Current Capabilities and Future Plans for Lepton Scattering Uncertainties in GENIE

and their Implications for Fermilab Neutrino Oscillation Experiments

•••

UNIVERSITY OF LIVERPOOL

Marco Roda
University of Liverpool

INT workshop
3 November 2023

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Overview

- GENIE introduction
  - Our view of the systematic problem and our roadmap
- Past - Present - Future in terms of uncertainties
- Some final comments

Collaboration

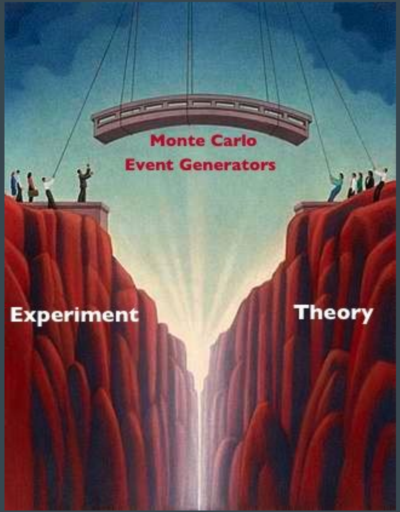
Luis Alvarez-Ruso (IFIC), Costas Andreopoulos (Liverpool and STFC/RAL), Adi Ashkenazi (Tel Aviv), Joshua Barrow (University of Minnesota), Steve Dytman (Pittsburgh), Hugh Gallagher (Tufts), Alfonso Andres Garcia Soto (Harvard and IFIC), Steven Gardiner (Fermilab), Matan Goldenberg (Tel Aviv), Robert Hatcher (Fermilab), Or Hen (MIT), Igor Kakorin (JINR), Konstantin Kuzmin (ITEP and JINR), Weijun Li (Oxford), Xianguo Lu (Warwick), Anselmo Meregaglia (Bordeaux, CNRS/IN2P3), Vadim Naumov (JINR), Afroditi Papadopoulou (Argonne), Gabriel Perdue (Fermilab), Komninos-John Plows (Oxford), Marco Roda (Liverpool), Beth Slater (Liverpool), Alon Sportes (Tel Aviv), Noah Steinberg (Fermilab), Vladyslav Syrotenko (Tufts), Júlia Tena Vidal (Tel Aviv), Jeremy Wolcott (Tufts), Qiyu Yan (UCAS and Warwick)

[Faculty, Postdocs, PhD Students, Master Students]

- 27 active authors
    - With many different backgrounds
    - > 10 institutions from various countries

- About 10 past authors
- Many contributors for specific projects that are not authors

Our vision for MC generators



- Connect neutrino fluxes and observables
  - predict event topologies and kinematics
- The community wants more
  - Coverage of physics processes
  - Uncertainty validation against data
  - Tune against data in order to obtain
    - Optimised initial configuration
    - Data-driven constraints of the generator parameters
  - Capability to propagate configuration changes to prediction
    - Usually reweighting
  - Support for geometry and flux

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

Status overview

- Well established generator
  - Used by many experiments around the world
  - Main generator for all the LAr experiments
- Two main efforts
  - Model development
  - Tuning
- Contacts, details and code are all available from our website: www.genie-mc.org/
- Latest release: version 3.04.00 from March 2023
  - http://releases.genie-mc.org/
- Recent publications
  - Neutrino-nucleon cross-section model tuning in GENIE v3 - Phys.Rev.D 104 (2021) 7, 072009
  - Hadronization model tuning in genie v3 - Phys.Rev.D 105 (2022) 1, 012009
  - Recent highlights from GENIE v3 - Eur.Phys.J.ST 230 (2021) 24, 4449-4467
  - Neutrino-nucleus CC0π cross-section tuning in GENIE v3 - Physical Review D (accepted last week) - arxiv

Release overview and systematic

- Historical systematic approach in GENIE
  - Reweight

GENIE v2

- Current activity
  - Professor tuning

GENIE v3

- How we can we go beyond this paradigm?
  - Professor based reweight

GENIE v4

- The systematic treatment is what drives the major GENIE release cycle
  - It is fundamental for our developments

