Genie

v3.4.0

...

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on behalf of the GENIE collaboration

Generator workshop
15 March 2023
Fermilab

UNIVERSITY OF LIVERPOOL

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Collaboration

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Konstantin Kuzmin (ITEP and JINR), Anselmo Meregaglia (Bordeaux, CNRS/IN2P3), Vadim Naumov (JINR),
Afroditi Papadopoulou (MIT), Gabriel Perdue (Fermilab), Marco Roda (Liverpool), Beth Slater (Liverpool),
Alon Sportes (Tel Aviv), Noah Steinberg (Fermilab), Vladyslav Syrotenko (Tufts), Júlia Tena Vidal (Tel Aviv), Jeremy Wolcott (Tufts)

[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

Status overview

- Two main efforts
  - Model development
  - Tuning

- Contacts, details and code are all available from an initial entry point: www.genie-mc.org/
  - The code lives on github so all github features are available

- We also offer a monthly User Forum on the 3rd Wednesday of the month
  - We share news, issues found by users, we discuss developments soon to be available, etc
  - Running experiments have representatives so the users can know how the code is used
  - Announcements sent to the GENIE user mailing list, please subscribe there if you are interested

- Recent releases - http://releases.genie-mc.org/
  - version 3.02.00 from March 2022 - physics changes and upgrades
  - version 3.02.02 from November 2022 - minor fixes
  - version 3.04.00 from March 2023
  - Same splines as for 3.02.00

- 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 - Phys. Rev. D 106 (2022) 11, 112001

Outlook for this presentation

- Overview of version 3.04.00 with respect to 3.00.00
    - Key concepts unique for GENIE
        - GENIE configurations
        - how to add models in an official release
        - GENIE output
    - What's new in models
        - Both standard and BSM physics
    - Reweight
    - Tuning strategy
    - Future developments and releases

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
    - One example of this line of development is the new AR23_20i_00_000 tune created by SBN and DUNE collaborations

Incubator projects

- An incubator project is the unique route for inclusion of physics or software developments into GENIE product releases.
  - in-house development activities
  - community development efforts overseen by the GENIE scientific and technical leadership

- Incubator projects may include, but not limited to:
  - development of a new physics model or improvement an existing one
  - systematic study
  - tuning of a physics component
  - development of a new tool or the addition of a new feature to an existing tool
  - upgrade of the framework
  - improvement of numerical procedure

- start with the identification of a GENIE development need
  - either by member of the GENIE collaboration or a contributor / member of the community
  - Following a consultation with GENIE leaders, one or more incubator projects may be launched to address the identified GENIE need
    - scope and milestones
    - requirements, including physics validation, tuning, software engineering, computational efficiency and documentation ones, as appropriate
    - A clear reporting line, and a plan for collaboration reviews encompassing both physics and technical aspects of work

- We don’t have more specifications based on the physics content
  - Every project is considered separately and different solutions will be used
  - BSM projects tends to be easier to be included because they couple less with the rest of the code
    - But things might change as more BSM physics is included

GENIE output format

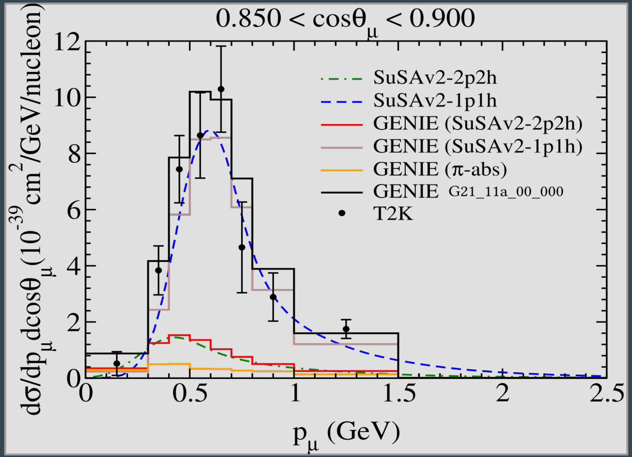
- ROOT file
- For each event we store
  - The particle stack including mother-daughter relations
    - To provide the history of the generation
      - Which particles underwent FSI, ...
    - on/off shellness of each particle
    - polarisation
    - momentum, position, time, binding energy
    - ... full definition here
  - A summary of the event
    - Process type, Scattering type
    - all the information used by GENIE to generate the event
      - Geometry agnostic
- Most of this is useful for reweighting too
- We also have a number of converters
  - gst (GENIE standard tree), gxml, rootracker, ...
  - In order to use reweight we have to use the main output which contains all the information

