The GENIE

Object-Oriented / C++

Neutrino MC Generator

http://www.genie-mc.org

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CCLRC, Rutherford Appleton Laboratory
Outline

• Introduction

• Software

• Physics
Models the neutrino interaction physics (particle spectrum & kinematics) and generates the primary physics events (particle spectrum & kinematics).
GENIE is a Universal Neutrino Generator Collaboration

• C. Andreopoulos (CCLRC, Rutherford)
• F. Cavanna (INFN & L'Aquila Univ.)
• J. Damet (LAPP)
• S. Dytman (Pittsburgh Univ.)
• H. Gallagher (Tufts Univ.)
• Y. Hayato (KEK)
• S. Kretzer (BNL)
• A. Meregaglia (ETH Zurich)
• D. Naples (Pittsburgh Univ.)
• G. Pearce (CCLRC, Rutherford)
• A. Rubbia (ETH Zurich)
• M. Whalley (Durham Univ.)

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GENIE is more than “a neutrino generator”...

GENIE is “many neutrino generators”!

The developers of leading procedural generators (*GENIE's legacy*):

- **GENEVE** *(F. Cavanna et al.)*
- **NeuGEN** *(H. Gallagher et al.)*
- **NEUT** *(Y. Hayato et al.)*
- **NUX** *(A. Rubbia et al.)*

support GENIE & contribute towards its development.

The goal is to bundle together the 'best of all worlds' into a system with modern, state-of-the-art software architecture.
GENIE is already a large & complex software system

It currently consists of ~100,000 lines of C++ code

(400 classes organized in ~40 packages)

GENIE’s first great success is the robustness, flexibility and extensibility of its framework.

Experience with OO/C++ event generators in other fields (PYTHIA-7/8 & HERWIG++) has shown how highly non-trivial is that even when you start from a well-defined legacy (PYTHIA-6, HERWIG)

Builds on best of software engineering experience.

GENIE framework is based on a combination of:

- the Factory design pattern,
- the Strategy design pattern,
- the Singleton design pattern,
- the Visitor design pattern
- the Chain of Responsibility design pattern
GENIE OO Generator has **extended scope** with respect to existing Procedural Generators

- standardizes the interface with Beam MC and includes Flux Drivers
- includes Detector Geometry Analysers for standard detector descriptions (ROOT/GEANT)
- interfaces with GEANT for feeding it with GENIE events

It becomes so much easier for the experimentalist to produce full scale, realistic MC
Finding out more...

Documentation

- Misc. Project information
- Detailed Download/Installation instructions
- Code browsers:
  - Doxygen web-based documentation
  - text browser of a recent CVS snapshot
- Manuals:
  - User manual
  - Reference manual
- Other material
  - material posted for GENIE and other meetings/workshops

Mailing lists @ CCLRC ListServ

NEUTRINO-MC-CORE:
for core developers / experiment liaisons

NEUTRINO-MC-SUPPORT:
for user support
... everything is available from the project web page

- Project info, LICENSE
- Download / Installation instructions
- Tools
- Mailing Lists
- Various documents, publications, talks, links...

http://www.genie-mc.org
GENIE distribution

GENIE is available from a CVS repository at Rutherford Lab:

- **Read-only access to CVS via AFS**
  - suggested for GENIE users
  - you do need AFS-access but you are not required to have AFS token / authentication

- **Read / Write access to CVS via SSH**
  - strictly for GENIE collaborators / developers
  - need you ssh keys & an account has to be created at Rutherford CVS server

- **Snapshots of the development version posted to the web as tar.gz**
  - for 'desperate' GENIE users
  - snapshots at random points in GENIE development & you can not get frozen versions

One can obtain the development version and a series of recent frozen releases using a usual version numbering scheme (GENIE tags: R-major_minor_revision, eg for GENIE vrs 2.1.3, use R-2_1_3)
GENIE is licensed.

