THE UNIVERSITY OF WARWICK

Quasi-elastic-like and other recent and future updates to GENIE

Andy Furmanski
GDR Neutrino, Nov 2014

GENIE

- **G**enerates **E**vents for **N**eutrino **I**nteraction **E**xperiments

- General-purpose neutrino interaction simulation software

- Written and maintained by an international collaboration

- Not directly linked to an individual experiment
  - But used by many
  - Expected to be ready out-of-the box for most purposes
  - Aim to be valid from MeV to PeV!

- Object-oriented code (C++)
  - Designed to be extendable and customisable

- Comes bundled with a large amount of experimental data and validation tools
  - Unique (I think) in its ability to simulate both neutrino and electron scattering

GENIE – a history

- Initially developed within MINOS, to replace their generator NEUGEN.

- **2004-2007**, development of framework, implementation of original physics models

- **2007**, first release v2.0.0

- Since 2007, several official releases have been made
    - Main improvements have been software related
    - Improvements to interfaces to flux drivers, detector geometries etc.
    - Systematic error evaluation

- GENIE is used by T2K, NOvA, MINERvA, MicroBooNE, Lar1-ND, LBNE, LAGUNA-LBNO, IceCuBE, OPERA, and several other experiments

- As GENIE has become very widespread, it is now important to keep it state-of-the-art!

Recent Releases

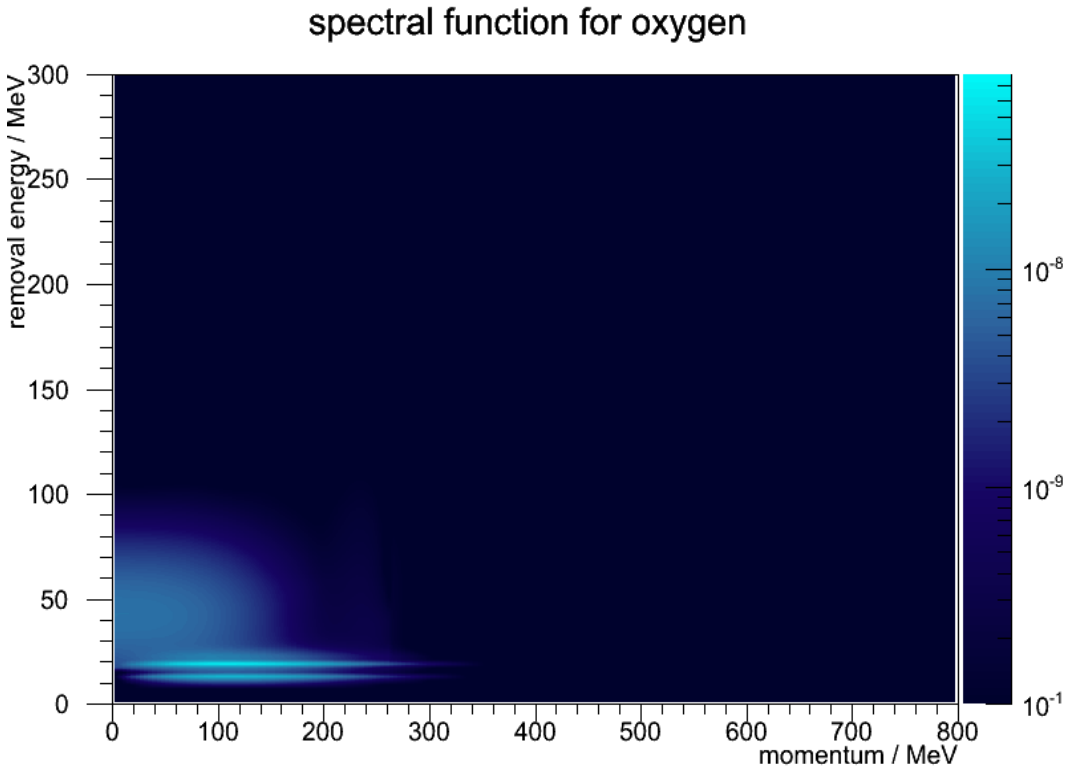
- **2.6.X** series :
  - Included electron scattering simulations
  - Improvements/additions to flux drivers
  - Bug fixes

