UPDATES FROM NEUTRINO GENERATOR LAND

P. Stowell, for J. Isaacson. C. Andreopoulos, M. Roda, J. Sobczyk,
U. Mosel, K. Gallmeister, Y. Hayato, and many others.

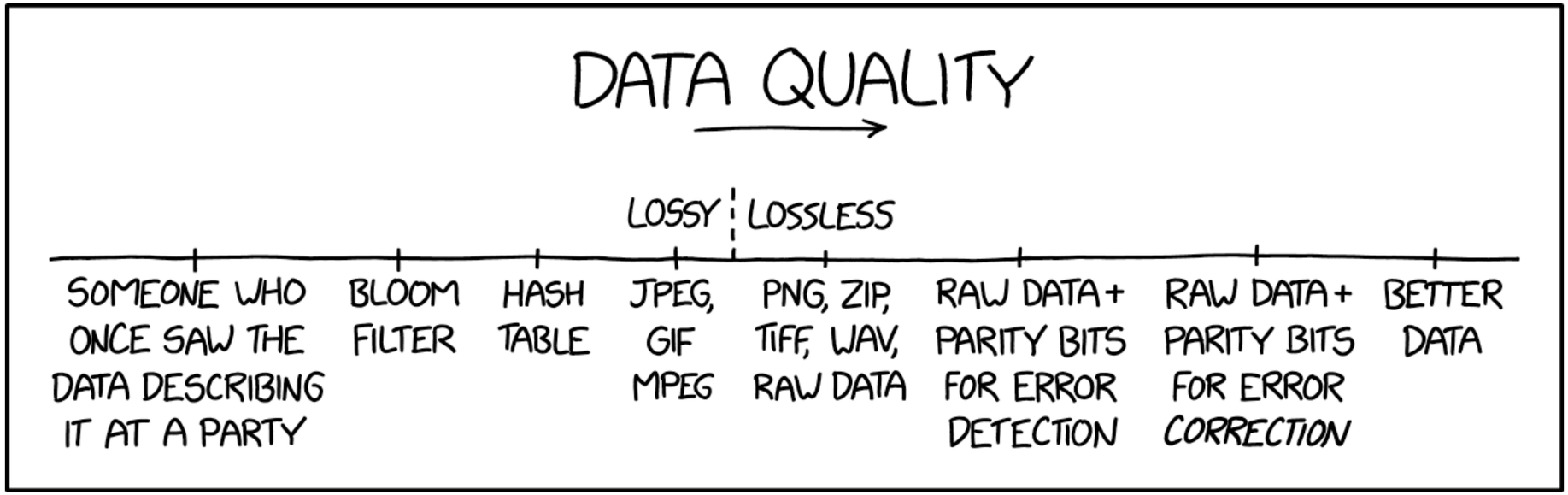
ECT* Neutrino Workshop 2024

University of Sheffield

WHY ARE WE HERE?

CCQE UNFOLDED IN BINS OF TRUE Enu

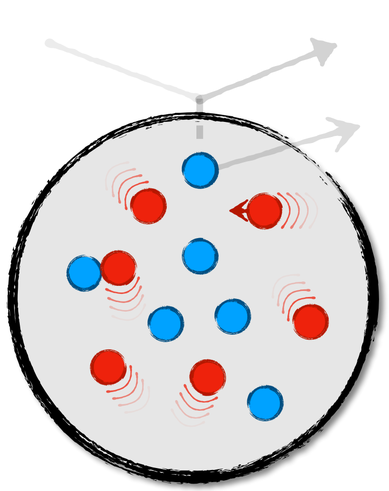
"Data quality" - xkcd



FINAL STATE IN BINS OF OBSERVABLE KINEMATICS

- Move to semi-inclusive final state topology measurements mean neutrino generators are continually needed to **bridge the gap between theory and experimental community.**

GENERATOR FACTORISATION



Initial State Model

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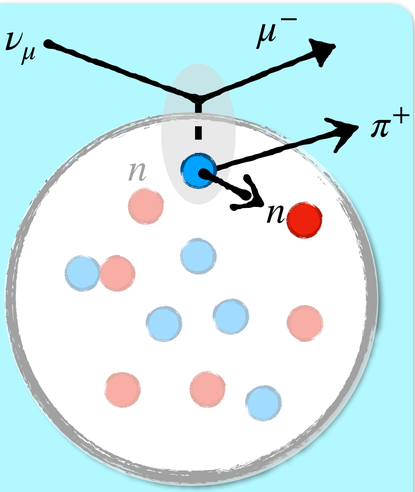

