The GENIE *
Neutrino Monte Carlo Generator

(*) http://www.genie-mc.org

Costas Andreopoulos
GDR Neutrino – LPNHE Paris, April 28, 2009
Outline

• GENIE Project overview / history

• Physics in current production release

• Improvements in upcoming releases

• Interaction uncertainties / systematics – not to be covered in this talk
The origins

GENIE evolved from primarily from **neugen**
(G.Barr, E.Edgecock, H.Gallagher, A.Mann, G.Pearce et al.)

**Neugen developed for the Soudan2 expt.**

Soudan2:
A proton decay experiment in the ~80's

Back then:
vA a background!

Many models within GENIE have long development history and encapsulate significant expertise.
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 NUIN'T workshops, it is not too optimistic to hope that within a relatively few years, members of the neut-

[From D.Casper's NuINT01 conference proceedings]
GENIE Project

**Generates Events for Neutrino Interaction Experiments**

A Neutrino Monte Carlo Generator (and extensive toolkit)

- ~120,000 lines
- Written in C++ following modern, OO design methodologies
- State of the art physics

Full list of collaborators at http://collaboration.genie-mc.org

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Heavily re-developed for MINOS analyses

- Cross section model partially re-written / re-tuned.
- Hadronic simulations almost completely re-written.

Many year*FTE effort!
GENIE Users

Primarily, the current / near future medium energy (~1GeV) experiments:

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

GENIE is already integrated with all of these experiments and being used for physics studies.

On-going efforts to push validity range down to ~1 MeV (reactor, super-novae, SNS, ...)

Costas Andreopoulos, Rutherford Appleton Lab.
• GENIE: (Nearly) universal generator

• An important tool for physics exploitation for the next decade+

Please find more information at http://www.genie-mc.org

Register at the mailing-list and don't hesitate asking questions!
The GENIE toolkit

GENIE features an extensive toolkit, including tools for:

• Setting up realistic event generation jobs
• Propagating neutrino interaction uncertainties to physics analyses
Handling complex event generation cases

Event generation for realistic fluxes and detailed detector geometries using off-the-shelf components

Event generation:
A complicated convolution of flux (x) distribution of nuclear targets

Complicated spatial distribution of nuclear targets (~100)

Neutrino flux that changes across the detector
Event reweighing tools

For illustration:
NC1pi0 err envelope (Jim Dobson, CA, SD)

GENIE-based reweighing tools encapsulate significant expertise in quantifying neutrino interaction systematics (minos, t2k)
Physics in latest GENIE production release
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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Cross section model in GENIE

Current focus:

Ev from ~50 MeV to ~500 GeV
Quasi-elastic scattering

• Critical for current accelerator LBL oscillation experiments

• \( \sim 50\% \) of total CC cross section at \( \sim 1 \) GeV

Full kinematical reconstruction just by looking at the leptonic system:

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

\[
Q^2 = -2E_{\nu}\left(E_\mu - p_\mu \cos \theta_\mu \right) + m_\mu^2
\]
Quasi-elastic cross section

\[
\frac{d\sigma^{\text{QES}}}{dQ^2} = \frac{G_F^2 \cos^2 \theta_C M^2 \kappa^2}{2\pi E^2 \nu} \left[ A(q^2) + \left( \frac{s-u}{4M^2} \right) B(q^2) + \left( \frac{s-u}{4M^2} \right)^2 C(q^2) \right]
\]

\[A, B, C = f(F_A, Fv1, Fv2)\]

vector form factors: determined from e-N via CVC

dipole axial form factor:

\[F_A = g_A \left( 1 + \frac{Q^2}{M_A^2} \right)^{-2}\]
Elastic nucleon form factors

vN QEL xsec expressed in terms of vector & axial form factors

\[ F_V^1(Q^2) = \frac{G^V_E(Q^2) - \tau G^V_M(Q^2)}{1 - \tau} \]

\[ F_V^2(Q^2) = \frac{G^V_M(Q^2) - G^V_E(Q^2)}{1 - \tau} \]

