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Simulation tools for neutrino experiments

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Radiative Corrections at the Intensity Frontier of Particle Physics

June 13th, 2017

Overview

- The (accelerator beam) neutrino software stack
- What is GENIE?
  - How does GENIE work?
  - Recent developments
  - Future plans
- (Briefly) Other generators and tools
  - NEUT is the big omission - not an expert, so I will refrain from comment.
  - Also won't say much about Geant.

(won't say much about Geant here...)

First, some history…

- Common wisdom: The most natural theory community partner for this work is the nuclear theory community.
    - Some debate about this - there is a lot of room for HEP theory to contribute. But the NP theory community is hugely important and we've largely been walled off from each other - very different case than at the "Energy Frontier."
- HEP/NP separation (especially in the US) has meant that neutrino event generators in heavy use at experiments (especially GENIE and NEUT) were largely developed and maintained by experimentalists.
    - The inmates have control of the asylum…
    - More theory oriented generators came from Europe (even GENIE is UK via MINOS), and often lacked critical tools for use in experiments (flux, geometry, tools for estimating uncertainties, etc.).
    - The two generator "types" are growing towards each other…
- We are definitely seeking to remedy this situation.
    - There is a track record of success (e.g., A. Meyer et al and the z-expansion in GENIE), but the collaboration model probably needs some work in order to best serve all parties.
        - We need better mechanisms for giving credit to theorists who work with us.
        - Theorists should join generator groups.

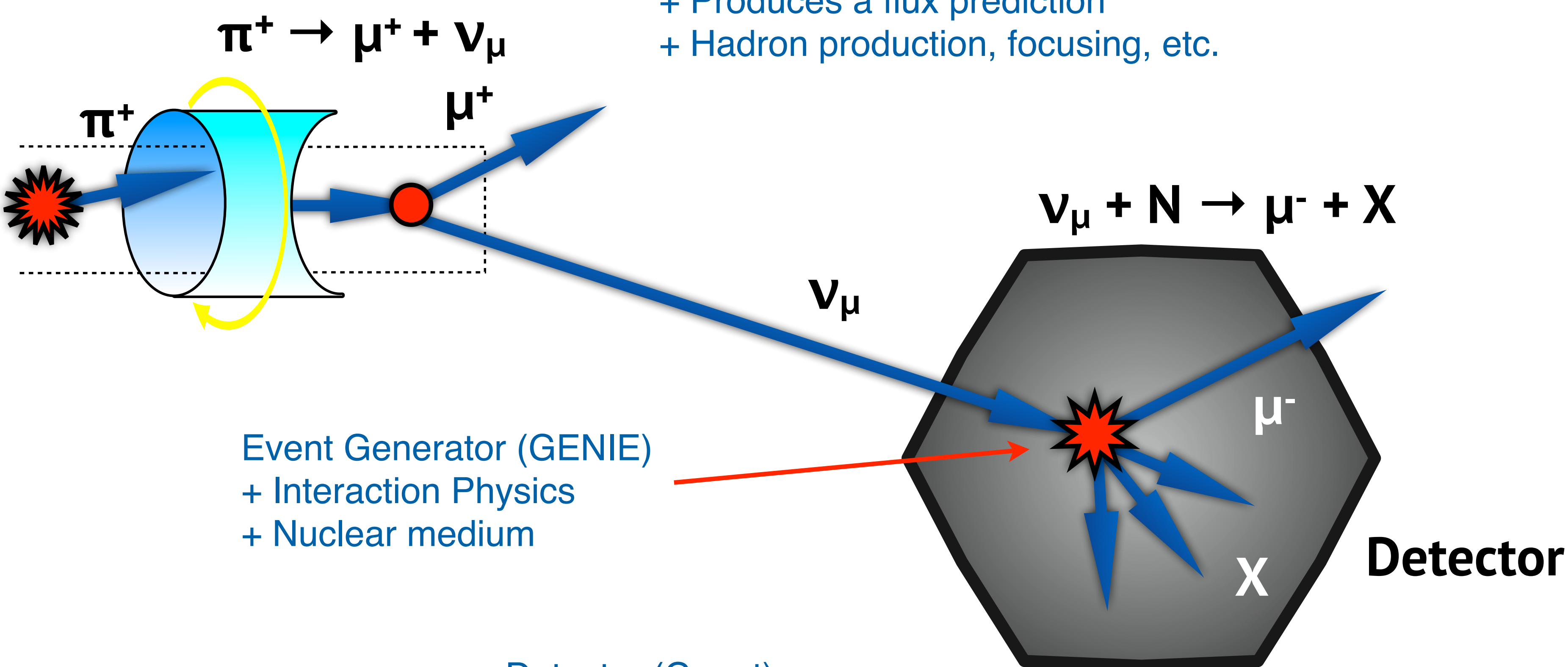
Perspectives*

- Theorists: The model doesn't need to match the data, it just needs to be correct.
- Experimentalist: The model doesn't need to be correct, it just needs to match the data.
  - *(Both camps are quite pleased with their positions.)*

*Attributed to U. Mosel

Neutrino Simulations: A Three-Part Software Stack

Beamline (FLUKA/Geant)
+ Produces a flux prediction
+ Hadron production, focusing, etc.

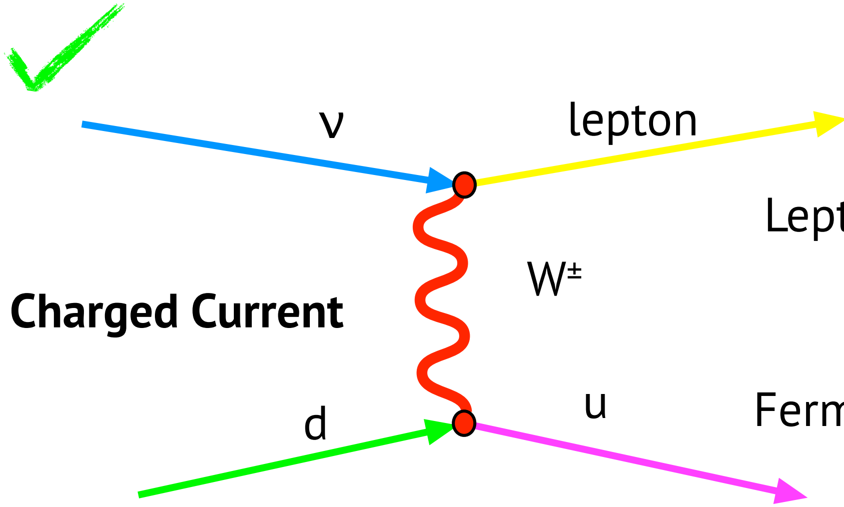


Event Generator (GENIE)
+ Interaction Physics
+ Nuclear medium

Detector (Geant)
+ Final state radiation traversing matter

Neutrino Interactions - Weak Force Only!

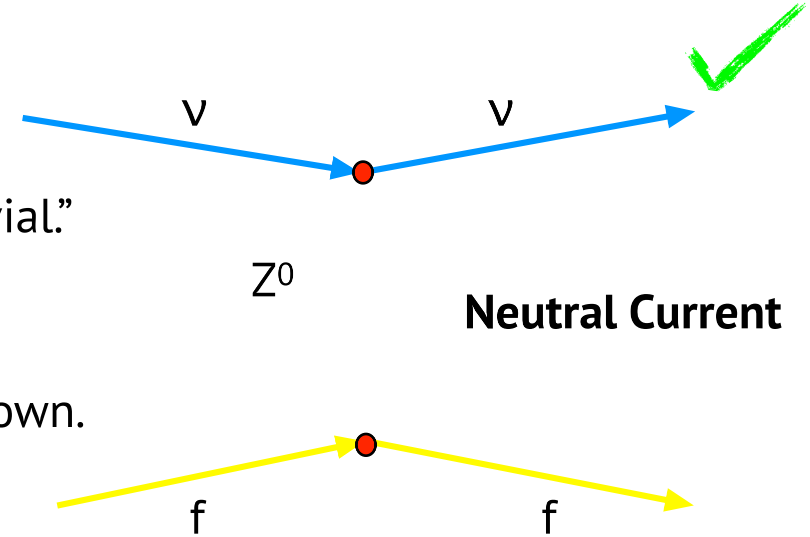
Charged Current



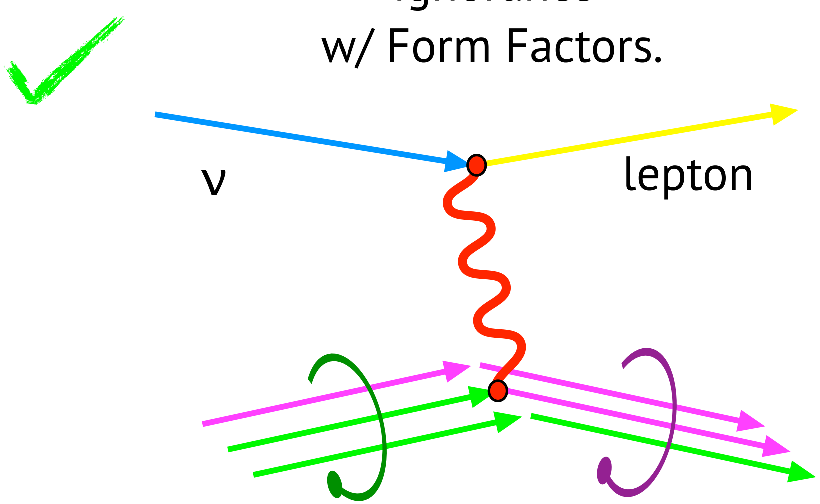
Lepton: "Trivial."

Fermion: Known.

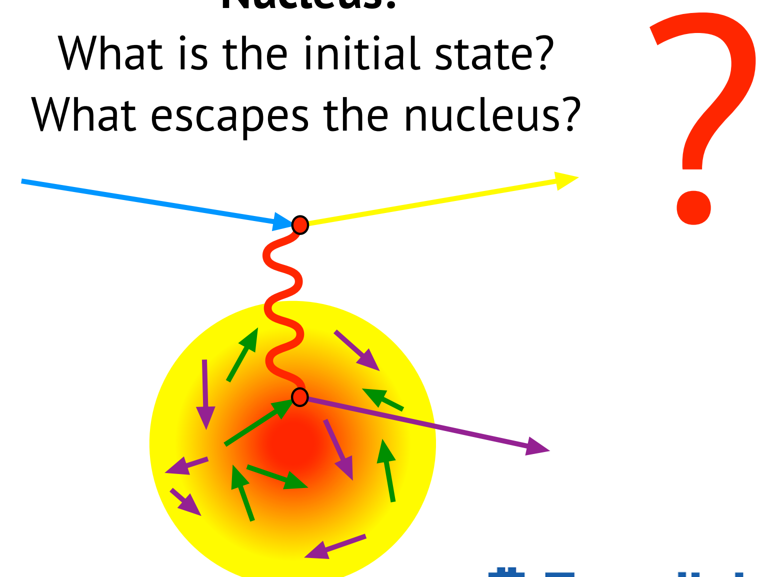
Neutral Current



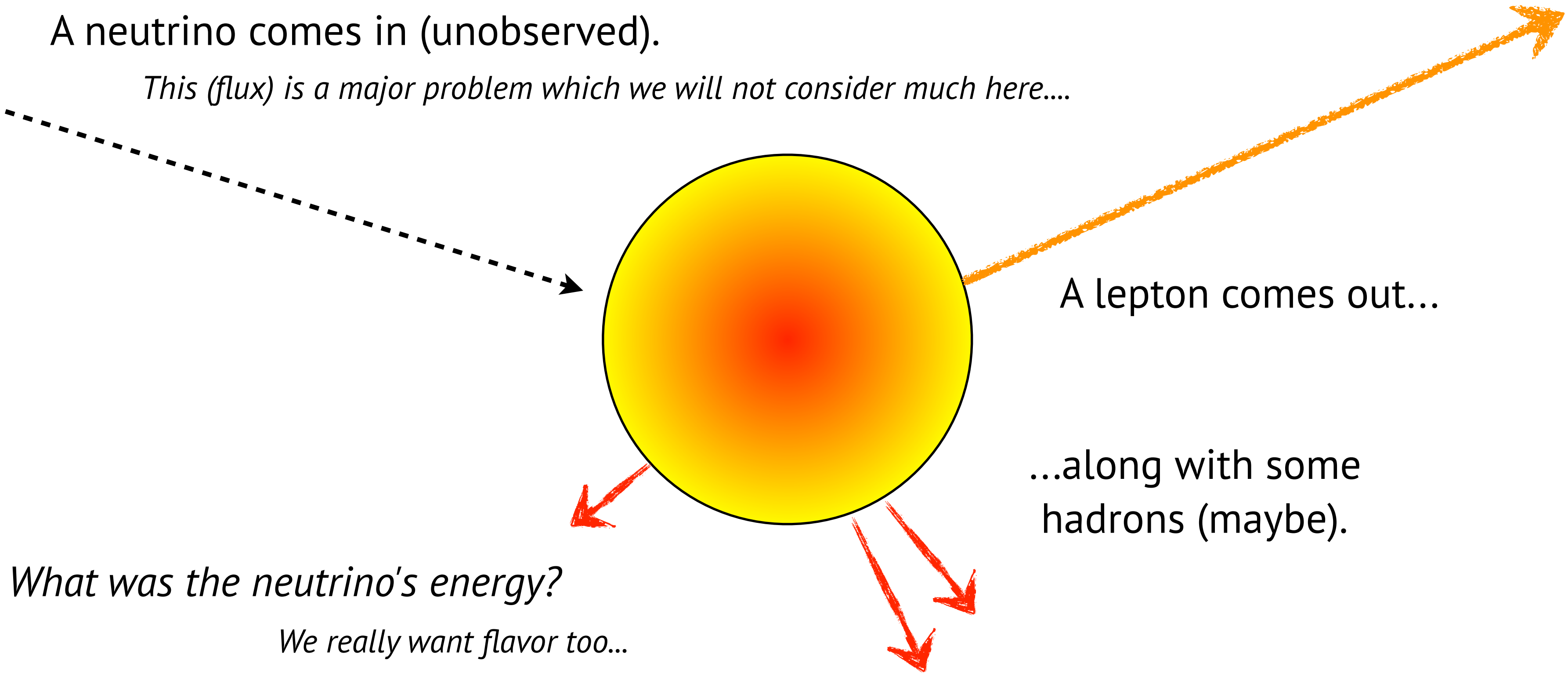
Free Nucleon: Parameterize ignorance w/ Form Factors.



Nucleus:
What is the initial state?
What escapes the nucleus?

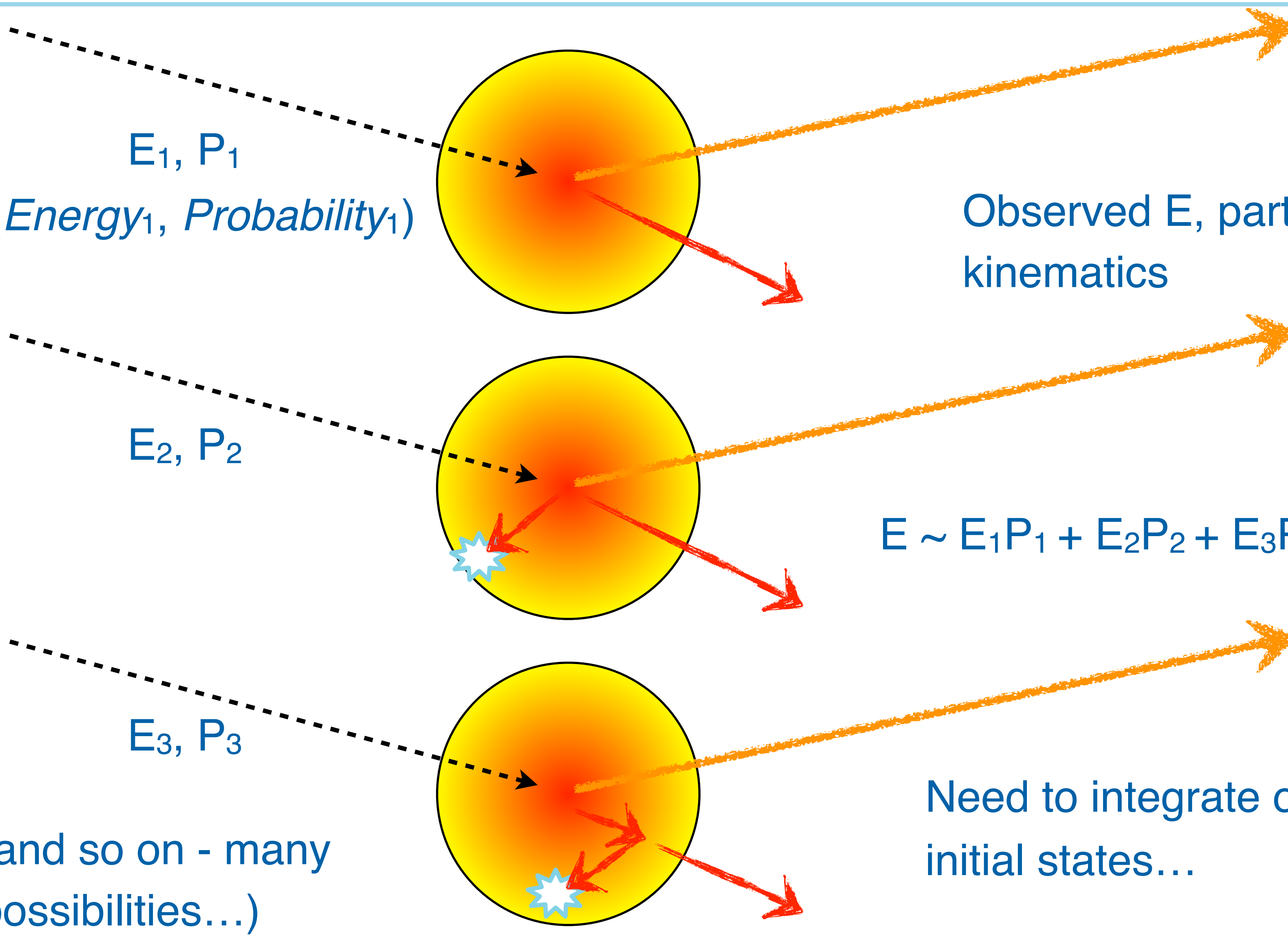


The Basic Problem



We have an unknown incoming energy and "missing" energy in the final state (neutral current reactions, neutrons in the final state, nuclear rescattering, etc.). We must infer the energy from incomplete final state information.

The Basic Problem: The Best We Can Do



E_1, P_1

(*Energy*$_1$, *Probability*$_1$)

E_2, P_2

E_3, P_3

(and so on - many possibilities…)

Observed E, particles, kinematics

$E \sim E_1P_1 + E_2P_2 + E_3P_3 + \ldots$

Need to integrate over initial states…

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The Basic Problem: The Best We Can Do

- The best we can do is build a map, weighted by probability, that provides all the possible initial states for an observed final state.
- With this map and a sample of events, we may infer a neutrino energy distribution (or some other kinematic distribution).
- How do we make any progress without an initial energy to begin with?
- For measurements, we use an *event generator* to predict backgrounds and the efficiency.
  - We may constrain the background prediction with data.
  - We must impose systematic uncertainties on our efficiency based on model estimates.
    - The more measurements we have, the better we may constrain these uncertainties and the better is our probability map.

```
std::map<observed_topolgy, std::list<std::pair<probability, physics>>> = ?
```

Neutrino MC Event Generators

- The generator must simulate all the types and momenta of every particle that appears in the final state.
- Some generators (MadGraph, Pythia, etc.) are computation aids for theorists, but GENIE is not.
- This is because we lack a theoretical framework that is both *complete* and *consistent*.
- The ideal input theory would be internally consistent and provide fully-differential cross sections in the kinematics of every final state particle over all reaction mechanisms, energies, and targets.
- Modern theory typically provides final state kinematics for the lepton only, and only over limited ranges in energy or momentum transfer, and may be fully exclusive or fully inclusive with no guidance on how to merge the regimes.
  - But the experiments must go on! So we must *stitch together* an ensemble that is consistent with all the data.

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What else do neutrino event generators provide?

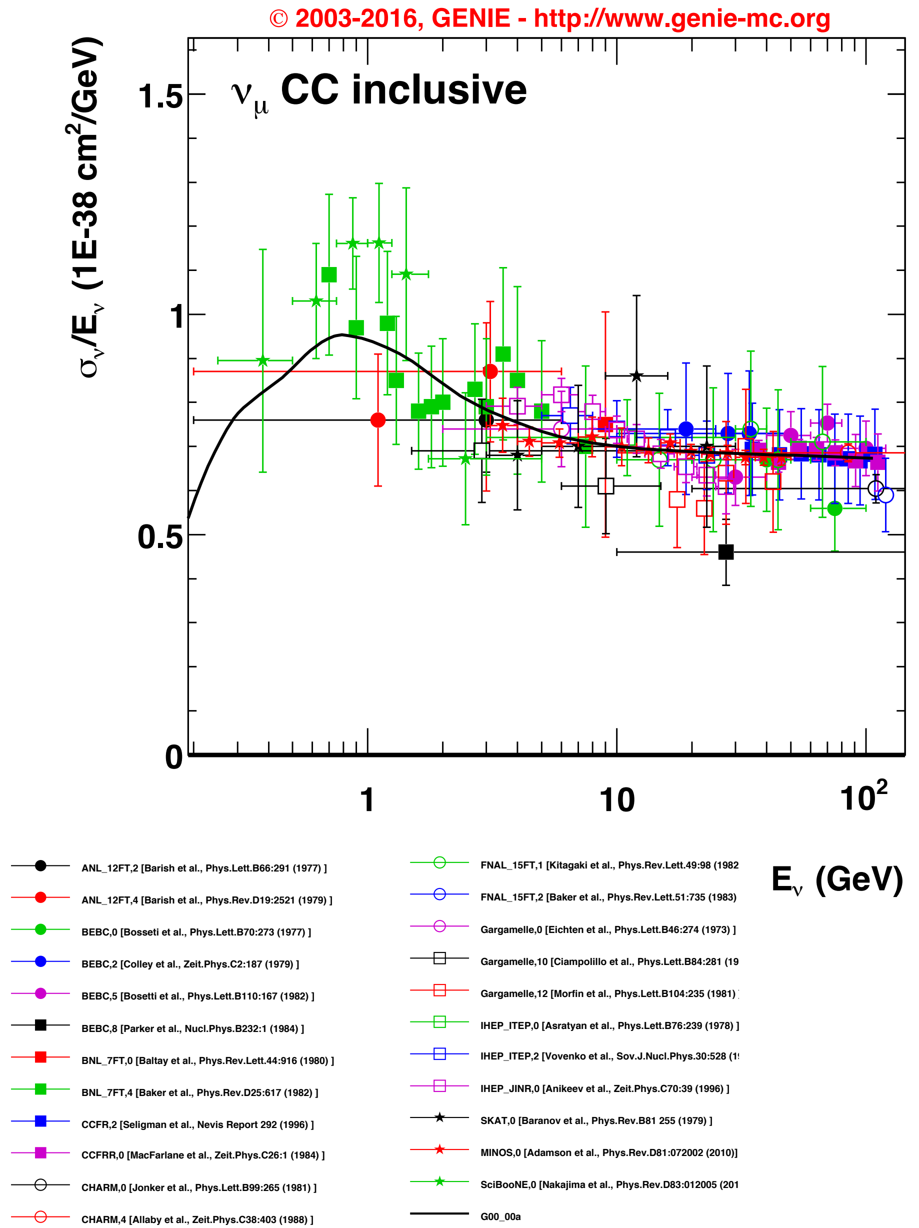
- Interfaces to geometry engines for modeling complex detectors.
- Flux drivers for computing exposure (atmospheric/solar sources) or normalizing responses to accelerator beams.
- Event re-weighting engines for studying systematic uncertainties and performing error propagation.
- Databases of electron, hadron, and neutrino scattering experiments with applications for comparing simulation and data.
    - Electron and hadron scattering event generator functionality.
- Nucleon decay generators.
- Libraries of pre-computed cross sections.

