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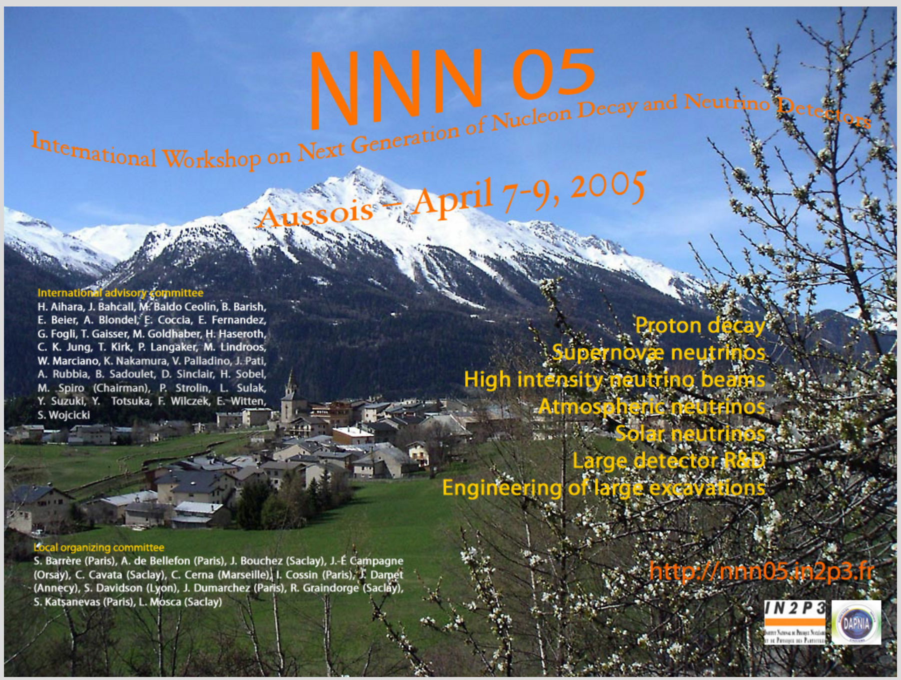


Neutrino Interactions & MC Event Generators

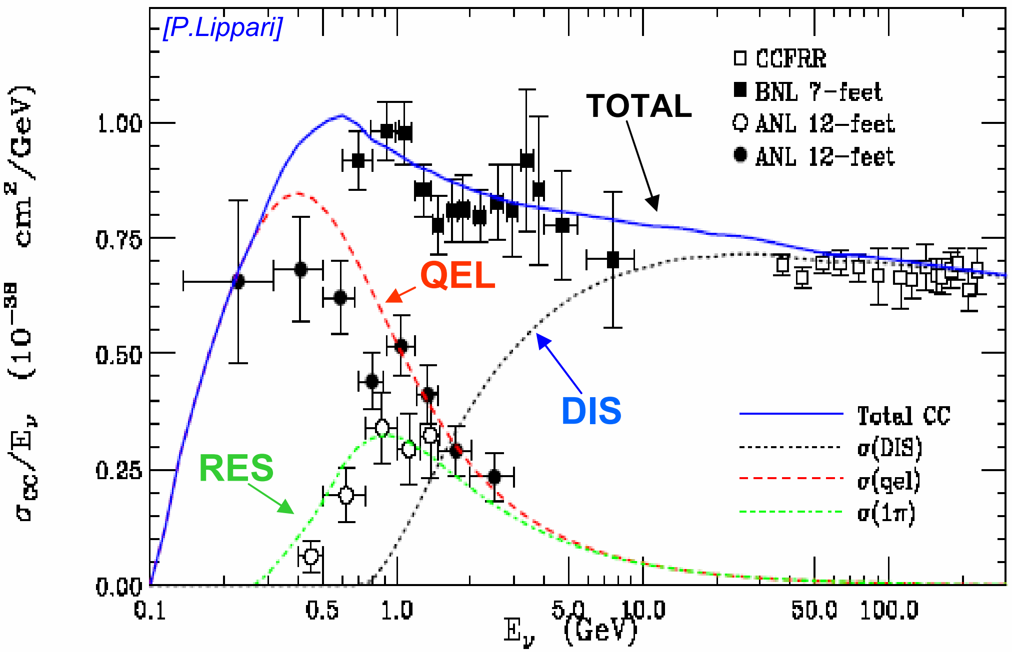
Costas Andreopoulos <C.V.Andreopoulos@rl.ac.uk>

Outline

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

- Neutrino Interaction Monte Carlo Generators

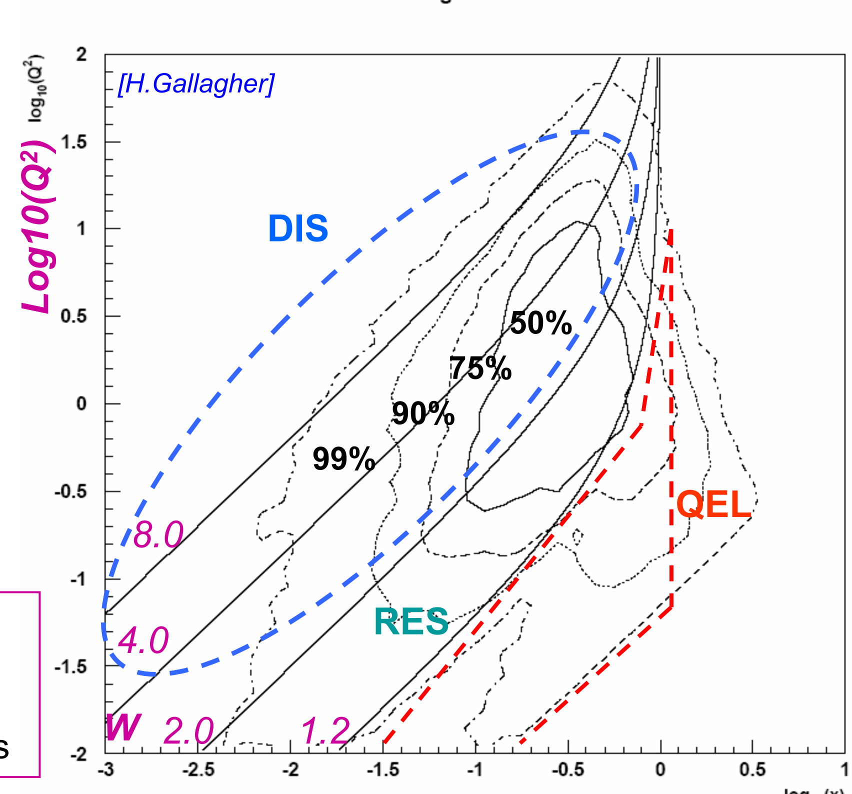
Neutrino Cross Sections in the ~ few GeV energy range



Most important components of total xsec @ few GeV

- Quasi-Elastic *(QEL)* scattering
  low Q^2, $W \approx M_N$
- Resonance *(RES)* excitation
  low Q2, ~1 GeV < W < ~ 2 GeV
- Deep-Inelastic *(DIS)* scattering
  large Q2, W >≈ 2 GeV

Kinematic Coverage of NUMI PH2LE Beam



Typical cross section decompositions

$$\sigma_{total} = \sigma_{QEL} + \sigma_{1\pi}\Big|_{W \le W_{CUT}} + \sigma_{DIS}\Big|_{W > W_{CUT}}$$

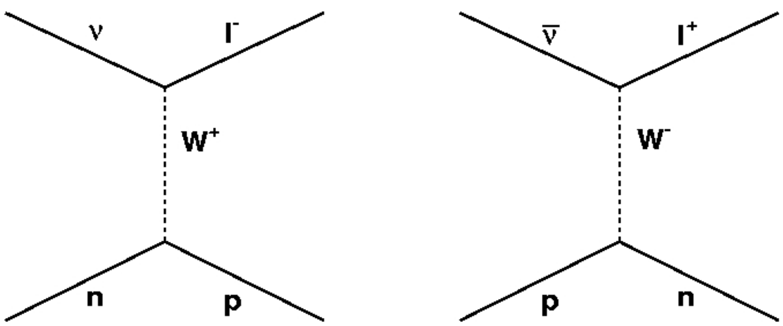
$$\sigma_{total} = \sigma_{0\pi} + \sigma_{1\pi} + \sigma_{2\pi} + \ldots$$