The License can be found at the GENIE web site and in the distributed along with the GENIE source code

Free for all purposes except for public redistribution of modified versions
A 'production quality' GENIE release (2.0.0) will be available in ~a month

Version 2.0.0 to be used (over the summer) for large scale MC production for the MINOS experiment

*** to allow a smooth transition to the new system ***
The GENIE version 2.0.0 “blessed” (default) neutrino interaction physics will be ~ identical to neugen-3 (current MINOS legacy system)

*** in preparation ***
• The physics would be described in detail in a hep-ex e-print (release note)
• The generator design would be described in a Comp.Phys.Comm. paper.
Production release 2.0.0

GENIE production release 2.0.0 is based on NeuGEN-3. Many people have contributed to NeuGEN since the Soudan days:

G.Barr (Oxford), R.Edgecock (RAL), G.Pearce (RAL), P.Litchfield (RAL), A.Mann (Tufts), R.Merenyi (Tufts), H.Gallagher (UMN, Oxford, Tufts)

Also, GENIE production release 2.0.0 is based on work carried out in MINOS for the ongoing oscillation analysis:

C.Andreopoulos, D.Bhattacharya, H.Gallagher, R.Gran, W.A.Mann, M.Kordosky, J.Morfin, D.Naples and P.Vahle,

Event Generator Uncertainties and the 1E+20 POT $\nu$-$\mu$ CC Analysis,
MINOS internal document
A couple of software design highlights...
The GHEP event record

output events are stored at a custom C++, STDHEP-like record

collection of GHePParticles, supports numerous particle querying methods, spontaneously re-arranges itself to maintain the compactness of its daughter lists,...

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in GHePRecord

GHePRecord

GHePParticle

ROOT TClonesArray

Interaction

Kinematics

ProcessInfo

InitialState

Target

XclsTag

initial, intermediate, final state particle or generator book-keeping action

“Interaction summary”

Redundant = Can be recreated by analyzing the GHEP record

Decouples physics algorithms (cross section models, hadronization models, ...) from event generation framework so that they can also be used independently

GENIE Universal Object-Oriented Neutrino Generator

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'nu\_mu + Fe56' DIS event

<table>
<thead>
<tr>
<th>GENIE GHEP Event Record</th>
<th>shown using $GHEPPRINTLEVEL = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>id</td>
<td>Name</td>
</tr>
<tr>
<td>0</td>
<td>nu_mu</td>
</tr>
<tr>
<td>1</td>
<td>Fe56</td>
</tr>
<tr>
<td>2</td>
<td>neutron</td>
</tr>
<tr>
<td>3</td>
<td>Fe55</td>
</tr>
<tr>
<td>4</td>
<td>mu_ -</td>
</tr>
<tr>
<td>5</td>
<td>HadrSyst</td>
</tr>
<tr>
<td>6</td>
<td>proton</td>
</tr>
<tr>
<td>7</td>
<td>pi0</td>
</tr>
<tr>
<td>8</td>
<td>pi0</td>
</tr>
<tr>
<td>9</td>
<td>pi+</td>
</tr>
<tr>
<td>10</td>
<td>pi-</td>
</tr>
<tr>
<td>11</td>
<td>proton</td>
</tr>
<tr>
<td>12</td>
<td>pi0</td>
</tr>
<tr>
<td>13</td>
<td>pi0</td>
</tr>
<tr>
<td>14</td>
<td>pi+</td>
</tr>
<tr>
<td>15</td>
<td>pi-</td>
</tr>
<tr>
<td>16</td>
<td>gamma</td>
</tr>
<tr>
<td>17</td>
<td>gamma</td>
</tr>
<tr>
<td>18</td>
<td>gamma</td>
</tr>
</tbody>
</table>

Flag: marking an unphysical event (can filter events using a user-specified 'mask')

Example vector in detector coordinate system, if a detector geom was used / particle position within the nucleus is also stored

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More example printouts

<table>
<thead>
<tr>
<th>GENIE GHEP Event Record [shown using $\text{GHEPPRINTLEVEL} = 2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Idx</strong></td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
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<td>4</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
</tbody>
</table>

**Vertex:** | nu_mubar $\otimes$ (x = 0.00000 m, y = 0.00000 m, z = 0.00000 m, t = 0 s) |

**Flags:** | UnPhys: [OFF] | ErrBits[16-0]:0000000000000000 | 1stset: | none |

**XSec/WUT:** | XSec[Event] = 2.3559e-38 cm$^2$ | XSec[Kinematics] = 5.3088e-38 cm$^2$(K) | Weight = 1 |

<table>
<thead>
<tr>
<th>GENIE GHEP Event Record [shown using $\text{GHEPPRINTLEVEL} = 2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Idx</strong></td>
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<tr>
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</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
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<tr>
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</tbody>
</table>

**Vertex:** | nu_mubar $\otimes$ (x = 0.00000 m, y = 0.00000 m, z = 0.00000 m, t = 0 s) |

**Flags:** | UnPhys: [OFF] | ErrBits[16-0]:0000000000000000 | 1stset: | none |

**XSec/WUT:** | XSec[Event] = 3.88624e-38 cm$^2$ | XSec[Kinematics] = 3.15033e-37 cm$^2$(K) | Weight = 1 |
Event generation threads

