Genie

event generator and recent developments

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on behalf of the GENIE collaboration

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UNIVERSITY OF LIVERPOOL

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Collaboration

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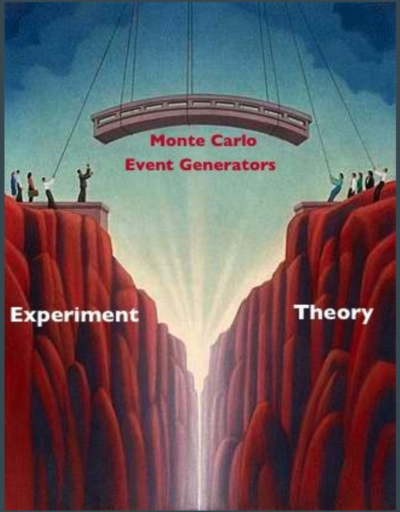
[Faculty, Postdocs, PhD Students, Master Students]

- 27 active authors
  - With many different backgrounds
  - 14 institutions from various countries
- About 10 past authors
- Many contributors for specific projects that are not authors
  - will be highlighted with their specific contributions

Our vision for MC generators



- Connect neutrino fluxes and observables
  - predict event topologies and kinematics
- Experiments and analysers need 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 new addition is JUNO
  - 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 3.04.02, released in April 2024
  - Previous release was 3.04.00, released in 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 - Phys. Rev. D 106 (2022) 11, 112001
  - First combined tuning on transverse kinematic imbalance data with and without pion production constraints - Arxiv 2404.08510

Physics overview

- Large physics coverage:
  - From very low energy (coherent scattering) to very high energy
  - Various incoming particles: neutrinos, electrons and hadrons
  - Extensive variety of models for GeV region
    - QEL (LS, Nieves, SuSAv2, ...)
    - 2p2h (Nieves, SuSAv2, empirical)
    - Resonant (RS, BS)
    - Nuclear Initial states: RFG, variations of LFG
    - FSI: two internally developed (hA, hN), two from 3rd party (INCL, Geant4)
    - etc, list too long to be reported here
  - We also have a number of BSM processes
    - For interactions (dark neutrino)
    - Or more exotic processes: nucleon decay, NNBar oscillations

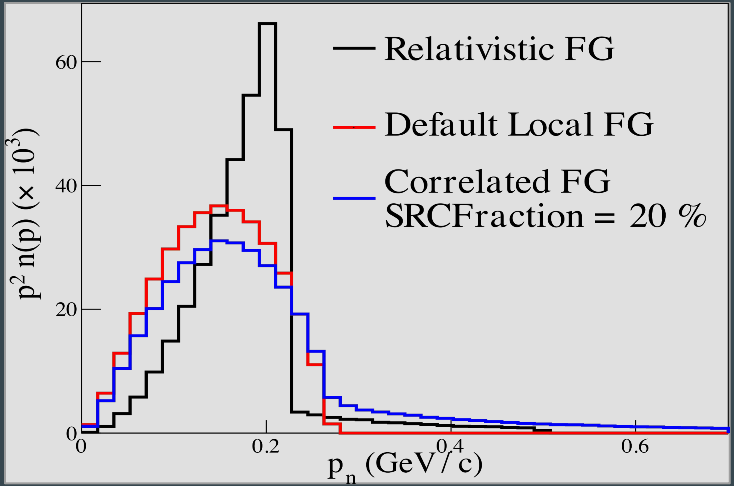
- The combinations are unlimited especially if we add parameters in the mix
  - We developed the concept of TUNE to make sure to provide consistent configurations
    - Of course users are free to create their own
    - We do consider maintaining configurations designed by users, should there be interest
  - http://tunes.genie-mc.org/