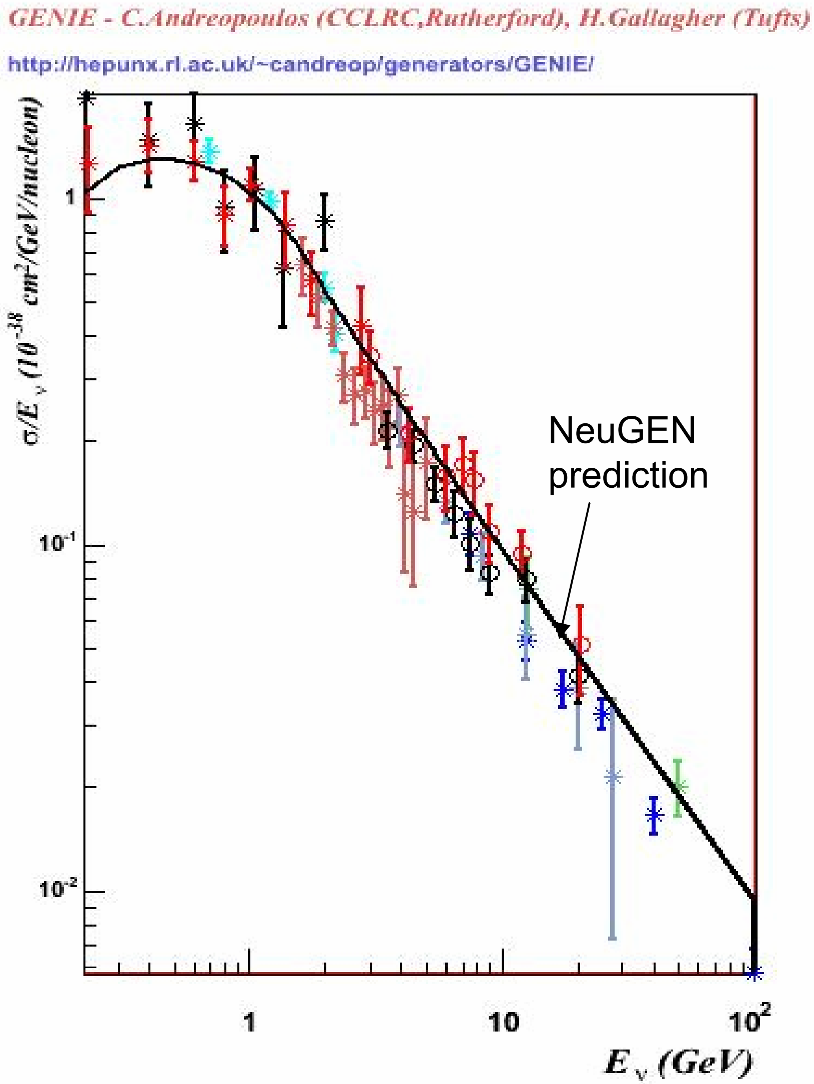
The situation:

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

Quasi-Elastic Scattering

$$\nu_l + n \rightarrow l^- + p \qquad \bar{\nu}_l + p \rightarrow l^+ + n$$





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

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

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)*

Resonance Excitation

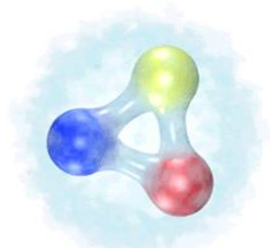
$$\nu + N \rightarrow l + Resonance$$
$$Resonance \rightarrow N' + n \cdot \pi$$

$$\begin{array}{lllll}
\nu\ CC: & \nu p \to l^- p \pi^+ & \nu n \to l^- p \pi^0 & \nu n \to l^- n \pi^+ & \\
\bar{\nu}\ CC: & \bar{\nu} n \to l^+ n \pi^- & \bar{\nu} p \to l^+ n \pi^0 & \bar{\nu} p \to l^+ n \pi^- & \\
\nu\ NC: & \nu p \to \nu p \pi^0 & \nu p \to \nu n \pi^+ & \nu n \to \nu n \pi^0 & \nu n \to \nu p \pi^- \\
\bar{\nu}\ NC: & \bar{\nu} p \to \bar{\nu} p \pi^0 & \bar{\nu} p \to \bar{\nu} n \pi^+ & \bar{\nu} n \to \bar{\nu} n \pi^0 & \bar{\nu} n \to \bar{\nu} p \pi^-
\end{array}$$

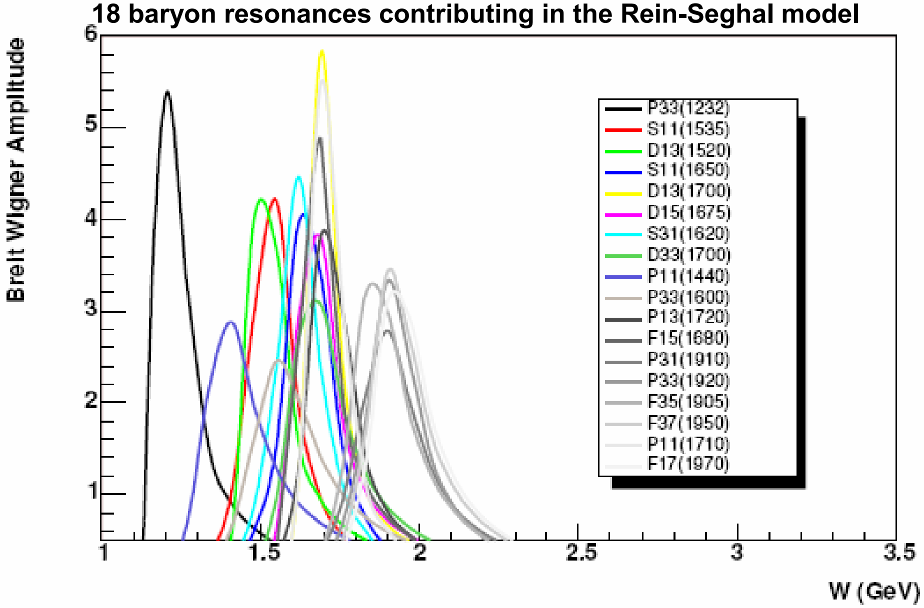
Very important channel(s) / ~30% of the total CC xsec around ~ 1 GeV

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

The most widely used model (*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.



