Genie

status update

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on behalf of the GENIE collaboration

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Seoul, South Korea

UNIVERSITY OF LIVERPOOL

Collaboration

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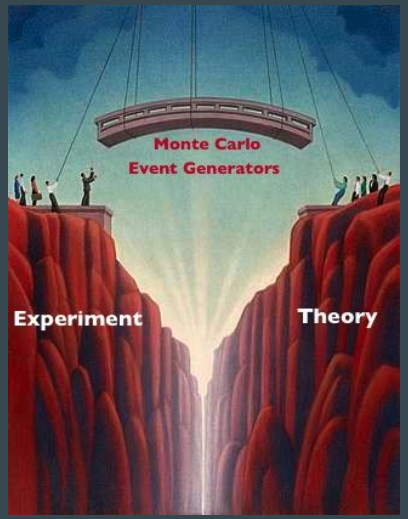
[Faculty, Postdocs, PhD Students, Master Students]

- 25 active authors
  - With many different backgrounds
  - 11 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 3.02.00 from March 2022
  - 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

Outlook for this presentation

- Overview of version 3.02.00
  - Key concepts unique for GENIE
  - What's new in models
    - Both standard and BSM physics
  - Reweight
  - Tuning strategy
  - Future developments and releases

- There will be another GENIE talk focusing on tuning using 0π datasets by Julia
  - tomorrow after the first coffee break

Configurations and tunes

- GENIE has a high level of configuration
  - Combinatory of possible configurations is starting to create confusion
    - Among users trying to reproduce results
    - Reusing splines that might be generated using different configurations
  - Just saying “We use GENIE v3.00.00” is not enough

- New system: standard configurations can be uniquely identified
  - Unique IDs identify both the models and the parameter’s values assigned to a certain model configuration
  - We call them tunes
    - Examples: G18_10a_02_11b, GEM21_11b_00_000, GHE19_00a_00_000
    - Full list http://tunes.genie-mc.org/ and explanation of the naming scheme in the manual
  - These are operative definitions
    - The code knows of these names and configures itself based on the selected tune
  - Of course, users are still able to try their own configurations without defining a dedicated tune

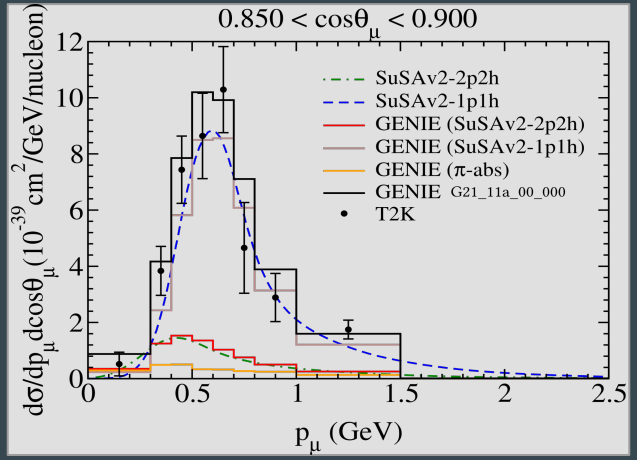
- The system has been in use since version 3.00.00
  - It working so far, new tunes are constantly added
  - Some of the current tunes will be discontinued eventually as we know they are not very used
    - G18_01* series
  - Experiments are invited to share their configurations, tunes, etc

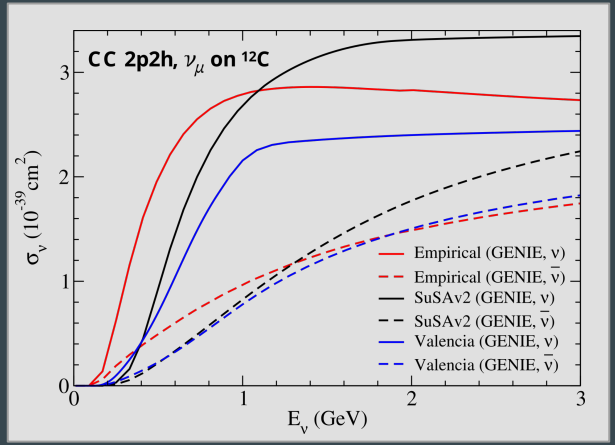
Modeling of standard processes

SuSAv2 - CC neutrino scattering

- Provides 1p1h and 2p2h predictions based on the SuperScaling approach
  - e.g., Phys. Rev. D 94, 093004 (2016)
- External contributors:
  - Stephen Dolan, Guillermo Magias and Sara Bolognesi
- The model is released in many tunes:
  - G21_11*_00_000
  - with 4 different variations for the FSI
- In principle the idea can be used also for NC
  - But we need the tables to add