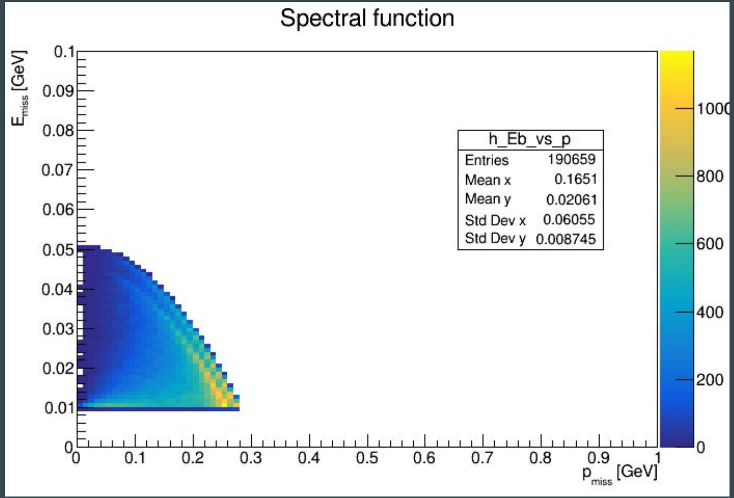
- Tools
  - Flux and geometry support
    - Including a support for external event library
  - additional package for reweight that is now a separate repository

Modelling effort

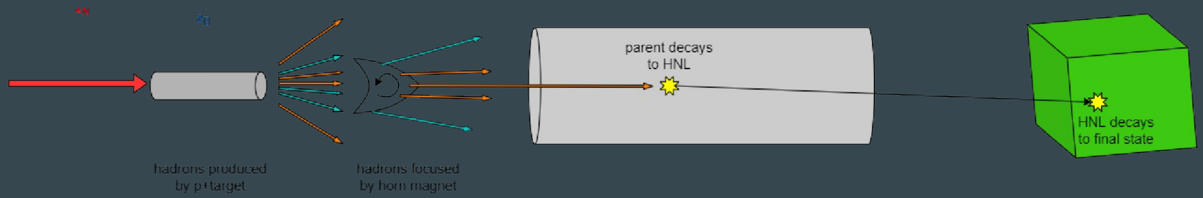
Initial state: Correlated Fermi Gas

- 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**
  - Deployed as an Argon tune requested by LAr based experiments
    - AR23_20i_00_000





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 standard model's neutrinos
  - 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
    - Use cases presented here Phys.Rev.D 107 (2023) 5, 055003

Other available things as 3.4.2

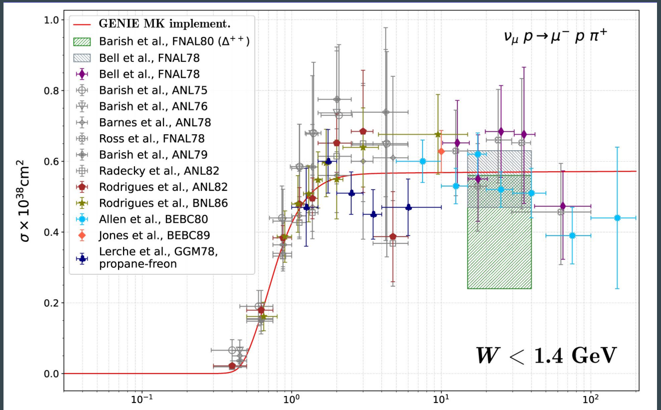
- Better handling of the 3rd party FSI
    - The parent-daughter relations of the particles has been improved
- GENIE Bosted-Christy Fit of eA Scattering Data
    - Boosted-Christy empirical fit to electron-nucleus scattering data
        - [PRC 77 (2008); PRC 81 (2010) 055213; arXiv:1203.2262].
    - Cross section only, as the model is inclusive
- A new normalization channel used to validate the efficiency of a generation