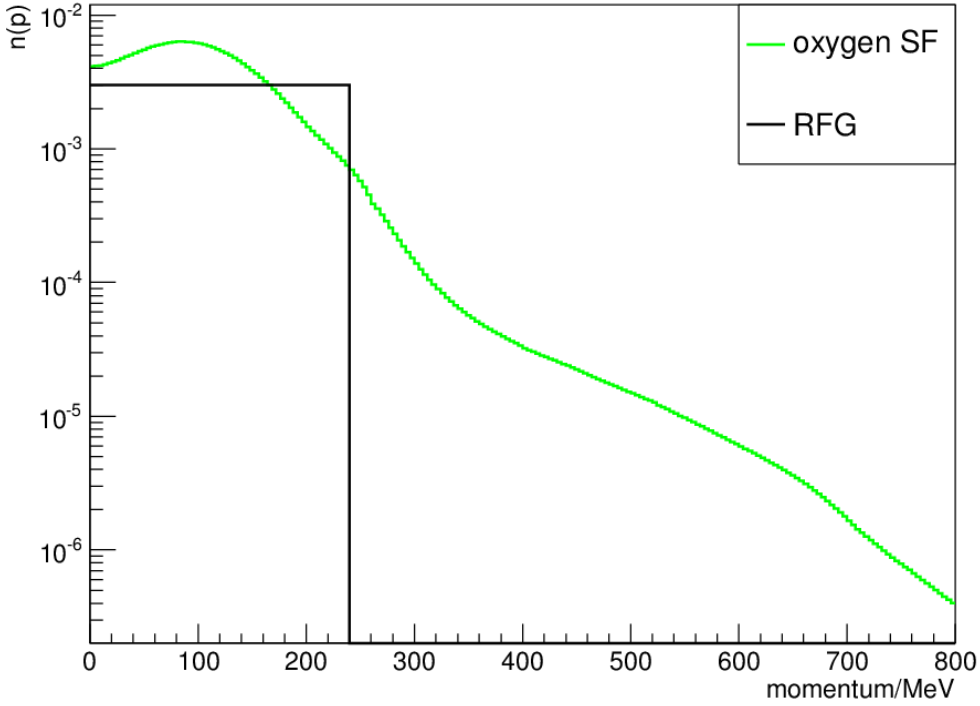
- **2.8.X** series
  - New interactions (MEC and inverse muon decay)
  - Included nucleon-decay simulations
  - Major overhaul of FSI routines
  - Improvements to data archives, validation, and reweighting
  - Many experimental features became full production features
  - Software improvements and bug fixes

Quasi-elastic: Spectral function

- Spectral function model is an alternative to the RFG model

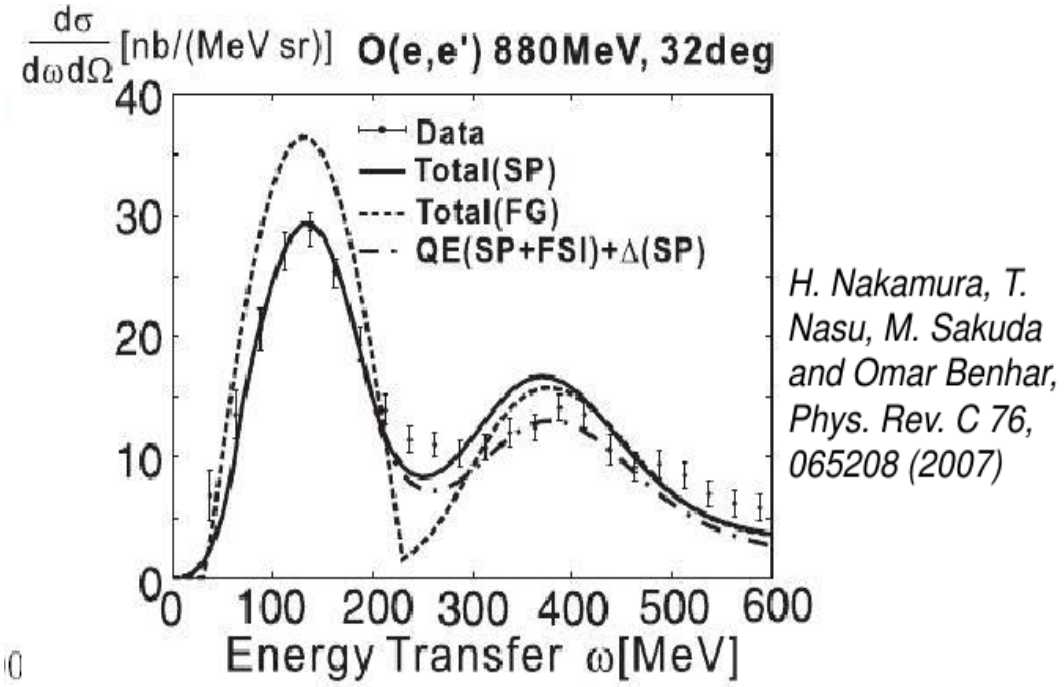
- Describes the initial state of the nucleus
  - Initial energy and momentum of nucleons
  - Correlation between momentum and binding energy
  - Long tail from correlated pairs of nucleons





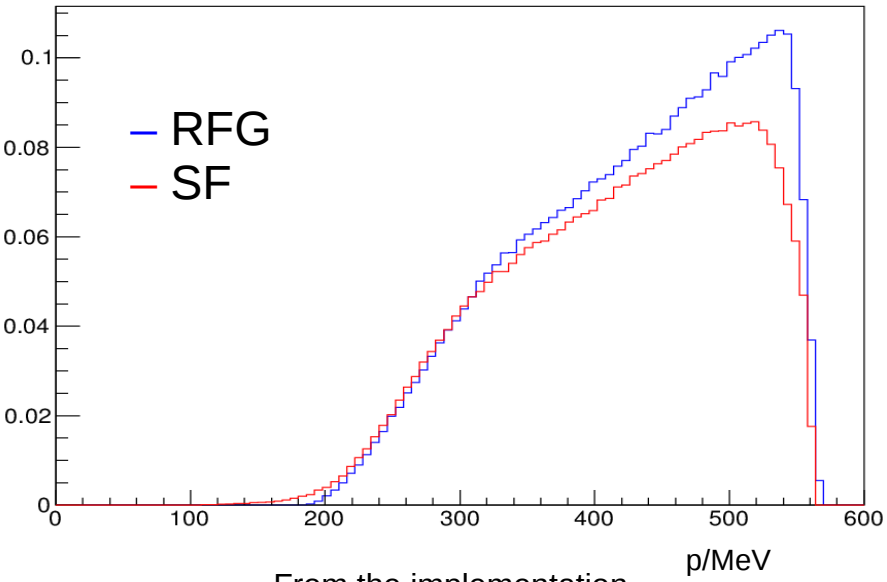
Quasi-elastic: Spectral function (2)