Event generation: built in *(ordered)* steps *(modules)*, around the output event record. Each module visits and modifies the event record *(visitor design pattern)*

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Will discuss which event generation threads are available at the 'physics' section
Event Generation Framework: Overview

Event Generation
- **EventGenerator**
  - Declares a validity context
  - Hands over an algorithm to create a list of all interactions it can generate
  - Hands over an algorithm to compute the cross section for the interactions it can generate

Event Record
- **EventRecord**
  - Generates some 'class' of events (e.g., DIS CC in Fe, > 5 GeV)
  - Accepts an event record visitor

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Example: Generating a QEL event...

- **step:** InitialStateAppender
- **step:** FermiMover
- **step:** QELKinematicsGenerator
- **step:** QELPrimaryLeptonGenerator
- **step:** QELHadronicSystemGenerator
- **step:** PauliBlocker
- **step:** Intranuke
- **step:** NucBindEnergyAggregator
- **step:** UnstableParticleDecayer

The essence of GENIE event generation software abstraction! heterogeneous processing steps (“visitors” or “event generation modules”) are treated in the same way focusing on common operational aspect (“visit” and modify the event record accordingly)

*modules can be plugged in/out & configured externally*

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**Example:** Switch on “transparent nucleus” flag to turn off intranuclear rescattering.

**Example:** Plug it out to turn off Fermi motion. Or, replace the attached nucleon momentum probability distribution model...

**Example:** Plug-out Intranuke and plug-in FLUKA to modify the intranuclear rescattering model
**Event Generation Drivers**

**How can I get framework to run?**

**[GEVGDriver]**

Provides the “basic” event generation functionality:

- *generate events for a given initial state (ν + target) for a given 4-p of an interacting ν*

  - *this drivers the core event generation machinery*

**[GMCJDriver]**

Provides a more “extended” functionality:

- *generate events for a given neutrino flux and for a given detector geometry*

  - *is built upon the previous layer, but provides hooks for detector geometries and fluxes*
  - *not handled by many current generators*
  - *better 'factorization' of the overall simulation chain if handled by the neutrino generator*
Flux and Geometry Drivers

GENIE can generate events for an input **neutrino flux** and for an input **detector geometry** both of arbitrary complexity (no limitation...)

It defines an interface for **flux drivers** (*GFluxI*) and **geometry drivers** (*GeometryAnalyzerI*)

You can load your **flux** and **geometry** drivers as **external pluggins** that extend the GENIE event generation capabilities

Respecting the GENIE driver interface guarantees **seamless integration**

**GENIE itself contains a couple of concrete flux drivers** (1 model specific & 1 generic)

- **[GFlukaAtmo3DFlux]**: the Battistoni FLUKA-based, 3-D atmospheric neutrino flux
- **[GCylindTH1Flux]**: a generic cylindrical flux with energy spectra from ROOT TH1D histograms

**GENIE itself contains a couple of concrete geometry drivers** including:

- **[ROOTGeomAnalyzer]**: for ROOT / GEANT-4 based geometries
A glimpse at the underlying framework:

**Algorithms & standardized Algorithmic Interfaces**

- **the 'root' object for every GENIE algorithm**
  - all concrete algorithms are accessed through some standard interface

- **standard algorithm interfaces**
  - all concrete algorithms implement one of the standard interfaces

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- has name
- names a configuration set,
- has methods to:
  - be configured
  - look-up its configuration
  - hand-over its configuration
  - report its status

---

provides seamless integration for your model!
A glimpse at the underlying framework:

**XML Algorithm Configuration**

Each algorithm has its own XML configuration file, declaring its configuration sets.

It looks like this:

```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
<alg_conf>
  -- Default configuration for KNOHadronizationHadronizationModel1
  <param_set name="Default">
    <param type="string" name="multiplicity-prob-alg-name"> genie::SchmitzMultiplicityModel </param>
    <param type="string" name="multiplicity-prob-param-set"> Default </param>
    <param type="double" name="prob-fs-pi0-pair"> 0.30 </param>
    <param type="double" name="prob-fs-pplus-minus"> 0.60 </param>
    <param type="double" name="prob-fs-Kplus-Kminus"> 0.05 </param>
    <param type="double" name="prob-fs-K0-Kbar"> 0.05 </param>
    <param type="bool" name="force-decays"> false </param>
  </param_set>

  <param_set name="Default-Decaying">
    <param type="string" name="multiplicity-prob-alg-name"> genie::SchmitzMultiplicityModel </param>
    <param type="string" name="multiplicity-prob-param-set"> Default </param>
  </param_set>
</alg_conf>
```

**Full external GENIE configuration using intuitive XML**

At GENIE initialization, all XML files are parsed.