Phys. Rev. D 101, 033003 (2020)



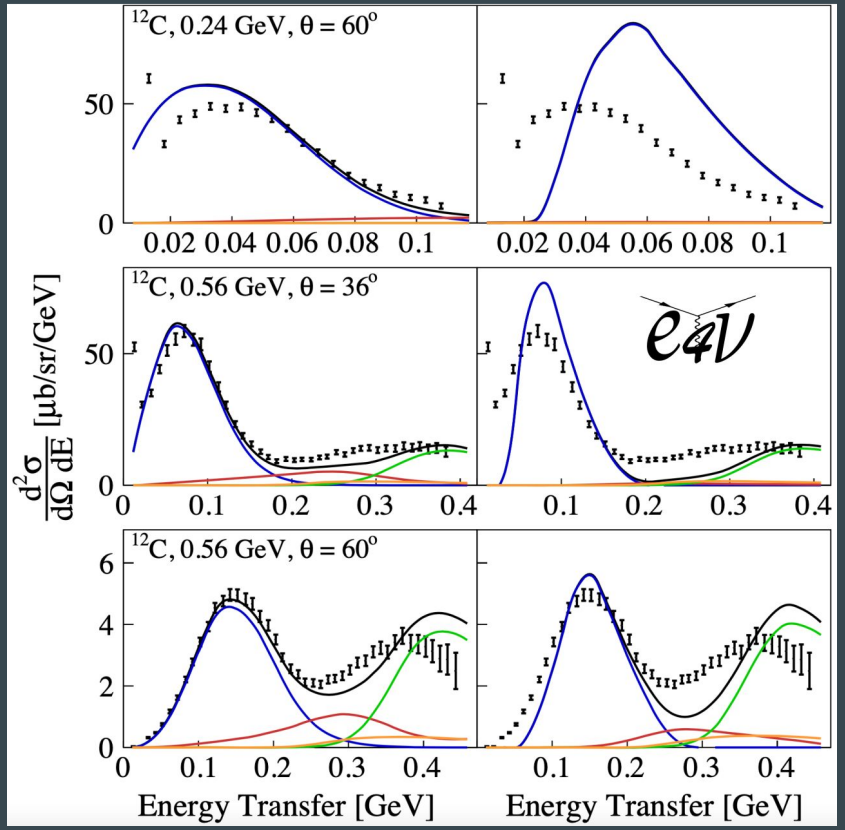


SuSAv2 - electron scattering

- Consistent with neutrino version
- Benchmarked against inclusive (e, e') data
  - by members of the e4ν collaboration
- Improvement with respect to G18_10a_02_11a
  - Which is not a tune used electrons
  - Rosenbluth + Empirical MEC (with no tuning)
- See this morning talk about e4ν programme

Phys. Rev. D 103, 113003 (2021)

