Suggesting an interaction model to further improve upon the NOνA ND Events Analysis

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Introduction

Summary of GENIE tuning for description of the neutrino-induced events rates recorded in the NOνA ND at neutrino energies above ~ 1 GeV:

- Sketch of used models
- Comparison of models with the ND data in FHC mode
- Future developments

All calculations were performed within CAF.

More details can be found in Docs 16335 and 23018.

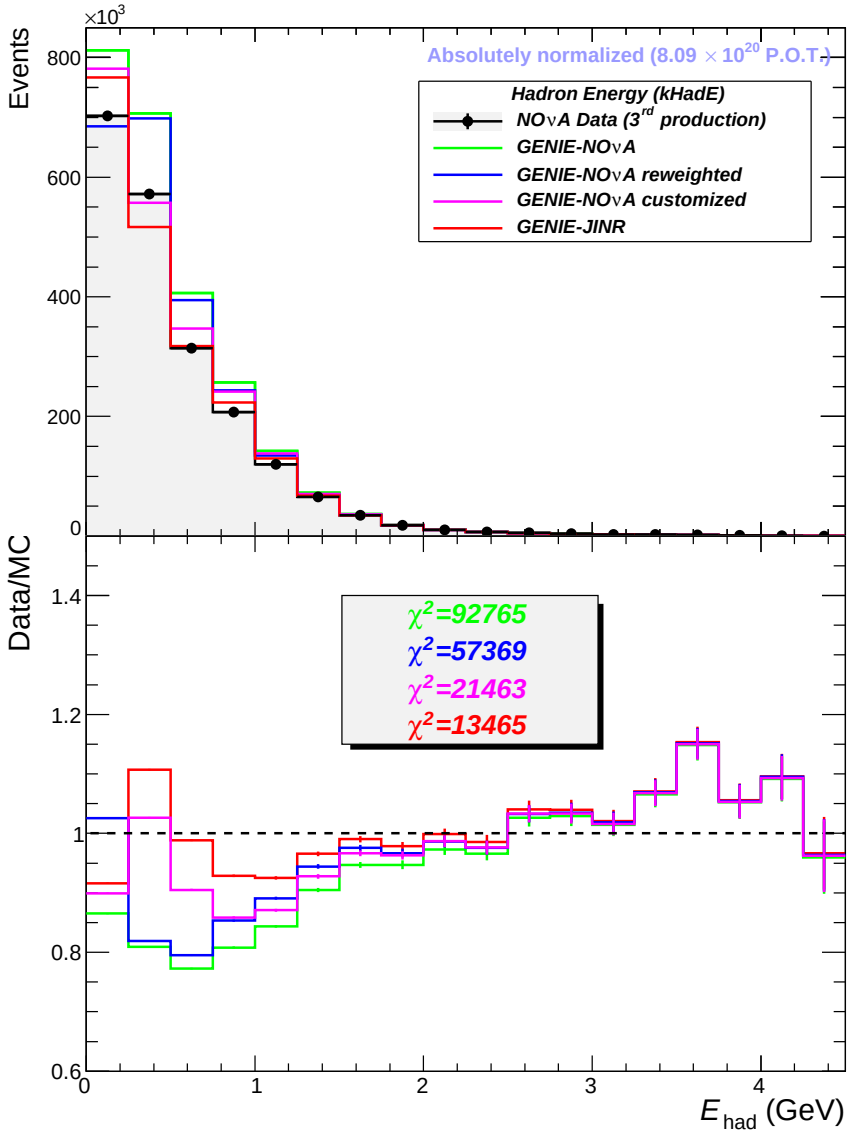
Models

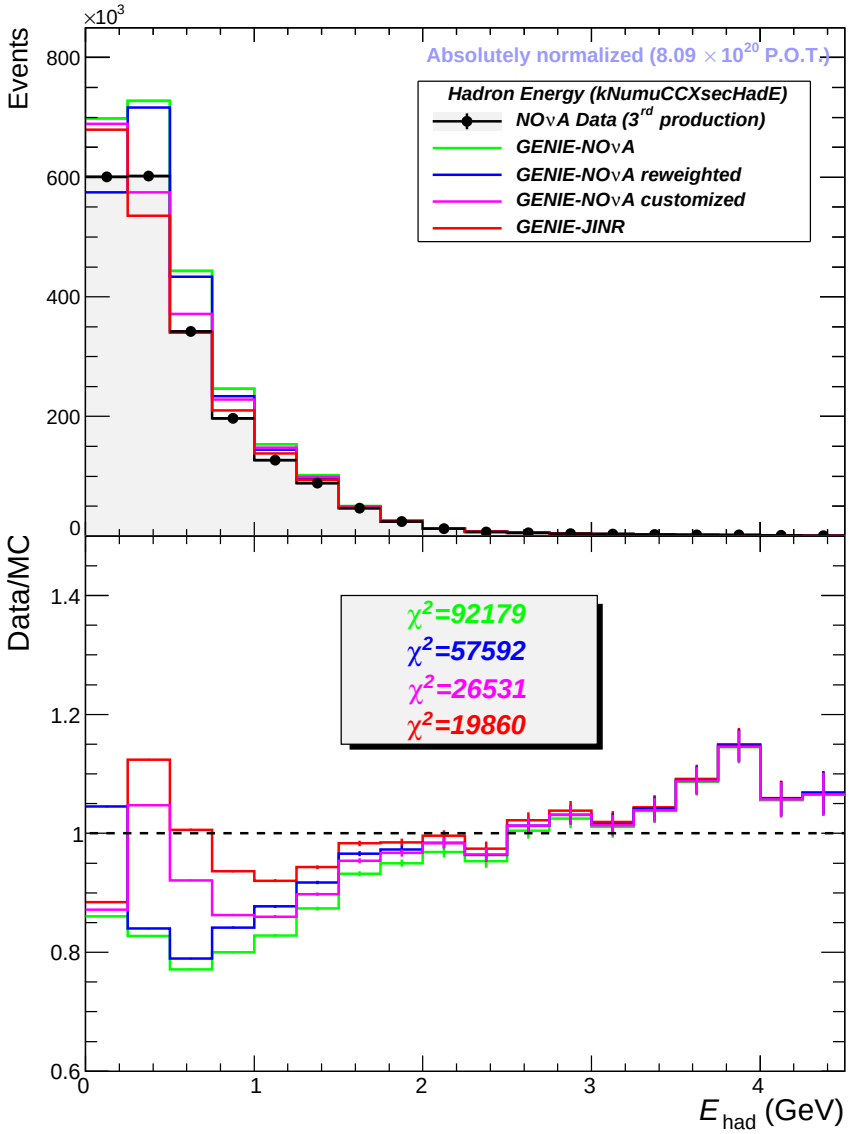
- **GENIE-NOνA** model – the GENIE 2.12.2 package currently employed in the NOvASoft with default settings (except minors ones). The re-weighting (`kXSecCVWgt2017`) is used to minimize the unavoidable discordances between the NOνA ND data and Monte Carlo simulation.
- **JINR** model has the following differences from **GENIE-NOνA**:
  the CCQE scattering from nuclei is evaluating with the RFG model by Smith and Moniz with small corrections and with an updated set of input parameters – Fermi momenta and binding energies;
  the nuclear effects beyond RFG is described by introducing the energy-dependent ("running") axial mass, which is implemented as option called `KuzminNaumov2016AxialFormFactorModel` in GENIE since version 2.11.0;
  the "KLN-BS" extension of the famous Rein-Sehgal approach (options `KuzminLyubushkinNaumovRESPXSec2014` and `BergerSehgalRESPXSec2014` in GENIE) with updated "resonance" axial mass value is used to model single-pion neutrinoproduction NC and CC reactions on nucleons.

