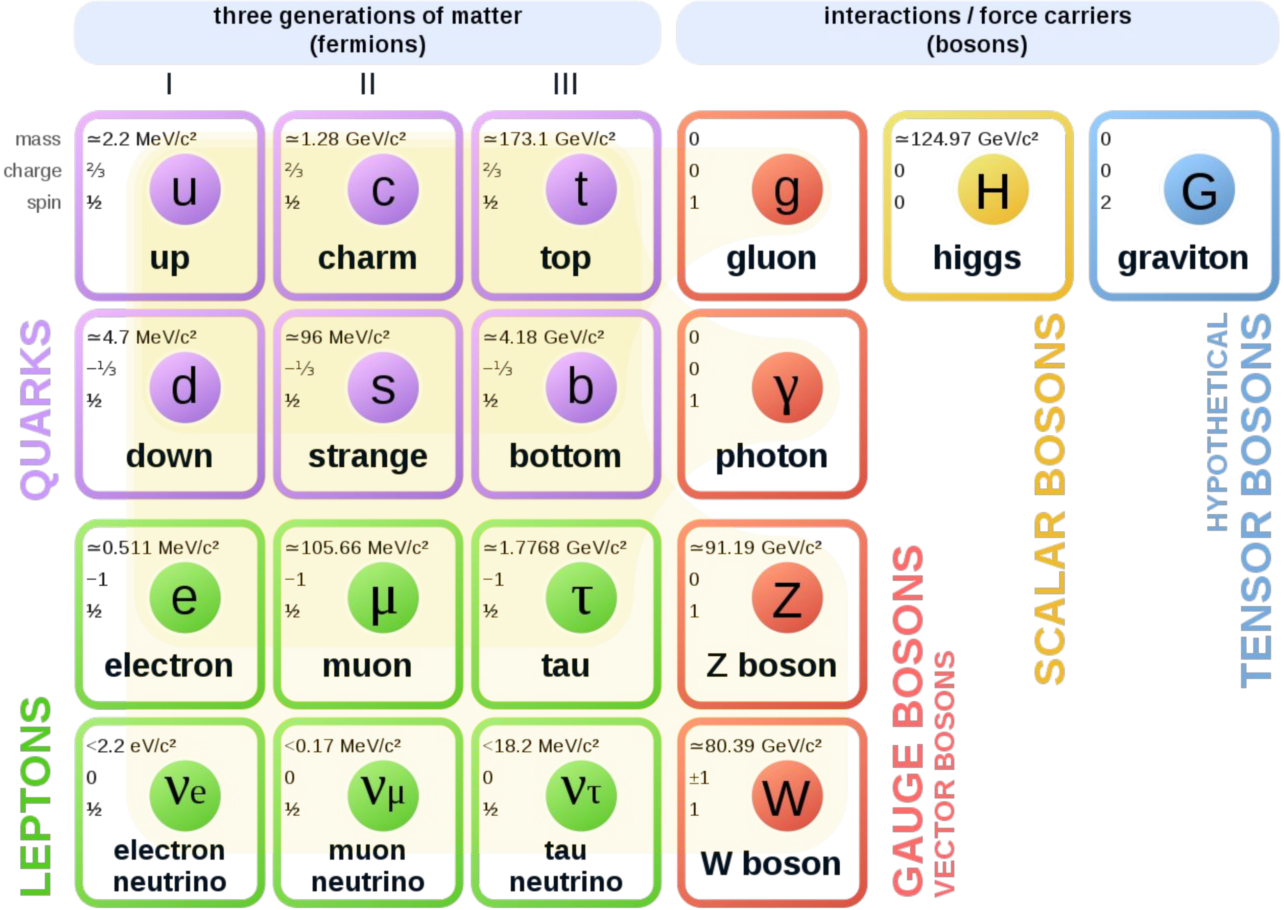






100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
4000
$P(\nu_\mu \rightarrow \nu_\alpha)$ [%]
L / E_ν [km GeV $^{-1}$]
ν_τ
ν_μ
ν_e

Standard Model of Elementary Particles + Gravity



Introduction to Neutrinos : Oscillations

Three flavor neutrino model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

If $\delta \neq 0,\pi$, then have CP violation $\Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Introduction to Neutrinos : Oscillations