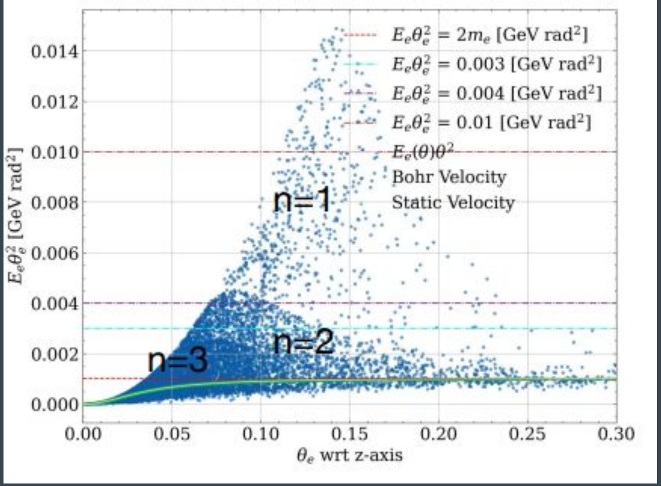
What's coming in the next release

- MK Single pion production model
  - 4-fold cross section – including angular distribution of final pion
    - interference between resonances
    - non-resonant background with Born diagrams
      - according to Hernández, Nieves and Valverde [PRD 76 (2007) 033005]
  - Deployed in a tune on its own as the moment we don't know how to combine it with the other pion productions

- Discontinuing pythia 6
  - Move everything to pythia8
  - Physics and functionality will be similar

- Electron motion
  - Adding a simple Bohr motion to the electrons in the initial states
  - Initial implementation valid for noble gasses
  - Main contributor is **Bear Carlson** from SBND collaboration





Tuning and reweight

Tuning requirements and objectives

- Tuning is always necessary whenever empirical approaches are used
  - Empirical models are always introduced when joining different models together
  - 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
    - ⇒ Once all of this is fully supported we will go in the v4 era

Tuning strategy

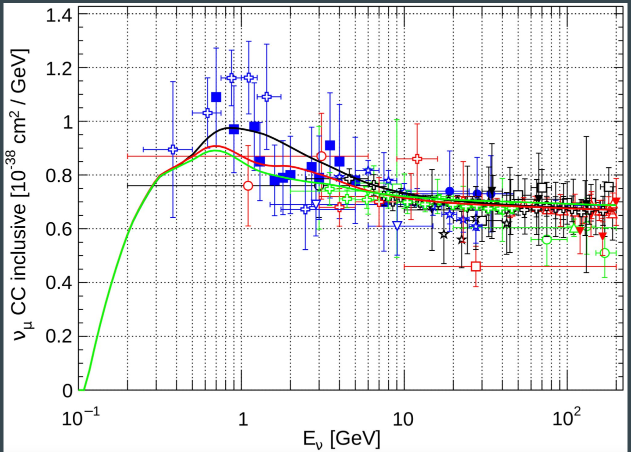
- Technology of choice consists of a brute force approach
  - Predictions are constructed in specific points of the parameter space
  - The predictions are then interpolated using multidimensional polynomials
    - As a function of the parameter space
    - Current numerical assistant is Professor
 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

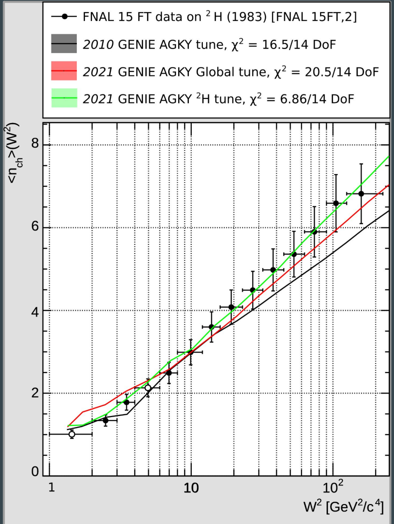
- On top of the parameterisation an entire fitting framework has been developed by GENIE
  - correlations between datasets
  - multidimensional priors on the parameters
    - And other priors
  - control weights associated to each degree of freedom
  - Validation of interpolated polynomials and population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

