GENIE (Overview)

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Outline

- What is GENIE?
  - How does it work?
  - What tools are available?
  - How does it compute a cross section?
  - What is the overall physics model?

- *Note: v3.0.0 will be released this summer, but it is not available yet. I will preview some high-level features of v3, but cannot show specifics yet. In particular, v3 features new global physics configuration switches and new tunes of the physics models - look for these soon!*

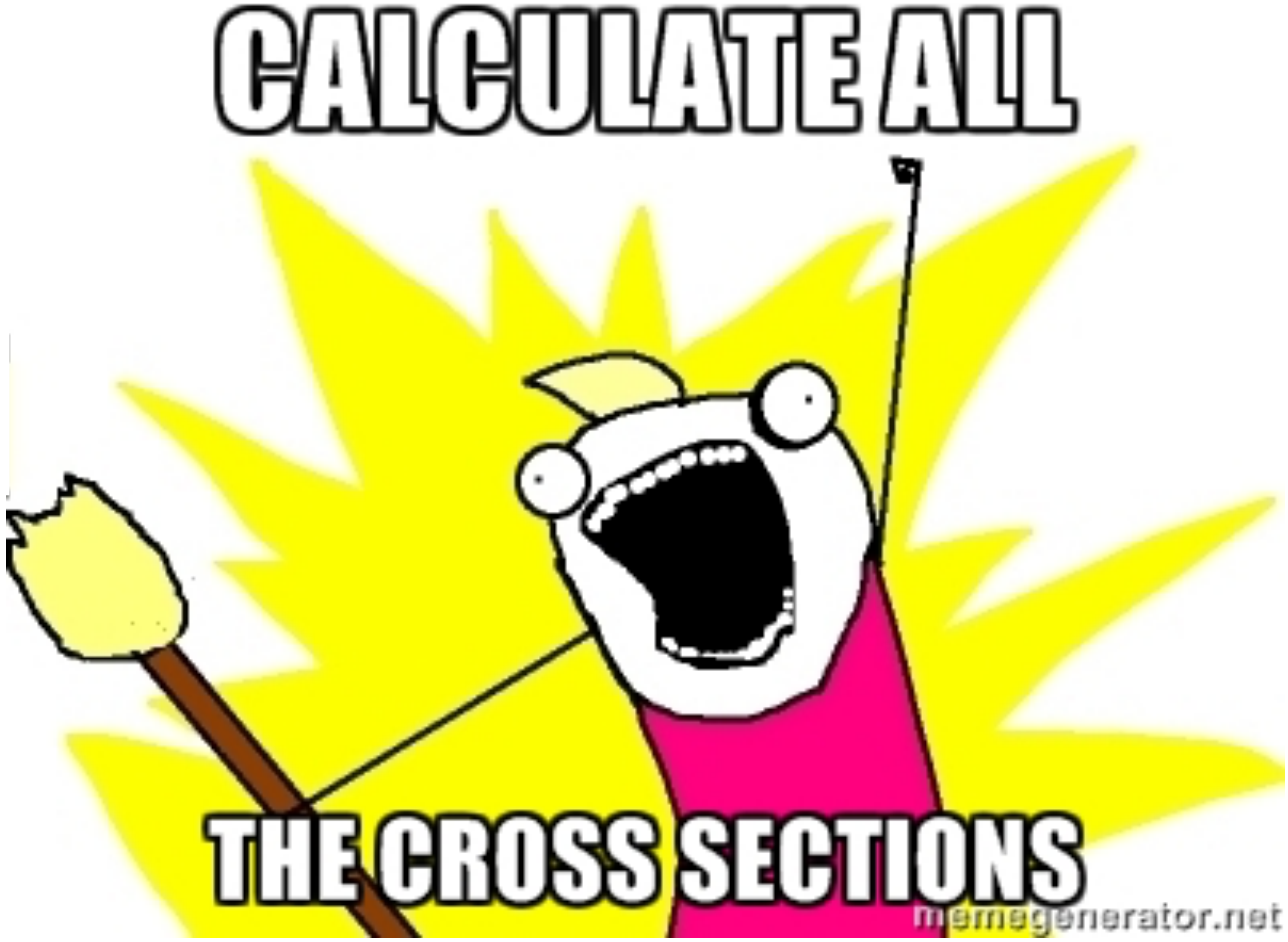
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

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.
  - Interfaces to HEP software frameworks (e.g., art, LArSoft).
- 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?

- GENIE must compute **fully differential cross sections** for **every final state particle** for **every (reasonable) target** across **all neutrino flavors and (all accelerator neutrino experiment) energies**. (We also try to go higher and lower in energy.)



What is GENIE?

- We can't write down one single input theory to do this.
- So we combine models and factorize processes...

ALL the cross sections?