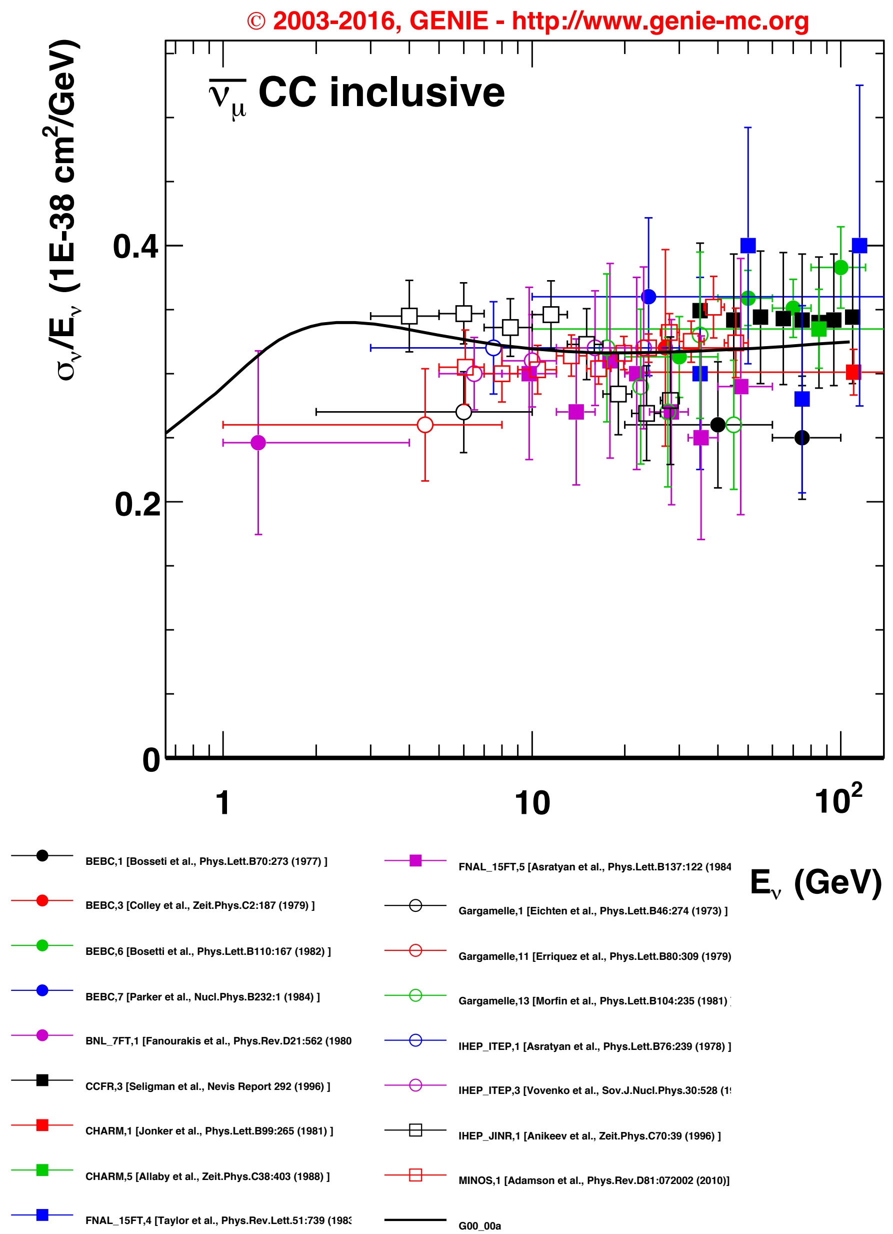
GENIE

- https://genie.hepforge.org
- The software:
  - Created to be a “universal event generator”.
    - Additionally run in electron and hadron scattering modes.
  - Many tools for studying systematics, comparison to data, etc.
  - Event handling is decoupled from physics routines, easy to create arbitrary algorithm stacks.
- The collaboration:
  - International collaboration with about a dozen collaborators (essentially all experimentalists) and many more contributors.
    - Collaborators do service work (validation, distribution, user support, developer support, etc.)
    - Contributors (many theorists) offer individual models or pieces of validation software, sometimes consulting, etc.

What is GENIE?

- We build a global physics model from a collection of exclusive state models (e.g., Llewellyn Smith QE, Rein-Sehgal resonant pion production, Bodek-Yang DIS, etc.).
  - (Many of these are *wrong but useful*.)
- When we add a new process (e.g., Nieves group MEC), we need to retune the total cross section by controlling the strength of the exclusive processes or subtracting processes.
- We try very hard to be consistent with data for the total cross section, so inclusive cross section calculations are very valuable as an additional constraint.
- We try to agree with a many other measured distributions as possible, but there are always tensions that are difficult to understand/reconcile.

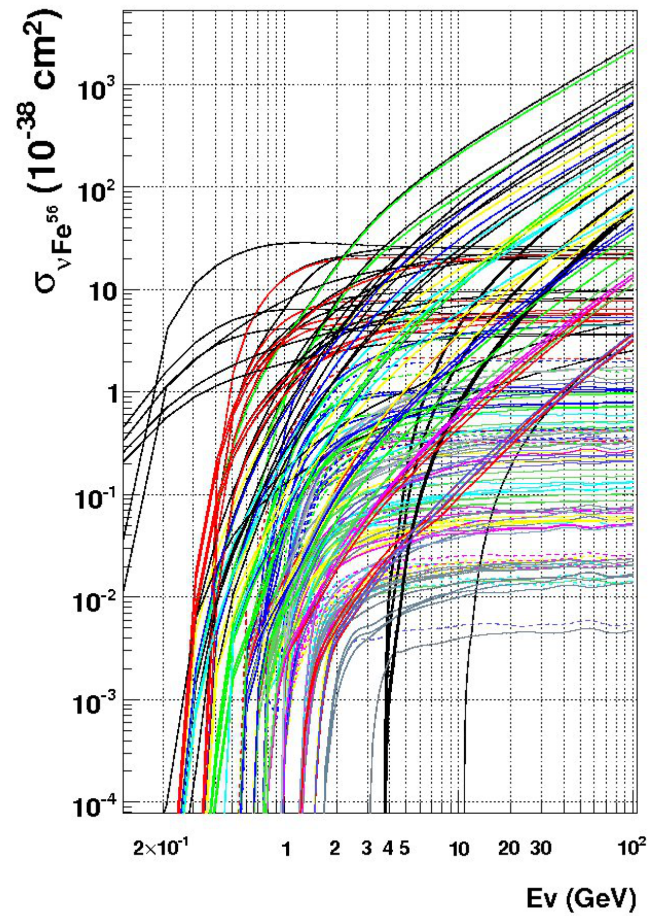

© 2003-2016, GENIE - http://www.genie-mc.org
ν_μ CC inclusive
σ_ν/E_ν (1E-38 cm^2/GeV)
1.5
1
0.5
0
1
10
10^2
E_ν (GeV)
ANL_12FT,2 [Barish et al., Phys.Lett.B66:291 (1977)]
ANL_12FT,4 [Barish et al., Phys.Rev.D19:2521 (1979)]
BEBC,0 [Bosseti et al., Phys.Lett.B70:273 (1977)]
BEBC,2 [Colley et al., Zeit.Phys.C2:187 (1979)]
BEBC,5 [Bosetti et al., Phys.Lett.B110:167 (1982)]
BEBC,8 [Parker et al., Nucl.Phys.B232:1 (1984)]
BNL_7FT,0 [Baltay et al., Phys.Rev.Lett.44:916 (1980)]
BNL_7FT,4 [Baker et al., Phys.Rev.D25:617 (1982)]
CCFR,2 [Seligman et al., Nevis Report 292 (1996)]
CCFRR,0 [MacFarlane et al., Zeit.Phys.C26:1 (1984)]
CHARM,0 [Jonker et al., Phys.Lett.B99:265 (1981)]
CHARM,4 [Allaby et al., Zeit.Phys.C38:403 (1988)]
FNAL_15FT,1 [Kitagaki et al., Phys.Rev.Lett.49:98 (1982
FNAL_15FT,2 [Baker et al., Phys.Rev.Lett.51:735 (1983)
Gargamelle,0 [Eichten et al., Phys.Lett.B46:274 (1973)]
Gargamelle,10 [Ciampolillo et al., Phys.Lett.B84:281 (19
Gargamelle,12 [Morfin et al., Phys.Lett.B104:235 (1981)
IHEP_ITEP,0 [Asratyan et al., Phys.Lett.B76:239 (1978)]
IHEP_ITEP,2 [Vovenko et al., Sov.J.Nucl.Phys.30:528 (1
IHEP_JINR,0 [Anikeev et al., Zeit.Phys.C70:39 (1996)]
SKAT,0 [Baranov et al., Phys.Rev.B81 255 (1979)]
MINOS,0 [Adamson et al., Phys.Rev.D81:072002 (2010)]
SciBooNE,0 [Nakajima et al., Phys.Rev.D83:012005 (201
G00_00a


© 2003-2016, GENIE - http://www.genie-mc.org
$\overline{\nu_\mu}$ CC inclusive
σ_ν/E_ν (1E-38 cm^2/GeV)
0.4
0.2
0
1
10
10^2
E_ν (GeV)
BEBC,1 [Bosseti et al., Phys.Lett.B70:273 (1977)]
BEBC,3 [Colley et al., Zeit.Phys.C2:187 (1979)]
BEBC,6 [Bosetti et al., Phys.Lett.B110:167 (1982)]
BEBC,7 [Parker et al., Nucl.Phys.B232:1 (1984)]
BNL_7FT,1 [Fanourakis et al., Phys.Rev.D21:562 (1980
CCFR,3 [Seligman et al., Nevis Report 292 (1996)]
CHARM,1 [Jonker et al., Phys.Lett.B99:265 (1981)]
CHARM,5 [Allaby et al., Zeit.Phys.C38:403 (1988)]
FNAL_15FT,4 [Taylor et al., Phys.Rev.Lett.51:739 (198
FNAL_15FT,5 [Asratyan et al., Phys.Lett.B137:122 (1984
Gargamelle,1 [Eichten et al., Phys.Lett.B46:274 (1973)]
Gargamelle,11 [Erriquez et al., Phys.Lett.B80:309 (1979)
Gargamelle,13 [Morfin et al., Phys.Lett.B104:235 (1981)
IHEP_ITEP,1 [Asratyan et al., Phys.Lett.B76:239 (1978)]
IHEP_ITEP,3 [Vovenko et al., Sov.J.Nucl.Phys.30:528 (1
IHEP_JINR,1 [Anikeev et al., Zeit.Phys.C70:39 (1996)]
MINOS,1 [Adamson et al., Phys.Rev.D81:072002 (2010)]
G00_00a

How does GENIE work?

- The first step is to compute the total cross section for the input energy, flavor, helicity, and target isotope.
- Perform a sum over exclusive channels (square then sum, sigh).
- Numerical integration of the corresponding differential cross section expression:
  - Computationally intensive procedure (100's of millions of differential cross section evaluations), but only needs to be run once per release.

$\nu_\mu, \bar{\nu_\mu} + Fe$, all processes



https://www.hepforge.org/archive/genie/data/

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The default model:

```
<param_set name="Default">
   <param type="int" name="NGenerators">    13                                  </param>
   <param type="alg" name="Generator-0">    genie::EventGenerator/QEL-CC        </param>
   <param type="alg" name="Generator-1">    genie::EventGenerator/QEL-NC        </param>
   <param type="alg" name="Generator-2">    genie::EventGenerator/RES-CC        </param>
   <param type="alg" name="Generator-3">    genie::EventGenerator/RES-NC        </param>
   <param type="alg" name="Generator-4">    genie::EventGenerator/DIS-CC        </param>
   <param type="alg" name="Generator-5">    genie::EventGenerator/DIS-NC        </param>
   <param type="alg" name="Generator-6">    genie::EventGenerator/COH-CC        </param>
   <param type="alg" name="Generator-7">    genie::EventGenerator/COH-NC        </param>
   <param type="alg" name="Generator-8">    genie::EventGenerator/DIS-CC-CHARM  </param>
   <param type="alg" name="Generator-9">    genie::EventGenerator/QEL-CC-CHARM  </param>
   <param type="alg" name="Generator-10">   genie::EventGenerator/NUE-EL        </param>
   <param type="alg" name="Generator-11">   genie::EventGenerator/IMD           </param>
   <param type="alg" name="Generator-12">   genie::EventGenerator/IMD-ANH       </param>
</param_set>
```

Interesting additions / alternatives:


```
<param_set name="DFR">
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   <param type="alg" name="Generator-0">  genie::EventGenerator/DFR-CC      </param>
   <param type="alg" name="Generator-1">  genie::EventGenerator/DFR-NC      </param>
</param_set>
```

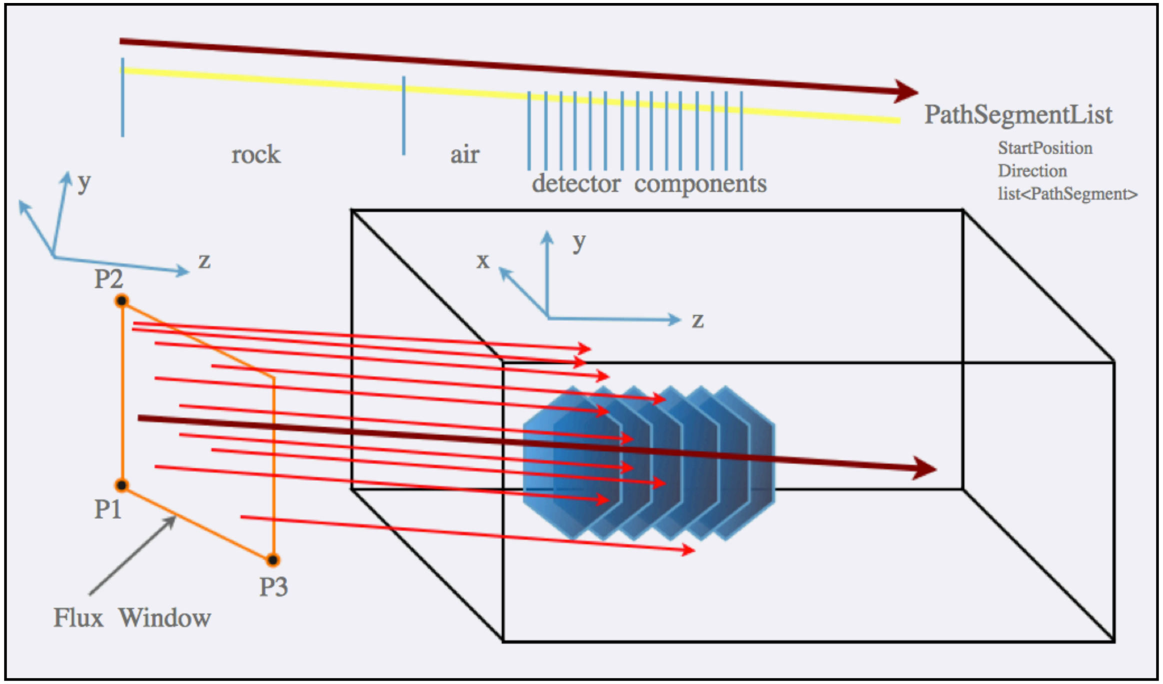
How does GENIE work?

- With the total cross sections in hand, event generation proceeds by projecting rays through the detector geometry and computing the total path length of all the materials along a trajectory.
- At the start of a run, we find the longest path length through the detector and normalize the interaction probability to 1 on that path, scaling the interaction probabilities appropriately, and incorporating this information into the flux driver.
  - Necessary to keep running times reasonable.
- Then for any given path, events are chosen randomly by channel according to their contribution to the total cross section in an accept-reject loop.

Why does GENIE need Geometry?

- Real fluxes and geometries are never uniform.
  - Experiments need to generate interaction vertices in the correct locations.
  - Fluxes vary in intensity and energy profile across the detector.
  - Detector structures (and the surrounding area!) have specific structures and boundaries.

"... so complicated!"



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Fluxes

- Many choices (including making your own):
  - User-specified histograms (no spatial variation, only energy and flavor)
  - Encapsulations of common parameterizations (e.g., atmospheric)
  - Simple, generic ntuple format (`GSimpleNtpFlux`*)
  - Experiment (NuMI, T2K) or institution specific.
- Wrap any of the above in a "flavor blender" adapter (`GFlavorMixerI`) - this is how you handle far detectors in an oscillation experiment.
- Some drivers have exposure counters (e.g., time, protons on target).

*FNAL beamlines committed to migrating to this common ntuple format (dk2nu).

How does GENIE work?

- Currently implemented GENIE physic models rely heavily on a factorization assumption.
- Some cases blend boxes together a bit (but for the most part they do not).

"Is that safe?"

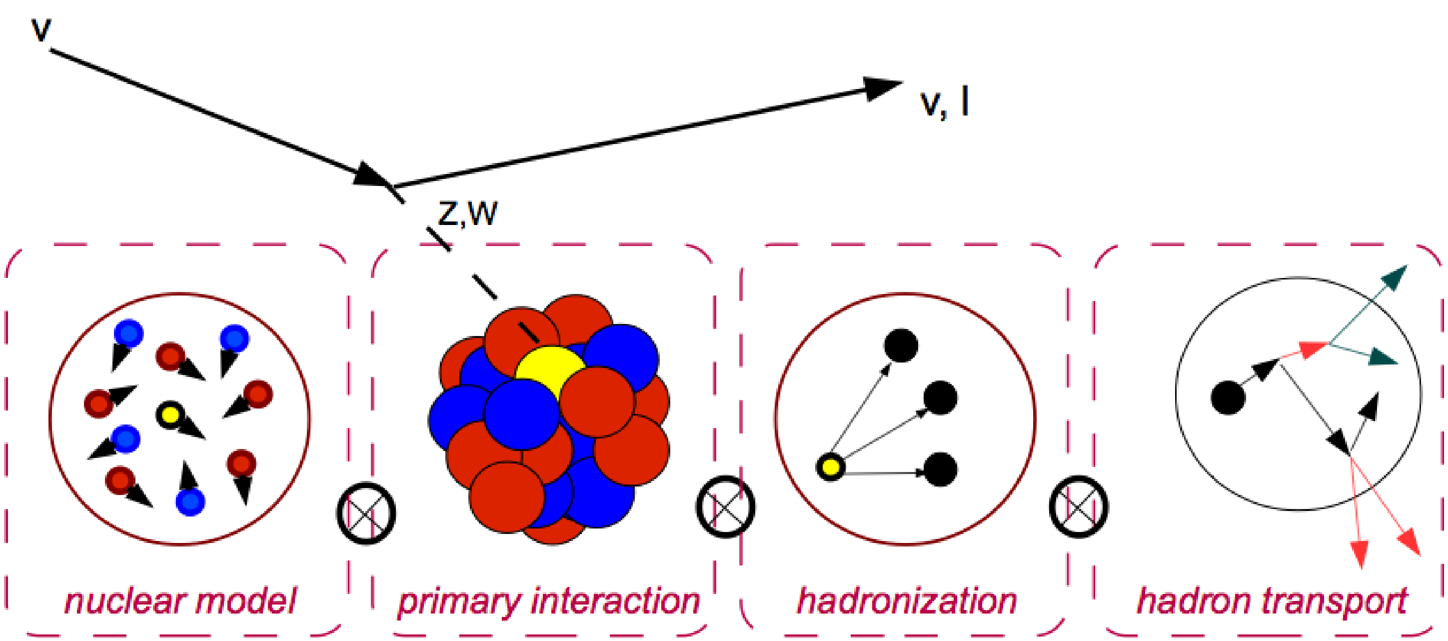


Figure by C. Andreopoulos

GENIE Physics Models

- GENIE 2.0 (~2007) used identical physics models as NEUGEN, a Fortran generator that was developed over a number of years by a succession of physicists, and used by MINOS. GENIE has evolved with each subsequent release.
- There are currently dozens of different physics models.
- The default nuclear model is the relativistic Fermi gas with Bodek and Ritchie high-momentum tails. GENIE also implements the Effective Spectral Function, and the Local Fermi Gas. Other spectral function implementations exist in development branches and need a bit more effort to become public.
- The quasielastic process defaults to Llewellyn-Smith, but we also have the Nieves et al model. The axial form factor model is the dipole but we offer (and are preparing to default to) the z-expansion model as well.
- Excitation of nucleon resonances (decaying by meson emission) and coherent pion production are both described by models by Rein and Sehgal, but we offer a number of alternatives (Berger and Sehgal, different form factor models, etc.).
  - We also offer a diffractive pion production model (Rein).
- Models for neutrino-electron scattering and inverse muon decay are included and mostly complete (additional radiative corrections required for neutrino-electron scattering).