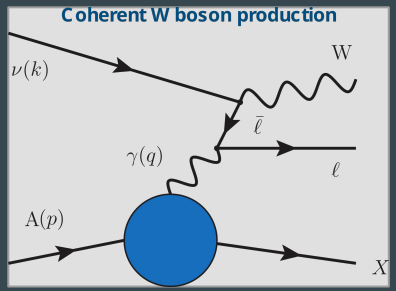
SuSAv2 G18_10a_02_11a



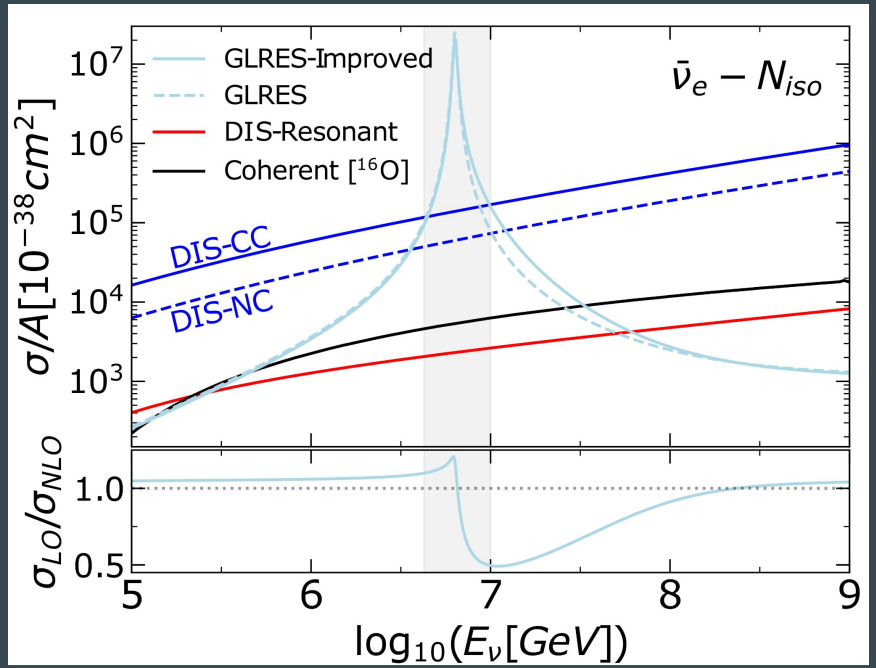
(blue) QE, (red) MEC, (green) RES and (orange) DIS

High energy DIS: extension up to 10^9 GeV

- Complete refactoring of the very high energy processes
  - Support for neutrino telescopes
  - Dedicated tune for High energy physics
    - Again in 4 variations with different FSIs
- New processes were included too
  - state-of-the-art NLO DIS cross sections and event generation
    - Based on APFEL code: optional GENIE dependency
  - COH W boson production
    - with NLO corrections
- External contributors:
  - Juan Rojo, Rhorry Gauld and Aart Heijboer (NIKHEF)
- First observation of a Glashow resonance candidate at IceCube
  - Nature 591, 220–224 (2021)

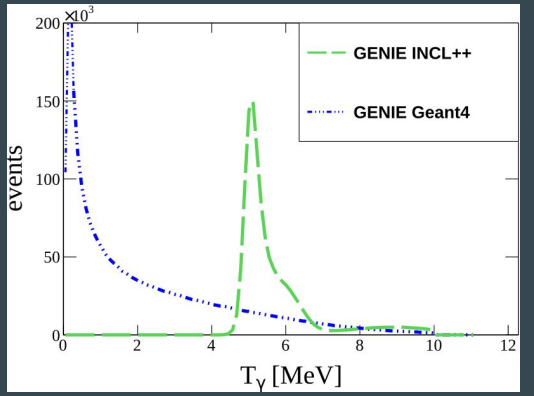


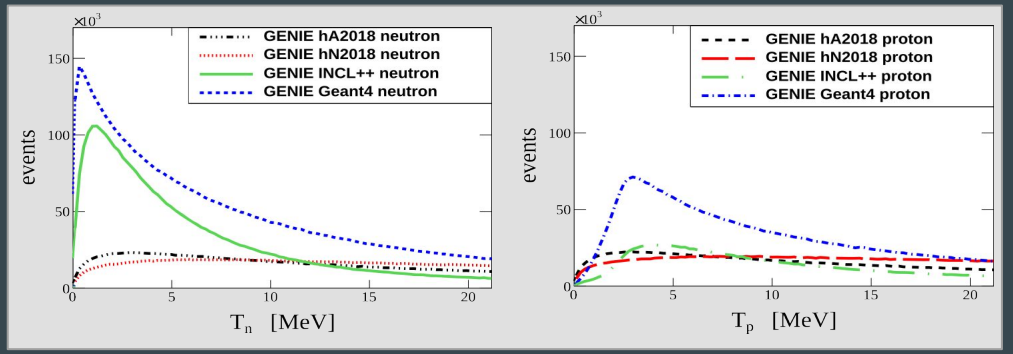
J. Cosmol. Astropart. Phys. 09 (2020) 025