- SF has been shown to provide good agreement with electron scattering data
- High-p tail helps to fill in the 'dip' region between QE and delta peaks
- Smoother distribution clearly more physical than RFG model



H. Nakamura, T. Nasu, M. Sakuda and Omar Benhar, Phys. Rev. C 76, 065208 (2007)

Cross section as a function of muon momentum for CCQE on carbon at 600MeV



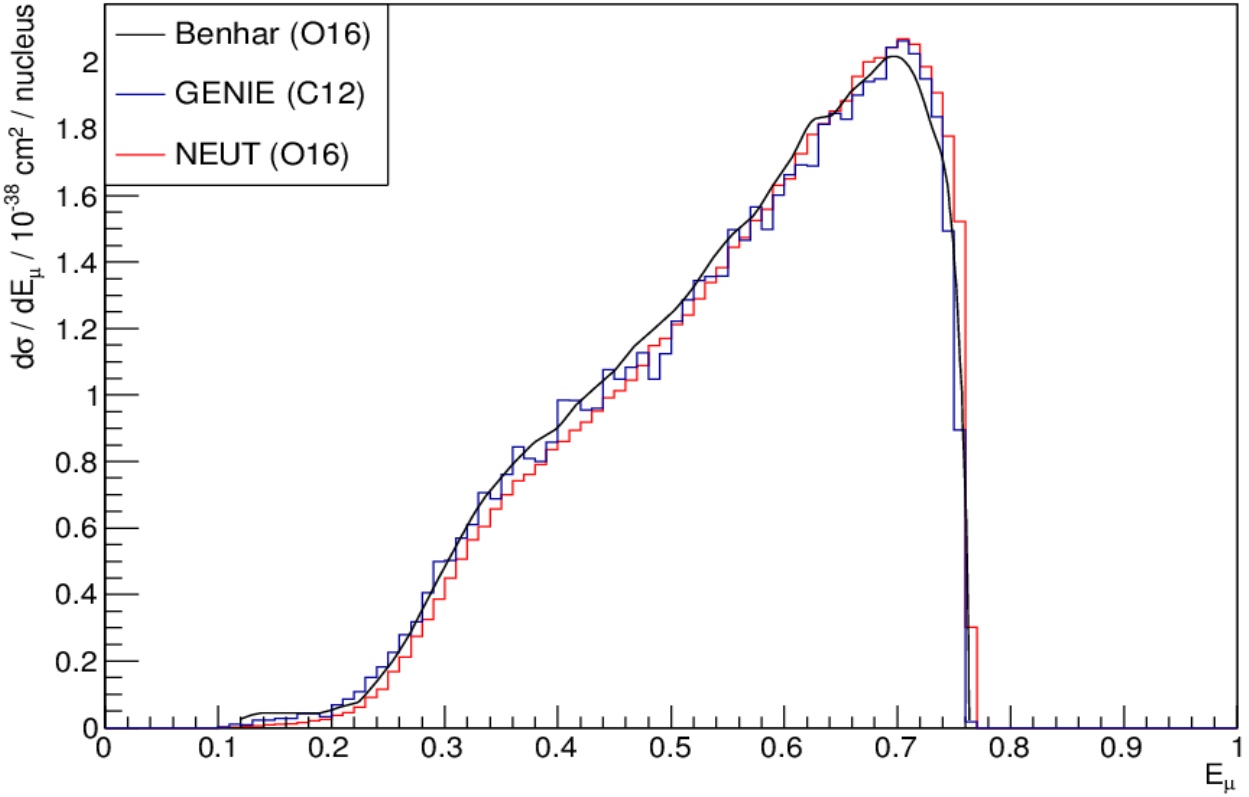
From the implementation in NEUT generator

Quasi-elastic: Spectral function (3)

- GENIE implementation developed by groups at Warwick and Virginia Tech

- Initial attempt to re-use RFG code, with a new nuclear model

- Lead to discovery of a minor bug in old code
  Fix is in place but causes a drop in efficiency