What GENIE consider uncertainties

- GENIE has hundreds of parameters that are used to generate events
  - Most parameters are physics related
    - Thresholds, form factors, constants, weights applied to control transition regions, ...
  - Some parameters are settings for numerical operations
    - Maximum number of iterations, integration boundaries, validity regions

- Each parameter that has an effect on the predictions is a source of uncertainty
  - We like to think that numerical settings are not uncertainty
    - our development process is supposed to identify all the parameter effect and make a distinction between physics and numerical aspects
  - But sometime the distinction is not so clear
    - e.g. validity ranges in a model turns into integration ranges
      - a larger integration range results in a different total cross section and so a process becomes more or less probable as a function of a validity range

Where are these parameters coming from?

- physics parameters with a “known” uncertainty
  - e.g. masses, couplings, ...
- empirical parameters
  - no prior on the uncertainty
- Sometimes we “duplicate” the parameters:
  - authors used different values so we have different values of the same quantity
- Parameters introduced in the implementation
  - Author didn’t specify the existence of a parameter but the implementation required it

What GENIE does NOT consider uncertainty

- Discrepancy between different models
  - GENIE has a number of models for most of the processes (e.g. Valencia and SuSAv2 for 2p2h)
    - That we formalise in
      - CMC: comprehensive model configuration
      - Tune: a CMC with a given set of parameter values
  - It is possible to build a variance on a given observable due to a sample of different CMCs or TUNE to build prediction for the same observable
    - But interpret this as uncertainty implies assuming a probability distribution for models
      - Statistical significance is constructed as a probability of data given a model

- We are thinking about ways to reweight between different models
  - But this is not considered a source of uncertainty

- Of course, users can build their own analyses and add additional parameters
  - We are simply not going to quantify uncertainties among all the configurations we have

What deliverables we imagine for ourselves

- Tools to facilitate the propagation of the effects of a parameter variation in a prediction
  - reweight
  - brute force
  - Can we do better?
    - R&D on the subject is expected from us

- Provide information on the parameter's PDFs
  - Most of the time this is just central value and sigma
    - correlation between the parameters
  - Also we need a source of these PDFs:
    - theoretical, data-driven, ad-hoc?
    - Is it something that can be revisited?

- Extract parameters from data: tuning
  - reduce the width of the PDF
  - Motivate the PDF according to data

For every tune

You can see that the combinatory make the problem not easy

GENIE reweight

Legacy reweight

- Weight assigned to an event based on the ration between the old and new differential cross section

- Works well with a particular FSI Model (HA) which is is designed with reweightability in mind
  - All the other FSI models are completely unreweightable

Limitations

- Not every parameter is reweightable
  - Sometimes in principle (e.g. thresholds or cascade parameters)
  - Sometimes because of the interplay with other parameters
    - e.g. when a differential cross section is a sum of different contribution
  - A lot of experimentation has been done by analysers in code outside GENIE
    - lots of approximation hard to control created a large uncharted territory
      - honestly questionable if this is enough for precision measurements
- Every new parameter needs dedicated code to apply the reweight correctly
  - considering there are new parameter for every new model, this model is hardly sustainable

Professor tuning

Tuning as a complementary strategy

- Reduce the uncertainty of parameters so that we don’t have to propagate it
    - The question is how?
    - Generator tuning has always been difficult
        - Lack of data or poor quality or poor analysis
        - Technical challenges
            - Computationally too challenging
            - only done for reweigthable parameters

negative reinforcement loop

- If the uncertainty is not enough for a parameter to be neglected
    - At least we can motivate its uncertainty
        - Very important for all the empirical parameters in our generators