Three flavor neutrino model

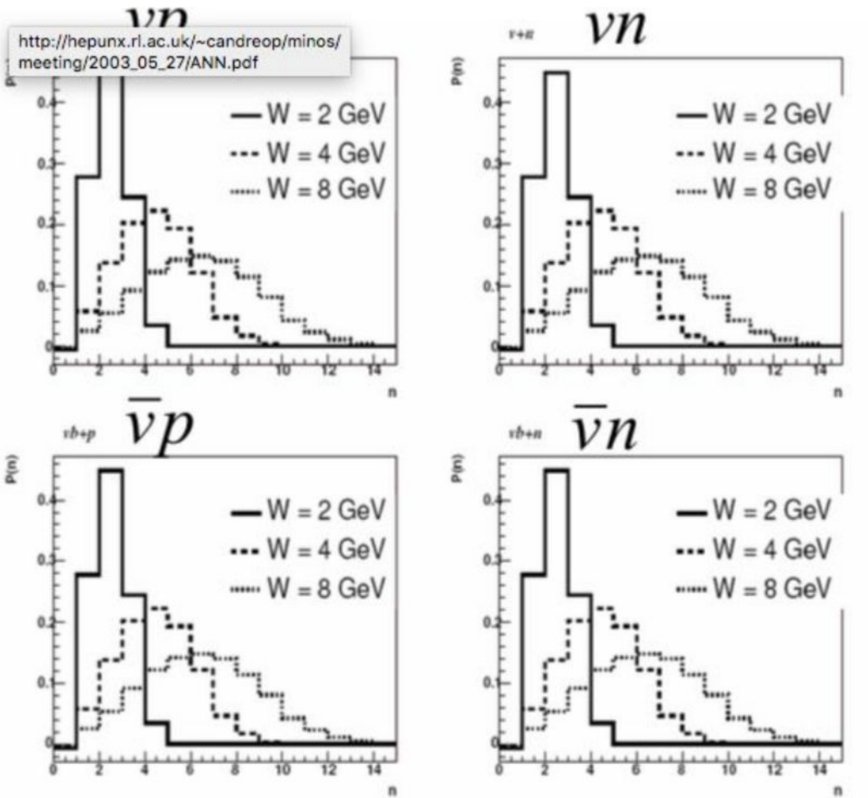
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

- **parameters to determine**
  - **CP violation phase δ**
  - **Mass hierarchy**
  - **3 Mixing angles**

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Multiplicity probability distributions



- We obtain them directly from the hadronization model (W<2.3GeV)
- P(m,W) probability distribution

$$\langle n \rangle = a + b\ lnW$$

$$\langle n \rangle \cdot P(n) = 2e^{-c} \frac{c^{c\frac{n}{\langle n \rangle}+1}}{\Gamma\left(c\frac{n}{\langle n \rangle}+1\right)}$$

GENIE Reweighting Scheme

- Propagating neutrino interaction uncertainties
- For a physical quantity P, introduce a systematics parameter x_P. Tweaking this systematic parameter modifies the corresponding physics parameter P as follows:

  $P \rightarrow P' = P(1+x_P*(\delta P/P)$

  δP is the standard deviation of P.

