Neutrino generators: NuWro, NEUT, GENIE

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Neutrino Event Generators

Monte Carlo codes link theory with experiment

- Experiments need them to make predictions and understand/interpret measured quantities.
- Theorist need them to validate their models against the data.

NEUT (Fortran) Developed for Japan based water Cherenkov experiments. New models added by Y. Hayato.

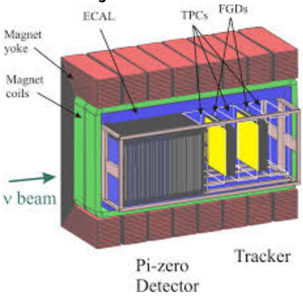
Genie (C++) http://www.genie-mc.org/
initially appeared ad a next version of **NEUGEN** (Fortran) generator which was developed for a number of years by a succession of physicists, and used by MINOS. Uses precomputed cross sections.

NuWro (C++) https://github.com/nuwro/nuwro
Initially created by theorists from Wroclaw University to test models of neutrino 1π production. Now general purpose neurino generator. Cross sections are calculated in the fly.

GiBUU https://gibuu.hepforge.org from Giesen group (U. Mosel) will not be covered today. (Takes a bit different approach)

NuWro main features

- Developed at Wrocław University by < 10 people
- $\sim$ 80k lines of C++ code (+$\sim$140k lines data)
- Written with efficiency in mind.
- Cross sections calculated on the fly.
- Plain text input file.
- Output is a root file with easy to analyze event objects.
- Capable of using the GEANT4 geometry definitions and MC generated experiment specific neutrino fluxes.
- ND280 geometry and beam interface included in the sources.
- QEL, RES, DIS, COS, MEC, COH interaction channels.
- FSI modeled as intranuclear cascade.



GENIE

The software:

- Aims to be a "universal event generator".
- Neutrino, but also electron and hadron scattering modes available.
- Many tools for studying systematics, comparison to data, tuning, etc.
- Interfaces to HEP software frameworks (e.g., art, LArSoft).
- Drivers for many detector geometries and beams.

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

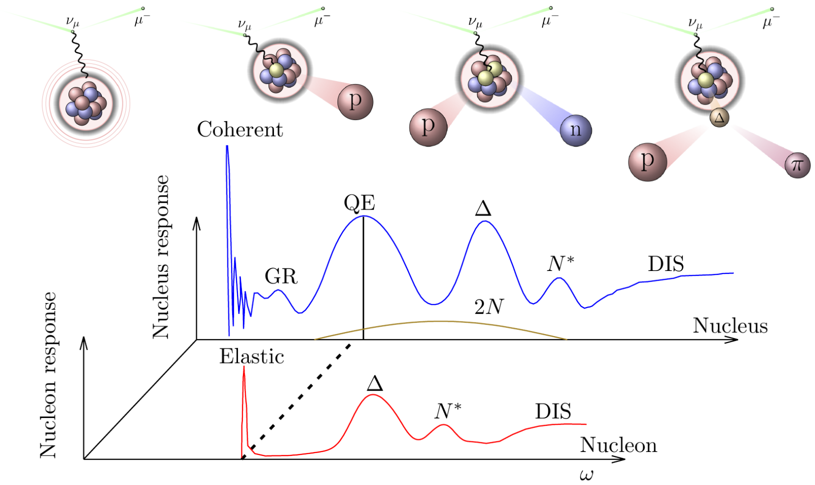
The collaboration:

- International collaboration with about a dozen collaborators (essentially all experimentalists) and many more contributors.
- Many theorists contribute algorithm implementations.