- Benefits
  - Every parameter becomes reweightable because we match the effect of the parameters directly on the experimental distribution
  - No additional code is necessary:
    - If there is a parameter we can configure we can exploit it in the tuning
  - Multiple parameters can be tuned at the same time, O(20)
  - Multiple datasets can be used at the same time
    - Of course we are trying to organise the tuning tackling different problems for each tune

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
  - Now starting exploring using TKI variables
    - Main contributor: **Weijun Li**

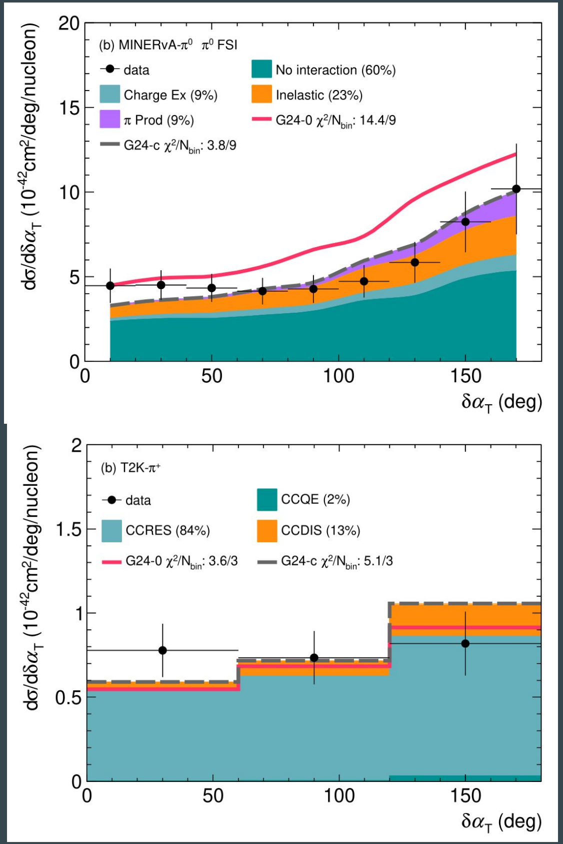




$$\nu_\mu + n \rightarrow \mu^- X^+$$

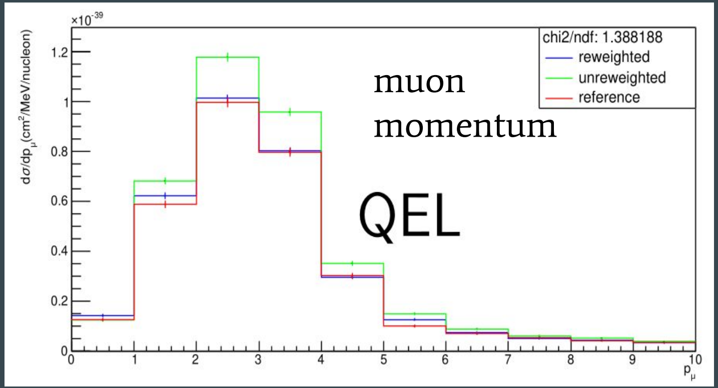
First combined tuning on transverse kinematic imbalance data

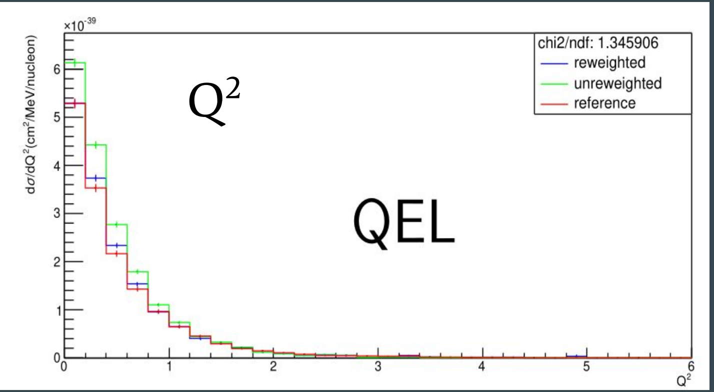
- Available from today on arxiv
- Using α_T and p_N TKI variables
- Data from Minerva and T2K
  - both with and without pion production
- It was an initial proof of concept to explore if there are tensions between the datasets
  - To see if there is a reasonable agreement across datasets
- We tuned parameters from LFG and from hA FSI
  - Starting from AR23_20i tune
    - Interesting starting point because of the new initial state and used by a number of experiments
- Results are encouraging
  - Complete results in the paper and the tune is available as part of the configuration of the master branch
  - To be released in version 3.6.0
- Comments are welcome



