Status and recent developments of the GENIE Generator

John Plows
On behalf of the GENIE collaboration

NuFact 2024

The 25th International Workshop on Neutrinos from Accelerators

17/Sep/2024, Argonne National Laboratory

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

UNIVERSITY OF LIVERPOOL

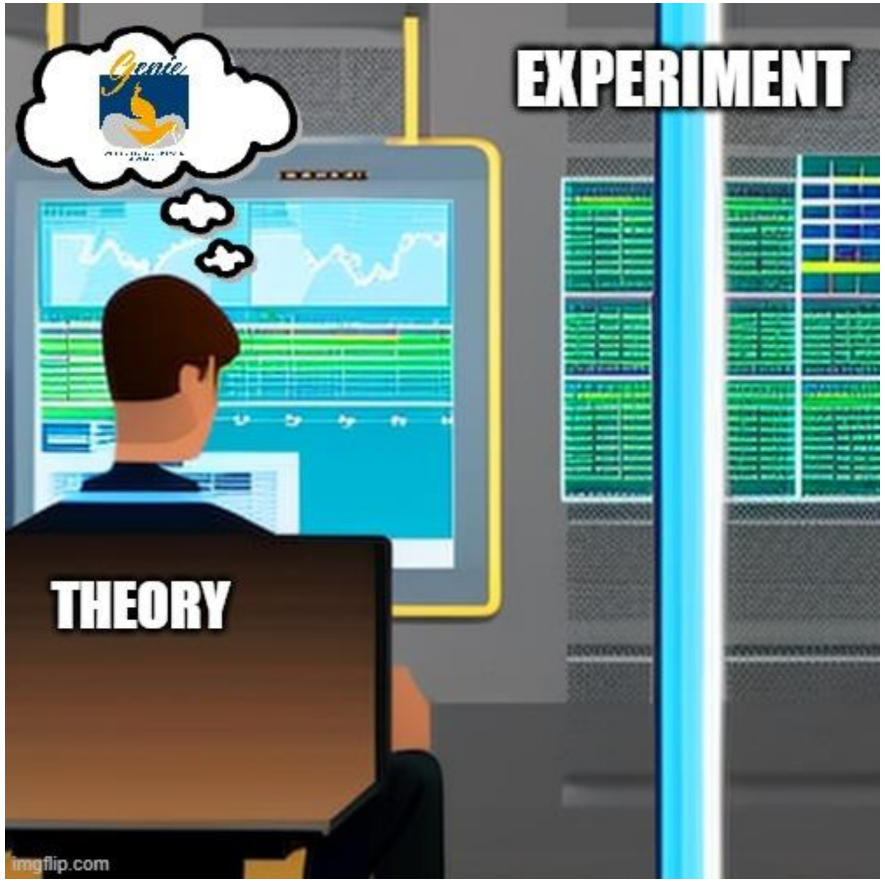
Who we are

- Body of active core members (shown in this slide)
- Many, many individual contributors beyond this!
  - **Incubator process** for contributions to GENIE
  - **Please do get in touch if you are interested in contributing!**
- We maintain a **user forum** for discussions
  - Announced via our **mailing list**

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

(The GENIE Collaboration)

What do we strive to do?



We have a core mission reflecting our **role** in the community!

1. Universal, self-consistent generator: **from MeV to PeV energy scales**.
2. Fundamental framework: modern event generation platform, **standardised applications for major experiments**
   - **specialised software** for electron-nucleus, hadron-nucleus, BSM applications
3. Global analyses: Using scattering data, GENIE provides **interaction model tunes** as well as estimates of generator-level systematic uncertainties.

But also:

- Provide many alternative comprehensive model configurations
- Provide support for interfaces with experiments, tools for simulation (especially with **flux predictions** and **detailed geometries**, as well as a **dedicated reweighting infrastructure**)
- Provide a platform for community discussions

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What does GENIE cover?

- Covers physics from low-energy CEvNS to ultra-high energy DIS + **large coverage in GeV region**
  - Nuclear initial states (including new correlated Fermi gas!)
  - 2 “internal” (hA, hN) and two “external” (INCL++, G4 Bertini) FSI models
  - Some BSM processes
    - “Dark neutrino” scattering
    - HNL decay
    - Nucleon decay
    - n-nbar oscillations
- **Comprehensive model configurations** (tunes) group consistent choices of models
  - User can request specific tune at runtime
  - Room for user-created tunes!

Modelling / CMC	Ground state	Cross-section: quasi-elastic	2p2h	resonance	shallow and deep inelastic	coherent π	diffractive π	$\Delta S=1$ quasi-elastic	$\Delta S=1$ inelastic	Hadronization	FSI
⋮											
G18_02a	RFG w/ NN tail	LS w/ dipole $F_A(Q^2)$	Dytman	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G18_02b											hN18
G18_02c											INCL
G18_02d											G4B
G18_10a	LFG	NAV w/ dipole $F_A(Q^2)$	NSV	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
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G18_10c											INCL
G18_10d											G4B
G18_10i	LFG	NAV w/ $F_A(Q^2)$ from z-exp	NSV	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G18_10j											hN18
G18_10k											INCL
G18_10l											G4B
G21_11a	LFG	SuSAv2 w/ dipole $F_A(Q^2)$	SuSAv2	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G21_11b											hN18
G21_11c											INCL
G21_11d											G4B
⋮											

Non exhaustive list at tunes.genie-mc.org

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  - Room for user-created tunes!

+ Tools: Geometry and flux support via dedicated drivers, Event Library interface
+ A Reweight repository for propagating model uncertainties

Modelling / CMC	Ground state	Cross-section: quasi-elastic	2p2h	resonance	shallow and deep inelastic	coherent π	diffractive π	ΔS=1 quasi-elastic	ΔS=1 inelastic	Hadronization	FSI
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⋮											

Non exhaustive list at tunes.genie-mc.org

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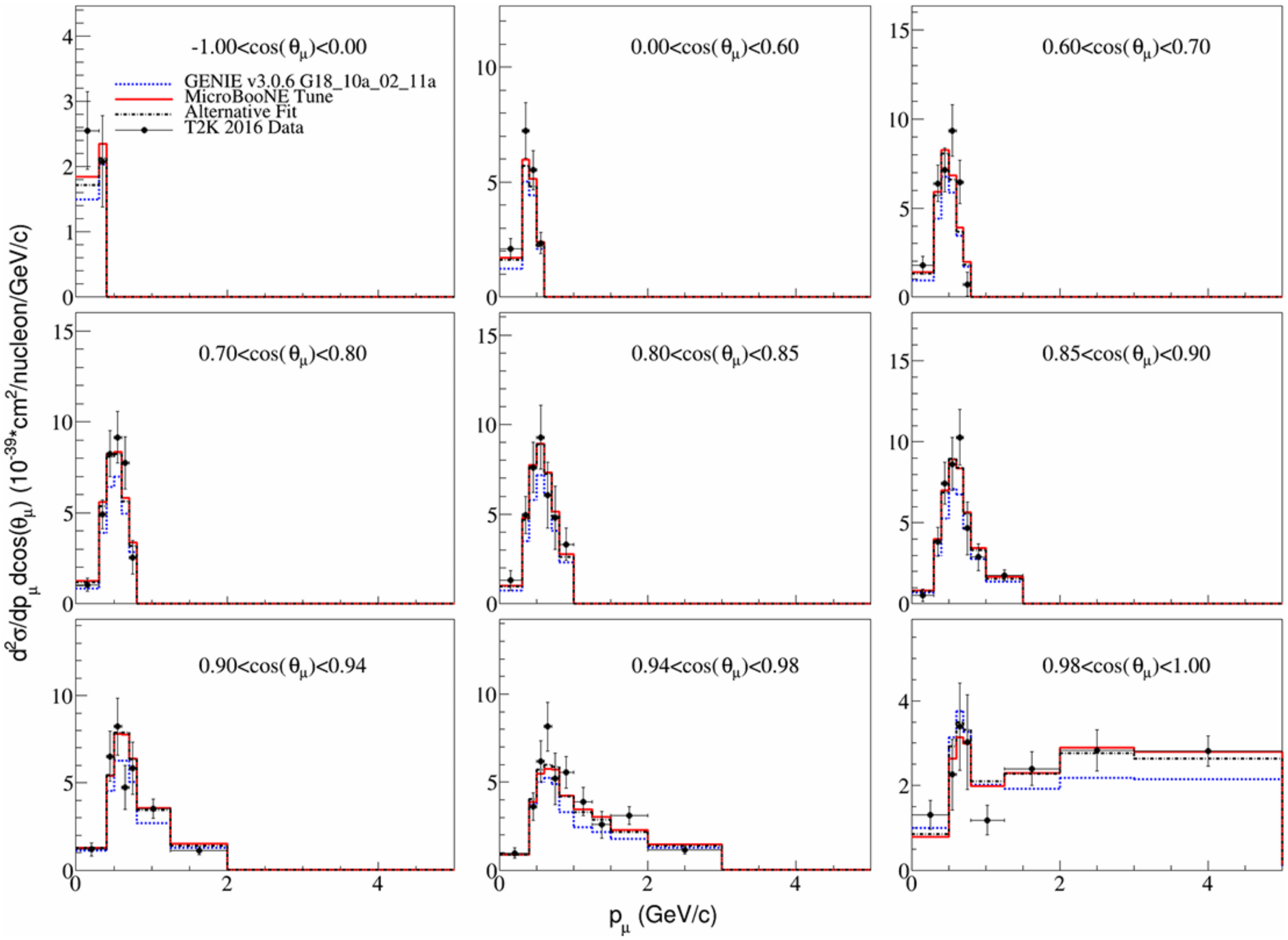
Where are we at?