18 baryon resonances contributing in the Rein-Seghal model



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

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

Assuming dipole form Q^2 dependence

Resonance Excitation

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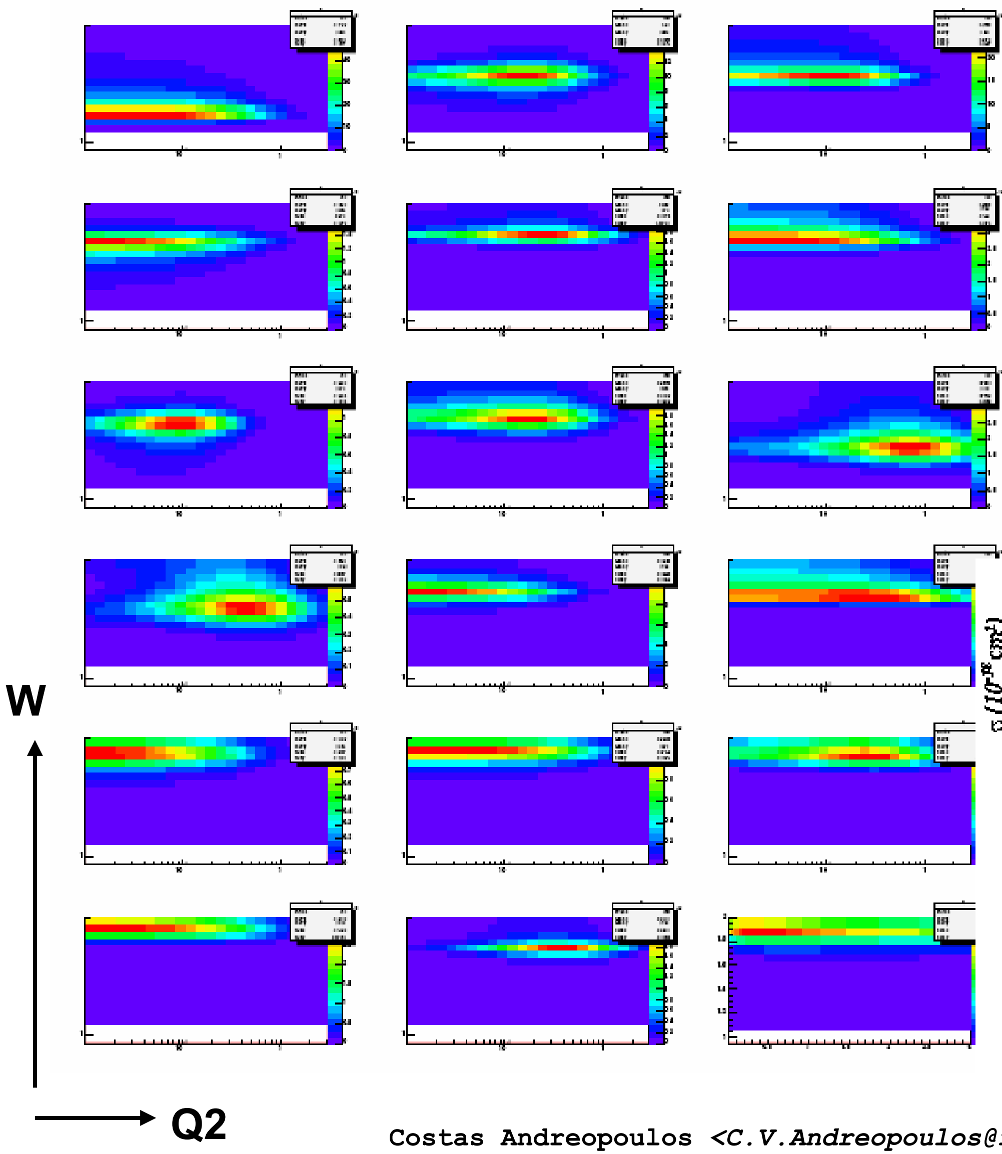
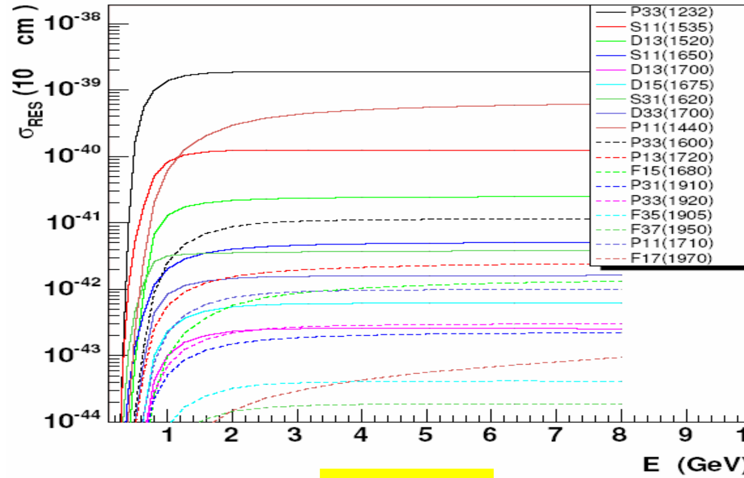
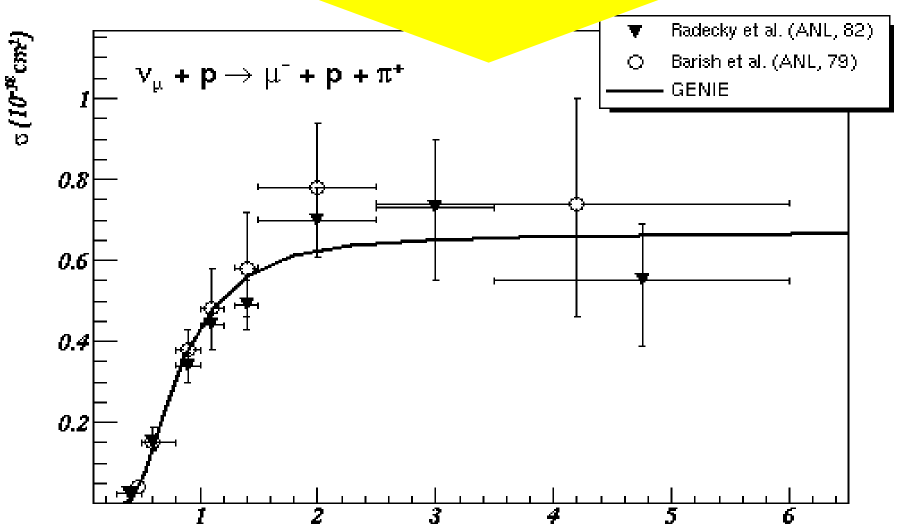
R/S Resonance Production Diff. Cross Sections (numu+p, 4 GeV)





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



Resonance Excitation
[new models]

New theoretical attempts to describe resonance excitation channels.

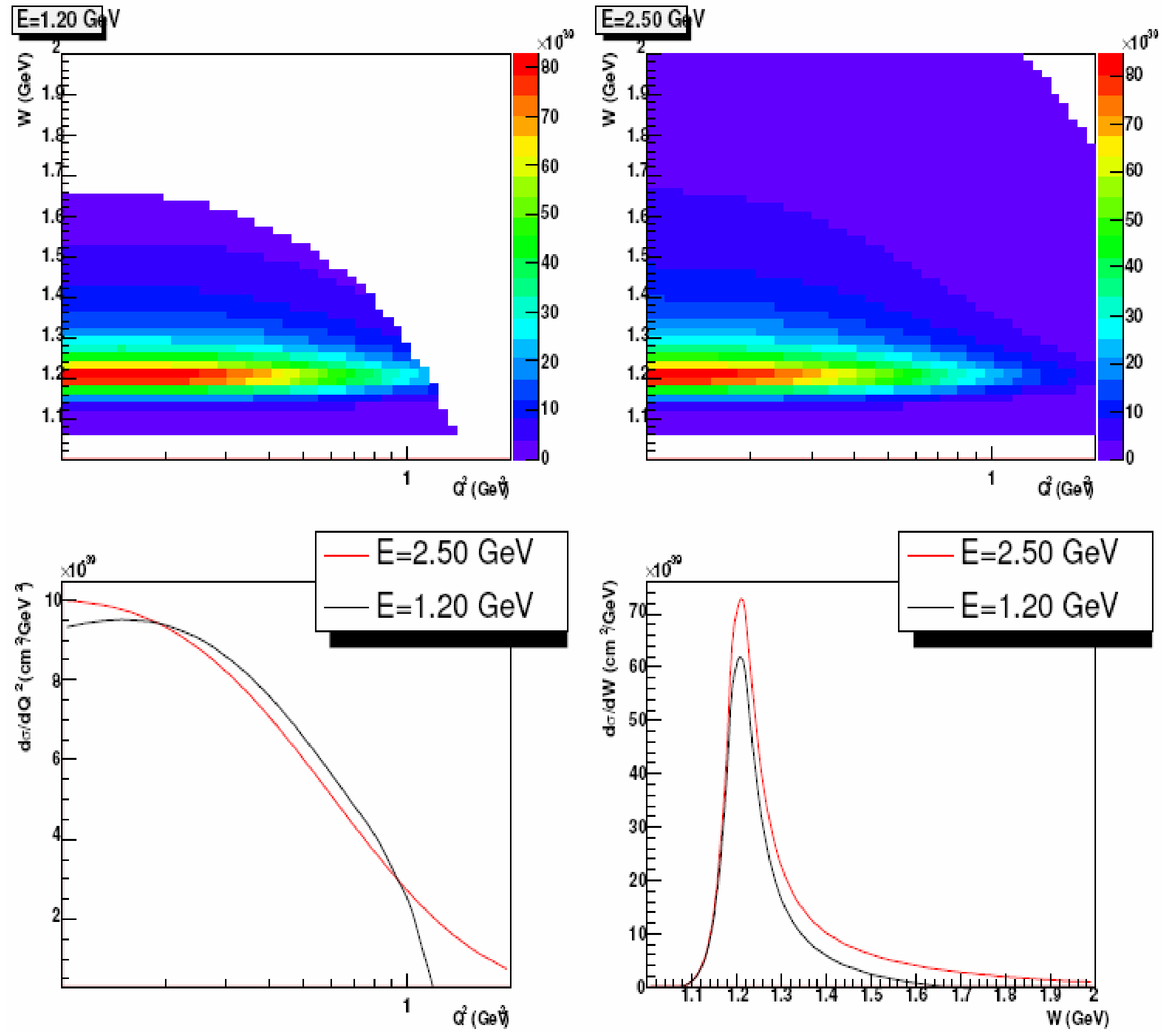
The new models address some known R/S model deficiencies