GENIE Physics Models

- We offer (non-default) a custom built and the Valencia 2p2h models.
- Bodek and Yang (2003) is used for nonresonant inelastic scattering.
- Other interesting exclusive states (QEL hyperon production, single Kaon production, etc.) are optional (making them default would lead to double counting in the hadronization model).
- The custom "AGKY" hadronization model, developed internally, covers the transition between PYTHIA at high (W > 3GeV/c2) invariant masses and an empirical model based on KNO-scaling at lower invariant masses.
- GENIE has two* internally developed models for final-state interactions; one is a cascade model and the other (the default) parameterizes the cascade a single effective interaction for easy re-weighting.
  - Actually many more than two - we are snap-shotting major changes with dated timestamps as we make improvements. Users can choose from our long-standing default and the bleeding edge, with a variety of options in between.
- GENIE uses the SKAT parametrization of formation zones (the effective distance over which a quark hadronizes).
- More detail in the back-ups...

Pieces (Usually)

- Vertex selection
  - Simple nuclear density model
- Initial state nuclear model
  - Removal energy and momentum
    - RFG with Bodek-Ritchie tails.
    - New: Local Fermi Gas
    - New: Effective Spectral Function
    - Almost there: "Benhar" spectral function
    - Just started: Correlated Fermi Gas (MIT)

GROUND STATE

- Hard scattering process
  - Differential cross section formula to get event kinematics (x, y, Q2, W, t, etc.)
- Lepton kinematics
- Hadronic system

INITIAL STATE

  - Propagation/transport (default is an "effective cascade")
    - Fast and re-weightable

FINAL STATE

Usual Pieces

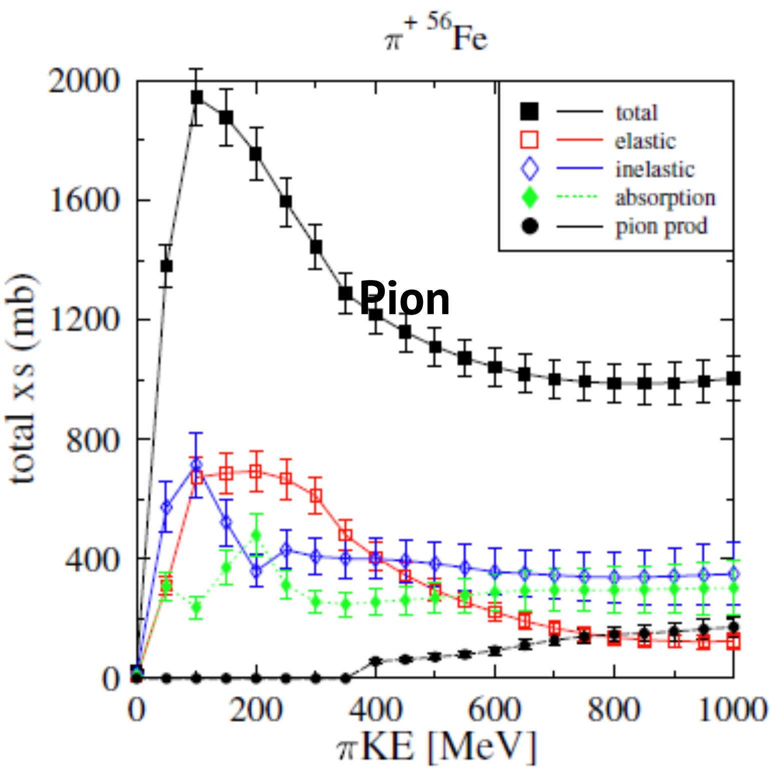
- Decays before and after propagation
- Remnant decay
  - Just started caring about this, really...
  - Current model is very simple
    - Working on adopting other codes (Geant4, INCL++, possibly GiBUU) to handle clustering, de-excitation, evaporation
    - May be a bridge to more sophisticated transport codes

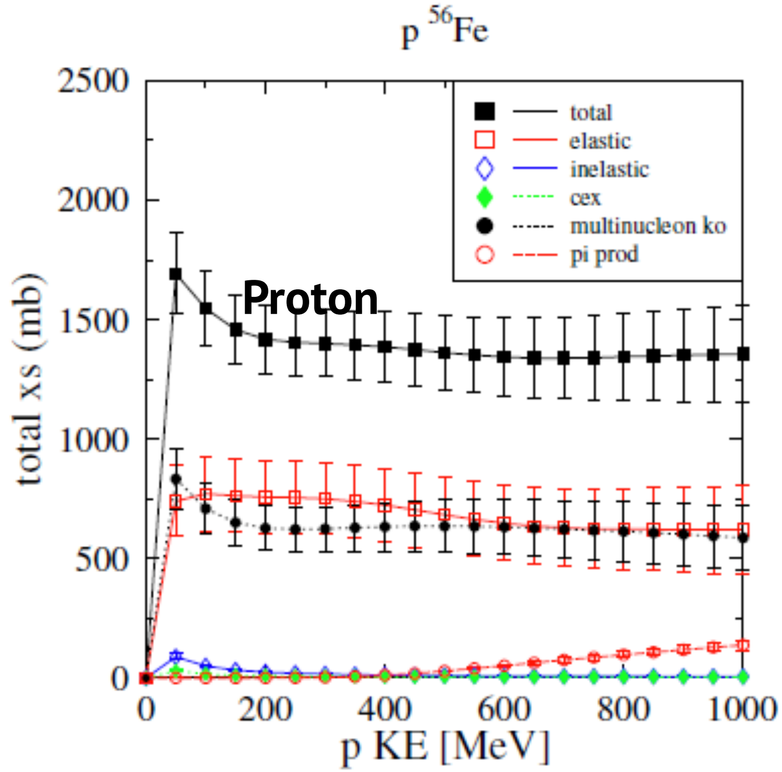
REMNANT STATE

- Sometimes models can't work this way - e.g., discovering we can't separate lepton and hadron kinematics into separate modules for QE events (can't compute cross section in Q2 and then compute lepton and hadron kinematics, need to flip the procedure and then accept-reject based on Q2), etc.
  - (Actually, we should do all events this way - but the code runs much slower and so we're working on ways to make that process fast enough to be more widely used.)

FSI Models

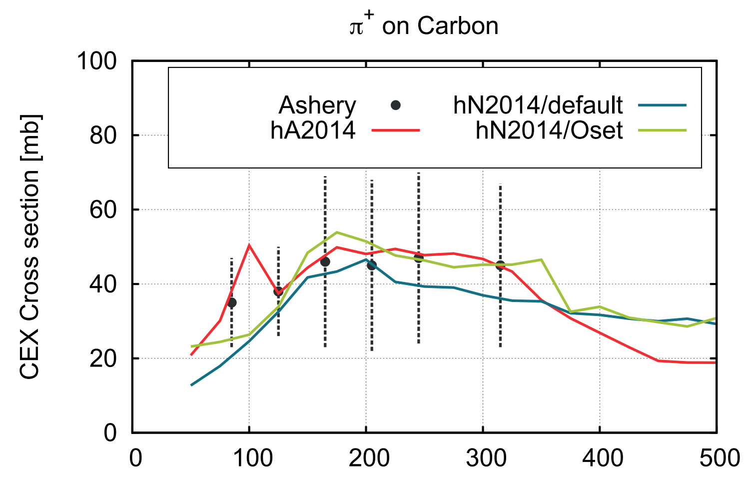
- GENIE: "hA" (default) - use iron reaction cross section data, isospin symmetry, and $A^{2/3}$ scaling to predict the FSI reaction rates.
- Individual particle energies and angles use data templates or sample from the allowed phase space.

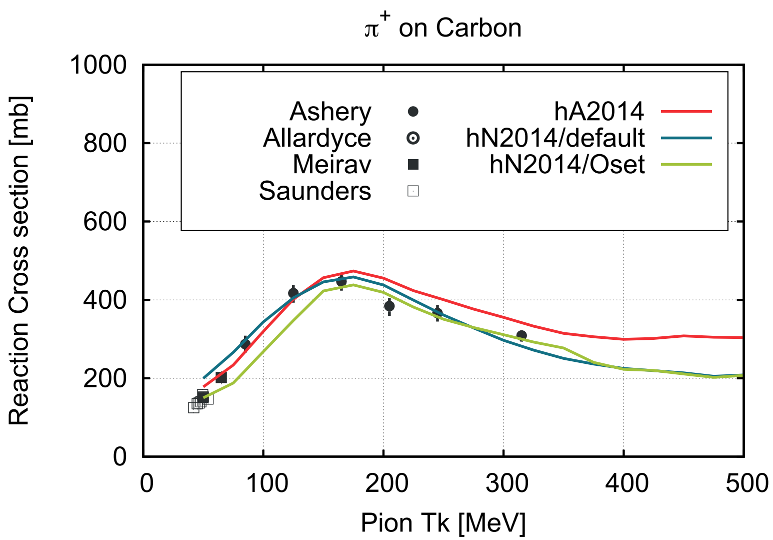


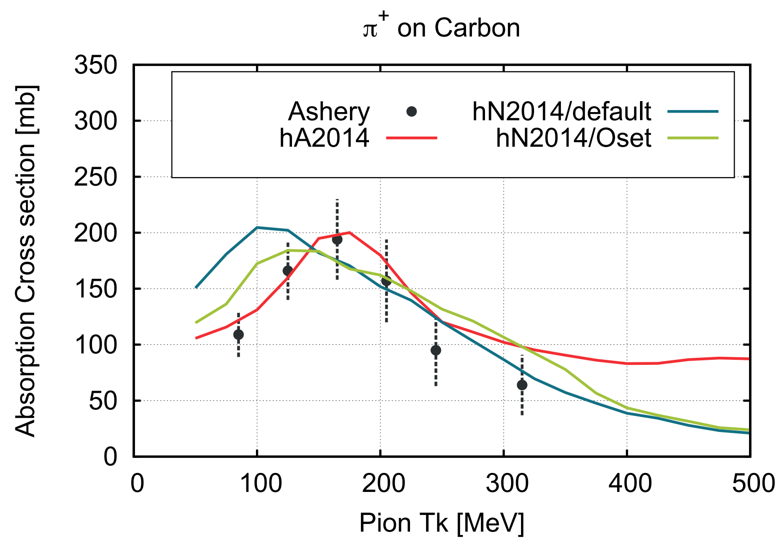


FSI Models

- GENIE "hN" is our cascade model.
- New to hN are: Oset et al, Nucl. Phys. A468 (1987), Oset et al, Nucl. Phys. A484 (1998)
- Model describes low energy (kinetic E around Delta peak, 85 MeV - 350 MeV) pion interactions inside nuclear matter.
    - Nuclear effects are implemented as modifications of the Delta width.
- Introduced here as a modification of the GENIE cascade model (hN). Modifications not yet filtered down into the parameterized (hA, default) model.

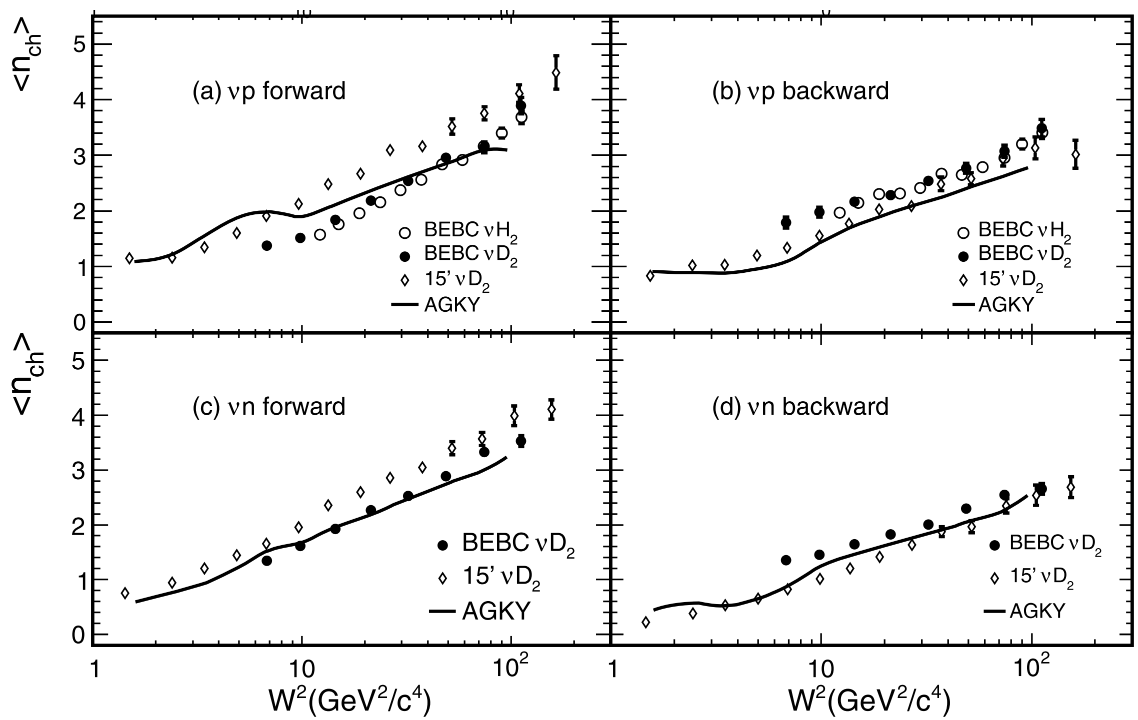






Modeling Nuclear Effects

- What about hadronization in the nuclear medium?
- We use Pythia (currently version 6, migration to 8 is on-going).
- GENIE does reasonably well, but the validation uses deuterium or hydrogen - little influence from nuclear effects.



T. Yang et al, Eur. Phys. J C (2009) 63:1-10

AGKY Hadronization

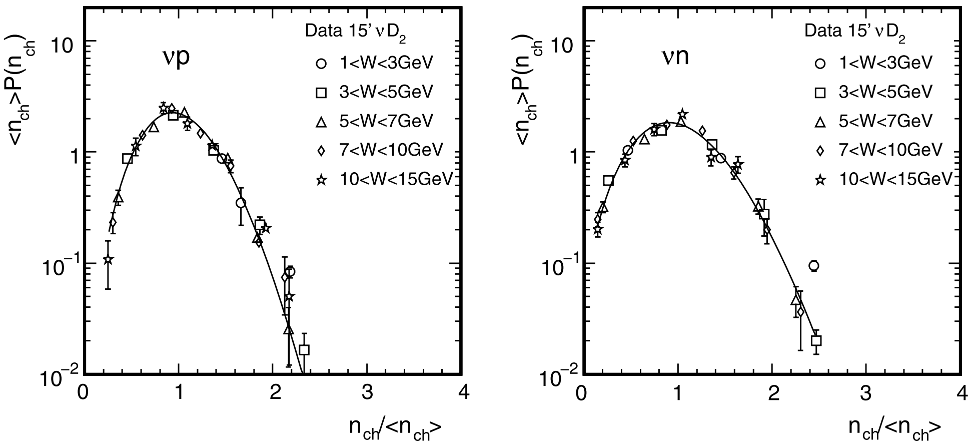


Fig. 1 KNO scaling distributions for νp (*left*) and νn interactions. The curve represents a fit to the Levy function. Data points are taken from [7]

T. Yang et al, Eur. Phys. J C (2009) 63:1-10

The AGKY model, which is now the default hadronization model in the neutrino Monte Carlo generators NEUGEN [9] and GENIE-2.0.0 [10], includes a phenomenological description of the low invariant mass region based on Koba–Nielsen–Olesen (KNO) scaling [11], while at higher masses it gradually switches over to the PYTHIA/JETSET model. The transition from the KNO-based model to the PYTHIA/JETSET model takes place gradually, at an intermediate invariant mass region, ensuring the continuity of all simulated observables as a function of the invariant mass. This is accomplished by using a transition window $[W^{tr}_{min}, W^{tr}_{max}]$ over which we linearly increase the fraction of neutrino events for which the hadronization is performed by the PYTHIA/JETSET model from 0% at W^{tr}_{min} to 100% at W^{tr}_{max}. The default values used in the AGKY model are

$$W^{tr}_{min} = 2.3\ \mathrm{GeV}/c^2, \qquad W^{tr}_{max} = 3.0\ \mathrm{GeV}/c^2.$$

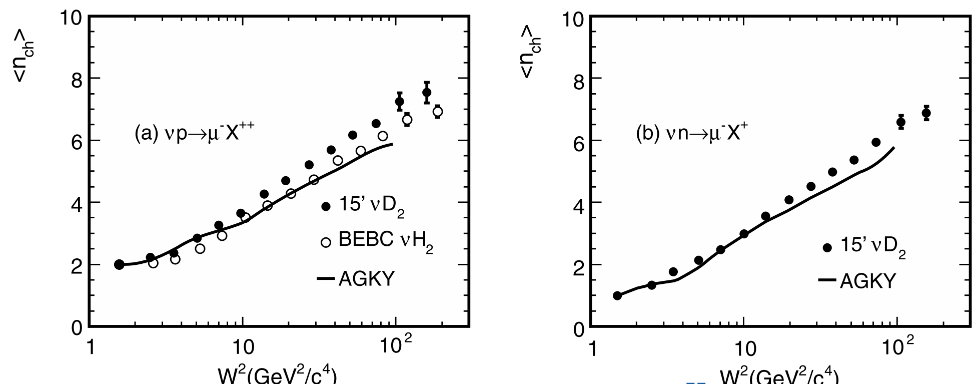
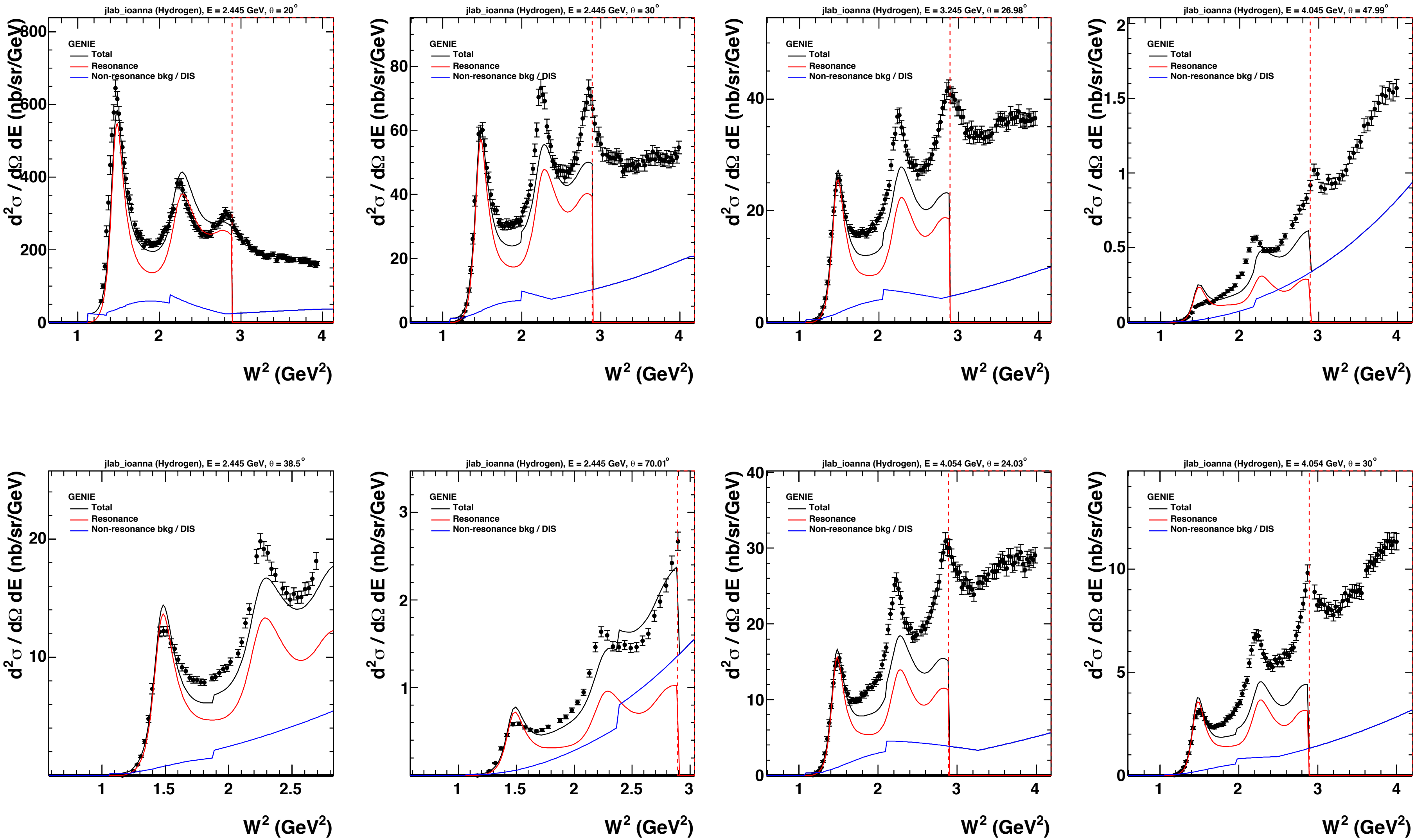


Fig. 3 Average charged-hadron multiplicity $\langle n_{ch}\rangle$ as a function of W^2. (**a**) νp events. (**b**) νn events. Data points are taken from [7, 20]

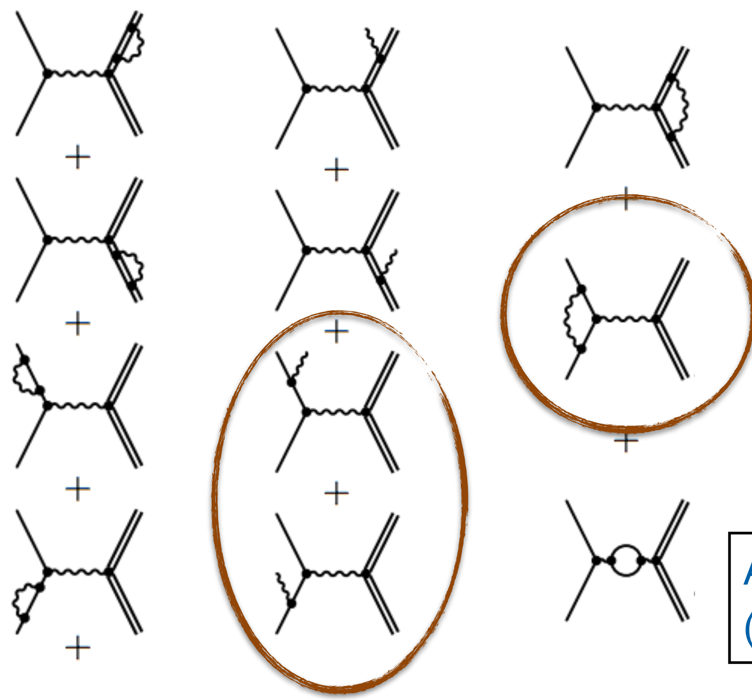
Electrons

- Some distributions look good, others are more challenging.