At **run-time**, all configurations can be made available as **Registries** (type-safe “name”->”value” containers)

**Pre-configured instances** of algorithmic objects are served by an **Algorithm Factory**
(uses the “Factory” design pattern)
... and very important: **GENIE Validation mechanisms**

GENIE framework gives extra weight to model tuning & validation

- **Model validation & tuning**
  
  *based on GENIE's NuValidator tool*

- **“Unit” testing**
  
  *based on the automatic generation of a validity document*

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**Summary Window**

<table>
<thead>
<tr>
<th>GGM</th>
<th>Target</th>
<th>Total CS</th>
<th>QE CS</th>
<th>One Plan</th>
<th>One Plan</th>
<th>Two Plan</th>
<th>Other</th>
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<tbody>
<tr>
<td>Eichten 1973</td>
<td>PL B46,274</td>
<td>Propane-Freeon</td>
<td>(1.9-5.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bonetti 1977</td>
<td>NC B3A,260</td>
<td>Propane-Freeon</td>
<td>(1.9-5.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Krenz 1978</td>
<td>NP B135,46</td>
<td>Propane-Freeon</td>
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<td></td>
<td></td>
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<tr>
<td>Lerche 1978</td>
<td>PL B78,510</td>
<td>Propane</td>
<td>(1-10.0)</td>
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<tr>
<td>Lerci 1978</td>
<td>NP B142,68</td>
<td>Propane-Freeon</td>
<td></td>
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<td></td>
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<tr>
<td>Armenise</td>
<td>NP</td>
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<td></td>
</tr>
</tbody>
</table>

**Data Window**

<table>
<thead>
<tr>
<th>Exp</th>
<th>Author/Reference</th>
<th>Target</th>
<th>Reaction</th>
<th>Energy (GeV)</th>
<th>sig + error (syst) 10^-38 cm^2</th>
<th>source</th>
<th>comment</th>
<th>yname</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGM</td>
<td>Bonetti 1977 NC</td>
<td>Propane-Freeon</td>
<td>numu n</td>
<td>1.625</td>
<td>1.05 + -0.20</td>
<td>plot</td>
<td>10-38cm^2</td>
<td>SIG</td>
</tr>
<tr>
<td></td>
<td>B3A,260</td>
<td></td>
<td>numu n</td>
<td>1.875</td>
<td>0.96 + -0.17</td>
<td>plot</td>
<td>10-38cm^2</td>
<td>SIG</td>
</tr>
</tbody>
</table>
Dynamic Validation mechanism: the NuValidator tool

The NuValidator was presented in NuINT-04 (and since then was significantly extended)

Its data-base contains Durham Neutrino Reaction Data (also presented in NuINT-04) and also JLAB electron scattering xsec database and the Durham structure function data

Currently:
- interfaced with NeuGEN only.
- GENIE interface to be added

Allows:
- searching the world’s xsec data
- plotting selected data,
- plotting generator predictions,
- fitting model parameters,
- extracting plots and data
  in:
  - graphical formats (gif, eps),
  - textual formats (xml, ascii),
  - as ROOT files and
  - as ROOT macros
Data included in GENIE’s NuValidator tool:

The world’s neutrino cross section data

Most of the available data come from old (’60-’80) bubble chamber experiments

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Data included in GENIE’s NuValidator tool:

The world’s neutrino cross section data

Most of the available data come from old (’60-’80) bubble chamber experiments

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Data included in GENIE’s NuValidator tool:

Electron cross section data in the resonance region

Loads of inclusive electron scattering data in the resonance region (mainly by JLAB)

Can be used for evaluating the vector part of neutrino interaction models

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Data included in GENIE's NuValidator tool: Structure function data

F2, xF3 data

Many on nuclear targets

Important for tuning the DIS component

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Physics - Outline

- How do neutrinos interact at few GeV?
- Neutrino Cross Sections at few GeV
- Cross Section Basics
- From free nucleons to nuclear targets
- Quasi-elastic scattering
- Resonance excitation
- Deep inelastic scattering
- Summing up contributions
- Resonance to DIS transition
- Low mass hadronization
- Intranuclear rescattering
- RFG, Binding energy subtraction, Off-shell kinematics,...
- Handling uncertainties / marginalization
How do neutrinos interact at ~ few GeV?