- Improved description of v 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
*"Resonance Production by Neutrinos - J=3/2 resonances." **hep-ph/0501109***

- 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**

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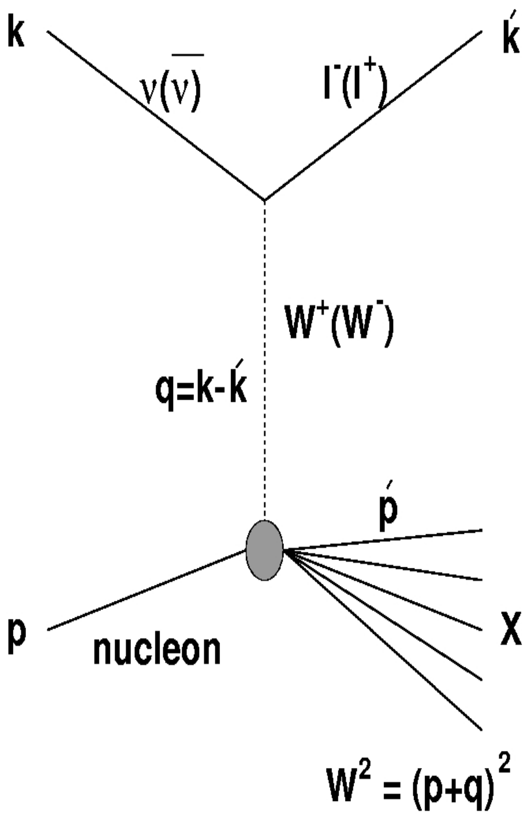
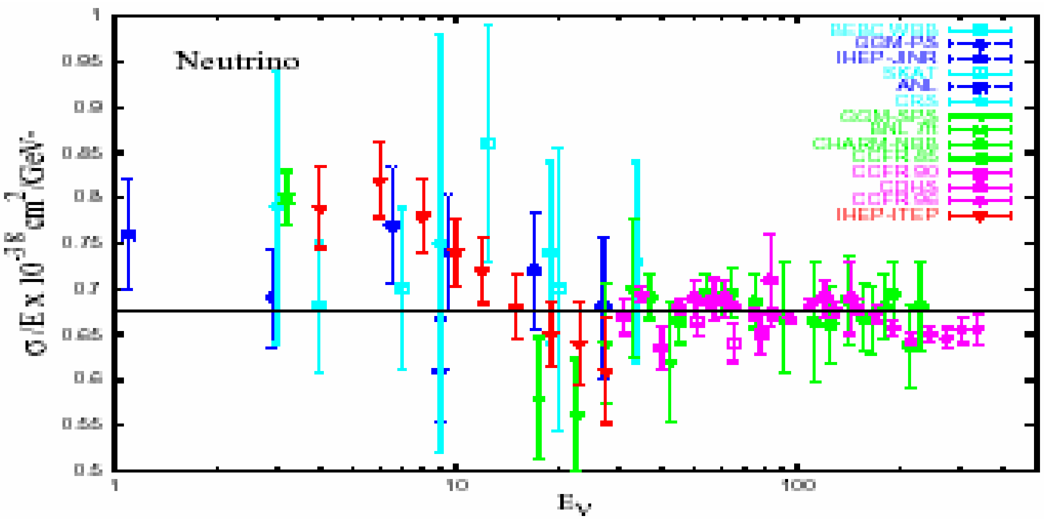
Deep Inelastic Scattering



$$\frac{d^2\sigma_{DIS}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi}\Bigg\{y(xy + \frac{m_l^2}{2E_\nu M})\cdot F_1 + (1 - y - \frac{xyM}{2E_\nu} - \frac{m_l^2}{4E_\nu^2})\cdot F_2 \pm$$
$$(xy(1-\frac{y}{2}) - \frac{y m_l^2}{4E_\nu M})\cdot F_3 + (\frac{xym_l^2}{2E_\nu M} + \frac{m_l^4}{4E_\nu^2 M^2})\cdot F_4 - \frac{m_l^2}{2E_\nu M}\cdot F_5\Bigg\}$$