Radiative corrections in GENIE

- To first order, we don't do them.
- Some on-going work (O. Hen's group at MIT) to include some basic effects.
  - Corrections for nuclear effects are not part of the current effort.



A. Ashkenazi
(Private communication)

initial state radiation

For the ISR, relevant only for the electron scattering case.

We aim to subtract energy and momentum from the initial state probe according to a given distribution.

final state radiation

Final state radiation should be applicable for both electron and neutrino mode.

We aim to add a final state photon and keep record of the decay.
We think of the possibility of doing this process via GEANT and not GENIE.

internal

We're currently looking at two approaches:

1. Based on PHYSICAL REVIEW C, VOLUME 62, 025501
   The energy loss, ΔE, can be sampled using the distribution:

$$I_{int}(E, \Delta E, a) = \frac{a}{\Delta E}\left(\frac{\Delta E}{E}\right)^a$$

where E is the incoming electron energy

$$a = \frac{\alpha_{EM}}{\pi}[ln(\frac{Q^2}{m^2}) - 1]$$

good approximation using Q^2 from elastic scattering

For Nuclei a should be multiply by Z

2. Based on L. W. Mo and Y. S. Tsai, SLAC-PUB-380.

$$I(E, \Delta E, t) = \frac{1}{E}\frac{ln(\frac{E}{E-\Delta E})^{\frac{t}{ln2}-1}}{\Gamma(\frac{t}{ln2})}$$

where t is target thickness in radiation lengths

A. Ashkenazi
(Private communication)

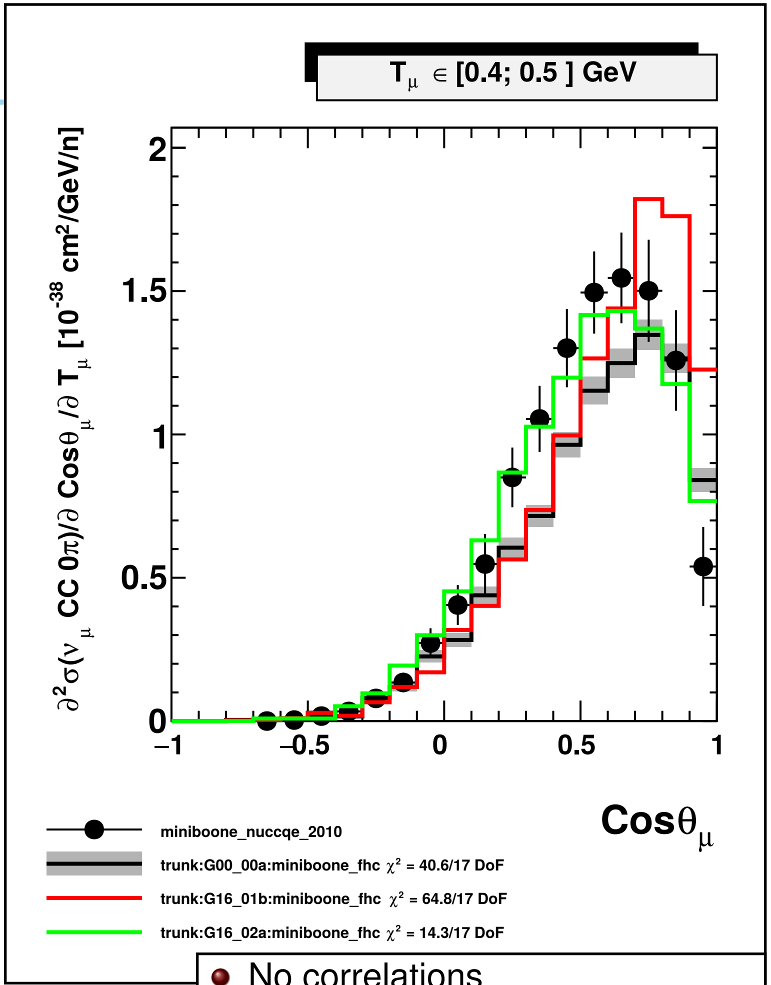
New Releases: GENIE 3.0

- The basic idea behind GENIE 3.0 is to vastly improve the configuration mechanisms to make it easier to change between model "constellations" and provide a mechanism for storing new constellations.
  - It should be a command line option to switch,
    - e.g., `--constellation minerva2017`, or
    - e.g., `--constellation best_theory`
- Of course, there will be *some* default and we will likely do some tuning/updates to improve it.
  - We are currently testing four basic variations.

Fermilab

GENIE 3.0 - versions

- Default - `G00_00a`
  - No MEC
  - CCQE process is LwlynSmith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie
- Default + MEC - `G16_01b`
  - with Empirical MEC
  - CCQE process is LwlynSmith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie
- Nieves, Simo, Vacas Model - `G16_02a`
  - Theory motivated MEC
  - CCQE process is Nieves
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Local Fermi Gas Model
- G17_02a (not presented in this talk) - `G17_02a`
  - with Z-Expansion for Axial form factor
  - Get rid of M_A



- No correlations
- Preferred model is Nieves Model (G16_02a)
  - excellent agreement for ν
  - $\chi^2 = 101/137$ DoF
- worse for $\bar{\nu}$
  - $\chi^2 = 176/78$ DoF

Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

GENIE Comparisons

The GENIE suite contains a package devoted to comparing GENIE predictions against publicly released datasets.

- Crucial technology for **new GENIE global fit** to neutrino scattering data
- Provides the opportunity to improve and develop GENIE models
- All sorts of data
  - **Modern Neutrino Cross Section measurement**
    - nuclear targets
    - typically flux-integrated differential cross-sections
    - MiniBooNE, T2K, MINERvA
  - **Historical Neutrino Cross Section Measurement**
    - Bubble chamber experiment
  - Measurements of neutrino-induced **hadronic system characteristics**

Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

GENIE 4.0 - GENIE + Professor

https://professor.hepforge.org

Current authors:
- Andy Buckley (Glasgow)
- Holger Schulz (IPPP)

Former members:
- Hendrik Hoeth
- Heiko Lacker
- Jan Eike von Seggern
- Daniel Weyh
- Simone Amoroso

Professor is a **tuning tool for Monte Carlo event generators**, based on the ideas described in "Tuning and Test of Fragmentation Models Based on Identified Particles and Precision Event Shape Data" (Z. Phys., C73 (1996) 11-60).

Professor has been successfully used to produce **most of the established "tunings"** of the general purpose MC event generators.

A collaboration between Professor and GENIE authors to produce a **Professor/GENIE interface** and **Professor-based GENIE tunes** was supported by Inst. of Particle Physics Phenomelogy via an IPPP Associateship Award.

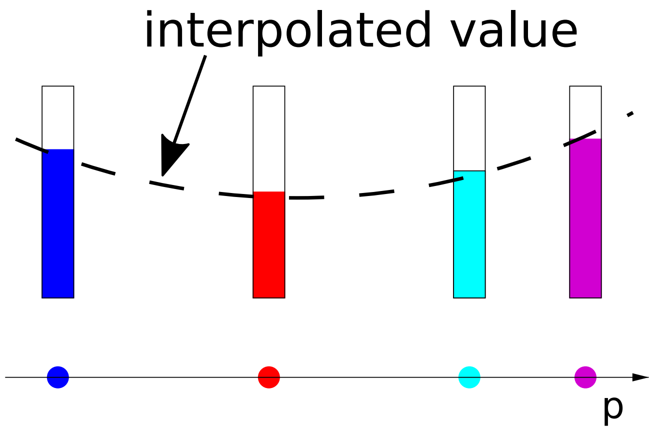
→ **Active ongoing work!**

Energy Frontier

Slide by C. Andreopoulos

GENIE + Professor

- http://professor.hepforge.org
- Numerical assistant
- Developed for ATLAS experiment
- $I(p)$ used instead of a full MC
  1. MC runs subset of param space
  2. sample bin's behaviour
  3. Parametrization $I(p)$
     - Polinomial interpolation
  - Repeat for each bin
- a parameterization $I_j(p)$ for each bin
- Minimize according to $\vec{I}(p)$
- $\sim$ 15 parameters



Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

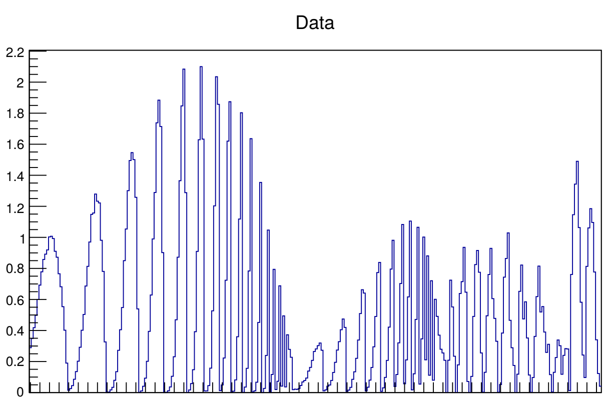
Fermilab

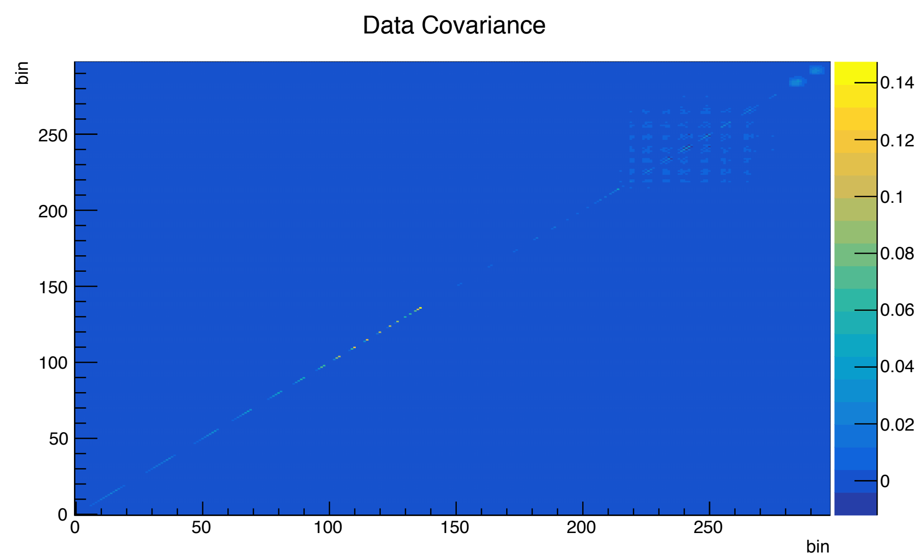
GENIE + Professor

- Highly parallelizable
  - independent from the minimization
- All kind of parameters can be tuned
  - Not only reweight-able
- Advanced system
  - Take into account correlations
  - weights specific for each bin and/or dataset
    - Proper treatment while handling multiple datasets
    - Restrict the fit to particular subsets
  - Nuisance parameters can be inserted
    - proper treatment for datasets without correlations (MiniB
- Reliable minimization algorithm
  - based on Minuit

Marco Roda - `mroda@liverpool.ac.uk`
on behalf of GENIE collaboration

- MiniBooNE ν_μ CCQE
  - 2D histogram
  - 137 points
- MiniBooNE $\bar{\nu}_\mu$ CCQE
  - 2D histogram
  - 78 points
- T2K ND280 0π (2015)
  - irregular 2D histogram
  - 67 points
- MINERvA ν_μ CCQE
  - 1D histogram
  - 8 points
- MINERvA $\bar{\nu}_\mu$ CCQE
  - 1D histogram
  - 8 points





Fermilab

Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

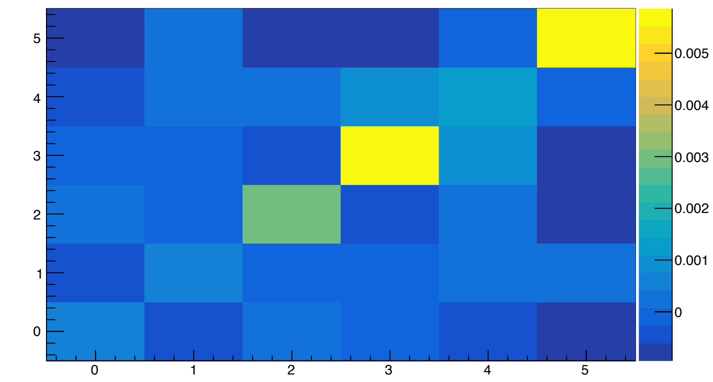
GENIE + Professor

- Default + Empirical MEC
- `G16_01b` in the new naming scheme
- Parameters:
  - QEL-$M_A \in [0.7; 1.8]$ *GeV* - Default value is 0.99 GeV
  - QEL-CC-XSecScale $\in [0.8; 1.2]$ - Default value is 1
  - RES-CC-XSecScale $\in [0.5; 1.5]$ - Default value is 1
  - MEC-FracCCQE $\in [0; 1]$ - Default value is 0.45
  - FSI-PionMFP-Scale $\in [0.6; 1.4]$ - Default value is 1
  - FSI-PionAbs-Scale $\in [0.4; 1.6]$ - Default value is 1

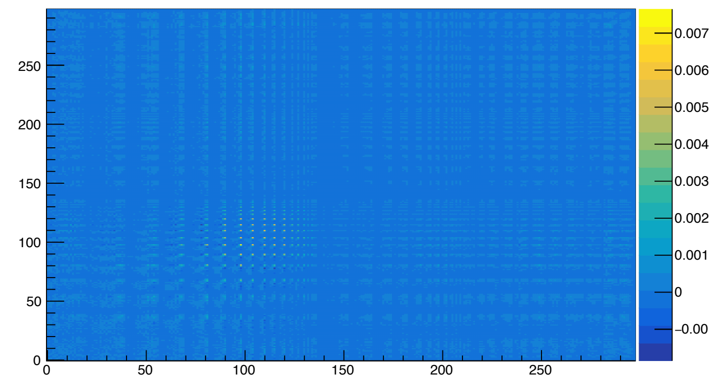
- Parameters best fit
  - 0 M_A
  - 1 QEL-CC-XSecScale
  - 2 RES-CC-XSecScale
  - 3 MEC-FracCCQE
  - 4 FSI-PionMFP-Scale
  - 5 FSI-PionAbs-Scale

- Prediction covariance
  - due to the propagation of the param. covariance
  - So far not used
  - Tool to propagate systematics parameters

Parameter Covariance



Prediction Covariance



GENIE + Professor

Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

Datasets were fitted separately (and together)

Parameter	Neutrino fit	Anti-neutrino fit	Global fit
M_A (GeV/c^2)	1.17 ± 0.02	1.26 ± 0.03	1.21 ± 0.02
QEL-CC-XSecScale	0.93 ± 0.01	0.97 ± 0.02	0.95 ± 0.02
RES-CC-XSecScale	0.86 ± 0.05	0.98 ± 0.09	1.02 ± 0.05
MEC-FracCCQE	0.85 ± 0.03	0.7 ± 0.1	0.53 ± 0.08
FSI-PionMFP-Scale	0.87 ± 0.02	1.39 ± 0.03	0.75 ± 0.04
FSI-PionAbs-Scale	1.51 ± 0.03	0.7 ± 0.1	0.87 ± 0.07

Fit Results	Neutrino fit	Anti-neutrino fit	Global fit	Nominal Values
Miniboone ν_μ χ^2	152 / 137	171 / 137	138 / 137	441 / 137
MiniBooNE $\bar{\nu}_\mu$ χ^2	60 / 78	32.4 / 78	36.2 / 78	50.4 / 78
T2K χ^2	237 / 67	276 / 67	252 / 67	135 / 67
MINERvA ν_μ χ^2	6.11 / 8	8.07 / 8	7.79 / 8	17.5 / 8
MINERvA $\bar{\nu}_\mu$ χ^2	8.19 / 8	11.5 / 8	5.7 / 8	6.23 / 8
Global dataset χ^2	463 / 292	499 / 292	440 / 292	650 / 298

- M_A and cross section scale factors are in good agreement
- FSI parameters are not
- The agreement with data is reasonable
    - Better than original model

- Default + MEC - `G16_01b`
    - with Empirical MEC
    - CCQE process is LwlynSmith Model
    - Dipole Axial Form Factor - Depending on $M_A = 0.99$ *GeV*
    - Nuclear model: Fermi Gas Model - Bodek, Ritchie

GENIE + Professor

Marco Roda - mroda@liverpool.ac.uk
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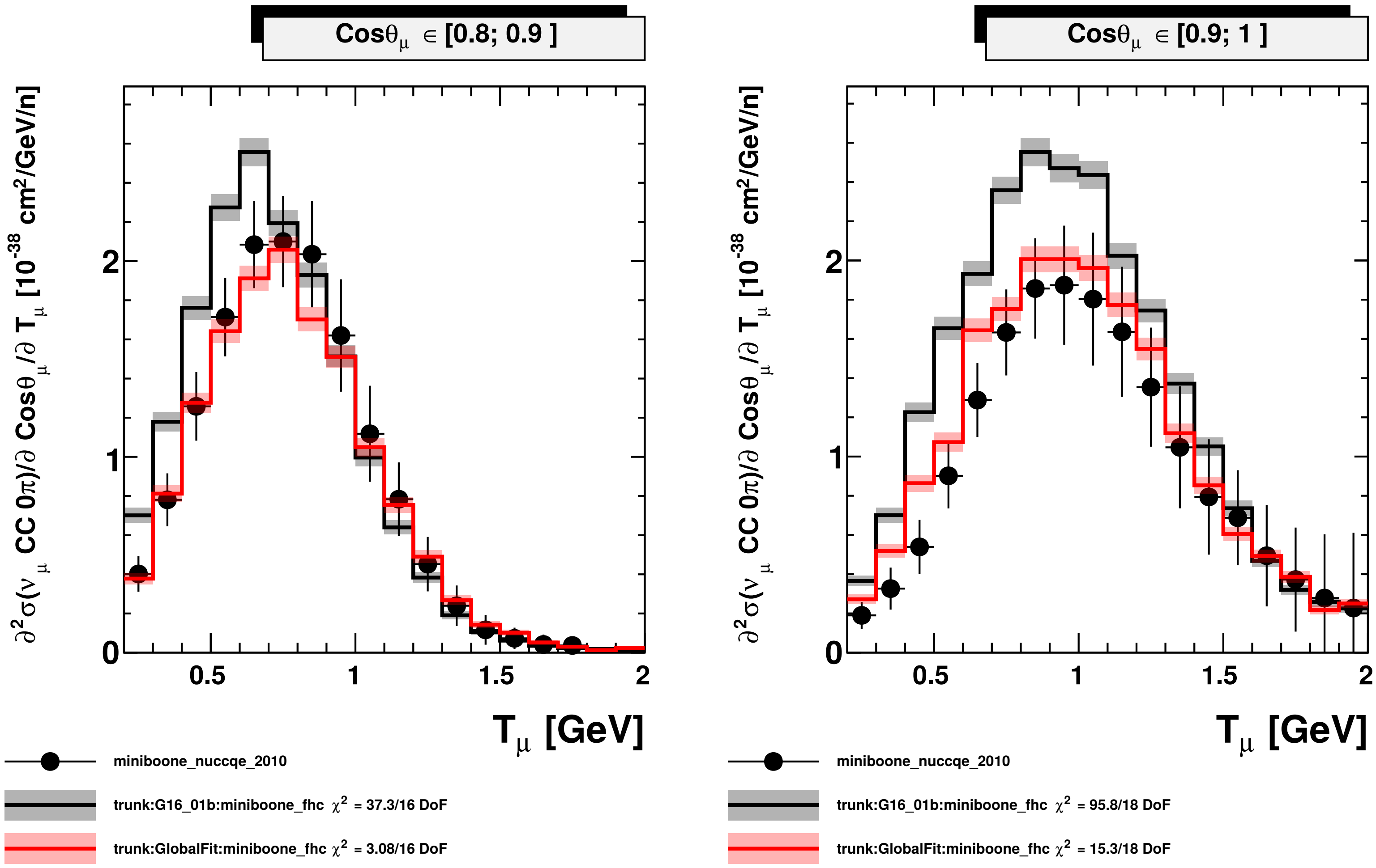
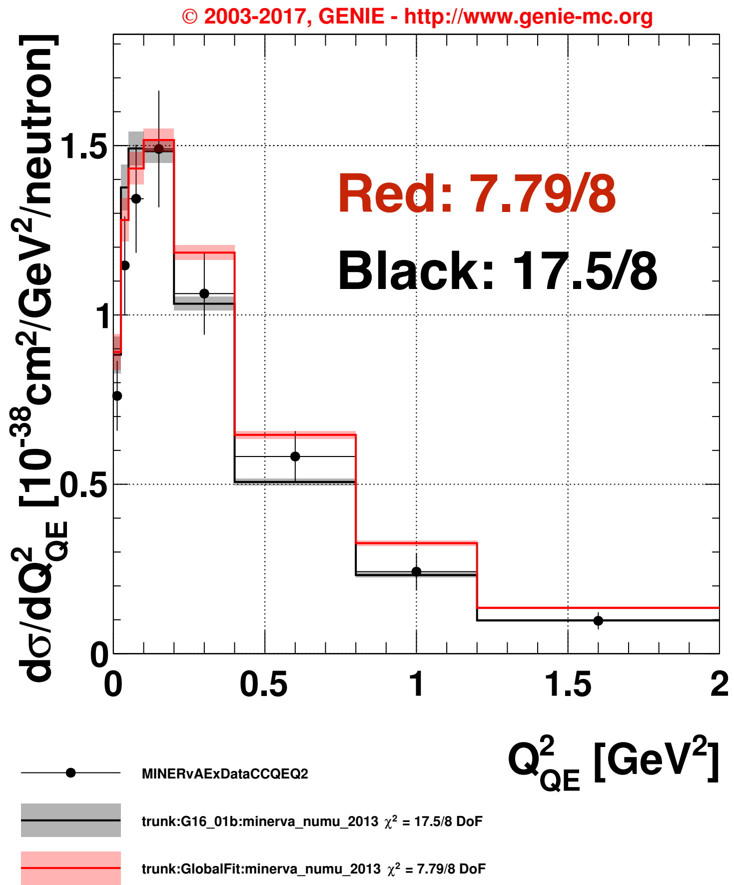
Best fit - MiniBooNE ν_μ CCQE



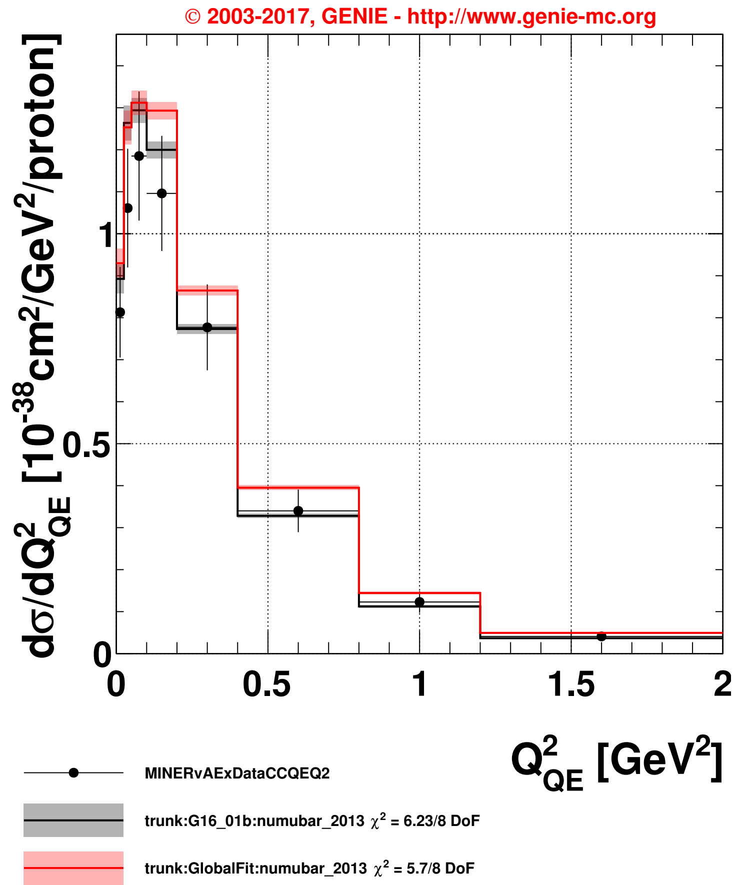
Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

Best fit - MINERvA

Neutrinos



Antineutrinos



⇒ "Eye evaluation" would prefer default model

Peelle's Pertinent Puzzle

Schedule

- GENIE 3.0 "soon"
  - finalizing comparisons
  - deciding on technical changes
- GENIE 4.0 is on an aggressive schedule also.
  - the goal is this calendar year
  - lots of technical progress already at Liverpool
  - but many thorny physics issues (dataset tensions, experiment-theory tensions, opinions about model selection, etc.) to sort out...