  Tweaking the systematic parameter by ±1 modifies

  the corresponding physics quantity P by ± P

Pythia

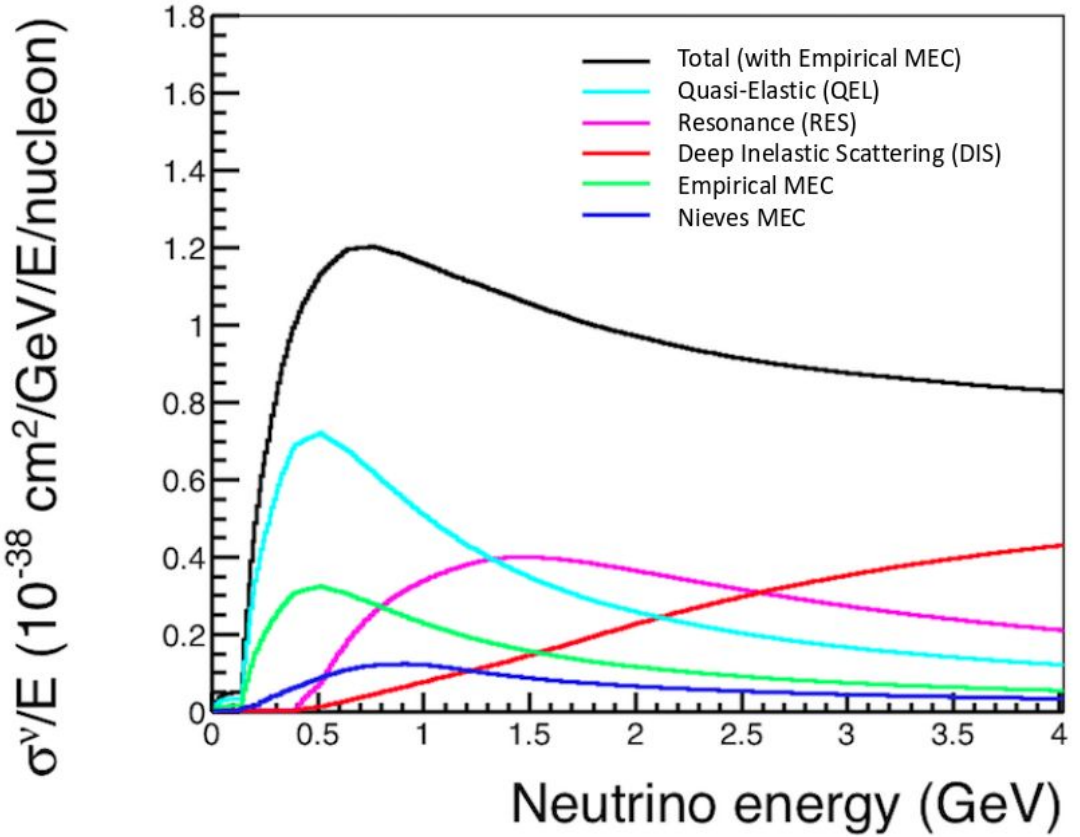
- The high invariant mass hadronization is performed by the PYTHIA model [85]. The PYTHIA program is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multi-hadronic final state. **It contains a library of hard processes and models for initial- and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation and particle decays.** The hadronization model in PYTHIA is based on the Lund string fragmentation framework.
- Fragmentation in PYTHIA is described by the Lund string fragmentation model, which is a model based on the dynamics of one-dimensional relativistic strings that are stretched between colored partons
- **Tuned on BEBC data.**

transverse momentum, $p_\perp^2 \, (= p_x^2 + p_y^2)$, for the produced hadron. The fraction of $E + p_z$ taken by the produced hadron is given by the variable z, defined by the hadron energy E and energy transfer ν ($z = E/\nu$). An associated fragmentation function $f(z)$ gives the probability that a given z is chosen. The simplified Lund symmetric fragmentation function is given by,

$$f(z) \propto z^{-1}(1-z)^a \cdot exp\left(\frac{-bm_\perp^2}{z}\right) . \qquad (1)$$

Here, $m_\perp^2$ is the transverse mass of the hadron ($m_\perp^2 \equiv m^2 + p_\perp^2$). The Gaussian term describes quantum tunneling in the transverse direction, and tunable "Lund a" and "Lund b" parameters decide the longitudinal distribution of energy. Thus, these two parameters mainly decide how to distribute available energy to the produced hadrons. Fig. 1 shows the Lund symmetric

Total Cross Section



Simulation in Neutrino Oscillation Physics

- **Interface between neutrino flux and experimental observables**
  - Calculate predictions
  - Constrain flux (ν-electron scattering)

- **Compare data with event generator models**
  - Cross sections
  - Experimental distributions: P, θ
  - Understanding models is key