- Latest release: v **3.04.02** (v 3.06.00 in development)
- Available as of v 3.04.00:
  - Spectral function-like approach for binding energies (S. Dolan, L. Munteanu)
  - External FSI models: INCL++, GEANT4 Bertini cascade
  - Implementation of the Bosted-Christy fit of e-A scattering data
    - This is an inclusive model so only affects the overall cross section

New tune proposed by argon experiments for SBN / DUNE:

AR23_20i_00_000

(aka G24_20i_00_000, available in master branch)



Phys. Rev. **D 105** (2022) 072001

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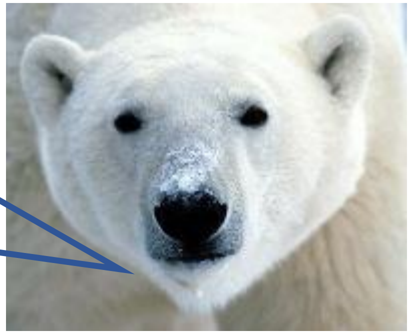
Where are we at?

For more information on our release schedule please visit

releases.genie-mc.org



- Latest release: v **3.04.02**

  v 3.06.00 in development

- Compared to last year's NuFact (v 3.04.00):
  - **Global analysis** of Transverse Kinematic Imbalance data (T2K, MINERνA) on arXiv [2404.08510], accepted for publication by Phys. Rev. D
  - Fixes to 3rd party FSI, nuclear binding energy, flux drivers
- Upcoming/planned:
  - MK single-pion model implementation (Dubna group; Igor Kakorin et al)
  - Professor based reweight tool (Qiyu Yan)
  - Migration from PYTHIA6 → PYTHIA8 (Robert Hatcher et al)
  - Extension to the Heavy Neutral Lepton module (John Plows)
  - Adding simple Bohr motion to initial state electrons (external, Bear Carlson)
  - And many more besides…

In master

Work in progress

Planned

Genie

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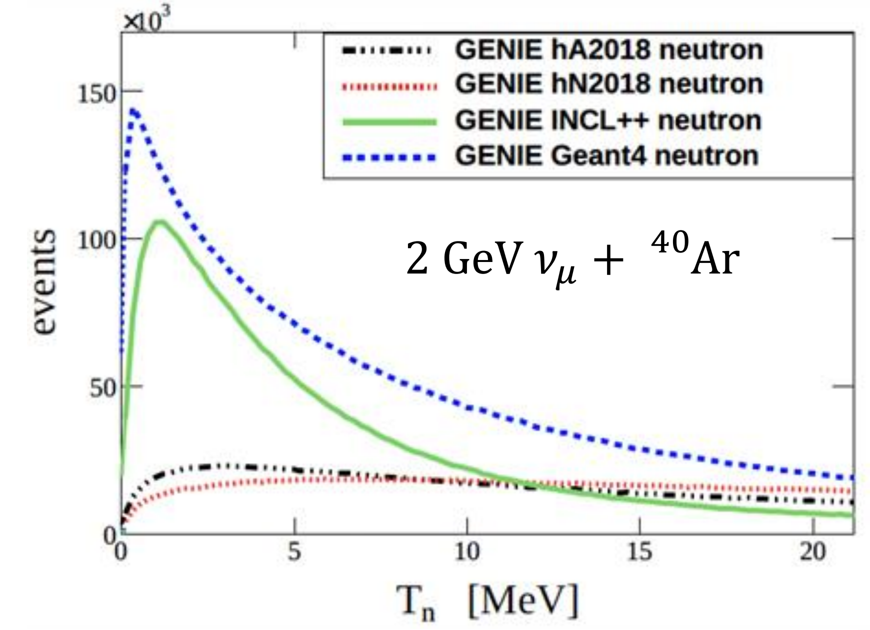
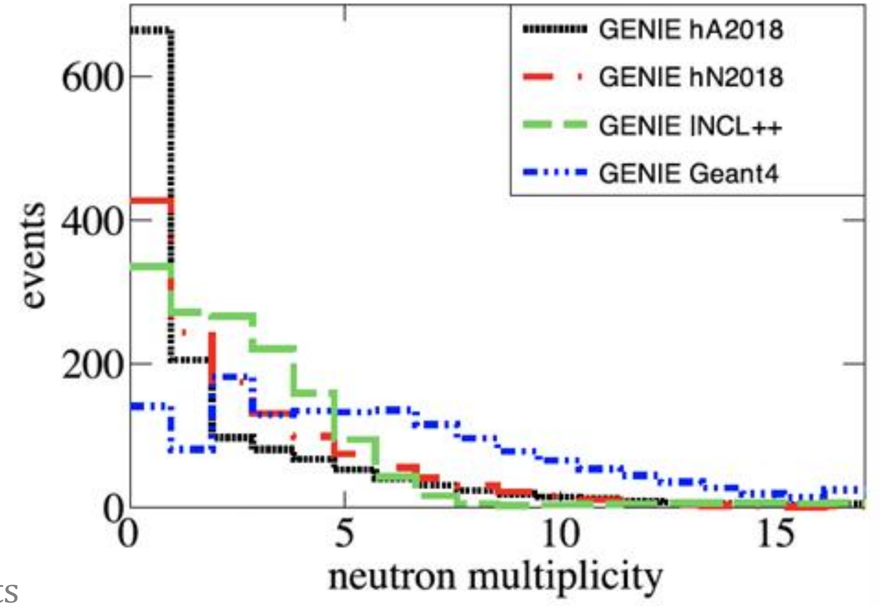
Where are we at?

- Our list of recent publications:
  - W. Li et al, First combined tuning on transverse kinematic imbalance data with and without pion production constraints, [2404.08510] (accepted for publication in Phys. Rev. **D**)
  - J. Tena-Vidal et al, Neutrino-nucleus CC0π cross-section tuning in GENIE v3, Phys. Rev. **D 106** (2022) 112001
  - J. Tena-Vidal, AGKY Hadronization Model Tuning in GENIE 3, PoS **2022** 078
  - L. Alvarez-Ruso et al, Recent highlights from GENIE v3, Eur. Phys. J. ST **230** (2021) 4449-4467
  - J. Tena-Vidal et al, Hadronization model tuning in GENIE v3, Phys. Rev. **D 105** (2022) 012009
  - J. Tena-Vidal et al, Neutrino-nucleon cross-section model tuning in GENIE v3, Phys. Rev. **D 104** (2021) 072009

Modelling: New external FSI models

- In addition to the INTRANUKE models
  - hA : effective model based on empirical data
  - hN : full intranuclear cascade
- Now have external dependencies for Liège (INCL++) and Bertini cascade (via G4)
  - Contributions by D. Wright and M. Asai
  - INCL++: almost parameter-free quasi-classical treatment of particle fates
  - Bertini: G4 re-engineering of INUCL code. Various models for fast and slow phases of collisions in nucleus
  - New feature: de-excitation photons!
- Significant differences between models in nucleon multiplicity + kinetic energy
  - New model uncertainties to consider
  - New tuning opportunity





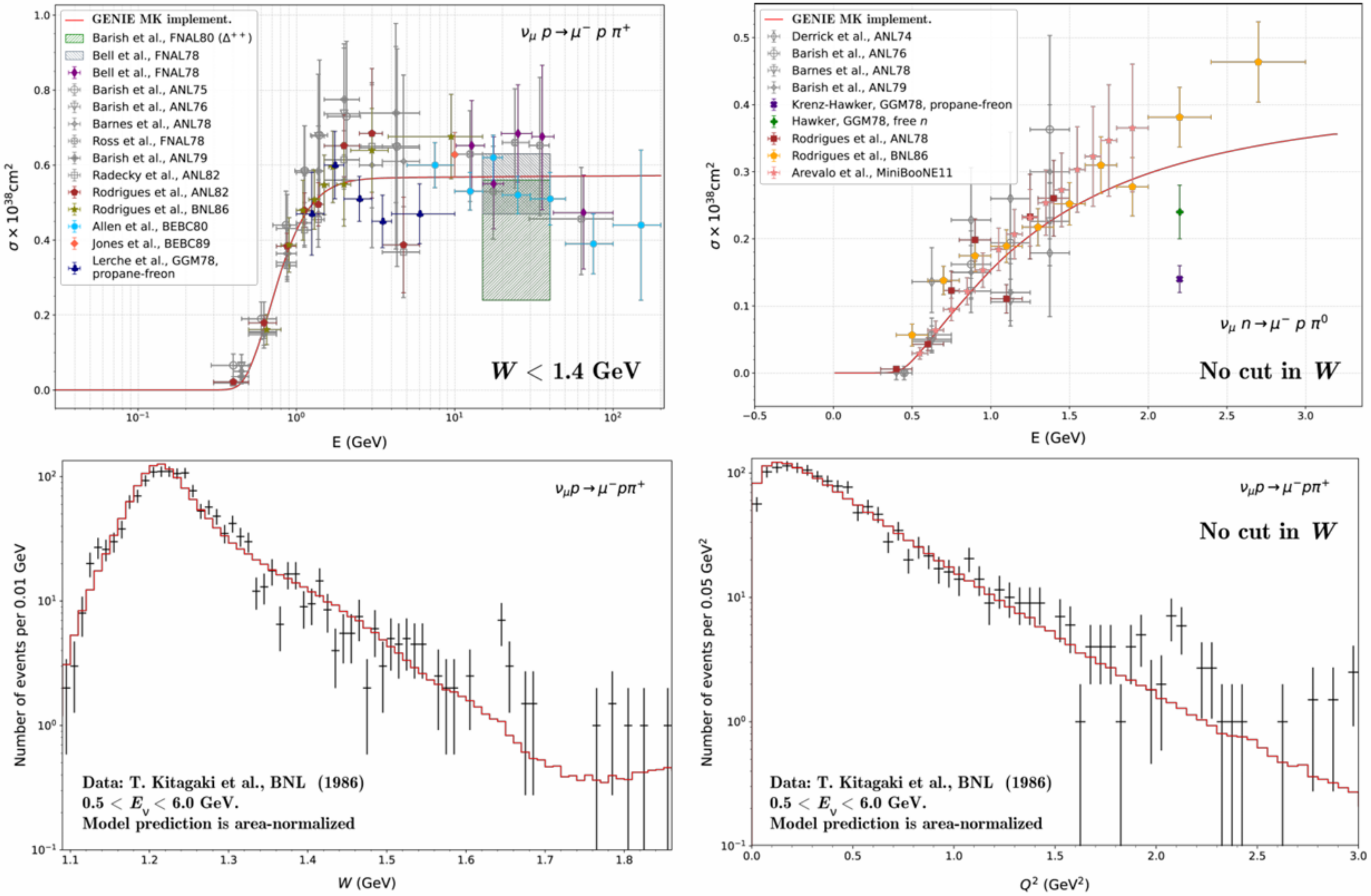
Modelling: Upcoming MK single-pion model