NuWro

- NuWro is not an official MC in any experiment and serves as a laboratory for new developments.
- New (or relatively new) ingredients:
  - Berger-Sehgal coherent pion production
  - π momentum distribution from Δ decay
  - effective density and momentum dependent potential for CCQE (C. Juszczak, J. Nowak, J. Sobczyk)
- eWro - electron scattering module (a work in progress) C. Juszczak, K. Graczyk, JTS, J. Zmuda

Jarek Nowak, Lancaster University

IPPP/NuSTEC topical meeting on Neutrino-Nucleus scattering

- http://school.genie-mc.org (lecture by T. Golan)
- https://github.com/NuWro/nuwro
- https://nuwro.github.io/user-guide/

NuWro

- All major interaction channels are implemented, for charged and neutral current, covering neutrino energy region from a few hundreds MeV (Impulse Approximation limit) to several TeV:
- QEL (quasi-)elastic scattering
- RES pion production through a Δ resonance excitation
- DIS more inelastic processes
- COH coherent pion production
- np-nh two body current contribution
- **Transition region treatment**: smooth transition from full RES(Δ) to full DIS starting from $W=1.3$ -$1.6\ GeV/c^2$

EWro (work in progress)

J. Nowak

The main idea: to test NuWro nuclear model using electron scattering data

- Fermi gas and local Fermi gas
- QE and Δ regions only
- for Δ non-resonant background after E. Hernandez, J. Nieves, M. Valverde, Phys. Rev. D76 033005 (2007)
- EM form factors from J. Zmuda, K.M. Graczyk, arXiv:1501.03086v4
- Δ self-energy following E. Oset, L.L. Salcedo, Nucl. Phys. A468 631 (1987)

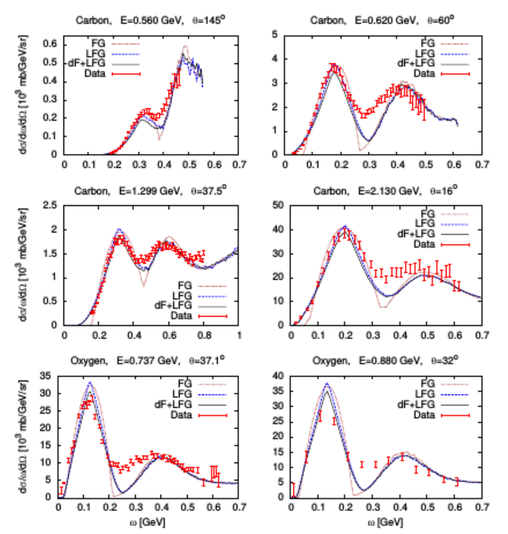
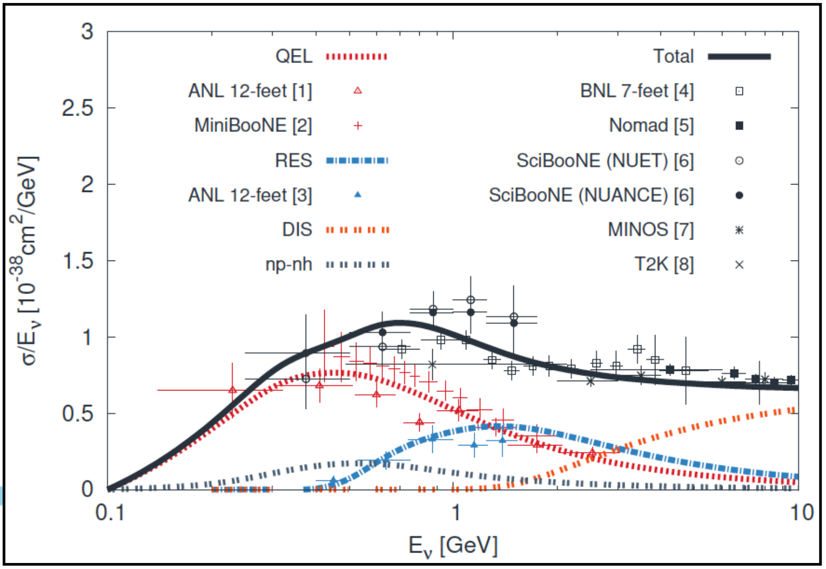


Fig. 1. Differential cross sections for electron scattering off carbon and oxygen obtained within eWro (for various beam energies, E, and scattering angles, θ).

K. Graczyk, C. Juszczak, JTS, J. Zmuda, arXiv:1510.03268

- Re-weighting utilities are new.



"Nature"

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- http://gibuu.hepforge.org
- Strives to use the "best possible theory" in all cases.

- *Initial interactions:*
  - Mean field potential with local Fermigas momentum distribution, nucleons are bound (not so in generators!)
  - Initial interactions calculated by summing over interactions with all bound, Fermi-moving nucleons
  - 2p2h from electron phenomenology
- *Final state interaction:*
  - propagates outgoing particles through the nucleus using *quantum-kinetic transport theory*, fully relativistic (off-shell transport possible).
    Initial and final interactions come from the same Hamiltonian.
    CONSISTENCY of inclusive and semi-inclusive X-sections

Ulrich Mosel

IPPP/NuSTEC (Durham) 2017

New in 2016:

- Stable groundstate implemented -> improved hole spectral functions
- 2p2h structure function for all kinematics, fitted to e-scattering, is used for neutrinos as well

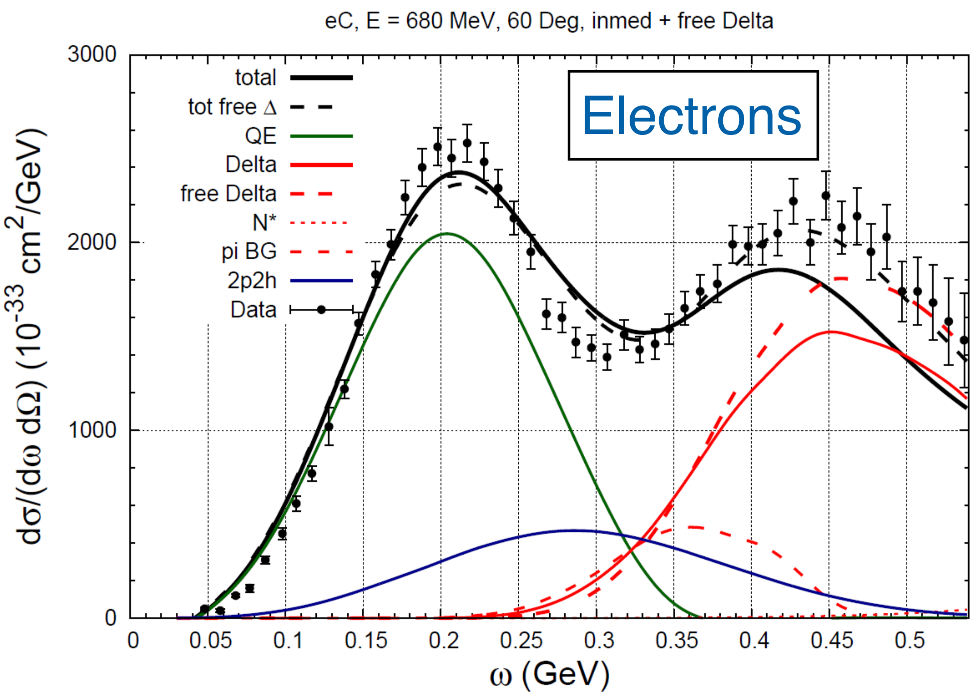
"Nature"

GiBUU

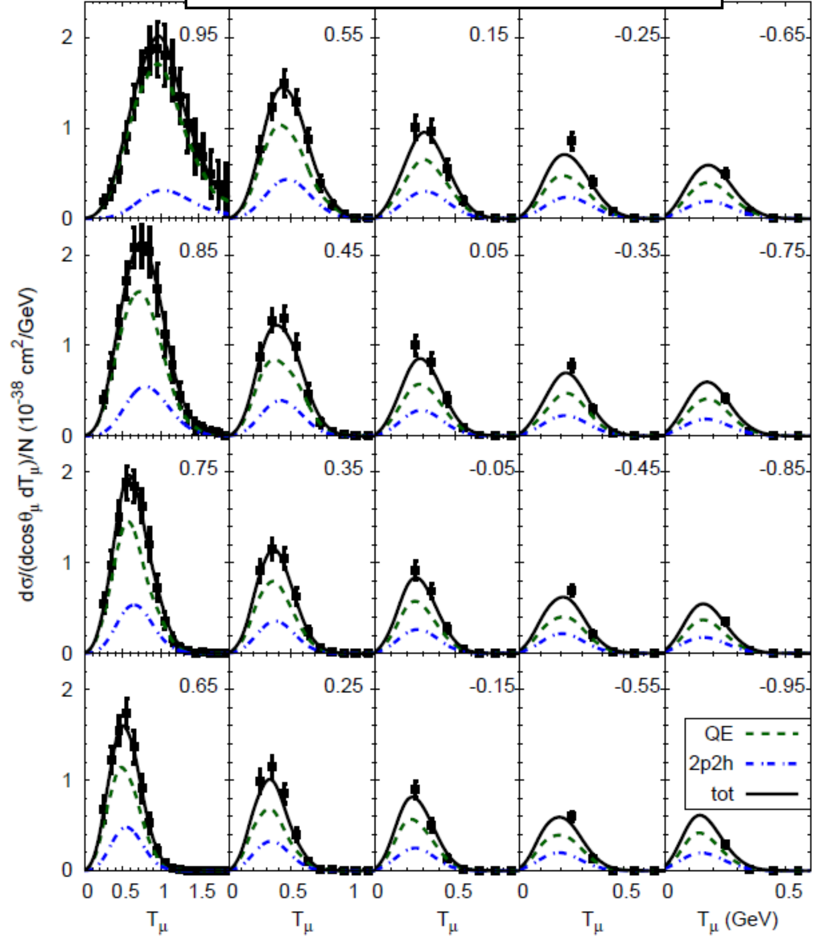
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- Compares well to many electron and neutrino data sets.
- Typically not re-weightable, no geometry/flux

Electrons



MiniBooNE Neutrinos

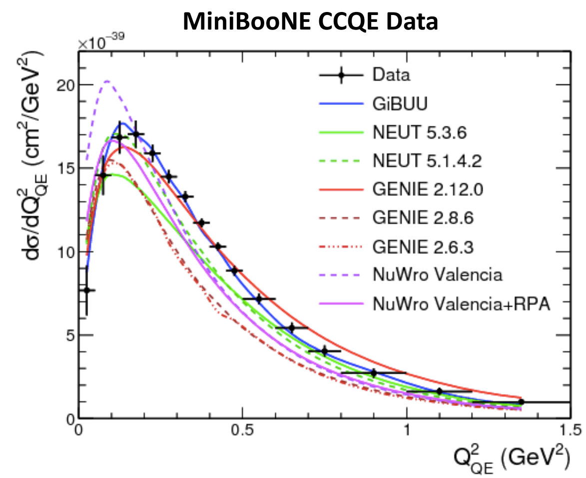


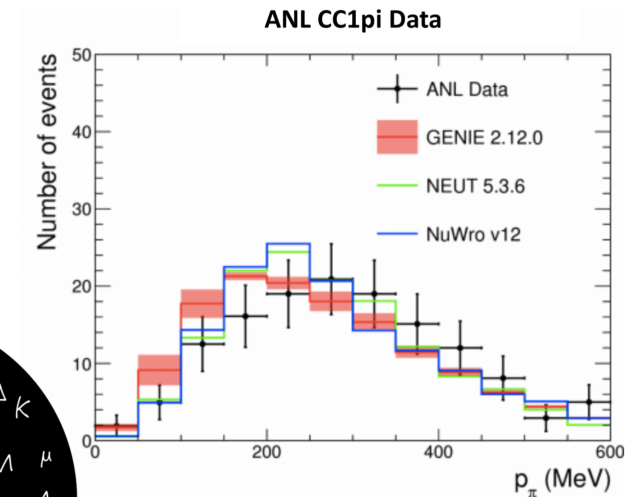
Ulrich Mosel

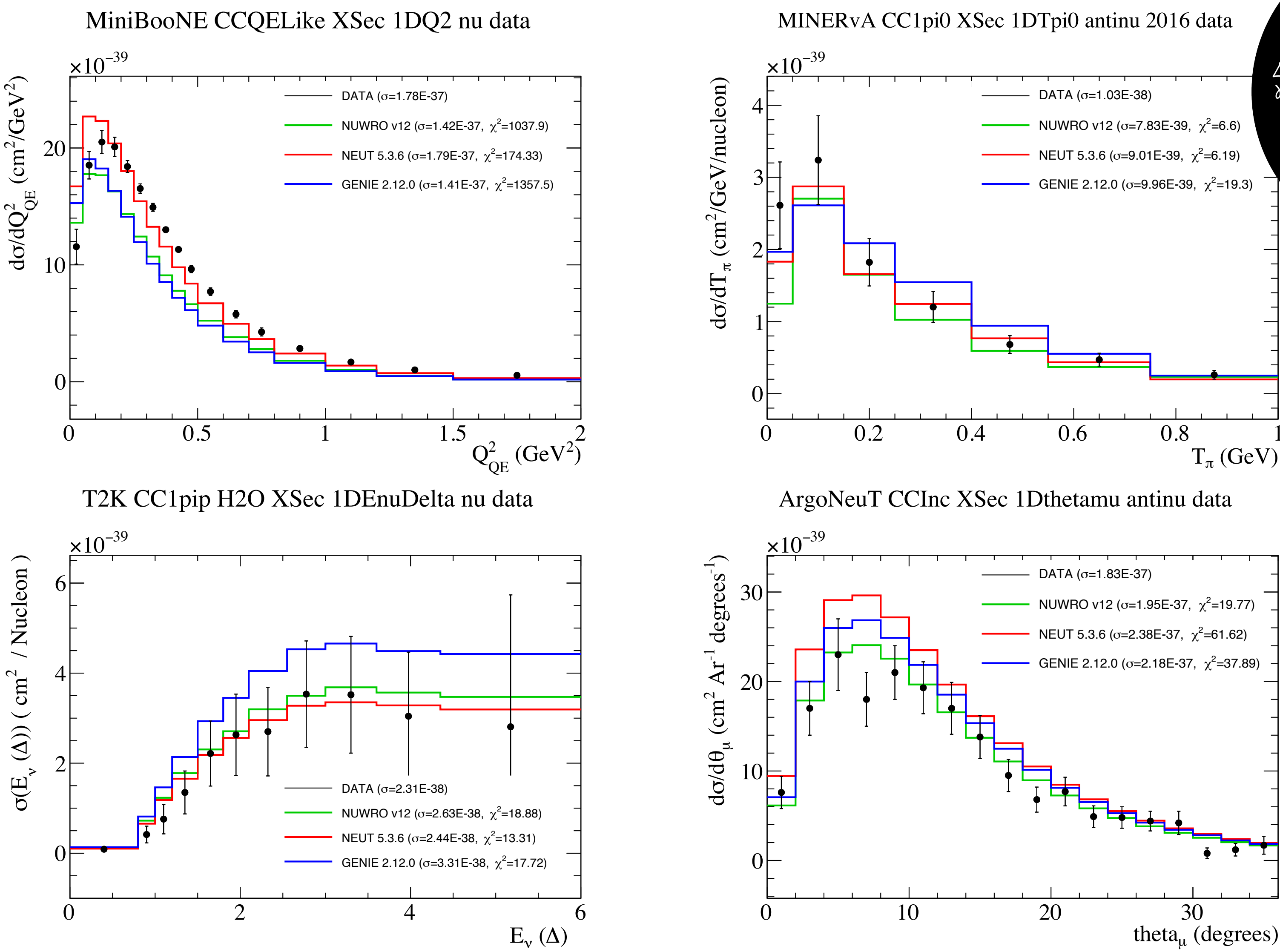
IPPP/NuSTEC (Durham) 2017

NUISANCE

- **Open source** generator tuning framework.
  - Tools for comparison plots, re-weighting (for NEUT, NuWro, and GENIE), fitting.
  - Interfaces to re-weighting tools in generators; can add ad-hoc weights as well.
  - Tuning mechanisms include support for priors via penalties in the likelihood.
  - Migrad & Bayesian tuning.
  - Reproducible results via job cards.
- http://nuisance.hepforge.org







http://nuisance.hepforge.org/files/validation/nuisancevalidation_v1r0_280217/nuisance_v1r0_validation_280217.pdf

NUISANCE

P. Stowel,
Communication to MINERvA

- Tuning mechanisms:

Frequentist Method (Migrad)

1. Form a joint likelihood for all samples included in a fit.
2. Use ROOT's GSL minimizer libraries to find a best fit.
3. Use MINOS to evaluate errors and parameter contours.

Bayesian Method

1. Throw 1-sigma prior uncertainties for all free params.
2. Bin prior distribution with no weights for each param.
3. Bin distribution again weighting each throw by the likelihood

NUISANCE can throw parameters according to arbitrary prior distributions and saves the Data-MC χ^2 value for each dataset.

Method	Pros	Cons
'Migrad' Tuning	• Can quickly see if parameters are pulled to crazy values.	• Need to run many different fits when looking at subsets of the data. • Risk of getting stuck in local minima.
Bayesian Tuning	• One single large set of throws should cover all possible fits to subsets of the data. • Additional prior penalty terms (BC tuning) can be included after throws are made.	• Requires many throws when looking at many dimensional fits. • Need to make sure prior covers all datasets.

Thanks!

Luis Alvarez-Ruso [8], Costas Andreopoulos [2,5], Christopher Barry [2],
Francis Bench [2], Steve Dennis [2], Steve Dytman [3], Hugh Gallagher [7], Tomasz Golan [1,4,*],
Robert Hatcher [1], Rhiannon Jones [2], Libo Jiang [3], Anselmo Meregaglia [6],
Donna Naples [3], Gabriel Perdue [1], Marco Roda [2],
Jeremy Wolcott [7], Julia Yarba [1]

(The GENIE Collaboration)

(1) Fermi National Accelerator Laboratory, USA
(2) University of Liverpool, UK
(3) University of Pittsburgh, USA
(4) University of Rochester, USA
(5) STFC Rutherford Appleton Laboratory UK
(6) Strasbourg IPHC, France
(7) Tufts University, USA
(8) University of Valencia, Spain
* Currently at the University of Wroclaw, Poland

Back-up

What is GENIE?

- GENIE (like the other widely-adopted generator, NEUT), is staffed by experimentalists.
- Obligatory quotation of U. Mosel:
  - "Theorists don't care if the they agree with data, they only care if they are right. Experimentalists don't care if they are right, only if they agree with data."
- In order to produce a global physics model that agrees with neutrino data, one must occasionally do some violence to the models.
  - We stand ready to do that hard act out of sight of our theoretical colleagues...

What is GENIE?

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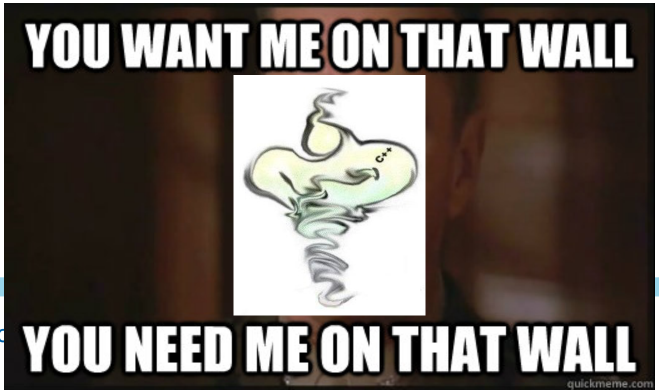


Nuclear Effects in *Electron* Scattering

EMC Effect and Quark Distributions in Nuclei

Measurements of F_2^A / F_2^D (EMC, SLAC, BCDMS,…) have shown definitively that quark distributions are modified in nuclei.