New FSI models: INCL++ and Geant4 Bertini cascade

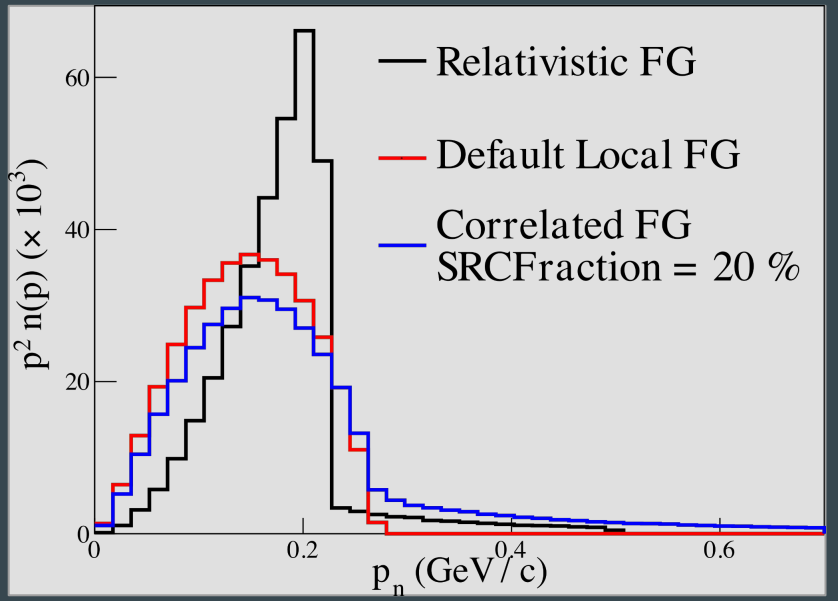
- New cascade FSI models added as external dependencies
  - Liege intranuclear rescattering model, via INCL++
  - Bertini cascade, via GEANT4
    - Contributions by Dennis Wright and Makoto Asai (SLAC)
- Both predict higher proton and neutron multiplicities
  - Room for the experiment to investigate
- Both predict lower energy nucleons
- New: de-excitation photons
  - Not available in previous GENIE FSI models
- No reweight modules available for these cascades





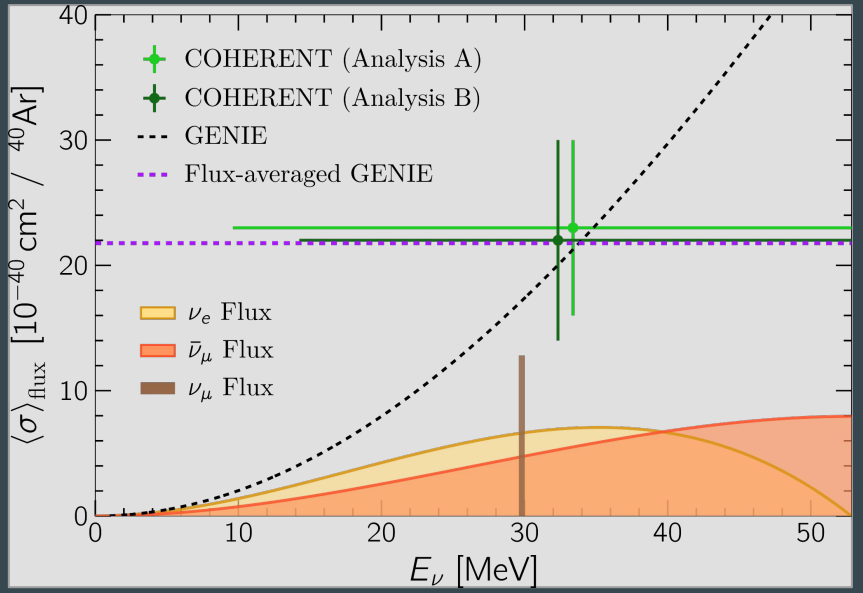
Initial state: Correlated Fermi Gas

- Attempt to model the high energy tail
  - Measured at electron scattering
    - Phys. Rev. C 68, 014313
  - expected from two-nucleon short range correlations
- Implementation inspired by
  - https://arxiv.org/abs/1710.07966
- Final result: extension of the Local FG
  - Fraction of nucleons are above Fermi momentum