NEUT

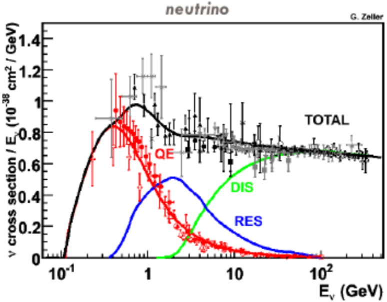
- NEUT was developed to study the interactions of atmospheric neutrino and to estimate the detection efficiencies of nucleon decay with the water Cherenkov detector, Kamiokande.
- Since then, NEUT has been continuously updated and used in the various experiments like Super-Kamiokande, K2K, SciBooNE and T2K.
- NEUT covers a wide energy range of neutrino energy from several tens of MeV to hundreds of TeV.
- Initially it was using only hydrogen and oxygen targets but now various nuclei including carbon, argon and iron are also available.

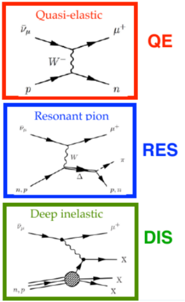
Nuclear response and neutrino interaction channels



T. Van Cuyck

Neutrino-Nucleon interaction modes





(from Sam Zeller; based on P. Lipari et al, Phys. Rev. Lett. **74** (1995) 4384)

CCQE is $\nu_\mu\ n \to \mu^-\ p$, or $\bar{\nu}_\mu\ p \to \mu^+\ n$.

RES stands for resonance region e.g. $\nu_\mu\ p \to \mu^-\ \Delta^{++} \to \mu^-\ p\ \pi^+$; one often speaks about SPP - single pion production

DIS stands for Deep Inelastic Scattering (more inelastic than RES).

νA interaction (impulse approximation)

In the 1 GeV region nuclear effects are treated in the impulse approximation (IA) scheme: neutrinos interact with individual bound nucleons.

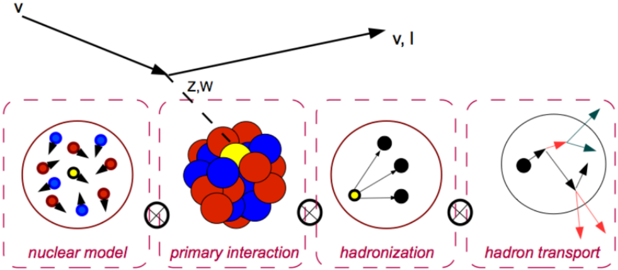


Figure by C. Andreopoulos

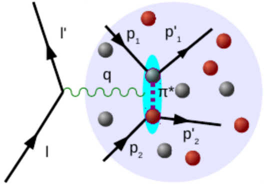
Neutrino-nucleus interaction is viewed as a multi-step process:

- selecting nucleon for interaction requires a density profile $\rho(r)$ and a spectral function $P(E, \vec{p})$ 2d distribution of nucleon momenta and binding energies. FG and LFG can be viewed as specific cases of SF.
- during primary interaction nucleons inside nucleus are off-shell and their transition matrix elements need to be modified (de Forest prescription). In case of RES the resonance widths, may be different in nuclear matter.
- final state interactions (FSI) are implemented as cascade codes. In Plane wave impulse approximation (PWIA) the FSI effects are neglected.

Multi nucleon channels (MEC and COH)

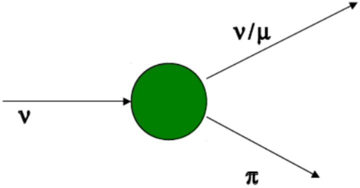
Such factorization is impossible for channels which involve more than one nucleon:

- MEC (Meson Exchange Current) also called two body current lepton scattering on two highly correlated nucleons.



from J. Żmuda

- COH (coherent pion production) at low energies the pion is created coherently on all the nucleons



Monte Carlo method

Einstein: "God does not throw dice.."
Quantum mechanics: "He does..."
Monte Carlo methods: "Lets do the same.."

MONTE CARLO method:

Strategy:

- Make choices with relative probabilities = those in Nature.
- Do so in every stage of event generation.
- Create many events.

