Physics Generators
(focusing on Neutrino Generators (focusing on GENIE))

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Snowmass Computational Frontier

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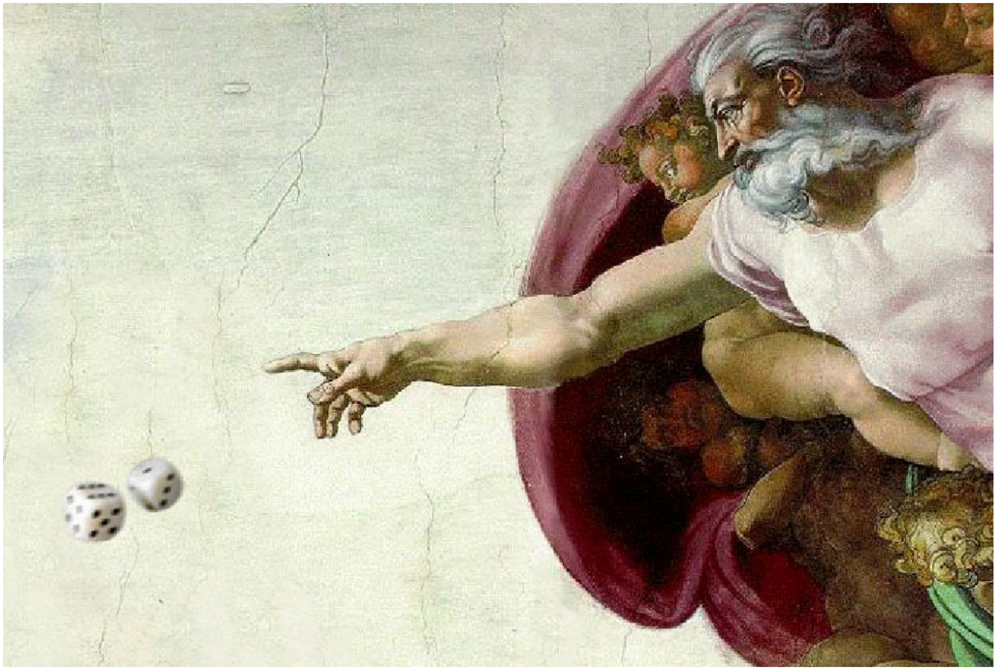
November 16, 2021

Outline

My task:
"a 15-20 minute talk, focusing on GENIE and how it is designed to support a diverse range experiments, along with ideas for how GENIE and other generators can be made as widely-applicable as possible in the future"

Neutrino MC Generators

- Why do we need them?
- What do they provide?
- Available generators
- GENIE and its remit
- Experimental interfaces
- Physics modeling
- Validation and tuning
- Getting involved / Contributing



I guess you are less interested in the details of physics modeling, but if you are, details can be found in the backup and in the following recent papers: 2106.09381 [hep-ph], 2106.05884 [hep-ph], 2104.09179 [hep-ph]

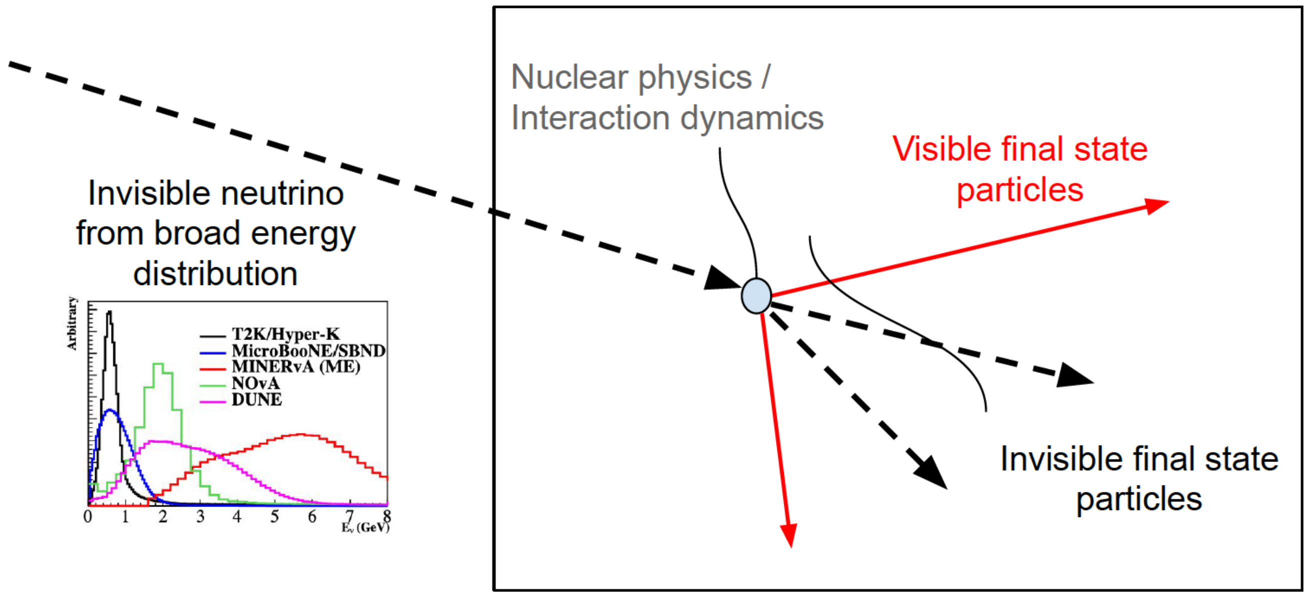
Neutrino MC Generators: Crucial and versatile tools

- **Front-ends** for fast neutrino MC generation / 4-vector level studies.
- **Back-ends** in experimental MC simulation chains.
- **Cross-section model libraries**
- **Event re-weighting engines**, used for evaluating systematic errors and propagating them in physics analyses.
- **Data-bases** of experimental neutrino, electron and hadron scattering data used for model tuning and systematic error evaluation.
- **Toolkits for model characterization and tuning**
- **Non-neutrino event generators**
  - electron-nucleus and hadron-nucleus generators, with many physics commonalities to neutrino-nucleus generators
  - BSM generators

Connecting true and observed quantities

Neutrino event rate

$$N_{\nu_f}(E_r) \propto \sum_{\nu_i} \int dE_t \frac{d\Phi_{\nu_i}(E_t)}{dE_t} P_{osc}^{\nu_i \to \nu_f}(E_t; \vec{\alpha}) \epsilon_{\nu_f}(E_t) \sum_A w_A \sum_i \int dK_t^n \frac{d^n \sigma^i_{\nu_f A}(E_t, K_t^n)}{dK_t^n} R_i(E_r; E_t, K_t^n)$$

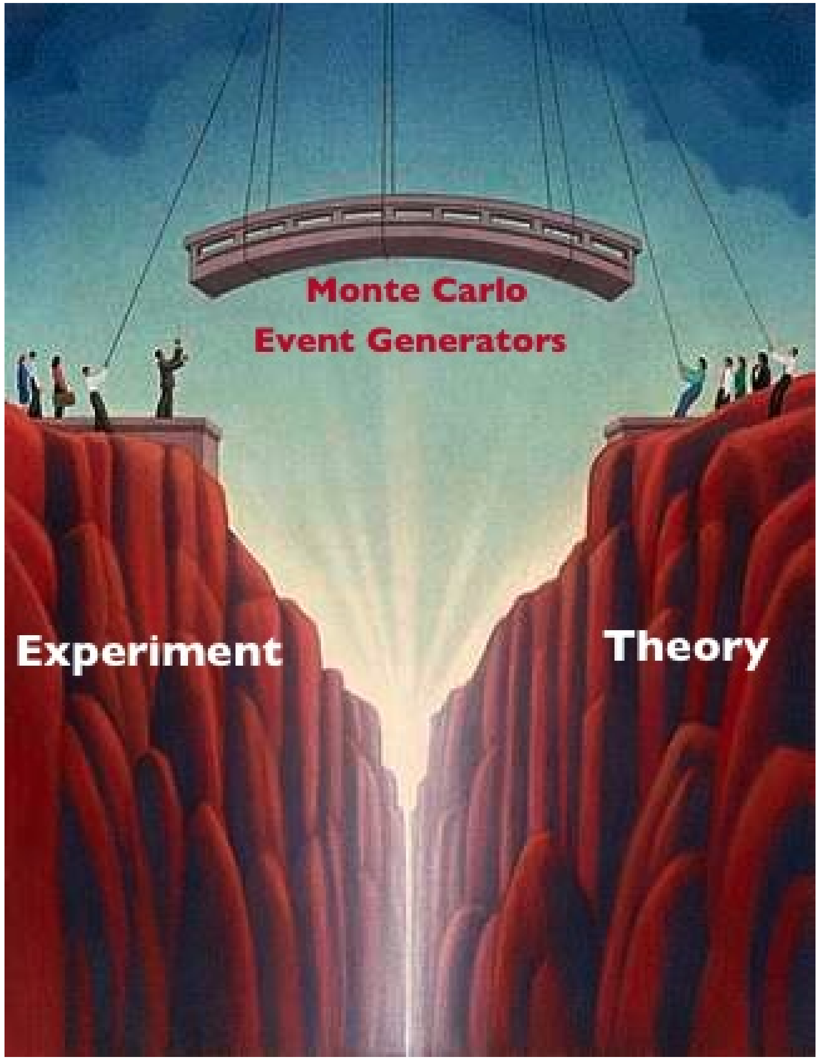


Neutrino oscillation experiments: Infering the incoming neutrino flux from measurements of event rate, where only a subset of the final state is observed.

Unavoidable model dependencies

Neutrino MC Generators: A Theory/Experiment Interface

Model dependence encapsulated in comprehensive Neutrino MC Generators



Neutrino MC Generators
connect the true and observed event topologies and kinematics.

Every observable a convolution of flux, interaction physics and detector effects.

Neutrino MC Generators allow experimentalists to access, improve, validate, assess the uncertainty of and tune the *physics* models that drive the result of that convolution.

Neutrino MC Generators (from experimental groups)

Only few such neutrino MCs exist, actively developed, and in wide use:

GENIE (http://www.genie-mc.org)

- Will discuss in more detail next.

NEUT

- A legacy fortran-77 generator developed for (Super-)Kamiokande.
- Developed by Yoshinari Hayato and collaborators.
- Currently, used primarily by Super-Kamiokande and T2K.

Nuance

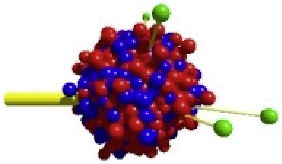
- A legacy fortran-77 generator developed for IMB and (Super-)Kamiokande.
- Developed by Dave Casper and collaborators.
- Currently, used primarily by MiniBooNE.

Neutrino MC Generators (from theory groups)

NuWro (https://github.com/NuWro)

- Developed by Jan Sobczyk and collaborators at Wroclaw (and now Ghent).
- Written in C++.
- Very quick deployment of new models (but at own risk) - Primarily a tool for R&D efforts of the Wroclaw group.
- Plays an important role! Used by several experiments for cross-checks, but usually not embedded in the full MC chain.

GiBUU (https://gibuu.hepforge.org)



- Developed by Ulrich Mosel and collaborators at Giessen.
- Written in Fortran-2003.
- A unified theory and transport framework (Boltzmann-Uehling-Uhlenbeck)
- U.Mosel:
  - *"GiBUU is nature"*
  - *"It doesn't matter if the theory describes the data, as long as the theory is correct"*

GENIE

Luis Alvarez-Ruso [4], **Costas Andreopoulos** [7,10], **Adi Ashkenazi** [8], **Christopher Barry** [7], **Steve Dennis** [7], **Steve Dytman** [9], **Hugh Gallagher** [11], **Alfonso Andres Garcia Soto** [3,4] **Steven Gardiner** [2], **Walter Giele** [2], **Robert Hatcher** [2], **Or Hen** [8], **Libo Jiang** [9], **Rhiannon Jones** [7], **Igor Kakorin** [6], **Konstantin Kuzmin** [5,6], **Anselmo Meregaglia** [1], **Donna Naples** [9], **Vadim Naumov** [6], **Afroditi Papadopoulou** [8], **Gabriel Perdue** [2], **Marco Roda** [7], **Vladyslav Syrotenko** [11], **Jeremy Wolcott** [11], **Natalie Wright** [8], **Júlia Tena Vidal** [7]

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Project with ∼20yr history.

Several authors (mainly from experiment).

Modern design

Very broad remit (not targeting any single experiment)

Dual purpose:

- **Open source generator** and central coordination of community devel efforts in common generator platform used by all experiments.
- **Proprietary global analysis**.

GENIE develops a number of software products to support the above.