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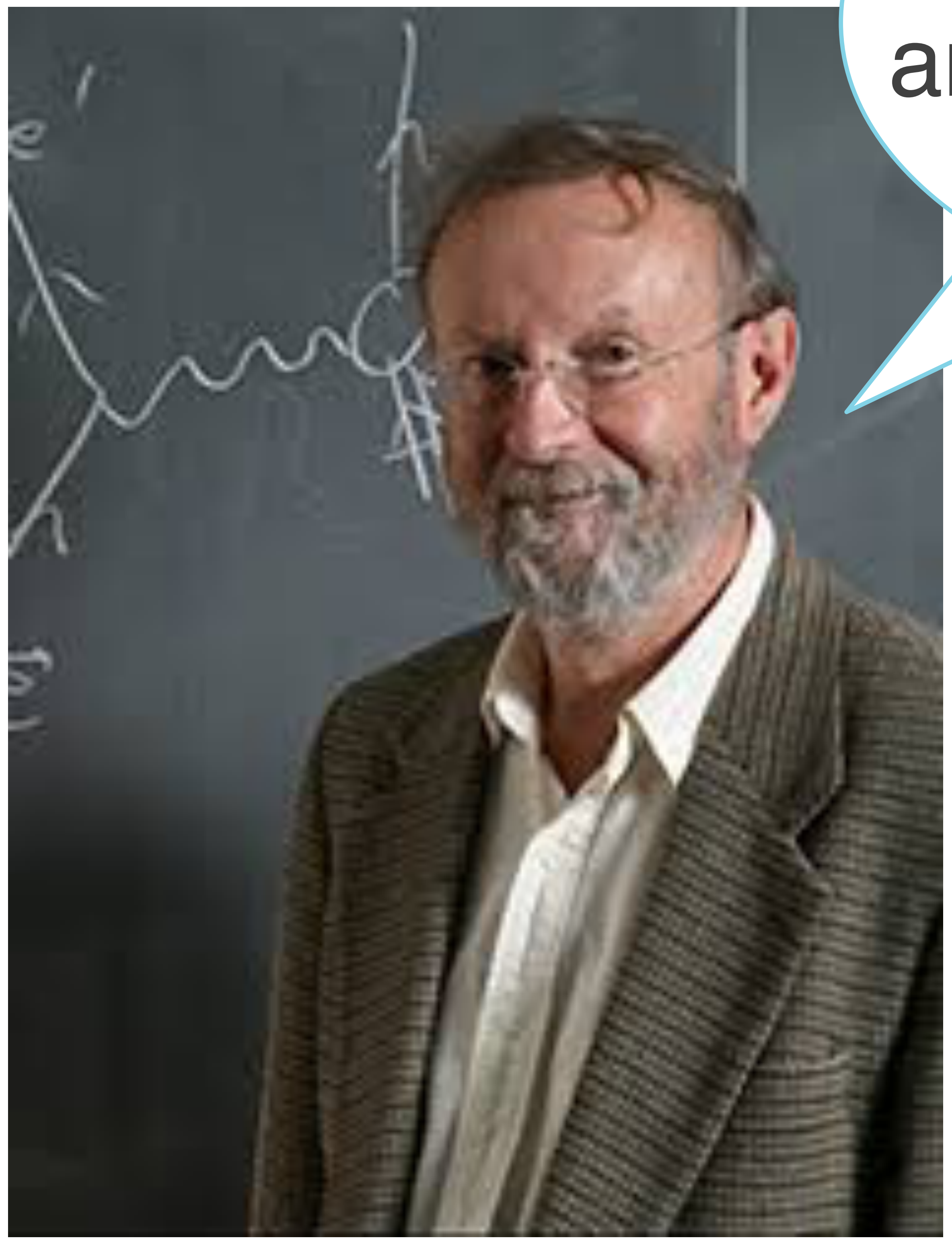


What is GENIE?

- 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*.
- GENIE is fundamentally a free-nucleon model with nuclear effects added on top.
  - New breed of models starting to be implemented that are truly "nuclear first".
- GENIE builds an inclusive cross section from an incoherent sum of "fully exclusive" (Donnelly "inclusive") models - we square then sum instead of summing and squaring.
  - This would fail in a Quantum Mechanics 101 course - but what else to do...
- When we add a new process (e.g., Valencia MEC), we need to retune the total cross section by controlling the strength of the exclusive processes or subtracting processes.

How to get GENIE

- If you are an experimentalist at Fermilab, you can set it up through UPS:
  - https://cdcvs.fnal.gov/redmine/projects/genie/wiki
- You can easily build it on Linux
  - https://github.com/GENIEMC/lamp
  - (Read the README)
- You can build on a Mac also, but we don't have a pre-packaged script (you need to manage your own dependencies).
  - It will build on Windows also, but we don't have materials to help set up dependencies, etc. Generally, you're better off running a Linux virtual image these days...
- It is available as an image on DockerHub:
  - https://hub.docker.com/r/gnperdue/genie/
  - Singularity image coming "soon"...