Result:

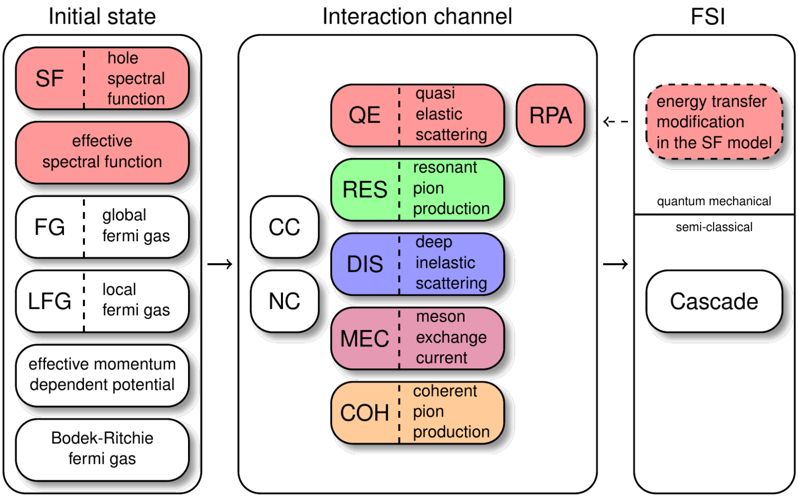
- Distributions of observables will be the same as in Nature

MC event generation scheme

Given neutrino flux description and target (detector geometry) definition, generate scattering events sample.

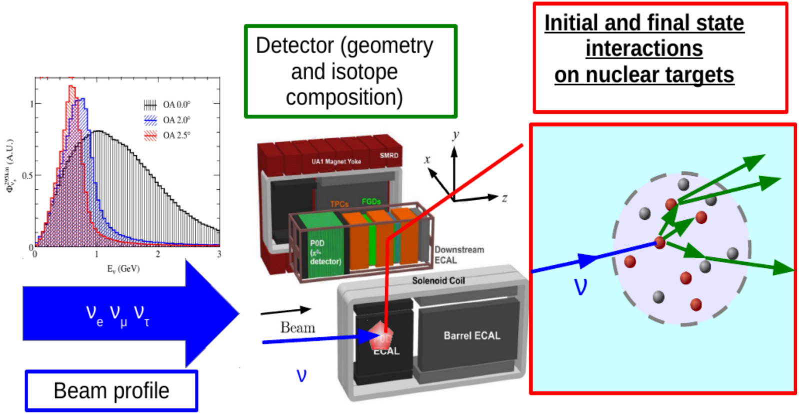
- INITIAL STATE
  - generate neutrino (flavor, energy, direction, starting point) according to beam definition (composition, energy profile...).
  - select nucleus (isotope, position) from target definition (should lie on neutrino trajectory inside detector geometry)
  - Select nucleon (position, momentum, removal energy) from nuclear density profile and nulear model: FG, LFG, SF, other.
- PRIMARY INTERACTION
  - select interaction channel: QEL, RES, DIS, MEC, COH ...
  - generate interaction kinematics specific for the channel
  - calculate event weight as the differential cross section
- FINAL STATE INTERACTIONS
  - propagate hadrons and let them interact with nuclear matter
  - subtract binding energy from nucleons leaving nucleus
  - apply Coulomb corrections
- Accept and save event with probability proportional to its weight.

NuWro scheme

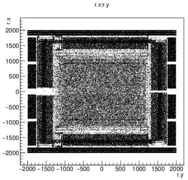


K. Niewczas

Beam and detector simulation

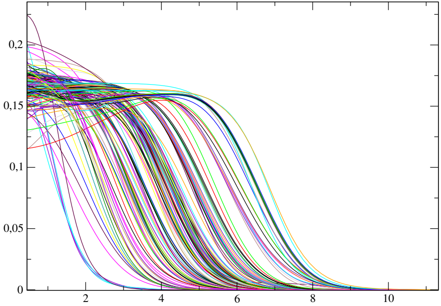


When using detector geometry events are concentrated where heavier parts of the detector are.



Nuclear model - density distributions

- In nuclear matter interaction probability depends on both scattering cross section and nuclear density.
- Proper modeling is essential for LFG and for FSI reinteractions modeling.
- Nuwro implements (see Fig.) all density profiles from ATOMIC DATA AND NUCLEAR DATA TABLES 36, 495536 (1987).
- Both NEUT and GENIE use Wood-Saxon shaped density profile parametrizations
- Constant density model is possible but not default.



Spectral function formalism for CCQE (no FSI)

Spectral function is 2D distribution of nucleon mometum and removal energy.
CCQE final state is assumed to be a nucleon of momentum $\vec{p}'$ decoupled from the remnant nucleus:

$$|f(p_f)\rangle = |R(p_R)\rangle \otimes |p'\rangle.$$

It can be shown that:

$$\frac{d^2\sigma}{d\omega dq} = \frac{G_F^2 \cos^2\theta_C q}{4\pi E_\nu^2} L_{\mu\nu} W^{\mu\nu}$$

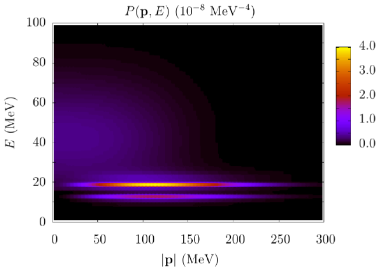
$$W^{\mu\nu} = \int dE \int d^3p \frac{\delta(\omega + M - E - E_{p'})}{E_p E_{p'}} H^{\mu\nu}(\vec{p} + \vec{q}, \vec{p}) P(E, \vec{p})$$

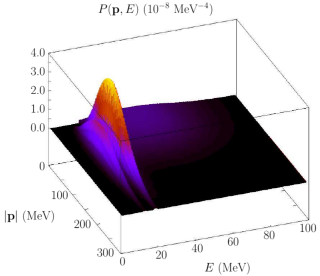
$L_{\mu\nu} = 2\left(k_\mu k'_\nu + k'_\mu k_\nu - k \cdot k' g_{\mu\nu} - i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda\right)$, $H^{\mu\nu}$ is the free nucleon hadronic tensor, k^μ, k'^μ are neutrino and charged lepton four-momenta, $q^\mu \equiv k^\mu - k'^\mu = (\omega, \vec{q})$ is four-momentum transfer.

$P(E, \vec{p})$ is called spectral function (SF) and fully determines the interaction cross section.
Fermi gas FG and local Fermi Gas LFG can be treated as special cases. However, they are consistent with using FSI (intra nuclear cascade).

Genuine (Benhar) spectral function.

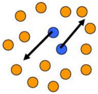
Below, the oxygen SF as calculated by Omar Benhar





Shell model orbitals are clearly seen.

	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$
E	45	18.44	12.11



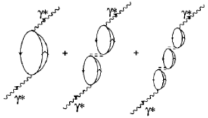
Contribution from correlated nucleon pairs is included.

Ab initio computations of SF does not exist.

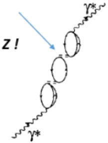
RPA - important for low momentum transfers

For low momentum transfers the mediating boson's length is larger and collective effects start playing a role. Random phase approximation (RPA) takes them into account.

- Corrects for collective effects at low q (longe range correlations).
- Analogy to in-medium polarization of Coulomb force.



Also for photons, W, Z !

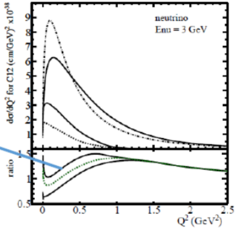


cannot be γ, *W, Z*, it should be V: ph-ph, ph-Δh interaction

Remarks:

RPA corrections should disappear (ratio goes to 1.0) **at very large Q^2 values, because this is a collective effect which strength decreases when sizes larger than one nucleon are no longer being probed**. Hence in any realistic model, one should expect a qualitative Q^2 behavior similar to that exhibited by the QE_{RPA}/QE_{noRPA} ratio line depicted in the figure.: **low Q^2 suppression, followed by an enhancement that could even give rise to a net increase of the cross section, and finally all RPA effects should disappear for sufficiently high Q^2 values**

QE_{RPA}/QE_{noRPA}



Juan Nieves, IFIC (CSIC & UV)

Monte Carlo choices for CCQE

All generators use the Llwellyn-Smith cross section but differ with nucleus modeling.