Primary Interaction

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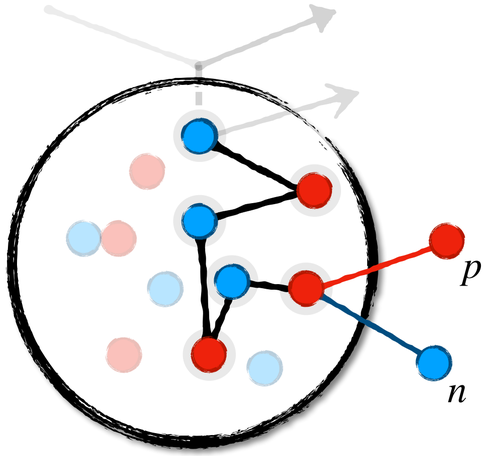
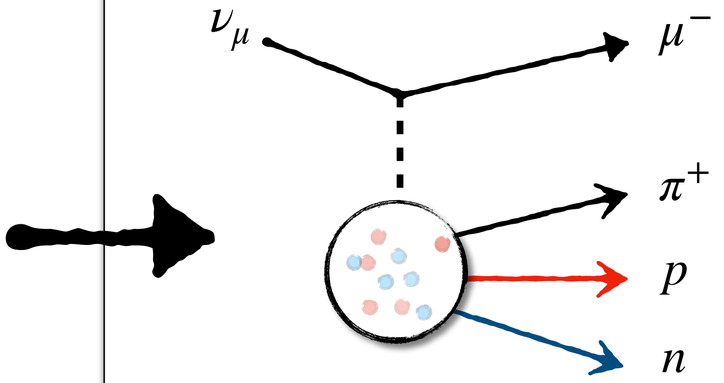
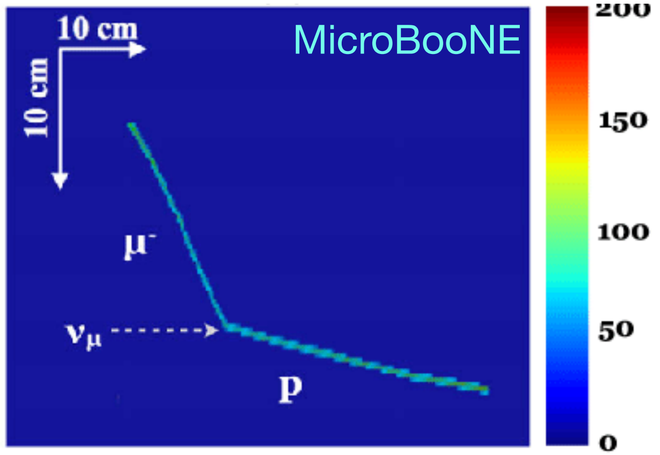


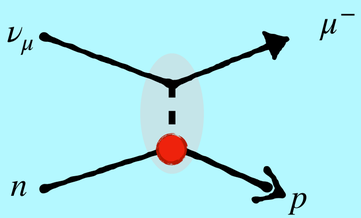
Intranuclear Cascade



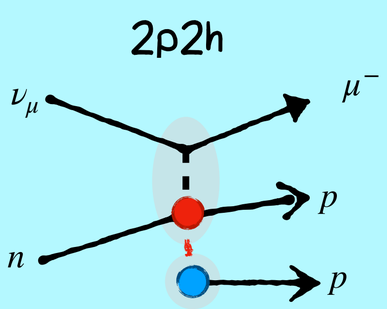
Semi-inclusive Prediction

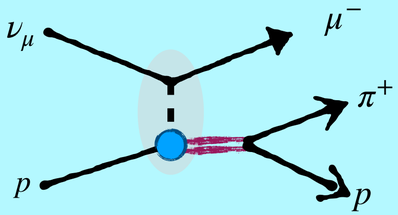


Semi-inclusive Data

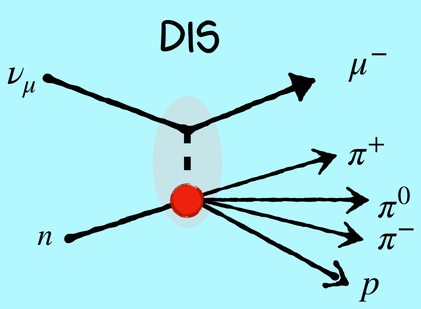


1p1h (CCQE)