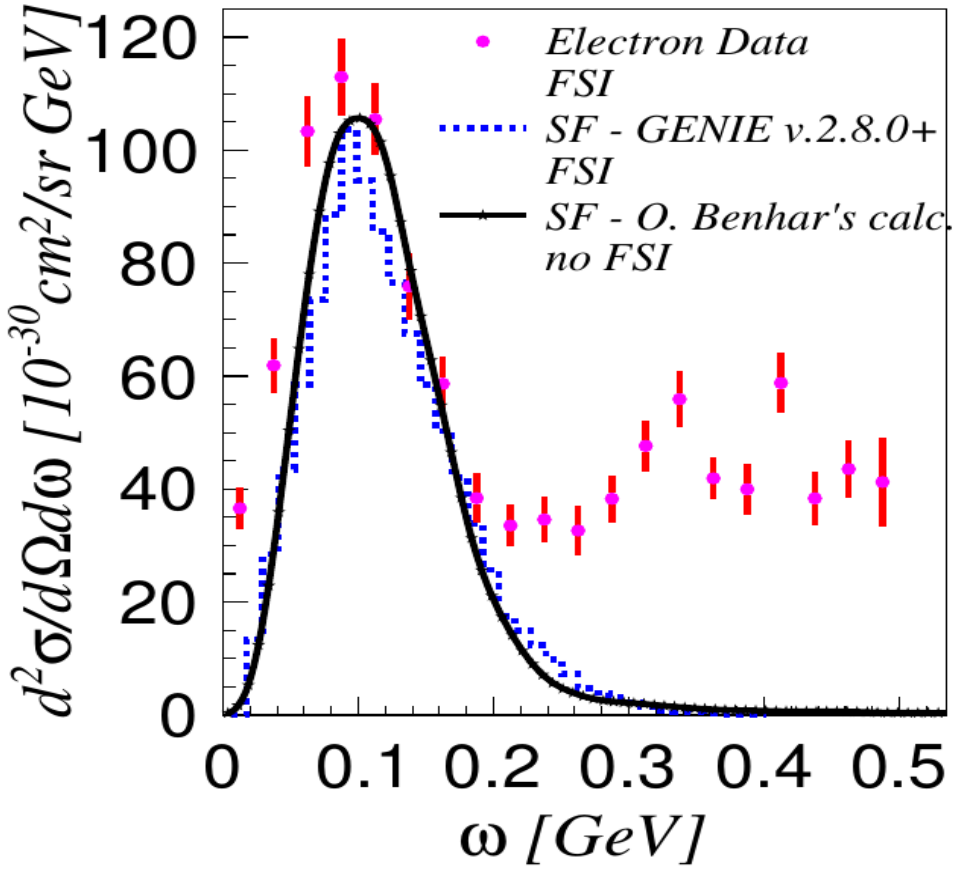


Spectral function plans

- Very good agreement shown in development branch
  - Likely to be included in the next minor release

- Code is very slow due to bug fix, not practical to use as default

- Effort is now focused on improving the efficiency



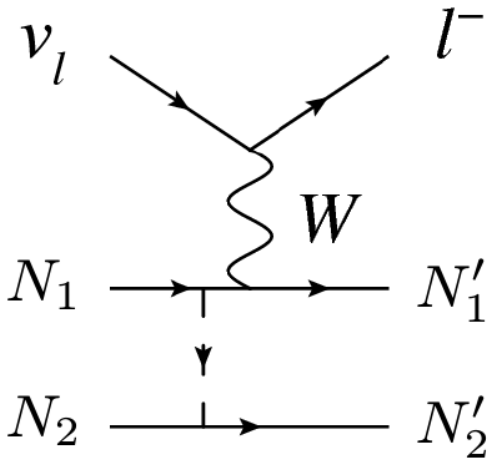
QE-like: MEC

Jackie Schwer

- Often suggested the reason for the MiniBooNE high MA is multi-nucleon processes

- If you can't see the nucleons, it looks like CCQE

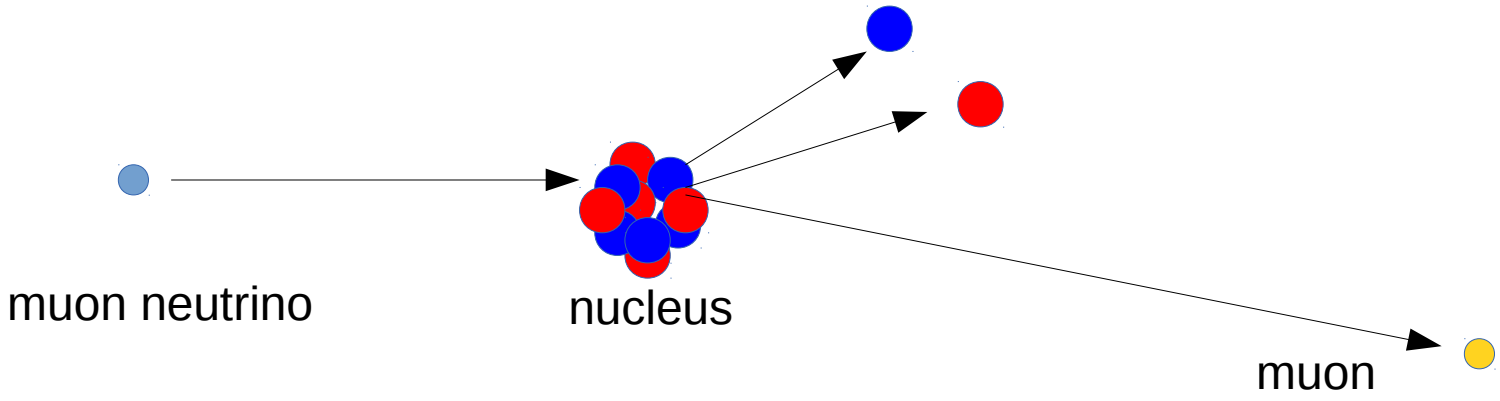
- Enhances the CCQE-like cross section



- A number of models on the market
  - Phenomenological fits (TEM)
  - Microscopic models (Nieves, Martini, …)

- Previously GENIE had a home-brew model
  - Fill the gap between CCQE prediction and MiniBooNE

- Work to implement a more rigorous model



Nieves' model

Jackie Schwer

- Interaction of neutrino with a pair of nucleons
  - 49 feynman diagrams calculated in full model

- Fortran code made available to GENIE developers
  - Calculates cross section double differential in lepton angle and kinetic energy