Models

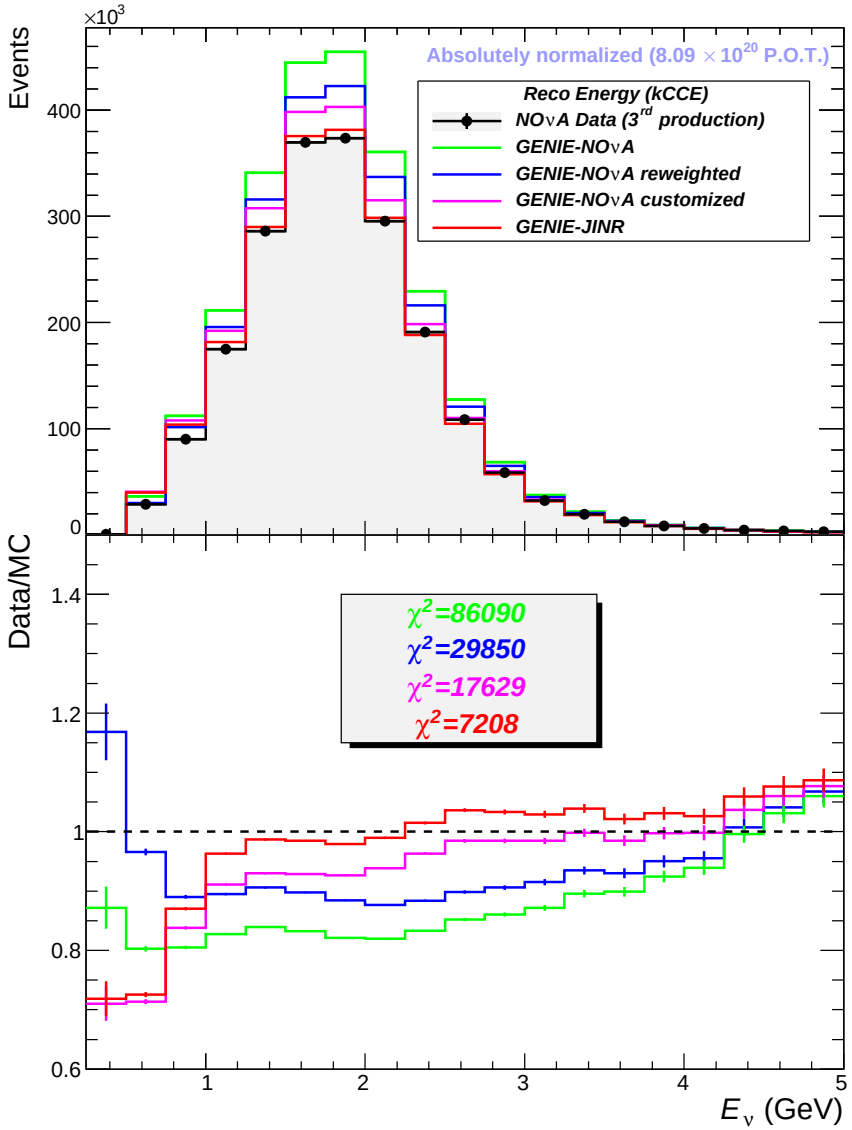
- **GENIE-JINR** model – subset of **JINR** model implemented in GENIE (doesn't include interference between the resonances, NRB model, and other technical details). Technically, it is calculated by re-weighting the **GENIE-NOνA** generated events:
  1. elimination of the "Empirical MEC" events.
  2. the default GENIE 1π NRB contribution is multiplied by factor 0.41 to adjust the simulated 1π production rate basing on the recent reanalysis of the earlier ANL and BNL deuterium bubble chamber data.
  3. re-weighting CCQE and CCRES with weight: $w_{\mathrm{c}}(E_\nu) = \dfrac{\sigma_{\mathrm{c}}^{\mathrm{JINR}}(E_\nu)}{\sigma_{\mathrm{c}}^{\mathrm{NO\nu A}}(E_\nu)}$.
- **GENIE-NOνA customized** – the GENIE release currently used by NOνA, but with some options which reproduce the most important features of the **JINR** model: using `BergerSehgalRESPXSec2014` option instead of `ReinSehgalRESPXSec`, the value M_A^{RES} is set to 1.18; using `KuzminNaumov2016AxialFormFactorModel` option instead of `AxialFormFactorModel`, the value M_A^{QE} is set to 1.01 GeV, and the value of $F_A(0)$ is set to -1.2695.