CEνNS event generator

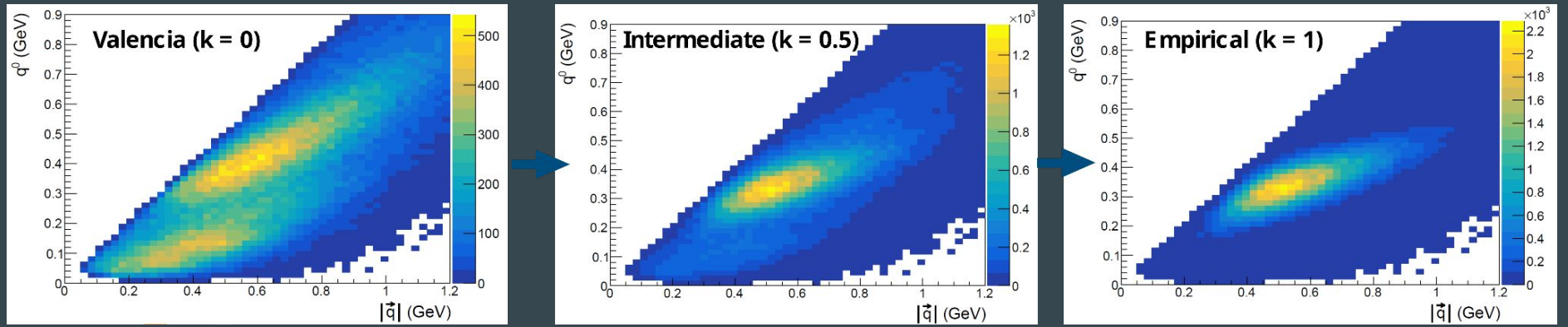
- NC process which leaves the struck nucleus in its ground state
  - Detection via recoil
- GENIE implementation based on Patton et al.
  - Phys. Rev. C 86, 024612 (2012)
- Part of a dedicated tune focused on very low energy neutrinos
  - GVLE18_01a_00_000



COHERENT data from Phys. Rev. Lett. 126, 012002 (2021)

Reweight improvements

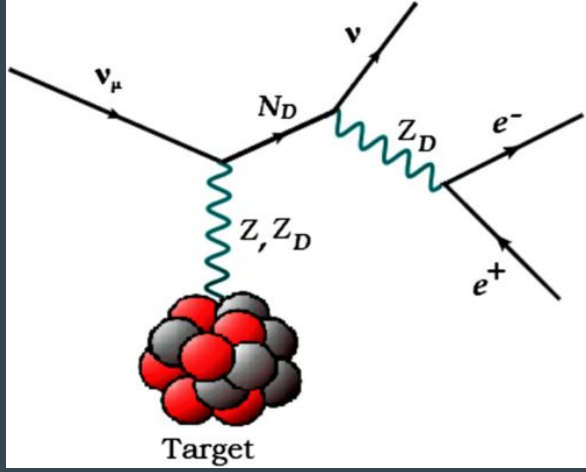
- "MicroBooNE tune": reweighting of CC QE+2p2h to fit T2K CC0π data
  - Details described in Phys. Rev. D 105, 072001 (2022)
  - Contribution of new calculators in GENIE Reweight
- Now available to the entire community as part of GENIE v3.2.0
- introduction of a shape variable k
  - controls the (q^0, |q|) distributions from Valencia (k=0) to empirical (k=1)
- Example plots obtained with BNB νμ CC 2p2h on argon



BSM generators and other tools

Dark neutrinos

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



- Model to explain EM excess
  - Main reference paper https://doi.org/10.1103/PhysRevLett.121.241801
- Neutrino interaction via exchange of a light dark boson (Z_D)
  - light compared to Z and W
  - producing dark neutrino with non-zero mass (ν_D)
- The dark neutrino then decays
  - In either neutrinos and/or electron pairs
  - The decay length is visible in our detectors!
    - varies a lot with couplings and mixings but it can be of the order of mm

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} \bar{\nu}_{\mathcal{D}} \gamma_\mu \nu_{\mathcal{D}} + e\epsilon Z_{\mathcal{D}}^{\mu} J_{\mu}^{\mathrm{em}} + \frac{g}{c_W} \epsilon' Z_{\mathcal{D}}^{\mu} J_{\mu}^{Z},$$

- The dark boson exchanged with the nucleus can give rise to all NC scattering mechanisms
  - The main process would be the coherent production (implemented in GENIE now)
  - The second leading process would be the QE process, not implemented yet
- Contributions by Iker de Icaza (Sussex) and Pedro Machado (FNAL)

Boosted Dark Matter

- Upgrade with what described in arXiv:1812.05616

- 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
  - has improved modeling of the elastic scattering process
    - including a pseudoscalar form factor
  - includes the simulation of scattering off electrons
  - includes anti-dark matter scattering

- Contribution by Joshua Berger (CSU)

Event Library Interface generator

- Importing events from a file interface to external events generated with
  - other generators
  - arbitrary physics models
- Users just need to be able to
  - Fill a ROOT TTree with the momenta of the particle generated by the interaction
  - Produce integrated cross sections
- The system will create GENIE events randomly selecting events from the library
  - The selection is based on the neutrino energy associated to the event
- the event library interface allows experiments to import events
  - re-using their existing GENIE MC production workflows
  - the extensive GENIE flux and geometry tools
  - The cost is that we lose true information from the generation
- Instructions on the file format are in the manual
- Contribution from NOvA experiment