Many interfaces between open source generator and proprietary analysis (tunes and uncertainty assignments published into the generator platform and related tools)

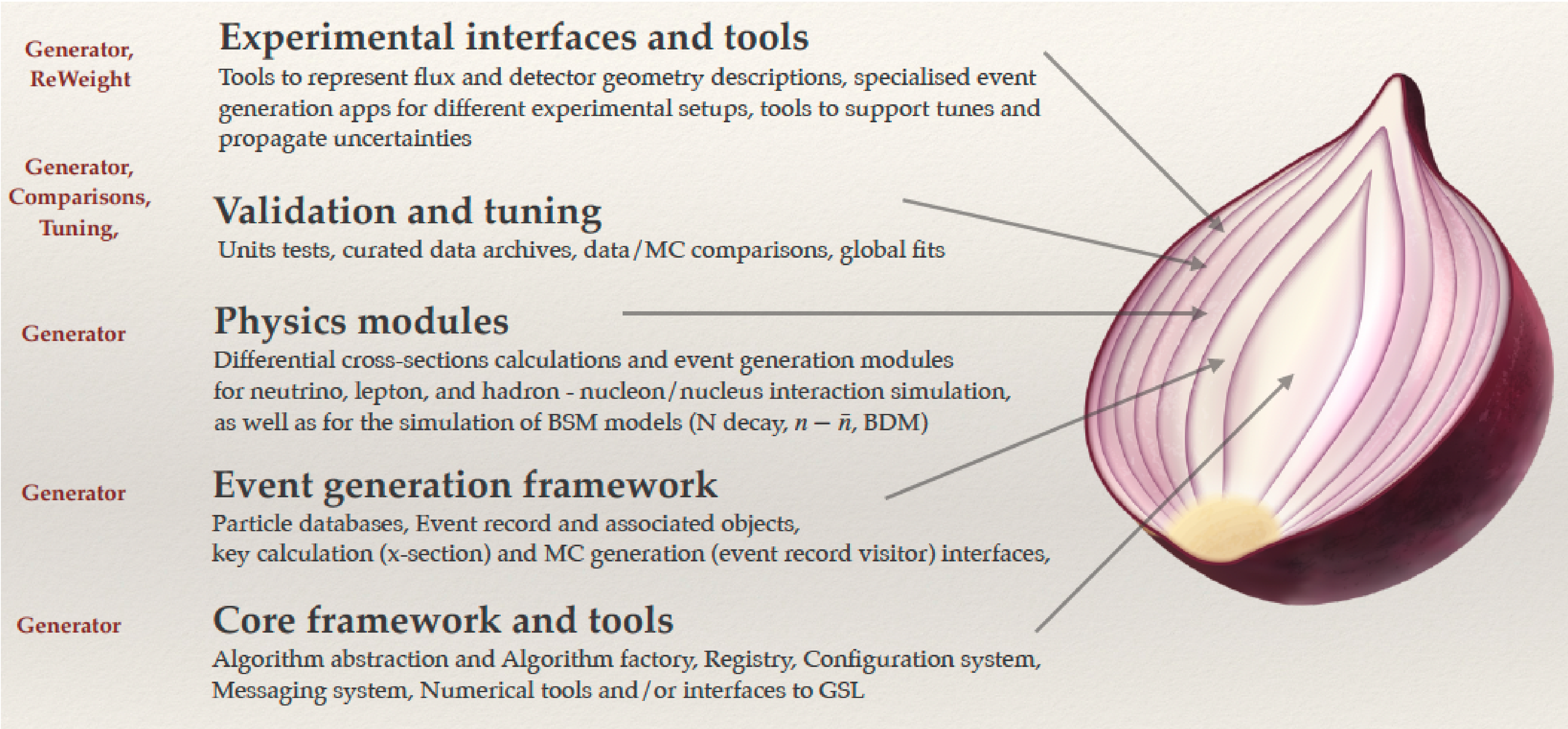
GENIE

GENIE develops a number of software products:

- **Generator** [open source]
  Modern framework for event generators, many advanced physics modules (neutrino, charged lepton, hadron scattering and several BSM channels), and experimental interfaces.
- **Reweight** [open source]
  Propagation of modeling uncertainties
- **Comparisons**
  Extensive data archives, and software for automating data/MC comparisons and bookkeeping MC runs with several alternative configurations
- **Tuning**
  GENIE global analysis of neutrino scattering data
- Prof-GENIE
  Interface to Professor: 'Reduces the exponentially expensive brute-force tuning to a scaling closer to a power law in the number of parameters and allows for massive parallelisation'
- UnitTests
- AVS-CI
- ...

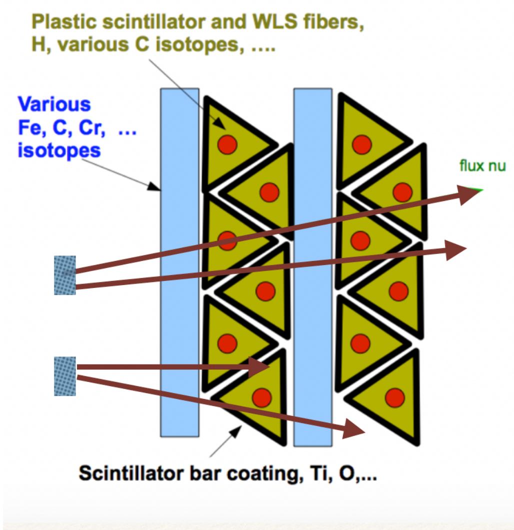
Layered structure of GENIE

GENIE has a broader remit.
It develops several tools beyond "an event generator"



Experimental interfaces

- To first order, all neutrino generators, have a call that looks like:
  `GenerateEvent(int neutrino_pdg, int target_pdg, double E_nu)`
- This is the **portal to all neutrino-nucleus interaction physics**



- Alas, we don't use mono-energetic ν and a single nucleus...
- Need toolkit to integrate **flux** and **detector** descriptions
- A complex computational problem!
  Non uniform detectors, seeing a different flux in different areas of the detector
- Most generators, besides GENIE, don't provide this toolkit
- Challenging to integrate in the MC chain of an experiment

$$N_{ev} \propto \int dE_\nu dcos\theta_\nu d\phi_\nu dxdydt \sum_{f(lavor)} \frac{d^6\Phi_f(E_\nu, cos\theta_\nu, \phi_\nu, x, y, t)}{dE_\nu dcos\theta_\nu d\phi_\nu dxdydt} \int_0^\infty ds \sum_{i(sotope)} \frac{\rho(\vec{r}) w_i(\vec{r}) \sigma^{tot}_{f;i}(E_\nu)}{A_i(\vec{r})}$$

Flux description

Detector description

Neutrino Interaction Physics

Experimental interfaces

- GENIE has standardised **flux** and **detector geometry** APIs
- Implements a number of **flux drivers**:
  - Barr - Gaisser - Lipari - Robbins - Stanev (BGLRS) atm. flux
  - Ferrari - Sala - Battistoni - Montaruli (FLUKA) atm. flux
  - Honda - Sajjad Athar - Kajita - Kasahara - Midorikawa (HAKKM) atm. flux
  - Driver for integration of detailed J-PARC neutrino beam-line simulation outputs
  - Driver for integration of a detailed NuMI neutrino beam-line simulation outputs
  - Generalised and customisable driver for histogram-based flux descriptions
  - Generalised and customisable driver for ntuple-based flux descriptions
- Implements a number of **geometry drivers**:
  - A driver consuming detector geometry desccriptions in ROOT/GDML formats
  - A simple "target mix" driver, with no detailed spatial information
- Provides a number of **specialised event generation applications**
  - `gevgen_atmo`, `gevgen_t2k`, `gevgen_fnal`, ...
  - GENIE physics w/ specialised tools, outputs, conventions, options
- Other relevant interfacing tools external to GENIE (eg. `gSeaGen`)

We are keen to help you build such tools interfacing your experiment with GENIE physics, and keen to help support many tools within GENIE.
We also enable interfacing with generators that lack GENIE's flux/geom toolkit.

Physics modeling

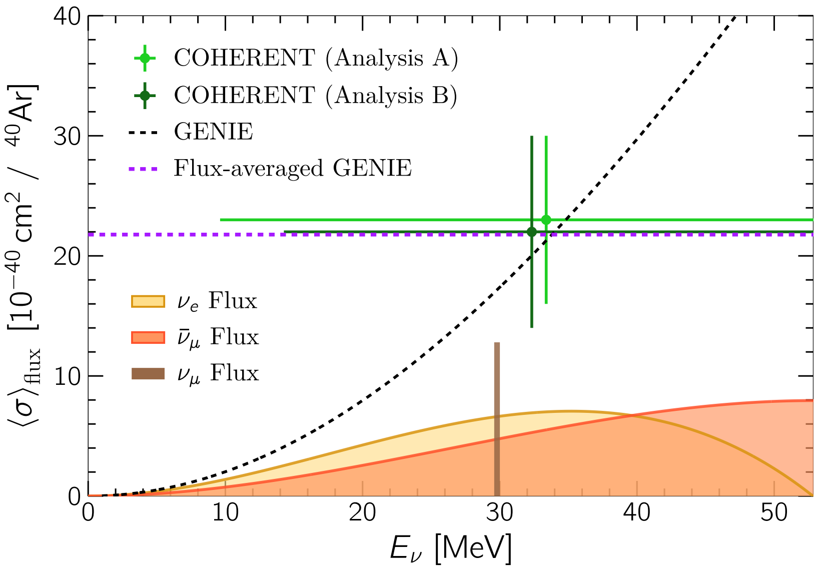
- Constant demand for **new model implementations**
  - Often difficult, time consuming, ambiguous
  - Inclusion in a comprehensive MC (for all probes and targets, in full kinematic space probed by experiments) not easy for many published theoretical models
  - Typically, evolves to year-long project, working together with a theorist.
  - Manpower limitations: Beyond what core GENIE team can achieve on its own
  - Contributors play a key role (see *Incubator*)
- Currently, GENIE has a very **large constellation of alternative models**
  - See backup slides for recent additions
  - See https://inspirehep.net/literature/1869034 (arXiv:2106.09381 [hep-ph]) for a recent review (accepted for publication by Euro.Phys.J. Special Topics)
- However, it is likely, especially if you work on a novel signature or in a new kinematic regime, that you will hit a limitation.

GENIE already supports many community development efforts.

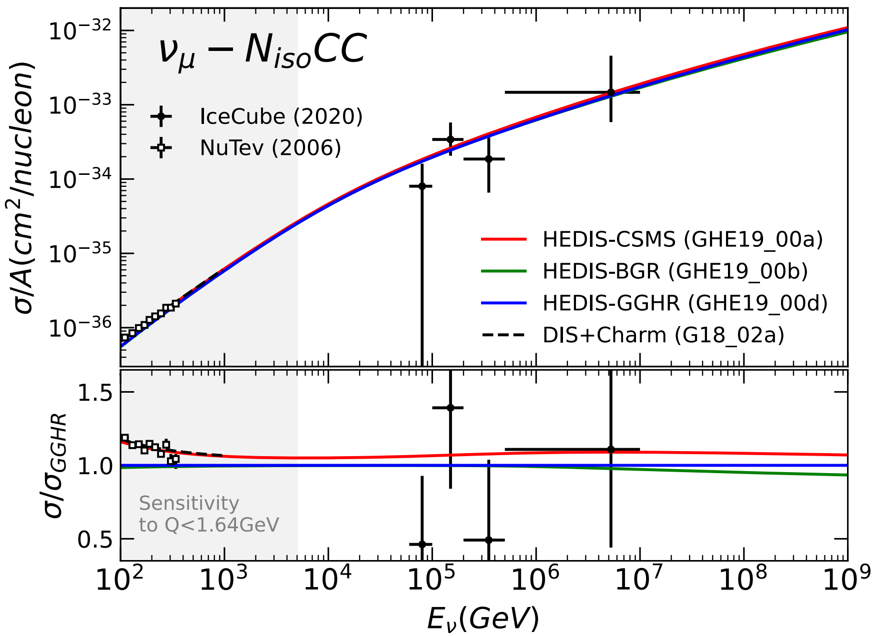
Keen to do more and support your simulation needs.

Physics modeling

- Constant demand for **new model implementations**
- Medium energy (100 MeV - 10 GeV) neutrino-nucleus a focal area...
- ... but, increasingly, expanding to **new kinematic regimes and channels**



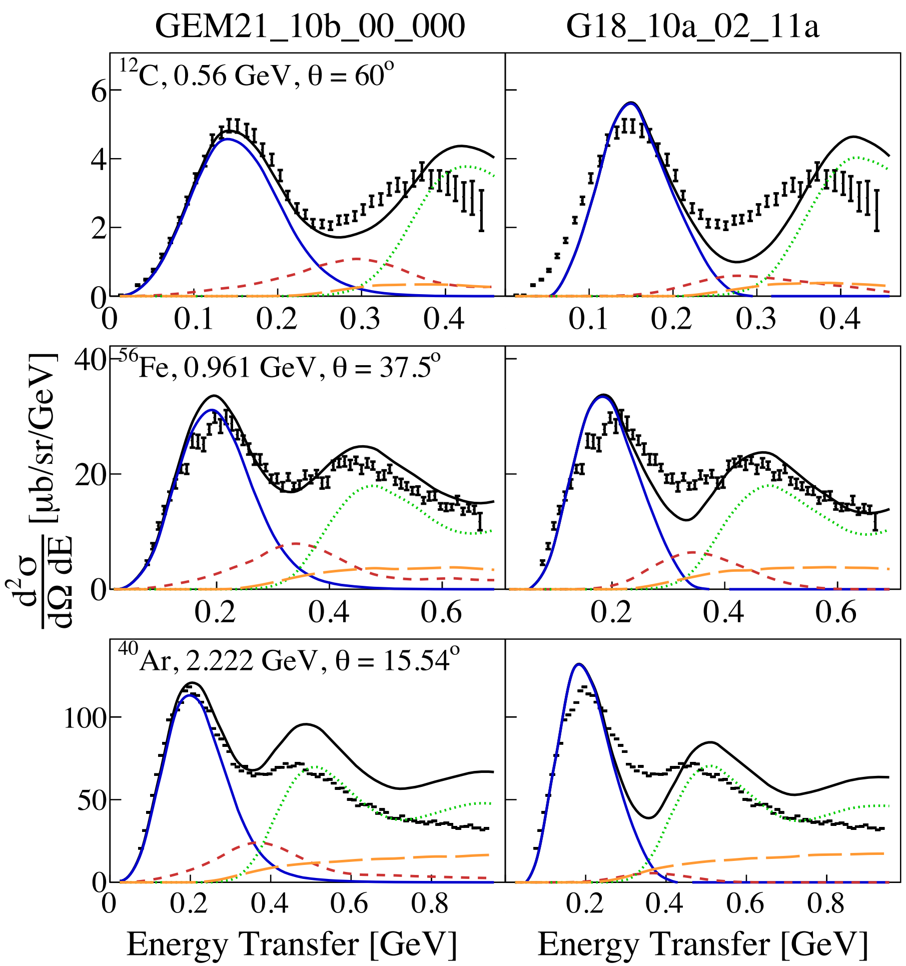
- New low energy configurations



- Several new high energy configurations
- Validated up to 10^9 GeV!
- Supporting telescopes, FASERν, SND@LHC
- Details in arXiv:2004.04756 [hep-ph]

Physics modeling

- Constant demand for **new model implementations**
- Medium energy (100 MeV - 10 GeV) neutrino-nucleus a focal area...
- ... but, increasingly, expanding to **new kinematic regimes and channels**



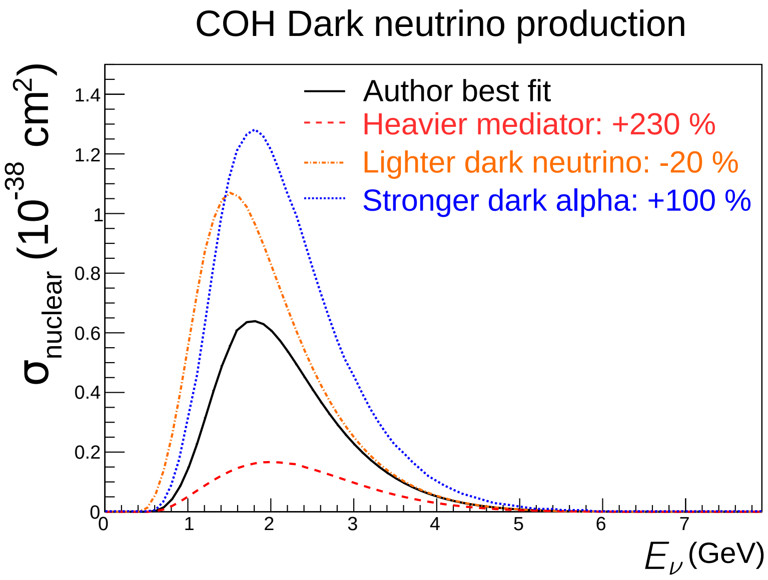
- Renewed effort in the validation and improvement of the GENIE electron scattering mode, that existed since around 2010
- Support work at JLAB experiments
- Extract modeling constraints for neutrino scattering (e4nu group)

Comparison of inclusive (e, e') scattering cross sections for data and for GENIE. (left) data vs GEM21_10b_00_000 and (right) data vs G18_10a_02_11a. (top) carbon at $E_0 = 0.56$ GeV, $\theta_e = 60^\circ$ and $Q^2_{\text{QE}} \approx 0.24$ GeV^2, (middle) iron at $E_0 = 1$ GeV, $\theta_e = 37.5^\circ$ and $Q^2_{\text{QE}} \approx 0.32$ GeV^2, and (bottom) argon at $E_0 = 2.22$ GeV, $\theta_e = 15.5^\circ$ and $Q^2_{\text{QE}} \approx 0.33$ GeV^2. Black points show the data, solid black lines show the total GENIE prediction, colored lines show the contribution of the different reaction mechanisms: (blue) QE, (red) MEC, (green) RES and (orange) DIS.

