• Neutrino Cross Sections in the ~ few GeV energy range
• The most important cross section components & related uncertainties

• Neutrino Interaction Monte Carlo Generators
Neutrino Cross Sections in the ~ few GeV energy range

Most important components of total xsec @ few GeV

- **Quasi-Elastic (QEL) scattering**
  \(\text{low } Q^2, W \approx M_N\)

- **Resonance (RES) excitation**
  \(\text{low } Q^2, \sim 1 \text{ GeV} < W < \sim 2 \text{ GeV}\)

- **Deep-Inelastic (DIS) scattering**
  \(\text{large } Q^2, W \gg \sim 2 \text{ GeV}\)

Typical cross section decompositions

\[
\sigma_{\text{total}} = \sigma_{\text{QEL}} + \sigma_{\text{DIS}}
\]

\[
\sigma_{\text{total}} = \sigma_{0\pi} + \sigma_{1\pi} + \sigma_{2\pi} + \ldots
\]

The situation:

- ~GeV neutrino cross sections not well understood
- Experimental data are quite poor
- Is the largest limiting factor for precision oscillation studies
Quasi-Elastic Scattering

\[ \nu_l + n \rightarrow l^- + p \quad \bar{\nu}_l + p \rightarrow l^+ + n \]

- Critical for current LBL oscillation experiments
- This is how the “oscillating neutrinos” in current LBL experiments prefer to interact (~60% of total CC cross section at 1 GeV)

\[ E_\nu = 1.2GeV \left( \frac{\Delta m_{23}^2}{2 \cdot 10^{-3} eV^2} \right) \left( \frac{L}{750km} \right) \]

Described with:
- **vector form factors**: determined from e-N via CVC
- **dipolar axial form factors**:
  \[ F_A = g_A \left( 1 + \frac{Q^2}{M_A^2} \right)^{-2} \]

The best understood channel…… but nevertheless, quite far from being well understood (see later)

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Resonance Excitation

\[ \nu + N \rightarrow l + \text{Resonance} \rightarrow N' + n \cdot \pi \]

\[
\begin{align*}
\nu CC : \quad \nu p & \rightarrow l^- p \pi^+ \\
\bar{\nu} CC : \quad \bar{\nu} n & \rightarrow l^+ n \pi^- \\
\nu NC : \quad \nu p & \rightarrow \nu p \pi^0 \\
\bar{\nu} NC : \quad \bar{\nu} p & \rightarrow \bar{\nu} p \pi^0 \\
\nu n & \rightarrow l^- n \pi^+ \\
\bar{\nu} p & \rightarrow l^+ n \pi^-
\end{align*}
\]

Very important channel(s) \( \sim 30\% \) of the total CC xsec around \( \sim 1 \) GeV

This process is very complicated theoretically and not very well constrained from existing data...


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

Helicity Cross Sections [depend on the details of the FKR model]

Assuming dipole form \( Q^2 \) dependence

\[ \text{Costas Andreopoulos \textlangle C.V.Andreopoulos@rl.ac.uk\textrangle, CCLRC – Rutherford Lab.} \]
Resonance Excitation

Include isospin amplitudes and 1π BR to weight the contribution of each resonance to exclusive single pion reactions.

\[ \nu_e + p \rightarrow \mu^- + p + \pi^0 \]

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC - Rutherford Lab.
New theoretical attempts to describe resonance excitation channels.

The new models address some known R/S model deficiencies

- Improved description of neutrino production of the Delta++ resonance. [Important for the K2K, MINOS, MiniBooNE]
- Inclusion of final state lepton masses [Important for low Q2 interactions and for tau neutrino CC interactions]

Kuzmin-Lyubushkin-Naumov model
“Extended Rein-Sehgal model for tau lepton production”, hep-ph/0408106

Paschos-Lalakulich model

- The model parameterizes the N -> Delta hadronic current using phenomenological form factors.

Examples: Paschos-Lalakulich model \( \nu_\mu p \rightarrow \mu^- p \pi^+ \) cross sections in the GENIE neutrino generator

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.
Deep Inelastic Scattering

\[
\frac{d^2\sigma_{DIS}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi} \left\{ y(xy + \frac{m_l^2}{2E_\nu M}) F_1 + \left(1 - y - \frac{xy M}{2E_\nu} - \frac{m_l^2}{4E_\nu^2}\right) F_2 \pm \right.
\]

\[
(xy(1 - \frac{y}{2}) - \frac{y m_l^2}{4E_\nu M} F_3 + \left(\frac{ym_l^2}{2E_\nu M} + \frac{m^4_l}{4E_\nu^2 M^2}\right) F_4 - \frac{m_l^2}{2E_\nu M} F_5 \right\}
\]

- quite well known at higher energies
- … but problematic at some phase space regions
  - PDF evolution stops at quite high Q^2
  - PDF uncertainties ‘explode’ at low Q^2, at low and high x
- …estimating non-resonance (DIS) bkg in the resonance region
- …

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.
Unlocking the hadronic tensor mysteries...