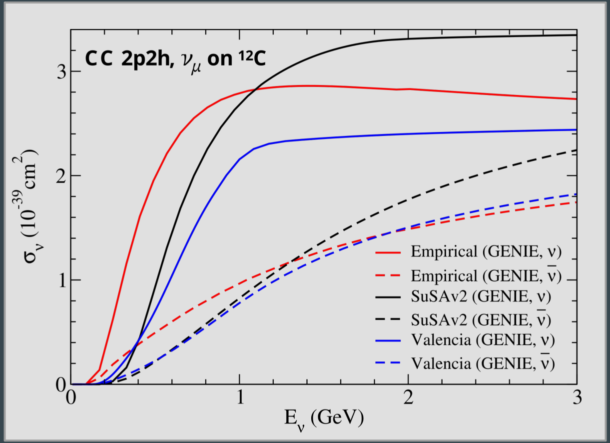
Modeling of standard model processes

SuSAv2 - CC neutrino scattering

- Provides 1p1h and 2p2h predictions based on the SuperScaling approach
  - e.g., Phys. Rev. D 94, 093004 (2016)
- Contributors:
  - Stephen Dolan, Guillermo Magias and Sara Bolognesi
  - Steven Gardiner
- 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)



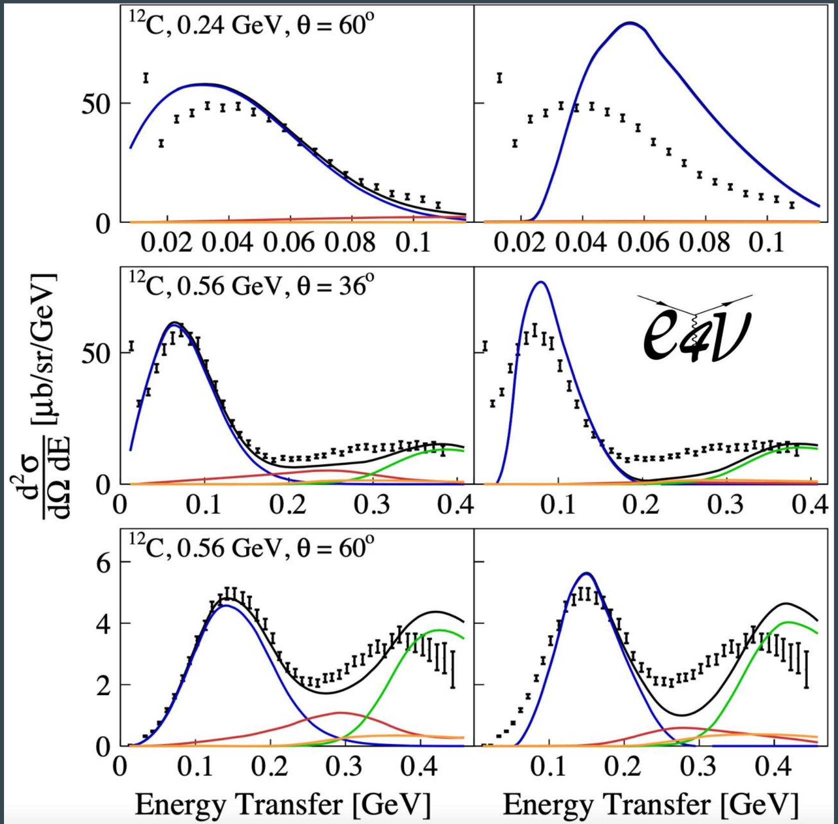


Phys. Rev. D 103, 113003 (2021)