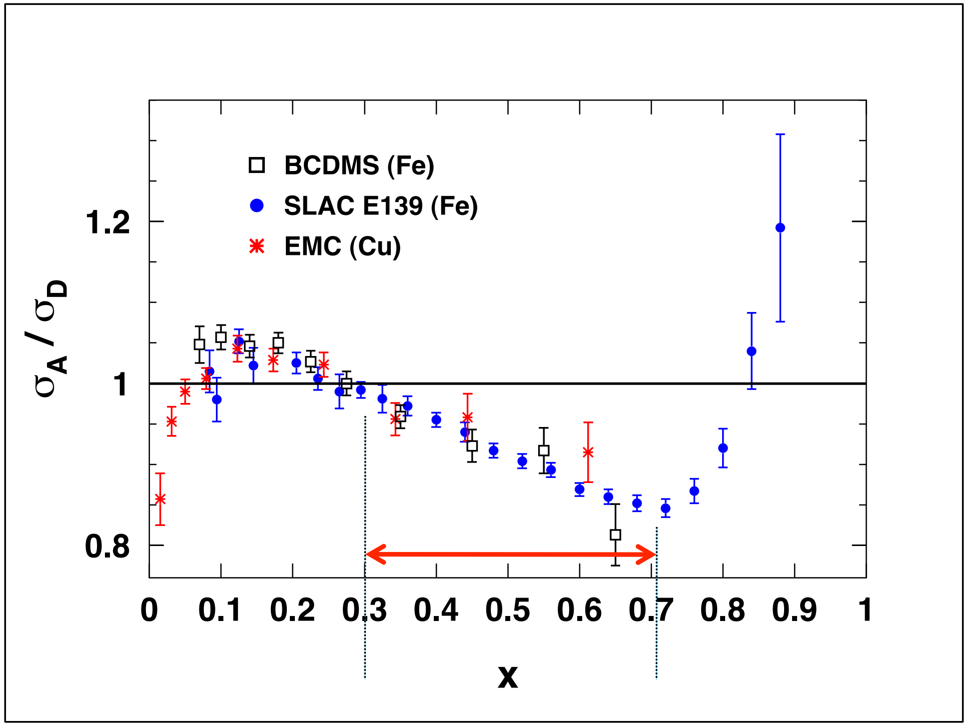
Nucleus is not simply an incoherent sum of protons and neutrons

Observed properties:

1. *x*-dependence same for all *A*

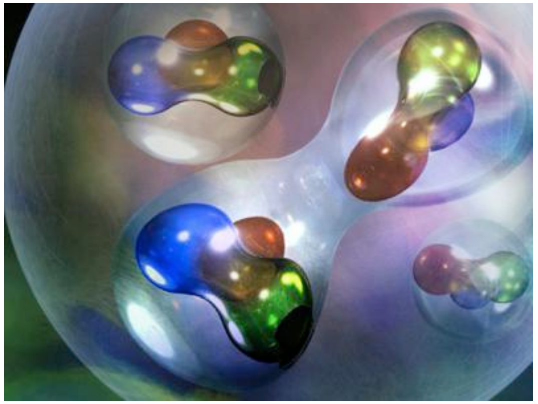
Shadowing:	*x<0.1*
Anti-shadowing:	*0.1<x<0.3*
EMC effect:	*x>0.3*

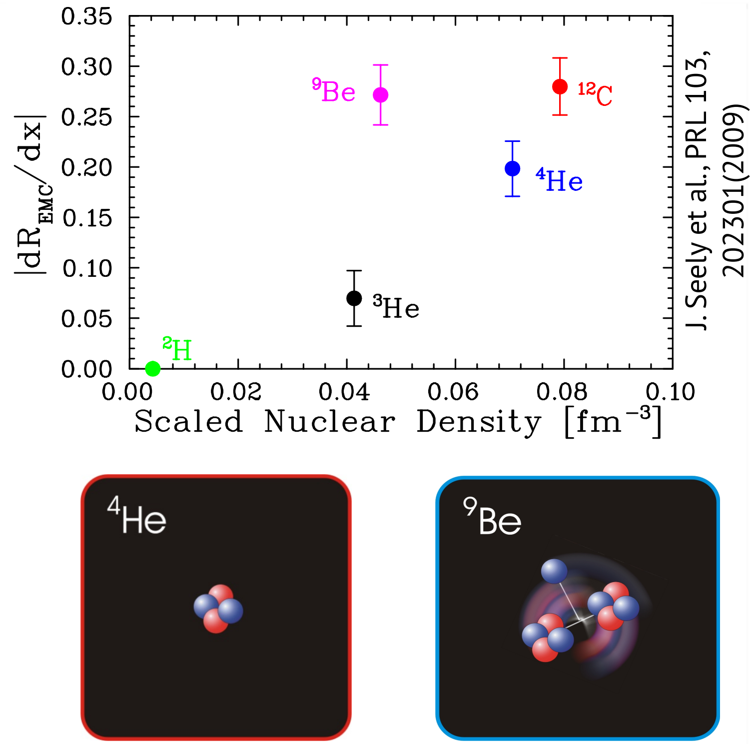
2. Size of EMC effect depends on *A* (i.e. minimum at *x=0.7*



D. Gaskell, ECT 2012, Trento
Hadrons in the Nuclear Medium

Short-Range Correlations and the EMC Effect



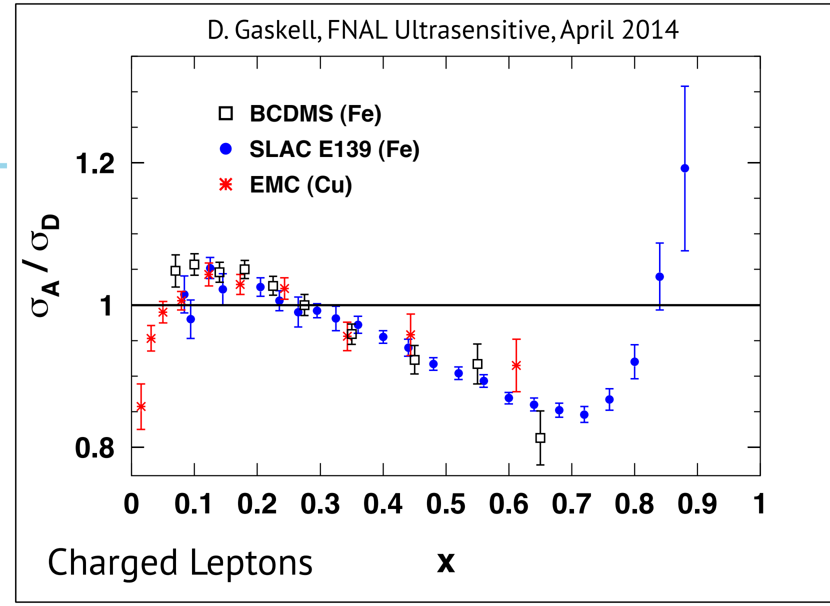


D. Gaskell, ECT 2012, Trento
Hadrons in the Nuclear Medium

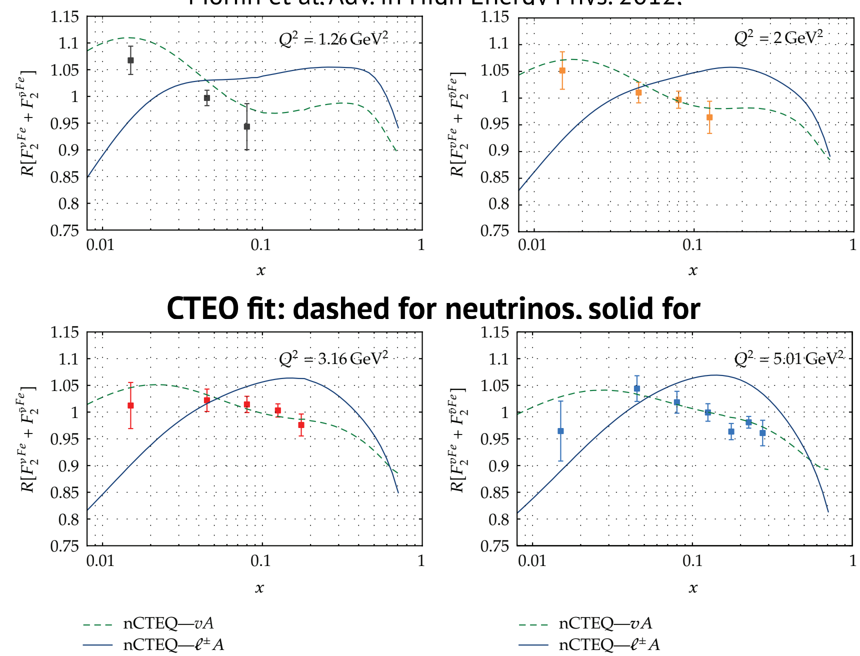
- ^{9}Be has a low average density - structure ~ 2α + n.
- Most nucleons are tightly-grouped (α-like).
- EMC effect modulated by local instead of average density?
- Is there a relation to MEC in neutrino scattering?

Nuclear Effects in Neutrino Scattering

- Quark distributions are modified in nuclei.
- Analogous data is lacking for neutrinos (the neutrino ratios use data on iron, but must calculate the denominator).
- Neutrinos see an additional structure function in the nucleus and so provide an important probe of nuclear physics.
- No good model of A-dependent nuclear effects in GENIE.



Morfin et al. Adv. in High Energy Phys. 2012.



New models in GENIE 2.12

- Valencia MEC
- Local Fermi Gas (nuclear model)
- Nieves et al CCQE model
- Oset modifications to cascade (hN) FSI model
- Kaon FSI
- z-expansion form of the Axial Form Factor for QE
- QEL hyperon production
- Berger-Sehgal coherent pion model
- Updated Rein diffractive pion model
- Energy-dependent MA model (Kuzmin-Naumov)

Valencia MEC

- Implementation discussed in arXiv 1601.02038
- Original model by Nieves, Simo, Vicente Vacas, PRC 83 (2011) 045501

arXiv 1601.02038

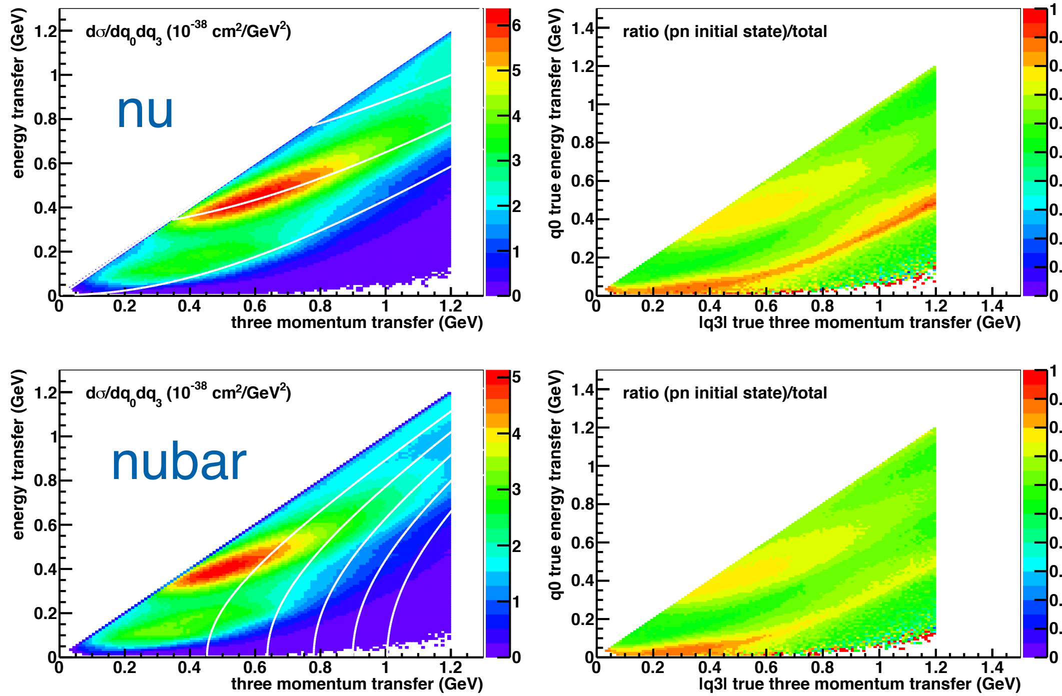
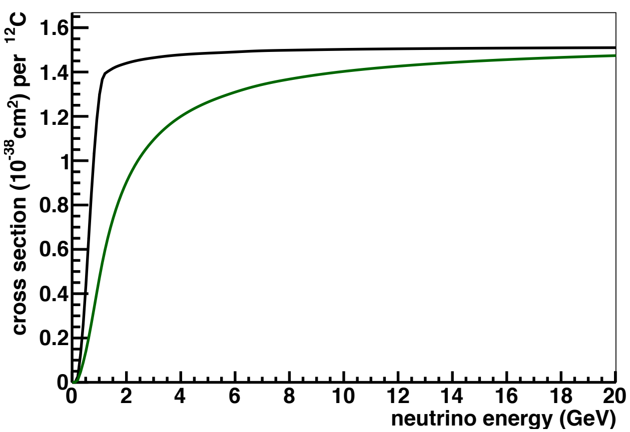


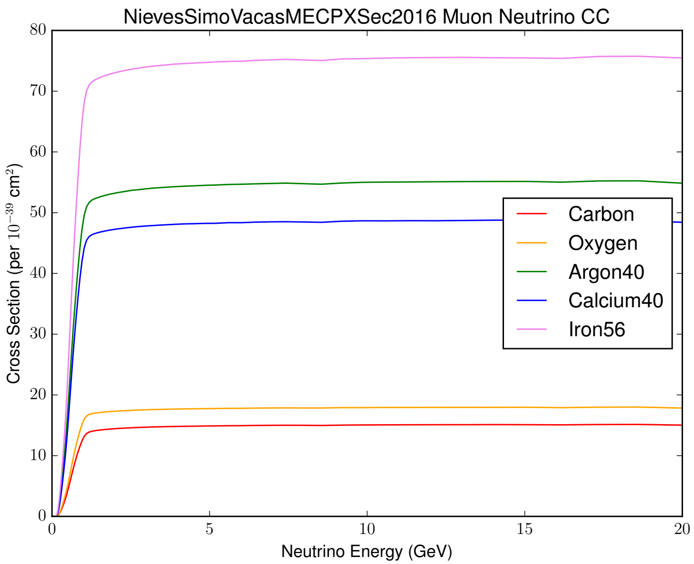
Figure 1: The differential cross section from the GENIE implementation of the QE-like 2p2h model (right) and the fraction of the total cross section with a pn initial state (left). The top plots are νC while the lower plots are $\bar{\nu}$C, both at 3 GeV. To guide the eye in this kinematics space, the neutrino figure has lines of constant W = 938, 1232, 1520 MeV emphasizing the dip region, and the anti-neutrino figure has lines of constant Q^2 from 0.2 to 1.0 GeV^2 emphasizing the low Q^2 nature of the cross section.

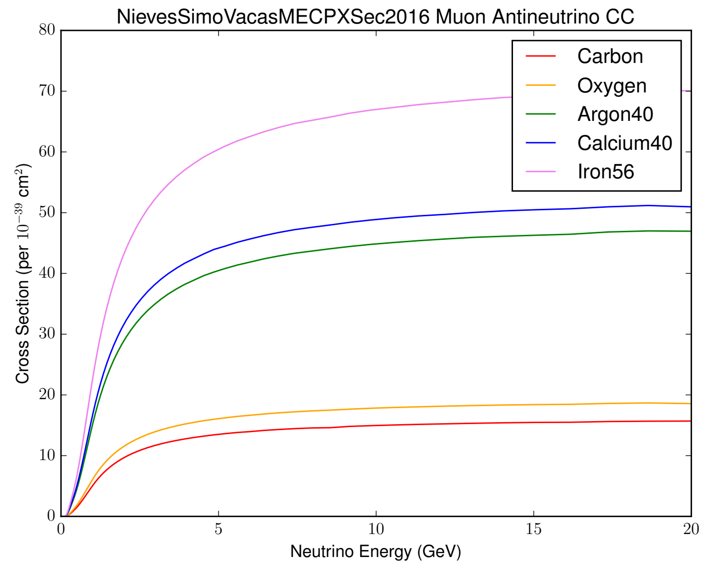


Fermilab

Valencia MEC - extension to non-isoscalar nuclei

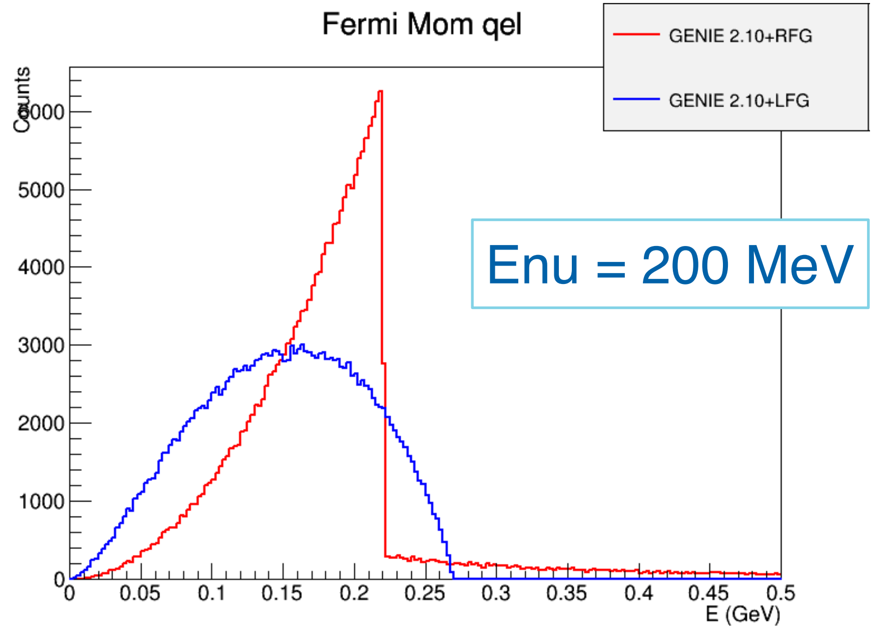
- The original model worked on isoscalar nuclei C12, O16, Ca40.
- New extension by Gran and Vicente Vacas covers most nuclei (e.g., Ar40).
- Modification covers three parts - effects of nuclear size, non-isoscalar features, Q-value.

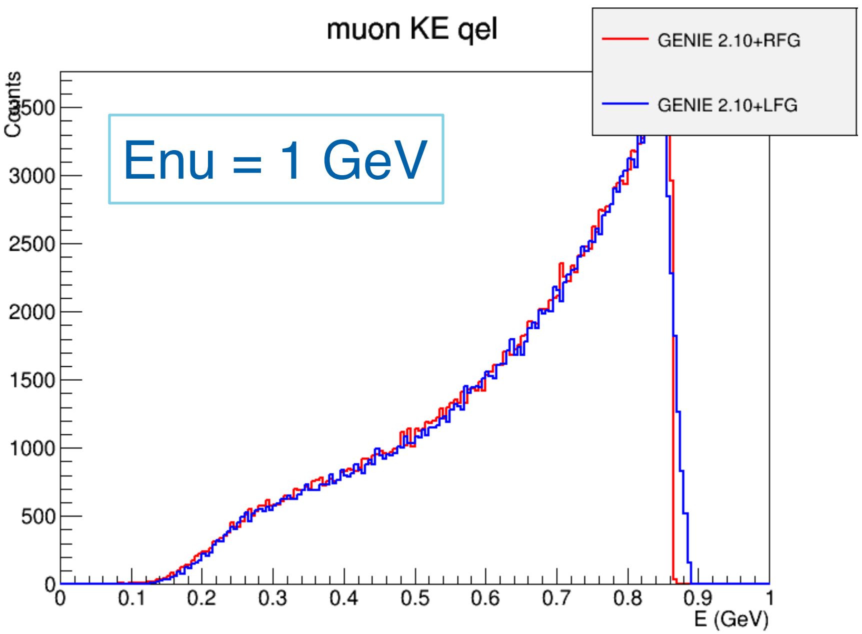


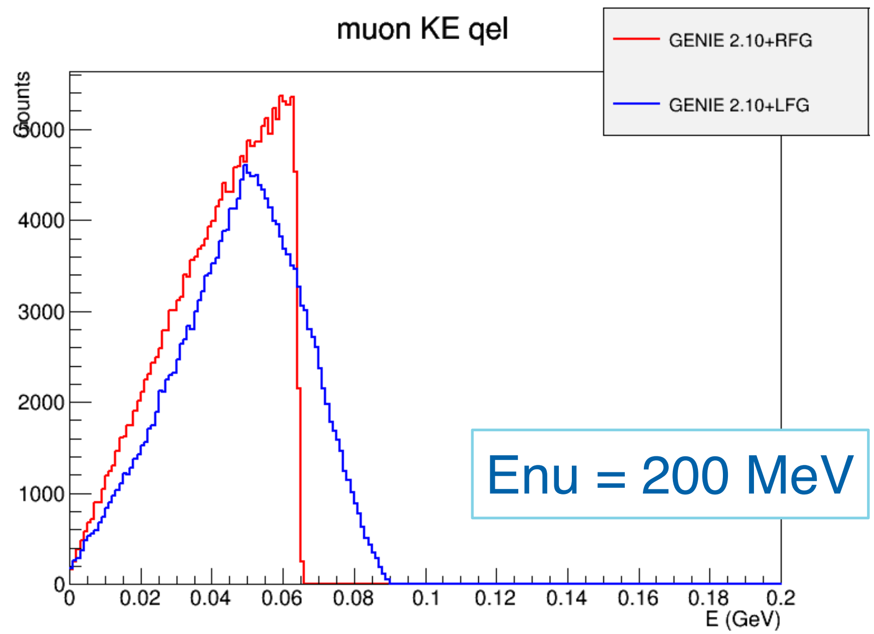


Local Fermi Gas

- In the LFG model, the Fermi momentum is a function of position in the nucleus.
- Target is C12 in the plots.