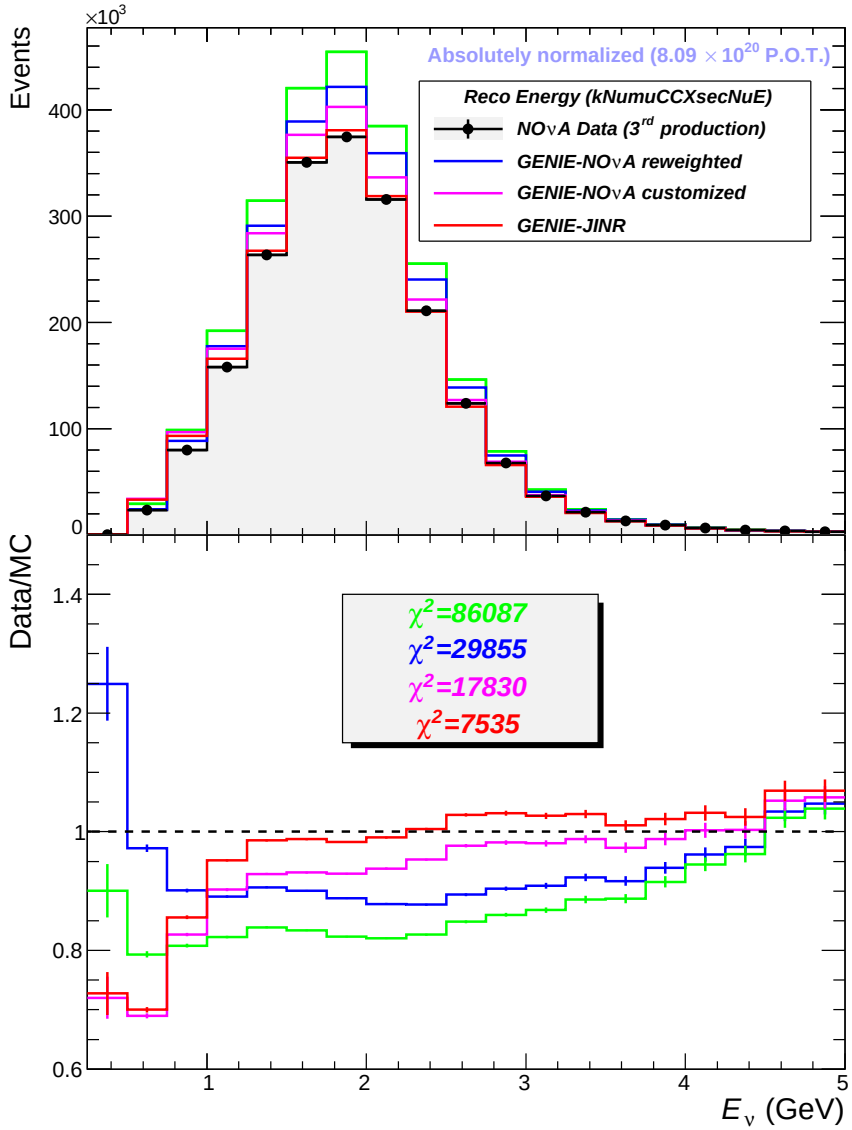
Comparison with the ND data





Comparison with the ND data





Comparison with the ND data

For quantitative comparison of the models under consideration it is useful the following relative characteristic:

$$r_i = \frac{\chi^2_i}{\chi^2_{\mathbf{GENIE-JINR}}},$$

where the index enumerates the models in the same sequence as in the legends of Figures, namely

$$i \;=\; \textbf{default, reweigted, customized}$$

The values of r_i for the four estimators are collected in the Table:

Var	r_{default}	$r_{\text{reweigted}}$	$r_{\text{customized}}$
kHadE	6.89	4.26	1.59
kNumuCCXsecHadE	4.64	2.90	1.34
kCCE	11.94	4.14	2.45
kNumuCCXsecNuE	11.42	3.96	2.37

Future developments

The **JINR** model can be further tuned at $E_\nu \gtrsim 1$ GeV:

- adjusting the value of the cutoff in the invariant hadron mass, W_{cut};
- adjusting the axial coupling g_A, which is quenched in nuclear matter;
- adding the 2π production contributions into the RS-based models;
- accounting for the interference between neighbouring resonances;
- accounting for the finite target mass correction and phenomenological higher-twist effects to improve the DIS contribution in the low-Q^2 region;
- testing and comparing different models for the 1π non-resonant background, electromagnetic and axial-vector transition form factors involved into the 1π neutrinoproduction within the RS-based models, and possibly the LO or NLO PDF models alternative to GRV98.

The lower-energy range, $E_\nu < 0.8 - 1$ GeV, seems to be more problematic for tuning up or readjusting (for details see doc 23018). However, the NOνA ND dataset shows considerable promise as a means for adjusting the **JINR** model at low energies through a new global fit.

Future developments

- Unfortunately, the suggested improvements may only be realized after corresponding revision of the GENIE suite. The NOνA Collaboration could inspire the GENIE Collaboration for this job if our proposal is of some interest to you.
- Using the **GENIE-NOνA customized** model does not demand any revision of GENIE but is not sufficiently accurate and thus it needs in some re-weighting procedure *a la* Tufts model. However such a "hybrid" could be useful.
- Obviously, any improvement of the interaction model is crucial for the $\overline{\nu}$ mode. We are ready to perform calculations for the $\overline{\nu}$-nucleus interactions if, again, this work is interesting for the NOνA Collaboration.