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)
- Contributors:
  - Afroditi Papadopoulou
  - Alon Sportes

SuSAv2 G18_10a_02_11a



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

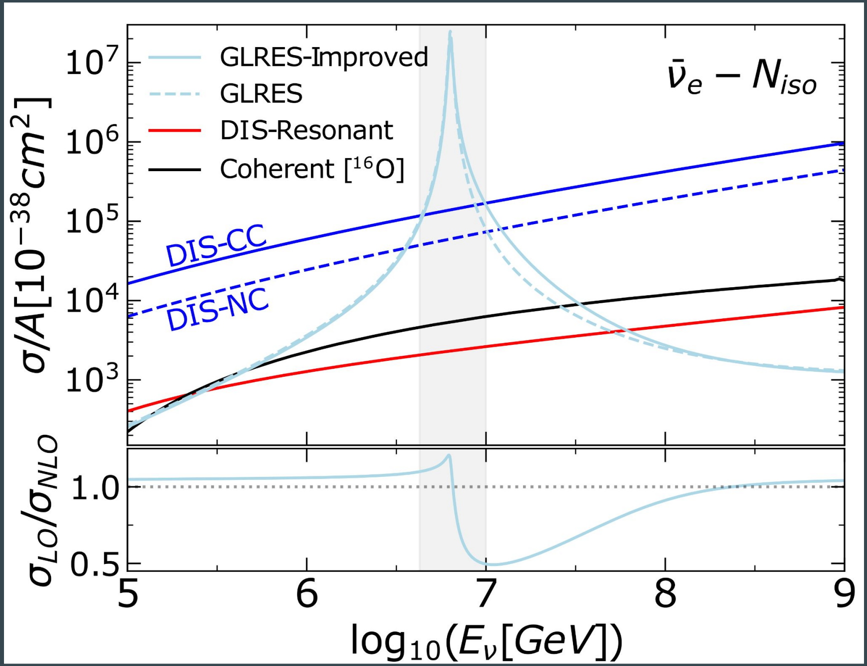
High energy DIS: extension up to 10^9 GeV

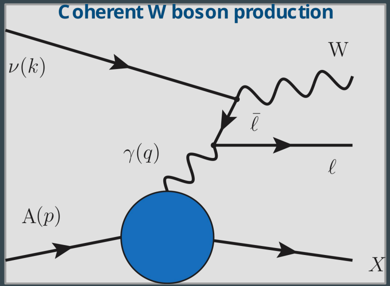
- Complete refactoring of the very high energy processes
  - Support for neutrino telescopes
  - Dedicated tune for High energy physics
    - Again in 4 variations with different FSIs

- 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

- First observation of a Glashow resonance candidate at IceCube
  - Nature 591, 220–224 (2021)

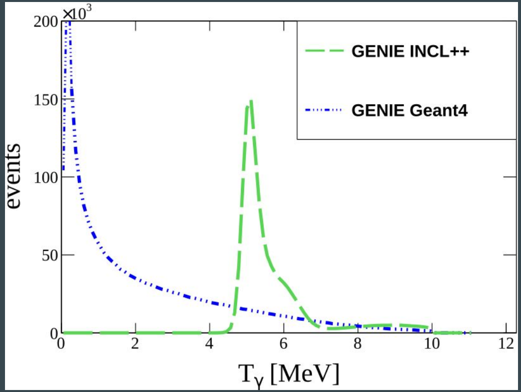
J. Cosmol. Astropart. Phys. 09 (2020) 025