- Code is too slow to incorporate directly into GENIE

- Solution is to pre-compute tables

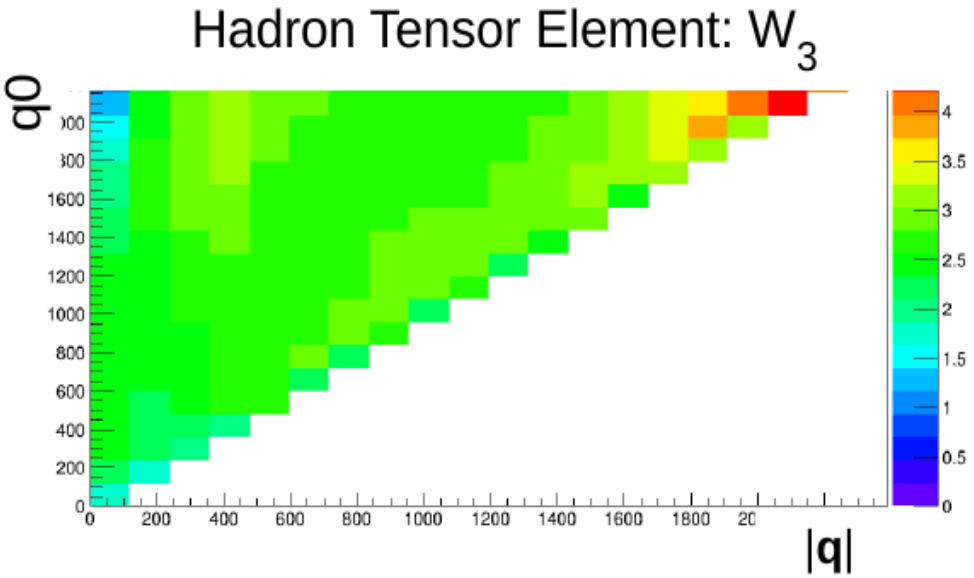
$$\left.\frac{\partial^2 \sigma}{\partial T_\mu \ \partial \cos(\theta_\mu)}\right|_{E_\nu}$$

Tables in GENIE

Jackie Schwer

- **Idea 1**: Store cross section as a function of muon kinematics and neutrino energy
  - Number of tables gets very large
  - Different tables required for each neutrino flavour

- **Idea 2**: Calculate hadronic tensor as a function of q^0 and **|q|**
  - Only need 5 2D tables for each target
  - Valid for all neutrino energies and flavours
  - Far less memory used
  - Cross section calculation is done quickly in GENIE



Hadronic simulation

Jackie Schwer

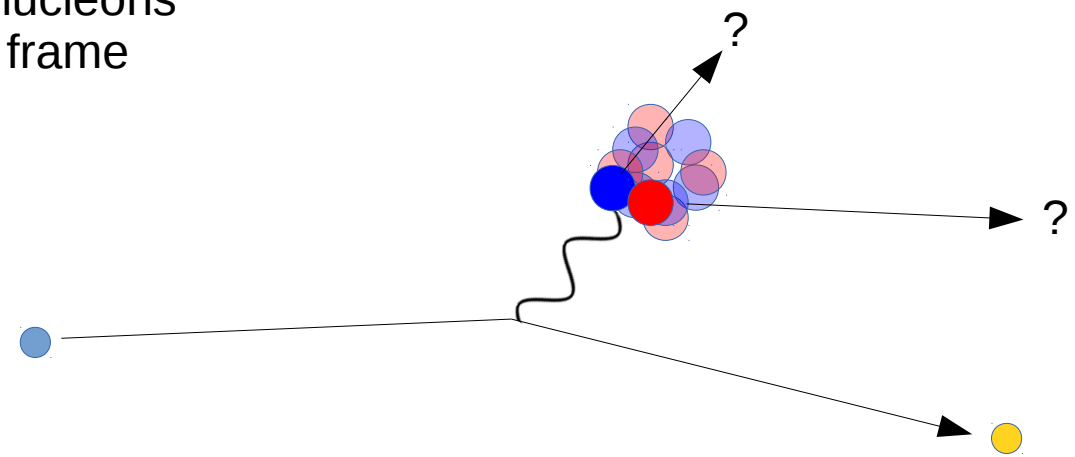
- Nieves' model makes no statement on the hadronic kinematics
    - Leptonic cross section is integrated over hadronic kinematics

- For a generator, we need all final-state particles simulated
    - Implement a simple model for the nucleons
    - Similar to implementation already present in GENIE

- Select two nucleons from the nucleus (global RFG)
    - Treat as one 'cluster'

