Event Generator Review

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Tufts University
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Thanks to: C. Andreopoulos, S. Dytman, Y. Hayato, T. Leitner, U. Mosel, G. Smirnov, J. Sobczyk, S. Zeller
Use by Experiments

Neutrino event generators are unique among the tools required to successfully envision, design and execute experiments in that they play vital roles “from cradle to grave”.

Infancy – generators are used to estimate sensitivity of proposed experiments and in making detector design optimization decisions.

Resolution vs. statistics vs. background rejection vs. ?
Use By Experiments

Event generators provide the backdrop against which any putative signal is measured and provide the best “expectation” in the absence of new physics.

Particularly crucial in the early days of an experiment as discrepancies between data and expectation are being investigated.

MINOS

Best Fit:

$|\Delta m^2| = 2.43 \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta) = 1.00$

K2K

$\Delta m^2 = 2.8 \times 10^{-3}$

$\sin^2(2\theta) = 1$

Use By Experiments

As the interface to the models, event generators are used in analyses all the way up to the final steps.

Fitting models to data.

Evaluation of model-related systematic uncertainties.
The generation of large analysis Monte Carlo samples for an experiment can consume significant manpower and computing resources. Separate Monte Carlo samples required for each detector/beam configuration.

Rough numbers from MINOS ND Generation:
One Monte Carlo job produced files of around 16k events each, taking 6 hours and producing files of around 600 MB. Around 70k files generated total, ~25TB of data.

Producing an analysis sample for the ND (1.5 times data) required 4.5 months real-time of dedicated running at four sites, with a total of around 440 cores.

Requires a MC Coordinator (Kregg Arms) as well as production site managers.
Event Generators - Challenges

In addition to these diverse uses, experiments are sensitive to different aspects of the physics and integrate these packages into their analyses in a variety of ways.

**Unique Challenges**

Experiments: Rapidly evolving

Theory: Rapidly evolving

Describing physics over a broad kinematic range

Lack of a ‘canonical’ package

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SPIRES: ti ‘neutrino’ and ‘quasielastic’
Event Generation

1) Choose $E_\nu$, flavor, and target nucleus from $(\sigma_{\text{tot}}, \phi, \rho, L)$
2) Choose interaction type $j$ from $\sigma_{\text{tot}} = \sum \sigma_j$
3) Choose kinematics $(x,y)$ from cross section model for $\sigma_j$ (with nuclear mods)
4) Determine particles in hadronic system (inside the nucleus)
5) Propagate particles in hadronic system through the nucleus, decay
Physics Models

Cross Section Model
1. Quasi-elastic: form factors
2. Resonance production: model choice, form factors
3. Non-resonant Inelastic: transition to DIS

Nuclear Cross Section Model
1. Coherent production
2. Modifications due to Fermi motion, nuclear binding, shadowing, N-N correlations…

Free nucleon cross sections → Nuclear cross sections
Free nucleon hadronization → Hadronization in nuclei

Hadronization Model
1. Resonance states: C-G coefficients
2. Non-resonant inelastic: string-based (JETSET), phenomenological models

Hadronization Model in Nuclei
1. Hadron formation zones
2. Hadron re-interactions in the target nucleus
Challenges – Cross Sections

Previous experiments (pre 2000) focused on 3 regimes:

- Quasi-elastic scattering (red)
- Delta Production (green)
- “safe DIS”: $Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$ (blue)

Large fraction of events in the few-GeV regime important to oscillation experiments are in the “mystery” region in terms of detailed knowledge of the interaction mechanisms.

Free nucleon scattering models:
- DIS low $Q^2$ modeling
- resonance modeling
- DIS / resonance transition region
Challenges - hadronization

For few-GeV neutrinos a large fraction of data come from non-resonant inelastic states which have invariant masses too low to be comfortably handled by standard packages like JETSET. (45% of events for $E_\nu = 3$ GeV).

Tuning done to bubble chamber experiments, where measurements of charged hadrons was easier than neutral hadrons.

“Gap” in a key area - neutral pion measurements from free nucleons at low invariant mass.

Challenges – Nuclear Physics

Fermi gas, spectral functions, other nuclear models.

*Effects of short and long-range correlations, MEC, 2p-2h processes*

Effects of final state interactions, intranuclear rescattering…

Modifications of structure functions (shadowing, EMC effect).

![Graph showing shadowing and anti-shadowing effects](image-url)
Where are the events?