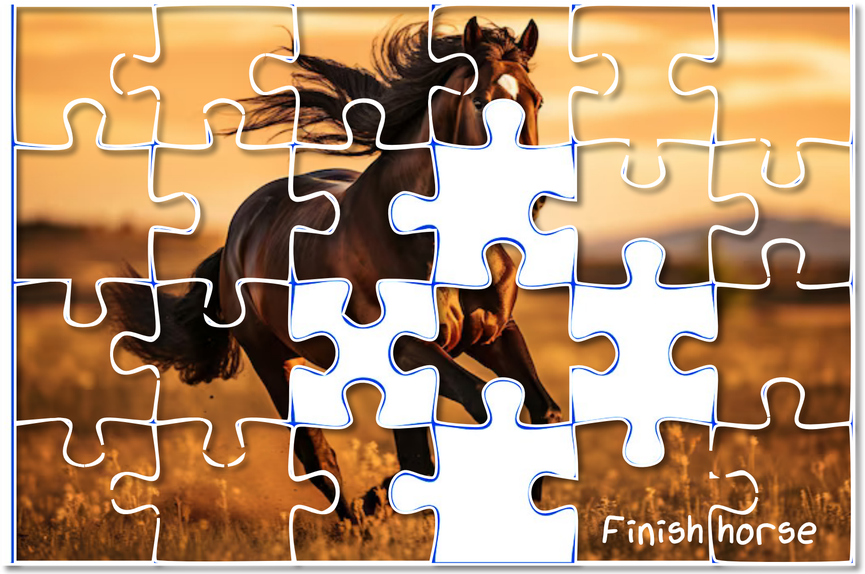
RES

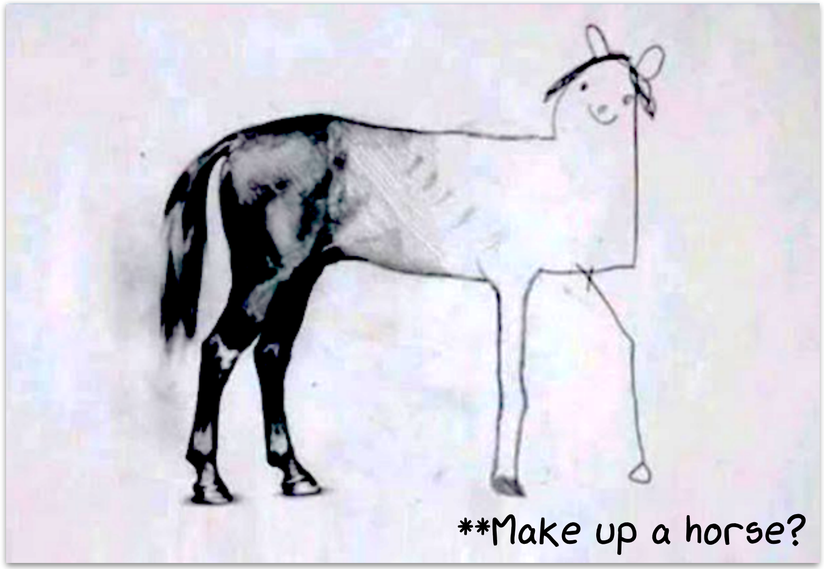


Increasing Energy

MODELLING JIGSAW

- **Common Challenge** : It is difficult for one self consistent theoretical model to cover available data across all $\nu - A$ energy, target, and channels we have measured to date.
- We are **forced to combine*** **or extend**** **models** to explore where additional coverage of the data is needed when understanding systematic uncertainties.



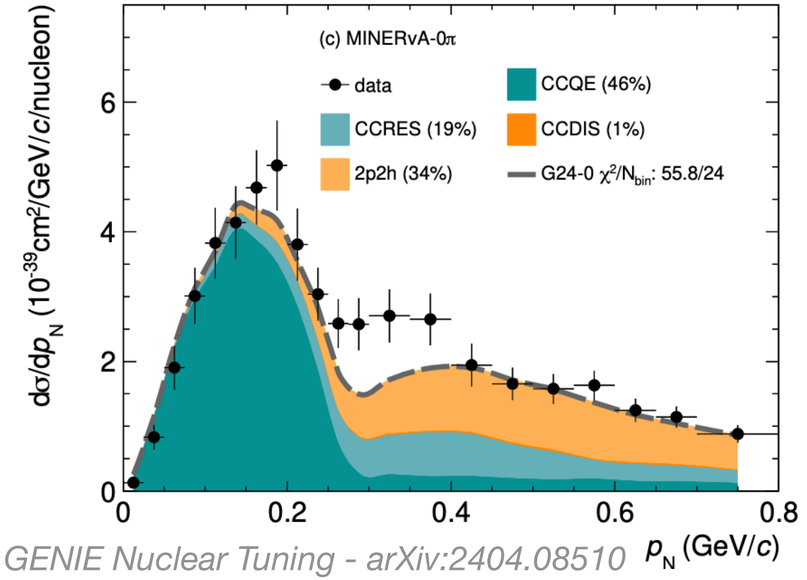


Data-MC Tensions ⟶ Model stitching ("Franken-models") ⟶ Ad-hoc corrections

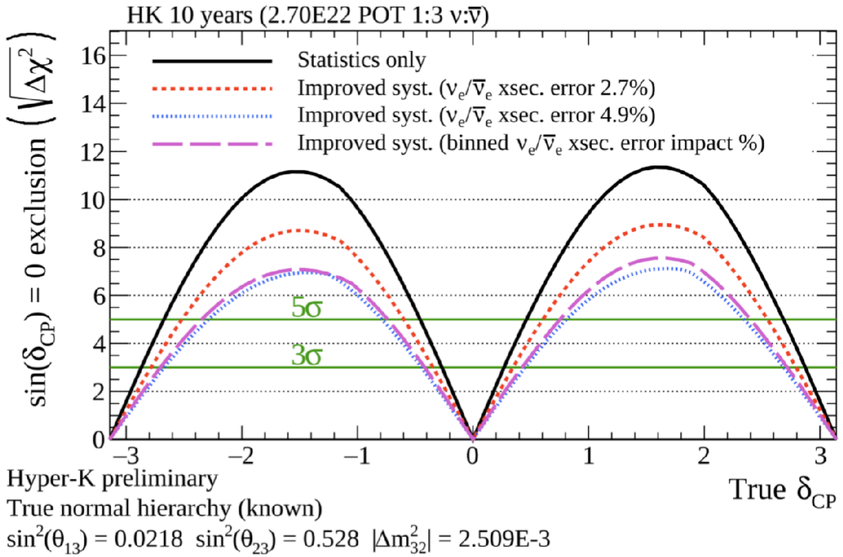
FUTURE EXPERIMENTS

- Regardless of extensions/combinations that are made in individual generators it is important to remember the fundamental goal we are all striving for:
  - A model providing clear description of all observable physics in the neutrino scattering sector.
  - A robust and appropriate systematic uncertainty band and tools for its propagation.
- Cross-section uncertainties a dominant systematic for future experiments.