Planned for v 3.06.00
Contribution by GENIE
Dubna group

Combines resonant pion production and nonresonant background

Differential cross section in $Q^2, \mathrm{W}, \theta_\pi, \phi_\pi$

Is accessed via its own tune-config, MK19_00a



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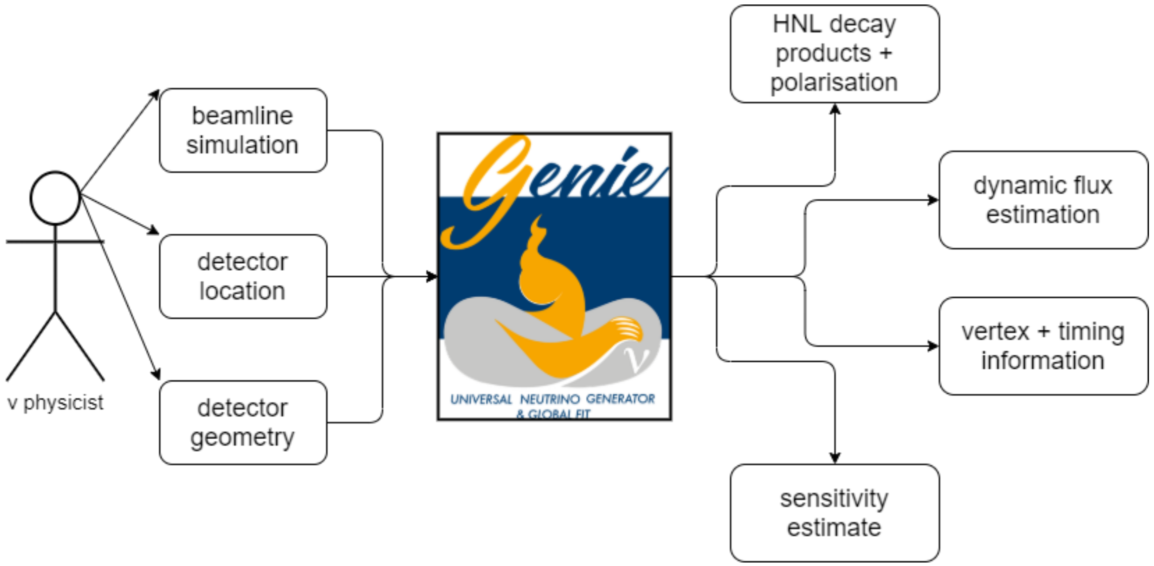
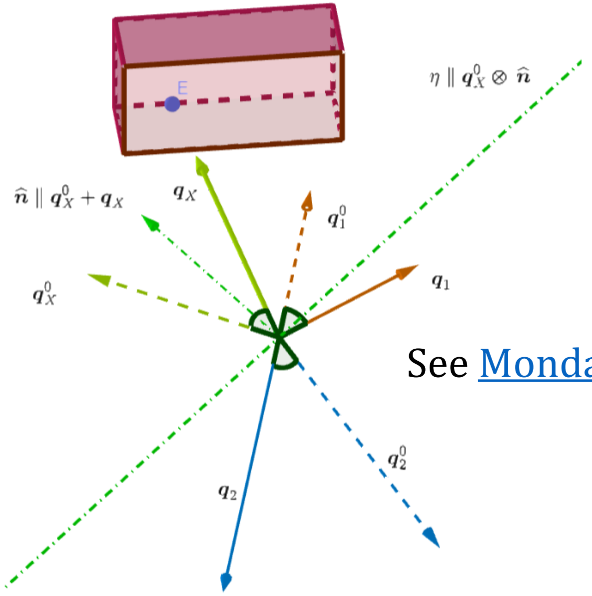
Modelling: Exotic long-lived particles (LLPs)

- In v 3.04.00 we introduced a Heavy Neutral Lepton (HNL) decay module
  - Effective field theory from Eur. Phys. J C **81** (2021) 78
  - Generic choice from 10 implemented decay channels
  - Interface with record of parent particles
  - Companion paper: Phys. Rev. **D 107** (2023) 055003
  - Caveat: **very model dependent**
- **Upcoming improvement:** A generic module for unstable long-lived particles
  - User specifies production **and** decay channels - complete freedom for phenomenology
  - Many individual weights stored for full reweighting capability
  - Reworked calculation of detector acceptance to accommodate atmospheric use cases as well





See Monday's WG5 talk

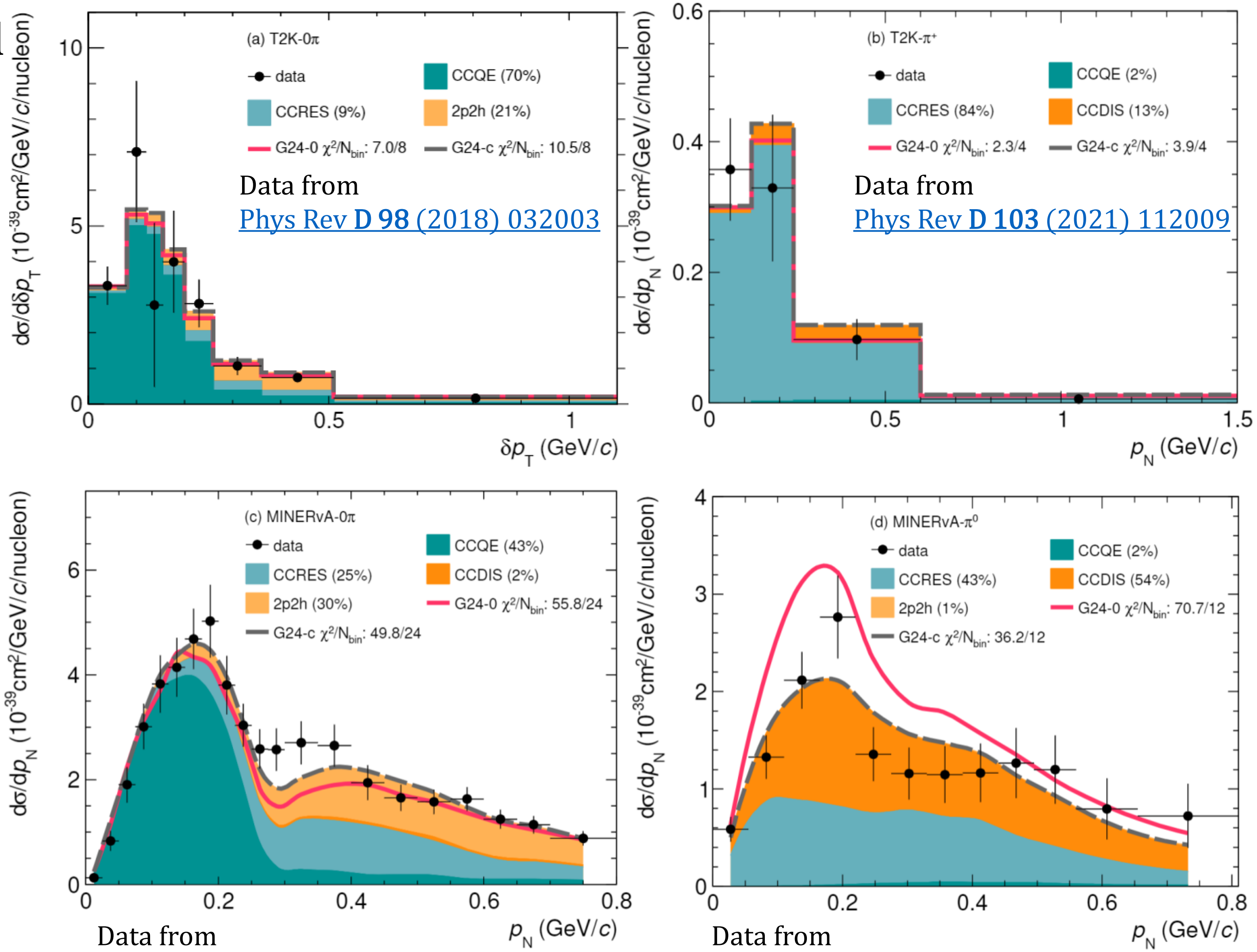
Tuning: The general strategy

- Empirical approaches necessitate ~free parameters to control them!
  - Complicates predictions further (What models did one use? Which kinematic region are they looking at? What phase space do they have access to?)
  - **Not all things are reweightable** (how does one access phase space that wasn't simulated in the first place?)
- **Tuning:** parametrisation based on brute-force scans of the parameter space
  - Multi-dimensional polynomials used to interpolate to different regions of space
  - Based on the Professor (Eur. Phys. J C **65** (2010) 331-357) toolkit
- GENIE is running a **global analysis effort** using tuning to different datasets incorporating priors on parameters & correlations between datasets!

For GENIE v4, we will need parameter sets + their covariance matrices + systematics for a sequence of curated tunes, which we then plan to publish and support

Tuning: Global fit to TKI data [2404.08510]

- First combined tuning on both nonzero- and zero-pion channels **simultaneously**
  - Four TKI data sets: T2K 1μNp (0π, 1π⁺), MINERνA 1μNp (0π, Mπ⁰), N,M > 0
  - Simultaneous fit using random sampling of high-dimensional parameter space
- **Alleviates tension** of G24_20i_00_000 tune with MINERνA-π⁰ while maintaining **good agreement** with the rest of the data
  - Generated a **new tune**, G24_20i_06_22c, available in master branch of Generator
  - Major contribution by W. Li et al



Data from Phys Rev **D 98** (2018) 032003

Data from Phys Rev **D 103** (2021) 112009

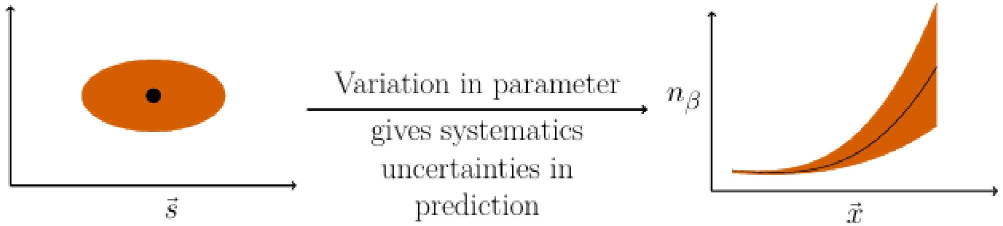
Data from
Phys Rev Lett **121** (2018) 022504
Phys Rev **D 101** (2020) 092001

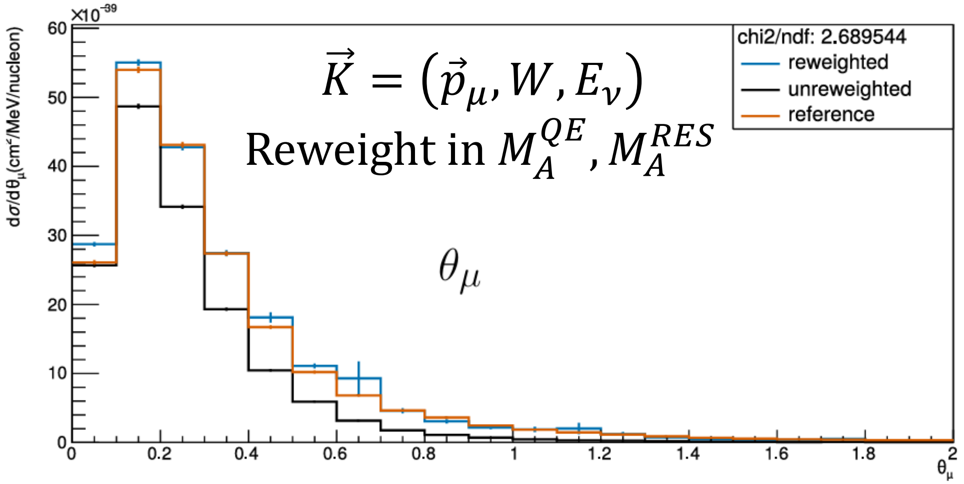
Data from Phys Rev **D 102** (2020) 072007

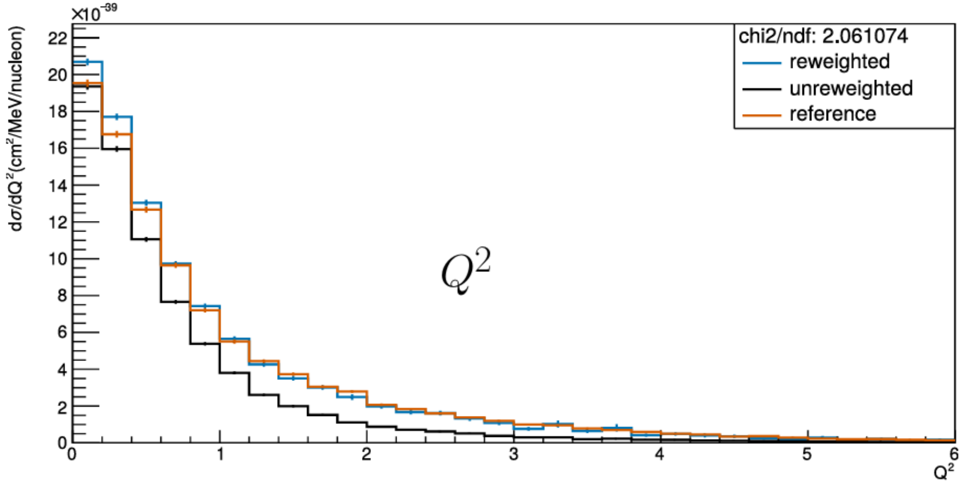
Reweight: The professor strikes back

Qiyu Yan, Neutrino 2024 poster

- Predictions are heavily dependent on initial choices of **relatively free parameter values**
  - Parameter variations yield **systematic uncertainties**! Need to propagate them somehow
- Use the sampling methods of Professor to extract a parametrisation for differential cross-section
- Planned as next major upgrade to GENIE Reweight
- Workflow: Experiments can **run their own brute force scans** (with all experimental inputs)
  - No dependence on internal model specifics (no code overhead, less maintenance!)
  - Ability to design own phase space and get sensible distributions to use for reweighting







Paper in preparation!

Main contributor: Qiyu Yan (Warwick / UCAS)

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Useful links

- Our website: genie-mc.org
- The GENIE releases: releases.genie-mc.org
- The GENIE tunes: tunes.genie-mc.org
- The GENIE Incubator (especially for new projects/ideas)!

- Our GitHub: github.com/GENIE-MC   Generator   Reweight
- The GENIE Slack: geniemc.slack.com

As always, huge thanks to all developers and contributors!
Please join us! We always welcome your ideas and support! ☺

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Backup

GENIE Tunes

- Main difference between GENIE v2 and GENIE v3: **TUNES**!
  - There are so many different models in GENIE the combinations are.. A Lot.
  - Instead, combinations of models that make sense together are used.
  - Users can still make own configurations
- Each tune is attached to a specific **name**:
  - e.g. G18_10a_02_11b   string defining tuning set

G18_10a	LFG	NAV w/ dipole $F_A(Q^2)$	NSV	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020)	hA18
G18_10b											hN18
G18_10c											INCL
G18_10d										AG	G4B

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Please reach out if you feel a new dedicated tune would be desirable!

e.g. SBN/DUNE AR23_20i (aka G24_20i) tune!

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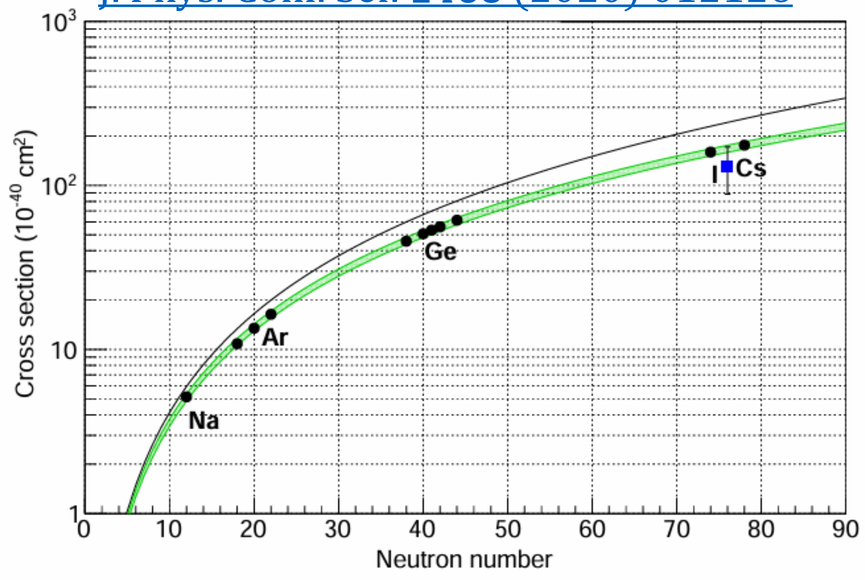
The GENIE Incubator