Tuning programme

Tuning requirements and objectives

- Tuning is always necessary whenever empirical approaches are used
  - Tuning has to be repeated whenever a modeling element is added or changed in the system
- Ideally, no additional code should be necessary for the tuning
  - Models are already complicated enough without requiring more tuning oriented development
  - We would like every parameter to be tunable
    - Going beyond the event-by-event reweight that is not always justifiable
- Expected Output
  - Parameter sets from data from various experiments
  - with estimated systematic errors
  - Parameter covariance matrix
    - $\Rightarrow$ No official support until v4

Tuning strategy

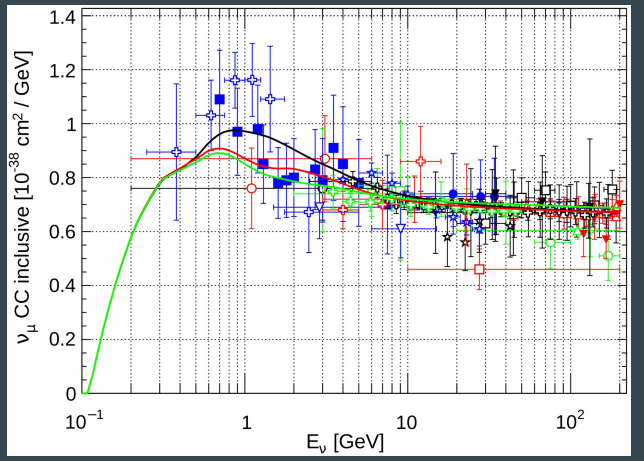
- Technology of choice consists in a brute force approach
  - Predictions are constructed in specific points of the parameter space
  - The predictions are then interpolated using multidimensional polynomials
    - As a function of the parameter space
    - Current numerical assistant is Professor
      - The European Physical Journal C volume 65, 331 (2010)
    - Possibly to be replaced by Apprentice in the future
      - EPJ Web Conf., 251 (2021) 03060

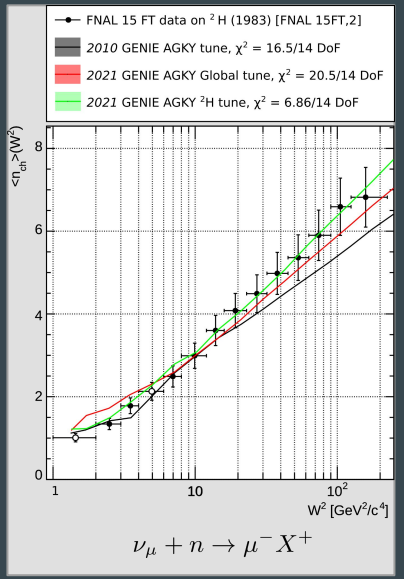
- On top of the parameterisation an entire fitting framework has been developed by GENIE
  - correlations between datasets
  - multidimensional priors on the parameters
    - And other priors
  - control weights associated to each degree of freedom
  - Validation of interpolated polynomials and population of the parameter space

- Future developments
  - We expect to develop a reweight machinery using similar strategies
  - That will allow reweight to operate using response functions obtained from brute force scan of parameter space
    - Provide a reweight for those parameters tuned with our machinery but without a reweight module

The tuning so far

- Tunes using bubble chamber data
  - hydrogen and deuterium
- Global CC inclusive, 1π, and 2π data sets
  - Tune the Shallow inelastic region
  - Phys. Rev. D 104, 072009 (2021)
- First neutrino-induced hadronization tune on average charged multiplicity data
  - as a function of W
  - Phys. Rev. D 105, 012009 (2022)
- We are starting working on nuclear tunes
  - using both neutrino data and electron scattering data
  - Details in Julia's talk





Take away

- We thanks all the developers for their important contributions
- GENIE is an active generator and widely used
  - Support for a variety of physics analyses
    - from SM to BSM and at many different energies
  - You had an overview of recent developments
    - But others are in progress, more details in recent publications
  - We expect a new release soon with the addition of Minoo's single pion production model
- We have developed a machinery to support a tuning programme
  - First results are already published
  - Work toward more ambitious goals in progress
- We host monthly forums for the users to collect feedback
  - 3rd wednesday of every month at 15.00 UK time
  - Details are sent around via the GENIE mailing list, please subscribe if interested