GENIE

Models and global fits of neutrino scattering

Libo Jiang for GENIE Collaboration

Univ. of Pittsburgh

August 17, 2018

http://www.genie-mc.org/

Role of MC generators in Oscillation Physics

- Interface between neutrino flux and experimental physics
  - Calculate predictions
  - Constrain flux
- Compare data and models
  - Reliability
  - Validity region

    You can not study oscillations without fully understood models
- Compare dataset against dataset
  - Data quality is increasing
  - Highlight tensions
- Global fits
  - Generator is the ideal place for global fits, control the model implementation
  - Finding the best nominal predictions
  - Cross-section priors based on data

Introduction to GENIE:
(Generate Events for Neutrino Interaction Experiments)

- has always been a modular software with different models(nuclear models, cross section models and so on)
- Dedicated web page: www.genie-mc.org

Home

Mission Statement
GENIE Collaboration
Policy Documents
Copyright Notices
Citing GENIE

Incubator
Public Releases
Global Fits & Tunes

Physics & User manual

Mailing lists:
→User
→Developer
→Admin

Getting the code
Installation instructions

Repository browser:
→Generator
→Comparisons
→Tuning

GENIE Collaboration

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

1. **CENBG, Université de Bordeaux, CNRS/IN2P3**, *33175 Gradignan, France*
2. **Joint Institute for Nuclear Research (JINR)**, *Dubna, Moscow region, 141980, Russia*
3. **Fermi National Accelerator Laboratory**, *Batavia, Illinois 60510, USA*
4. **University of Liverpool**, Dept. of Physics, *Liverpool L69 7ZE, UK*
5. **University of Pittsburgh**, Dept. of Physics and Astronomy, *Pittsburgh PA 15260, USA*
6. **STFC Rutherford Appleton Laboratory**, Particle Physics Dept., *Oxfordshire OX11 0QX, UK*
7. **Tufts University**, Dept. of Physics and Astronomy, *Medford MA 02155, USA*
8. **University of Valencia**, *Valencia, Spain*

Collaboration structure and organogram

- **Co-spokespersons**: Costas Andreopoulos (Liverpool/STFC-RAL), Steve Dytman (Pittsburgh)
- **Executive Board**: Costas Andreopoulos (Liverpool/STFC-RAL), Steve Dytman (Pittsburgh), Hugh Gallagher (Tufts), Gabe Perdue (Fermilab)
- **Working Group Coordinators**
  - **Technical Coordination**: Robert Hatcher (Fermilab)

Mission of GENIE:

- provide a state-of-the-art neutrino MC generator for the world experimental neutrino community. GENIE shall simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales
- perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes

GENIE version 2.12.X

Models	Default	Example of Alternative
Nuclear Model	Bodek-Ritchie Relative Fermi Gas(RFG with short-range correlations)	Local Fermi Gas(LFG) effective spectral function model
CCQE	Llewellyn-Smith	Nieves
MEC	Empirical	Nieves
Resonance	Rein-Sehgal	Berger-Sehgal
FSI	hA	tuned hA
Nonresonant	Scaled Bodek-Yang	Scaled Bodek-Yang
Diffractive		Rein's Model
Charm Production	QEL-CC: Kovalenko's model DIS-CC: Aivazis' model	QEL-CC: Kovalenko's model DIS-CC: Aivazis' model
SingleK Production		DIS-CC: Alam Simo Athar model
LAMBDA Production		QEL: Pais's model

- Nieves QE Model: includes Random Phase Approximation(RPA), in-medium propagator effects and Coulomb effect.
- Berger-Sehgal: Lepton Mass Correction.
- Bodek-Yang vs Scaled Bodek-Yang: scaled Bodek-Yang uses a factor that decreases model strength to get agreement with data.
- hA : is tuned to π^+-^{56}Fe and p-^{56}Fe data, then extrapolated to other targets based on $A^{2/3}$ scaling(where A is the atomic number).