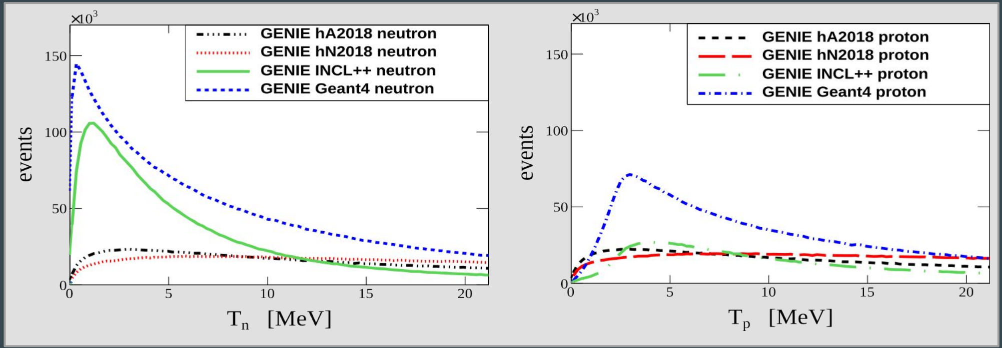




New FSI models: INCL++ and Geant4 Bertini cascade

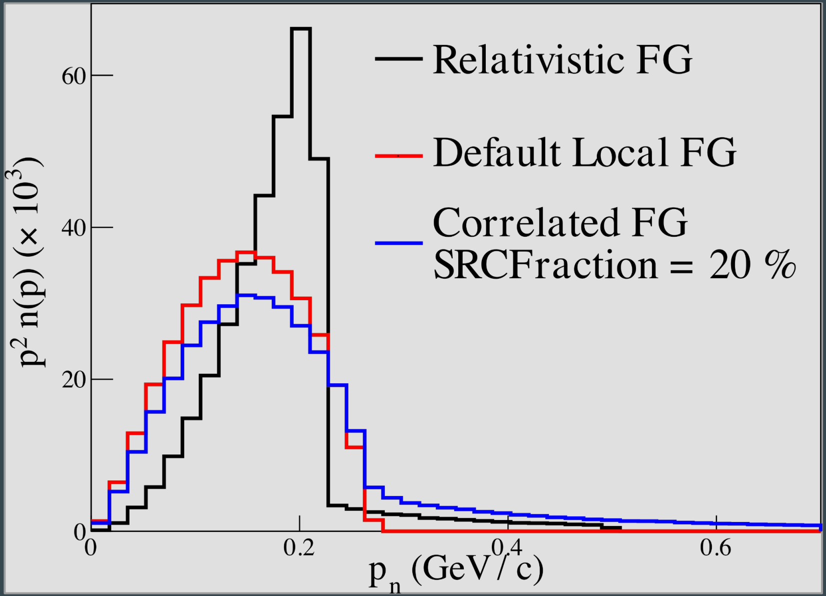
- New cascade FSI models added as external dependencies
  - Liege intranuclear rescattering model, via INCL++
  - Bertini cascade, via GEANT4
- Both predict higher proton and neutron multiplicities
  - Room for the experiment to investigate
- Both predict lower energy nucleons
- New: de-excitation photons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