NEUT

FG - default	from Smith-Moniz paper
LFG	Nieves model, with or without RPA
SF	without FSI*
Nieves	under development?

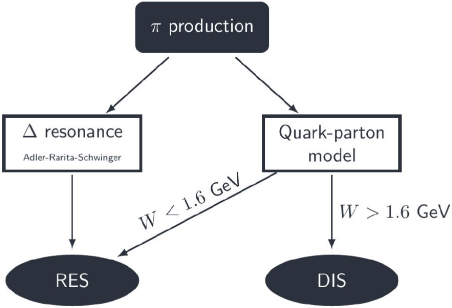
GENIE

FG - default	Bodek-Ritchie approach
SF	without FSI*
effective SF	Bodek paper
Nieves	LFG, RPA, Coulomb potential

NuWro

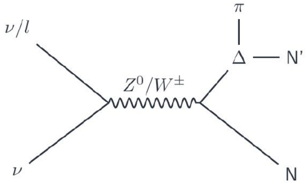
LFG - default	with or without RPA
FG	with or without RPA
SF	without FSI* (available for O, C, Fe, Ar, Ca)
momentum, density dependent potential	from Brieva-Dellafiore paper

Single π production in Nuwro



Most of the π production comes from the Δ in Adler Rarita Schwinger formalism.

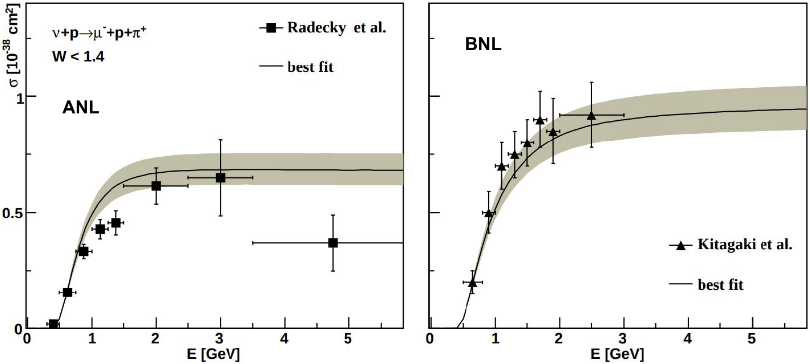
The lack of other resonances is filled up with quark-parton model with Pythia6 hadronization adjusted (J. Nowak) to work in low energy regime $W < 1.6$ GeV.



The following channels are considered for SPP (labeled as RES):

$$
\begin{aligned}
\nu + p &\rightarrow l^- + \left(\Delta^{++} \rightarrow p + \pi^+\right) \\
\nu + n &\rightarrow l^- + \left(\Delta^{+} \rightarrow p + \pi^0 \text{ or } n + \pi^+\right) \\
\overline{\nu} + p &\rightarrow l^+ + \left(\Delta^{0} \rightarrow p + \pi^- \text{ or } n + \pi^0\right) \\
\overline{\nu} + n &\rightarrow l^+ + \left(\Delta^{-} \rightarrow n + \pi^-\right) \\
\nu(\overline{\nu}) + p &\rightarrow \nu(\overline{\nu}) + \left(\Delta^{+} \rightarrow p + \pi^0 \text{ or } n + \pi^+\right) \\
\nu(\overline{\nu}) + n &\rightarrow \nu(\overline{\nu}) + \left(\Delta^{0} \rightarrow p + \pi^- \text{ or } n + \pi^0\right)
\end{aligned}
$$

The Delta model was scaled to fit to both ANL and BNL data.