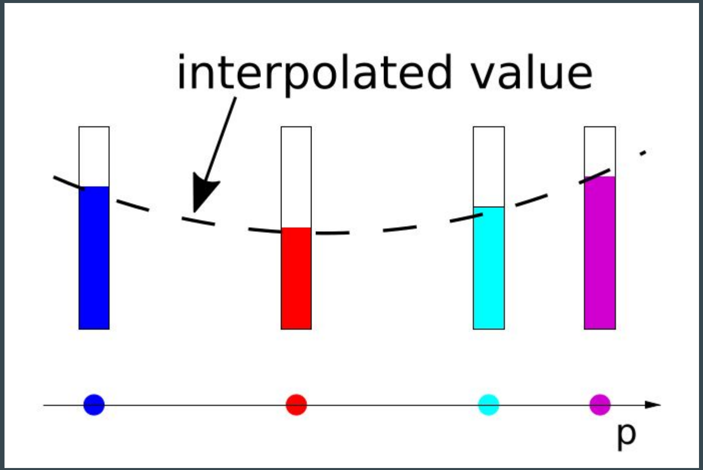
The strategy

- Brute force approach
  a. Select points in a parameter space
  b. Evaluate observable predictions with a full scale calculation
     - One bin for each data point
  c. build a parameterisation as a function of the parameters

- Repeat for each bin
  - Obtain parameterisation for every bin using N dimensional polynomial

- Minimisation (fit) using the parameterisations

- Problems we solved:
  - No need for reweight - all parameters can be tuned
  - We can build correlations between parameters
  - We can build tunes on top of tunes, every time we reduce some uncertainty
  - No additional software on the generator side
    - Of course you need data, construct the predictions in an organised way, etc
  - Systematic study of the hundreds of parameters we have in our generators



- Open source numerical assistant
  - https://professor.hepforge.org/
  - Developed for Pythia tuning at LHC
  - GENIE adopted it and we started a tuning campaign

The tuning so far

- SIS region on free nucleons
  - Neutrino-nucleon cross-section model tuning in GENIE v3
  - Pretty straightforward
- Hadronisation tune
  - AGKY Hadronization Model Tuning in GENIE 3
  - First tune of this kind, we started to highlight tensions in data
- Nuclear tune
  - Neutrino-nucleus CC0π cross-section tuning in GENIE v3
  - Initial experiment, not completely comprehensive because of tensions in the data
- What to expect in the future
  - We are working on more tuning
    - Electron scattering
    - TKI variable for neutrino nuclear tunes

Considerations

- Positive outcomes
  - We are optimising configuration
  - We are improving understanding of data
  - We are starting to build a library of covariance on our parameters
- Limitations
  - Tensions are limiting our solutions
  - We cannot propagate uncertainty of all the parameters because we don't have reweight for all the parameters
- Things we learned
  - The systematic definition had to be upgraded to be tune dependent
  -

Professor based reweight

The idea

- Professor tuning defines predictions to match the data we have
- But the professor interpolations can be constructed on any observable
  - That include differential cross section as a function of any kinematic space
- The idea is to create a reweight that uses configurable kinematic spaces
  - The internal distributions are created with brute force scans
  - Parameterised with Professor splines
- The kinematic space can be flux integrated so we can reweight also threshold like
  - The weight associated to a single event might be not fully correct, but collectively they will be
  - Experiments will need to create their own splines based on the reweight they intend to do

What to expect

- In terms of physics
  - Correct reweigth of multiple parameters at the same time
    - Extremely important for
      - parameters that are functionally (e.g. FSI fates)
      - parameters that are statistically correlated (e.g. tuned on the same data)
  - Possibility to use the statistical information from our tunes for reweight
    - Make the statistical uncertainty tune dependent across the software suite

- In terms of tools
  - Support the creation of the interpolation
  - configuration for reweight kinematic space
  - validation tools