- Add transferred momentum and energy to the cluster

- Decay cluster into two nucleons
    - isotropically in rest frame



MEC summary

Jackie Schwer

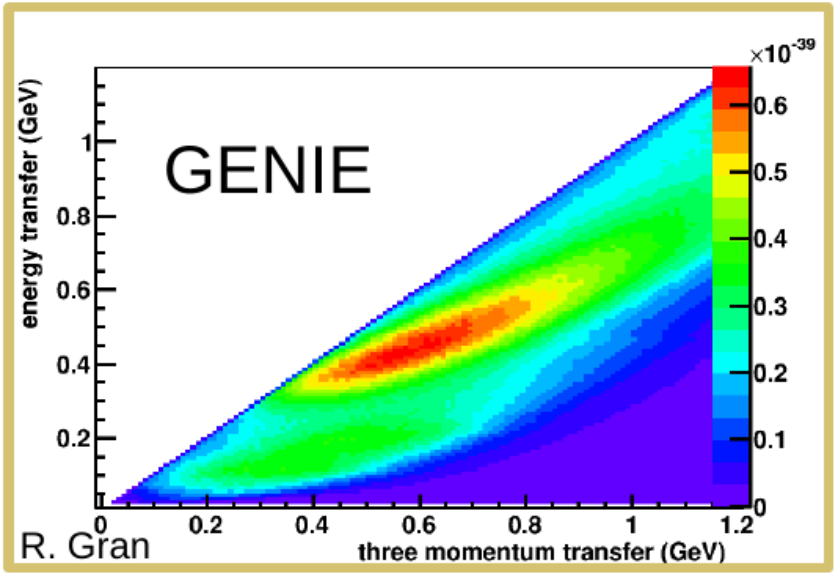
- Implementation working well

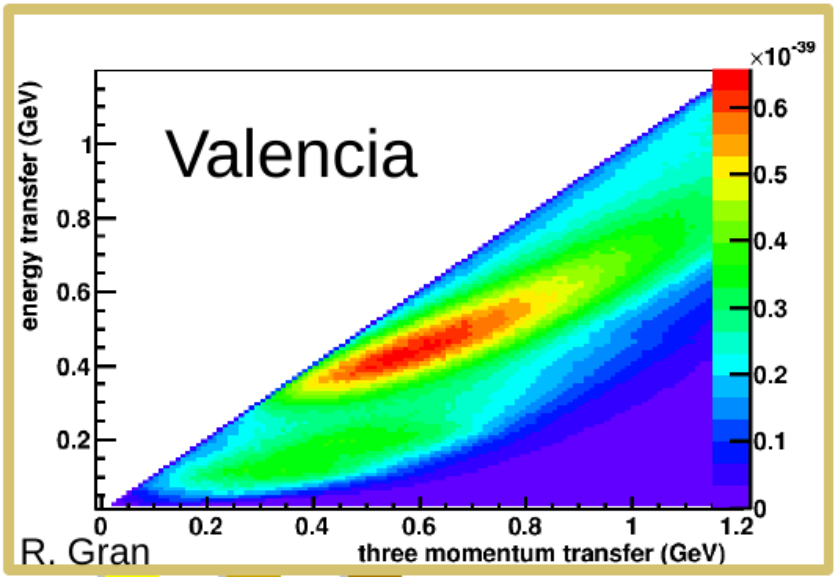
- few percent differences between Nieves' prediction and GENIE output

- Validation underway

- More additions to come
  - Correct selection of isospin
  - (ratio of nn / pn pairs)

- Expected in the next GENIE release





Other QE and QE-like

- There are now many QE (or QE-like) models on the market
    - Previously, we just used RFG with no questions!
    - Work starting to include more of these in GENIE

- If these models are implemented in generators, strict comparisons can be made with data

- Work also ongoing to incorporate the following :

- Rochester effective SF and TEM
    - Coopersmith, Bodek
    - Fits to electron scattering data
    - Extract effective parametrisations of the spectral function and MEC components

- Nieves full QE model
    - Johnston, Dytman
    - Includes Nieves 'QE' and 2p2h in a consistent manner

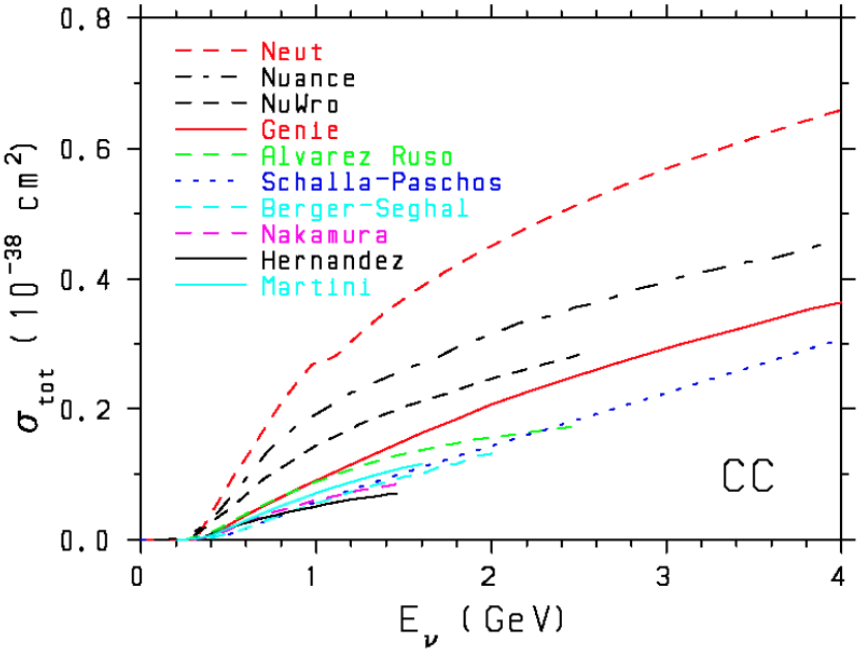
Coherent (PCAC)

Gabe Perue, Dan Cherdack

- Previously included Rein-Sehgal model
  - PCAC based model
  - Large differences between different generators for the 'same' model
  - Due to differences in input data

- Rein-Sehgal not expected to be valid at low (< 2GeV) energies

- Alternative PCAC-based models exist
  - Berger-Sehgal
  - Implemented using Pion cross section lookup