- What have we measured?
- How well do we understand cross sections?
- What are the major unknowns?

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

\[ W^{\mu\nu} = W_1 g^{\mu\nu} + W_2 p^\mu p^\nu + W_3 \epsilon^{\mu\nu\alpha\beta} p_\alpha p_\beta + W_4 q^\mu q^\nu + W_5 (p^\mu q^\nu + p^\nu q^\mu) \]
Most of the available data come from old ('60-'80) bubble chamber experiments, which provide valuable resource in developing / tuning neutrino interaction models. Data are rather poor with large errors but nevertheless are an invaluable resource in developing / tuning neutrino interaction models.
Differential Neutrino Cross Sections

- even more sparse and even more useful data
- many effects (radiative corrections, nuclear effects,…) can change the differential xsec more dramatically than the total xsec

Structure Functions

Measurements exist mainly from higher energy experiments (CCFR, NuTeV…)

... but not enough data where they would be more important to us…

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.
Available data – 3/3:

Electron Scattering Data

Lots of precise, low energy eN scattering data
[mainly eN inclusive scattering data in the RES region from JLAB for hydrogen, deuterium and nuclear targets. (E04-001)]
ares (or are becoming) available.

Very useful data for neutrino physics:

• Evaluating the vector part of neutrino interaction models

• Studying the RES/DIS joining region

• Modelling nuclear effects

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.

GENIE - C. Andreopoulos (CCLRC, Rutherford), H. Gallagher (Tufts)
http://hepunix.rl.ac.uk/~candreop/generators/GENIE/
### Unknowns...

*just some highlights*

<table>
<thead>
<tr>
<th>Process</th>
<th>uncertainty</th>
</tr>
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<tbody>
<tr>
<td>Quasi-Elastic scattering</td>
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Large uncertainties even for the major ~GeV cross section components

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Some exclusive channels are extremely poorly constrained

Example: $\nu N \rightarrow \nu N \pi^0$

Important background in $\nu_\mu \rightarrow \nu_e$

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Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.
Unknowns... [nuclear effects]

What we can do best is:

- Predicting cross sections for free nucleons and the final state primary lepton variables
- Predicting the final state primary lepton variables for ν interactions with nuclear targets
- Predicting the final state hadronic system variables

...but these are strongly affected by nuclear effects

**EXAMPLES:**

**MiniBooNE**
*From J. Raaf (NOON04)*

**SciFi**

**K2K**
*From T. Ishida (NuINT-01)*

Low-Q2 problems seen in all K2K detectors and in MiniBooNE
(Final State re-Interactions/ FSI)

eg: Pion absorption
and how it affects the neutrino energy calibration

Affects differently the near & the far detector energy spectra.
This is a major source of systematic errors in LBL exp.

[Debbie Harris, NuINT-04]

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC - Rutherford Lab.
The list can become quite long...

Neutrino Cross Sections can be the limiting factor for current & future precision neutrino studies

There is no real alternative to measuring what we do not know

- in near detectors of LBL neutrino experiments (K2K, MINOS)
- in ~GeV SBL neutrino experiments (MiniBooNE)
- in dedicated experiments (MINERvA)

The importance of Neutrino Monte Carlos for making the most out of the data that we have already got can not be overstated
Neutrino Monte Carlos are critical components for our research.

(In the absence of clear theoretical / phenomenological prescriptions)
They contain invaluable experience in tweaking / tuning models, the experimenter’s “magic”
tricks that get the poor theoretical inputs into agreement with the data…

Plenty of available Neutrino Monte Carlo’s developed by brilliant physicists

GENEVE – NeuGEN – NEUT - NUANCE - NUX

These are certainly the state of the art in physics they describe, but…

• developed within specific experiments and they usually work best
  • for some targets, and
  • in some fraction of the total phase space

• written in fortran (with ‘fortran-style’ software engineering…)
  • difficult to maintain & improve
  • difficult to integrate into the Object-Oriented Analysis framework of modern experiments
  • difficult to integrate with other popular MC’s making the transition to the OO-world
    • eg GEANT, PYTHIA
  • serious problems with dependencies on software products that eventually will stop
    being supported (eg CERNLIB etc…)
There is no neutrino generator that
(technically) is up to the challenges we face

A well-engineered software product with a lifetime of ~20+ years
(from now to the Neutrino Factory era)

A scalable & easily maintainable software product that will be
easier to extend as ‘knowledge’ accumulates fast from current experiments
(K2K,MiniBooNE,MINOS…)

A neutrino generator that will combine the best of all worlds
(whatever each existing generator does best)

A neutrino generator that will work for all nuclear targets in all energies…
The GENIE Object-Oriented Neutrino Generator

(Generater for Neutrino Interaction Experiments)

Being developed for MINOS

(Hugh Gallagher [Tufts] and myself)

but not MINOS specific

Large Scale Effort / Currently:

• ~75,000 lines of C++
• 270 classes organized in 32 packages.