Professor based reweight

- Extracting values from data is not useful if we cannot use the new information in our analyses
  - We need to propagate the uncertainty of all the parameters we tuned
- What if we used the same idea used in the tuning?
  - Brute force extraction of parameterisation of “differential cross sections”
  - Using those parameterisation to reweight events
- Number of benefits
  - No additional reweight code that is specific for the interaction
  - Driven by exact simulation and no approximation
- Colossal work in progress
  - Main contributor is **Qiyu Yan**
  - Initial draft that proves that reweighting on a differential cross section of p_μ and W makes a valid distribution also for Q^2
- Status
  - We are improving the API of reweight and generator to allow this development to proceed
  - A paper in preparation to showcase the possibility of this tool
- Expected workflow
  - Experiments will run their own brute force scans according to the need of their analyses
    - Using all experiment inputs, e.g. flux
  - They will be able to design their own reweight phase space





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 have a formal process to add contributions, called incubator
    - This is to support developers during implementation and validation
    - Contact us if you are interest to start a project

- We have developed a machinery to support a tuning programme
  - First results are already published
  - Work toward more ambitious goals so that the results can be directly used by analysers

- News are sent around via the GENIE mailing list
  - please subscribe if interested

Backup

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

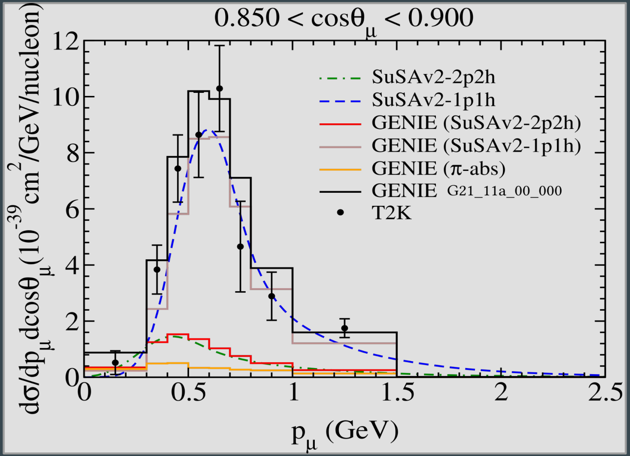
- start with the identification of a GENIE development need
  - either by member of the GENIE collaboration or a contributor / member of the community
  - Following a consultation with GENIE leaders, one or more incubator projects may be launched to address the identified GENIE need
    - scope and milestones
    - 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

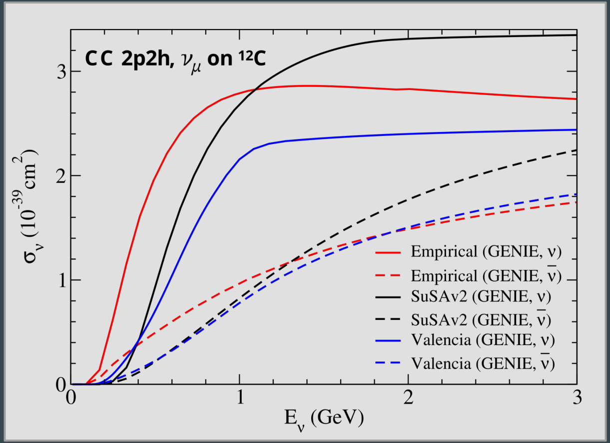
- We don’t have more specifications based on the physics content
  - Every project is considered separately and different solutions will be used
  - BSM projects tends to be easier to be included because they couple less with the rest of the code
    - But things might change as more BSM physics is included