CVC allows us to determine \( G_{ve}, G_{vm} \)

\[ G^V_E(Q^2) = G_{ep}(Q^2) - G_{en}(Q^2) \]

\[ G^V_M(Q^2) = G_{mp}(Q^2) - G_{mn}(Q^2) \]

Elastic form factor measurements:

- **Rosenbluth separation:**

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2 \theta_e}{4 E_e^3 \sin^4 \theta_e} \frac{\theta_e}{2} \left[ G_e^2 + \frac{\tau}{\epsilon} G_m^2 \right] \left( \frac{1}{1 + \tau} \right) \]

- **Polarization measurements:**

\[ \frac{G_e}{G_m} = - \frac{P_t}{P_t} \frac{E_e + E_e'}{2M} \tan \left( \frac{\theta_e}{2} \right) \]

- The 2 methods do not agree
- Polarization measurements seen as more reliable
Elastic nucleon form factors: Beyond the dipole ones

**BBA** fit based mostly on polarisation data (eg Budd / Bodek / Arrington. See hep-ex/0308005)

![Graph 1](image1)

![Graph 2](image2)

**[R.Bradford et al, NuINT05]**

- GENIE includes all Sachs, BBA2003 and BBA2005 parameterizations
- BBA2005 is the default.

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Resonance Neutrino-Production

\( \nu + N \rightarrow l + Resonance \)

- \(~30\%\) of the total CC xsec around \(~1~GeV\)
- A number of resonances is considered
- Mostly single-pion final states; but a multitude of states are possible.

The most widely used model for resonance production (D.Rein, L.M Sehgal, *Ann.Phys.*133, 79 (1981)) uses the FKR dynamical model (R.P.Feynman, M.Kislinger, F.Ravndall, *Phys.Rev.D* 3, 2706 (1971)) to describe excited states of a 3 quark bound system.

\[
\frac{d^2\sigma}{dW dq^2} \propto u^2 \sigma_L(q^2, W) + v^2 \sigma_R(q^2, W) + 2uv \sigma_S(q^2, W)
\]

Helicity Cross Sections \((L,R,S)\)

They depend on the details of the FKR model

Axial & Vector transition form factors:
assuming dipole form \(Q^2\) dependence

\[
G^{V,A}(Q^2) = \left(1 + \frac{Q^2}{4M^2}\right)^{1/2-n} \left(1 + \frac{Q^2}{M^2_{V,A}}\right)^{-2}
\]

\(M_v=0.84~\text{GeV/c}^2, M_A \sim 1~\text{GeV/c}^2 \pm 20\%\)
Resonance Neutrino-Production

Resonance excitation cross sections (as a function of energy / for muon neutrinos)

Single pion production cross sections

A \( \nu_p \rightarrow l^+ p \pi^+ \)

B \( \nu_n \rightarrow l^- n \pi^+ \)

C \( \nu_n \rightarrow l^- p \pi^0 \)

Include isospin amplitudes and 1\( \pi \) BR to weight the contribution of each resonance to exclusive single pion reactions

Can add coherently

For simplicity, many calculations add incoherently
Deep Inelastic Scattering

Differential cross section in terms of 5 structure functions:

\[
\frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M_N E}{\pi(1 + Q^2 / M_W^2)^2} \sum_{i=1}^{5} A_i (x, y, E) F_i (x, Q^2)
\]

where:

\[
A_1 = y \left( x y + \frac{m_\mu^2}{2 M_N E} \right),
\]

\[
A_2 = 1 - \left( 1 + \frac{M_N x}{2 E} \right) y - \frac{m_\mu^2}{4 E^2},
\]

\[
A_3 = \pm y \left[ x \left( 1 - \frac{y}{2} \right) - \frac{m_\mu^2}{4 M_N E} \right],
\]

\[
A_4 = \frac{m_\mu^2}{2 M_N E} \left( y + \frac{m_\mu^2}{2 M_N E x} \right),
\]

\[
A_5 = -\frac{m_\mu^2}{M_N E}.
\]

LAr images, courtesy A.Currioni

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Deep Inelastic Scattering / Structure functions