Model configurations and tunes

- What is the "GENIE physics model?"
- As of version 2.X.Y, there was only one available (experiments often change the default parameters and model constellations, leveraging GENIE's flexibility). Beginning with v3.0.0, we will deploy multiple comprehensive configurations and tunes, configurable on the fly with a `--tune` parameter.
- The model configuration is named according to the following convention:
  - Gdd_MMv
  - G -> author (often, but not always "G"ENIE - could be "Y"OUR-GROUP), dd -> year the configuration was developed, MM -> number identifying model configuration branch, v -> character ("a", "b", "c", ...) enumerating variations.

Model configurations and tunes

- The tune is named according to the following convention:
  - Gdd_MMv_PP_xxx
  - PP -> a number (key) identifying the set of tuned parameters (unique only in the context of a specific model configuration), xxx -> number (key) identifying the dataset used for model configuration tuning. (`_00_000` -> indicates the "tune" has not been tuned, but rather uses a set of legacy model parameters).

Name	Brief description	Supp.	Vrs.
G00_00a	Preserved historical 'Default' model of the GENIE / Generator v2 series.	No	3.0.0 -
G00_00b	Preserved historical 'Default+MEC' model of the GENIE / Generator v2 series.	No	3.0.0 -
G18_01a	**An adiabatic evolution of the historical empirical model.** The comprehensive configuration retains all the main elements of the historical 'Default+MEC' cross-section model (using the nuclear model of Bodek and Ritchie and simulating NCEL using an implementation of the Ahrens model, CCQE using Llewellyn Smith, NC and CC multi-nucleon processes using the empirical GENIE MEC model, NC and CC resonance production using Rein-Sehgal, NC and CC shallow and deep inelastic scattering using Bodek-Yang, NC and CC coherent production of pions using Rein-Sehgal), but adds generators for previously missing processes: Coherent production of ρ mesons is simulated using the vector meson dominance model of Kopeliovich and Marage, diffractive production of pions using the Rein model, and hyperon production using the Pais model. The hadronization model used is AGKY and it is unchanged wrt to previous versions. The intranuclear hadron transport model used is the upgraded INTRANUKE hA 2018 one. The details of the construction of this comprehensive configuration are presented in Sec. 4.3.2.1. Several new tunes are provided for this comprehensive model (See. Tab. 4.2).	Yes	3.0.0 -
G18_01b	As G18_01a, but replacing INTRANUKE hA 2018 with hN 2018.	Yes	3.0.0 -

G18_10a	**A theory-driven comprehensive model.** This comprehensive model embeds the best theoretical modelling elements implemented in GENIE. It uses the Local Fermi Gas nuclear model and an implementation of the theory calculation of Nieves et al. for the simulation of CCQE and CC multi-nucleon processes. The empirical GENIE MEC model is used for the NC multi-nucleon processes since they are not included in the Nieves calculation. NCEL is simulated using an implementation of the Ahrens model, NC and CC resonance production using Berger-Sehgal, NC and CC shallow and deep inelastic scattering using Bodek-Yang, NC and CC coherent production of pions using Berger-Sehgal. Like the other G18* configurations, it adds generators for previously missing processes: Coherent production of ρ mesons is simulated using the vector meson dominance model of Kopeliovich and Marage, diffractive production of pions using the Rein model, and hyperon production using the Pais model. The hadronization model used is AGKY and it is unchanged wrt to previous versions. The intranuclear hadron transport model used is the upgraded INTRANUKE hA 2018 one. The details of the construction of this comprehensive configuration are presented in Sec. 4.3.2.3. Several new tunes are provided for this comprehensive model (See. Tab. 4.2).	Yes	3.0.0 -
G18_10b	As G18_10a, but replacing INTRANUKE / hA 2018 with hN 2018.	Yes	3.0.0 -
G18_10i	As G18_10a, but replacing the QE dipole axial form factor with a z expansion.	Yes	3.0.0 -
G18_10j	As G18_10b, but replacing the QE dipole axial form factor with a z expansion.	Yes	3.0.0 -