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)]



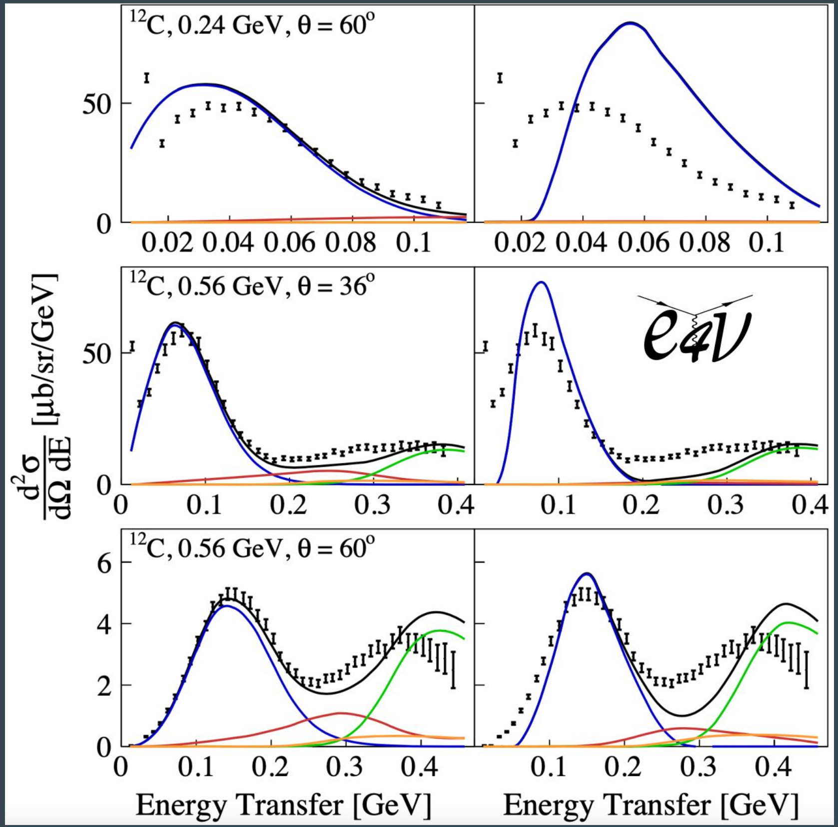


Phys. Rev. D 103, 113003 (2021)

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)
-

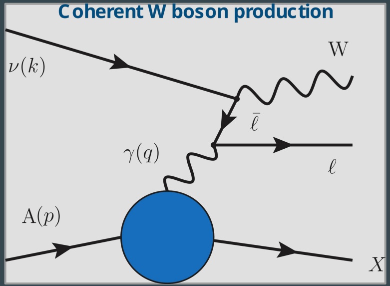
SuSAv2 G18_10a_02_11a



(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)