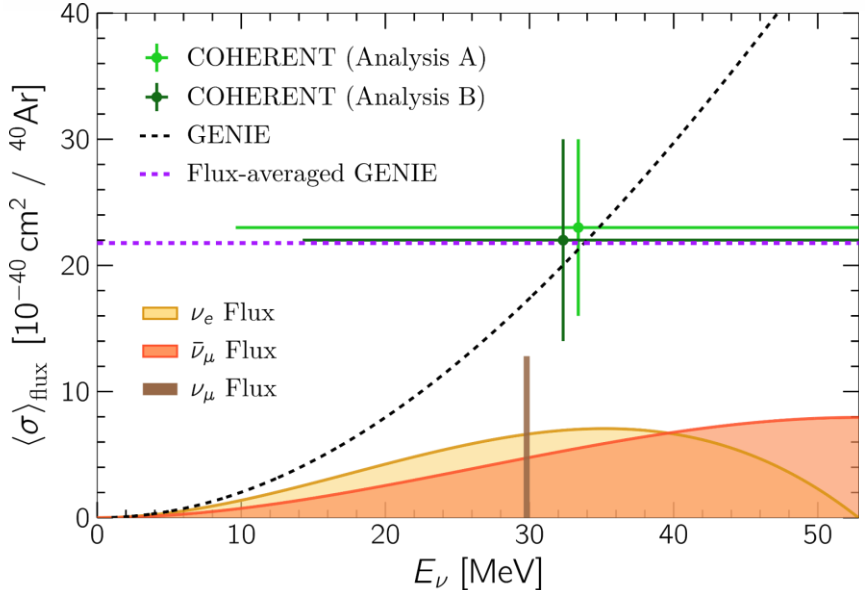
- If you have an idea for a project and would like to see it included in GENIE / contribute to the generator, **please get in touch with us for an Incubator project**
- With the Incubator, you benefit from GENIE expertise, and we can coordinate development efforts!
- How it works:
  - Identify a development need
  - Consult with GENIE leadership to address the need
    - Set scope, deliverables, validation plans, software engineering, review schedule etc.
  - Each project is considered on its own merits! Depending on integration with other GENIE modules, scope, and output
- For example, one may:
  - Develop a new physics model / improve an existing one / add an entire new module
  - Improve numerical procedures / upgrade tools / drivers / framework elements
  - Perform systematic studies / tune physics components

Low-energy: CEvNS

- CEvNS: coherent elastic neutrino-nucleus scattering (NC interaction) that leaves nucleus in its ground state
  - Coherence condition (ground state nucleus) valid for $E_\nu \lesssim 50$ MeV
  - Cross section scales as N^2 with N the number of n
- Event generator with dedicated "VLE" tune GVLE18_01a including CEvNS, neutrino-electron scattering, and inverse beta decay
  - Not in standard tunes, since the final-state channel (recoil nucleus) is almost invisible
- Based on the Patton et al. cross section, Phys. Rev. **C 86** (2012) 024612

J. Phys. Conf. Ser. **1468** (2020) 012126

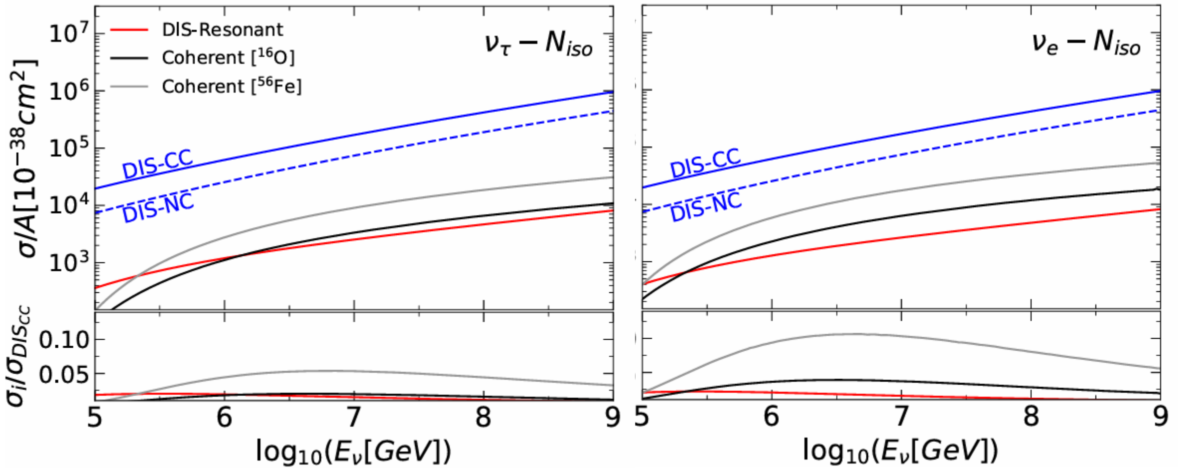


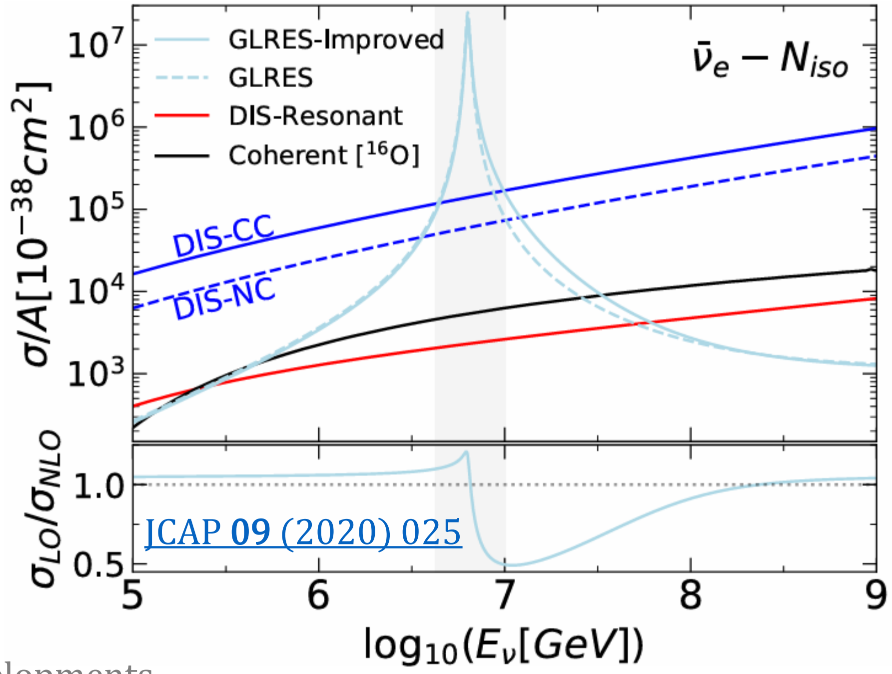


COHERENT data from Phys. Rev. Lett. **126** (2021) 012002

High-energy: PeV scale extension

- Part of the HEDIS module (external contributors A. Garcia, R. Gauld, A. Heijboer and J. Rojo)
- Extends the validity of GENIE to 10^{10} GeV (10^4 PeV)
  - PoS **ICRC2019** 895, JCAP **09** (2020) 025
- Dedicated high-energy physics tunes GHE19_00*
- NLO DIS cross-sections and event generation based on APFEL code
- Coherent W production with NLO corrections





SuSAv2 : superscaling approach

- External contributors: S. Dolan, G. Megias, S. Bolognesi (Phys. Rev. **D 101** (2020) 033003)
- Superscaling: cross section scales as