Physics modeling

- Constant demand for **new model implementations**
- Medium energy (100 MeV - 10 GeV) neutrino-nucleus a focal area...
- ... but, increasingly, expanding to **new kinematic regimes and channels**

- BSM searches form an important science pillar of many neutrino experiments.
- Standard neutrino interactions are a background to BSM searches.
- Important to simulate BSM and neutrino interactions in a common framework (for example, using common nuclear and intranuclear hadron transport models).
- Available:
  - **Nucleon Decay**
  - $n - \bar{n}$ **Oscillations**
  - **Boosted Dark Matter**
  - **Dark Neutrinos**
  - **Neutral Heavy Leptons** (in devel)
  - **The signature for your new search?** (please contribute)



Integrated cross section for coherent dark neutrino scattering from ν_μ on Ar for different parameters. The values used for the black curve are the one obtained from a MiniBooNE excess fit by Bertuzzo et al (arXiv:1807.09877 [hep-ph]) and they are: $M_N = 420$ MeV, $M_{Z_D} = 30$ MeV and $\alpha_D = 0.25$. Other curves vary one parameter at a time, according to the legend: the new values are selected purely for plotting purposes.

Physics modeling

- Constant demand for **new model implementations**
- But a physics generator is not just a random patchwork of models (well,...)
  - Using the best theory models, each one in the region where it is valid.
  - Determining how to best extrapolate models outside of their stated validity range.
  - Determining how to merge models and address double-counting issues.
  - Bridging the gaps to cover the full required phase space.
  - Validating and tuning using a variety of complementary data.
  - Maintaining CPU-efficiency, as experiments require high-statistics samples.
  - Evaluating sources of model uncertainty (knowledge of the error on the model is as necessary as the model itself).
- Core GENIE group has active role in defining well-motivated **comprehensive configurations**, that span all modelled processes and phase space.
  - Validated and tuned as a whole
  - Running out of the box (eg `'--tune G18_01a_02_11a'`)
- GENIE gives users the freedom to setup entirely new configurations, but anything more than perturbations to existing ones carries a big risk!

We are keen to work with you and define and maintain suitable new comprehensive configurations for the needs of your experiment.

Validation and Tuning

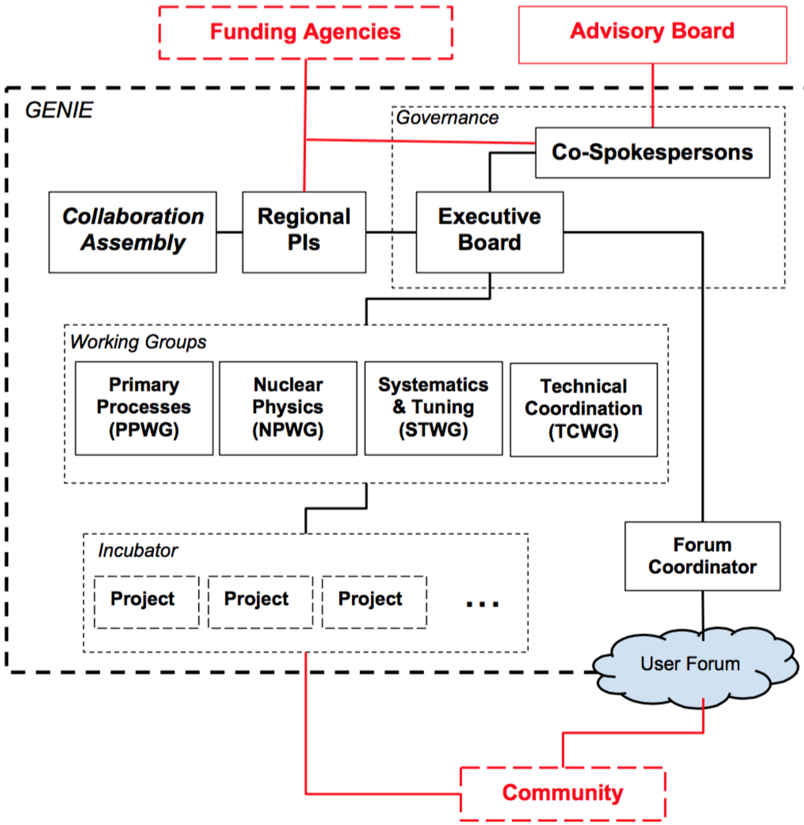
- With large model constellations and several alternative comprehensive configurations, **validation** and **tuning** are key activities.
- Key activities of the core group over the past few 5-6 years
- Have extensive data archives and automated data/MC comparison suites. Can produce thousands of plots upon pressing a button, but currently have no good way of organizing, summarizing and feeding that information to users instantaneously
  - We are keen to automate and improve this
- New GENIE global analysis is the state-of-the-art

  Recent papers showcasing global analysis capabilities:
  - Neutrino-nucleon cross-section tuning, 2104.09179 [hep-ph], Published in PRD
  - Hadronization model tuning, 2106.05884 [hep-ph], Accepted by PRD

  Nuclear tunes in progress
- Powerfull global analysis based on a GENIE-Professor interface
  - Efficient brute-force scans and massive parallelization
  - Working beyond limitations of exact reweightability
  - However, our full parameterization and error analysis not fully supported by our error propagation product (ReWeight)
    - Need new toolkit to fully support tunes

Working with GENIE

- Get in touch (free to join GENIE Slack and mailing lists, submit Github issues)
- Join the monthly User Forum
  Experiments can appoint a GENIE liaison.
- Contribute in the **GENIE Incubator**.
  - Where all work happens
  - Unique route to a public release for any development
  - Central coordination of community devel efforts
  - Geared towards fast deployment, of peer-reviewed and well-developed / documented contributions
  - 4 phases:
    -Launch
    -R&D
    -Graduation
    -Integration and deployment
- If you have longer-term interest in GENIE, and want to support modelling areas and tools, join the collaboration (see bylaws)



Final thoughts

Many proponents of ‘silver bullets‘ and magical solutions

- Magical interfaces that simplify inclusion of new models
- Magical tools that get theorists to go from Mathematica to full blown event generators intergated with fluxes and detector descriptions
- Magical organisational structures that would allow modelling contributions to be easily assembled into coherent and consistent comprehensive generators
- Software factorizations (in absense of corresponding physics factorization)

There are many useful tools but no ‘silver bullets’

Nothing is easy

A lot can be achieved through work and meaningful engagement in the Incubator

Several success stories / great contributions to GENIE over past few years (over 100 contributors)

- See recent contributions in https://hep.ph.liv.ac.uk/∼costasa/genie/releases.html

Summary

- Neutrino event generators is a hugely interesting field
- Not-well funded but, parasitically to funded activities, and through community engagement, a lot has been achieved
  - though can always do better
- GENIE is a very mature platform, interfaced to all neurtino experiments
- Provides νA, ℓA, hA and several BSM generators
- Central coordination and peer-review of community development efforts
- Tries to respond to experiment needs via User Forum (experiment liaisons)
- Parallel global analysis and model tuning activities
- I hope this talk gave an improved understanding of what GENIE can do for you, and how you can contribute.

Backup slides

Table of contents

GENIE v3 series (Bear)

First new major release in a decade and the start of an exciting new release series (2018-2022)

- **v3.0.0 released on 10th October 2018**.
- v3.0.2 released on 9th December 2018.
- v3.0.4 released on 12th April 2019.
- v3.0.6 released on 23rd July 2019.
- **v3.2.0 planned for release in February 2021**.

GENIE v2.12.10, released on 19th February 2018, is the last in the long-lived series of GENIE v2 (*Auk*) releases (2007-2018)!

GENIE v3 series (Bear)

The new series is underpinned by:

- **A proven and accelerated development paradigm**
  - Well over 50 devel projects completed within the GENIE incubator over the past 5 years, many with community support.
- Availability of **new physics validation tools**
  - GENIE/Comparisons product
- A **continuous integration** suite
- A new **global analysis of neutrino scattering data**
  - GENIE/Tuning product and interfaces to Professor
  - Characterization of new GENIE comprehensive models
  - Improved characterization of generator uncertainties
    - Beyond the constraints of reweightability
    - New GENIE hadronization tune showcases capabilities

Change of philosophy with GENIE v3

Previously, in GENIE v2

- Provided a single *Default* comprehensive model and tune,
- Represented our **best "general purpose" model** that could be used with any target and at any energy range (a requirement that introduced severe limitations).
- Provided a host of alternative modelling components that could be enabled and integrated by users at "own risk", potentially
  - invalidating tuning
  - introducing avoidable inconsistencies
  - breaking strategies to account for double counting

GENIE v3 provides multiple comprehensive models and tunes <u>all running out of the box</u>.

Change of philosophy with GENIE v3

GENIE v3 provides multiple comprehensive models and tunes all running out of the box.

- Resist combinatorial explosion, but maintain, improve & tune several alternative, well-motivated comprehensive models.
- Can bundle together comprehensive models suitable for different energy regimes (LE, UHE), or models specific to single targets (Argon tune a medium-term goal)
- Faster deployment of experimental configurations in prep. for next major release.

All tunes fully characterised. Documentation (slowly) improving

- A summary list of available tunes is maintained at `http://tunes.genie-mc.org`
- Thousands of validation and tuning plots in GENIE docdb (Looking for efficient ways to make public and couple to tune summaries)
- Details to be presented in dedicated journal articles (2 tuning papers in final stage of internal review, and a further detailed description of model construction and characterisation to be published in early summer).
- Physics and User manual under major upgrade (1510.05494 revision in progress) `https://genie-docdb.pp.rl.ac.uk/DocDB/0000/000002/006/man.pdf`

First order of business, is to familiarise yourselves with the **uniform model and tune naming conventions** introduced by GENIE.

Comprehensive model configurations in GENIE v3

A **comprehensive**[1] **model configuration** (CMC) is identified by a ($>$)7-character string in the form:

Gdd_MMv

where

- **G** is a capital letter string of arbitrary length that identifies the **authors of the tune** (typically just G for GENIE).
- **dd** is a 2-digit number describing the **year** during which the model configuration was first developed.
- **MM** is a 2-digit number (00, 01, 02, ...) identifying a **family of model configurations**.
- **v** is a single character (a, b, c, ...) **enumerating different members of the given family** of model configurations.

[1] Comprehensive: Covering all initial states and reaction processes, and the full kinematic space relevant to a particular simulation task.

Tunes in GENIE v3

Once a comprehensive model configuration is defined, a number of different **tunes** may be produced[2].
A tune is identified by the model configuration, and additional information enumerating the parameters and datasets used.

Gdd_MMv_PP_xxx

where

- **Gdd_MMv** describes the model configuration (see above).
- **PP** is a number identifying the set of tuned parameters. This parameter set is defined uniquely only in the context of a particular model configuration.
- **xxx** is a number that identifies the dataset used for the model configuration tuning. This may include a unique set of weights associated with each component dataset.

[2]Each distinct choice of a) fit datasets and dataset weighting scheme, b) parameters of interest and nuisance parameters, and c) prior constraints, leads to a different tune.

Physics content of GENIE v3.0.0 - I

GENIE v3.0.0 was presented in some detail in several conferences and seminars held at major labs, so only a brief summary presented here.

The following configurations were made available in GENIE v3.0.0. These are complex comprehensive models that are not well-described by a 1-liner but, to first order, this is how we think of these models:

- **G18_01a/b**: An adiabatic evolution of the GENIE-v2 empirical model
- **G18_02a/b**: An *improved empirical model*
- **G18_10a/b**: A model built around a complete microscopic calculation
- **G18_10i/j**: Simple variants of G18_10a/b

In addition, the following (*unsupported*) configurations were made available to support transition between v2 and v3.

- **G00_00a**: Preserves the GENIE-v2 "Default" model
- **G00_00b**: Preserves the GENIE-v2 "Default + Emp. MEC" model

G00* configurations use preserved (old) versions of all models

Physics content of GENIE v3.0.0 - II

G18_01a/b: An adiabatic evolution of the GENIE-v2 empirical model

Reuses the v2 "Default + Emp. MEC" cross-section model construction:

- RFG nuclear initial state model by Bodek and Ritchie [23].
- NC elastic: BNL / Ahrens et al. [6]
- CC quasi-elastic: Llewellyn Smith [47]
- CC/NC MEC: Empirical GENIE model
- CC/NC resonance neutrino-production: Rein and Sehgal [56] (heavily tweaked)
- CC/NC non-resonance bkg: GENIE DIS extrapolation and tuning scheme
- CC/NC deep inelastic: Bodek and Yang [25]
- CC/NC coherent pion production: Rein and Sehgal [55, 57] (heavily tweaked)
- CC $\Delta C = 1$ (quasi-elastic): Kovalenko duality model [46] w/ NOMAD tune
- CC $\Delta C = 1$ (deep inelastic): Aivazis et al. slow-rescaling model [8]

Physics content of GENIE v3.0.0 - III

Adds missing processes:

- Diffractive pion production: Rein [54]
- CC $\Delta S = 1$ (quasi-elastic): Pais [49]
- **Note**: Inelastic CC $\Delta S = 1$ implemented only for neutrinos (Rafi Alam et al. [53]) and, by default, remains switched off.