A Perfect Generator Model for OA



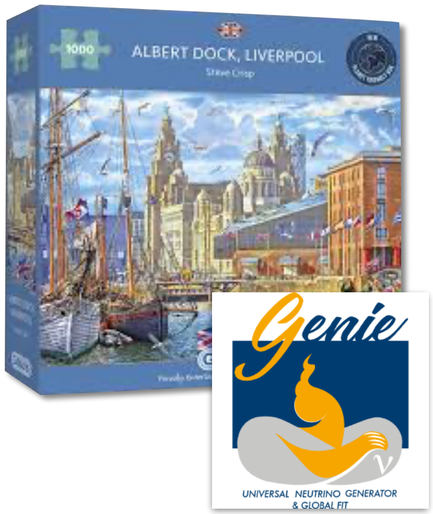
GENIE Nuclear Tuning - arXiv:2404.08510

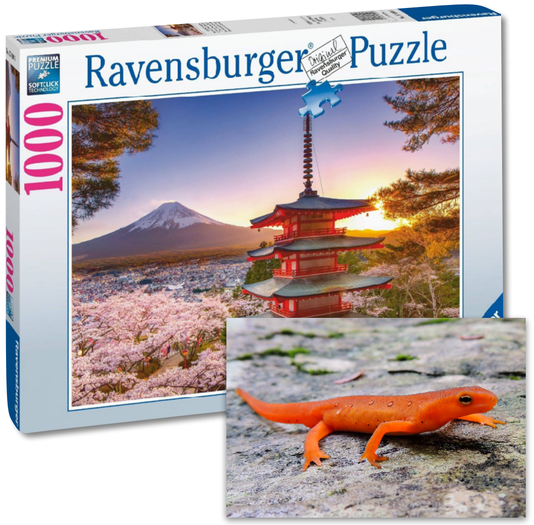


T. Dealtry - HK VALOR

THE PLAYERS

- This talk will just focus on highlights, for extended summaries and details see talks below.





GENIE
NuFACT
NuINT

NEUT
NuFACT
NuINT

NuWro
NuFACT
NuINT

GiBUU
NuFACT
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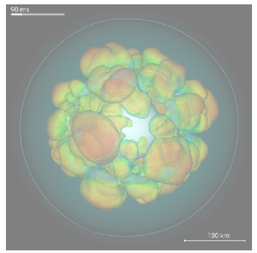
NuFACT

ACHILLES
NuFACT
NuINT

THE GAME

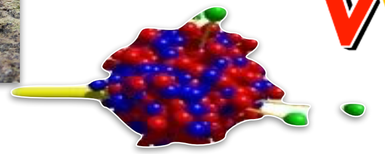
- Also, just focussing on the next generation uncertainties (few GeV range).

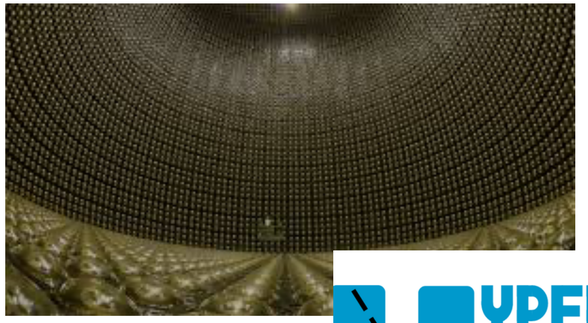
marley

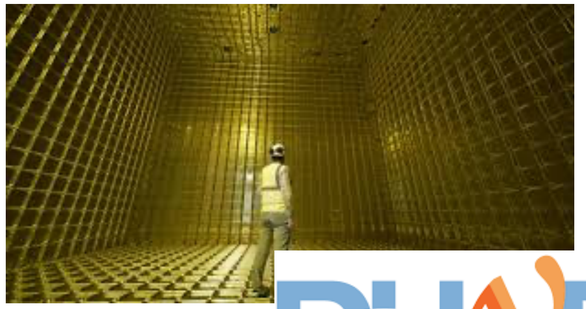


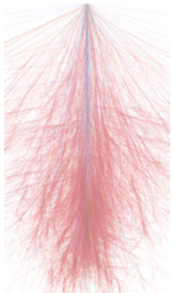
sntools

Increasing Energy









CORSIKA

GENIE

- Universal neutrino generator in use by majority of neutrino experiments - MeV to PeV scale.
- International effort with core developers having both theory and experimental backgrounds.
- Generator of choice for future LAr experiments.
- Large collection of different interaction models and non-standard physics.
  - Geometry and flux support via dedicated drivers, Event Library interface
  - Collection of “tunes” and a reweight repository for propagating standard model uncertainties

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)

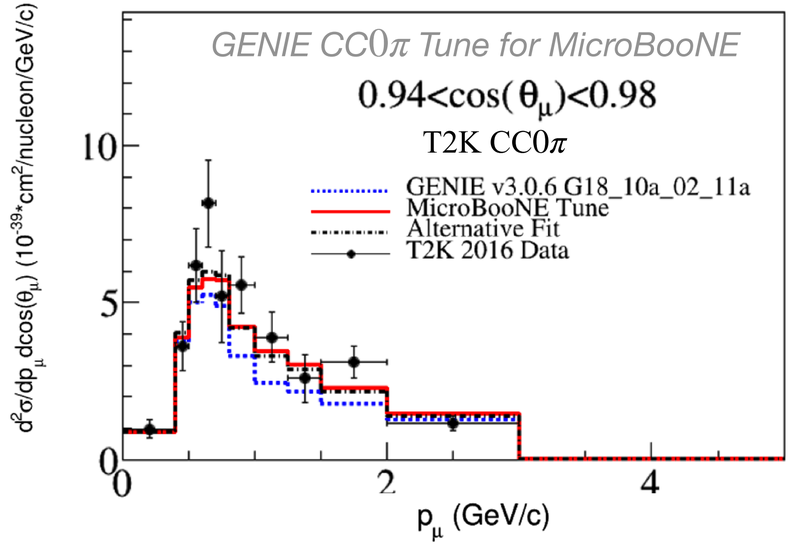
(The GENIE Collaboration)

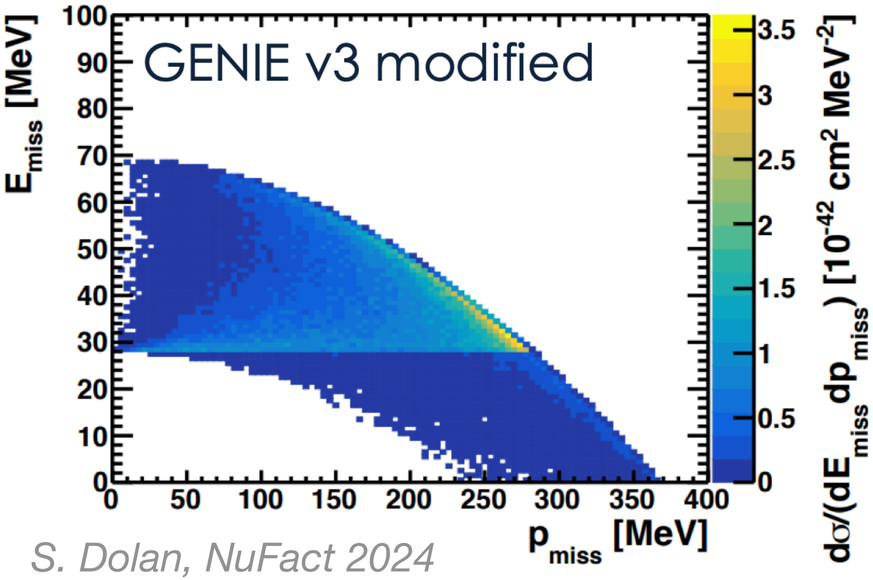
GENIE : MODELS

Available as of v3.04.00:

- 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

- **Latest release: v 3.04.02 (v 3.06.00 in development)**
- Many models for GeV region
  - QEL (LS, Nieves, SuSAv2, ...)
  - 2p2h (Nieves, SuSAv2, empirical)
  - Resonant (Rein-Sehgal, Berger-Sehgal)
  - Nuclear Initial states: RFG, variations of LFG
  - FSI: two internal (hA, hN), two 3rd party (INCL, Geant4)





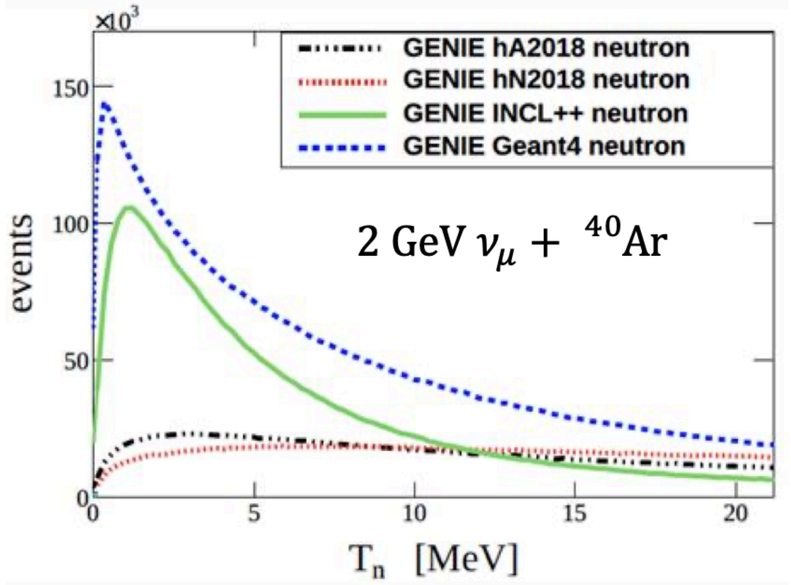
S. Dolan, NuFact 2024

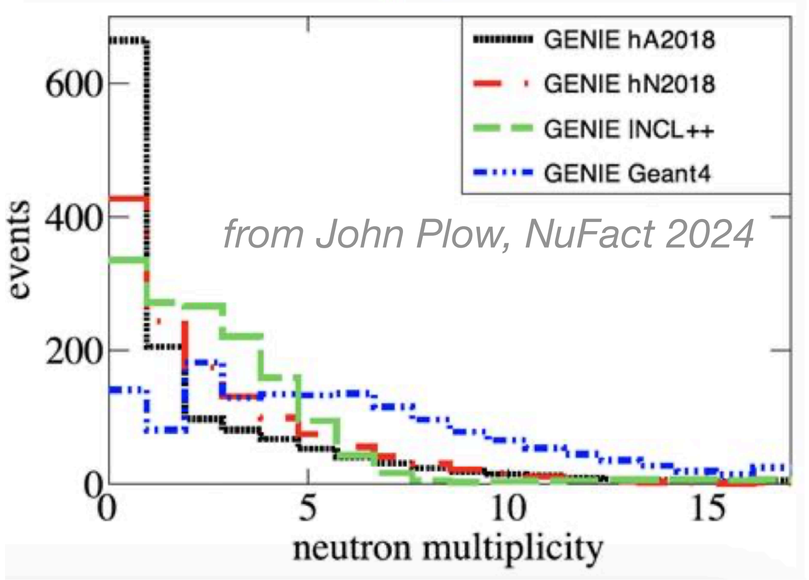
GENIE : RECENT FSI UPDATES

- 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)
  - INCL++: almost parameter-free quasi-classical treatment of particle fates - further work ongoing on FSI interface.
  - Bertini: Interface to run the Geant4 Bertini cascade directly within GENIE for hadron transport.

- Large model variations when looking at outgoing nucleon multiplicity and kinetic energy
  - Work ongoing to understand how to input high multiplicity events into cascade with formation time effects.

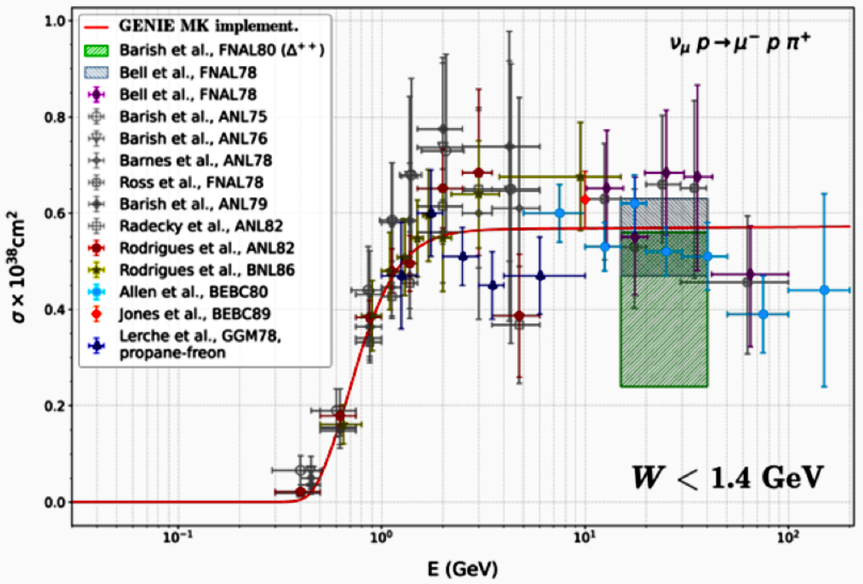


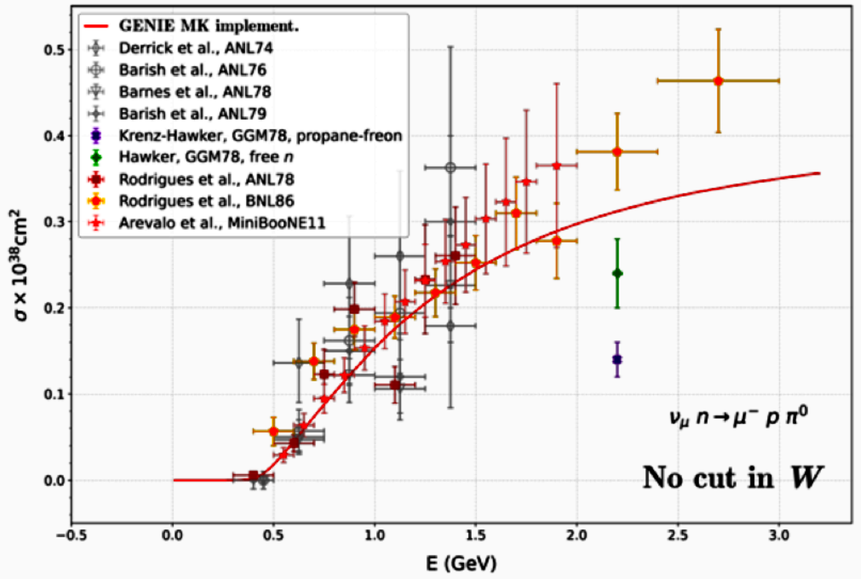


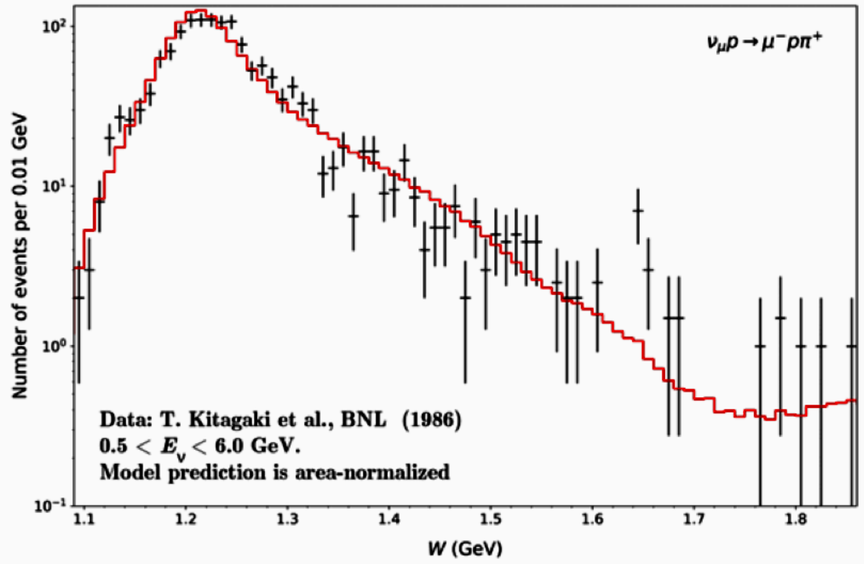
GENIE : MK MODEL IMPLEMENTATION

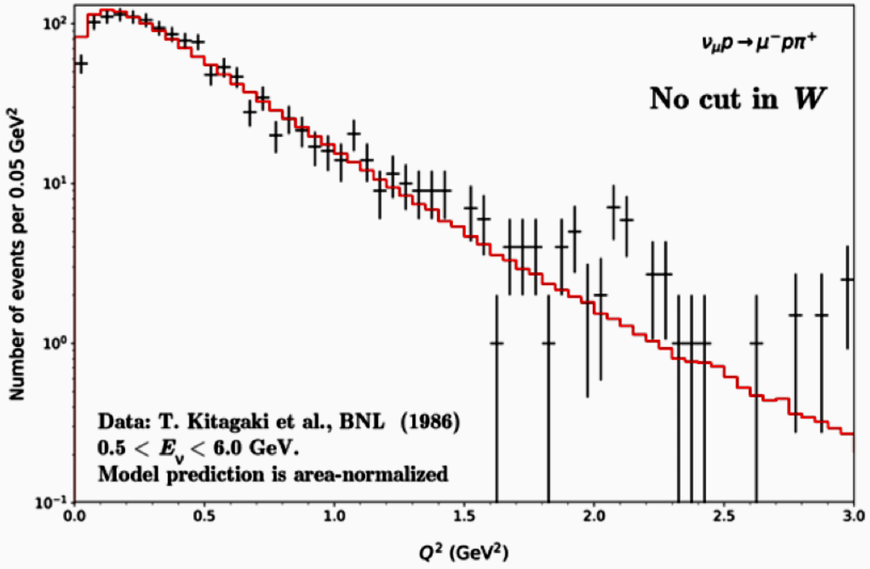
- 4D cross section – including angular distribution of final pion with interference between resonances.
- Non-resonant background with Born diagrams Hernández, Nieves and Valverde.
- Implementation of private MK Model Variants by Dubna group.

Phys Rev D.97.013002



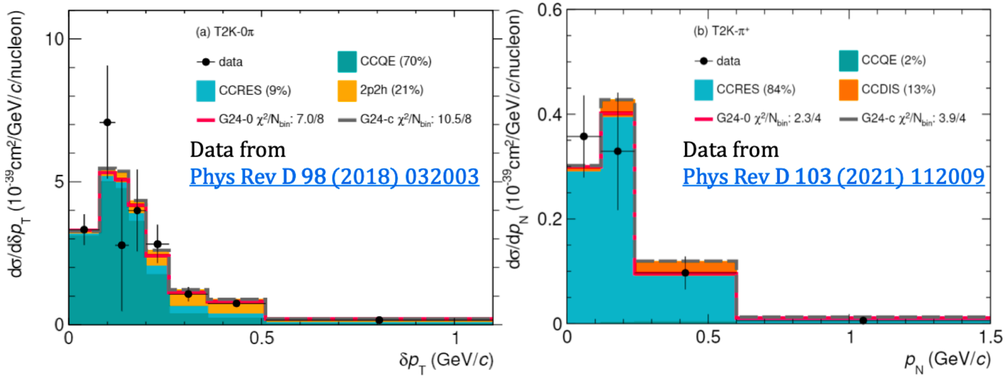


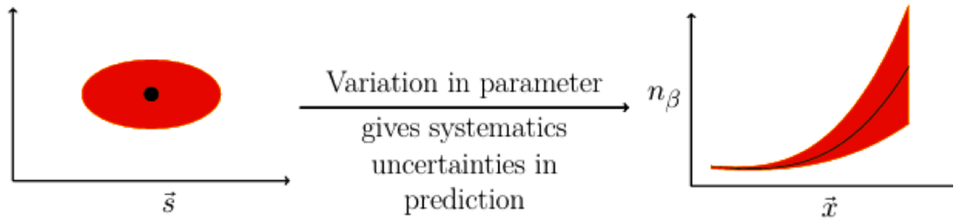


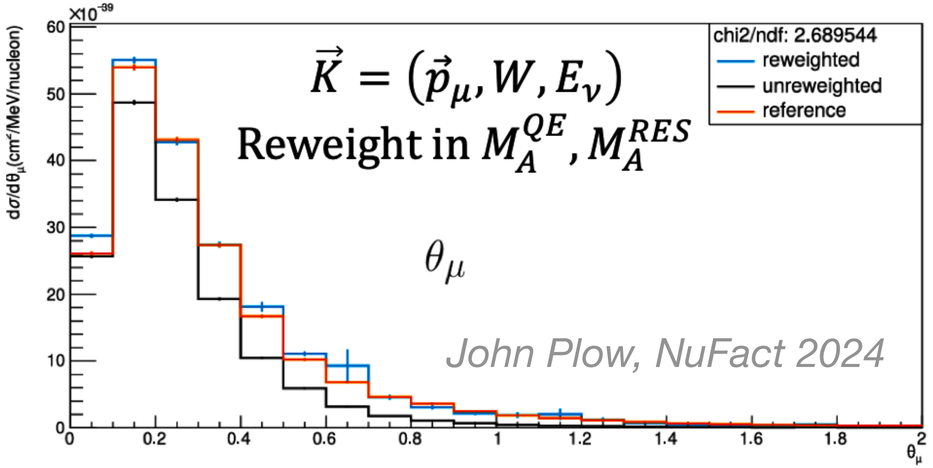


GENIE : TUNES

- Use of Professor tool to perform multi-parameter tunes including dials that are typically ‘non-reweightable’.
- GENIE v3 ships with a collection of different tuned configurations based on specific experimental requirements (variations in model and datasets considered in tuning).
- Number of tuning studies on BC, CC-inc, 1pi, 2pi, hadronization already carried out.
- Work underway to understand how systematic uncertainties can be correctly propagated to experiment predictions.







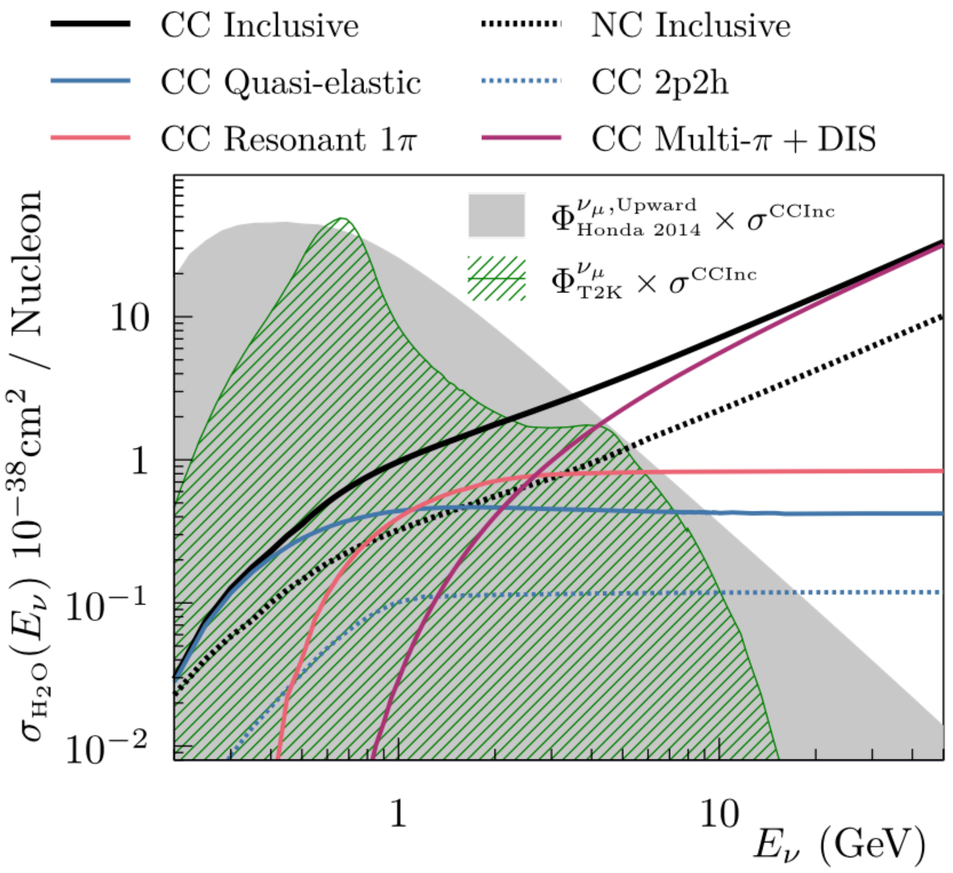
NEUT : Modern Update

- Currently the primary interaction generator for SK and T2K, used in all oscillation/cross-section analyses.
- Modern NEUT benefits from decades of work understanding systematic response.
- Range of interaction channels/models have been added on the quest for full systematic coverage on SK/T2K experiments.
- Freedom for in-NEUT systematic studies using Reweighting approaches for several model components.

The NEUT neutrino interaction simulation program library

Yoshinari Hayato[1,a] and Luke Pickering[2]

The European Physical Journal Special Topics
volume 230, pages 4469–4481 (2021)



NEUT : STRUCTURE

- Extensive development on NEUT6 in the last two years - Targeted at HK and final T2K analyses:
  - Significant reorganisation of code-base with modern C/ Fortran interoperability.
  - