The GENIE *
Neutrino Monte Carlo Generator
(a status update)

Costas Andreopoulos
45th Karpacz Winter School in Theoretical Physics
Neutrino interactions: from theory to Monte Carlo simulations
Feb 10, 2009

(*) http://www.genie-mc.org
It has been a fantastic school!

Students worked hard. They learnt how to use the codes and analyse event samples and performed the first cross-generator (GENIE/NEUT/NUANCE/NuWRO/FLUKA) comparisons we have seen for years!

We had the chance to:
- get feedback from students
- exchange notes with other experts

Very instructive for all of us.

Jan, Danuta, Artur, Cezary, all

THANK YOU!
Outline

• GENIE – Overview (& a bit of history)

• Current production release (v2.4.2): Physics & capabilities

• Improvements in upcoming releases
A bit of history

GENIE evolved from *neugen* / Many models within GENIE have long history.

**Neugen originates from the Soudan2 expt.**

Soudan2: A proton decay experiment in the ~80's
Back then: vA a background.

**Heavily re-developed for MINOS analyses**

Cross section model partially re-written / re-tuned.
Hadronic simulations almost completely re-written.
Many year*FTE effort!
NuINT01 / 'Call to arms'

[early ~2000]

- Entering a precision era in neutrino physics:
  Neutrino interaction uncertainties start to matter!
- Also, changes in software devel paradigm:
  C++ expt. offline softw., Geant4, ROOT

Many (~ 6+) major fortran generators in use.
Developed by small groups / very experiment-specific.
Mostly 'similar' but with no trivial / not understood differences.

For the longer term, the efforts of many will be required to produce a carefully-tested and universal model of neutrino interactions. In addition to purely technical considerations, theoretical guidance and new experimental data will be vital. Still, with the success of NuINT’01 and the promise of renewed and expanded collaboration punctuated and reinforced by future NuINT workshops, it is not too optimistic to hope that within a relatively few years, members of the neutrino community will be able to achieve a truly unified picture of neutrino physics.

From D.Casper's NuINT01 conference proceedings
GENIE

Generates Events for Neutrino Interaction Experiments

A Neutrino Monte Carlo Generator (and extensive toolkit)

Validity:
from few MeV to many hundreds of GeV / handles all nuclear targets

Large scale effort:
110,000 lines of C++

Modularity / Flexibility / Extensibility:
Models can be swapped in/out. Models can be easily reconfigured. All done consistently.

Licensed:
To ensure openness and synergies between experiments

State of the art physics:
GENIE has lots of developers & support. Draws heavily from many people's expertise

Full list of collaborators at http://collaboration.genie-mc.org
Who is using GENIE now?

Primary clients are the current / near future medium energy experiments:

- T2K
  - nd280
  - SuperK
  - ingrid
- MINOS
- NovA
- MINERvA
- ArgoNEUT
- MicroBooNE
- EU LAr R&D projects
- ...

After ~4 yrs of development (from scratch) now have a nearly universal neutrino physics MC (an important tool for physics exploitation for the next decade++)

GENIE already interfaced to most of these expts & used in physics MC prod.

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Official GENIE web site

You can find:

- Physics documentation
- A user manual
- Release tables
- Download instructions
- Installation instructions
- Doxygen documentation
- News feeds
- ...
- ...

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Physics in GENIE v2.4.*
Neutrino interaction simulation steps

Neutrino interaction modelling can be broken-up in the following 4 pieces:

- **nuclear model**
- **primary interaction (cross section)**
- **hadronization**
- **intranuclear hadron transport**

Note: A simplified picture

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“Divide & conquer”

numu+O16 - All processes

Kinematical coverage
JPARC neutrino beam @ nd280 site

transition-”DIS”

Q2=1 GeV^2

Safe-DIS
(W>2, Q2>1)

lowQ2-DIS

W=4 GeV

W=2 GeV

W=1.2 GeV

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Putting everything together

\[ \sigma_{\nu N}^{\text{tot}} = \sigma_{\nu N}^{(Q)ES} \oplus \sigma_{\nu N}^{1\pi} \oplus \sigma_{\nu N}^{2\pi} \oplus \ldots \oplus \sigma_{\nu N}^{1K} \oplus \ldots \oplus \sigma_{\nu N}^{\text{DIS}}. \]

numu+Fe56, Ev = 5 GeV

See Hugh's talk on the details of modelling the transition region (non-resonance background)
The GENIE cross section model

v2.5.1 free nucleon cross section prediction vs B/C data & estimated uncertainty

Sam Zeller. circa-2002 / Cross-generator comparisons

- QEL: Llewellyn-Smith with BBBA05 elastic f/f
- RES: Rein-Sehgal / incoherent / 16 resonances up to W=2GeV
- Non-resonance background
- COH pi production: Rein-Sehgal / includes updated PCAC
- DIS: latest Bodek-Yang
  - Including parametrization of the longitudinal structure function FL
  - Including NuTeV parameterization of nuclear effects

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Free-nucleon cross section → Nuclear cross sections
Fermi Gas model in GENIE

Example:
Bound (off the shell) nucleon mass in Fe56
Off-shell kinematics handed a-la Bodek

\[ p = -p_F \]
\[ E = \sqrt{M_{A-1}^2 + p_F^2} \]
\[ E = M_A - \sqrt{M_{A-1}^2 + p_F^2} \]
Moving to a spectral function implementation

Option currently available in GENIE

Switch to a S/F momentum profile and use the average binding energy at each momentum
Moving to a spectral function implementation

Measurable effect to observable distributions

Reconstructed energy shifts of the order of few x 10 MeV

Distorts final state lepton kinematics

numu+C12, Ev=800MeV
Moving to a spectral function implementation

This workshop has catalysed the process

- Enlightening talks by Omar Benhar during the school

- Analytical S/F's for C,O,Ca,Ar,Fe available by Artur Ankowski

- Figuring out how to do inclusive e- scattering in GENIE (for model validation)
More 'rare' processes included in GENIE

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Coherent pion production

Cross section computed as in Rein, Sehgal, hep-ph/0606185

Including the PCAC formula with the non-vanishing muon mass causing destructive interference between AV and PS amplitudes.
**ve- elastic**


**Inverse muon decay**

QEL charm production

S.G.Kovalenko, Sov.J.Nucl.Phys.52:934 (1990) re-scaled to NOMAD limit

\[ \nu + n \rightarrow l^- + \Lambda_c^+(2285) \]
\[ \nu + n \rightarrow l^- + \Sigma_c^+(2455) \]
\[ \nu + p \rightarrow l^- + \Sigma_c^{++}(2455) \]
**DIS charm production**

Aivazis, Chang and Tung (or a slow rescaling) model for the Inclusive Cross Section for neutrino LO Charm Production

PYTHIA and/or other decayer

Hadronic Remnants: PYTHIA and/or hadronization

PDFs from PDFLIB & BY d/u corrections

Peterson / Collins-Spiller Fragmentation Functions & pT from an exp. distribution

Experimentally known Charmed Fractions ($D^0, D^+, D_s^+, L^+$)

$R = \frac{\sigma_{(charm)}}{\sigma_{(CC)}} \%$

$<m_{charm}> = 1.74$ GeV

$<m_{charm}> = 1.71$ GeV

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Hadronic simulations in GENIE

>>>
Hadronization modelling

(v, l) 
Z, W

Hadronization modelling
(= v-induced primary hadronic shower modelling)

nuclear model
primary interaction (cross section)

hadronization

intranuclear hadron transport

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Hadronization modelling

- Standard tools of the trade (PYTHIA/JETSET, HERWIG) don't work at the low hadronic invariant masses which are of interest to us.

- Important to get that right.
  - Determines shower shapes & particle content
    - Eg, electromagnetic (π0) fraction of the shower -> nue backgrounds
    - Eg, CC/NC shower shapes -> CC/NC PIDs
  - Used to decompose inclusive vN->lX to exclusive contributions
    - Eg, Contribution of 1 π DIS channels in RES/DIS transition region
The GENIE hadronization model

At low hadronic invariant masses:
• severe kinematical constraints – limit dynamics
• effective model using KNO scaling and data-driven modelling of average multiplicities, forward/backward asymmetries, pT-dep. Etc...

At high hadronic invariant masses:
• rich dynamics
• using JETSET model
• tuned energy cutoff, pT, ssbar suppression (as in NUX)
• not really relevant at t2k energies

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The GENIE hadronization / AGKY low-W model

Get average multiplicity from empirical parameterization

\[ <n> = a + b \cdot \ln W^2 \]

Generate the actual multiplicity using the KNO scaling law:

\[ <n> P(n) = f \left( \frac{n}{<n>} \right) \]

(taking into account that \( <n_{\text{neutral}} > = 0.5 \times <n_{\text{ch}} > \))

Simple arguments (charge conservation, quark model) to derive particle spectrum
The GENIE hadronization / AGKY low-W model

At the hadronic CM, the nucleon direction be should be correlated with the diquark direction (opposite to the direction of the momentum transfer $q$)
The GENIE hadronization / AGKY low-W model

Building in experimental data on nucleon $p_T$ and $x_F (= p_L/p_L^{max} = 2^*p_L/W)$

Fig. 11: $x_F$ normalised distributions for protons ($\nu$) WA24 data and lambda's ($\bar{\nu}A21$ data, Bossetti et al, Nucl. Phys. B194, 1 (1982).
The GENIE hadronization / AGKY low-W model

The GENIE hadronization / AGKY low-W model

\[ p^4_{\text{meson `remnants'}} = p^4_X - p^4_{\text{nucleon from target fragments}} \]

Meson 4-momenta:

- Boosting to the remnant hadronic system CM and performing a phase space decay.
- A pT-limited decay to match experimental pion PT distribution.
The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data examples:

**Charged pion multiplicities**

**Charged pion dispersion**

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The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

**Neutral / charged pion correlation**

![Graphs showing neutral/charged pion correlation for different energy ranges](image-url)
The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

Normalized topological cross sections

For more data/mc comparisons see GENIE-PUB/2007/002 and T.Yang’s talk/proceedings at NuINT07

The model and its shortcomings are very well understood. Improvements for low multiplicity ($n=2$) hadronic systems under way
Hadronization in nuclei: Formation zone

SKAT parameterization:

\[ f_{\text{zone}} = \frac{P \times c t_0 \times m}{m^2 + K \times P_T^2} \]

Hadron momentum

Transverse hadron momentum

In v2.4.*: \( K=0, \ c t_0 = 0.342 \ \text{fm} \)

No intranuclear rescattering within formation zone

(SKAT) model dependence
Intranuclear hadron transport

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The GENIE hadron transport modelling

Transport primary (and secondary, tertiary, ...) hadrons out of the hit nucleus. Allow hadron interactions in the nuclear matter. Predict particle spectrum & particle 4-momenta “outside” the hit nucleus.
Intranuclear rescattering

\[ \text{nu}_\mu + \text{C12} \]
\[ E_v = 1 \text{ GeV} \]

Most particles (2/3) re-interact

Particles re-interacting

Particles escaping with no re-interaction
Intranuclear rescattering effects

[shown for an nd280 event sample]

Reweighting tool to provide error estimates for these predictions. To be used for physics analysis. See next talk.

Severe effect on observed topologies
The GENIE hadron transport modelling

Currently **have 2 alternative models** (using different techniques) –

Development of both is **led by Steve Dytman**

**Intranuke / hA**
(effective MC)

Anchored to a large body of experimental data (including hadron+nucleus data)

available since 2.0.0

**Intranuke / hN**
(true cascade MC)

Builds everything up from hadron-nucleon xsecs

In advanced development stage to become available soon

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The GENIE hadron transport modelling (INTRANUKE/hA)

Stepping primary hadrons within the target nucleus

\[ P_{\text{rescat}}^h = 1 - P_{\text{surv}}^h = 1 - \int e^{-r/\lambda} \left( \vec{r}, h, E_h \right) dr \]
The GENIE hadron transport modelling (INTRANUKE/hA)

- Hadrons stepped by 0.05 fm at a time
- Hadrons traced till they reach $r_{\text{max}} = N \times R_{\text{nucl}} = N \times R_0 \times A^{(1/3)}$ ($R_0 = 1.4$, $N = 3.0$) so as to include the effects of the tails (Fe56: $R_{\text{nucl}}=5.36\text{fm}$, $r_{\text{max}}=16.07\text{fm}$)

The nuclear density distribution is `stretched' by $n$ times the de Broglie wavelength of the tracked particle ($n=1$ for nucleons, $n=0.5$ for pions).
The GENIE hadron transport modelling (INTRANUKE/hA)

INTRANUKE/hA considers 5 types of 'hadron fates' (some may include many channels)

- **elastic**
  - Pion deflected. Its kinetic energy stays the same.

- **inelastic**
  - Pion deflected. Its kinetic energy is degraded.

- **charge exchange**
  - ~ Similar fates for nucleons

- **pion production**
  - followed by emission of low energy nucleons

- **absorption**

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The GENIE hadron transport modelling (INTRANUKE/hA)

Fractions taken mostly from data

Final state hadron 4-momenta generated using built-in expt distributions and phase space decays.

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Nuclear excitations

Included in an ad-hoc way
Only for O16
INTRANUKE/hA Data/MC comparisons

Much effort went into validation – utilising experience from non-neutrino probes, mainly hadron+A reactions

Lot of effort in tuning mean free path & including the elastic contrib – difficult to model in context of INC

\[
\text{total} = \text{reaction} + \text{elastic} \\
\text{reaction} = \text{cex} + \text{inel} + \text{absorption} + \text{pi prod}
\]

Then, components modelled directly from data – requires total xsec to be modelled correctly first

`MC experiments`: throw hadrons into nuclei, 'measure cross sections' and compare with data.

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GENIE models – A summary

• Cross section model
  • QEL: Llewellyn-Smith with any of Sachs/BBA03/BBA05 elastic f/f
  • RES: Rein-Sehgal
  • COH pi production: Rein-Sehgal / includes updated PCAC
  • DIS: latest Bodek-Yang
    – Including parametrization of the longitudinal structure function FL
    – Including NuTeV parameterization of nuclear effects
  • Many other more rare channels: DIS & QEL charm / ve- elastic / inv.mu-decay/...

• Nuclear model
  • Fermi Gas model
  • Including high momentum tail due to N-N correlations modelled from eN data
  • “Standard” FG prescription for off-shell kinematics...

• Transition region cross section modelling
  • Non resonance background modelled from DIS & AGKY hadronization
  • Tuned to the world exclusive multi-pion cross section data

• Neutrino-induced primary hadronic shower modelling
  • AGKY
  • Effective KNO-based hadronization at low-W
  • Switching gradually to PYTHIA/JETSET at high-W
  • SKAT-type formation zone parametrization

• Intranuclear hadron transport
  • INTRANUKE/hA model
  • Anchored to a set of hadron+Fe56
  • Scaled to all nuclei

Fairly standard at all ν MCs
Careful implementation as MINOS spans a huge kinematical region (E ~ <1 to >100 GeV)

Unique to GENIE

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GENIE includes an extensive toolkit

Facilitate experiments in

- Propagating vA uncertainties in physics measurements
- Generate realistic MC for complex experimental situations
Event Reweighting

Ma = 1.00 GeV
pi absorption = 20%
...
...

Ma = 1.20 GeV
pi absorption = 40%
...
...

See next talk by Jim Dobson (Imperial)
Handling complex event generation cases

Using off-the-shelf components

Event generation:
A complicated convolution of things:

Complicated spatial distribution of nuclear targets (~100)

Neutrino flux that changes across the detector

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Improvements in upcoming releases

Much faster geometry navigation code.

Support for event generation in user-defined `fiducial volume' not necessarily corresponding to any actual geometry volume.

Including specialised drivers for NuMI beam-line experiments (as we already did for the JPARC expts)
Further physics improvements
In upcoming releases

>>>>

Many important changes are in the pipeline
New intranuclear cascade

See Steve's talks during the school

New hN model successful in describing a broad set of features.

Some issues to resolve.

Development ~80% done.

hN can feed-back to the faster & reweightable hA model

Updated nuclear model

Full spectral function implementation – using de Forest kinematic prescription
Using C,O,Ca,Ar,Fe S/F parameterizations by Artur Ankowski
New reaction channels

Adding coherent diffractive scattering in v2.6.0

Adding coherent elastic scattering in v2.8.0
Short and long range correlations

20%
- 18% np
- 1% nn
- 1% pp

Near future improvements cont’d

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Some changes to the B/Y structure functions & R/S form factors. **Global cross section model retuning.**

Improvements at AGKY strange particle production

Improvements at AGKY fwd/bwd asymmetry

Improvements at angular distributions of resonance decays

… ... ...
Summary

Heavily validated and robust comprehensive MC generator

Nearly universal!

*Provides high quality simulations for T2K, MINOS, MINERvA, NOvA*

Roadmap to v3.0.0

*Advancing simulations beyond current level*  
*(S/F nuclear model, state-of-the art hadronization & cascade models, comprehensive list of simulated processes, short/long range correlations, ...)*

For: Final MINOS analyses, first T2K analyses, first MINERvA analyses, ...