- 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
- …



Unlocking the hadronic tensor mysteries…

- *What have we measured?*

- *How well do we understand cross sections?*

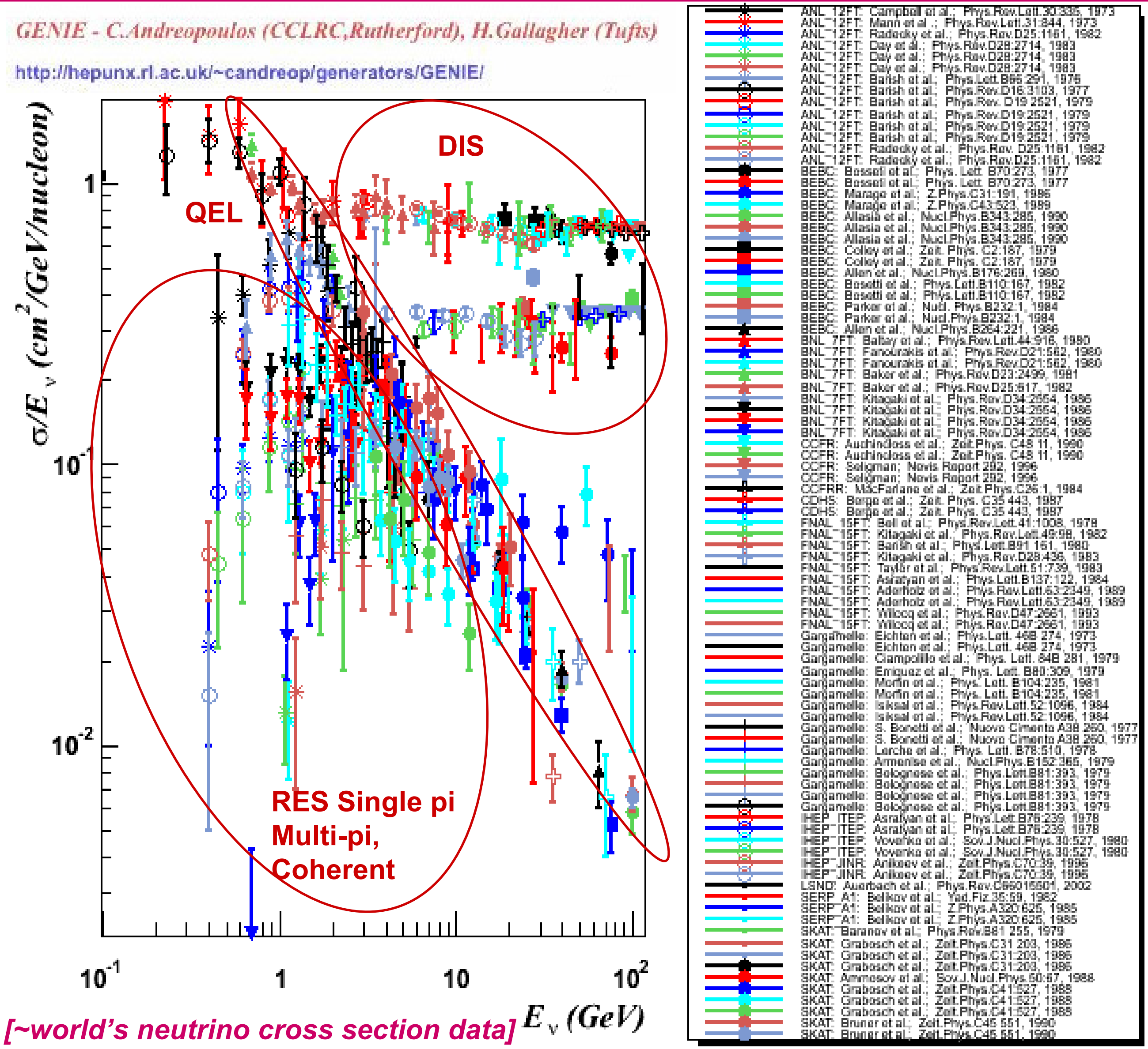
- *What are the major unknowns?*

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

Hadronic tensor

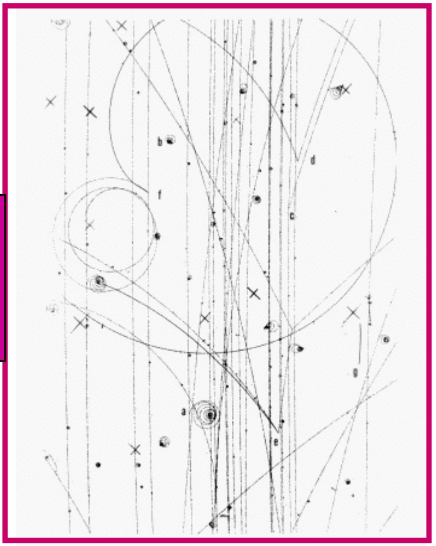
$$W^{\mu\nu} = W_1 g^{\mu\nu} + W_2 p^\mu p^\nu + W_3 \varepsilon^{\mu\nu\alpha\beta} p_\alpha p_\beta + W_4 q^\mu q^\nu + W_5 (p^\mu q^\nu + p^\nu q^\mu)$$

Available data – *1/3*
[*Neutrino Cross Sections*]



[~world's neutrino cross section data]

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



Data are rather poor with large errors

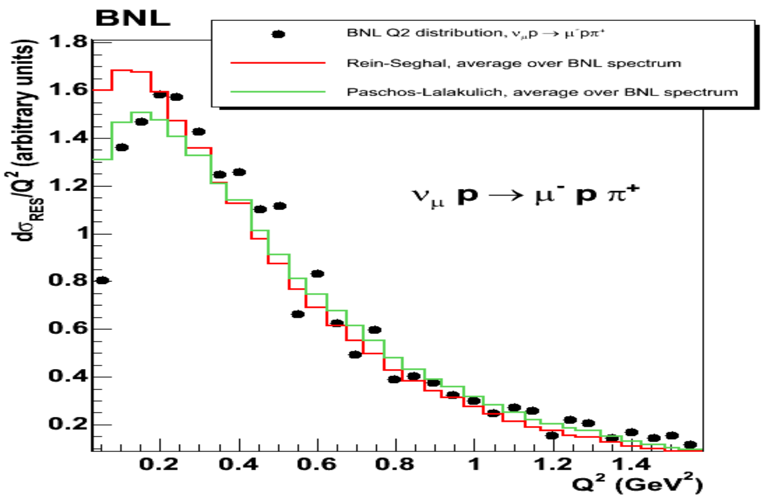
but nevertheless

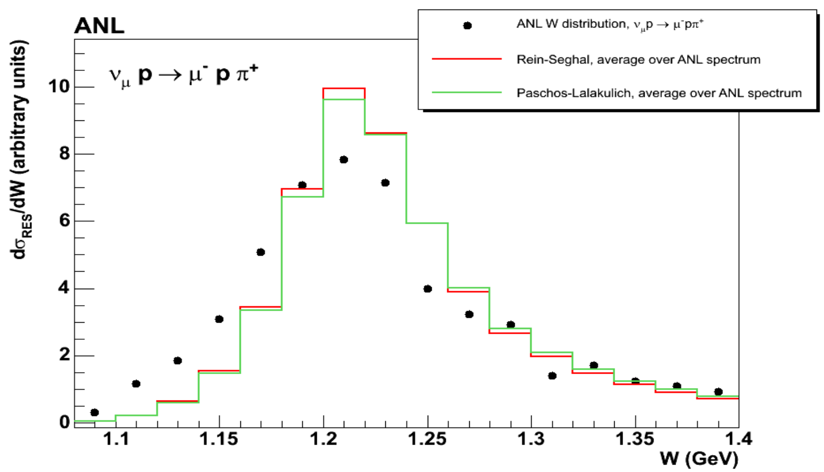
are an **invaluable resource** in developing / tuning neutrino interaction models

Available data – 2/3

Differential Neutrino Cross Sections

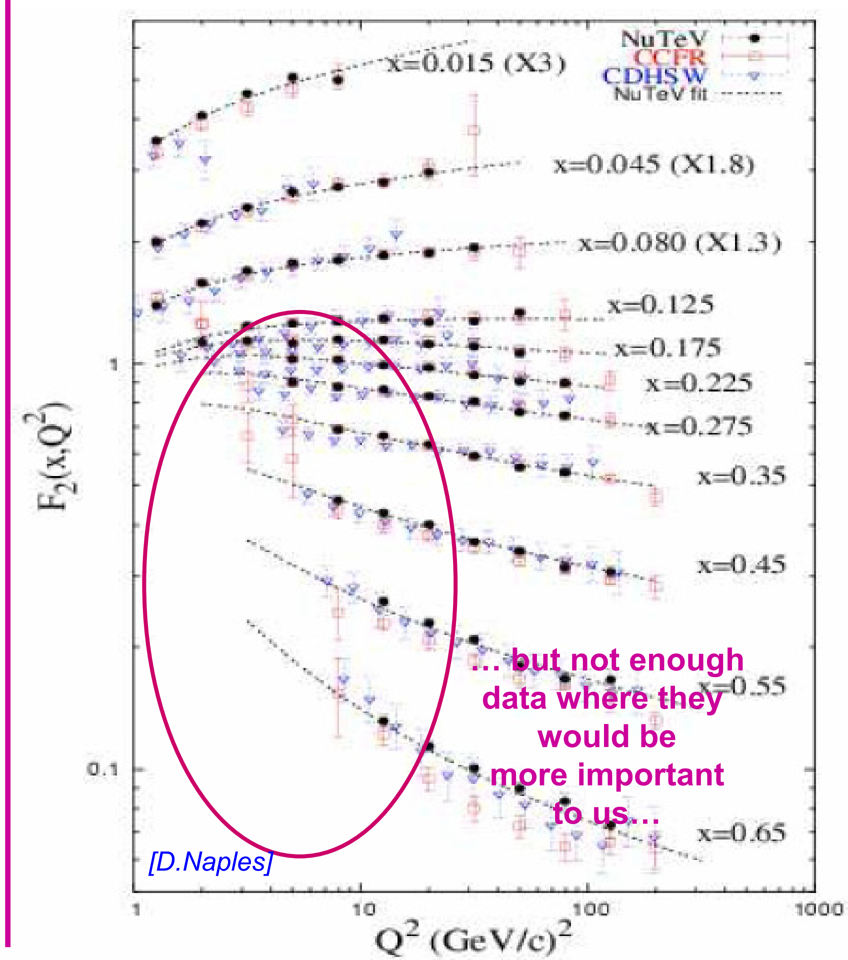
- *even more sparse and even more useful data*
- *many effects (radiative corrections, nuclear effects,…) can change the differential xsec more dramatically than the total xsec*