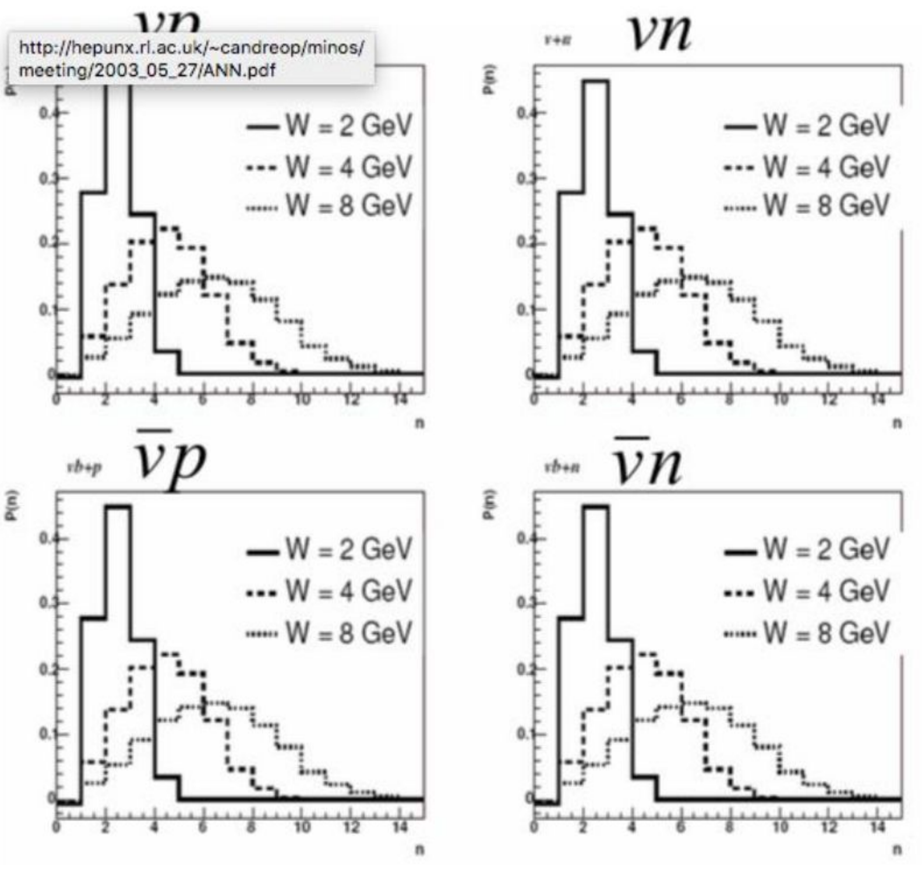
- **Compare dataset against dataset**
  - Data quality is increasing, analysis are improving
    - Inconsistency/bias can be introduced
  - Highlight tensions→ can not use a single model to do everything(e.g. MINERvA and MinibooNE QE-like).

How does GENIE work? - KNO Model

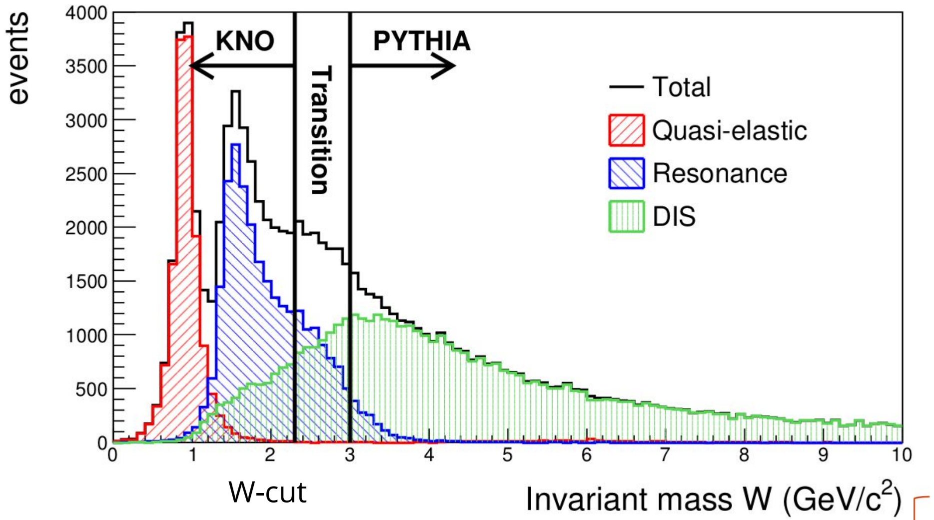
- Averaged charged hadron multiplicity data are fit to a function of invariant mass squared, W^2
  $\langle n_{ch}\rangle = a_{ch} + b_{ch} * \log W^2$
- Total hadron multiplicity $\langle n\rangle = 1.5 * \langle n_{ch}\rangle$
- probability distribution $P(n,W) * \langle n\rangle$ parameterized by the Levy function

$$\langle n\rangle = a + b\ lnW$$

$$\langle n\rangle \cdot P(n) = 2e^{-c}\frac{c^{c\frac{n}{\langle n\rangle}+1}}{\Gamma\left(c\frac{n}{\langle n\rangle}+1\right)}$$



How does GENIE work? - Modeling the Transition Region



W<Wcut: RES+scaled DIS with some multiplicity factors

$$f_m = R_m * P_m$$

- m=multiplicity of the hadronic system
  - -- 2 for 1π
  - -- 3 for 2π
- **R_m** Tunable parameter
- P_m Is the probability that the DIS final state has multiplicity m, obtained directly from the hadronization model.