Model / Tune name		Brief description	Vrs.
	G00_00a_00_000	Historical tune of G00_00a comprehensive model configuration.	3.0.0 -
	G00_00b_00_000	Historical tune of G00_00b comprehensive model configuration.	3.0.0 -
G18_01a	G18_01a_01_010	Free nucleon cross-section model re-tune using mainly bubble chamber CCQE, CC1π, CC2π, and CC inclusive cross-section data.	3.0.0 -
	G18_01a_01_020	Free nucleon cross-section model re-tune using mainly bubble chamber CCQE, CC1π, CC2π, CC inclusive and normalised topological cross-section data.	3.2.0 -
	G18_01a_01_030	Free nucleon cross-section model re-tune using mainly bubble chamber CCQE, CC1π, CC2π, CC inclusive and normalised topological cross-section data, and a retune of the GENIE AGKY hadronization model.	3.4.0 -
	G18_01a_02_100	Global nuclear cross-section model tune (based on the G18_01a_01_010 free nucleon cross-section model re-tune) using neutrino and antineutrino CC0π and CC1π data on Carbon (from MiniBooNE, T2K and MINERvA).	3.0.0 -

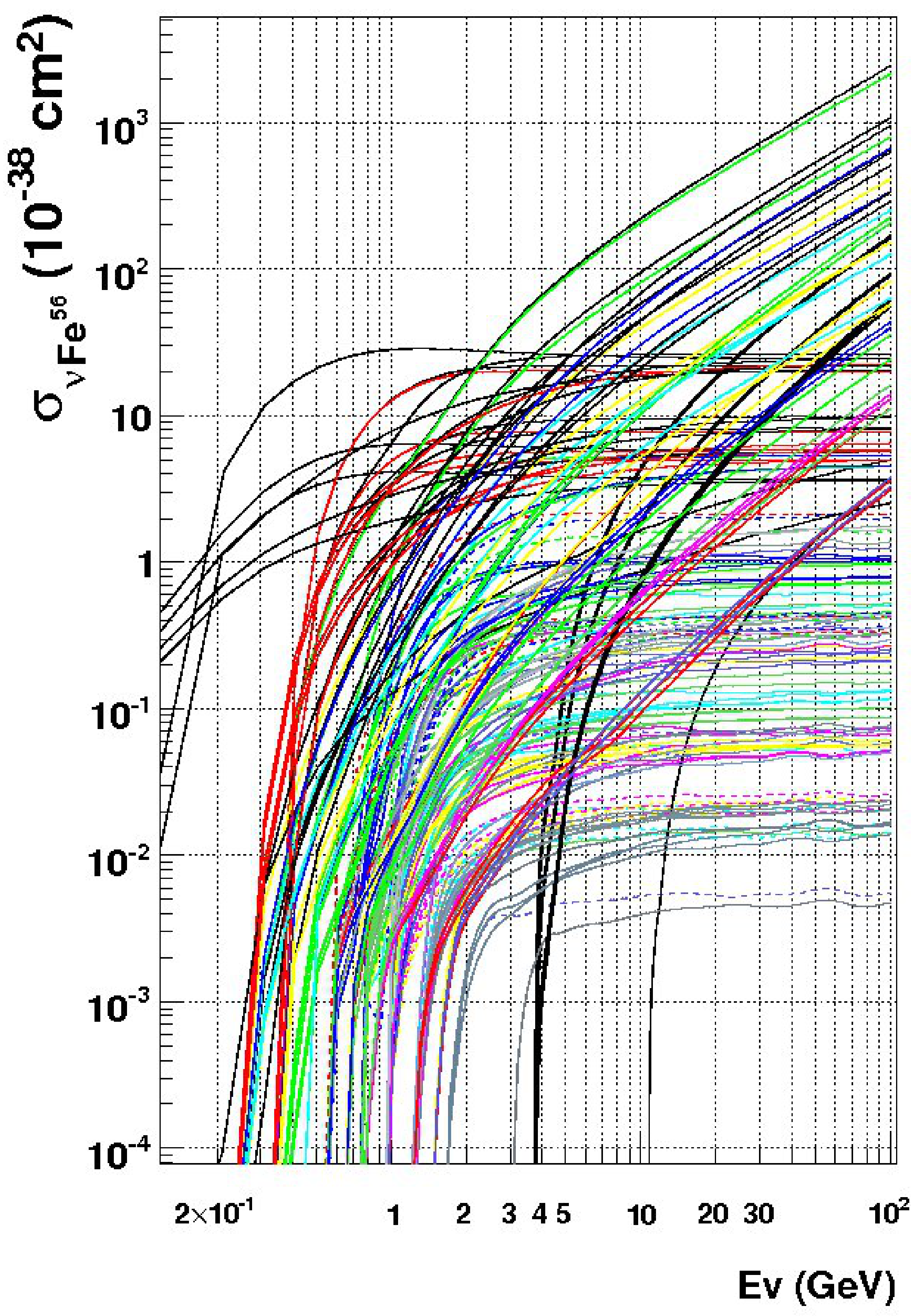
etc.

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.