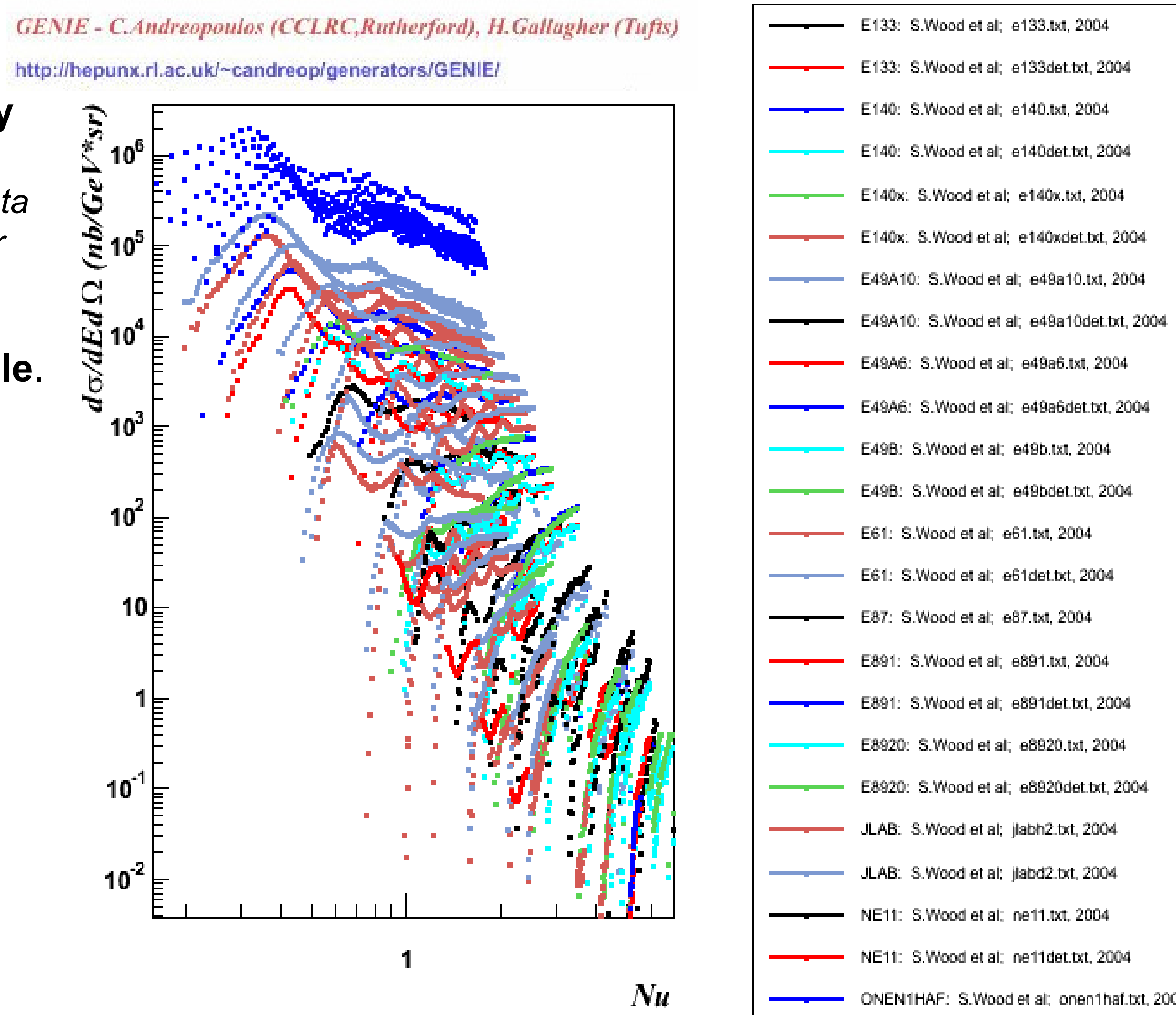
Structure Functions

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



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)]
are (or are becoming) **available**.



Very useful data for neutrino physics:

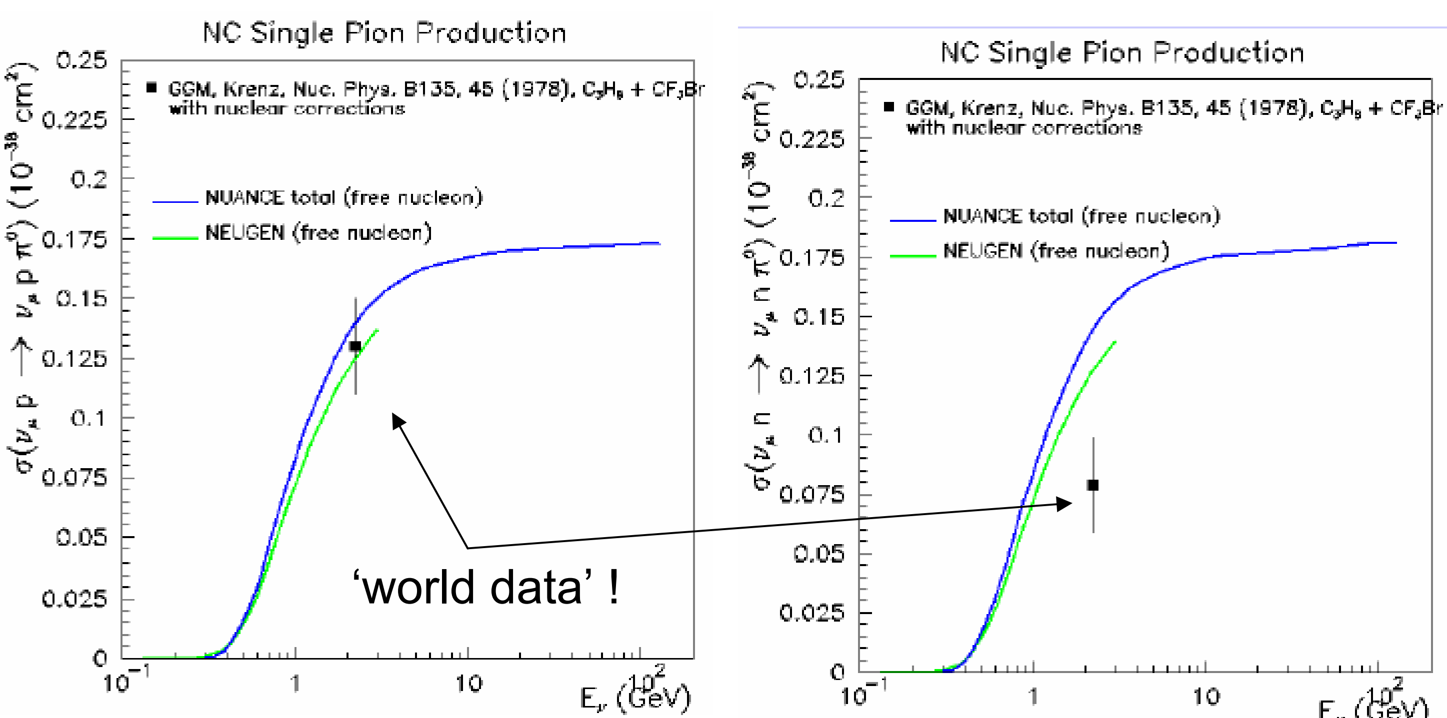
- Evaluating the vector part of neutrino interaction models
- Studying the RES/DIS joining region
- Modelling nuclear effects

Unknowns…

[just some highlights]

Process	uncertainty
Quasi-Elastic scattering	**~20%**
Resonance excitation	**~40%**
Deep-Inelastic scattering	**~15% at high E**

Large uncertainties even for the major ~GeV cross section components



[Sam Zeller, NuINT-01]

Some exclusive channels are extremely poorly constained

example

$$\nu N \to \nu N \pi^0$$

Important background in

$$\nu_\mu \to \nu_e$$

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Unknowns… [nuclear effects]

What we can do best is:

Predicting cross sections for free nucleons and the final state primary lepton variables

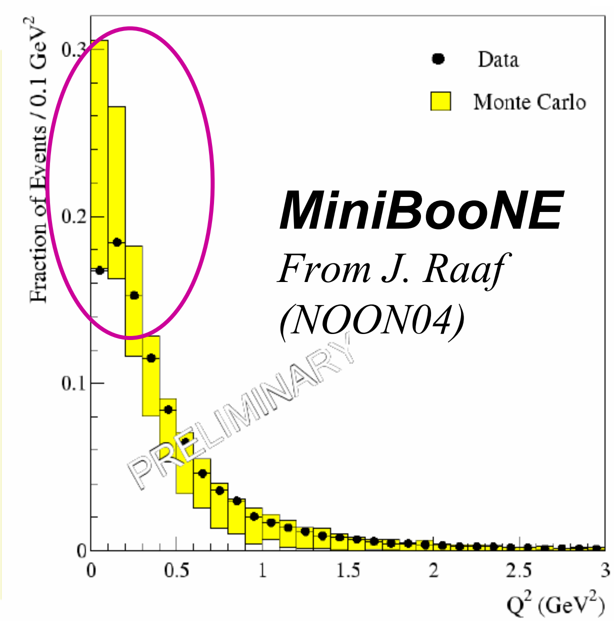
Predicting cross sections for nuclear targets