Kinematical coverage

JPARC neutrino beam @ nd280 site

- W=4 GeV
- W=2 GeV
- W=1.2 GeV

transition-"DIS"

QEL

RES

Q2=1 GeV^2

lowQ2-DIS

Safe-DIS

(W>2, Q2>1)
Validation and Tuning

Neutrino Event Generators are tuned and validated using a wide variety of experimental data: neutrino data, charged lepton data, hadron scattering data, photo-production data all have relevance.


Data from R.D. McKeown et al., PRC 24 (1981) 211.
Oscillation experiments and $\nu$ physics models

**Cross section models:**
- Low $Q^2$ DIS / transition region
- NC
- $\sigma_{1\pi}/\sigma_{qel}$
- Coherent production
- Charm production
- Hadronization modeling

**Nuclear model:**
- Low $Q^2$ scattering
- FSI - topology changes
- FSI – effect on calorimetry

**Misc:**
- Rare electron-like processes
- Tau polarization
- $\Delta S=1$ anti-neutrino modes

**MINOS:** $\nu_\mu$ disappearance

**K2K:** $\nu_\mu$ disappearance

**miniBoone:** $\nu_e$ appearance

**NoVA/T2K:** $\nu_e$ appearance

**CHORUS/OPERA:** tau appearance

**NOMAD:** tau appearance

**Future multi-purpose expt**
- (e.g. SUSY proton decay)
Build on success of FLUKA: Over 2000 users in cosmic ray physics, accelerator design, particle physics detector simulation, shielding design, dosimetry, medical applications…

Based on original and well-tested microscopic models, minimizing free parameters. An integrated set of physics models – not a toolkit. Correlations preserved within interactions and among shower components.

The same models should be valid in neutrino interactions.

Double differential $\pi^+$ production for $pC$ interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)
Neutrino generators in FLUKA

QEL included since 1997
NUX-FLUKA (A. Rubbia): DIS only, for ICARUS collaboration.

Work on a DIS generator (NunDIS) and resonance production (NunRES) generator totally embedded in FLUKA started around 2005, available now in beta version in the standard FLUKA 2008 release.

GRV98-LO with extrapolation to $Q^2=0$

$$F_i(Q^2, x) = \frac{2Q^2}{Q_0^2 + Q^2} F_i(Q_0^2, x)$$

Resonance production based on Rein-Sehgal, with non-resonant component from NunDIS.

Hadronization using FLUKA routines. Recent improvements include a new treatment for low mass states, improving agreement with single pion data.

Transition fro RES to DIS: linearly transition in $\sigma$ as a function of $W$

To be used by ICARUS.
Users: T2K, MINOS, Minerva, NOVA, ArgoNEUT, microBoone, EU Lar R&D.
QEL: BBBA05 FF, $M_A$ is 0.99 GeV/c^2
Resonance: Rein & Sehgal ($K, \rho, \eta$ production, $\Delta N \gamma$)
Coherent-$\pi$: Rein-Sehgal
DIS: GRV94/GRV98 with Bodek-Yang
$1\pi$ and $2\pi$ channels tuned in transition region to electron scattering and neutrino data.
Nuclear Model: RFGM with NN correlations
Hadronization Model: AGKY – transitions between KNO-based and JETSET
Formation zone: SKAT $\mu^2=0.08$ GeV^2
Intranuclear Rescattering: cascade model
INTRANUKE-hA (S. Dytman, AIP Conf Proc, 896, pp. 178-184 (2007))
anchored to $\pi, p/n$-Fe data, scaled to all nuclei

Collaborations with theorists crucial: Alvarez-Ruso, Benhar, Paschos
**Coming in GENIE 2.8.0:**

INTRANUKE-hN (S. Dytman, NuINT11)

Full INC code: 2 and 3-body cross sections +
Fermi motion, extensive use of PWA data (SAID)

Goal is to describe $\pi, p, n, K$ in nuclei up to 2 GeV KE

Comparisons to hundreds of hadron-nucleus distributions

Numerous developments over the past several years have focused on software infrastructure needed by experimental users.

**Flux Drivers**

- Speed optimizations when generating events over complex detector geometries with neutrinos drawn from beam-line simulation ntuples.
- Inclusion of atmospheric neutrino flux drivers.

**Event Reweighting**

- Allows for efficient use of MC computing resources
- Evaluation of systematic errors

*Dobson and Andreopoulos, Acta Physica Polonica B40:9, 2613 (2009).*
NEUT

*Primary author: Y. Hayato*


Initially developed for Kamiokande, used by SuperKamiokande, K2K, T2K, SciBooNE.