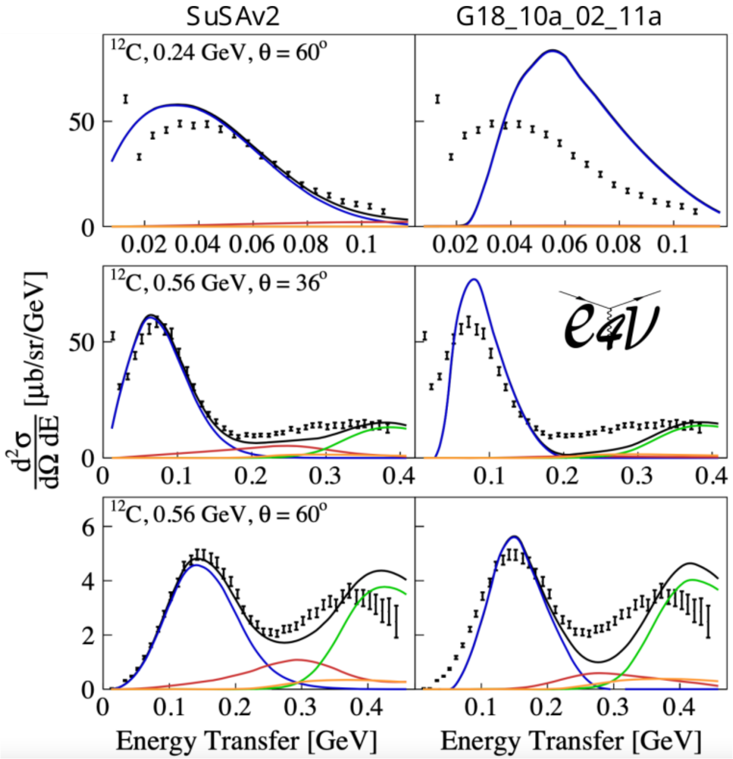
$$f(\psi) \cdot \sigma_{1-nucleon},$$

where f depends neither on q nor on nuclear species

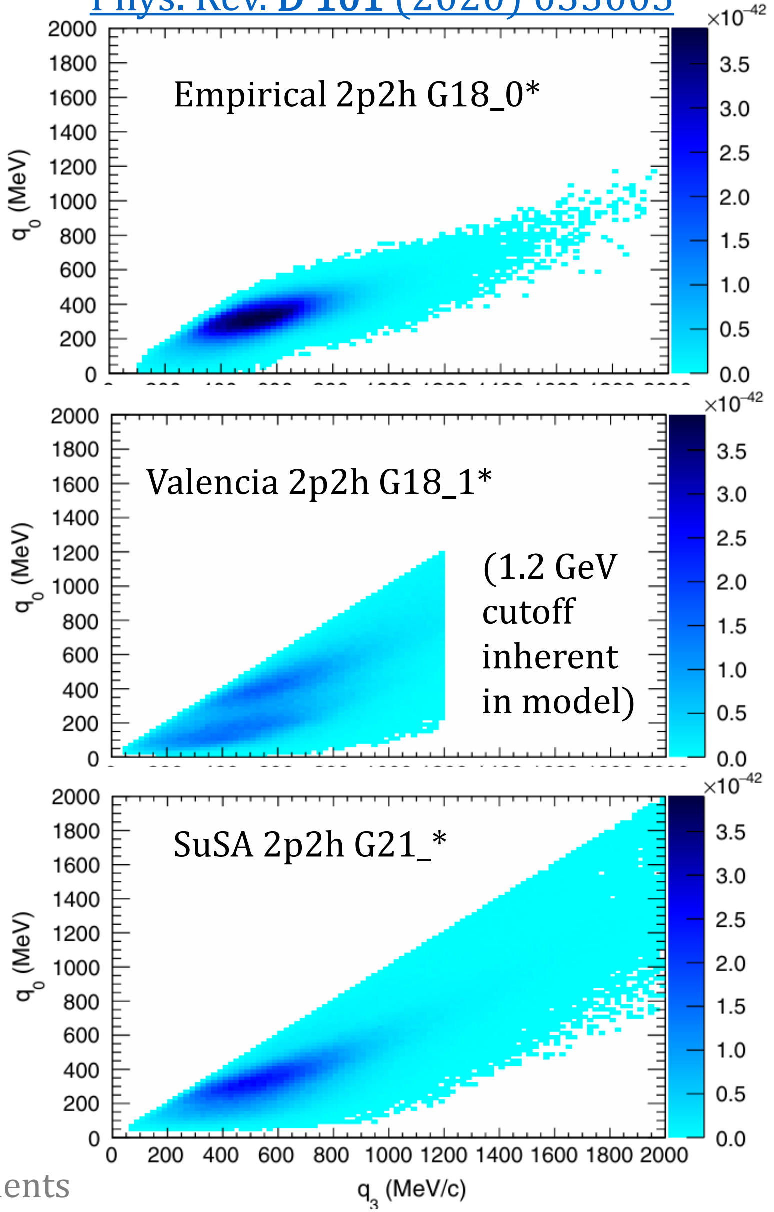
(AIP Conf Proc **1382** (2011) 167-169)

- Part of the G21_11* tunes for QE and 2p2h scattering
- Also describes electron scattering
  - Benchmarked against inclusive electron-scattering data by e4ν collaboration (Phys. Rev. **D 103** (2021) 113003)

Phys. Rev. **D 103** (2021) 113003



Phys. Rev. **D 101** (2020) 033003



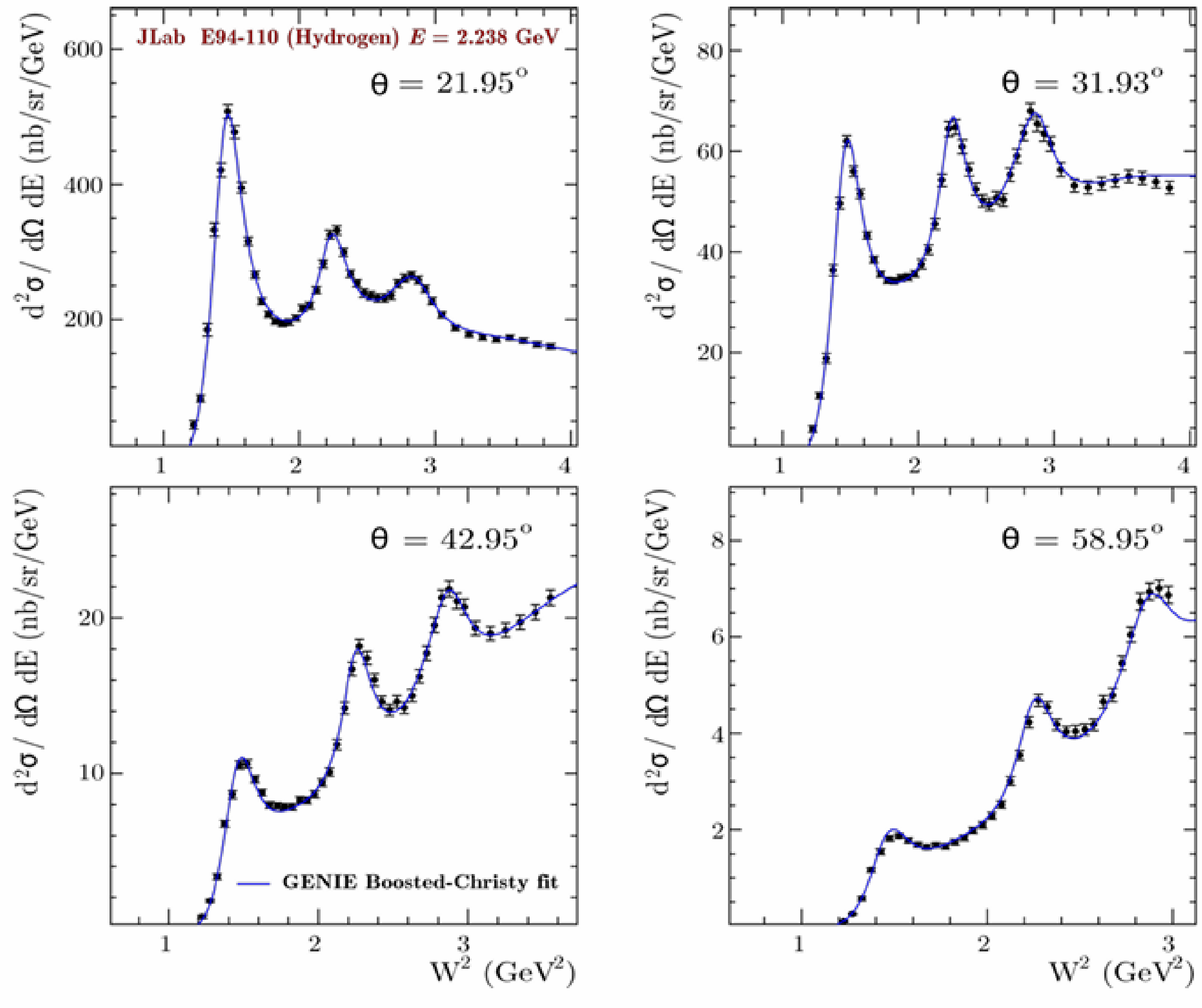
Electron data: Bosted-Christy fit

- Implementation by the GENIE Dubna group
- 2-fold cross section valid at $0 < Q^2 < 10\ \text{GeV}^2, 0 < W < 3\ \text{GeV}$
- Inclusive model → modifies overall cross section and not the kinematics

Phys. Rev. **C 77** (2008) 065206

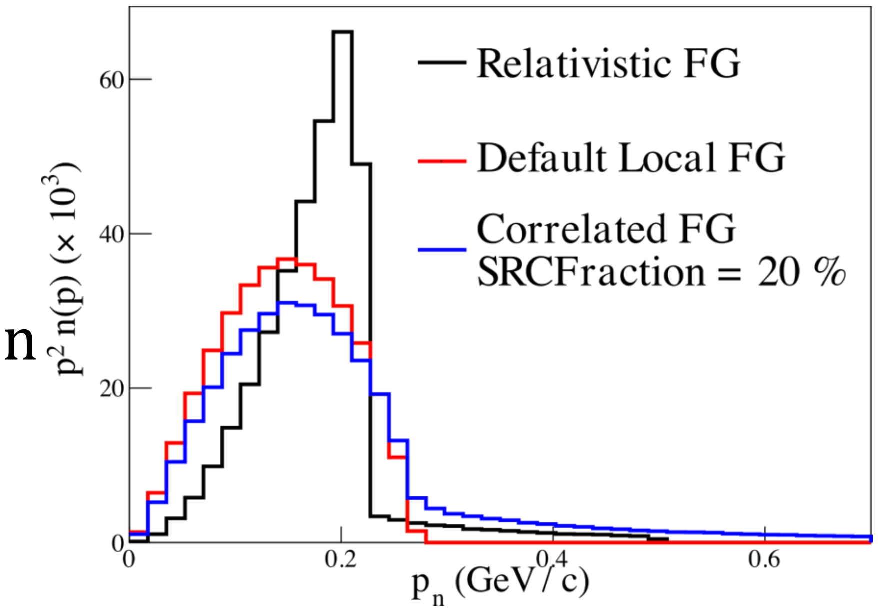
Phys. Rev. **C 81** (2010) 055213

[1203.2262 (nucl-th)]