W>Wcut: Pure DIS model (not scaled)

$$\frac{d^2\sigma^{inel}}{dQ^2dW} = \frac{d^2\sigma^{RES}}{dQ^2dW} + \frac{d^2\sigma^{DIS}}{dQ^2dW}$$

$$\frac{d^2\sigma^{RES}}{dQ^2dW} = \sum_k \left(\frac{d^2\tilde{\sigma}^{RES}}{dQ^2dW}\right) \cdot \Theta(W_{cut} - W)$$

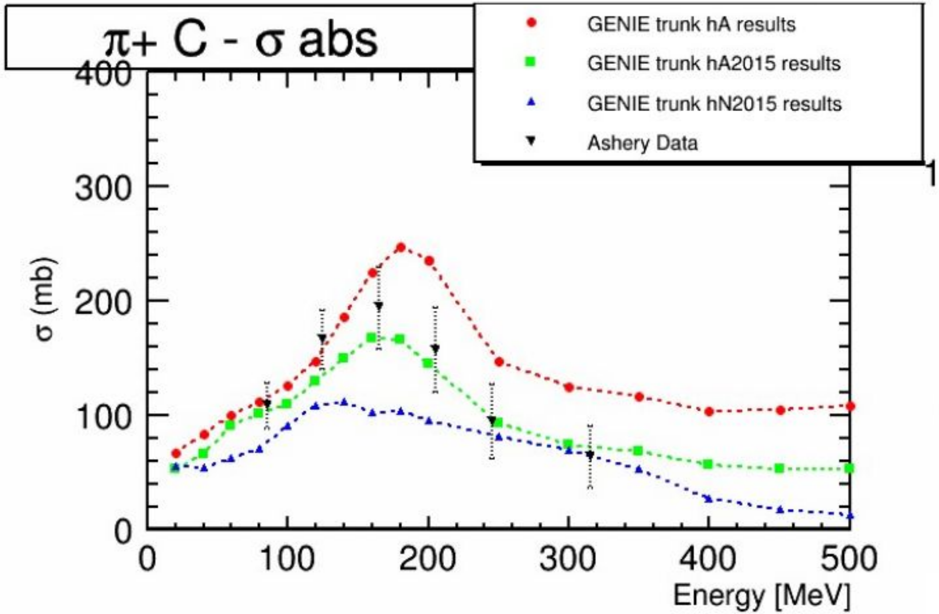
$$\frac{d^2\sigma^{DIS}}{dQ^2dW} = \left(\frac{d^2\tilde{\sigma}^{DIS}}{dQ^2dW}\right) \cdot \Theta(W - W_{cut})$$

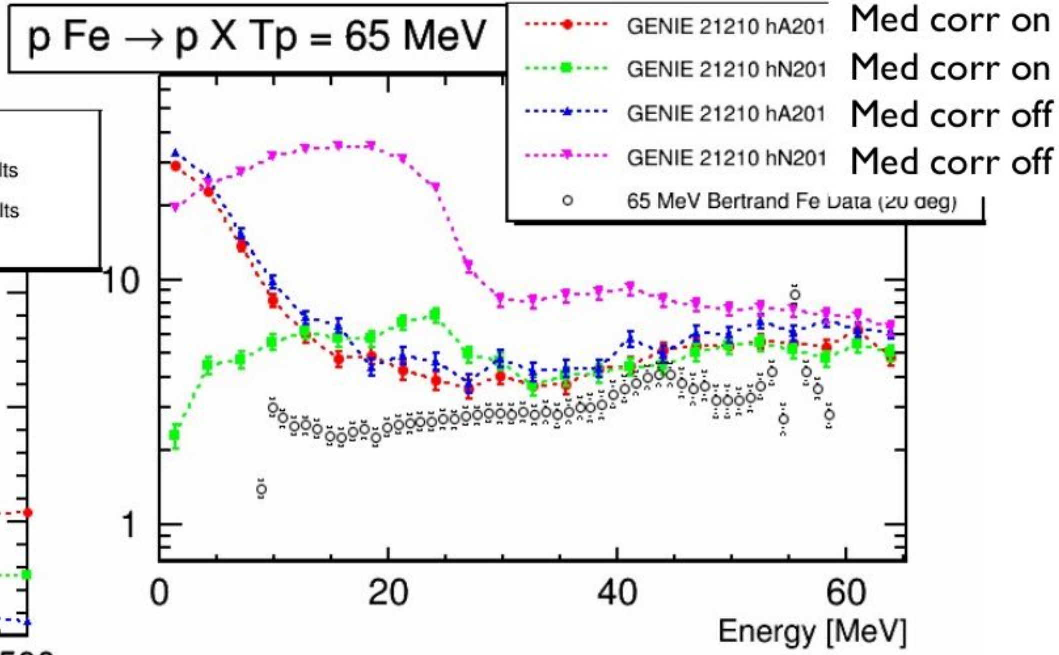
$$+ \left(\frac{d^2\tilde{\sigma}^{DIS}}{dQ^2dW}\right) \cdot \Theta(W_{cut} - W) \sum_m f_m$$