Single π production in NEUT (Rein, Seghal model)

- Based on D.Rein, L.M.Sehgal, Ann. of Phys. 133(1981), and D.Rein, Z.Phys. C35 (1987) 43-64
- Relativistic harmonic oscillator model by Feynman, Kislinger and Ravndal (Feynman et al. Phys. Rev. D3 (1971) 2706)
- Initial helicity amplitude code was provided by one of the authors.
- The interferences between the resonances are taken into account.
- Total cross-section: Integrated over whole kinematic region of W and q^2. (mass of the lepton taken into account)

Further improvements:

- Lepton mass and spin correction: Kuzmin et al. Mod.Phys.Lett. A19 (2004) 2815-2829 Phys.Part.Nucl. 35 (2004) S133-S138
- Lepton mass correction Berger , Sehgal Phys.Rev.D76:113004,2007
- Form factors
  1) Original Axial vector mass is set to 1.21 GeV/c 2 by default. (1.01, 1.11 and 1.31 GeV/c2 are supported.)
  2) Graczyk-Sobczyk Phys.Rev. D77 (2008) 053001 (Nowak Arxiv:0909.3659)
  Parameters are fixed by re-fitting the ANL and BNL data.

Taken from Y. Hayato talk @ Trento 2018

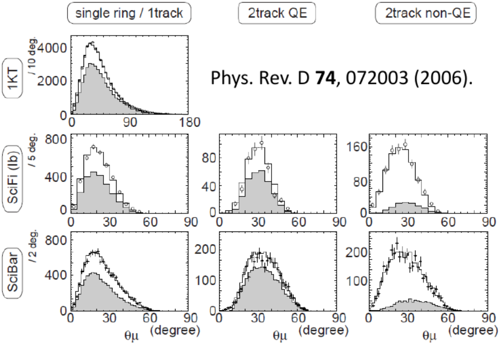
Single π production in NEUT

Axial vector mass 1.21 GeV/c^2

1) Suppression of forward going μ in inclusive sample (K2K)

Larger M_A for CCQE + Bodek-Yang correction were not sufficient.

(K2K oscillation analysis : M_A=1.1 GeV/c^2 for CCQE & 1π production)

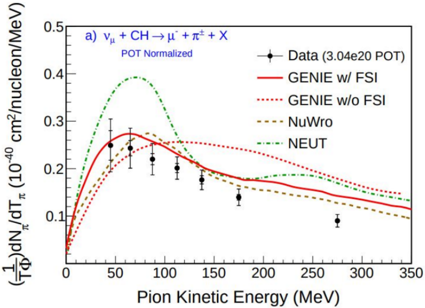


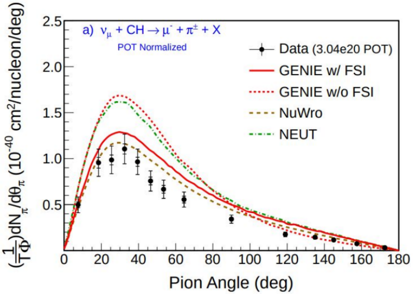
Phys. Rev. D **74**, 072003 (2006).

Shaded area : CCQE

Resonant single pion production comparision

Comparison with MINERvA ν Data CC $1\pi^+$





C. L. McGivern et al. (MINERvA Collaboration) Phys. Rev. D 94, 052005

Monte Carlo choices for RES region

NEUT

Reinn Sehgal interference terms handled properly with $W < 2$ GeV cut
inclusion of lepton mass and spin correction Kuznin + Berger Sehgal

GENIE

Rein Sehgal incoherent sum of all resonences $W < 2$ GeV cut in hadronic mass

NuWro

only delta included NuWro pion production model includes:

* single resonance pion production through Delta excitation
* more inelastic processes described by quark-parton model with Pythia6 used for hadronization
* hadronization parameters are tuned to get a good agreement with experimental data
* in the region 1.3 GeV $< W < 1.6$ GeV
  smooth transition from Δ to DIS with Pyhia6 hadronization
* final state interactions modeled via intranuclear cascade based on Oset et al model