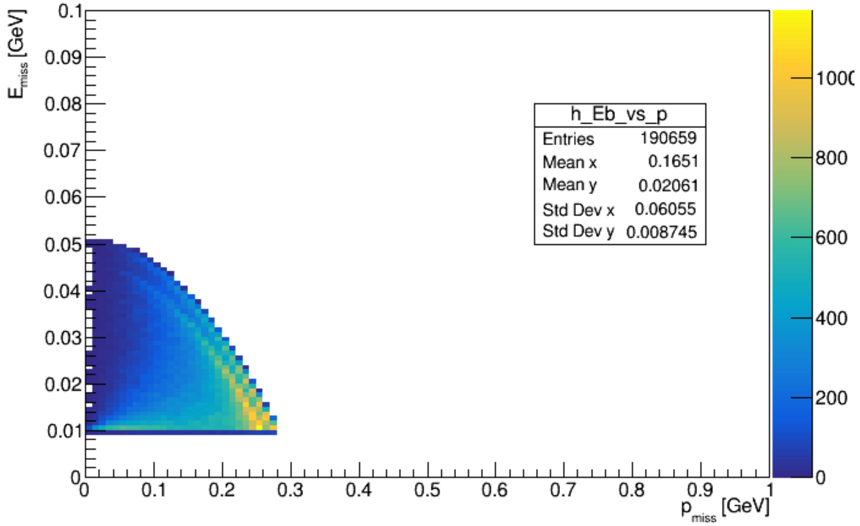
Correlated Fermi Gas implementation

- Implementation inspired by Phys. Lett. B **785** (2018) 304-308
- Contributors: A. Papadopoulou, S. Dolan, L. Munteanu
- Model high-energy tail of initial state for nucleon in nuclear potential
- Extends the local Fermi Gas to higher nucleon energies



Spectral function

- As of v 3.04.00:
- Spectral function-like approach where nuclear binding energy is function of nucleon momentum
  - **Not a full Spectral Function**! Just populates the phase space
  - Can be reweighted to a SF distribution by a reweighter



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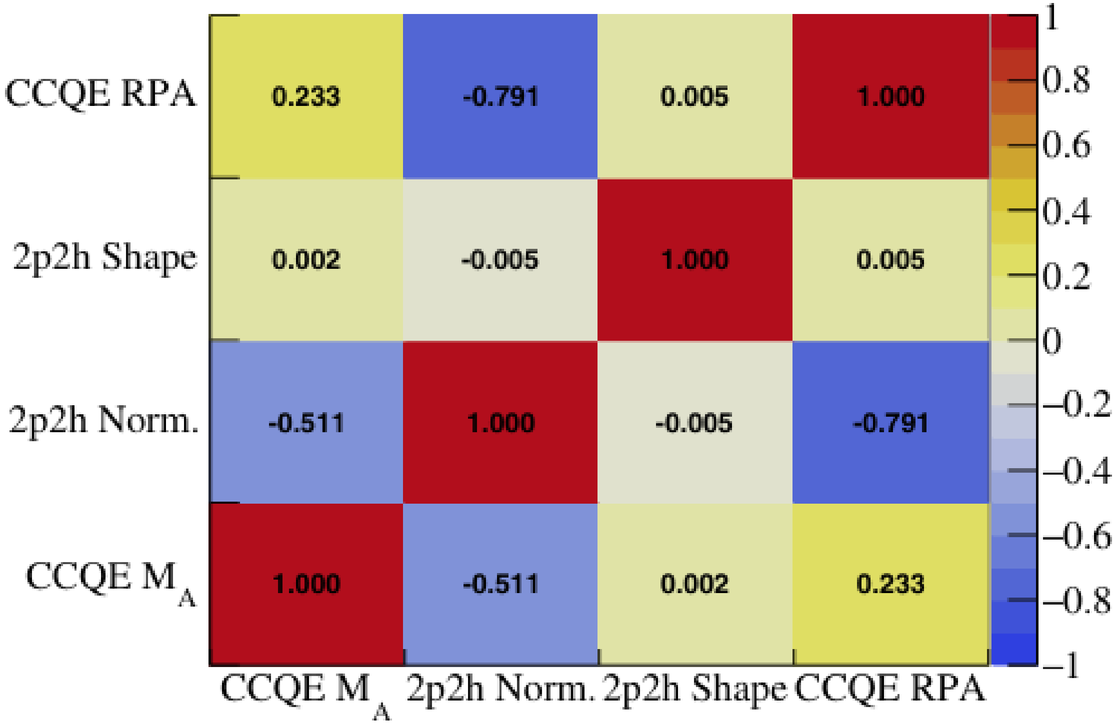
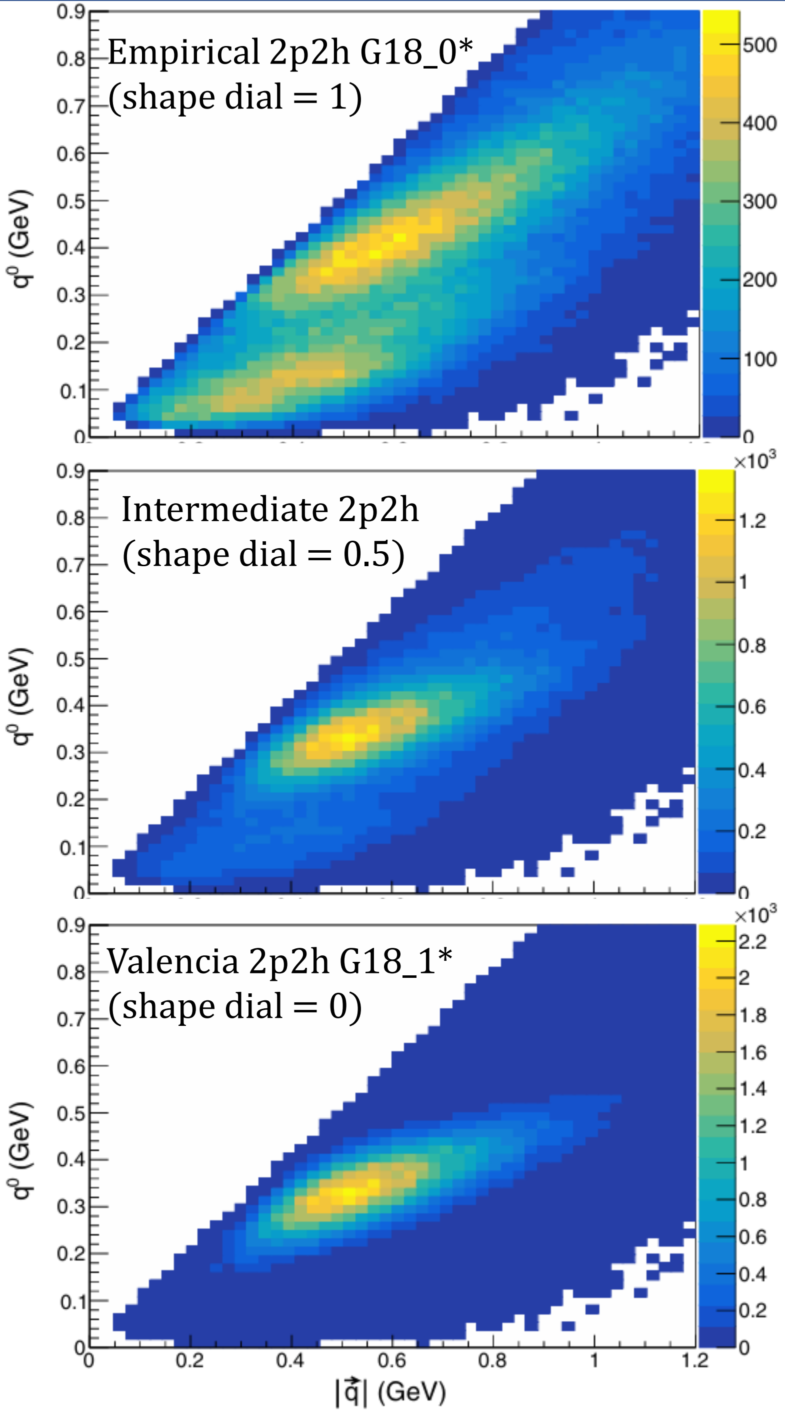
User-motivated tune: MicroBooNE