F2

xF3

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Bodek / Yang model

Based on LO cross section model with new scaling variable to account for higher twists and modified PDFs to describe low-Q2 data

\[
\xi_w = \frac{2x(Q^2 + M_f^2 + B)}{Q^2[1 + \sqrt{1 + (2Mx)^2/Q^2}] + 2Ax}
\]

\[
K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}
\]

\[
K_{valence}(Q^2) = \left[1 - G_D(Q^2)\right] \times \left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}\right)
\]

Fits based on GRV98LO and free nucleon charged lepton data

[|Bodek & Yang|]

[hep-ph/0411202]
Deep Inelastic Scattering / Nuclear corrections

[Graph showing data points and curves labeled with shadowing, anti-shadowing, and EMC.]
Kinematical coverage JPARC neutrino beam @ nd280 site

transition-"DIS" (non-resonance background)

Safe-DIS (W>2, Q^2>1)
lowQ^2-DIS

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

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Non-resonance bkg

Fraction of DIS 1\pi and 2\pi final states; with predicted kinematical (Q2,W) dependence

Added to resonance piece at W < 2 GeV

Fraction tuned to world's low multiplicity exclusive inelastic reaction data
Putting everything together

numu+Fe56, Ev = 5 GeV

resonance

“safe” and “lowQ2” DIS

GENIE

transition DIS

CC 1pi+

all sources

all resonances only

P33(1232) resonance only
Coherent meson 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.

For the time-being:

- Ignore coherent production of vector mesons
- Ignore coherent production of photons
- Ignore diffractive scattering
Charm production

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

**DIS**
M.A.G.Aivazis, F.I.Olness and W.K.Tung

![Graph showing charm production cross sections](image-url)
Neutrino-Electron scattering

**ve- elastic**

Fairly standard. Cross sections implemented as in W.J.Marciano and Z.Parsa, J.Phys.G: Nucl.Part.Phys.29 (2003) 2629. Radiative corrections currently neglected.

**Inverse Muon Decay**

D.Yu.Bardin and V.A.Dokuchaeva, Nucl.Phys.B287:839 (1987), includes all 1-loop radiative corrections
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

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Free-nucleon cross section $\rightarrow$ Nuclear cross sections
Fermi Gas model in GENIE

Example;
Bound (off the shell) nucleon mass in Fe56
Quasi-elastic cross section for nuclear targets

Off-shell kinematics

A suppression factor $R(Q^2)$, derived from an analytical calculation of the Pauli blocking effect, is included.
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 $\times$ 10 MeV

Distorts final state lepton kinematics

$\cos(\theta)$

numu+C12, $E_v=800$ MeV
Hadronic simulations in GENIE

>>>
Hadronization modelling

- \( \nu \)
- \( Z, W \)
- \( \nu, l \)

**Hadronization modelling**

(= \( \nu \)-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 (\(\pi^0\)) 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 pi DIS channels in RES/DIS transition region
The GENIE hadronization model

hep-ex/0904.4043

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.

At high hadronic invariant masses:
- rich dynamics
- using JETSET model
- tuned energy cutoff, pT, s-sbar suppression

Minos kinematical coverage at PH2LE beam (spans a large area of kinematical phase space space - t2k much more limited)
The GENIE hadronization / AGKY low-W model

- Get average multiplicity from empirical parameterization:
  \[ \langle n \rangle = a + b \cdot \ln W^2 \]

- Generate the actual multiplicity using the KNO scaling law:
  \[ \langle n \rangle P(n) = f \left( \frac{n}{\langle n \rangle} \right) \]

  (taking into account that
  \[ \langle n_{\text{neutral}} \rangle = 0.5 \times \langle n_{\text{ch}} \rangle \]

+ deriving particle spectrum (*skipping details here*)
At the hadronic CM, **the nucleon direction is correlated with the diquark direction** (opposite to the direction of the momentum transfer $q$)

- Building in experimental data on nucleon $p_T$ and $x_F = p_L/p_{L\text{max}} = 2*p_L/W$)
- $PT$ limited phase space decay (reproducing experimental pion $p_T$ 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

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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 hep-ex/0904.4043

The model and its shortcomings are very well understood. Improvements in progress

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Special case: Hadronization model for DIS charm production

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

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

PYTHIA decayer

Hadronic Remnants: PYTHIA hadronization

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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: At $E_v \sim 1$ GeV most hadrons re-interact.