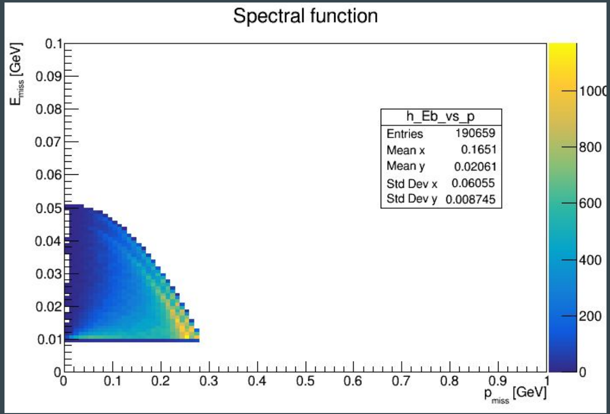




Initial state: Correlated Fermi Gas

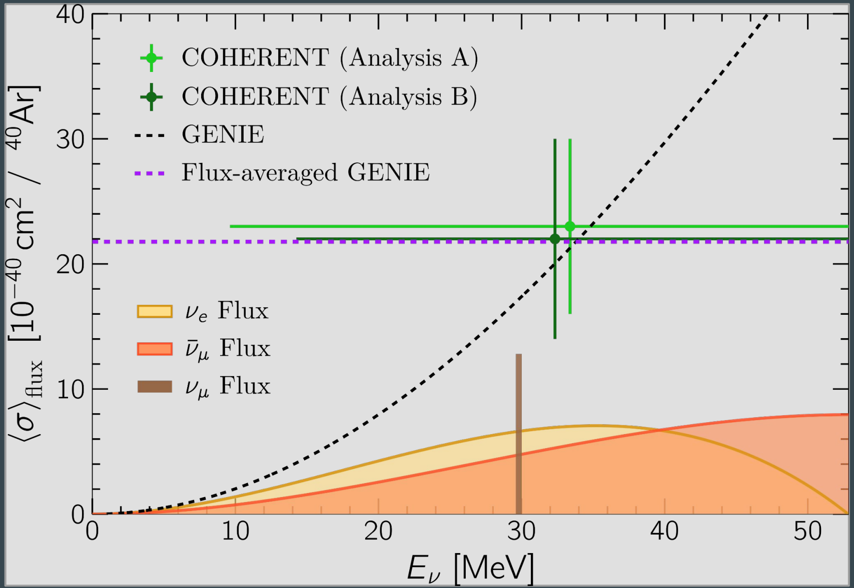
- Attempt to model the high energy tail
  - Measured at electron scattering
    - Phys. Rev. C 68, 014313
  - expected from two-nucleon short range correlations
- Implementation inspired by
  - https://arxiv.org/abs/1710.07966
- Final result: extension of the Local FG
  - Fraction of nucleons are above Fermi momentum
- In v3.4.0 we also added the possibility for the binding energy to be a function of the nucleon momentum
  - We call it spectral-function-like approach
  - It's not a full implementation of the spectral function
    - It just populates the space
      - A reweight module can use this as an input to proper SF distribution
- Contributor
  - Afroditi Papadopoulou
  - Steven Dolan and Laura Munteanu





CEνNS event generator

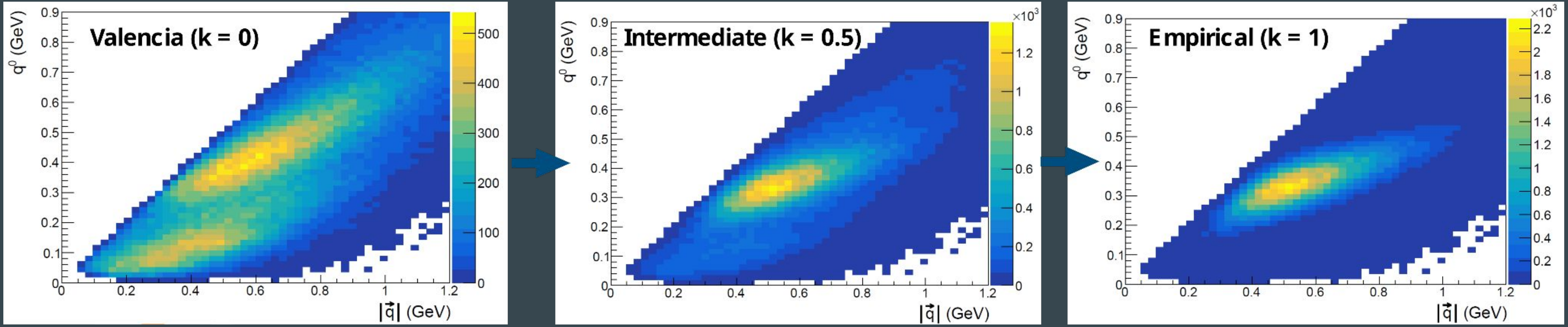
- NC process which leaves the struck nucleus in its ground state
  - Detection via recoil
- GENIE implementation based on Patton et al.
  - [Phys. Rev. C 86, 024612 (2012)]
- Part of a dedicated tune focused on very low energy neutrinos
  - GVLE18_01a_00_000