Non-Resonant Background
Contribution to this particular multiplicity channel

How does GENIE work? - FSI model

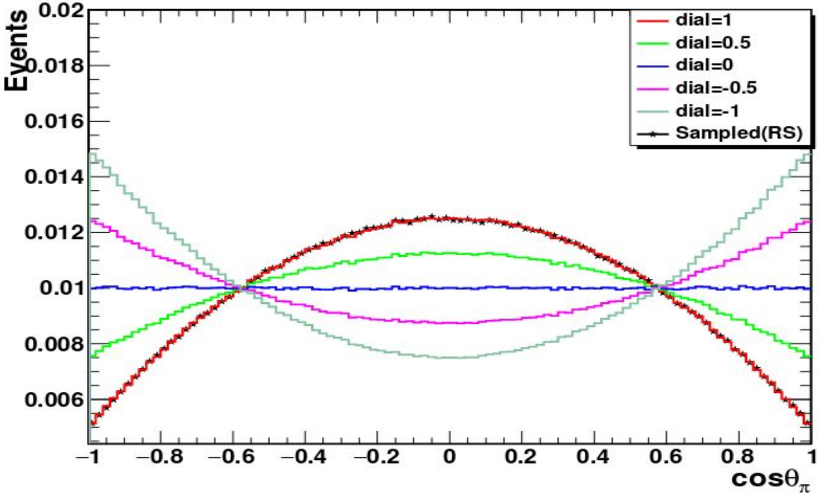
- hA 2018 is latest version of schematic model
- Recent emphasis on medium corr. hN2018 is new intranuclear cascade (INC) model with same nuclear medium corrections(π N) as NuWro
- Medium corrections suppress multiple scattering, decrease cross section. Strong A dependence!

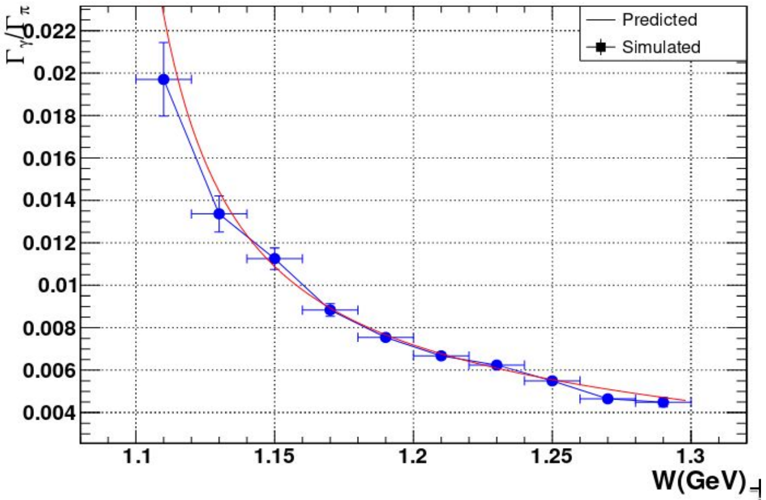




Improvements of Delta Decay

- Sampled π angular distributions from Delta decay non-isotropically with function.
  - Parameters in the function come from fitting to ANL and BNL(same as NuWRO)
- Branching Ratio between Δ->N+γ and Δ->N+ π changed from a constant into a function of W





How to get GENIE

- If you are an experimentalist at Fermilab, you can set it up through UPS:
  - https://cdcvs.fnal.gov/redmine/projects/genie/wiki
- You can easily get the source code from github and build it on Linux
  - https://github.com/GENIE-MC/Generator.git
- You can build on a Mac/windows also, but we do not have a pre-packed script
  - Additional products need to setup to build GENIE, e.g. ROOT, LHAPDF, Pythia...
- New Physics And User Manual in preparation (private temporarily)