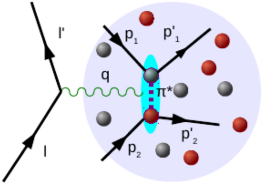
DIS modeling

- Bodek Young cross section formula

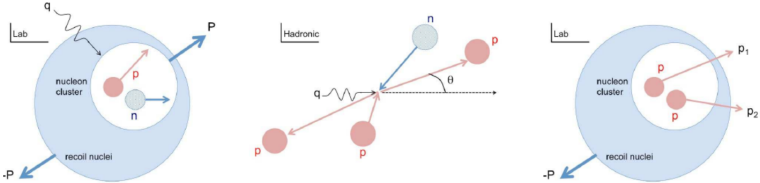
$$\frac{\mathrm{d}^2\sigma^{\nu/\overline{\nu}}}{\mathrm{d}x\mathrm{d}y} = \frac{G^2 M E_\nu}{\pi\left(1+Q^2/M_{W,Z}^2\right)^2}\left[y\left(xy+\frac{m^2}{2E_\nu M}\right)F_1 + \left(1-y-\frac{Mxy}{2E_\nu}-\frac{m^2}{4E_\nu^2}-\frac{m^2}{2ME_\nu x}\right)F_2 \pm \left(xy\left(1-\frac{y}{2}\right)-y\frac{m^2}{4ME_\nu}\right)F_3\right]$$

  and Pythia6 hadronization library are used by all three generators
- Both NEUT and GENIE use it for $W > 2$ GeV while NuWro performs smooth passage from Δ to DIS in the 1.3 GeV $< W < 1.6$ GeV region.
- In NuWro Pythia6 hadronization parameters were fine tuned and specific quark configurations were treated separatly (J. Nowak PhD thesis) to make it work in so low energies.
- Bodek-Young modification to the parton distribution functions for low Q2 were also included.

MEC - Meson Exchange Current (Two-body current)



- Significant enhancement due to one-body and two-body current interference.
- Effect comes from short range correlated nucleon-nucleon pairs.
  - Present in spectral function formalism.
  - Mostly pn due to tensorial nuclear force.
- For neutrino scattering Nieves and Martini microscopic models:
  - Based on LFG. Correlations and Interference effects are included.
- Nucleon pair kinematics based on hadronic system phase space
  - guarantees that both final state nucleons are on-shell



Monte Carlo choices two-body current contribution (MEC)

NEUT

Nieves default; $q \leq 1.2$ GeV/c cut
based on LFG
phase space model for hadrons

GENIE

empirical matched to MB data: Comp Phys vol2 (1988)

Nieves extension to all nuclei

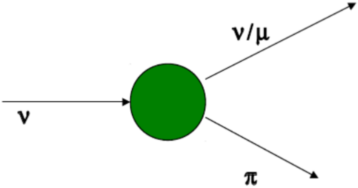
TEM Bodek et al

NuWro

Nieves default; $q \leq 1.2$ GeV/c cut

TEM fit to NOMAD data Bodek et al
phase space model (for both Nieves and TEM) with many options

COH - Coherent pion production



Interaction takes place **on the whole nucleus** (coherently an all nucleons)
NuWro, GENIE and NEUT use the same models:

- D. Rein, L.M. Sehgal, Nucl. Phys. B223, 29 (1983)

$$\frac{d^3\sigma}{dQ^2 dy dt} = \frac{G^2 M_N}{2\pi^2} f_\pi^2 A^2 E_\nu (1-y) \frac{1}{16\pi} \left[\sigma_{\text{tot}}^{\pi N}\right]^2 \times (1+r^2) \left(\frac{m_A^2}{m_A^2+Q^2}\right)^2 e^{-b|t|} F_{\text{abs}} ,$$

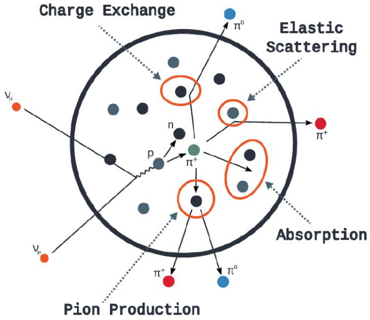
$$r = \mathrm{Re} f_{\pi N}(0) / \mathrm{Im} f_{\pi N}(0) ,$$

- Berger, Sehgal model (modification of RS model)

The model are simple to implement but the $e^{-b|t|}$ factor leads to very inefficient generation of unweighted events. In NuWro simple change of variables brought 1000 fold improvement.