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

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



Total cross section files are distributed as XML (and sometimes ROOT):


```
<?xml version="1.0" encoding="ISO-8859-1"?>

<!-- generated by genie::XSecSplineList::SaveSplineList() -->

<genie_xsec_spline_list version="3.00" uselog="1">

  <genie_tune name="G18_10i_00_000">

    <spline name="genie::AhrensNCELPXSec/Default/nu:-12;tgt:1000000010;N:2112;proc:Weak[NC],QES;" nknots="200">
        <knot> <E>    0.01000 </E> <xsec> 3.5947888118e-15 </xsec> </knot>
        <knot> <E>    0.01056 </E> <xsec> 4.1301320645e-15 </xsec> </knot>
        <knot> <E>    0.01115 </E> <xsec> 4.7235109483e-15 </xsec> </knot>
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        <knot> <E>    0.01243 </E> <xsec> 6.1095880952e-15 </xsec> </knot>
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        <knot> <E>    0.01545 </E> <xsec> 9.8928858435e-15 </xsec> </knot>
...
```


NEW: cross section files are *tune aware* - "safety" mechanism.

How to add new models to GENIE

- GENIE features a very flexible framework and "physics API":
  - Roughly speaking, models need to understand the event record,
  - Physics is implemented by defining a sequence of classes that operate on the event record,
  - The sequence is captured in XML, each model that operates on the event record ("visitor pattern") is a class,
  - Each part of the sequence also requires configuration XML,
  - Sequences can be of arbitrary length (as few as ~one, or as many as desired - it depends on the level of factorization in the model and which pieces of existing GENIE you want to re-use).
- The documentation is not good enough to make this process easy to do completely independently, but it isn't so far off either!
- Some pieces of GENIE do not factorize well (e.g., hadronization is difficult to change independently of the DIS model - if you want to completely swap the hadronization model, you have to change the DIS cross section).

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>
```

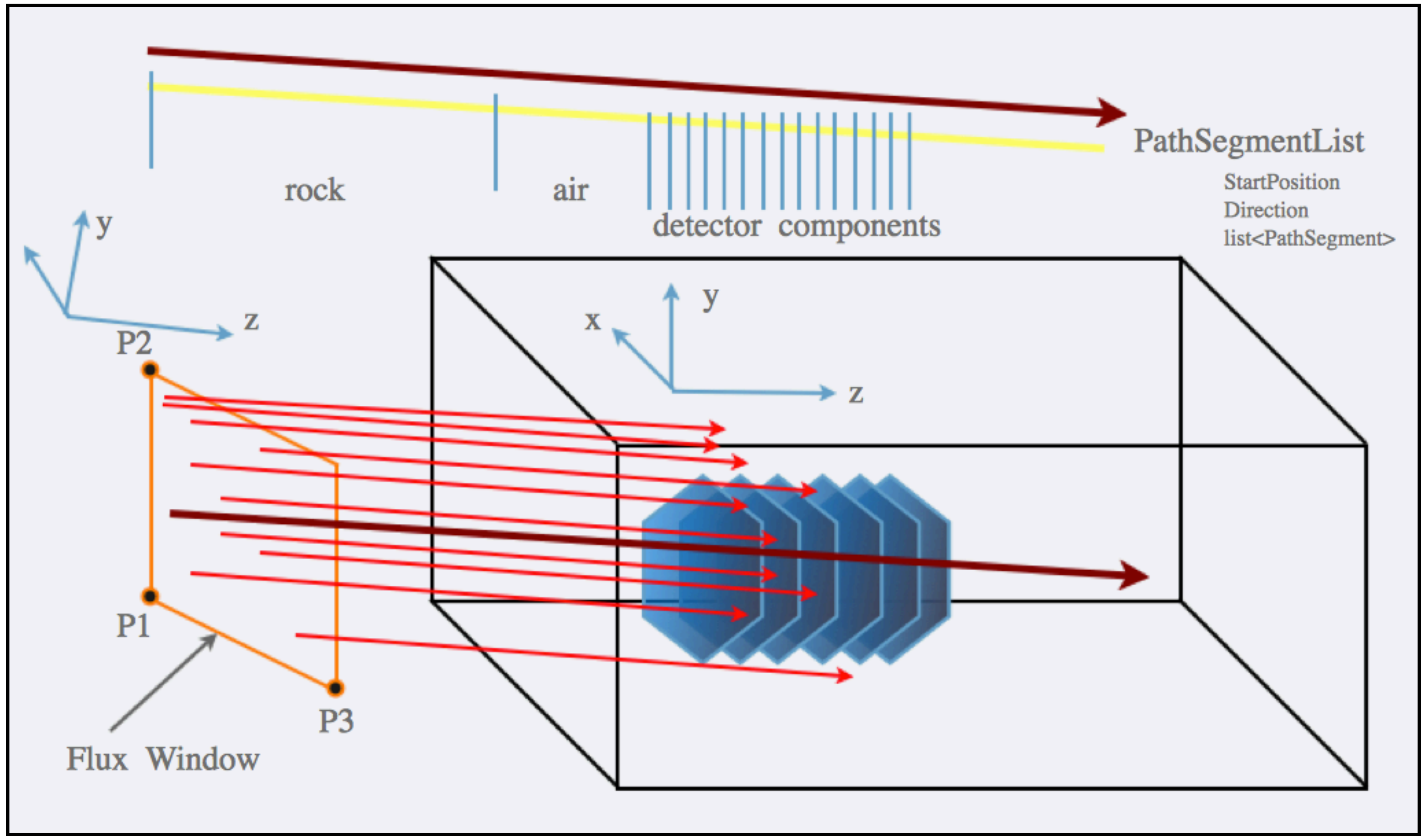
Interesting additions / alternatives:


```
<param_set name="DFR">
   <param type="int" name="NGenerators">   2                                  </param>
   <param type="alg" name="Generator-0">   genie::EventGenerator/DFR-CC       </param>
   <param type="alg" name="Generator-1">   genie::EventGenerator/DFR-NC       </param>
</param_set>
```

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!"



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?"

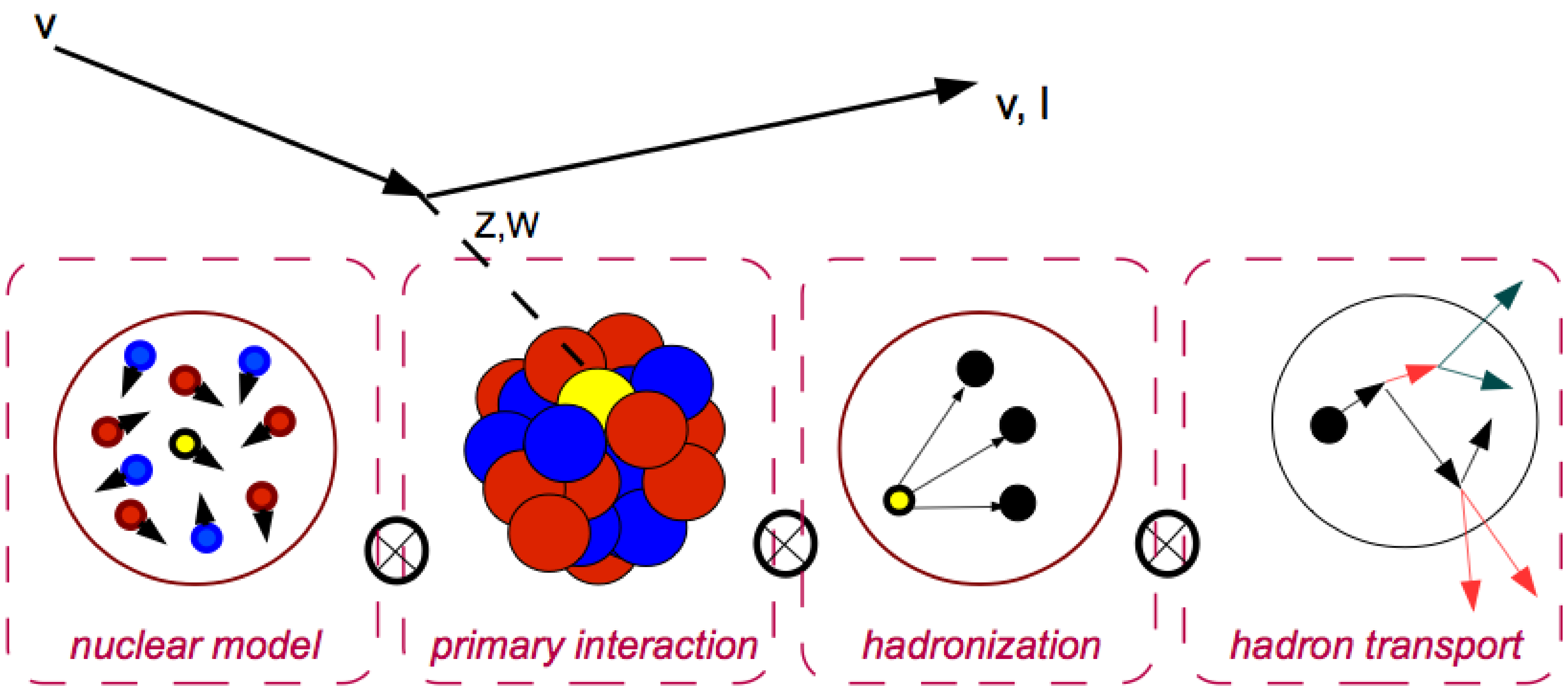


Figure by C. Andreopoulos

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).

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

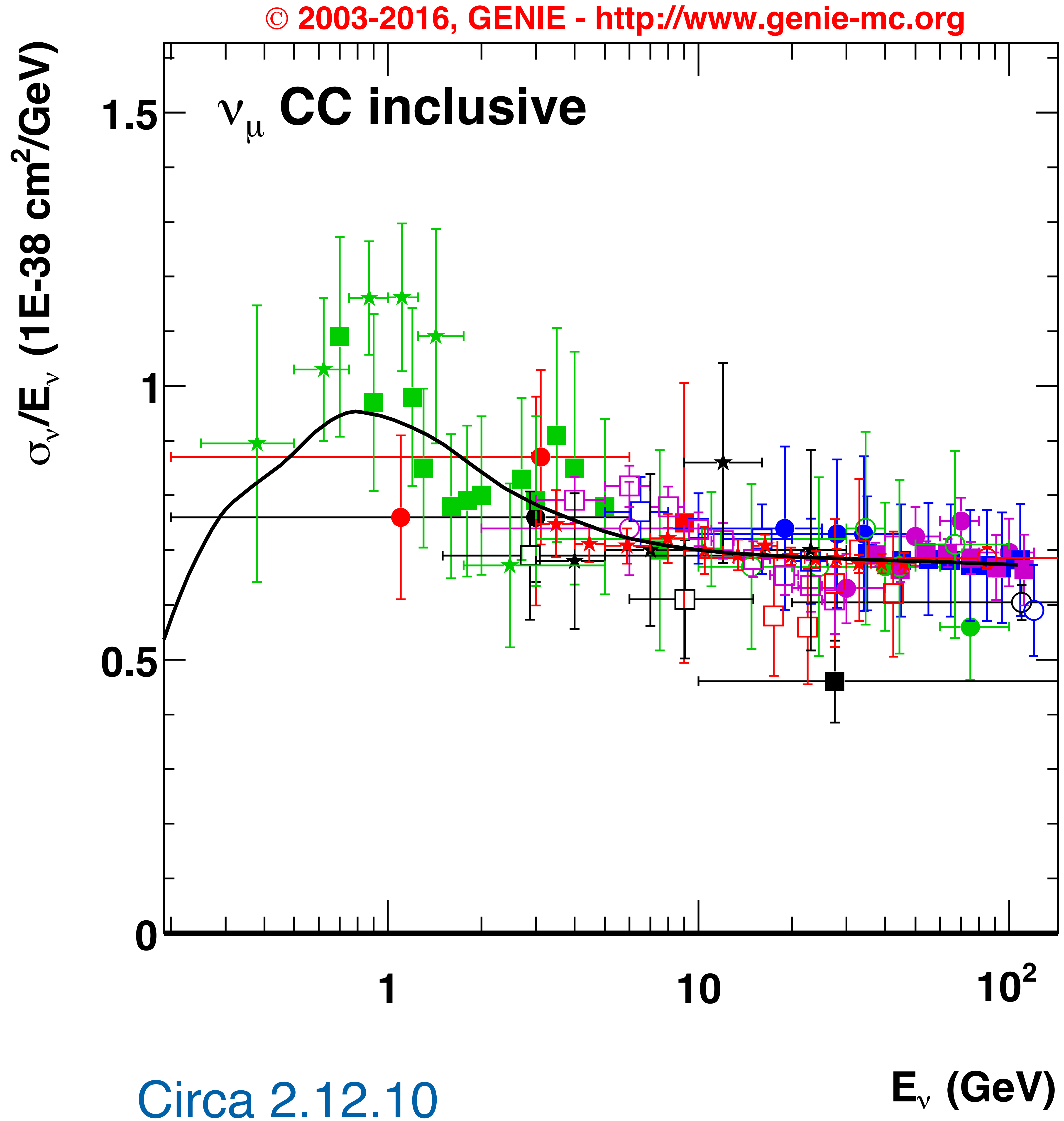
FINAL STATE

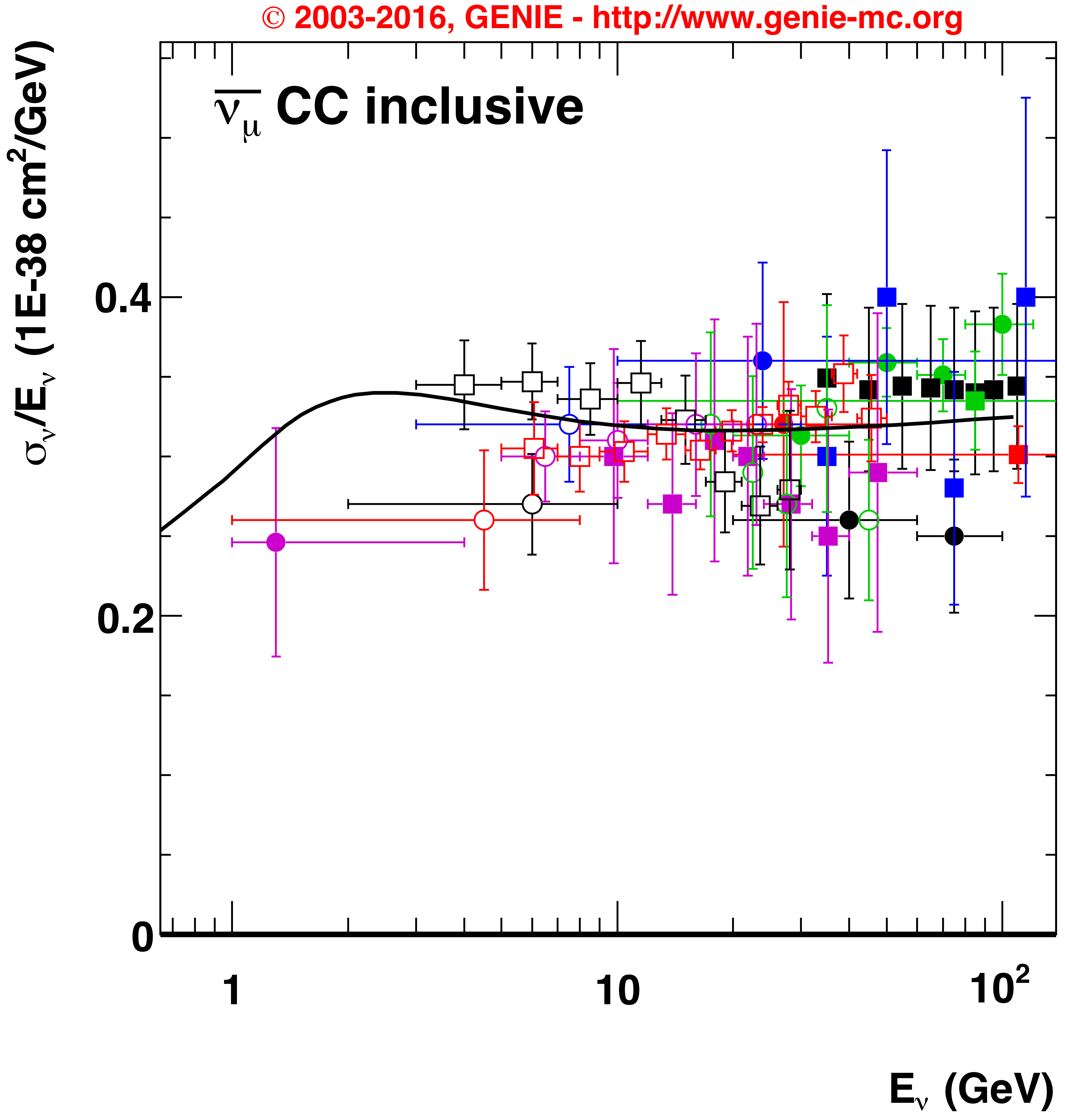
Usual Pieces

- 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, and in particular there is a strong trend in the future (especially "nuclear first" models) to blend stages together (e.g., integrate over the ground state model in a way that is not factorizable.