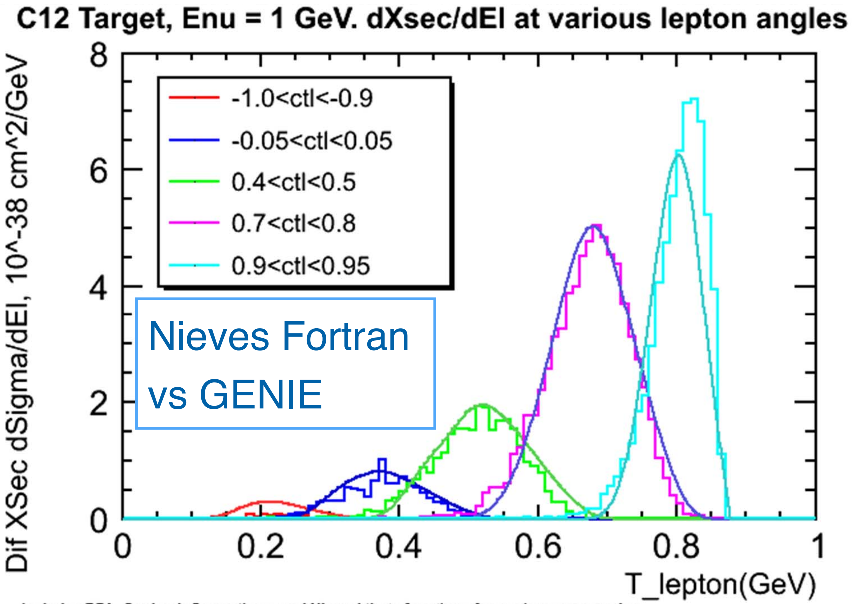




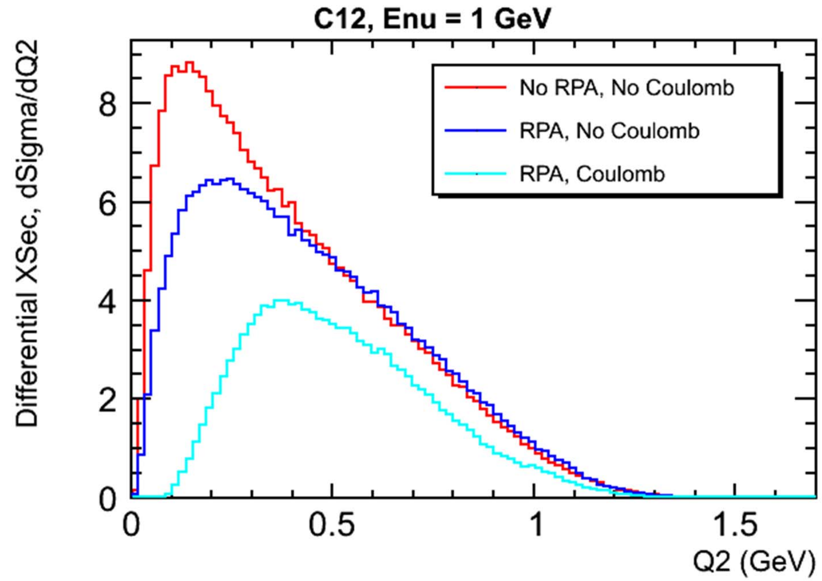
Fermilab

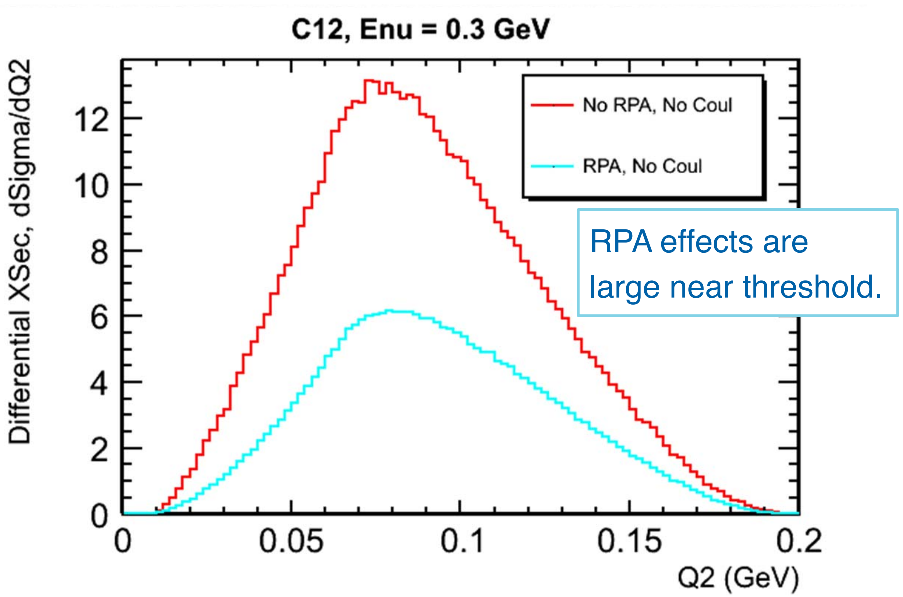
Nieves et al CCQE

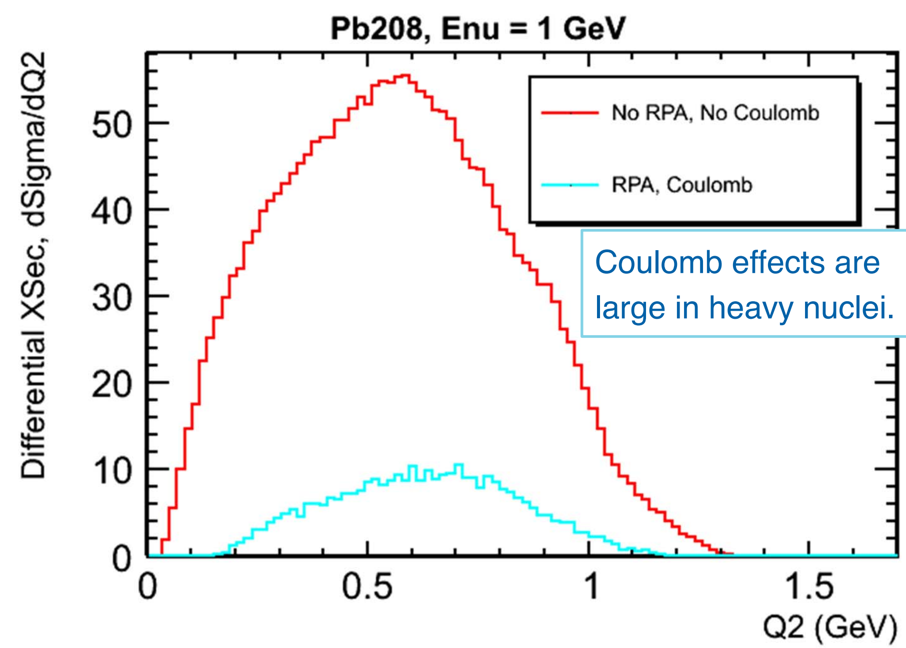
- Potential drop-in replacement for Llewelyn Smith QEL model, PRC 79, 055503 (2004).
- Adds RPA long range correlation (Weak charge screening) effect.
- Additionally accounts for the struck nucleon's initial momentum, Coulomb corrections, etc.
  - Formulae are identical for free nucleons, but Nieves et al varies from Llewelyn Smith in a nucleus).
- Requires LFG.



Includes RPA, Coulomb Corrections, and Nieves' theta functions for nuclear suppression

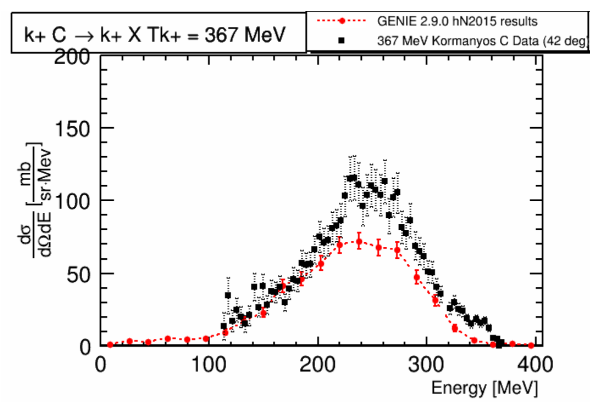


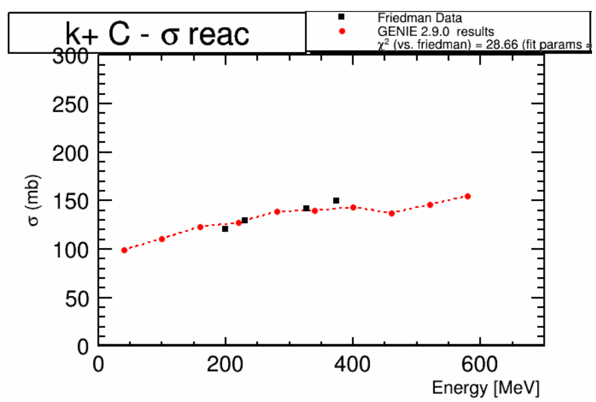


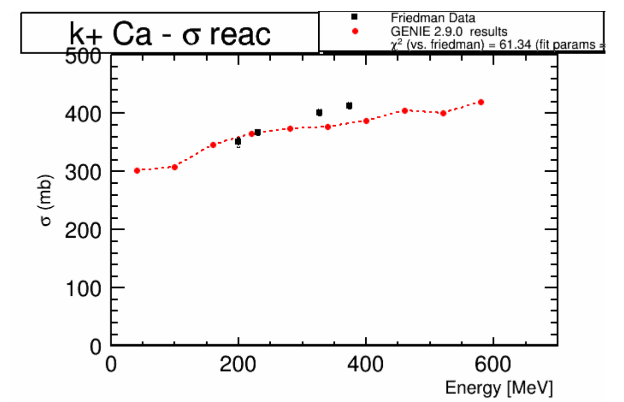


Kaon (+) FSI

- Improved treatment of K+ FSI.
  - Added new data and K + n -> K0 + p processes.
  - Better handling of K + NN -> k + NN
- Modification to hN (cascade) model only at this point. Integration into effective cascade (hA, default) is ongoing.







z-Expansion of the axial form factor

- Model independent determination of axial mass parameter, PRD 84 (2011) 073006
  - No need to assume a dipole shape.
- Change of variable from q^2 to z for actual expansion parameter.
- Current (configurable via xml) parameters derived from fits to deuterium bubble chamber data, in Meyer, Betancourt, Gran, Hill arXiv 1603.03048
- Also includes new re-weighting routines to re-weight from the dipole model to the z-expansion of the axial form factor.

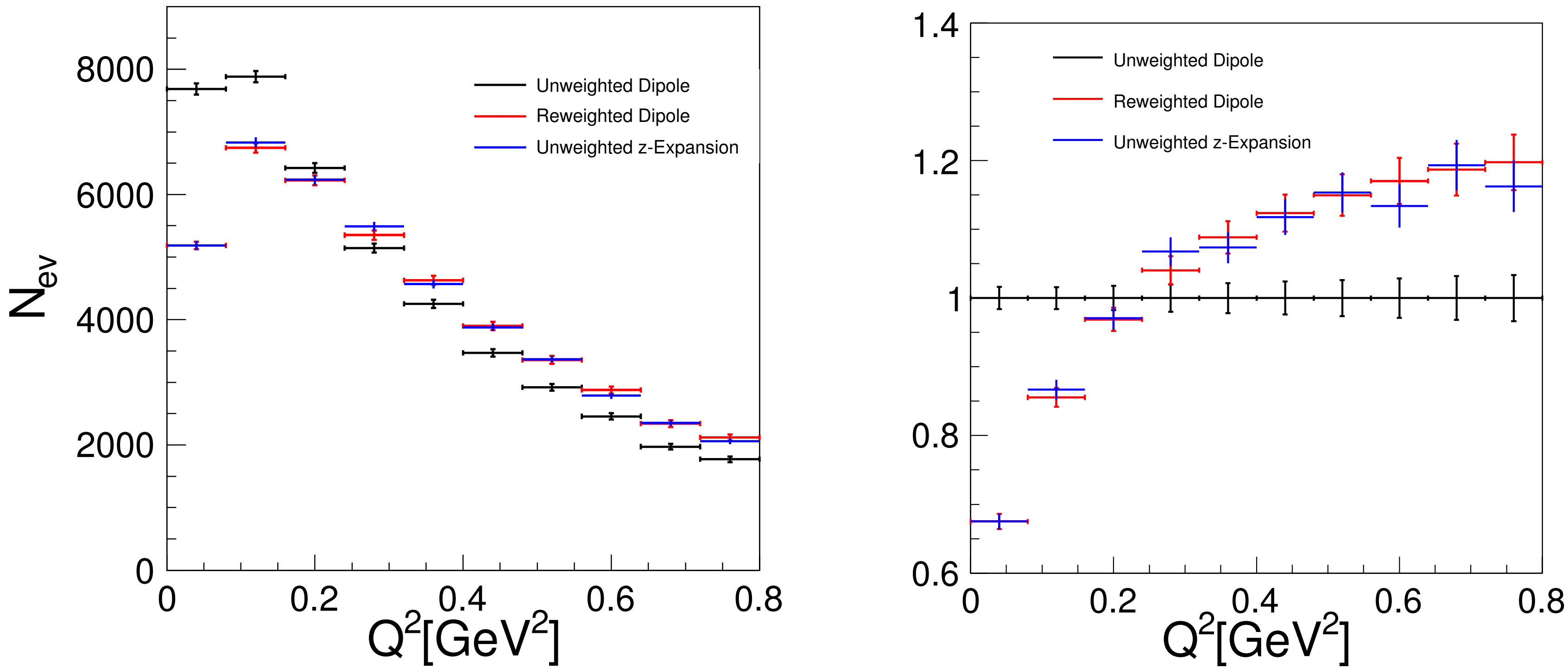
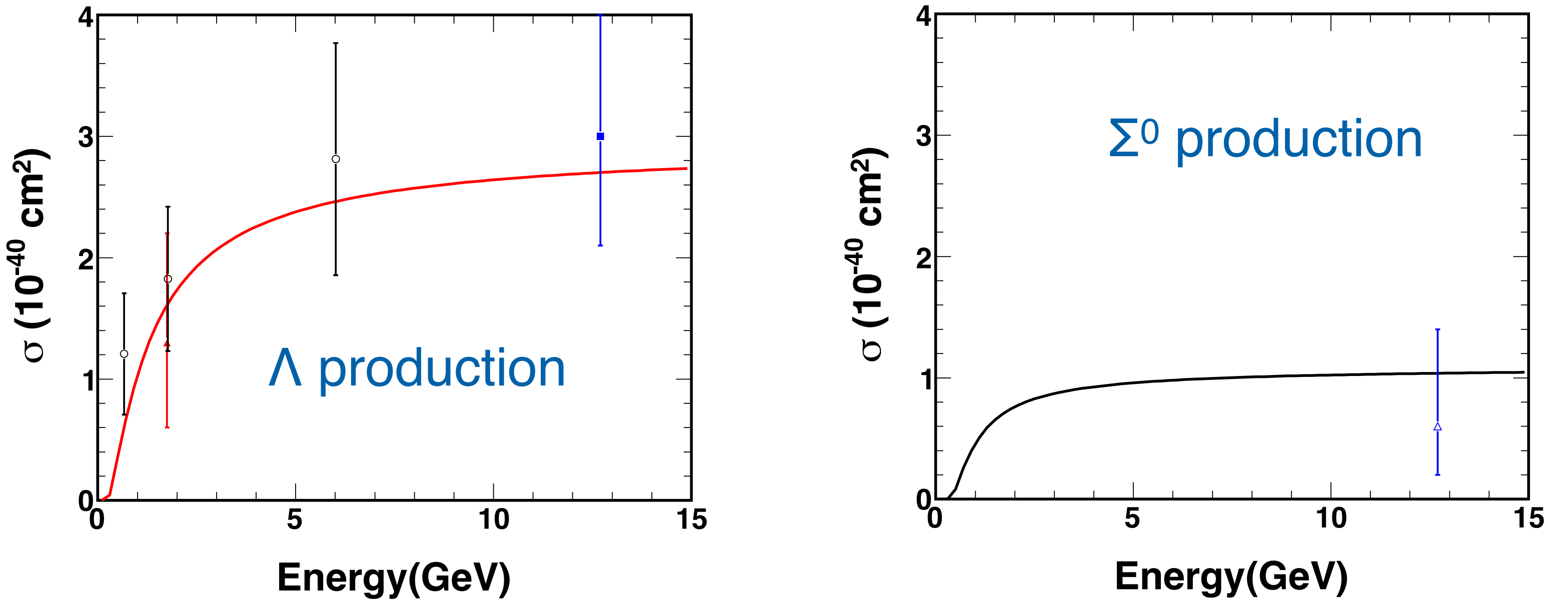


Figure 2: A nominal dipole event sample which has been reweighted to a z-expansion sample. The dipole Monte Carlo sample is represented in black, with statistical error bars. The reweighted dipole sample is shown in red, and the independent sample with z expansion values is shown in blue. The left plot shows the raw number of events in each bin for a 50k event sample of pure CCQE, and the right plot shows the events normalized by the nominal sample. The agreement between red and blue is a validation of the reweighting procedure. The study was done using a carbon target at 1 GeV.

QEL hyperon production

- Original calculation in Weak Interactions at High Energies, A. Pais, Annals Phys. 63 (1971) 361
- Model processes ΔS = 1 events, produced by antineutrinos in three related channels (below).



$$\overline{\nu}_\mu + p \rightarrow \Lambda + \mu^+,\ \overline{\nu}_\mu + p \rightarrow \Sigma^0 + \mu^+,\ \overline{\nu}_\mu + n \rightarrow \Sigma^- + \mu^+$$

Berger-Sehgal Coherent Pion

- Actually two new models - one version as presented in PRD 79 053003 (2009) and another with custom modifications to relax the "infinite target mass" assumptions.
  - Very little difference in the cross sections, largely validating the original assumption.
  - "Finite mass" model is a triple-differential integral (can integrate out the t-dependence in the cross section as presented in Berger and Sehgal's paper), so it is a bit slower.

The models may be activated by setting either

```
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  genie::BergerSehgalCOHPiPXSec2015/Default </param>
<param type="alg" name="XSecModel@genie::EventGenerator/COH-NC">
  genie::BergerSehgalCOHPiPXSec2015/Default </param>
```