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

Boosted Dark Matter

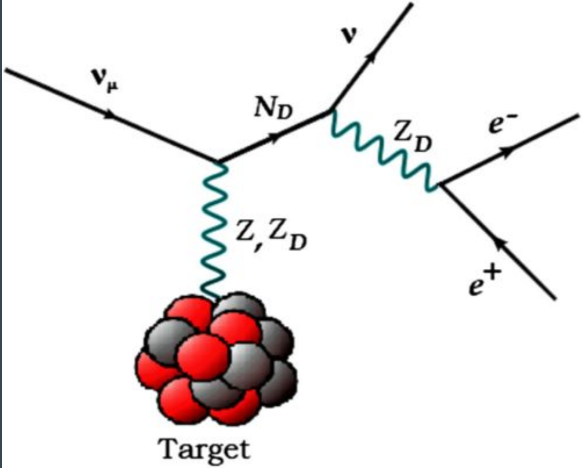
- Upgrade with what described in arXiv:1812.05616

- 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)

Dark neutrinos

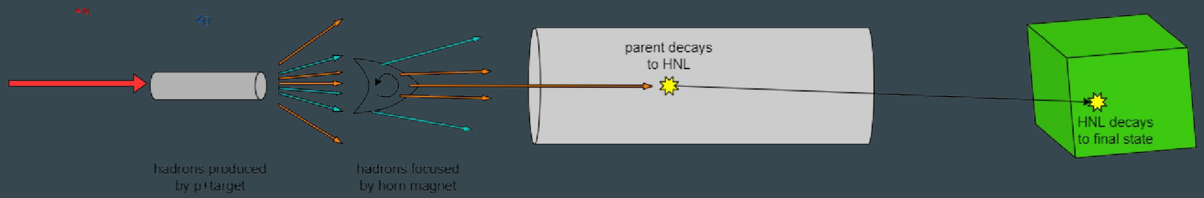
$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + U_{\alpha 4} N_{\mathcal{D}}, \quad \alpha = e, \mu, \tau, \mathcal{D}$$



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

- 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
    - Only tree-level decays are allowed so far
      - We can add more but we need the decay amplitudes
  - The decay length is visible in our detectors!
    - varies a lot with couplings and mixings but it can be of the order of mm
- 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)
  - Inputs from Pedro Machado (FNAL)

Heavy neutral lepton



- neutrino mass eigenstates with masses O(MeV)
  - In our implementation $m_4 < m_K$
  - Lagrangian implemented according to Eur. Phys. J. C 81, 78 (2021)
    - With caveats for some decay channels: link to code review for details
      - The link contains all the instructions to run etc

- HNL are produced in same beam as SM neutrinos
  - Use dk2nu flux files as simulation input
- • HNL decay to some appropriately selected decay channel
  - Particle stack constructed appropriately
    - Probe is the decaying HNL particle
- • Decay vertex assigned along HNL trajectory inside detector
  - Detector ROOT geometry used as simulation input

- Provides tools for POT accounting
  - usually intended to generate weighted events

- This is a huge amount of work
  - Started from a MINERvA development
  - That has been generalised to be used by other experiments

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 one of the strategies to tackle the problem of systematics
  - some dataset can constraint a parameter to the point that variations are pointless
  - The other part of the strategy being reweight, which is a more traditional approach