Final state interactions

The original idea is due to Metropolis: *N. Metropolis et al., Phys. Rev. 110 (1958)*
Nucleons, and pions from primary vertex are propagated in nuclear matter and:



T. Golan

Pions...

- can be absorbed,
- can be scattered elastically,
- (if energetic enough) can produce new pions,
- can exchange electric charge with nucleons.

Nucleons...

- can be scattered elastically,
- can exchange electric charge,
- can produce more pions.

Kaons... in NEUT and GENIE,
η... in NEUT.

Monte Carlo choices for FSI

NEUT

cascade π from Oset model scaled to reproduce p-A exp. data. with angular distributions from phase shift analysis and medium corrections by Seki et al.
nucleon ejection after π absorption – nucleon multiplicity and charge determined using π-A absorption experimenal data

* nucleons – Bertini model (MECC7).
* kaons and ηs are propagated with K-N and η-N cross sections
* no Coulomb potential

GENIE

hA effective model

hN cascade model: Oset and Pandharipande/Pieper are alternate models

* kaons are included in both hA and hN

NuWro

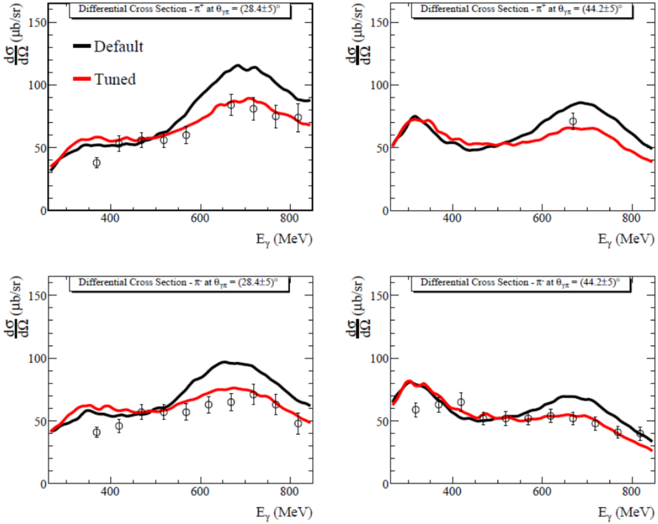
cascade π based on Oset model

* nucleons - Pandharipande, Pieper model
* no Coulomb potential, no kaons

FSI tuning - pion Carbon scattering in NEUT

π interaction simulation in NEUT

~ comparisons with π-C scattering



slide from Y. Hayato talk (Trento 2018)

Formation time/Formation zone in FSI

Hadrons propagate some distance before they can reinteract.

- The effect is measured in lepton-nucleus scattering at large energies.
- FSI effects are expected to be smaller.
- The effect is stronger for two quark systems (pions) than for three quark systems (nucleons)

NEUT

SKAT in DIS and optionally in 1π channels.

GENIE

SKAT only in DIS (Baranov et al., PHE 84-04, 1984)

NuWro

Ranft model only in DIS (fit to NOMAD data)

Summary and outlook

- All three generators evolve over time and learn from each other.
- GENIE is more experiment oriented: has good tools for validation and estimation of statistical errors. It aims to become a Universal MC generator.
- NuWro gives comparable results and is easy to use and program, well suited to test new models. Reweighting and validation tools are under development. When ready may help it gain more recognition in experiments.
- NEUT is very high quality software, developed and fine tuned over years but actively seeking to improve existing models an introduce new effects. It is unrivaled in making predictions and analyzing results for water Cherenkov detectors.