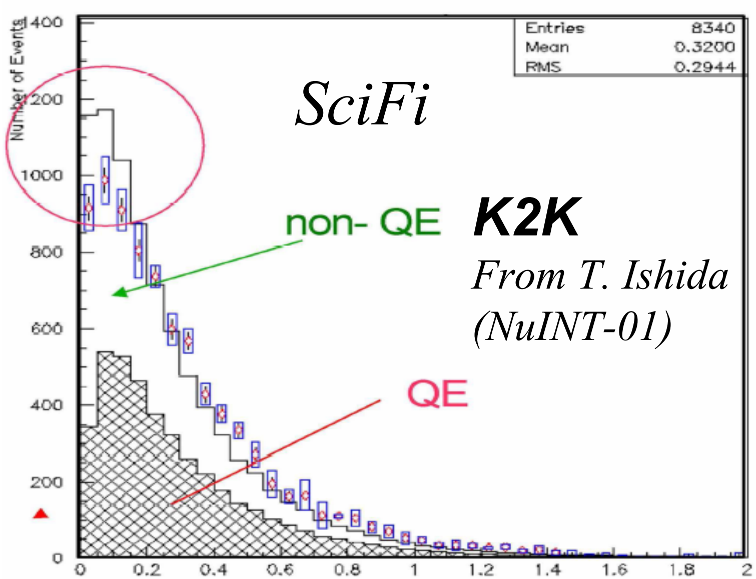
Predicting the final state primary lepton variables for ν interactions with nuclear targets

Predicting the final state hadronic system variables

…but these are strongly affected by nuclear effects

EXAMPLES:





Low-Q2 problems seen in all K2K detectors and in MiniBooNE

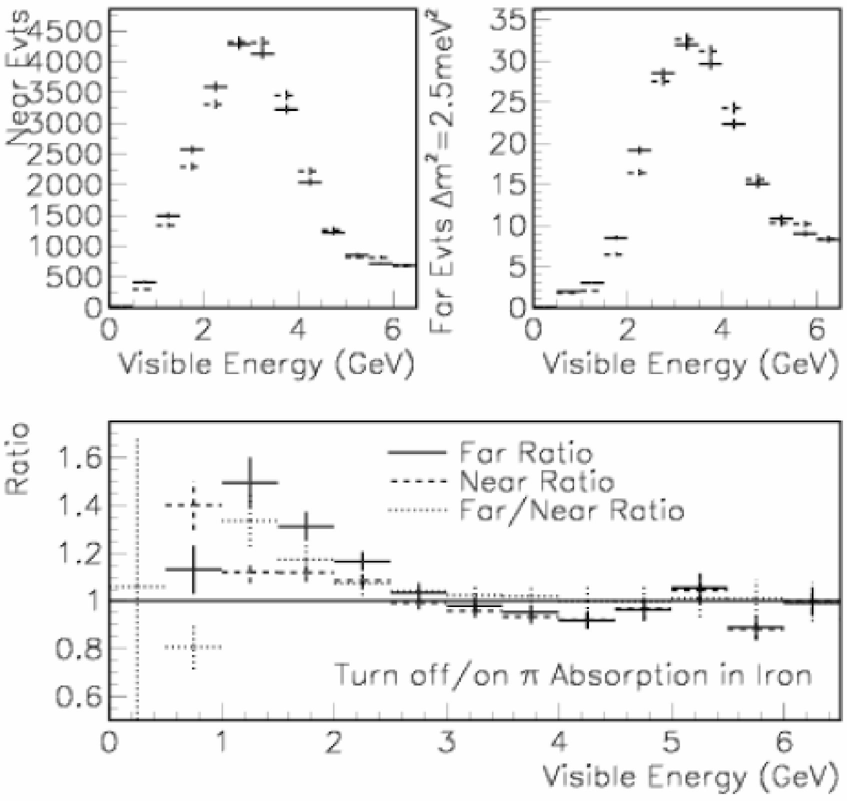
Unknowns…

[nuclear effects / examples continued]

(Final State re-Interactions/ FSI)

eg: Pion absorption

and how it affects the neutrino energy calibration



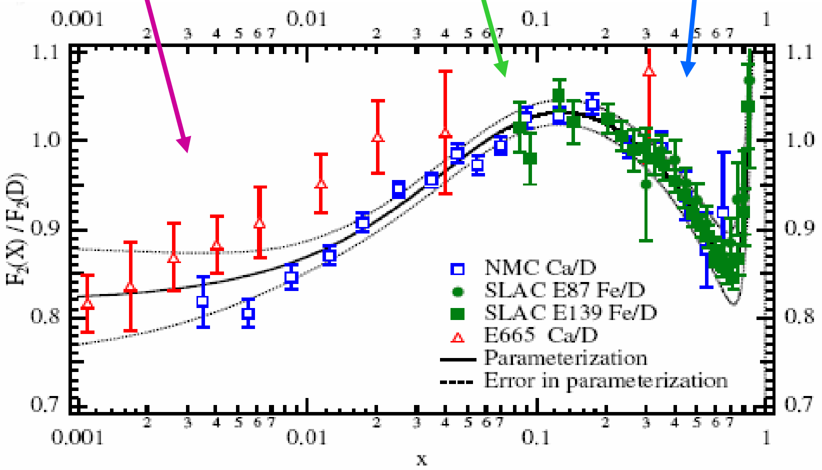
Affects differently the near & the far detector energy spectra. This is a major source of systematic errors in LBL exp.

[Debbie Harris, NuINT-04]

[EMC effect]

[anti-shadowing]

[shadowing]



- Never really measured with neutrinos
- Theoretical expectations for neutrinos differ

Unknowns…

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**

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Neutrino Monte Carlos

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…)*

The Universal Neutrino Generator

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

*(**GE**nerator for **N**eutrino **I**nteraction **E**xperiments)*

GENIE

OBJECT - ORIENTED
NEUTRINO GENERATOR

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 GENIE 'collaboration'

The right way ahead is through a <u>cross-experiment</u> but still <u>small & focused</u> 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

GENIE Component Overview – 1/2

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]*

GENIE Component Overview – 2/2

Physics:

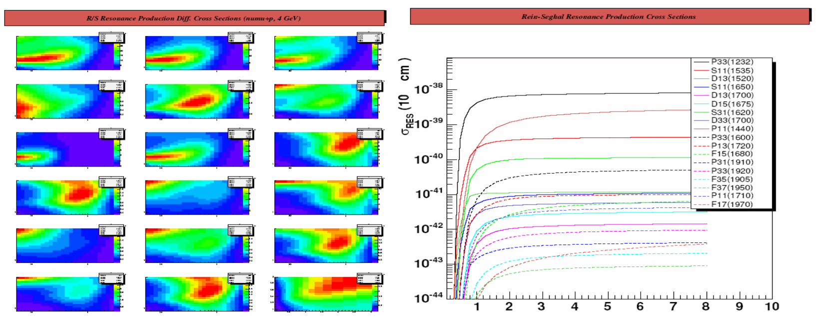
- ***Cross-Section models:***
  - **Quasi-Elastic:** *Paschos and Yu,* **hep-ph/010760**
  - **Resonance Excitation:** *Rein and Sehgal*, **Ann.Phys.133, 79 (1981)**; Paschos and Lalakulich, ***hep-ph/0501109***
  - **Deep Inelastic:** *Paschos and Yu,* **hep-ph/010760**
  - **Deep Inelastic + radiative corrections:** *Bardin and Dokuchaeva*, **JINR-E2-86-260 (1986)**
  - **Coherent NC pi0:** *Rein and Sehgal*, **Nucl.Phys.B233, 29 (1983)**
  - **LO DIS charm production:** *Aivazis et al.*, **Phys.Rev.D50, 3085 (1994)**
  - **QEL charm production:** *Kovalenko,* **Sov.J.Nucl.Phys.52:934(1990)**
  - **Inverse Muon Decay + radiative corrections:** *Bardin and Dokuchaeva*, **Nucl.Phys.B287:839 (1987)**
  - *…*
- ***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**