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QEL CC
- Low multiplicity inelastic CC (RES)

DIS CC
- LAr images, courtesy A.Currioni
Neutrino cross sections at ~ few GeV

- ~GeV neutrino cross sections not well understood
- Experimental data are quite poor
- Is a large limiting factor for precision oscillation studies
Neutrino cross sections at ~ few GeV

- Exclusive inelastic cross sections?
- Low mass hadronization?
- Intranuclear rescattering?
- DIS/RES joining and summing up CC contributions?
- Beyond RFG?
process dynamics described by the invariant amplitude

\[ |M|^2 = L_{\mu \nu} W_{\mu \nu} \]

\[ W_{\mu \nu} = W_1 \delta_{\mu \nu} + W_2 p_{\mu} p_{\nu} + W_3 \epsilon_{\mu \nu \alpha \beta} p^\alpha p^\beta + W_4 q_{\mu} q_{\nu} + W_5 (p_{\mu} q_{\nu} + p_{\nu} q_{\mu}) + W_6 (p_{\mu} q_{\nu} - p_{\nu} q_{\mu}) \]

**Complicated! Depends on the initial / final hadronic state**

(eg **QEL**: “structure-less” nucleon -> ok, **RES**: nucleon as a dynamical 3q system -> difficult)

**Constraints:** from hadronic current continuity, \( T \) invariance \( (W6=0) \), CC/NC given \( \theta_W \), ...
From free nucleons $\rightarrow$ to nuclear targets

Neutrino cross sections “better known” for free nucleon targets. But experiments have nuclear targets!
Quasi-Elastic scattering (QEL)

- Critical for current accelerator LBL oscillation experiments
- > ~50% of total CC cross section at ~1 GeV
- “Elastic”: Full kinematical reconstruction just by looking at the leptonic system:

\[
E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu} \quad \quad Q^2 = -2 E_\nu (E_\mu - p_\mu \cos \theta_\mu) + m_\mu^2
\]
Quasi-Elastic scattering (QEL)

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

A, B, C = \(f(F_A, F_{v1}, F_{v2})\)

vector form factors: determined from e-N via CVC

dipole axial form factor:

\[F_A = g_A \left( 1 + \frac{Q^2}{M^2_A} \right)^{-2}\]
### Connection with Elastic Form Factors

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

\[
F_y^V(Q^2) = \frac{G_E^V(Q^2) - \sigma G_M^V(Q^2)}{1 - \tau}
\]

\[
\xi F_y^A(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1 - \tau}
\]

**CVC allows us to determine Gve, Gvm from the elastic form factors**

\[
G_E^V(Q^2) = G_{ep}^V(Q^2) - G_{en}^V(Q^2)
\]

\[
G_M^V(Q^2) = G_{mp}^V(Q^2) - G_{mn}^V(Q^2)
\]

### Elastic form factor measurements:

- **Rosenbluth separation:**

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

- **Polarization measurements:**

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

- The 2 methods do not agree
- Polarization measurements seen as more reliable
**Elastic Form Factors: Measurement / Parametrization**

**Beyond the dipole form factors:**

**BBA2005:** New fit based mostly on polarization data (eg Budd/Bodek/Arrington see hep-ex/0308005)

QEL Axial Mass

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Axial mass extractions from \( \nu N \)
and \( \bar{\nu} N \) scattering experiments
- Deuterium filled bubble chambers
- Heavy liquid bubble chambers and spark chambers

World average value, \( 1.026 \pm 0.021 \) GeV/c^2,

[Naumov et al, 20th Max Born]
In the upcoming GENIE production release

**Default:** Dipole elastic form factors (BBA03 & BBA05(?) to be included for re-weighting)

**Default:** $M_a=1.032$, $M_v=0.84$, $F_a(q^2=0)=-1.26$ (can be trivially modified)

**Note:** large uncertainties in NC ($\nu N$ elastic) case - ~20% on top of the CC case because of the strange axial form factor contributions (Default: $\eta=0.12$, see: L.A.Ahrens, PRD35, 3:785(1987))

For nuclear targets, a suppression factor $R(Q^2)$ is included from an analytical calculation of the Pauli blocking effect:

[Graph showing $R(Q^2)$ for different nuclei, such as Fe$^{56}$, Fe$^{56}$, and C$^{12}$, along with $\sigma_{QEL}(10^{-40}\text{ cm}^2)$ for $\nu_\mu n \to \mu^- p$ for free nucleon and $\nu_\mu n \to \mu^- p$, n bound in Fe$^{56}$]

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QEL @ GENIE 2.0.0 / Notes
Relevant event generation threads:

- **QEL-CC**
- **QEL-NC**
- **QEL** \((QEL-CC + QEL-NC)\)
Resonance Excitation

\[ \nu + N \rightarrow l + \text{Resonance} \rightarrow N + \text{pion} \]

**Very important channel(s)**

\(~30\% \) of the total CC xsec around \(~1 \) GeV

**Very complicated!**

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<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>( L(2I,2J) )</th>
<th>PDG status</th>
<th>Breit – Wigner Width (MeV)</th>
<th>FKR ( n )</th>
<th>BR ( N^* \rightarrow N \pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta(1232) )</td>
<td>( p_{1/2} )</td>
<td>****</td>
<td>120</td>
<td>0</td>
<td>100%</td>
<td></td>
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<tr>
<td>( N(1535) )</td>
<td>( S_{11} )</td>
<td>****</td>
<td>150</td>
<td>2</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>( N(1520) )</td>
<td>( D_{15} )</td>
<td>****</td>
<td>120</td>
<td>1</td>
<td>55%</td>
<td></td>
</tr>
<tr>
<td>( N(1650) )</td>
<td>( S_{11} )</td>
<td>****</td>
<td>150</td>
<td>1</td>
<td>73%</td>
<td></td>
</tr>
<tr>
<td>( N(1700) )</td>
<td>( D_{15} )</td>
<td>***</td>
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<td>1</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>( \Delta(1700) )</td>
<td>( D_{33} )</td>
<td>****</td>
<td>150</td>
<td>1</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>( N(1440) )</td>
<td>( P_{11} )</td>
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<td>350</td>
<td>1</td>
<td>65%</td>
<td></td>
</tr>
<tr>
<td>( \Delta(1600) )</td>
<td>( P_{33} )</td>
<td>***</td>
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<td>2</td>
<td>18%</td>
<td></td>
</tr>
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<td>( N(1720) )</td>
<td>( P_{13} )</td>
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<td>2</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>( N(1680) )</td>
<td>( P_{33} )</td>
<td>****</td>
<td>130</td>
<td>1</td>
<td>66%</td>
<td></td>
</tr>
<tr>
<td>( \Delta(1910) )</td>
<td>( P_{11} )</td>
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<td>2</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>( \Delta(1920) )</td>
<td>( P_{33} )</td>
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<td>2</td>
<td>13%</td>
<td></td>
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<tr>
<td>( \Delta(1905) )</td>
<td>( P_{33} )</td>
<td>****</td>
<td>350</td>
<td>2</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>( \Delta(1950) )</td>
<td>( P_{37} )</td>
<td>****</td>
<td>300</td>
<td>2</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>( N(1710) )</td>
<td>( P_{11} )</td>
<td>***</td>
<td>100</td>
<td>2</td>
<td>35%</td>
<td></td>
</tr>
</tbody>
</table>
**Resonance Excitation: Rein – Sehgal model**

\[ \nu + N \rightarrow l + \text{Resonance} \rightarrow N + \text{pion} \]

*Very complicated* theoretically and not very well constrained from existing data...

The most widely used model for resonance neutrino production


uses the FKR dynamical model


to describe excited states of a 3 quark bound system.

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

They depend on the details of the FKR model

(and “maybe” a snapshot of the PDG resonance tables as they were in early ’70’s?)

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

**Axial & Vector transition form factors:**

assuming dipole form \(Q^2\) dependence

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

\[M_v=0.84 \text{ GeV}/c^2, M_A\]
Resonance excitation cross sections
(as a function of energy / for muon neutrinos)

Single pion production cross sections

\[ \text{vp} \to \text{l} \, \text{p} \, \text{pi}^+ \]

\[ \text{vn} \to \text{l} \, \text{n} \, \text{pi}^+ \]

\[ \text{vn} \to \text{l} \, \text{p} \, \text{pi}^0 \]

Include isospin amplitudes and 1pi BR

to weight the contribution of each resonance
to exclusive single pion reactions

Can add coherently

For simplicity, many calculations add incoherently

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>
In the upcoming GENIE production release

- The RES / DIS joining scheme will be discussed in a while...
- Resonances are added incoherently – **Interference is neglected.**
- **Default:** Ma=1.032, Mv=0.84, Z=0.75, Omega=1.05
- The Rein-Sehgal model assumes massless leptons. **For tau leptons a suppression factor is included by hand.** An “revised” model exists to take into account the lepton masses (“Extended Rein-Sehgal model for tau lepton production”, hep-ph/0408106, Kuzmin-Lyubushkin-Naumov) but is not currently included.