Current situation

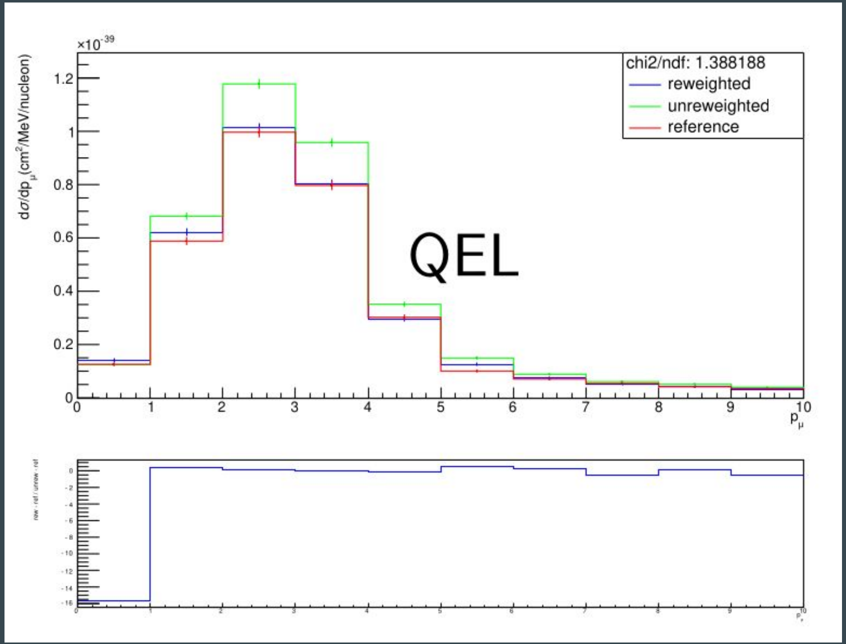
- The development has started!
  - simple usage case as a starting point to
    - Develop initial observables
    - Demonstrate the feasibility and investigate limitations
- Current exercise
  - QEL - reweighted in p_mu and E_nu
    - Both in the hit nucleon at rest reference frame
  - RES - reweighted in p_mu, W, E_nu
    - p_mu, E_nu in the hit nucleon at rest reference frame
  - Checked that other distributions are also ok
    - theta_mu, Q^2
- Note that this is simple exercise is already more that the current reweight is able to do
  - Multi Dimensional reweight for free!

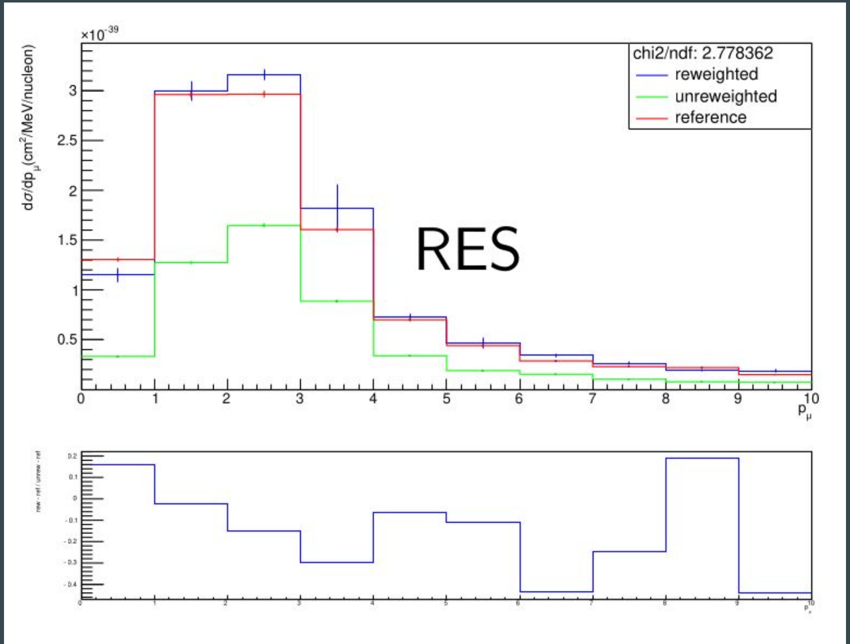
Some plots

- 3 samples
  - Unweighted: QEL M_A= 0.994989 GeV, RES MA= 1.088962 GeV
    - default values for G18_10a_02_11b
  - Reference and reweight target: QEL M_A = 0.77 GeV, RES M_A = 1.64 GeV
    - Reference: generation with the change in the configuration
    - reweight: Unweighted reweighted using the new system (in progress)

- At the bottom you see the relative discrepancy between reweight and reference with respect to the difference between reference and unweighted
  - We are still working on a metric that takes into account the statistics
    - And possibly the known error on the underlying interpolations