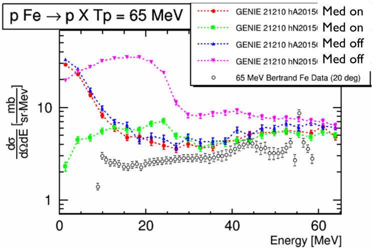
FSI Strategy

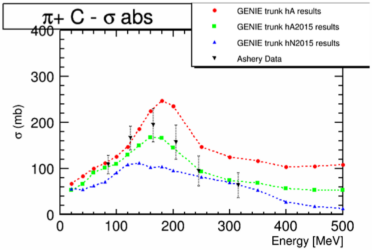
Comparison between hN and hA

hN	hA
Intranuclear Cascade(INC)	data-driven/simplified version
with medium correction for π(Oset), and nucleons(Pandharipande/Pieper)	with medium correction for nucleons
Multiple Scattering	models QE peak
	fully reweightable
too little absorption	too much absorption
too little scattering at low E	

- New versions of hA every year, always in alternative model.
- Both are fit to hadron-nucleus data. hN only recently available for public.
- GENIE v2.12.10 has preliminary versions of what will be in GENIE v3; hA2015 and hN2015.
- Compared to hA and hN, Suppression for low energy proton-proton collisions due to medium effects was added in hA2015 and hN2015.
- hA2018 and hN2018 are the most recent versions, hA maintained as legacy code.

FSI Strategy

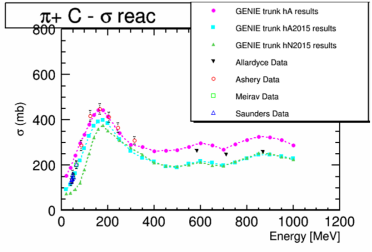


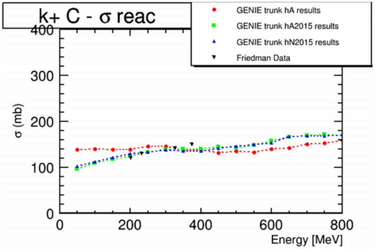


- hN has medium corrections for π, p; hA has none.
- Medium corrections suppress multiple scattering, decrease cross section. Strong A dependence.
- hA has too much absorption, hA2015 uses these data as input, hN has too little absorption(feature of Oset model).

Genie

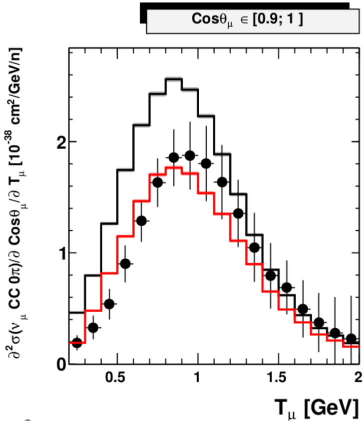
FSI Strategy





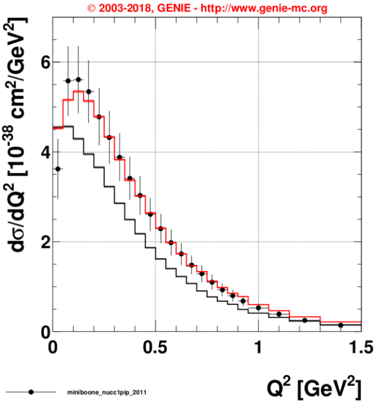
- π^+ has a significant peak for Δ excitation, none for K^+
- Both hA2015 and hN2015 underpredict pion peak cross section.

GENIE version 2.12.X: default vs alternate



- Black Dots: MiniBooNE QE data; Black Curve L-S; Red Curve: Nieves.
- Figure on the left side shows double differential cross section with respect of the muon's momentum of the CC QE from MiniBooNE.

GENIE version 2.12.X: default vs alternate



- Black Dots: MiniBooNE CC one π data; Black Curve: Rein-Sehgal; Red Curve: Berger-Sehgal.
- Figure on the left side shows double differential cross section with respect of the Q2 of the CC 1 pion event from MiniBooNE.
- Berger Sehgal in Alternate vs Rein Sehgal in Default.