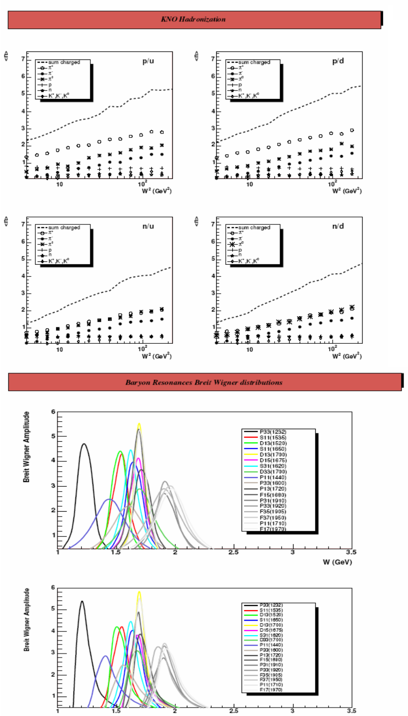
- *… [many more]*

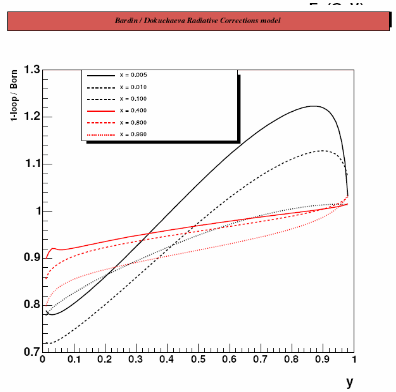
GENIE Framework Support for Model Validation

“Static” Model Validation Scheme

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





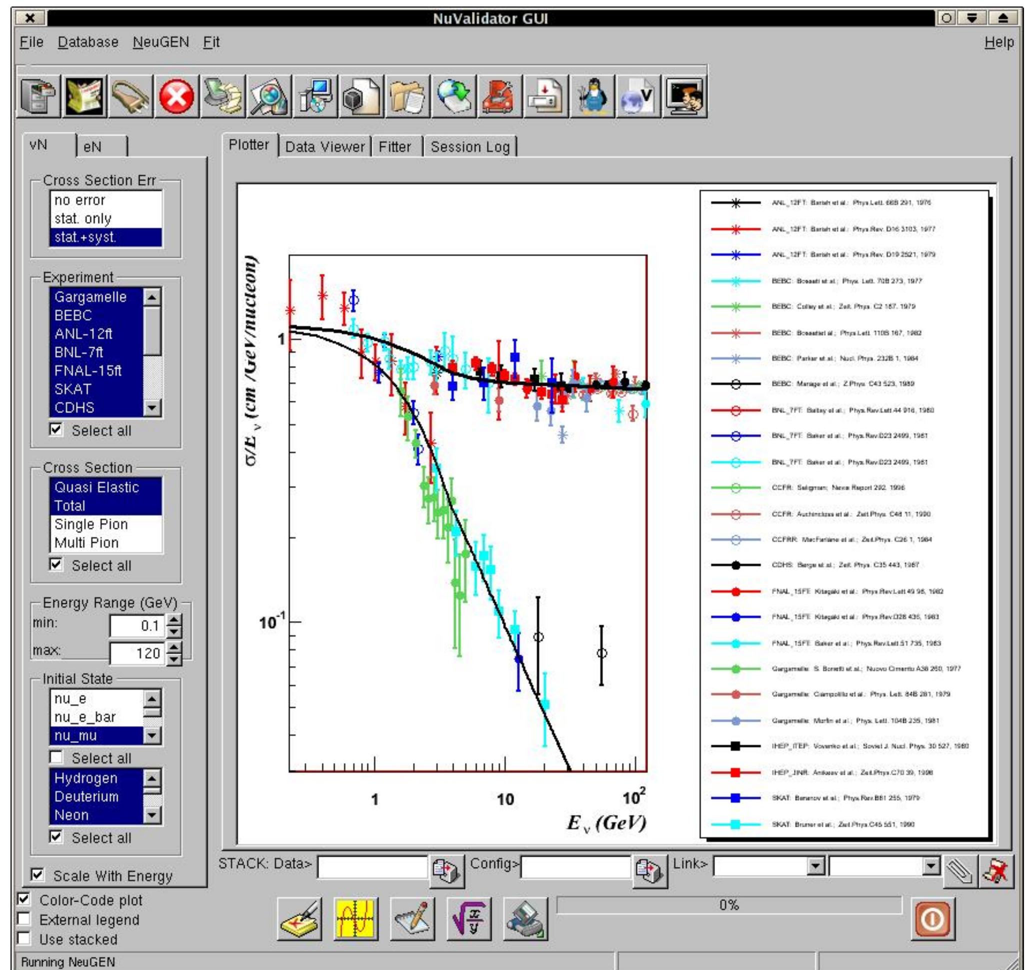


[many more]

...

“Dynamic” Model Validation Scheme

GUI application accessing MySQL dbase with the world’s ν data, showing cross sections for various channels / physics config., performing global fits…



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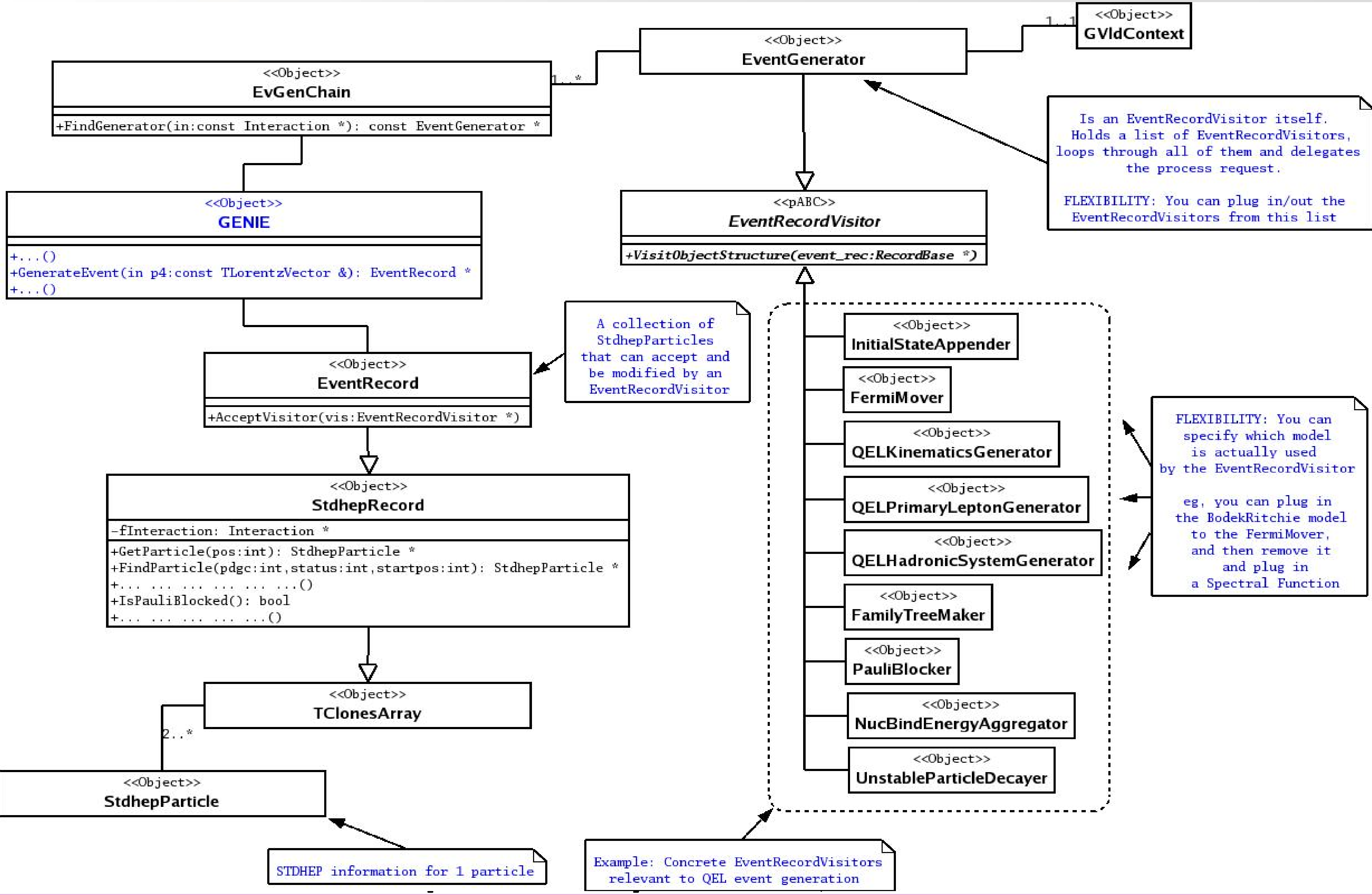
GENIE OO Design Highlight: Event Generation Framework



Summary

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