Boyd et. al. AIP conf. Proc. 1189

Coherent (microscopic)

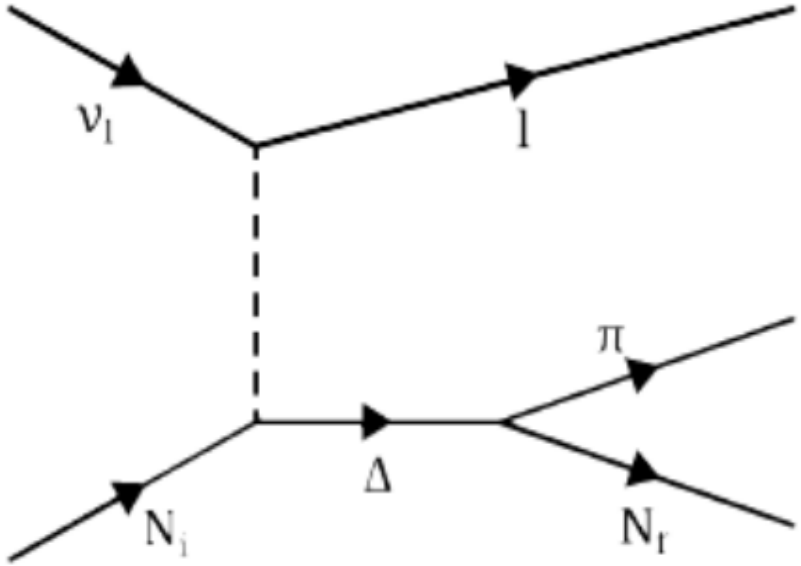
Dan Scully, Steve Boyd

- Known issues with PCAC at low energies
  - Q2 → 0 limit in PCAC assumption ignores angular dependencies

- Alternative is a microscopic model
  - Model v + N → l + N + pi
  - Final nucleus still in the same initial state
  - Coherent sum over all nucleons

- Alvarez-Ruso et al, PRC 75, 76 (2007)
  -Implemented in GENIE

- Model only valid at low energies (< 5GeV)

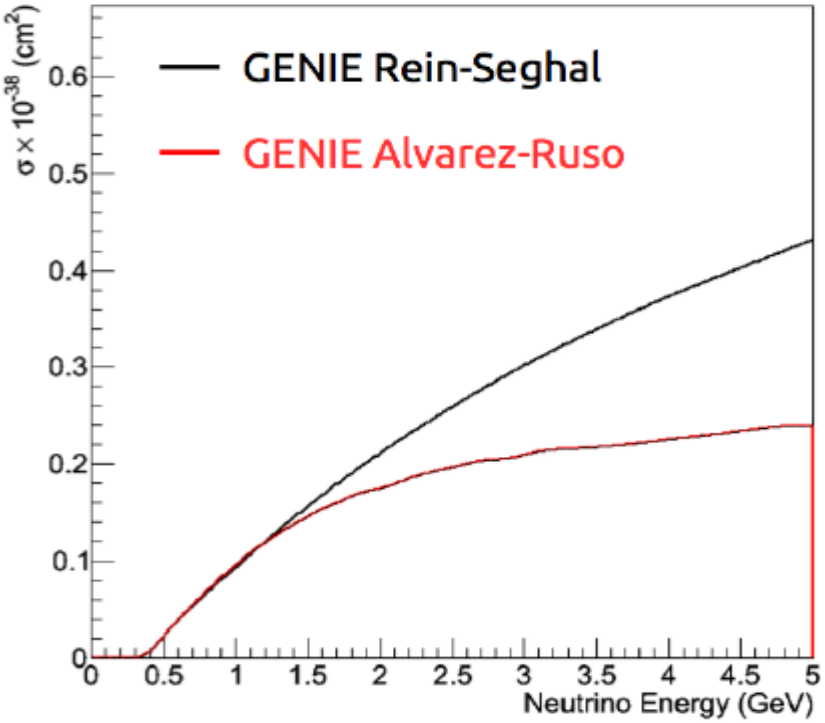


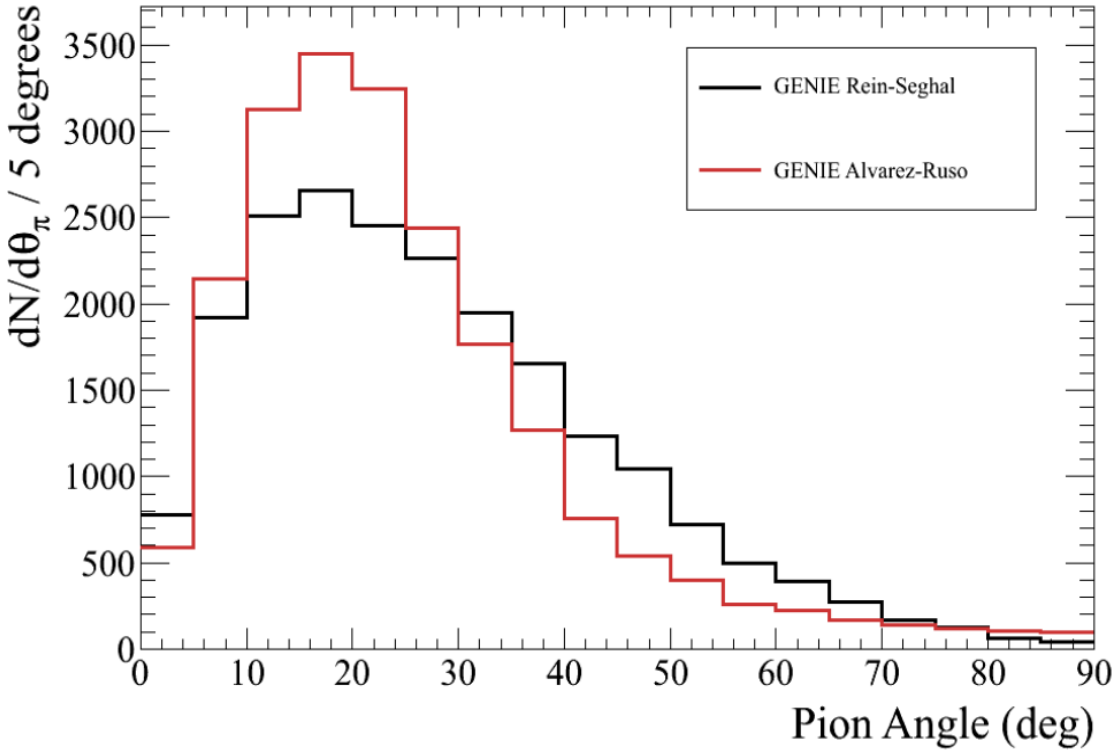
Coherent (microscopic 2)