Compare GENIE to other Generators

Model/Generator	GENIE	NuWro	NEUT
QE	Lwlyn-Smith Nieves, running MA	Lwlyn-Smith RPA	Lwlyn-Smith Eff RPA
Nuclear Model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function
MEC	Valencia Empirical	Valencia Marteau	Valencia
Resonance	Rein-Sehgal Berger-Sehgal	Home-grown	Rein-Sehgal
Coherent	Rein-Sehgal Berger-Sehgal Alvarez-Ruso	Rein-Sehgal Berger-Sehgal	Rein-Sehgal Berger-Sehgal
FSI	Schematic Cascade(med corr)	Cascade(med corr)	Cascade(med corr)

- Model comparison in 2017.
- Main difference is that GENIE has larger goals, it handles all neutrinos and targets, and all processes relevant from MeV to PeV energy scales.
- Differences in physics more in detail than fundamental.
  - Modified Rein-Sehgal.
  - GENIE has the best interfaces to experiment.

GENIE version 3
Comprehensive Model Configurations(CMC)

- GENIE has always been a modular software where different models could be combined in different comprehensive configurations.
- Starting from v3.0.0, with the deployment of multiple comprehensive configurations and tunes, and the addition of a '–tune' argument in several apps, GENIE adopted the following uniform naming convention for its model configurations and tunes: **Gdd_MMv** or **Gdd_MMv_PP_xxx**;
  - **G**: is a capital letter that identifies the author of the tune. The default value is G (for the GENIE collaboration).
  - **dd**: is a number describing the year during which the model configuration was developed.
  - **MM** :is a number (00, 01, 02, ...) identifying a model configuration branch.
  - **v** is a character (a, b, c, ...) enumerating variations / offshoots of a model configuration branch.
  - **xxx** is a number that identifies the dataset used for the model configuration tuning. This may include a unique set weights associated with each component dataset. The number 00 indicates that a model configuration has not been tuned by GENIE.
- CMC are defined in order to easily identify sets of models and their corresponding parameters.

GENIE version 3

Comprehensive Model Configurations(CMC)

- G00_00: Historical default configuration.
- From G00_00 to G18_01 series: adiabatic evolution of old default.

	G00_00	G18_01
Hadron Transport Model	HAIntranuke/HNIntronuke	HAIntranuke2018/HNIntranuke2018 Added diffractive and Lambda production

- From G18_01 to G18_02 series:

	G18_01	G18_02
RES	Rein-Sehgal	Berger-Sehgal
COH	Rein-Sehgal	Berger-Sehgal

- From G18_01 to G18_10 series: theory driven configuration.

	G18_01	G18_10
Nuclear Model	FGM BodekRitchie	Local Fermi Gas (LFG)
QEL	LwlynSmitch	Nieves
MEC-CC	Empirical	Nieves
RES	Rein-Sehgal	Berger-Sehgal

GENIE comparisons

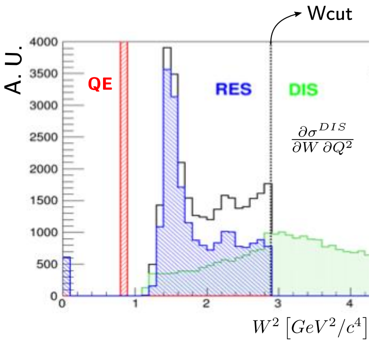
The GENIE suite contains a package devoted to comparison GENIE predictions against publicly released datasets → GENIE comparisons

- Provide the opportunity to improve and develop GENIE models.
- Crucial database for new GENIE global fit to neutrino scattering data.
- Many possible formats and variety of signals.
- Can store systematic correlations, even between different datasets.

The Database of GENIE comparison:

- Modern Neutrino Cross Section Measurement
  - nuclear targets
  - typically flux-integrated differential cross-sections
  - MiniBooNE, T2K, MINERνA
- Historical Neutrino Cross Section Measurement
  - Bubble chamber experiment
- Measurements of neutrino-induced hadronic system characterristics
  - Forward/backward hadronic multiplicity distributions
  - Multiplicity correlations
- Measurement of Hadron-nucleon and hadron-nuclaus event characteristics(for FSI tuning)
  - For pion, Kaons, nucleons and several nuclear targets
  - Spanning hadron kinetic energies from few tens MeV to few GeV
- Semi-inclusive electron scattering data
  - electron-nucleus QE data
  - electron-proton resonance data

Modelling the transition region



One pion production mechanisms:

- **RES:** Rein-Sehgal, Berger-Sehgal
- SIS: shallow inelastic scattering, non resonance background
- DIS Bodek-Yang

Modelling the transition region:

- GENIE models transition region by exptrapolating the DIS contribution at low W to describe non-resonance interactions and rescaling it with some ad-hoc topology dependent parameters.