In future releases we anticipate including the Paschos-Lalakulich model, integrating it in the RES threads extensively validating it and using this as default or a supported suggested alternative.

- **The model parametrizes the hadron current using phenomenological form factors (hep-ph/0501109)**
  - Similar to DIS formulation.
  - Determine 'structure functions' either from general principles (CVC, PCAC) or electro-production data
  - Simple & elegant approach

We currently include their model for P33(1232) but not their latest work.
Relevant event generation threads:

- **RES-CC**
- **RES-NC**
- **RES** (*RES-CC + RES-NC*)
- **RSPP-CC**
- **RSPP-NC**
- **RSPP** (*RSPP-CC + RSPP-NC*)

- The RES threads model more final states
- The RSPP threads can take into account resonance interference --if needed-- for the most important channels (1pi)

- Don't use both at the same time! The RES threads are included in the Default thread.

**RES @ GENIE 2.0.0 / Notes**

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**Deep Inelastic Scattering (DIS)**

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:

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

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

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

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

\[
A_8 = - \frac{m_\mu^2}{M_N E}.
\]
**F2 & xF3 measurements**

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**F2**

![Graph F2](image1)

**xF3**

![Graph xF3](image2)

---

**Costas Andreopoulos**  
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---

**GENIE Universal Object-Oriented Neutrino Generator**
Structure functions: kinematical coverage

- new kinematic regime
- large non-perturbative contributions

large PDF uncertainties at large $x$ for low $Q^2$
Bodek – Yang model

Based on LO cross section models with new scaling variable to account for higher twists and modified PDFs to describe low-Q^2 data

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

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

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

Fits based on GRV98LO and free nucleon charged lepton data

[hep-ph/0411202]
In the upcoming GENIE production release:

- Some suppression of 1pi and 2pi final states as part of the RES/DIS tuning scheme *(see later)*

- “Custom” hadronization model:
  - no-charm: using a KNO scaling based approach...
  - charm: using a charm fraction table and fragmentation functions...

- Nuclear corrections included by hand
Relevant event generation threads:

- DIS-CC
- DIS-NC
- DIS \((DIS-CC + DIS-NC)\)
- Charm
**Summing up CC contributions**

The total inclusive cross section is the sum of contributions from:

- exclusive channels
- DIS

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

The transition from the RES to DIS region is quite tricky.

---

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**RES -> DIS transition**

*In MINOS, a data-driven approach:*

\[
\frac{d\sigma}{d\theta dE'} = \frac{d\sigma}{d\theta dE'}^{\text{RES}} + \frac{d\sigma}{d\theta dE'}^{\text{DIS}}
\]

where

\[
\frac{d\sigma}{d\theta dE'}^{\text{RES}} = \sum_{i=1}^{17} \frac{d\sigma}{d\theta dE'}^{\text{RS}} \Theta(W_{\text{cut}} - W)
\]

where the summation is over the 17 resonances in the Rein-Seghal model, and

\[
\frac{d\sigma}{d\theta dE'}^{\text{DIS}} = \frac{d\sigma}{d\theta dE'}^{\text{DIS-BY}} \Theta(W - W_{\text{cut}}) + \frac{d\sigma}{d\theta dE'}^{\text{DIS-BY}} \Theta(W_{\text{cut}} - W) \sum_k f_k
\]
Kinematic coverage of the NuMI beam

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Kinematic Coverage of NUMI PH2LE Beam

\( W = 8 \text{ GeV} \)
\( W = 4 \text{ GeV} \)
\( W = 2 \text{ GeV} \)
\( W = 1.2 \text{ GeV} \)

50%
75%
90%
99%

\( Q^2 = 1 \text{ GeV}^2 \)

\( \log_{10}(x) \)

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>
**Low-W hadronization**

**basic approach:**

- **experimental data:**
  - get average multiplicity \(<n>\) for given invariant mass

- **use KNO scaling law to generate actual multiplicity**

- **use isospin / charge conservation arguments for particle spectrum**
- **use a phase space generator for generating 4-p**

Standard hadronization models (e.g., PYTHIA)