Is more than a neutrino generator:

Is a framework for developing neutrino generators

Is NOT fortran dressed as C++

Has a proper object-oriented design and
implements successful OO Architecture Design Patterns

More information at:  http://hepunx.rl.ac.uk/~candreop/generators/GENIE/
Code is available: free read-only CVS repository (at Rutherford Lab) accessed via AFS

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.
The right way ahead is through a **cross-experiment** but still **small & focused** collaboration  
(along the lines of the HERWIG collaboration for example)

We are in the process of inviting all neutrino MC authors and other experts to join us

**We wish that:**

- all major neutrino experiments will be represented
- neutrino experts will be joining, understanding the system and leading various aspects of its development by transferring their expertise and migrating their MC’s into the new framework
- ‘experiment liaisons’ bringing in requirements that are specific to their experiment so they can all be integrated into a unified design…

We intend to hold phone conferences and maybe a small workshop for all interested parties (*somewhere – RAL? FNAL?*) BEFORE the upcoming NuINT-05 in Japan.

There is more than enough initial momentum…

We really have the opportunity here to produce something which will be the state of the art in both the neutrino interaction physics & software engineering
Framework:

- All algorithms **fully externally configurable** via an **XML-based config system**
- (Named) algorithm **configurations** (>=1/algorithm) **available at run-time as ‘Registry’**
  (key->value) **containers** served from a (singleton) **Configuration Pool**
- **Error/Message logging** system based on log4cpp
- Algorithm abstractions & **standardized interfaces**
- **AlgFactory** (‘Factory Design Pattern’) **serves pre-configured algorithm instances**
- **Data / Algorithm decoupling** using the ‘Strategy Pattern’ guarantees scalability
- **Static & Dynamic Validation Schemes**
- Access to standard PDG data and extensions (eg Baryon Resonance data)
- **Access to the world’s data on neutrino scattering cross sections** ( & SFs, hadronic multiplicities,…)
- **Extensible / Scalable event generation framework built using a combination of the ‘Visitor’ and the**
  ‘Chain of Responsibility’ **Design Patterns** (see later)

•... [many more]
Physics:

• **Cross-Section models:**
  • ...

• **Hadronization schemes:**
  • NeuGEN’s KNO-based hadronization (tuned to reproduce exp. data for low multiplicity interactions)
  • Interface to PYTHIA hadronization model (suitable for higher multiplicity interactions)
  • Charm hadronization scheme (using fragmentation functions + charm fractions)

• **Particle Decays:**
  • Interface to PYTHIA decayer
  • Custom resonance decayer using ROOT’s phase space generator

• **Nuclear effects:**
  • Bodek-Ritchie Fermi Gas model
  • Pauli blocking

• **PDFs:** PDFLIB interface, Bodek-Yang PDFs

• **Event Generation Modules:** developed for QEL, RES & DIS

  • … [many more]
GENIE Framework Support for Model Validation

“Static” Model Validation Scheme

Automatically generated multi-page document
Showing model predictions / comparisons with data

“Dynamic” Model Validation Scheme

GUI application accessing MySQL database with the world’s data,
showing cross sections for various channels / physics configurations,
performing global fits...

Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>, CCLRC – Rutherford Lab.
GENIE OO Design Highlight:
Event Generation Framework

**Event Generation Framework**

- **EventGenerator**
  - A collection of EventRecordVisitors that can accept and be modified by an EventRecordVisitor
  - Is an EventRecordVisitor itself. Holds a list of EventRecordVisitors, loops through all of them and delegates the process request.
  - FLEXIBILITY: You can plug in/out the EventRecordVisitors from this list

- **EventRecordVisitor**
  - VisitsObjectStructure(event_rec::RecordBase *)

- **EventRecord**
  - AcceptsVisitor(vis: EventRecordVisitor *)

- **StdhepRecord**
  - Interaction: Interaction *
  - SetParticle(pos:int): StdhepParticle *
  - FindParticle(pdg:int, status:int, startpos:int): StdhepParticle *
  - IsPauliBlocked(): bool

- **TClonesArray**

- **StdhepParticle**
  - STDM information for 1 particle

- **TClonesArray**
  - Example: Concrete EventRecordVisitors relevant to QEL event generation

- **GENIE**
  - GenerateEvent(in p4: const TLorentzVector &): EventRecord *

- **EvGenChain**
  - FindGenerator(in: const Interaction *): const EventGenerator *

- **GVtdContext**

**CCLRC Rutherford Appleton Laboratory**

**Costas Andreopoulos**
<br>CCLRC – Rutherford Lab.
<br>C.V.Andreopoulos@rl.ac.uk
Lots of interesting ideas were discussed in previous talks

• *Measurements in the neutrino sector with unprecedented accuracy*
  • *In detectors of mind-blowing size*

However, to study neutrinos you must get them to interact…

_and understanding neutrino interactions can be a major limiting factor for future precision studies with ~GeV neutrinos_

We are trying to address the MC generator issues

_and we hope that we have kick-started what will evolve into the Universal Neutrino Generator_