Generates events on all target nuclei

QEL: dipole FF

Resonance: Rein & Sehgal, including
  - lepton mass effects
  - K, ρ, η production
  - Δ-Nγ decay

Coherent-π: Rein-Sehgal

DIS: GRV94/GRV98 with Bodek-Yang

All 1π resonance-produced for W<2 GeV/c²

Nuclear Model: RFGM Smith-Moniz

Formation zone: SKAT \( μ^2 = 0.08 \text{ GeV}^2 \)

Intranuclear Rescattering: cascade model

\( p_\pi < 500 \text{ MeV/c} \): radius and momentum dependent mfp
  - \( k_F \) has radius dependence

Kinematics from phase shift analysis of π-N scattering

\( p_\pi > 500 \text{ MeV/c} \): π-N σ used, multi-π prod taken from data
NC Elastic Scattering Cross Section
- Calculated from form factors, BBBA05
- Spectral function calculation for nuclei

Gamma Ray Emission from $^{16}$O
- Recent results from (e,e’p) experiment
- Energy of $\gamma$ from excited state
  (K. Kobayashi et al., nucl-ex/0604006)
- Energy of $\gamma$ following pion absorption
  (H.D. Engelhardt et al., NPA258, 480 (1976))

$\pi$ Interactions in Nuclei
- Tune pion mean free paths in nucleus using pion scattering data, density dependence from the model of Salcedo, Oset, Vincente-Vacas, Garcia-Reno
- Comparisons with $\pi$ scattering data and $\pi$ photo-production data.
- Incorporate model for nucleon ejection after pion absorption, multiplicities and charge determined from experimental data
  (Rowntree et al., Phys. Rev. C60 (99) 054610)
Originally developed for IMB, used also by SuperKamiokande, MINOS, MiniBooNE, ArgoNEUT.

QEL: BBA03 FF, $M_A$ is 1.103 or 1.234 GeV/c$^2$
Resonance: Rein & Sehgal formalism, including
  - Interference between resonances
  - $K, \rho, \eta$ production
  - $\Delta-N\gamma$ decay
Coherent+diffractive $-\pi$: Rein-Sehgal
DIS: Bodek-Yang modification
LUND-based hadronization (KNO-based if fails)
Nuclear Model: RFGM Smith-Moniz ($\kappa$)
Intranuclear Rescattering: cascade model
  - Measured cross sections and angular distributions are used for p-N and N-N reactions.
  - Nuclear de-excitations from $^{16}$O and $^{12}$C simulated.
Many recent MiniBooNE improvements:

- Parameter ($\kappa$) to control low $Q^2$ suppression of QEL
- Adjustment of coherent/resonant $\pi$ production
- Incorporation of updated vector and axial-vector form factors in the Rein-Sehgal model for pion production (including modern $g_A$)
- Added non-isotropic Delta decays
- De-excitation photon emission model for carbon
- Added Delta radiative decays including invariant-mass dependent branching fraction
- Added reweighting capabilities within MiniBooNE MC
- tuned final state interaction model for pion propagation (namely, pion absorption and charge exchange cross section normalizations) based on external pion-carbon data
First neutrino event generator to be developed by a theory group (Wroclaw University).


Careful comparison between PYTHIA fragmentation and experimental data.

Implementation of Spectral Functions as an alternative to the Fermi Gas model.

Intranuclear cascade modeling:
• Uses the model of Oset in the Delta region
• Work underway on formation zones

Efficient detector interface (T2K ND280).
GiBUU

Primary Authors: T. Leitner, O. Buss, U. Mosel, L. Alvarez-Ruso

Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) is a semiclassical transport model in coupled channels. Takes into account numerous nuclear effects: local density approximation, mean-field potentials and in-medium spectral functions.

Extensively checked against data for heavy-ion collisions, eA, γA, pA, πA.

Is being extended to MINOS/OPERA energies.

QEL, Δ, 13 N* and non-resonant single-pion channels. Recent electron scattering data used for state-of-the-art parametrizations of vector form factors, axial refit to neutrino-scattering data.

Involves solving a set of coupled 8-dimensional integral-differential equations. → speed implications.
Details Matter!

A standard combination: Llewellyn-Smith + Rein-Sehgal + Bodek-Yang

Quasi-Elastics:
Which form factors?
Value of $m_A$?

Resonance Production:
Which form factors?
Value of $m_A$?
interference between resonances?
Updated to include lepton mass terms and psuedo-scalar terms?

Non-resonant Inelastic model:
Construction of $x F_3$
Consistent use of $x_{HT}$
Low $Q^2$ behavior of terms like $F_1 = F_2 (1 + 4 M^2 x^2 / Q^2) / (2x(1 + R))$
Tuning of total cross section at high energy to match world data

Combining Resonant and DIS models to avoid double counting!

Conclusions

Generators on the market today – FLUKA-NuNDIS, GENIE, GiBUU, NEUT, Nuance, and NuWRO, while they share some common ingredients, bring a variety of different physics models and software engineering approaches to the task of neutrino event generation.

**Future challenges and opportunities:**

Slowly incorporating what has been learned in electron scattering: moving away from fast, venerable models, like the FGM or Rein-Sehgal model.

Missing processes? np-nh excitations produce sizable cross section!?

Balancing speed, experimental convenience and accuracy

Upcoming experiments (MINERνA, T2K ND, ArgoNEUT, OPERA, MicroBooNE…) will be vital to improvements.

Bridging the gap between theory and experiment:
- Having code provided by theorists
- Experimental results presented with a minimum of model-based correction
Backup Slides
Quasi-Elastics

Identify “QEL-like" events:

\[ \nu_\mu + n \rightarrow \mu^- + p \quad \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]

1-track events
2-track events
2\textsuperscript{nd} track proton-like

\[ E_v = \frac{M E_\mu - m_\mu^2 / 2}{M - E_\mu + p_\mu \cos \theta_\mu} \]

\[ Q^2 = -2E_v(E_\mu - p_\mu \cos \theta_\mu) + m_\mu^2 \]

Numerous measurements from the era of bubble chamber experiments with hydrogen and deuterium targets painted a fairly consistent picture:

\[ M_A = 1.026 \pm 0.021 \text{ GeV} \]
Quasi-Elastics

**Fast-Forward to Today:**
Low $Q^2$ - nuclear effects

K2K: $M_{A}=1.20\pm0.10$ GeV

miniBoone: $M_{A}=1.23\pm0.20$ GeV

MINOS (Preliminary) Effective $M_{A}^{QE} = 1.26^{+0.12}_{-0.10} \text{ (fit)}^{+0.08}_{-0.12} \text{ (syst)}$ GeV
Quasi-Elastics

OLD vs. NEW (carbon): NOMAD

$M_A = 1.05 \pm 0.02 \text{(stat)} \pm 0.06 \text{(syst)} \text{ GeV}$

Consistent with value from antineutrinos and $Q^2$ shape fit.

V. Lyubushkin, NuI0T09  \textbf{arXiv:0812.4543}

$M_A^{\text{eff}} = 1.35 \pm 0.17 \text{ GeV (stat+sys)}$

$\kappa = 1.007 \pm 0.007 \text{ (stat+sys)}$

$\chi^2/\text{ndf} = 47.0/38$
Quasi-Elastics

If this discrepancy is a nuclear effect, it has some curious features:

- Affects shape of $Q^2$ distribution at moderate $Q^2$ values.
- Increases total QEL-like cross section.
- Similar sized discrepancy for iron and carbon.
- Less evident in antineutrinos at higher energy (NOMAD).
- Less evident in neutrino-carbon at higher energy (NOMAD, but with different selection).
Q: In neutrino-nucleus scattering there are processes which do not occur on free nucleons!

Martini and Ericson,
Since final physics results can be sensitive to the modeling, the evaluation of physics-related uncertainties as manifested in the simulation are a crucial and time-consuming part of every analysis.
Evaluating Systematic Errors

Experiments have devised a number of different methods for determining the systematic errors associated with model uncertainties. Assuming that the uncertainty in a particular model aspect has been estimated one can:

1) Generating entirely new Monte Carlo samples with the model shifted by some amount (1 \( \sigma \)). Analyze data with the new Monte Carlo to determine the change in the result.

2) If the effect of the model change is in a parameterization in one of the models, and one can quickly calculate the probability for generating a particular event given a particular model, one can reweight the standard Monte Carlo sample to achieve the same result as in (1).

3) Perform other estimates based on parameterizations of detector response ‘fast MC’.

4) Estimate systematic errors using data-based techniques from independent samples.
MINOS: $\sigma$ Model Uncertainties

Overall Model Uncertainties, including nuclear effects:
- Total cross section: 3.5%
- $M_A$: 15% for both quasi-elastic and resonance production
- Transition region parameters: $r_{ij2} \pm 0.1$, $r_{ij3} \pm 0.2$.

Anti-neutrino/neutrino cross section uncertainty:
- overall: 4%
- QEL/RES: 8%
- Transition region parameters: $r_{132} \pm 0.2$, $r_{i42} \pm 0.2$.

$\nu_\tau$: Pseudo-Scalar Form Factor

$$F'_p = (1.05 + 0.095Q^2)F_p$$

For these tasks the input of theorists, and the NuINT series, have been vital!
Example: NC $1\pi^0$ topology error envelope

200k evts (before truth selection) @ 1.5GeV on O16

Select single $\pi^0$ topology:
- 14,783 before FSI
- 12,538 after FSI

Scan intranuke/hA phase space:
- Treat Pion and Nucl fates independently.
- Treat mfp parameter separately.
- Add above three in quadrature.

(\sim 170 parameter configs)
Flux and Detector

C. Andreopoulos

Neutrino generator's job is:
Generate an event once it is handed over an initial state
\((\nu + \text{target, at a given energy})\)

The problem here is how to select that initial state (and take into account its energy and spatial dependence)

Eg in MINOS:
6 neutrino flavours \(\times\) ~60 (!) isotopes in detector geom = 360 possible initial states

BTW, the generator should handle all these initial states!

Event generation:
A complicated convolution of things:

Complicated spatial distribution of nuclear targets

Neutrino flux that changes across the detector

GENIE: 5 events/sec for ND280
70 events/sec for simple initial state \((E_\nu = 1 \text{ GeV})\).
9. Deep Inelastic scattering \( \nu + N \rightarrow l + \text{hadrons} \)

Avoid double counting: the resonance region to the DIS region

\( W < 2\text{GeV} \):
Restrict # of mesons to be larger than 1
Exclude 1 meson production
by using multiplicity function \( \langle n \rangle(W) \)
Because non-resonant background is already included in the single \( \pi \) production.

Multiplicity is determined based on the experimental result.
(There are recent reports from CHORUS collaboration.
\[
\langle n_\pi \rangle = 0.09 + 1.83 \ln(W^2)
\]

\( W > 2\text{GeV} \):
Use PYTHIA to generate vectors.

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<td># of ( \pi = 1 )</td>
<td>Rein &amp; Sehgal</td>
<td>PDF + Custom kinematics (Bodek &amp; Yang Corr.)</td>
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As for the parton distribution function, we use the correction suggested by Bodek and Yang.
Single pion production cross section has a form

\[
\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^{\Delta}}{dW} \left( 1 - \alpha(W) \right) + \frac{d\sigma^{DIS}}{dW} F^{SPP}(W) \alpha(W)
\]  

\[
\alpha(W) = \Theta(W_{min} - W) \frac{W - W_{th}}{W_{min} - W_{th}} \alpha_0 
\]

\[
+ \Theta(W_{max} - W) \Theta(W - W_{min}) \frac{W - W_{min} + \alpha_0(W_{max} - W)}{W_{max} - W_{min}}
\]

\[
+ \Theta(W - W_{max})
\]

We observe that the best values of parameters are

\[
W_{min} = 1.3 GeV, \quad W_{max} = 1.6 GeV
\]

Non-resonant background is simulated by appropriate DIS contribution. \(\alpha_0 \in (0, 0.3)\) (depending on the channel)
Intranuclear Rescattering

INTRANUKE-hA


1. Transport hadrons through the nucleus to decide whether or not they interact. This transport is done with a realistic nuclear model and $\pi N$ total cross sections. Roughly account for quantum mechanical nature of scattering at low momentum by $R_{\text{eff}} = R_{\text{nucl}} + 0.5 \cdot \lambda$.

2. If an interaction occurs, decide what kind. (“fate”: elastic, charge exchange, inelastic, absorption, or $\pi$ production). These “fate probabilities” for $\pi$-Fe interactions are taken from data.

3. For each fate, determine the outgoing particles and their 4-momenta.

Formation Zones: SKAT parametrization: formation time= 0.342 fm/c.

V. Ammosov, NuINT01.
GENIE: Transition Region

Tune model to give the correct single pion cross section and the correct total cross section (as determined by integrating the DIS model alone).

\[
\frac{d\sigma}{d\theta dE'}^{DIS} = \frac{d\sigma}{d\theta dE'}^{B-Y} \Theta(W_{cut} - W) \sum_{k=1}^{10} f_k
\]

\[f_4, f_5 \ldots = 1\]

\[f_2\] determined from single $\pi$ fit

\[f_3\] determined from
11. Nuclear effects (Final state interactions of hadrons)

Checked with $\pi^+^{16}$O scattering or photo - $\pi$ production experiments.

Monte-Carlo simulation reproduces various distributions quite well.

Comparison with $\pi^+^{16}$O scattering experiment

- (a) $p_\pi = 213$ MeV/c
- (b) $p_\pi = 268$ MeV/c
- (c) $p_\pi = 353$ MeV/c
“quasielastic” and “neutrino”

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