- “collapse” at low invariant masses

**Hadronic shower contents**

- very important
- particularly for non-compensating calorimeters
Intranuclear rescattering

Very important effect at low energies!!

\[ E_{\text{visible}} \neq E_{\text{neutrino}} \]

- Large fraction of the pion energy can be lost within the nucleus
- Hadronic energy scale calibration has MC-dependence

“Missing energy” as a function of neutrino energy

[P. Sala et al]
MINOS model (INTRANUKE)

- has its roots on work by R. Merenyi, PhD thesis, Tufts (1990))
- originally in NeuGEN – translated to GENIE
- physics input improvement has been taken over by S. Dytman

- Cascade MC (simple version of the Bertini cascade MC)
- Pion absorption = absorption by a multi-nucleon cluster
- Formation zone included using the SKAT parametrization

In FLUKA: PEANUT: low / intermediate energy hadron interaction model

A 3-step model:  
• *(Generalized) IntraNuclear Cascade (GINC)*
  • + Preequilibrium
  • + Evaporation/Fission or Fermi break-up

My own priority in GENIE development is a GENIE / FLUKA, DPMJET interface
**Describing target nucleus using a Relativistic Fermi Gas (RFG) model**

(degenerate Fermi Gas / all states up to $k_F$ populated)

<table>
<thead>
<tr>
<th>Initial state nucleus</th>
<th>$A$</th>
<th>$A-1$</th>
<th>$1$</th>
</tr>
</thead>
</table>

\[ p = -p_F \quad \text{and} \quad p = p_F \]

\[ E = \sqrt{M_{A-1}^2 + p_F^2} \quad \text{and} \quad E = M_A - \sqrt{M_{A-1}^2 + p_F^2} \]

- Taking into account Pauli blocking:
  
  $f/s$ nucleon must have $p > k_F$

- Taking into account binding energy:

  Subtracting the $E_{\text{bind}}$ of the most loosely bound nucleon from the $f/s$ nucleus

  What to do with to conserve energy (?). Unavoidable crappiness (geantinos, bindinos and the likes)
• Using off-shell kinematics

in any Feynmann diagram all incoming and outgoing particles are on the mass shell.

For interactions off bound nucleons, use the selected cross section model (as if on the mass shell) and take the off-shellness into account when computing kinematical limits...

• Nucleon-Nucleus recombination...

More rigorous approaches: Mean field approximation, Random phase approximation (RPA)
Never used before in MCs (?). A next priority for GENIE...
coherent scattering

relevant event generation threads:

COH-NC, COH-CC, COH

inverse muon decay

relevant event generation threads: IMD

All other ve-processes are currently neglected. To be added at a near-future revision.
ve- elastic scattering *(other than IMD)* is currently neglected

- trivial / to be added at a near-future revision

non-DIS charm production is currently neglected

- QEL charm production to be added at a near-future revision

diffractive scattering is currently neglected
** Marginalization **

\[ P(X|I) = \int_{-\infty}^{+\infty} P(X, Y|I) dY \]

X: measured oscillation parameters
Y: nuisance parameters (neutrino interaction model parameters...)

In GENIE 2.0.0 we will use the same method used in MINOS so far with NeuGEN-3

We will provide:

- an “event re-weighting” facility
- a list of physics parameters affecting the default threads that is meaningful to modify
- a reasonable variation range for these parameters

Handles uncertainties other than the ones coming from intranuclear rescattering
Development path after releasing 2.0.0

- Intranuclear rescattering: Interfaces with FLUKA and DPMJET
- Intranuclear rescattering: INTRANUKE improvements (S.Dytman et al)
- Hadronization: KNO model improvements and transition to PYTHIA at large W
- Switch PYTHIA6 --> PYTHIA8 and PDFLIB --> LHAPDF (& scrap CERNLIB)
- Compute mu, tau polarizations correctly. Interface with TAUOLA for tau decays.
- Run GENIE using the Grid
- Support F.Cavanna et al. to migrate any other GENEVE – specific stuff into GENIE
- Support Y.Hayato et al. to migrate any other NEUT – specific stuff into GENIE
- C++ adaptation of S.Kretzer's DISCO NLO Charm MC
- Extending the generator validity: down to ~MeV (reactor) & up to > ~TeV (telescopes)
- Completeness: add missing “small xsec processes” such as ve-, diffractive, etc...
- ... ...

*** All (?) the above to be included in the next major production version 3.0.0 ***
in ~ summer 2007 / minor production releases to be made available along the way
Stay tuned for the upcoming GENIE production release 2.0.0!