© 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)


© 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)

Circa 2.12.10

Back to adding models to GENIE...

- GENIE is fantastic platform to work with.
- We could do better (the whole community could do better!), but our framework is very general, easy to plug a new model into, we run weekly physics validation on Fermigrid, use Continuous Integration (with expanding unit test coverage), we have excellent flux and geometry drivers and interfaces, and we are fully integrated into art and LArSoft (primary software frameworks for FNAL neutrino experiments).
- In general, implementing a model in GENIE is easy - see new boosted dark matter code.
  - It can be harder to get the code approved for a public release... we're bandwidth-limited in terms of expert time.
- We warmly welcome contributors and collaborators!

Conclusions

- GENIE is a flexible event generator with a general API, reasonable documentation, careful versioning and support, excellent flux and geometry drivers, and full integration with many of the accelerator neutrino software frameworks.
- We feature a professionalized development infrastructure including weekly physics validation and Continuous Integration (with an expanding suite of unit tests).
- It is easy to get, build, and run GENIE on essentially any computing platform.
- New contributors and collaborators are always welcome and there is no better way to make new models useful to a large fraction of the experimental neutrino community than by implementing your new calculation in GENIE.

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],
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Donna Naples [3], Gabriel Perdue [1], Marco Roda [2], Julia Tena Vidal [2],
Jeremy Wolcott [7], Julia Yarba [1]

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