- 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
  - It also helps to understand which parameters are constrained by available data
    - Good starting point for experimental analyses

- 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
    - ⇒ No official reweight support until v4
  - These outputs can be fed into reweights

Tuning strategy

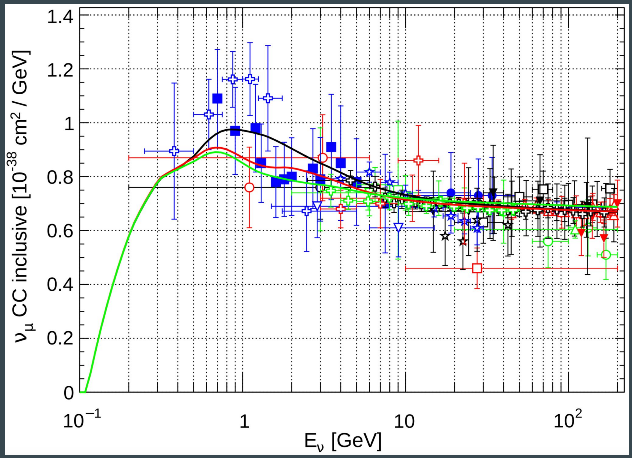
- Technology of choice consists in a brute force approach
  - Predictions are constructed in specific points of the parameter space
  - The predictions are then interpolated using multidimensional polynomials
    - As a function of the parameter space
    - Current numerical assistant is Professor
 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

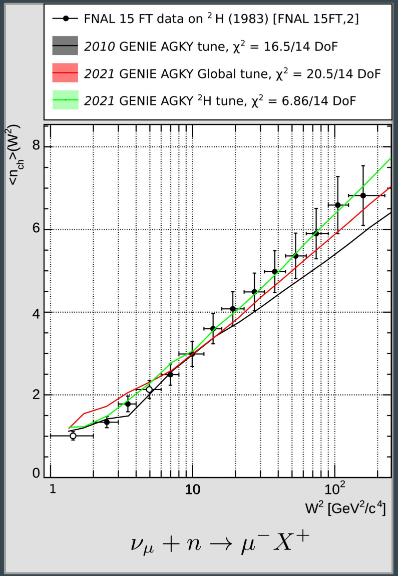
- On top of the parameterisation an entire fitting framework has been developed by GENIE
  - correlations between datasets
  - multidimensional priors on the parameters
    - And other priors
  - control weights associated to each degree of freedom
  - Validation of interpolated polynomials and population 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
  - Phys.Rev.D 106 (2022) 11, 112001
  - to be extendws using both neutrino data and electron scattering data





Conclusions

Future developments

- Getting close to the release of Minoo's model for single pion production
- upgrade for the **ν**-e elastic scattering to include electron initial distribution
  - This will require a change in the data model we write in the file
- COH single gamma production is also getting close to completion

Take away

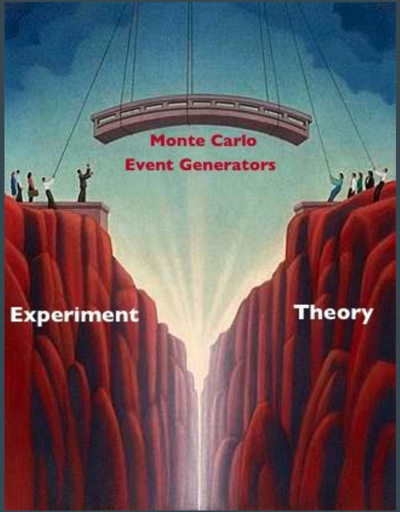
- Lots of new models and configurations
  - Plenty choice and we are happy to receive requests and inputs

- New models are being in the process of being merged
  - Incubators are the way we track new code
  - When things are discussed in advance it's easier to include new processes

- Tuning campaign ongoing
  - Julia will go into details tomorrow

Backup

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 ..."