Uses unchanged hadronization model:

- $\Delta C = 0$: Andreopoulos-Gallagher-Kehayias-Yang (AGKY) [63]
- $\Delta C = 1$: Andreopoulos-Gallagher (AGcharm)

Attaches **improved FSI** model:

- Configuration "**a**" uses the **revised** 2018 INTRANUKE / hA model
- Configuration "**b**" uses the **new** 2018 INTRANUKE / hN model

Implements **two tunes** for each configuration:

- **00_000**: Baseline tune
- **02_11a**: Preliminary GENIE non-resonance bkg retune

Physics content of GENIE v3.0.0 - IV

G18_02a/b: An *improved empirical model*

With respect to G18_01, G18_02 has 2 main changes:

- CC/NC resonance neutrino-production: Rein and Sehgal → Berger and Sehgal []
- CC/NC coherent pion production: Rein and Sehgal → Berger and Sehgal []

Attaches **improved FSI** model:

- Configuration "**a**" uses the **revised** 2018 INTRANUKE / hA model
- Configuration "**b**" uses the **new** 2018 INTRANUKE / hN model

Implements **two tunes** for each configuration:

- **00_000**: Baseline tune
- **02_11a**: Preliminary GENIE non-resonance bkg retune

Physics content of GENIE v3.0.0 - V

G18_10a/b: A model built around a complete microscopic calculation

With respect to G18_01, G18_10 has several changes:

- Initial state nuclear model: RFG → LFG
- CC genuine quasi-elastic (1p1h): Llewellyn Smith → Valencia model []
- CC 2p2h: Empirical GENIE → Valencia model []
- CC/NC resonance neutrino-production: Rein and Sehgal → Berger and Sehgal []
- CC/NC coherent pion production: Rein and Sehgal → Berger and Sehgal []

Attaches **improved FSI** model:

- Configuration "**a**" uses the **revised** 2018 INTRANUKE / hA model
- Configuration "**b**" uses the **new** 2018 INTRANUKE / hN model

Implements **two tunes** for each configuration:

- **00_000**: Baseline tune
- **02_11a**: Preliminary GENIE non-resonance bkg retune

Physics content of GENIE v3.0.0 - VI

G18_10i/j: Simple variants of G18_10a/b

G18_10i is derived from G18_10a, and G18_10j is derived from G18_10b. The variants are identical in all but one aspect:

- G18_10a/b use a **dipole axial form factor** for CC QE scattering

$$F_A(q^2) = F_A(0)\left(1 - \frac{q^2}{M_A^2}\right)^{-2}$$

- G18_10i/j use a **z expansion** [48] of the axial form factor for CC QE scattering

$$F_A(q^2) = \sum_{0}^{k_{max}} a_k z(q^2)^k$$

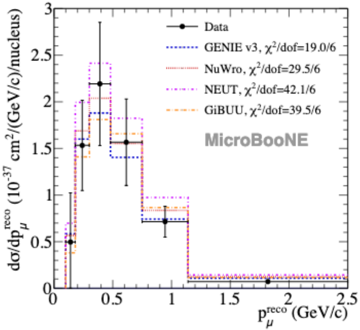
$$z(q^2, t_{cut}, t_0) = \frac{\sqrt{t_{cut} - q^2} - \sqrt{t_{cut} - t_0}}{\sqrt{t_{cut} - q^2} + \sqrt{t_{cut} - t_0}}$$

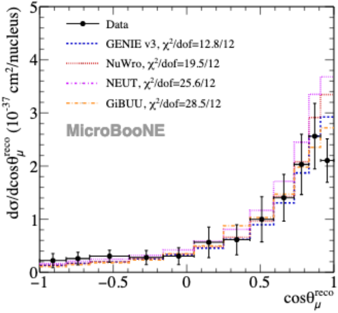
Implements **one tune** for each configuration:

- **00_000**: Baseline tune

Physics content of GENIE v3.0.0 - VII

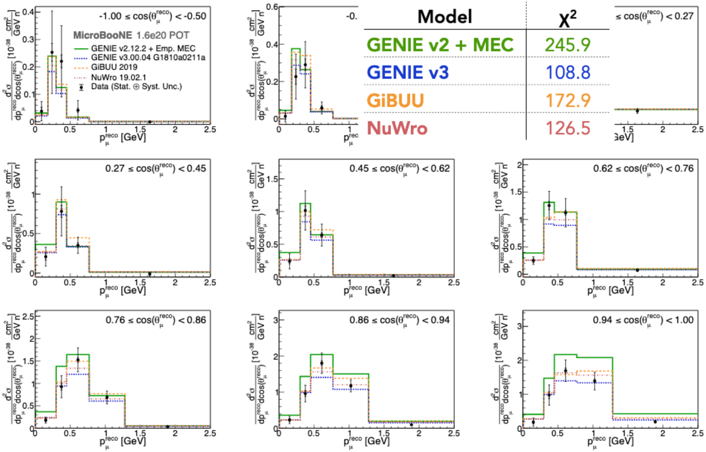
First GENIE-v3 use for a published analysis (CC0π) by MicroBooNE [5]





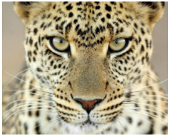
Physics content of GENIE v3.0.0 - VIII

First GENIE-v3 use for a published analysis (CCincl) by MicroBooNE [4]



Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5

Beyond GENIE v3 - Scope of GENIE v4 and v5



GENIE v4 (Cheetah): Planned for release near the start of physics exploitation of the full SBN program at Fermilab (∼2022)

- several new microscopic / theoretical calculations
- improved hadronic simulations
- expanded set of alternative FSI codes
- expanded set of alternative comprehensive model constructions
- incorporating results from new GENIE global fits (nuclear neutrino cross-sections, hadronization, FSI)

GENIE v5 (Dugong): Incorporating first explicit Argon tunes derived using a comprehensive analysis of all SBND measurements (∼2025-26)

Development work towards GENIE v4

The release of GENIE v3.2.0 is a **key milestone**, incorporating a very large fraction of new modelling work targeted for GENIE v4.

Summary of changes in v3.2.0 - I

Contributions from non-GENIE authors working with the GENIE team are highlighted

New and/or updated physics models:

- **Addition of the SuSAv2 1p1h and 2p2h cross-section models.** Details in [31]
  - Contribution by Stephen Dolan, Guillermo Megias and Sara Bolognesi (Ecole Polytechnique and IRFU, Saclay, DPP).
  - GENIE pull request #55
- **Addition of the published Minoo Kabirnezhad single-π cross-section model** by the Dubna GENIE group, and a critical review of the published work leading to model variants currently under consideration for GENIE v4. Details of the original model in [42]. Details of other development work currently internal.
  - Contribution by Minoo Kabirnezhad (Oxford).
  - GENIE pull request #130, #131, #132

Summary of changes in v3.2.0 - II

- **Addition of a new NLO DIS cross-section calculation and event generation modules** (including an implementation of the LEPTO interface to the PYTHIA6 hadronization routines) tested/validated up to 1E+9 GeV. Details in [37].
  - Contribution by Alfonso Garcia and Juan Rojo (NIKHEF).
  - New GENIE external dependence: **APFEL DGLAP evolution code**.
- **Addition of the Liege intranuclear rescattering model** through an interface to the INCL generator.
  New GENIE external dependence: **INCL**.
- **Addition of the Bertini intranuclear rescattering model** through an interface to the GEANT4 generator.
  - Contributions by Dennis Wright and Makoto Asai (SLAC).
  - This model requires a new GENIE external dependence: **GEANT4**.
- **Addition of a first working interface the PYTHIA8 hadronization code**, as part of an alternative, experimental configuration of the AGKY hadronization model.
  - Contributions by Shivesh Mandalia (QMUL).
  - New GENIE external dependence: **PYTHIA8**.

Summary of changes in v3.2.0 - III

- Addition of the **Correlated Fermi Gas nuclear model**.
- A native implementation of a **new BSM generator, simulating the production and decay of Dark Neutrinos**. Details in [15].
    - Contributions by Iker de Icaza (Sussex) and Pedro Machado (FNAL).
    - GENIE pull request #114
- A substantial upgrade in the native **BSM generator for the simulation of Boosted Dark Matter (BDM)**, bringing it sync with the model described in [17].
    - Contribution by Joshua Berger (Pittsburgh).
- Addition of a **new and complete implementation of a CEvNS event generator**. Uses an implementation of the CEvNS cross-section model described in [51].
    - GENIE pull request #45

Summary of changes in v3.2.0 - IV

New comprehensive model configurations and tunes:

- For each cross-section model construction, **released two new comprehensive model variants using the INCL (Liege) and GEANT4 (Bertini) FSI codes**, in addition to the existing variants incorporating the hA and hN FSI codes.

Example:

For example, for our G18_02 (theory) cross-section model construction, that incorporates the results of the GENIE 02_11b global analysis, users can obtain the following tunes:

- **G18_02a_02_11b** (uses INTRANUKE/hA),
- **G18_02b_02_11b** (uses INTRANUKE/hN),
- **G18_02c_02_11b** (uses INCL),
- **G18_02d_02_11b** (uses Bertini).

Summary of changes in v3.2.0 - V

- **Incorporated the final results of the GENIE global analysis of bare-nucleon cross-section data into all G18_[01a-d/02a-d]_02_11b GENIE tunes.**
  The corresponding journal paper is in the last phase of an internal review.

> Preliminary versions of our results were released in v3.0.0 - v3.0.6 in tunes carrying the label 02_11a. These preliminary (02_11a) are maintained in v3.2.0, but they will be phased out in the next release.

- **Added 02_11b variants (tunes) for the G18_10 class of comprehensive models.**
- **Released optional AGKY hadronization model configurations, incorporating the first results from the GENIE global analysis of data on neutrino-induced hadron shower characteristics.**
  The corresponding journal paper is in the last phase of an internal review.

Summary of changes in v3.2.0 - VI

- **Released a new set of comprehensive models (GHE19_00a, GHE19_00b, and GHE19_00c) optimised for our ultra high energy user communities**, based on our new NLO DIS cross-section calculation and event generation modules.
- **Released a new comprehensive model (GVLE18_01a) optimised for our low energy ($<$ 100 MeV) user communities.**
- **Released a series of experimental (and untuned) comprehensive models** incorporating new cross-section modelling elements (SuSAv2) in preparation of a new generation of comprehensive models and tunes for GENIE4.

Event generation and core framework improvements:

- **Added a new toolkit to generalise and simplify the implementation of cross-section models relying on tabulated hadron tensors**.
  The change underpinned newly developed implementation of the SuSA2 model.
  Old models were upgraded to use the new toolkit.
- **Large-scale refactoring of the GENIE decayer and hadronization modules**, upgrading them to full-blown GENIE *event record visitors* and eliminating PYTHIA6-specific elements from GENIE interfaces. The change underpinned newly developed interfaces to PYTHIA8.

Summary of changes in v3.2.0 - VII

Improvements in generator tools:

- Added a **new toolkit** (**EvtLib**: Event Library Interface Generator) providing a file **interface to external neutrino MC generators**. EvtLib allows experiments to run external neutrino MC generators, re-using their existing GENIE MC production workflows and the extensive GENIE flux and geometry tools.
  - Contribution by Chris Backhouse (UCL)
  - GENIE pull request #103
- **Improvements in atmospheric neutrino event generation app** (gevgen_atmo). Added a new option (-T) in the GENIE atmospheric neutrino event generation app, to generate the number of corresponding to a given livetime (in sec). Automatically select flux surface radii when a detector geometry is specified in the GENIE atmospheric neutrino event generation app.
  - Contribution by Tony LaTorre (Chicago)
  - GENIE issue 83; GENIE pull request #93

Summary of changes in v3.2.0 - VIII

- **New options installed in the generic GENIE MC Job driver** (GMCJDriver). Options to a) always force an interaction of the input neutrino flux ray, b) use logarithmic binning in the histogram that records the maximum possible interaction probability, as a function of neutrino energy, in the current MC job, and c) change the safety factor applied in the estimated maximum interaction probabilities when rejection sampling is used.
    - Contribution by Alfonso Garcia (NIKHEF)
    - GENIE pull request #75
- Added the option to use variable bin width flux histograms in the T2K and FNAL (applicable to all FNAL experiments) specialised event generation apps. Previously, this option for histogram-based flux descriptions existed in the generic event generation app but was left out of the more specialised apps, since the power of these apps is exploited by providing detailed ntuple-based flux descriptions produced by beamline simulations. This update improves these specialised apps for users who wish to use them with simpler flux descriptions.
    - GENIE pull request #124

Summary of changes in v3.2.0 - IX

Other improvements / bug fixes:

- Bug fix: **Fix an issue with electron (anti)neutrino scattering on Helium**. The Smith-Monitz model (like any other RFG model) is not applicable to Helium, and cross-section calculation code was crashing. An ad hoc solution was implemented.
  - GENIE pull request #107
- Bug fix: **Fixed two bugs with signs used in the Berger-Sehgal and Kuzmin-Lyubushkin-Naumov resonance models**. The fix was installed for clarity and it has no effect, as the wrong signs were cancelling each other out.
  - GENIE pull request #107
- Bug fix: Added code to **handle P33(1600) in the event generation modules**. The P33(1600) resonance (a 4-star resonance in 2019 PDG) was added in the GENIE v3 cross-section calculations but, due to missing resonance data, the resonance was ignored during event generation. In versions affected by this bug, P33(1600) was added as a "Rootino" (pseudo-particle PDG code = 0) and its decay was not simulated.
  - GENIE pull request #65

Summary of changes in v3.2.0 - X

- Bug fix: Fixed a mistake in BaryonResonanceDecayer::IsHandled() (returned input PDG code, as opposed to the correct boolean flag).
- Bug fix: Installed a fix in AGCharm2019 hadronizatiom model, **allowing the production of charmed-mesons (D+, D_s and D0) above a previously existing cutoff value of 100 GeV**.
  - Issue reported by Emircan Elikkaya and Murat Ali Guler (METU) of the SHiP experiment.
  - GENIE issue #77
- Bug fix: **Fixed a mistake in a Jacobean used in the Rosenbluth cross-section calculation**. The bug affects the GENIE electron scattering mode only.
  - GENIE pull request #121
- **The time coordinate of all particles in the event record (time increments with respect to the event vertex time) is now recorded**.
  A new convention was introduced: The particle time increments are given in ys (yocto-seconds = 1E-24 seconds).
  - GENIE pull request #119

Summary of changes in v3.2.0 - XI

- **The correct space and time coordinates of the daughter particles produced in PYTHIA decays are now stored in the GENIE event record**. Previously, the coordinates of the daughter particles were set to be the ones of the mother particle.
    - GENIE pull request #119

Other features:

- Now **supports C++14** (previously C++98)
- **Dropped support for ROOT5**

Development highlights

Upgraded hadron tensor tools ($\geq$ v3.2.0) - I

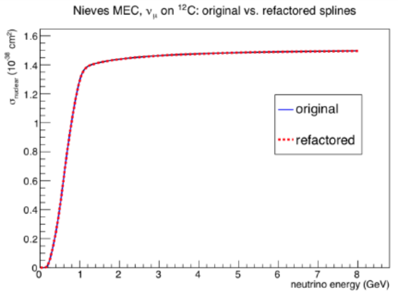
GENIE continued work to develop **suitable new code interfaces to simplify inclusion of new theoretical calculations**.