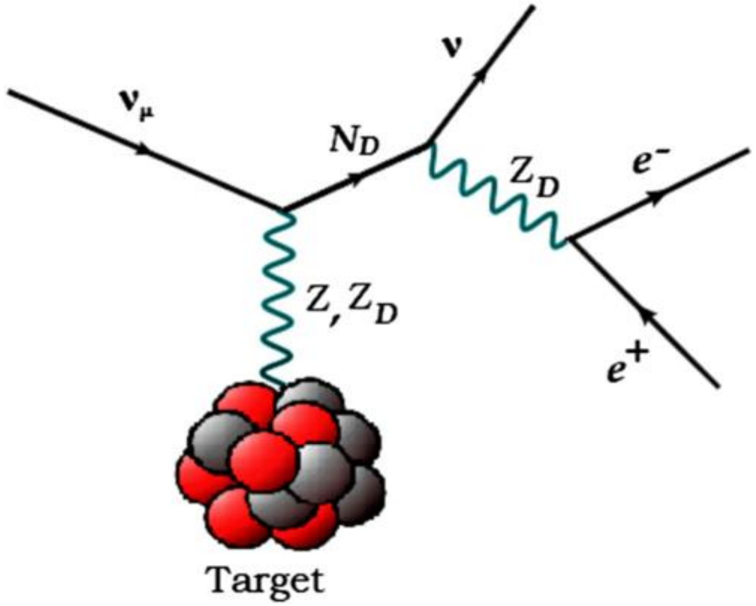
- Fit T2K CC0π data (Phys. Rev. D 105 (2022) 072001)
  - Four parameters previously unconstrained by theory or data
  - New calculators contributed to GENIE Reweight
  - Available since v3.02.00

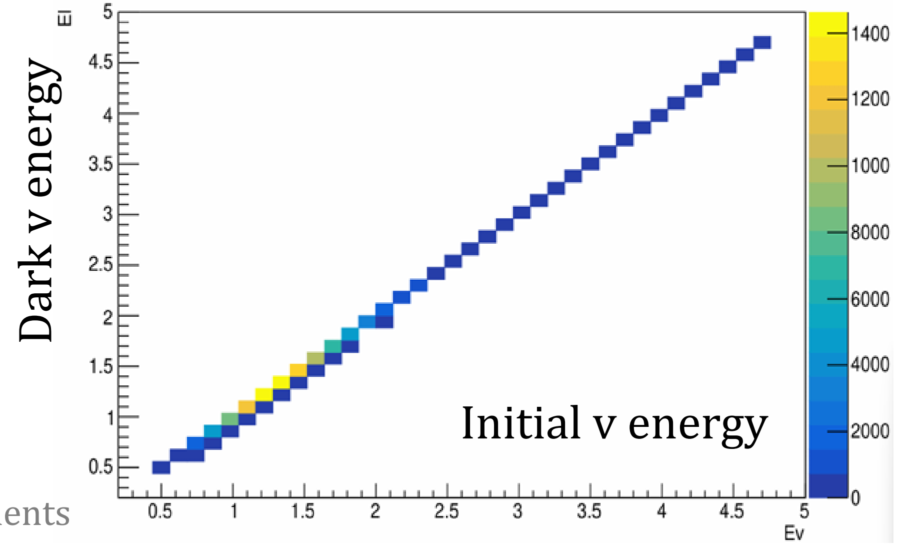




Dark neutrino scattering

- Grew out of the MiniBooNE low-energy excess (Phys. Rev. Lett. **121** (2018) 241801)
  - BSM explanation could be an HNL with a **transition magnetic moment** (couples to "dark photon" Z_D)
  - $\mathcal{L} \supset e\epsilon Z_D^\mu J_\mu^{\text{em}} + \frac{g}{c_W}\epsilon' Z_D^\mu J_\mu^Z + g_D Z_D^\mu \bar{\nu}_D \gamma_\mu \nu_D$
  - Similar to "simple" HNL but with additional coupling g_D
  - Dark photon is light compared to Z, W $\Rightarrow \epsilon'$ negligible
- Contribution by I. de Ikaza and P. Machado
- Extensively stress tested against target isotopes, neutrino flavours, and $E_\nu \leq$ 1PeV (see more in this NuSTEC workshop talk)

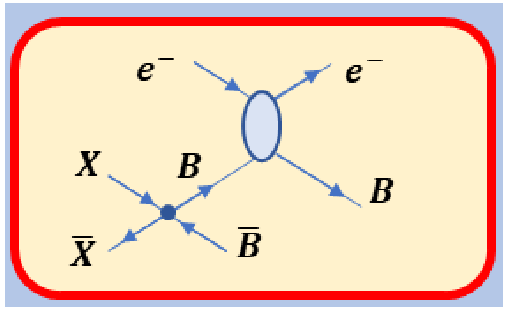


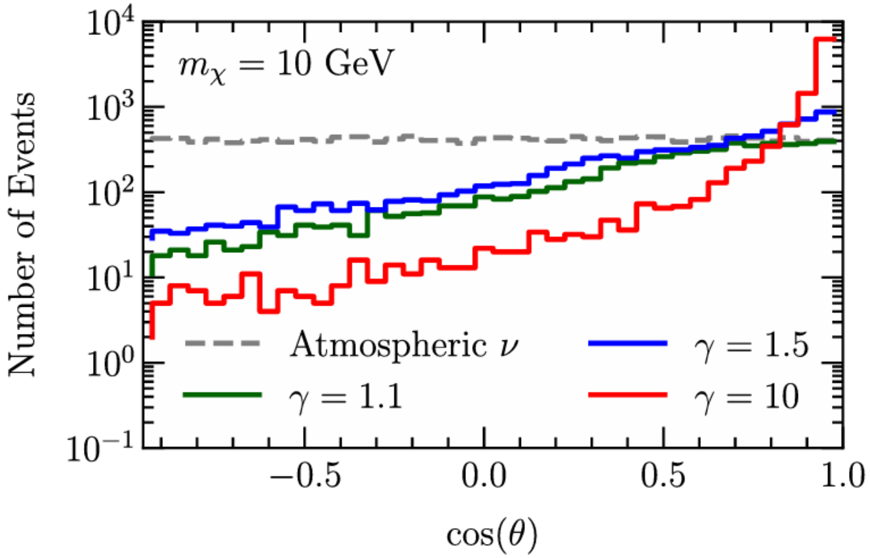


Boosted dark matter scattering

- Substantial improvement over v3.00.00 into v3.02.00
- Contribution by J. Berger [1812.05616]

- Scalar or fermionic BDM
- Vector and axial couplings
- Improved modelling of elastic scattering + pseudoscalar form factor
- B-electron scattering
- B-bar scattering

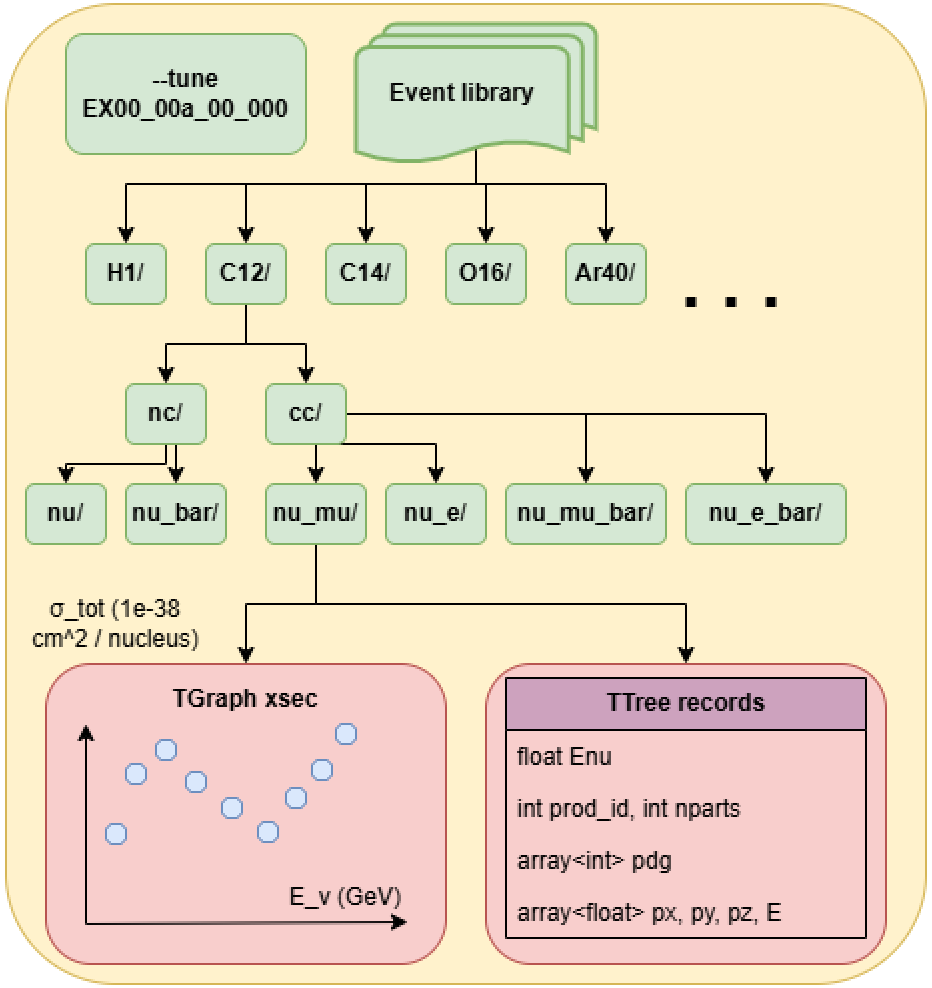




Expected BDM hadron-producing signal from the Sun at DUNE FD (Phys. Rev. D 103 (2021) 095012)

Event library

- Use GENIE's flux and geometry drivers with events generated with other generators
- Streamlines workflow: keep production pipelines (already integrated with GENIE) available for use
- But lose some truth information about events
- Simple organisation: user needs to fill out total cross-sections and information about final state for each (current x flavour x target)



- Contribution from NOνA experiment