For illustration:

$\nu_\mu + \text{C}12$, $E_v = 1$ GeV

$2/3$ of hadrons re-interact.
Re-scattering: Modifies the observed topologies

| Final- State | 0πX | 1π⁰X | 1π⁺X | 1π⁻X | 2π⁰X | 2π⁺X | 2π⁻X | π⁰π⁺X | π⁰π⁻X | π⁺π⁻X |
|--------------|-----|--|--|--|---|--|--|---|--|--|
| 0πX         | **2934** | **4464** | 22033 | 3038 | 113 | 51 | 5 | 350 | 57 | 193 |
| 1π⁰X        | 1744 | **4464** | 3836 | 491 | 1002 | 25 | 1 | 1622 | 307 | 59 |
| 1π⁺X        | 2590 | 1065 | **82459** | 23 | 14 | 660 | 0 | 1746 | 5 | 997 |
| 1π⁻X        | 298 | 1127 | 1 | **12090** | 16 | 0 | 46 | 34 | 318 | 1001 |
| 2π⁰X        | 0 | 0 | 0 | 0 | **2761** | 2 | 0 | 260 | 40 | 7 |
| 2π⁺X        | 57 | 5 | 411 | 0 | 1 | **1999** | 0 | 136 | 0 | 12 |
| 2π⁻X        | 0 | 0 | 0 | 1 | 0 | **134** | 0 | 31 | 0 |
| π⁰π⁺X       | 412 | 869 | 1128 | 232 | 109 | 106 | 0 | **9837** | 15 | 183 |
| π⁰π⁻X       | 0 | 0 | 1 | 0 | 73 | 8 | 5 | **1808** | 154 |
| π⁺π⁻X       | 799 | 7 | 10 | 65 | 0 | 0 | 0 | 139 | 20 | **5643** |

**Example:**
numu+O16; nd280 spectrum

Re-scattering: Degrades the pion energies

**Example:**
numu+Fe56; Ev = 1 GeV

Costas Andreopoulos, *Rutherford Appleton Lab.*
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*

Costas Andreopoulos, *Rutherford Appleton Lab.*
The GENIE hadron transport modelling (INTRANUKE/hA)

Stepping primary hadrons within the target nucleus

\[ P_{rescat}^h = 1 - P_{surv}^h = 1 - \int e^{-r/\lambda} \frac{d}{d\lambda} \left( r, h, E_h \right) dr \]
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
  \( (n=1 \text{ for nucleons, } n=0.5 \text{ for pions}) \).
The GENIE hadron transport modelling (INTRANUKE/hA)

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

- **elastic**
  - ![Diagram of elastic scattering]
  - Pion deflected. Its kinetic energy stays the same.

- **inelastic**
  - ![Diagram of inelastic scattering]
  - Pion deflected. Its kinetic energy is degraded.

- **charge exchange**
  - ![Diagram of charge exchange]

- **pion production**
  - ![Diagram of pion production]

- **absorption**
  - ![Diagram of absorption]
  - followed by emission of low energy nucleons

~ Similar fates for nucleons
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.
**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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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.**: K=0, ct0 = 0.342 fm

No intranuclear rescattering within formation zone

(SKAT) model dependence
Included in an ad-hoc way
Only for O16
To be added for C, Ar
Further physics improvements
In upcoming releases

 >>>
New intranuclear cascade

See Steve's talks during the Ladek winter 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
Near future improvements cont’d

Improvements at B/Y structure functions & R/S form factors.

Global cross section model retuning.

Improvements at AGKY

  strange particle production

  fwd/bkw asymmetry

Improvements at angular distributions of resonance decays

... ... ...
Summary

Heavily validated, robust, comprehensive MC generator

Nearly universal!

Already provides high quality simulations for T2K, MINOS, MINERvA, NovA, others

Effort to extend validity range down to ~1 MeV (SNS, reactor, super-novae)