Dan Scully, Steve Boyd

- Previously the implementation was too slow (minutes per event)
  - Huge effort to improve efficiency
  - Now the model is useable
  - Obvious shape differences to Rein-Sehgal

- Fully implemented in devlopment branch
  - Work to include in next GENIE release





Kaon production

Chris Marshall, Martti Nirkko

- Associated production already in GENIE

- Cabbibo suppressed kaon production modes not currently simulated e.g.

$$\nu + N \rightarrow l^- + N + K^+$$

- Dominant at low (<GeV) energies (lower threshold)

- Can be important background to nucleon decay searches
  - $p \rightarrow \nu + K^+$

- Model by Alam et al.
  - Predicts full final-state three-particle kinematics

Kaon production (2)

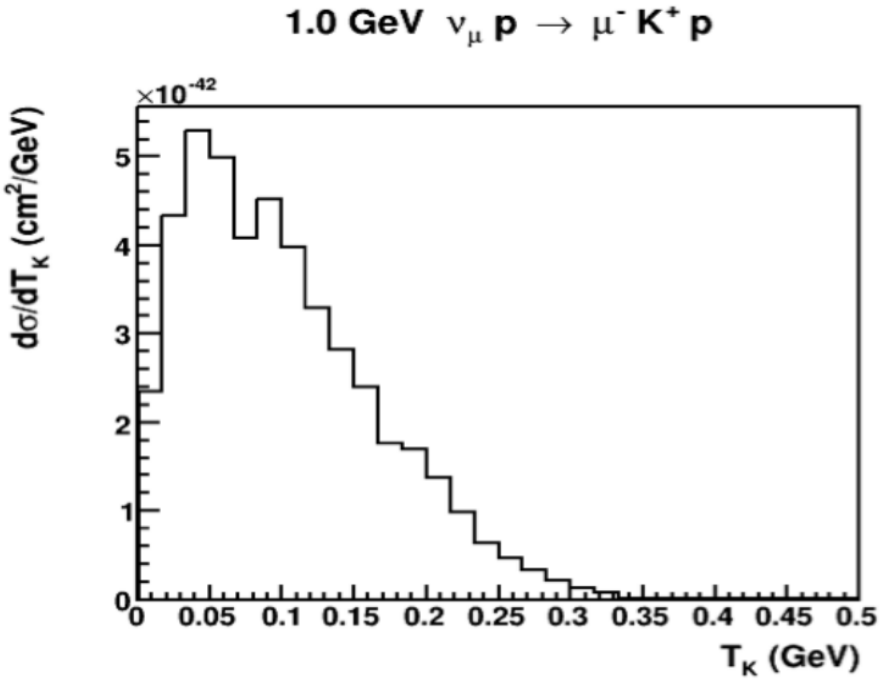
Chris Marshall, Martti Nirkko

- Good agreement found between GENIE and authors predictions

- Working to move code into a future release

- No antineutrino modes simulated
  - Plan to add these modes in coming months

- Model authors also have associated production model
  - Plans to include this aspect
  - Consistent kaon production framework



Other work

- Many more physics changes being worked on

    - Very high energy extension, for IceCube (Hoshina)
        - Could be very important for DeepCore/PINGU
    - Eta production improvements (Liu)
    - Berger-Sehgal and Kuzmin muon mass dependence to resonance (Nowak)
    - Expansion of hA splines (Geary, Dytman)
    - Updates to PCAC coherent (Perdue, Gallagher)

- In addition, many software improvements on the way

- Improvements to the automation of validation procedure
    - Reduce time taken to test new builds
    - Increase rate of releases

Release plans

- A number of new physics models are being developed in GENIE

- Next release (**2.9.0**) expected **end of 2014**
    - Hope to include the first implementations of several new models
    - Those discussed here, plus many others
    - All configurable as options, but defaults won't change

- Next major physics release (**2.10.0**) hopefully **summer 2015**
    - Incorporate new models into default
    - Ideally, perform a complete global tune
    - Represents a huge addition of physics models compared to 2.8.0

- Schedules are subject to change due to limited man-power

Thankyou for listening