or

```
<param type="alg" name="XSecModel@genie::EventGenerator/COH-CC">
  genie::BergerSehgalFMCOHPiPXSec2015/Default </param>
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  genie::BergerSehgalFMCOHPiPXSec2015/Default </param>
```
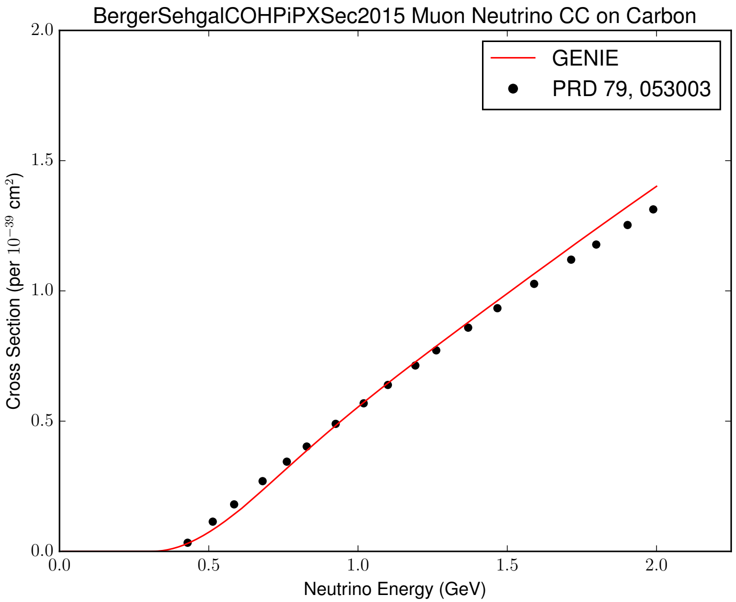
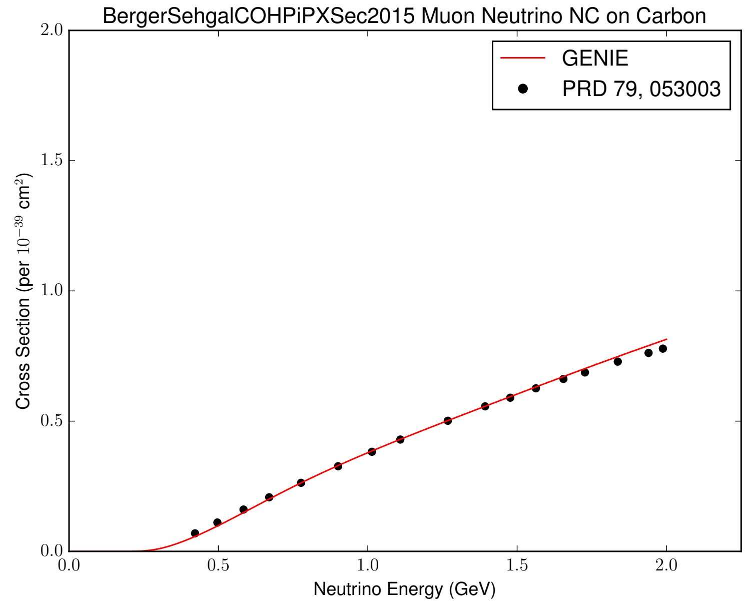
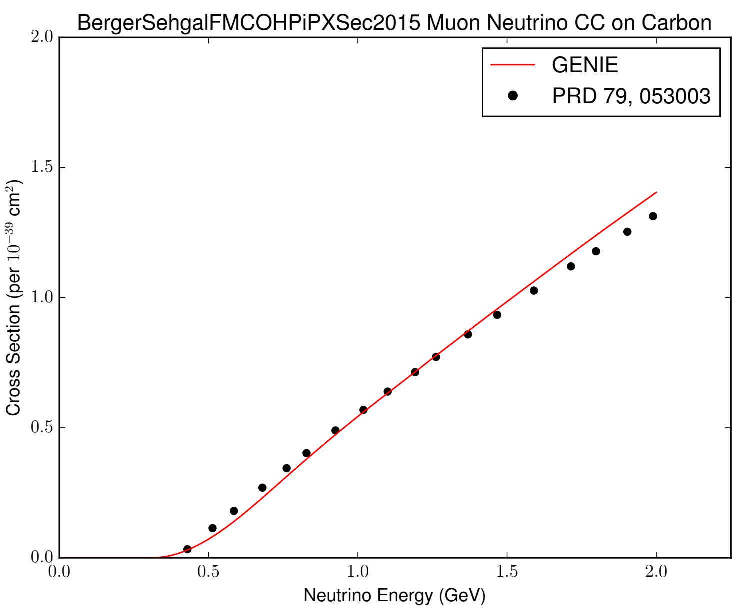
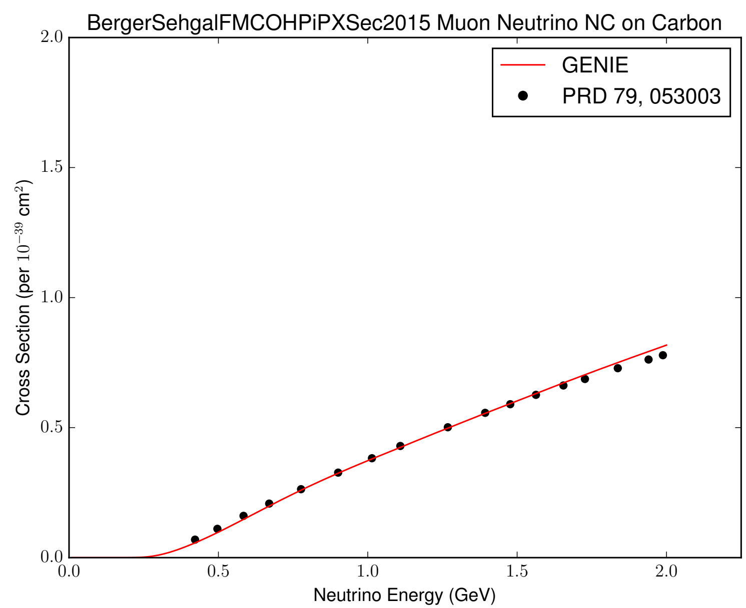
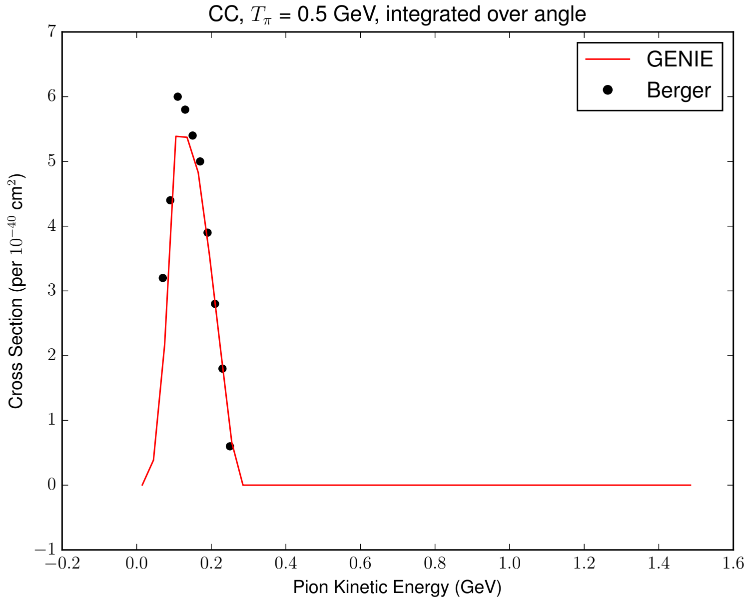
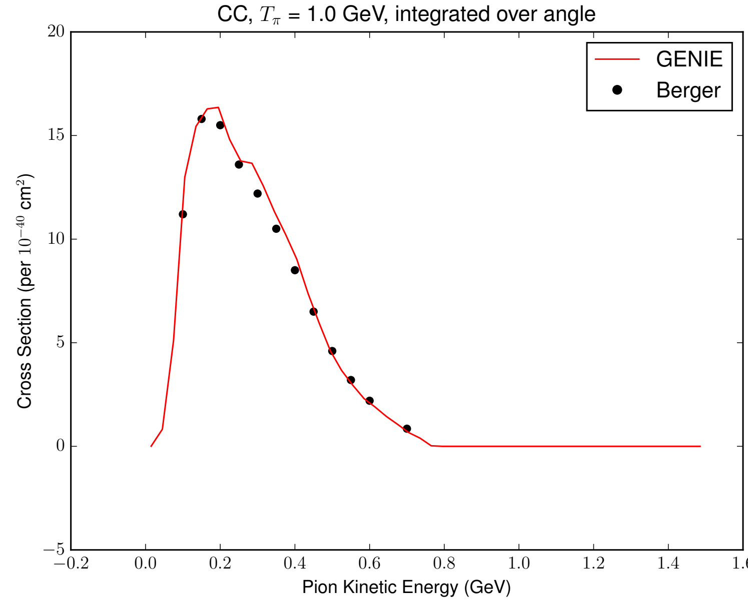


BergerSehgalCOHPiPXSec2015 Muon Neutrino CC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)

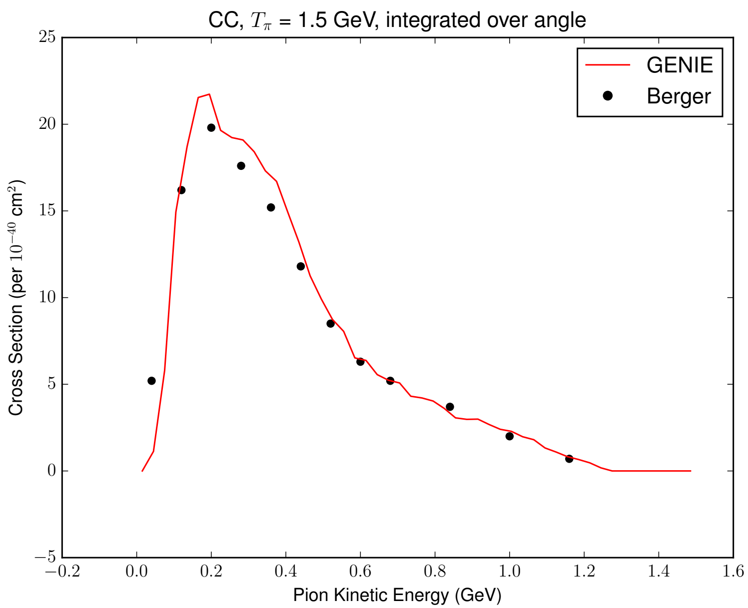

BergerSehgalCOHPiPXSec2015 Muon Neutrino NC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)

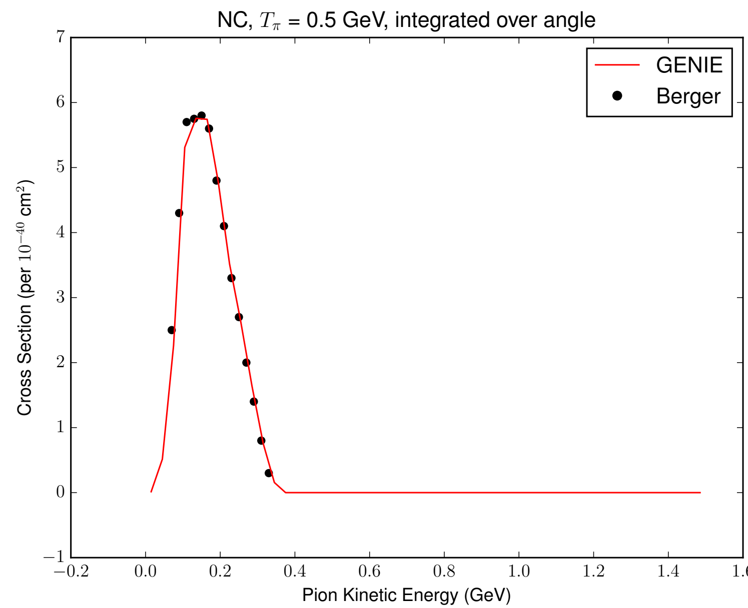

BergerSehgalFMCOHPiPXSec2015 Muon Neutrino CC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)

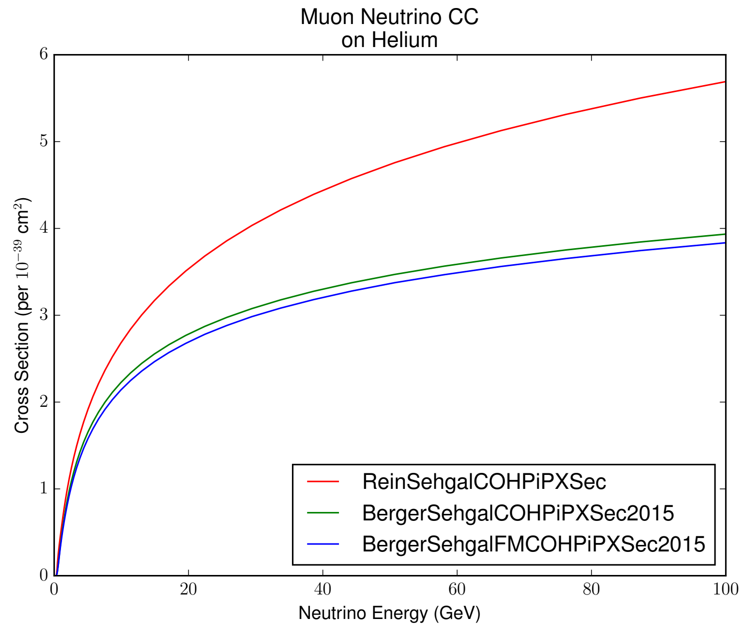

BergerSehgalFMCOHPiPXSec2015 Muon Neutrino NC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)

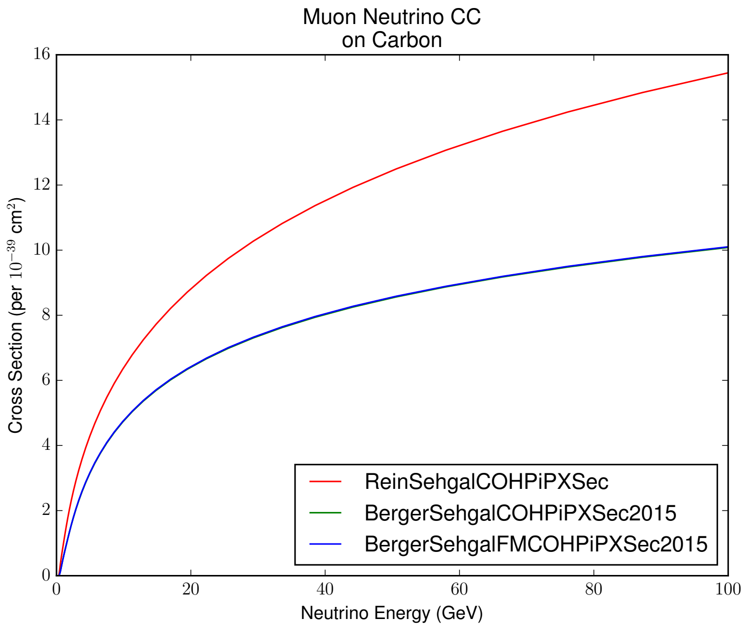

CC, T_π = 0.5 GeV, integrated over angle
GENIE
Berger
Cross Section (per 10^{-40} cm^2)
Pion Kinetic Energy (GeV)

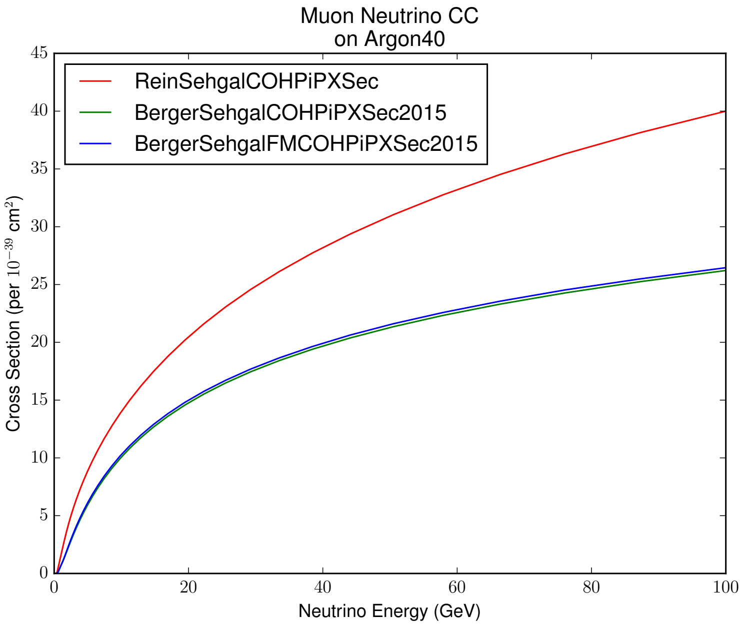

CC, T_π = 1.0 GeV, integrated over angle
GENIE
Berger
Cross Section (per 10^{-40} cm^2)
Pion Kinetic Energy (GeV)

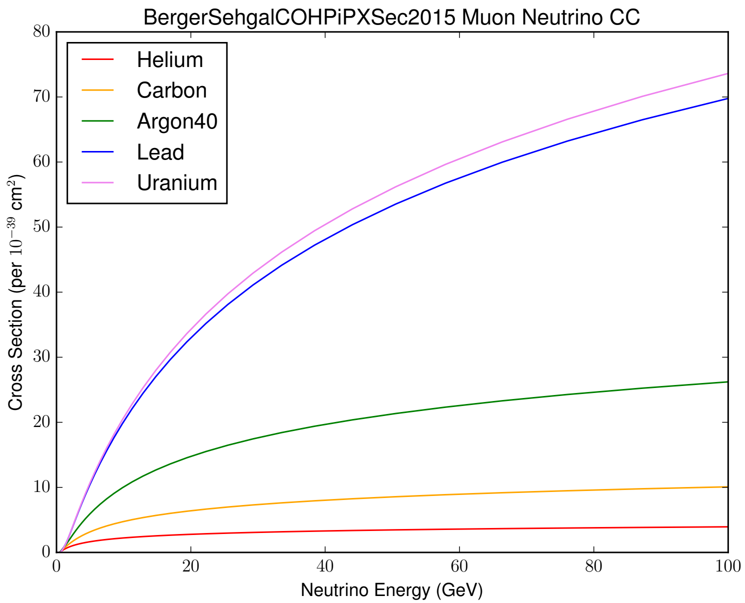

CC, T_π = 1.5 GeV, integrated over angle
GENIE
Berger
Cross Section (per 10^{-40} cm^2)
Pion Kinetic Energy (GeV)


NC, T_π = 0.5 GeV, integrated over angle
GENIE
Berger
Cross Section (per 10^{-40} cm^2)
Pion Kinetic Energy (GeV)


Muon Neutrino CC
on Helium
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
ReinSehgalCOHPiPXSec
BergerSehgalCOHPiPXSec2015
BergerSehgalFMCOHPiPXSec2015


Muon Neutrino CC
on Carbon
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
ReinSehgalCOHPiPXSec
BergerSehgalCOHPiPXSec2015
BergerSehgalFMCOHPiPXSec2015


Muon Neutrino CC
on Argon40
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
ReinSehgalCOHPiPXSec
BergerSehgalCOHPiPXSec2015
BergerSehgalFMCOHPiPXSec2015


BergerSehgalCOHPiPXSec2015 Muon Neutrino CC
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
Helium
Carbon
Argon40
Lead
Uranium

GiBUU: References

- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains the latest changes in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators
  4. Mosel et al, arXiv:1702.04932
     pion production comparison of MiniBooNE, T2K and MINERvA

Durham 04/2017

Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Ulrich Mosel

IPPP/NuSTEC (Durham) 2017

Fermilab

Quantum-kinetic Transport Theory for FSI

On-shell drift term — Off-shell transport term — Collision term

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)\ .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

Spectral function

Phase space distribution

Kadanoff-Baym equations with BM offshell term

Durham 04/2017

Institut für Theoretische Physik — Justus-Liebig-Universität Giessen

Ulrich Mosel

IPPP/NuSTEC (Durham) 2017

T2K effect on the fit

Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

- T2K ND280 data are complicated
  - Tensions
  - Correlations $\Rightarrow$ anti-intuitive
- T2K ND280 data can not even be fitted by their own with the current model

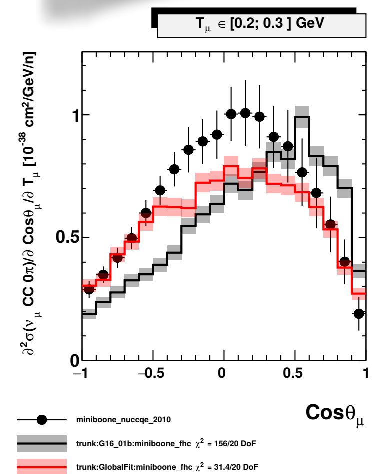
$\Rightarrow$ $\chi^2 = 127/61$

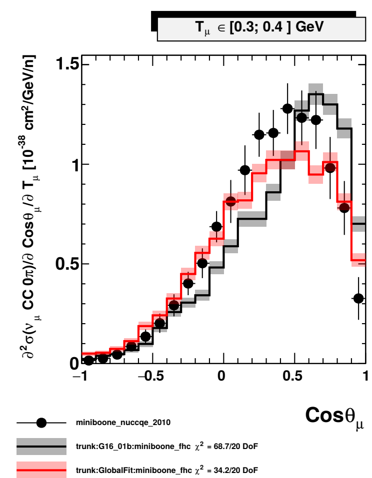
- T2K fit results are not compatible with other dataset

$\Rightarrow$ $\chi^2 = 1023/137$ vs MiniBooNE ν_μ CCQE

$\Rightarrow$ $\chi^2 = 1567/292$ vs whole fitted dataset

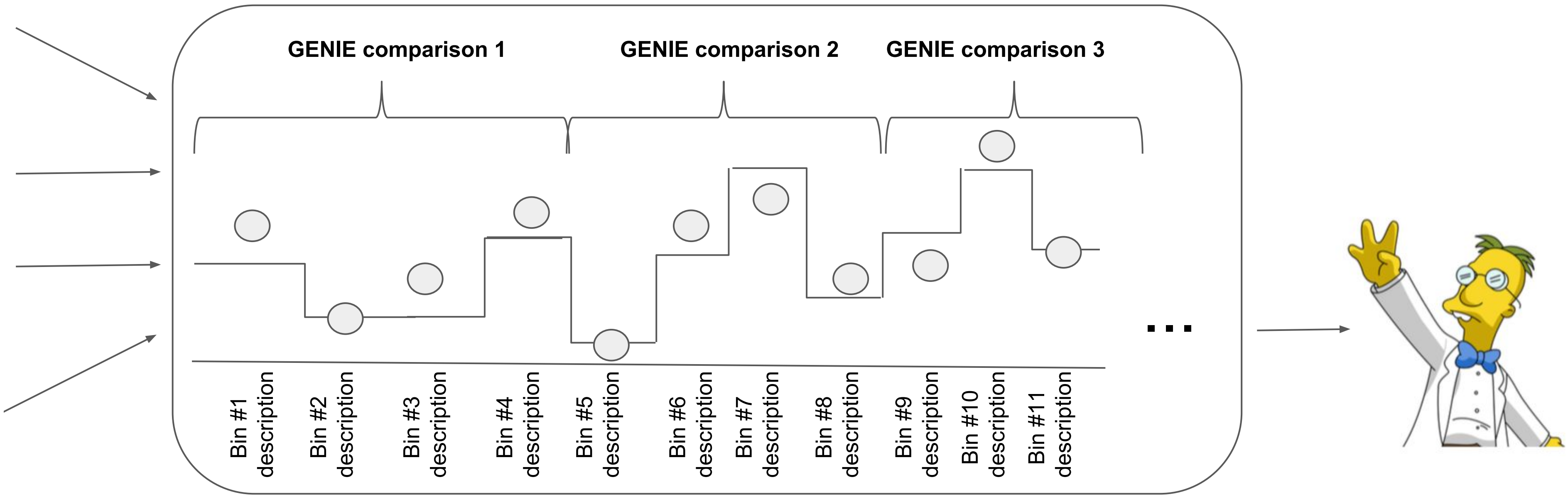
- global fit can suffer from this
- Effect is clear
- discrepancy in low momentum muons
  - $T_\mu < 400$ MeV
- No reason to remove this dataset from the fit
  - Their effort on the error estimation should be praised





GENIE 4.0

GENIE / Professor interface



Pass to Professor:

- **A single 1-D array with all data**
- **A single 1-D array with all predictions** (per given model configuration and parameter values)
- **A single 2-D covariance matrix**

Slide by C. Andreopoulos

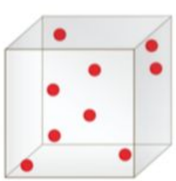
GENIE 4.0

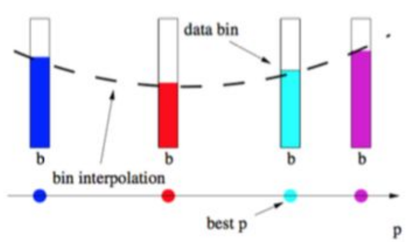
Fundamentally, the idea of Professor is to:

- **Reduce the exponentially expensive process of brute-force tuning** to a scaling closer to a power law in the number of parameters.
- **Allow for massive parallelisation** and systematically improve the scan results by use of a deterministic parameterisation of the generator's response to changes in the steering parameters.

Tuning with Professor

- Random sampling: N parameter points in n-dimensional space
- Run generator and fill histograms (e.g. Rivet)
- For each bin:
  - Don't care about actual dependence on parameters
  - Polynomial approximation
- Construct overall (now trivial) $\chi^2(\vec{p}) \approx \sum_{bins} \frac{(D_b - I_b(\vec{p}))^2}{error^2}$
- and numerically *minimise* with `iminuit`





Professor approach

- Replace exakt $f(\vec{p})$ by **analytic** approximation $I(\vec{p})$
- Thus replace CPU time for evaluation from hours . . . days to milliseconds

Basic work cycle

1. Define and sample M-times from d-dimensional parameter space $\mathcal{P}$
2. For each of the M points $\vec{p}_i$: evaluate exact $f(\vec{p}_i)$
   N.b. this step is trivially parallelisable
3. Fit **polynomial** $I(\vec{p})$ through $[(\vec{p}_1, f(\vec{p}_1)), (\vec{p}_2, f(\vec{p}_2)), \cdots, (\vec{p}_M, f(\vec{p}_M))]$
   e.g. $I(p_1, p_2) = \alpha_0 + \beta_1 p_1 + \beta_2 p_2 + \gamma_{11} p_1^2 + \gamma_{12} p_1 \cdot p_2 + \gamma_{22} p_2^2$
   Store coefficients in text file

[H.Schulz]

Slide by C. Andreopoulos