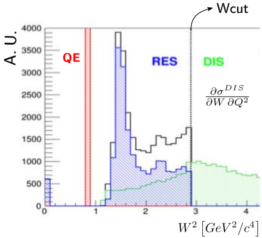
Challenges of the transition region:

- The shallow inelastic scattering (SIS) in transition region can contribute significantly to the determination of neutrino oscillation parameters through feed-down via nuclear effect into both signal and background estimations.
- It is essential to optimize the description of the transition region from DIS to resonance production and definition of the kinematic limits of applicability of the DIS formalism for structure functions.

Global Fit of the Transition Region

- GENIE version 3 collects model sets in user-friendly way. The other major goal is to add user-callable tunes to each model set. Tunes are based various data sets with accompanying estimated errors
- For v3, we added updated tunes to single nucleon pion production:
  - Small errors in v2 are known(e.g. Rodigues, ref)
  - New importance for MINERν, NoνA, DUNE ...-experiments at higher neutrino energy.
  - Tune to both exclusive and inclusive cross section data.

Global Fit of the Transition Region



$$\frac{\partial^2\sigma^{inel}}{\partial Q^2\partial W} = \frac{\partial^2\sigma^{RES}}{\partial W\partial Q^2} + \frac{\partial^2\sigma^{DIS}}{\partial W\partial Q^2}$$

$$\frac{\partial^2\sigma^{DIS}}{\partial W\partial Q^2} = \frac{\partial^2\tilde{\sigma}^{DIS}}{\partial W\partial Q^2}\cdot\Theta(W - W_{cut}) + \boxed{\frac{\partial^2\tilde{\sigma}^{DIS}}{\partial W\partial Q^2}\cdot\Theta(W_{cut} - W)\cdot\sum_m f_m} \quad (1)$$

$$f_m = R_m \cdot P_m^{had}$$

- SIS Transition Regin: Resonant+ Non-resonant background
- $W < W_{cut}$: RES+scaled DIS with some multiplicity functions f_m
- $W > W_{cut}$: pure DIS model(not scaled)

m= multiplicity of the hadronic system:

- 2 for 1π
- 3 for 2π

R_m: Tunable parameter
P_m^{had}: Probability that the DIS final state has multiplicity m, obtained directly from the hadronization model.

Global Fit of the Transition Region

The parameters describe the transition region:

- effective parameters
- extracted from data
- fitted against integrated cross sections
- R-vp-CC-m2, R-vp-CC-m3, R-vn-CC-m2, R-vn-CC-m3 are parameters for the f_m functions that depend on the reaction channel and the final state multiplicity scaling factors.
- RES-CC-XSecScale, DIS-CC-XSecScale: scaling factors for the RES and DIS cross sections.

Parameter	Default	Best Fit
Wcut(GeV)	1.70	1.92
RES-Ma(GeV)	1.12	0.93
R-vp-CC-m2	0.10	0.19
R-vp-CC-m3	1.00	0.16
R-vn-CC-m2	0.30	0.15
R-vn-CC-m3	1.00	1.20
DIS-XSecScale	1.03	1.05
RES-CC-XSecScale	1.00	0.87

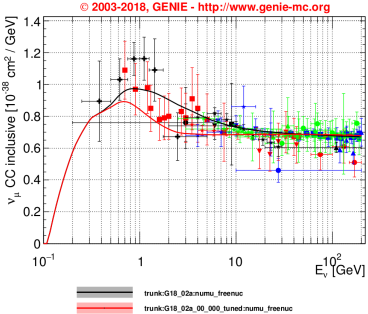
- Wcut determines the end of the transition region.
- RES-Ma(M_A^{RES}): used in the dipole modelling of the form factor $F_A(Q^2) = \frac{F_A(0)}{1+\frac{Q^2}{(M_A^{RES})^2}}$

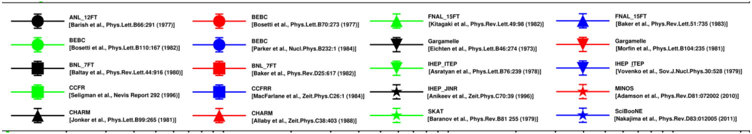
Global fit:

- tuned the parameters relative to both transition and pure RES and DIS region.
- used inclusive, single pion and two pion datasets.