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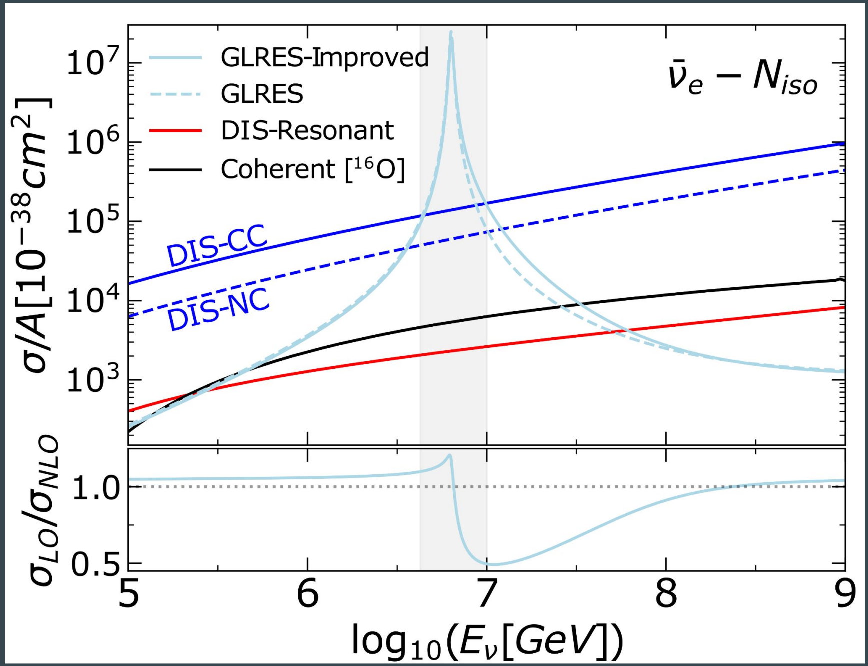
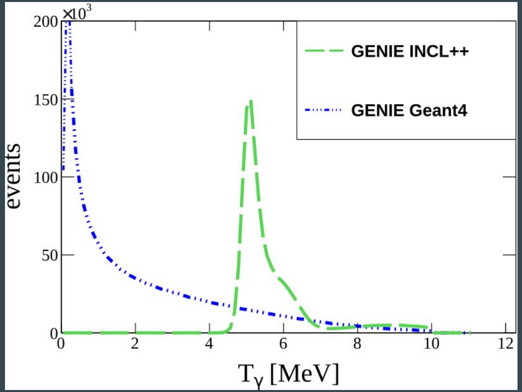
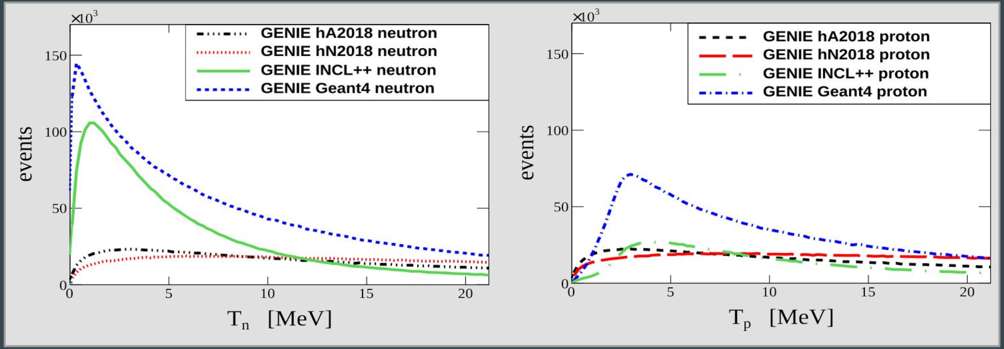


New FSI models: INCL++ and Geant4 Bertini cascade

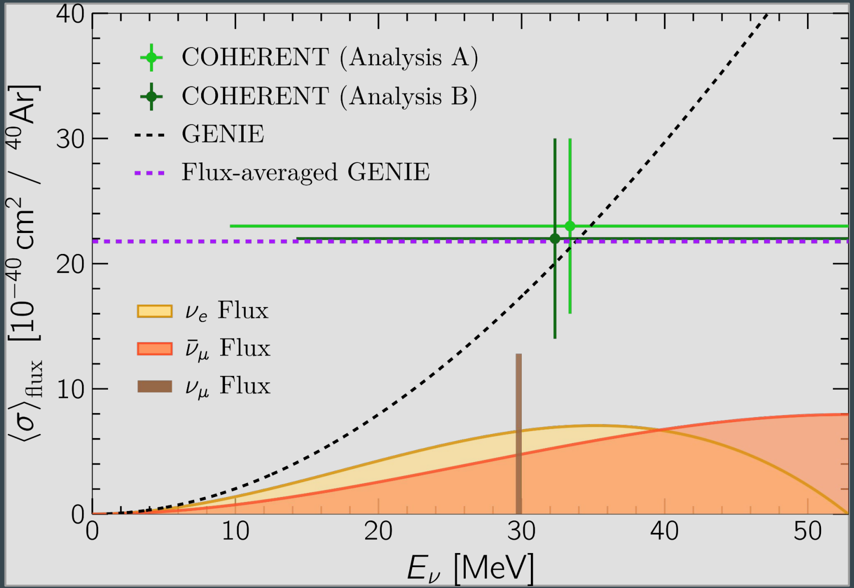
- New cascade FSI models added as external dependencies
  - Liege intranuclear rescattering model, via INCL++
  - Bertini cascade, via GEANT4
    - Contributions by Dennis Wright and Makoto Asai (SLAC)
- Both predict higher proton and neutron multiplicities
  - Room for the experiment to investigate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