Several ideas, through comparative study of the requirements for implementing different types of 0-pion models:

- Valencia
- SuSA
- Short-time approximation
- CBF spectral function

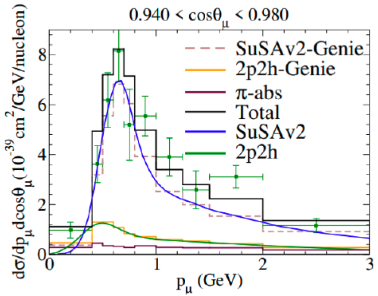
A refactoring and generalisation of code to handle hadron tensors was a necessary ingredient towards improving 0-pion theory interfaces.

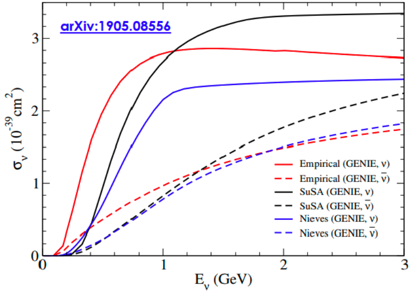
- Tech details in **GENIE docdb #137**.
- Old models migrated to new scheme.
- Physics unchanged.



New QE/MEC models: SuSAv2 ($\geq$ v3.2.0)

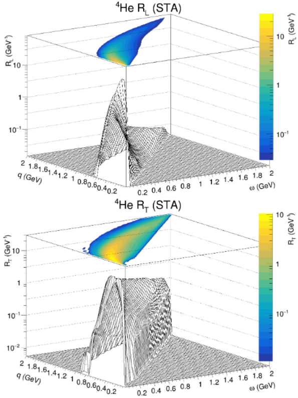
New hadron tensor tool allowed quick implementation of the SuSAv2 model. Details are given in [31].

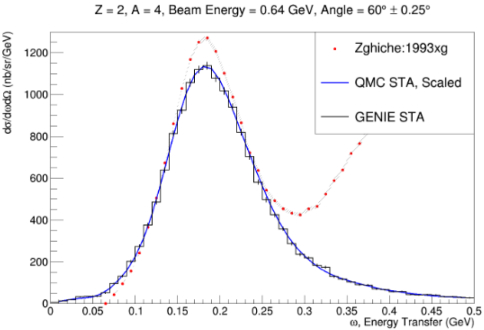




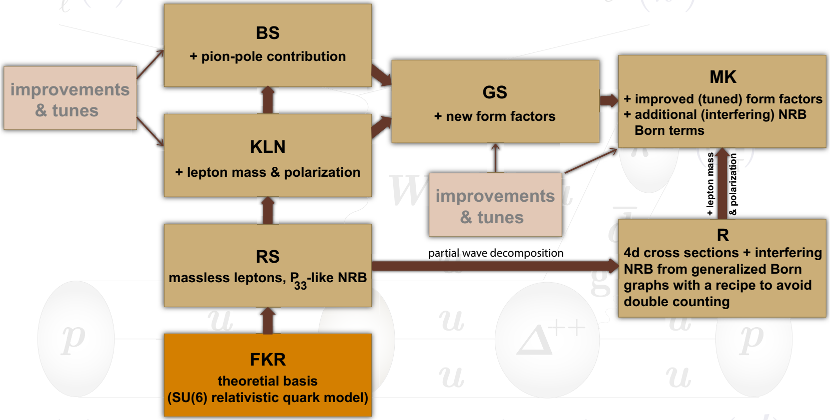
New QE/MEC models: QMC STA (> v3.2.0)

Similar tools underpin the GENIE implementation of the **Quantum Monte Carlo Short-Time Approximation** model. Details in [10].





New 1π production models: MK model implementation ($\geq$ v3.2.0) - I

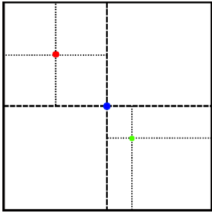


The genealogical tree of MK model

New 1π production models: MK model implementation ($\geq$ v3.2.0) - II

- Allows to calculate angular distribution of the final pions $\frac{d\sigma}{dW\,dQ^2 d\cos\theta_\pi\,d\varphi_\pi}$ for CC and NC processes.
- Takes into account final lepton mass, interference with non-resonance background (NRB) and uses original sets of form-factors.
- The NRB is calculated with generalized Born graphs for 1π.
- For theoretical aspects, see Refs. [42, 43].
- $\frac{d\sigma}{dW\,dQ^2 d\cos\theta_\pi\,d\varphi_\pi}$ can be analytically integrated over φ_π which allows faster numerical integration.
- The model parameters such as resonance masses, widths, branching ratios and decay channels were updated according to PDG-2018 [58].

New 1π production models: MK model implementation ($\geq$ v3.2.0) - III



- The event is generated in Breit frame and then boosted to laboratory frame.
- Based on MINUIT heuristic algorithm to seek differential cross section maximum for accept-rejection method is used.
- We seek the global maximum by MINUIT. To choose proper starting value and limits on variables we use two approach.
- The first is for low-energy neutrino $E_\nu < 15$ GeV.
- The invariant mass W goes over all resonance masses, M_R, the maximum is sought in the limits $(M_R - \Gamma_R, M_R + \Gamma_R)$, where Γ_R is the width of given resonance.

New 1π production models: MK model implementation ($\geq$ v3.2.0) - IV

- The region of φ_π-variation is divided into 4 parts $(0, \pi/2)$, $(\pi/2, \pi)$, $(\pi, 3\pi/2)$ and $(3\pi/2, 2\pi)$; the starting values are chosen equal to $0, \pi/2, \pi, 2\pi$.
- The region of $\cos\theta_\pi$-variation is divided into 2 parts$(-1, 0)$, $(0, 1)$; the starting values are chosen equal to ± 1.
- The region of Q^2-variation are $(Q^2_{\text{min}}, Q^2_{\text{max}})$ for$E_\nu <$1 GeV with starting $(Q^2_{\text{min}} + Q^2_{\text{max}})/2$ and $(Q^2_{\text{min}}, 2Q^2_{\text{min}}/3 + Q^2_{\text{max}}/3)$ for1 GeV$< E_\nu <$15 GeV with starting value equal to $5Q^2_{\text{min}}/6 + Q^2_{\text{max}}/6$.
- The second method is for high-energy neutrino $E_\nu > 15$ GeV. We apply transformation: $x_1 = (W - W_{\text{min}})/(W_{\text{max}} - W_{\text{min}})$, etc. So the full kinematic space is represented by 4d-cube with vertex $(0, 0, 0, 0)$ and $(1, 1, 1, 1)$

Genie

New 1π production models: MK model implementation ($\geq$ v3.2.0) - V

- At first, we seek a maximum in full kinematic phase space with starting value at the centre of the 4d-cube: $(1/2, 1/2, 1/2, 1/2)$.
- After the maximum is founded we divide the phase space into 16 4d-cubes, all them have founded maximum as a corner (●).
- Then we seek maximums in each of 16 4d-cube, again with starting value at the centre of 4d-cube.
- If founded maximum in one of sixths 4d-cube is distant from one from previous step, by a given value in all coordinates (●) then we set this maximum as dividing point, if not we set it as $(1/2, 1/2, 1/2, 1/2)$ (●), again divide this 4d-cube as in previous step and repeat maximum search in new cubes.
- Tests show that heuristic method works about **10 times** faster.

Resonance pion decay updates ($\geq$ v3.0.6) - I

- Baryon resonance decay is not isotropic in Δ reference frame
  - The pion follows a distribution as function of θ^*
- The previous version was bugged
  - The angles were calculated with respect to the LAB z direction
  - It should be w.r.t. $\overrightarrow{q}$
- We took the opportunity and we made refinements
  - We fixed the bug
  - We added further distributions
    - ANL [52]
    - early BNL [11]
    - late BNL [44, Figure 13]

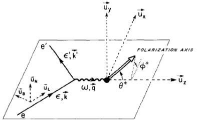


FIG. 2. Kinematics and coordinate systems for the scattering of polarized electrons from polarized nuclear targets.

Resonance pion decay updates ($\geq$ v3.0.6) - II

- The new system has
  - different distributions depending on Q^2
  - Possible dependencies on the ϕ^* angle as well
  - None of the new distributions are used in the official tunes
    - They can all be enabled with proper configuration

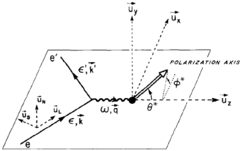
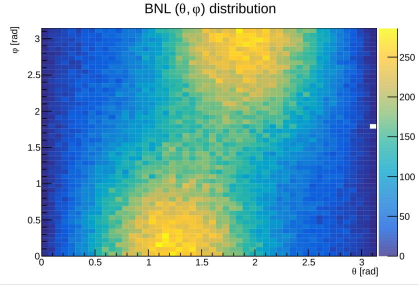


FIG. 2. Kinematics and coordinate systems for the scattering of polarized electrons from polarized nuclear targets.



NLO DIS and VHE/UHE tunes ($\geq$ v3.2.0) - I

Complete theoretical description of VHE/UHE neutrino interaction scattering and new tunes suitable for neutrino telescopes [37].
Distinct comprehensive models, used for energies above 100 GeV.

- Planning to bridge with ME model in future.

Validated for neutrino energies up to 10^9 GeV!

Can be coupled with tools, such as *NuPropEarth* [37] or *gSeaGen* [7].

Includes several relevant scattering mechanisms:

- Deep inelastic scattering (DIS) off nucleons at NLO level.
    - Incorporating sub-leading resonant DIS effects (due to neutrino interactions with the photon field of the nucleon)
- Coherent scattering off nucleus
- Resonant scattering upon atomic electrons (Glashow scattering)

NLO DIS and VHE/UHE tunes ($\geq$ v3.2.0) - II

For DIS scattering off gluons and quarks, in the perturbative regime, the structure functions $F_i^{\nu N}$ factorise in terms of process-dependent coefficients $C_{i,a}^{\nu}$ and process-independent PDFs f_a^N as follows

$$F_i^{\nu N}(x, Q^2) = \sum_{a=g,q} \int_x^1 \frac{dz}{z} C_{i,a}^{\nu}(\frac{x}{z}, Q^2) f_a^N(z, Q^2)$$

- The coefficients $C_{i,a}^{\nu}$ can be computed in perturbation theory as a power expansion in the strong coupling constant a_s.
- The DGLAP equations determine the evolution of PDFs.
- Option to account for the impact of small-x resummation (logarithmic enhancements arising from high-energy gluon emissions) of coefficient functions and PDF evolution.

NLO DIS and VHE/UHE tunes ($\geq$ v3.2.0) - III

Structure functions are computed using the *APFEL* program [12].

- Small-x resummation through interface to *HELL* [21].

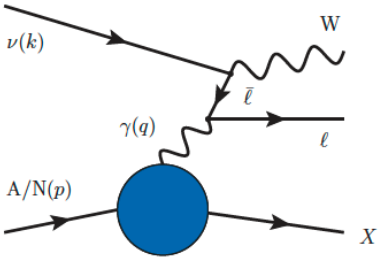
The baseline calculation is **BGR18** [20].

- All inputs at NLO accuracy.
- PDF sets from NNPDF3.1sx [9] global analysis of collider data.
- Incorporating (through PDF reweighting) the impact of LHCb D-meson production in pp collisions (small-x PDF constraints beyond the kinematic range of HERA data) [1–3].
- Using the FONLL scheme [35] to account for quark mass effects.
- Nuclear corrections computed using the EPPS16 nPDFs [32, 34].

The **CMS11** [26] calculation is also implemented for reference.

- Uses the the NLO HERA1.5 PDF set [27].

NLO DIS and VHE/UHE tunes ($\geq$ v3.2.0) - IV



Resonant interactions with the nucleon's photon field, can amount to up to a 3% correction of the total DIS cross-section, when the neutrino has enough energy to produce an on-shell W boson ($\sqrt{2M_N E_\nu} \geq M_W$).

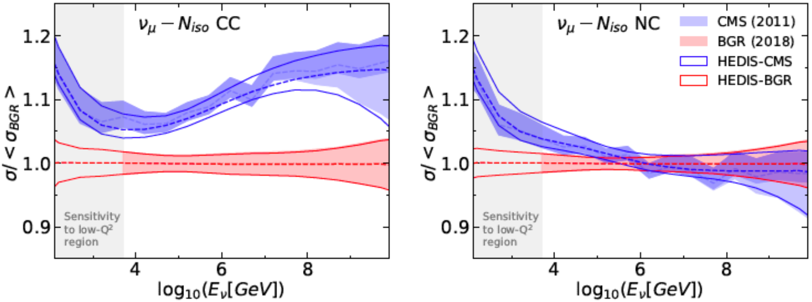
The contribution to the cross-section taken into account [37] by convoluting the cross-section for the partonic process $\nu\gamma \to \ell W$, with the inelastic photon PDF of the nucleon

$$\sigma_{\nu N}(E_\nu) = \int dx\ \gamma^N_{inel}(x, \mu_F^2)\ \hat{\sigma}_{\nu\gamma}(x, \mu_F^2, E_\nu)$$

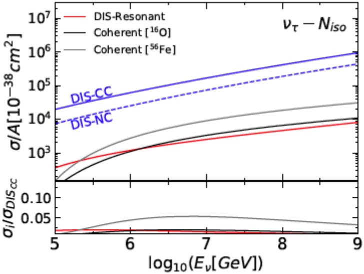
NLO DIS and VHE/UHE tunes ($\geq$ v3.2.0) - V

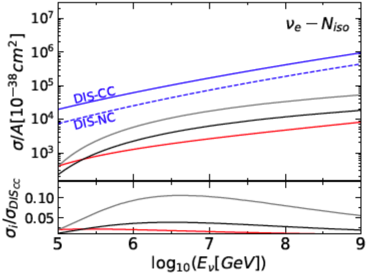
Comparison of neutrino-nucleon interaction cross-sections:

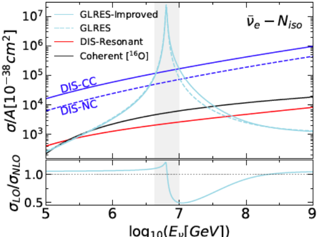
- The original (NLO) BGR18 and CMS11 calculations are compared with their corresponding GENIE implementations
- Bands correspond to the PDF uncertainties



NLO DIS and VHE/UHE tunes ($\geq$ v3.2.0) - VI

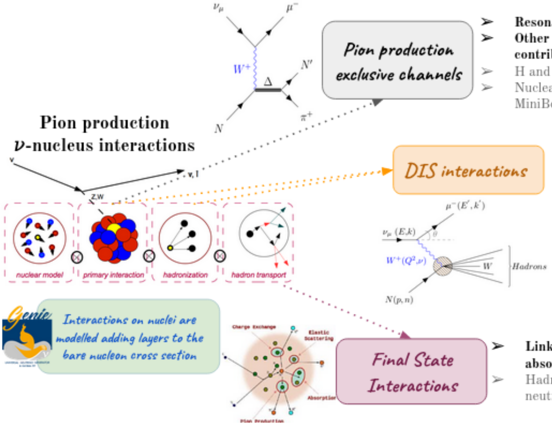






- Up: GENIE BGR18 DIS CC and NC cross-sections for ν_τ and ν_e, and corresponding DIS resonant and coherent cross-sections (shown for 2 nuclei in order to illustrate the Z^2/A scaling effect)
- Left: Glashow resonance contribution

Bare nucleon x-section retune ($\geq$ v3.2.0) - I



- Resonance neutrino-production events
- Other non-resonance, low-Q2/low-W contributions (SIS)
- H and ^{2}H bubble chambers
- Nuclear data from MINERvA, T2K and MiniBooNE

- Modelling of CC DIS events
- Hadronization processes

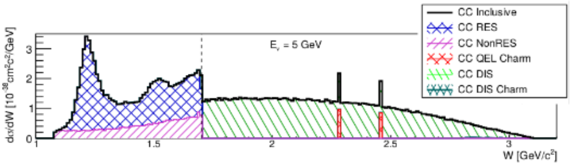
DIS events play an important role in:

- Inclusive cross section data
- Neutrino hadroproduction data
- H and ^{2}H bubble chambers
- CHORUS and OPERA data

- Linked to pion production and absorption in the nuclear medium
- Hadro-nucleus interaction data and neutrino transparency data

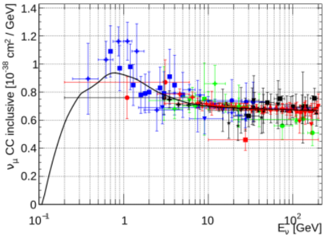
Bare nucleon x-section retune ($\geq$ v3.2.0) - II

- Resonance production is described with either the Rein-Sehgal or Bergher-Seghal models
- The non-resonant background is described using a duality inspired inclusive model
  - DIS cross section extrapolated down to the W inelastic threshold
  - Includes, on average, the effect of the resonances
  - Tuning to address double-counting with resonances
- Hadronization model used to decompose inclusive cross section into exclusive cross section for a number of 1π and 2π channels

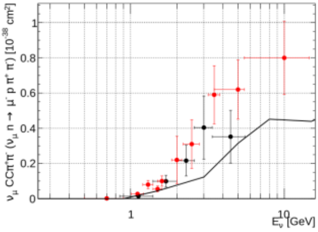


Bare nucleon x-section retune ($\geq$ v3.2.0) - III

- In the old tune, **more emphasis was given on inclusive data**
- **Tensions exist between inclusive and exclusive data**
  Known issues with the old tune, re-discovered many times:
  - One pion production was overpredicted
  - Underestimating two pion production



G00_00a default - ν_μ CC inclusive



G00_00a default - ν_μ CC p$\pi^+\pi^-$

Bare nucleon x-section retune ($\geq$ v3.2.0) - IV

Experiment	N_p	Energy [GeV]	Target	Cuts	Ref.
		$\nu_\mu + N \to \mu^- X$			
BNL 7FT	13	0.6-10	^{2}H		[42]
BEBC	3	10-50	H-^{10}Ne		[40]
FNAL	6	10-110	^{2}H		[72]
	5	100-110	H-^{10}Ne		[45]
		$\bar{\nu}_\mu + N \to \mu^+ X$			
BEBC	3	11-110	^{1}H-^{10}Ne		[28]
	1	10-50	^{1}H-^{10}Ne		[40]
	6	30-110	^{1}H-^{10}Ne		[29]
	1	10-110	^{1}H-^{10}Ne		[41]
BNL 7FT	1	1-4	^{1}H		[51]
FNAL	5	10-110	^{2}H$-^{10}$Ne		[47]
	7	10-80	^{2}H$-^{10}$Ne		[52]
		$\nu_\mu n \to \mu^- n \pi^+$			
ANL 12FT	5	0.3-2	^{1}H and ^{2}H		[65]
ANL 12FT,ReAna	7	0.3-3	^{2}H		[66]
BNL 7FT,ReAna	11	0.1-4	^{2}H		[66]
		$\nu_\mu p \to \mu^- p \pi^+$			
ANL 12FT,ReAna	8	0-1.6	^{2}H		[66]
BNL 7FT,ReAna	7	0-7	^{2}H		[66]
BEBC	7	1-30	^{1}H	$W < 1.4$ GeV	[68]
	6	5-100	^{2}H	$W < 2$ GeV	[56]
	5	10-80	^{1}H	$W < 2$ GeV	[70]
FNAL	3	10-30	^{1}H	$W < 1.4$ GeV	[75]
		$\nu_\mu n \to \mu^- p \pi^0$			
ANL 12FT	5	0.2-2	^{1}H and ^{2}H		[65]
ANL 12FT,ReAna	7	0.2-2	^{2}H		[66]
BNL 7FT,ReAna	10	0.4-3	^{2}H		[66]
		$\nu_\mu p \to \mu^- n \pi^+ \pi^+$			
ANL 12FT	5	1-6	^{2}H		[73]
		$\nu_\mu p \to \mu^- p \pi^+ \pi^0$			
ANL 12FT	5	1-6	^{2}H		[73]
		$\nu_\mu n \to \mu^- p \pi^+ \pi^-$			
ANL 12FT	5	8-6	^{2}H		[73]
BNL 7FT	10	0-20	^{2}H		[33]
		$\bar{\nu}_\mu p \to \mu^+ p \pi^-$			
FNAL	1	5-70	^{1}H	$W < 1.9$ GeV	[71]
		$\nu_\mu + n \to \mu^- + p$			
ANL 12FT	7	0-2	^{2}H		[55]
	8	0-2	^{1}H and ^{2}H		[27]
BNL 7FT	4	0.2-2	^{2}H		[60]
BEBC	5	20-40	^{2}H		[56]
FNAL	2	0-50	^{2}H		[57]

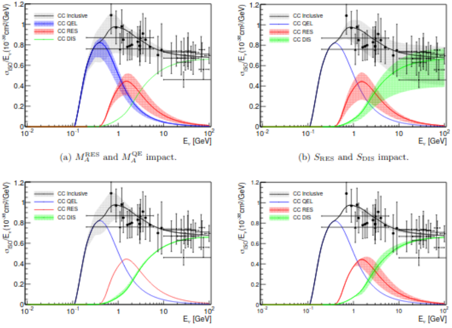
The SIS region is tuned against ν_μ / $\bar{\nu}_\mu$ CC data on ^2H targets for the following **topologies**:

- Inclusive
- One pion production
  - $\nu_\mu n \to \mu^- n \pi^+$
  - $\nu_\mu p \to \mu^- p \pi^+$
  - $\nu_\mu n \to \mu^- p \pi^0$
  - $\bar{\nu}_\mu p \to \mu^+ p \pi^-$
- Two pion production
  - $\nu_\mu p \to \mu^- n \pi^+ \pi^+$
  - $\nu_\mu p \to \mu^- p \pi^+ \pi^0$
  - $\nu_\mu n \to \mu^- p \pi^+ \pi^-$
- Quasi-elastic data†

† To constrain flux normalization

Bare nucleon x-section retune ($\geq$ v3.2.0) - V

1. RES parameters
   - M_A^{RES}
   - RES-XSecScale
2. SIS parameters
   - W_{cut} to determine the end of the SIS region
   - R_m parameters for proton and neutron, multiplicity 2 and 3
3. DIS parameters
   - DIS-XSecScale
4. QEL parameters
   - M_A^{QEL}
5. Flux nuisance parameters



(a) M_A^{RES} and M_A^{QE} impact.
(b) S_{RES} and S_{DIS} impact.
(c) $R_{\nu p}^{CC1\pi}$, $R_{\nu p}^{CC2\pi}$, $R_{\nu n}^{CC1\pi}$ and $R_{\nu n}^{CC2\pi}$ impact.
(d) W_{cut} impact.

These parameters are common for both G18_01a and G18_02a CMC

Bare nucleon x-section retune ($\geq$ v3.2.0) - VI

- The datasets from the same experiment are not independent
  $\Rightarrow$ same flux, analysis methodology,...
- The data releases do not contain any correlation
- By adding an **extra nuisance parameters** per experiment we take into account the correlation
  $\rightarrow$ ν and $\bar{\nu}$ beams have different nuisance parameters
- They are **scaling factors** applied to the prediction
- Each nuisance parameter has a Gaussian prior centered on 1 with $\sigma = 15\%$
- To further constrain the fluxes, **we included quasi-elastic data as well as M_A^{QE} in the fit**

Bare nucleon x-section retune ($\geq$ v3.2.0) - VII

Parameter	Default	G18_01a(/b)	G18_02a(/b)
W_{cut}	1.7	1.94	1.81
M_A^{QE}	0.99	1.00 ± 0.01	1.00 ± 0.013
M_A^{RES}	1.12	1.09 ± 0.02	1.09 ± 0.014
$R_{\nu p}^{\mathsf{CC}1\pi}$	0.1	0.06 ± 0.03	0.008
$R_{\nu p}^{\mathsf{CC}2\pi}$	1	1.1 ± 0.2	0.94 ± 0.075
$R_{\nu n}^{\mathsf{CC}1\pi}$	0.3	0.14 ± 0.03	0.03 ± 0.010
$R_{\nu n}^{\mathsf{CC}2\pi}$	1	2.8 ± 0.4	2.3 ± 0.12
S_{RES}	1	0.89 ± 0.04	0.84 ± 0.028
S_{DIS}	1.032	1.03 ± 0.02	1.06 ± 0.01
χ^2/157 DoF		1.84	1.64

$\Rightarrow$ The correlation between the tuned parameters is in the backup slides

Priors applied

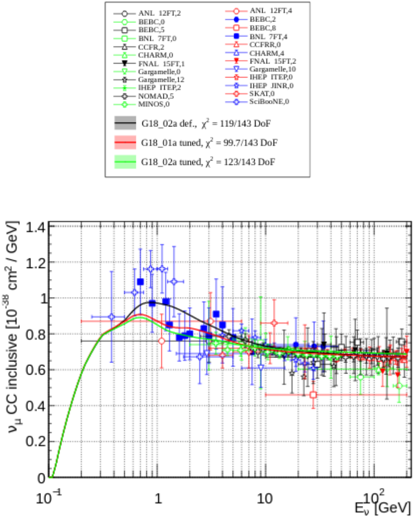
$M_A^{QE} = 1.014 \pm 0.014$ GeV/c^2, [ArXiv:0708.1946]
$M_A^{RES} = 1.12 \pm 0.03$ GeV/c^2, [ArXiv:0606184]

DIS-XSecScale$= 1 \pm 0.05 \rightarrow$ Motivated by DIS high energy cross section values

Bare nucleon x-section retune ($\geq$ v3.2.0) - VIII

Global tune with respect to ν_μ CC Inclusive datasets:

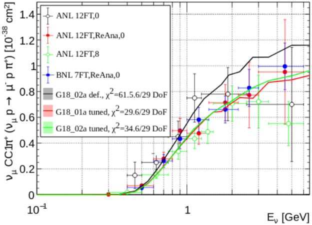
- The cross section is reduced at low energies to match the low cross section of pion production
- Pion production is better described without ruining the inclusive cross section

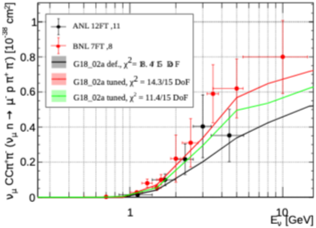


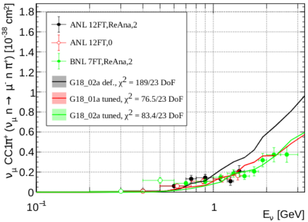
Disclaimer: Only filled data points are used in the tune

Bare nucleon x-section retune ($\geq$ v3.2.0) - IX

Retune brings an **improved description of both inclusive and exclusive data**.



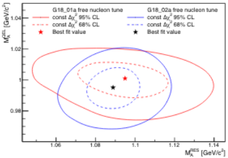




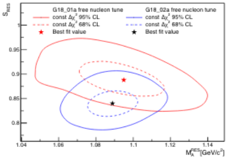
Genie

Bare nucleon x-section retune ($\geq$ v3.2.0) - X

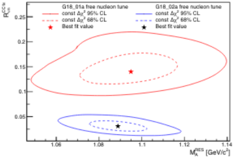
New data-driven constraints on generator uncertainty.
Our goal is that with GENIE v4, *ReWeight* will **support error propagation for all GENIE tunes** (including the intrinsically non-reweightable parameters included in tunes).



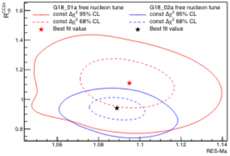
(a) Contour M_A^{RES} vs M_A^{QE}



(b) Contour M_A^{RES} vs S_{RES}



(c) Contour M_A^{RES} vs $R_{\nu n}^{\mathrm{CC}1\pi}$



(d) Contour M_A^{RES} vs $R_{\nu p}^{\mathrm{CC}2\pi}$

Bare nucleon x-section retune ($\geq$ v3.2.0) - XI

This work is almost ready for submission in a journal. Stay tuned!

Bare-Nucleon Cross-Section Model Tuning in the GENIE/Generator v3.

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Abstract

We summarise the results of a study performed within the GENIE global analysis framework, revisiting the GENIE bare-nucleon cross-section tuning and, in particular, the tuning of a) the inclusive cross-section, b) the cross-section of low-multiplicity inelastic channels (single-pion and double-pion production), and c) the relative contributions of resonance and non-resonance processes to these final states. The same analysis was performed with several different comprehensive cross-section model sets available in GENIE Generator v3 (v3.0.6 was

CEvNS and VLE tunes ($\geq$ v3.2.0) - I

- **Added a new CEvNS event generator**.
- The corresponding CEvNS cross-section calculation is based on the work of Patton et al. [51].
- In this model the differential CEvNS cross-section is given by

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left\{ 2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2} \right\} \frac{Q_w^2}{4} F^2(Q^2)$$

where M is the nuclear mass, T is the kinetic energy of the nuclear recoil,

$$T = \frac{Q^2 E}{2EM + Q^2},$$

CEvNS and VLE tunes ($\geq$ v3.2.0) - II

Q_w is the weak charge,

$$Q_w = N - Z(1 - 4sin^2\theta_w),$$

and $F(Q^2)$ is the nuclear form factor

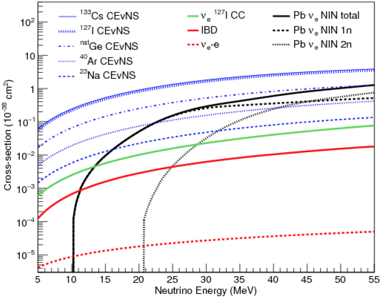
$$F(Q^2) = \frac{1}{Q_w}\int\Big(\rho_n(r) - (1 - 4sin^2\theta_w)\rho_p(r)\Big)\frac{sin(Qr)}{Qr}r^2dr \Rightarrow$$

$$F(Q^2) = \frac{N}{Q_w}\Big(1 - \frac{Q^2}{3!} < R_n^2 > + \frac{Q^5}{5!} < R_n^4 > - \frac{Q^6}{7!} < R_n^6 > + ...\Big)$$

where

$$< R_n^k > = \frac{\int \rho_n(r)r^k d^3r}{\int \rho_n(r)d^3r}$$

CEvNS and VLE tunes ($\geq$ v3.2.0) - III



Calculation by Patton et al. [51] fully reproduced by GENIE implementation.

- The new CEvNS generator is omitted from the standard comprehensive model configurations
    - Large cross-section to nearly invisible channel
- A new, dedicated low-energy configuration (**GVLE18_01a**) was setup, including
    - CEvNS
    - νe^-
    - IBD
- Single, baseline tune (**000_00**)

Coherent single-γ production ($\geq$ v3.2.2) - I

- NC photon emission reactions with heavy nuclei [60]
- At intermediate energies, dominated by the weak excitation of the $\Delta(1232)$ resonance
  - and its subsequent decay into Nγ
  - Further contributions from other resonances are also available
    - The effect is $< 10\%$
    - to be released in a later version ($\geq$ v3.2.4 or even v3.4)
- The model takes into account
  - Pauli blocking
  - Fermi motion
  - in-medium Δ resonance broadening

Genie

Coherent single-γ production ($\geq$ v3.2.2) - II

- DeVries form factors for proton charge distributions [30]
  - Interpolated to be used on nuclei not available in DeVries' paper
  - Neutron distributions are similar to the proton of the nucleus and scaled to insure normalisation
- Model reliable only for $E_\gamma < 2\,\mathrm{GeV}$
  - and for nuclei heavier than Carbon

- Integrated cross sections for

  ν - continuous

  $\bar{\nu}$ - dotted

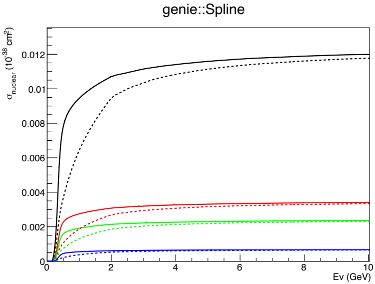
- on different nuclei

  $^{12}\mathrm{C}$ - blue

  $^{40}\mathrm{Ar}$ - green

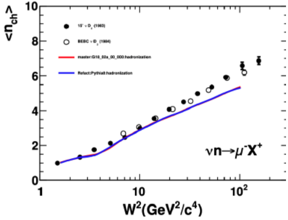
  $^{56}\mathrm{Fe}$ - red

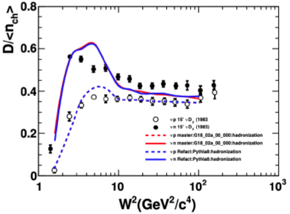
  $^{208}\mathrm{Pb}$ - black



Interface to PYTHIA8 ($\geq$ v3.2.0) - I

- Large-scale code refactoring completed.
- Changed of hadronization and decayer interfaces
  - Upgrade to *event record visitors*
  - Eliminated PYTHIA6-specific (but misunderstood as generic) ROOT objects (TMCParticle) from interfaces
- Interfaced to PYTHIA8 directly (not via ROOT)
- **PYTHIA8 is a working PYTHIA6 alternative within AGKY**
  - PYTHIA6/8 yield identical results
- **PYTHIA8 not a full PYTHIA6 replacement yet**
  - Particle decayers, charm hadronization, LEPTO (HEDIS) still support only PYTHIA6
  - Fully transition to PYTHIA8 in v3.4
  - Drop PYTHIA6 entirely in v4.0
- Still useful for exercising / testing new future mandatory dependency.



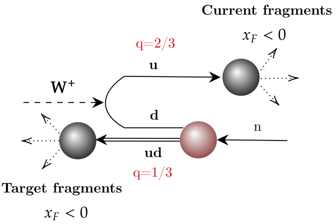


Hadronization retune ($\geq$ v3.2.0) - I

Hadronization models are a key ingredient for predictions of **exclusive hadronic multiparticle production**.

It affects:

- E_ν reconstruction (detector response to hadronic showers)
- Efficiency / background estimation



νn neutrino interaction.

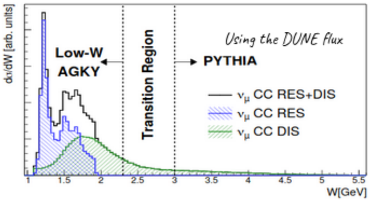
Conventional picture:

- Two correlated hadron jets (current and target fragments)
- Smooth transition through a central rapidity region
- At low W, the two fragmentation regions overlap

Hadronization retune ($\geq$ v3.2.0) - II

GENIE AGKY Hadronization model [63]
Further details in this NuSTEC talk

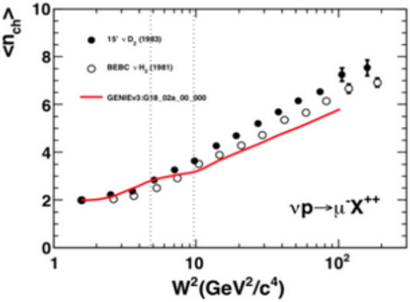
- Empirical model at W $<$ 2.3 GeV
- PYTHIA at W $>$ 3 GeV
  - home.thep.lu.se/Pythia/
- Linear transition in between



Hadronization is one of the current focal areas of development:

- Integrate PYTHIA8
- Improve GENIE/PYTHIA interface (gluon radiation)
- In-medium effects
- Relax strong x_F asymmetry at low W
- Non asymptotic forms of KNO scaling
- Address double-counting following introduction of ΔS=1 modes
- Parameter tuning
- Evaluation of model uncertainty
- Tools for propagating hadronization model uncertainty
- ...
- ...

Hadronization retune ($\geq$ v3.2.0) - III



Decided to address:

- $\langle n_{ch} \rangle$ underestimation at the PYTHIA region
- No explicit GENIE tune
- Lack of data-driven constraints to quantify the generator uncertainty

$< n_{ch} >$ is controlled by a large set of non-reweightable parameters. Test-driving aspects of our tuning machinery, relevant for several future tunes.

Hadronization retune ($\geq$ v3.2.0) - IV

In the empirical GENIE model, the averaged charged multiplicity follows an empirical logarithmic law:

$$\langle n_{ch} \rangle = \alpha_{ch} + \beta_{ch} \cdot \ln\left(\frac{W^2}{GeV^2/c^4}\right) + \cancelto{0}{\beta'_{ch}} \cdot \ln\left(\frac{Q^2}{GeV^2/c^2}\right)$$

- α_{ch} and β_{ch} are free parameters and depend on the type of interaction
- In GENIE, α_{ch} and β_{ch} are those measured by the FNAL 12FT and BEBC 7FT bubble chambers.

Parameter	νp	νn	$\bar{\nu}$p	$\bar{\nu}$n
α_{ch}	0.40	-0.20	0.02	0.80
β_{ch}	1.42	1.42	1.28	0.95

Hadronization retune ($\geq$ v3.2.0) - V

At high W, GENIE is based on the Lund string fragmentation framework (PYTHIA).

- Tuned to high energy pp and ep experiments.
- NOMAD (NUX) PYTHIA6 tuning was adopted in 2007.
- Some PYTHIA6 defaults were restored in later GENIE re-tune (2010).
- Not previously tuned with neutrino data

	PYTHIA default	NUX 2001	GENIE 2010 re-tune
$s\bar{s}$ production suppression	0.30	0.21	0.30
$< p_T^2 > (GeV^2)$	0.36	0.44	0.44
Non-gaussian p_T tail parameterization	0.01	0.01	0.01
Fragmentation cut-off energy (GeV)	0.80	0.20	0.20

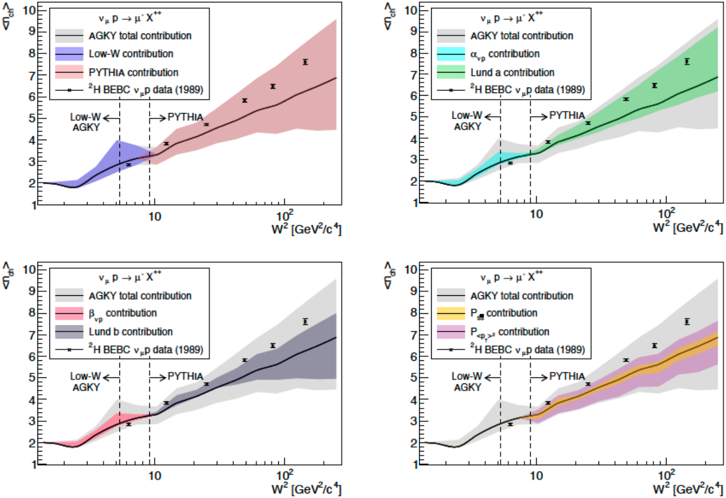
Hadronization retune ($\geq$ v3.2.0) - VI

Experiment	N_p	W^2 [GeV^2/c^4]	Cuts	Syst.	In Fit	Ref.
			$\nu_\mu + p \to \mu^- X^{++}$			
FNAL 15FT (1983)	14	[1, 225]	$p^\mu \geq 5$ GeV/c $p^T_\mu \geq 1$ GeV/c $p^{Ch}_L \geq 5$ GeV/c $p_p \leq 340$ MeV/c^2 $W \geq 1.5$ GeV/c^2 $E^{reco}_\nu \geq 10$ GeV	10%	$W^2 > 4$GeV^2/c^4	[35]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c	included	✗	[56]
			$\nu_\mu + n \to \mu^- X^+$			
FNAL 15FT (1983)	14	[1, 225]	$p^T_\mu \geq 1$ GeV/c $p^{Ch}_L \geq 5$ GeV/c $E^{reco}_\nu \geq 10$GeV $p_p \leq 340$ MeV/c^2	10%	✓	[35]
BEBC (1984)	8	[6, 112]	ε_{cut} $p^\mu \geq 4$ GeV/c $Q^2 \geq 1$ (GeV/c)^2 $W^2 \geq 5$ GeV^2/c^4 $p_p \leq 300$ MeV/c^2	$\sim$ stat	✓	[57]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c $W \geq 5$GeV/c^2	included	✗	[56]
			$\bar{\nu}_\mu + p \to \mu^+ X^0$			
BEBC (1982)	8	[5, 75]	$p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c	$\sim$ stat	✓	[36]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c	included	✗	[56]
			$\bar{\nu}_\mu + n \to \mu^+ X^-$			
BEBC (1982)	8	[1.5, 56]	$p^\mu \geq 4$ $p_p \leq 300$ MeV/c	$\sim$ stat	✓	[36]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ $p_p \leq 300$ MeV/c	included	✗	[56]

Parameter	GENIE parameter name	Nominal value	Allowed range
	Low-W empirical model		
$\alpha_{\nu p}$	KNO-Alpha-vp	0.40	[-1.0, 2.0]
$\alpha_{\nu n}$	KNO-Alpha-vn	-0.20	[-1.0, 2.0]
$\alpha_{\bar{\nu} p}$	KNO-Alpha-vbp	0.02	[-1.0, 2.0]
$\alpha_{\bar{\nu} n}$	KNO-Alpha-vbn	0.80	[-1.0, 2.0]
$\beta_{\nu p}$	KNO-Beta-vp	1.42	[0.0, 2.5]
$\beta_{\nu n}$	KNO-Beta-vn	1.42	[0.0, 2.5]
$\beta_{\bar{\nu} p}$	KNO-Beta-vbp	1.28	[0.0, 2.5]
$\beta_{\bar{\nu} n}$	KNO-Beta-vbn	0.95	[0.0, 2.5]
	PYTHIA		
$P_{s\bar{s}}$	PYTHIA-SSBarSuppression	0.30	[0.0, 1.0]
$P_{<p_T^2>}$ [GeV^2]	PYTHIA-GaussianPt2	0.44	[0.1,0.7]
$P_{E_{cut\,off}}$ [GeV]	PYTHIA-RemainingEnergyCutoff	0.20	[0.0 ,1.0]
Lund a	PYTHIA-Lunda	0.30	[0.0,2.0]
Lund b [GeV/c^2]	PYTHIA-Lundb	0.58	[0.0,1.5]

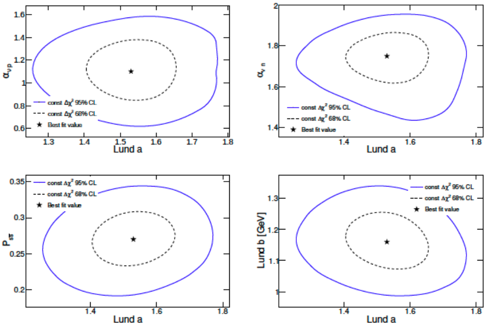
Large set of neutrino-induced hadron shower characteristic data were brought into the first hadronization tune focussing explicitly on $< n_{ch} >$. A large set of non-reweightable parameters was allowed to float.

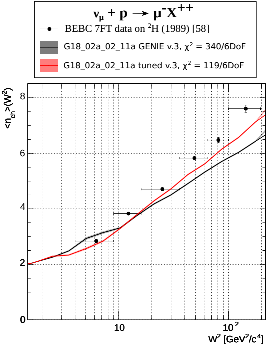
Hadronization retune ($\geq$ v3.2.0) - VII



Hadronization retune ($\geq$ v3.2.0) - VIII

- Desired increase $\langle n_{ch} \rangle$ at the PYTHIA region
- Full error matrix for several key modelling parameters





Hadronization retune ($\geq$ v3.2.0) - IX

This work is almost ready for submission in a journal. Stay tuned!

AGKY Hadronization Tuning in the GENIE/Generator v3.

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(Dated: January 5, 2021)

The GENIE neutrino Monte Carlo developed an effective low-mass hadronization model, known as AGKY, which incorporates PYTHIA events at high invariant mass [1]. Only the low-AGKY model parameters were extracted from neutrino hadroproduction data. Comparisons of the GENIE model against an expanded and carefully curated archive of neutrino-induced hadron shower data exposed disagreements between different data sets, which further deteriorates at the PYTHIA region. In this paper, the first hadronization tune on averaged charged multiplicity data on deuterium and hydrogen bubble chamber experiments is presented, with a complete estimation of parameter uncertainties.

I. INTRODUCTION

"shallow inelastic scattering (SIS)" region also influ-

Interface to Bertini cascade in G4 ($\geq$ v3.2.0) - I

- Details of the G4 Bertini implementation can be found in [40].
- G4 work based on re-engineering the INUCL code [59].
- The original INC model by Alsmiller, Bertini, Guthrie [36] [18] [19] solves the Boltzmann equation on the average to simulate the fast (10^{-23} - 10^{-22} s) phase of particle collisions.
- As the INC proceeds, an *exciton* model, where the excited state of the nucleus is characterised by the number of particles and holes, is updated.
    - G4 implements the Griffin exciton model [38].
- Pre-equilibrium emission is based on the exciton model.
    - Transitions to states with different number of excitons compete with particle emission, and emission of light fragments.
- For the simulation of the slower (10^{-18} - 10^{-16} s) compound phase, several competing evaporation / break up models exist.

Genie

Interface to Bertini cascade in G4 ($\geq$ v3.2.0) - II

- For the simulation of the slower (10^{-18} - 10^{-16} s) compound phase, several competing evaporation / break up models exist.
    - Nuclear explosion
        - Allowed in extreme cases (for light nuclei and excitation energies much larger than the binding energy).
    - Fission
        - Based on the model of Bohr and Wheeler [24]
    - Evaporation of nucleons and light fragments
        - Based on the Weisskopf statistical theory of particle emission [62] [61] or, for lighter nuclei (A $<$ 28), on the Generalised Evaporation Model [45] (p. 1045).
    - Evaporation of photons
        - Both with discrete and continuous (from giant resonance de-excitation) energy levels.
        - Typically modelled using tabulated transition probabilities

Interface to Liége (INCL) cascade ($\geq$ v3.2.0) - I

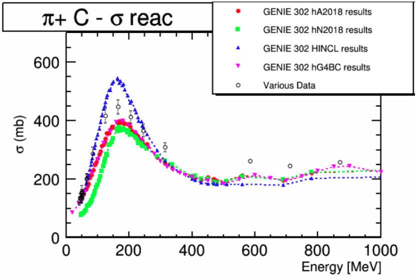
INCL is an advanced intranuclear cascade code [22, 28, 29].

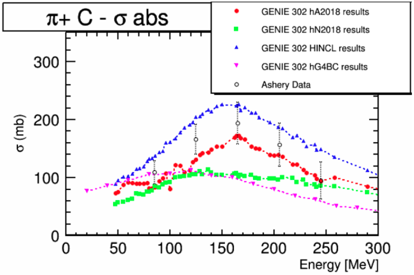
Solid **quasi-classical treatment**: It is **almost parameter free**, and it is able to successfully describe at the same time a large set of various observables [22].

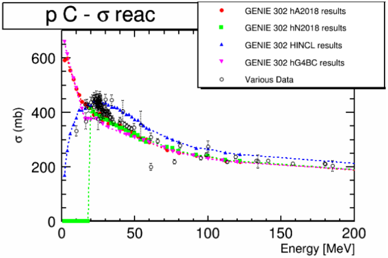
- Includes a realistic target density distribution
- The fate of all particles is followed as time evolves
- Incorporates a self-consistent determination of the stopping time
- Pauli blocking is implemented consistently with the progressive depletion of the Fermi sphere

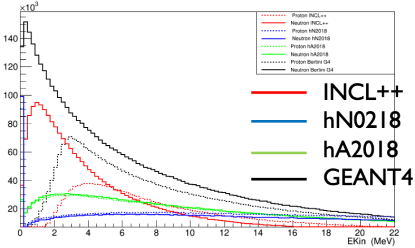
Coupled with the ABLA [13, 39, 41] evaporation / fission code, which de-excites the remnant nucleus.

Comparisons of the 4 FSI models in GENIE - I





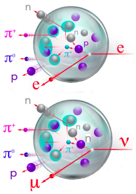


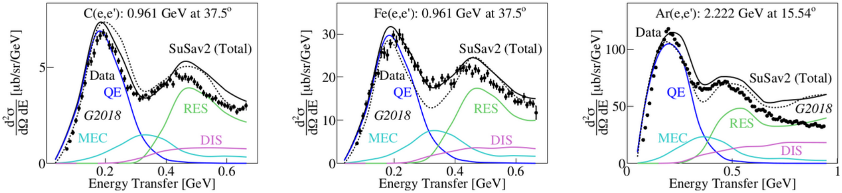


Electron scattering improvements ($\geq$ v3.0.0) - I

Renewed focus on GENIE electron mode. Details in [50]. Benchmarking of ν mode:

- Very similar interactions
- Nuclear effects practically identical
- Known electron beam energy





BSM models in GENIE - An overview

Substantial effort to implement & deploy **GENIE BSM generators**.

Available in v3.2.0

- **Nucleon decay**
- $n - \bar{n}$ **oscillations**
- **Boosted dark matter**
- **Dark neutrinos**

- BSM searches form an important science pillar of many neutrino experiments.
- Standard neutrino interactions are a background to BSM searches.
- Important to simulate BSM and neutrino interactions in a common framework (for example, using common nuclear and intranuclear hadron transport models).

Updated BDM generator ($\geq$ v3.2.0) - I

A native implementation of a **Boosted Dark Matter** (BDM) generator was available in GENIE 3.0.0.

A substantial upgrade of the GENIE BDM generator was deployed in GENIE 3.2.0, bringing it sync with the model described in [17]. The GENIE implementation was prepared by the original author (Josh Berger).

The newly deployed BDM code:

- allows a broader set of particle physics models, including both vector and axial couplings, as well as different isospin structures,
- as improved modeling of the elastic scattering process, including a pseudoscalar form factor,
- includes the simulation of scattering off electrons, and
- includes anti-dark matter scattering.

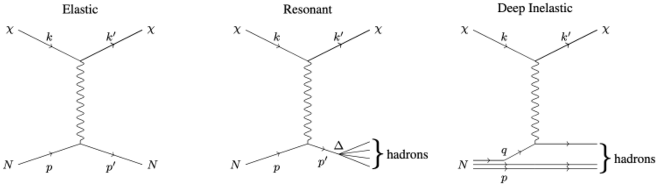
Updated BDM generator ($\geq$ v3.2.0) - II

The GENIE BDM generator covers a broad class of models:

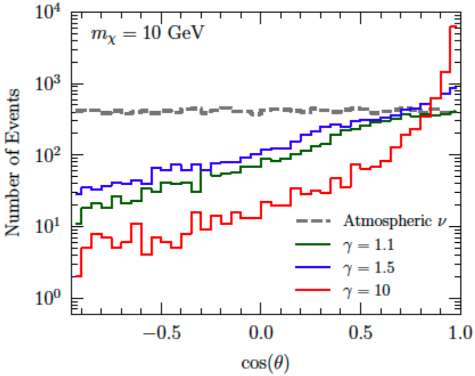
$$J^{\mu}_{Z',\psi} = \bar{\psi}\gamma^{\mu}(Q^{\psi}_{L}P_L + Q^{\psi}_{R}P_R)\psi$$

$$\mathcal{L}_{int} = g_{Z'} Z'_{\mu} J^{\mu}_{Z',\psi}$$

where $\psi = \chi, u, d, s, c, e$. The model is specified by charges Q^{ψ}_{LR}, the gauge coupling $g_{Z'}$ and the masses of the dark matter particle χ and of the mediator Z'.



Updated BDM generator ($\geq$ v3.2.0) - III



Example DUNE sensitivity study [16] using the GENIE BDM module.

Angular distribution of hadronic BDM signal wrt the direction of the Sun.
The plot shows 10k event distributions for a DM particle with a mass of 10 GeV, for 3 different boost factors γ.

New Dark Neutrino generator ($\geq$ v3.2.0) - I

- Framework that provides an explanation to the long-standing excess of electronlike events in the MiniBooNE experiment at Fermilab [14]
- The model extends the SM Lagrangian including
  - A new massive “dark” neutrino that mixes with SM one

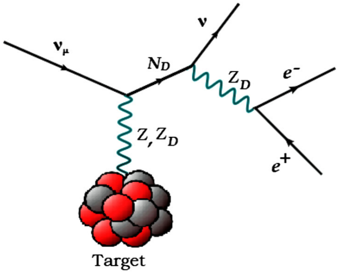
$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + U_{\alpha 4}N_4 \qquad \alpha = e, \mu, \tau, \mathcal{D} \tag{1}$$

  - light dark neutral vector boson that couples with $\nu_{\mathcal{D}}$ and EM charge

$$\mathcal{L}_{\mathcal{D}} \supset g_{\mathcal{D}} Z^{\mu}_{\mathcal{D}} \bar{\nu}_{\mathcal{D}} \gamma_\mu \nu_{\mathcal{D}} + e\varepsilon Z^{\mu}_{\mathcal{D}} J^{em}_{\mu} \tag{2}$$

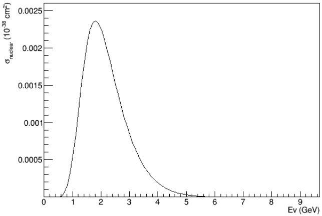
New Dark Neutrino generator ($\geq$ v3.2.0) - II

- Once the heavy neutrino is produced it decays into
  - light neutrinos
  - e pair
  - μ pair - if the mass is high enough
- Decay length and branching rations are strongly dependent on the mixing parameters and masses
  - with the parameters from [14] it can be of the order of mm or cm
  - and mostly decay into e-pair
- The new flavour can have the equivalent of any NC interaction available in the SM

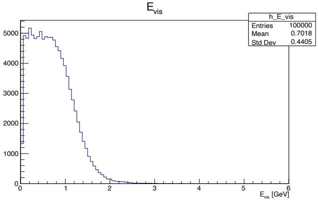


New Dark Neutrino generator ($\geq$ v3.2.0) - III

- The main contribution is from Coherent interaction
  - now implemented inside GENIE
  - further interactions will be implemented later
- Implementation based on the Engel form factors [33]
  - Later more sophisticated FF can be included
- The generator also takes care of the decay of the dark particles
  - Downstream code will not need upgrades



Plots from ν_μ on ^{40}Ar



Visible energy for BNB-like beam

Event Library Generator Interface ($\geq$ v3.2.0) - I

- Ability to read from an external library of cross-sections and pre-computed final particle kinematics
  - Possibly computed using an alternative neutrino generator
- GENIE will use:
  - the appropriate cross-section from the file
  - kinematics from the library entry with the closest-matching energy

$\Rightarrow$ this will then reproduce the physics of the external generator

  - Making use of the flux and geometry handling of GENIE
  - Within the limits of the library statistics

Genie

Event Library Generator Interface ($\geq$ v3.2.0) - II

- xsec and kinetmatics to be provided for every combination of
  - Target, Interaction, ν flavour
- ROOT file input
- For each combination directory there will be
  - `TGraph` for xsection vs energy
  - `TTree` for kinematics
- `TTree` with the following branches
  - E_ν
  - `int` prod_id
  - nparts
  - array of pdgs
  - array of Final state momenta

- Structure of the input

```
H1/
            ...       ...
C12/
            cc/
                      nu_mu/
                      nu_mu_bar/
                      nu_e/
                      ...
            nc/
                      nu/
                      nu_bar/
O16/
            ...       ...
Cl35/
            ...       ...
```

Summary - I

- **GENIE v3.0.6 (July 2019) provided a solid basis**
  - Many new technical capabilities
  - Powerful associated global analysis
  - Multiple comprehensive model configurations and tunes
  - Improved physics, as evidenced from comparisons with new LArTPC data
- **GENIE v3.2 (v3.2.0 expected February 2021) a major milestone towards GENIE v4**
  - Several new ME modelling components and comprehensive configurations (*SuSAv2, MK 0^{th} order, prep for QMC-STA, CBF Spectral function, coherent NC1γ, interfaces to Liege/INCL and Geant4 Bertini cascades, interface to PYTHIA8,...*).
  - New NLO DIS model and full VHE/UHE generator (validity $< 10^9$ GeV)
  - New LE generators
  - Improved electron mode
  - New BSM generators (*BDM, dark neutrinos*)
  - Finalised SIS tuning (to be published soon)
  - First hadronization retune (to be published soon)
  - New generator interfacing tools (reuse of GENIE flux/geometry tools)

Summary - II

- **Development priorities towards GENIE v4**
  - Completion of as many of the main outstanding modelling components as possible (*MK, QMC-STA, CBF Spectral function, full NC1γ, antineutrino single-Kaon, Huma Haider DIS, DCC*)
  - Development / characterization of several new comprehensive configurations
  - Steps towards GENIE FSI tune
  - Finalisation of GENIE hadronization retune
  - Finalisation of new nuclear x-section tunes
  - Upgrade ReWeight tools to support GENIE tunes out of the box
    - Including support for intrinsically non-reweightable parameters, with release of Professor/YODA response functions (à la GENIE tuning)
- **Usual manpower limitations: Contributions welcome**
- **We can provide some level of support for GENIE v2 $\rightarrow$ v3 migration in T2K**
  - We accept requests for special code configurations, internal draft documentation, the preparation of new revisions
  - Participation in the monthly GENIE User Forum is a good starting point
    - Typically, T2K absent.
  - Invitations to GENIE Slack can be sent to anyone interested

Supplementary Slides

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