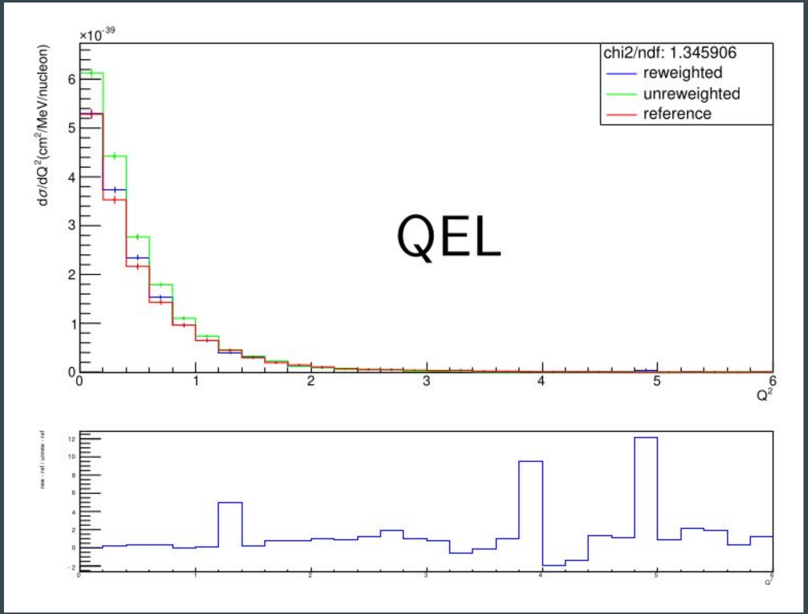
Some Plots - muon momentum

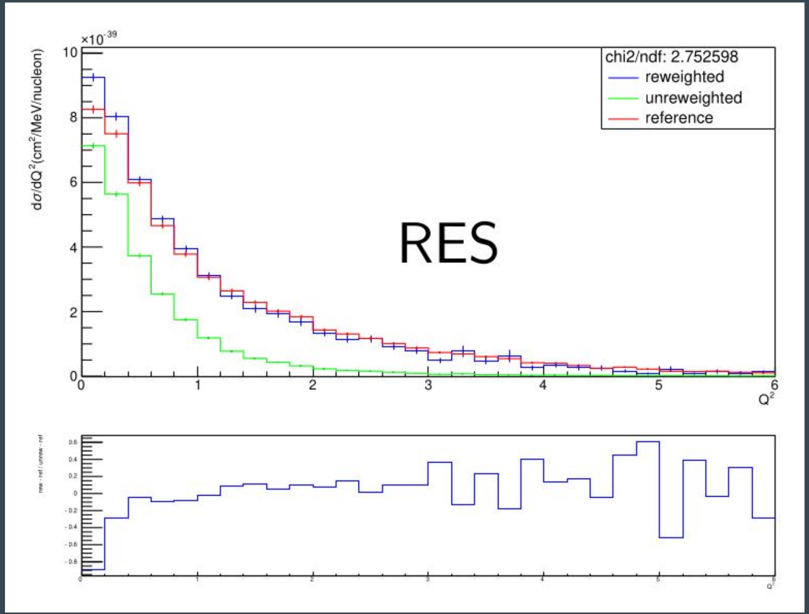




- Kind of obvious that it works
  - As this is exactly one of the variable of the kinematic space

Some Plots - Q^2





- Not perfect agreement on RES, but it's encouraging
  - These are the worst agreement we have
    - Other variables look better

Our vision of the future

Implications for experiments

- Compared to the past we are really pushing on the systematic treatment
    - All solutions are computationally expensive but we brought the developments in the domain of the feasible

- We are considering an approach that has never been tempted on this scale before
    - We are starting to see the results
    - Development driven by JUNO
        - Hopefully SBN can join the effort too

- Ways experiments can help
    - Release data assuming a full tuning is possible
        - Releasing as much information as possible
            - Correlations, selection efficiencies, etc
                - All can be used
    - Using the tunes we provide
    - Considering dedicating manpower for experiment specific developments

- Ways we expert to support the experiments
    - Provide tools for the reweight
    - Libraries of configurations ready in the code

Final remarks

- Systematic treatment is a tough beast
  - Complex problem with many aspects
- Used to be tackled with a single recipe
  - Reweight
- We are convinced that approaching from different aspects is the key to success
  - better models
  - tuning