CEνNS event generator

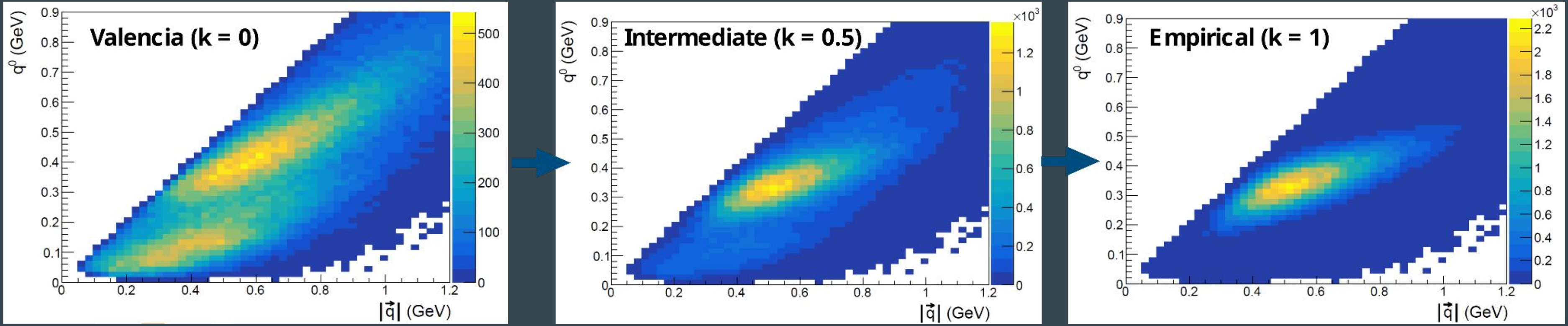
- NC process which leaves the struck nucleus in its ground state
  - Detection via recoil
- GENIE implementation based on Patton et al.
  - Phys. Rev. C 86, 024612 (2012)
- Part of a dedicated tune focused on very low energy neutrinos
  - GVLE18_01a_00_000



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

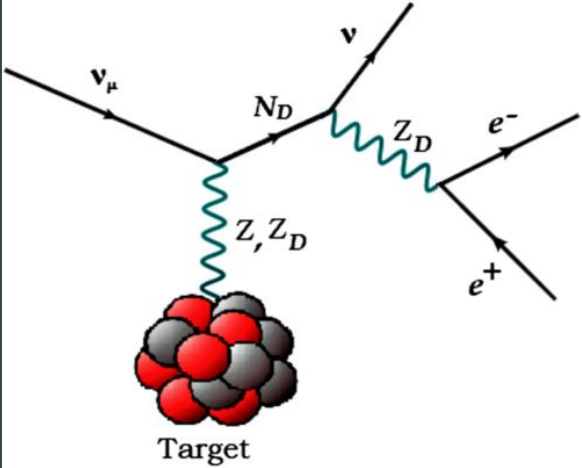
Reweight improvements

- "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 ν_μ CC 2p2h on argon



Dark neutrinos

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



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

- 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
  - 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) 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