Global fit and inclusive datasets

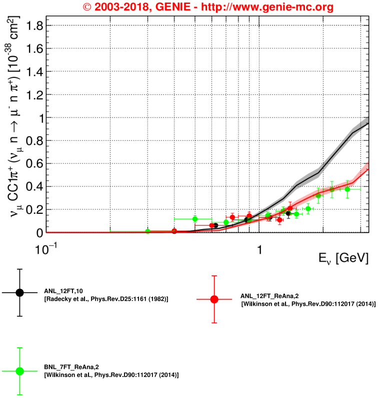
- Black Curve: Before tuned; Red Curve: tuned result.
- Global tune with respect to ν_μCC Inclusive free nucleon datasets.
- The global fit is reducing the inclusive cross section to match the lower cross section of single pion production.
- The global tune describes the π production without ruining the inclusive cross section.

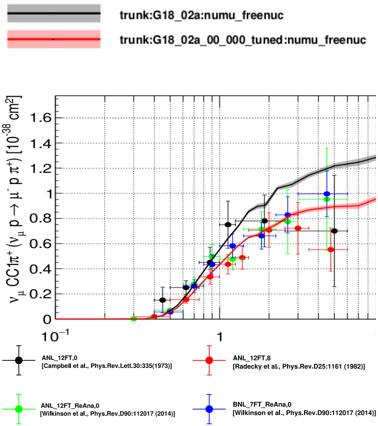




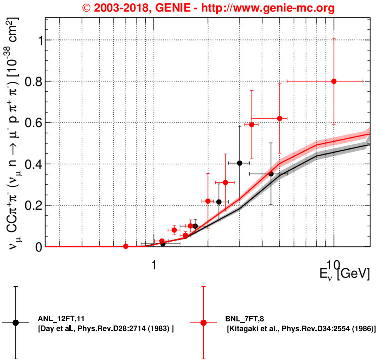
Global fit and CC1π datasets

- Global tune with respect to ν_μ CC 1 π data.
- The description of 1π data has improved.





- Global tune with respect to ν_μ CC 2 π data.
- The description of 2 π data has improved.



Conclusion

- GENIE v3 official release is close: a beta version is already public. It will provide a number of configurations validated with respect to publicly available datasets and a set of tunes obtained with dedicated machinery.
- Deuterium tunes have been completed and are public. QE tuning and tunes on nuclear target are forthcoming.
- The tune you have just seen is available –tune G18_02a_02_11a.
- Nuclear tuning(MiniBooNE datasets), transition region tuning for G18_01.

Backup Slides

Empirical MEC

- Based on early work by Lightbody and O'Connell.
- MEC channel is Gaussian (mean 1.9GeV).

L-S for Quasi-Elastic

In this model the hadronic weak current is expressed in terms of the most general Lorentz-invariant form factors. Two are set to zero as they violate G-parity. Two vector form factors can be related via CVC to electromagnetic form factors which are measured over a broad range of kinematics in electron elastic scattering experiments. Several different parametrizations of these electromagnetic form factors including Sachs [32], BBA2003 [33] and BBBA2005 [34] models are available with BBBA2005 being the default. Two form factors - the pseudo-scalar and axial vector, remain. The pseudo-scalar form factor is assumed to have the form suggested by the partially conserved axial current (PCAC) hypothesis [31], which leaves the axial form factor F A (Q 2) as the sole remaining unknown quantity.

INC

Prominence of the quasifree reaction mechanism shows why INC models are valuable. These models assume the nucleus is an ensemble of nucleons which have Fermi motion and binding energy. The incident particle interacts in a series of encounters with single nucleons called a cascade

hA

The first FSI model is in the spirit of the other models in GENIE. It is simple and empirical, data-driven. Rather than calculate a cascade of hadronic interactions as is done in a complete INC model, we use the total cross section for each possible nuclear process for pions and nucleons as a function of energy up to 1.2 GeV. Thus, it is called hA. The emphasis is on iron because the first application was to MINOS where production of high energy pions is important.
hA2015:

Genie

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

Thank You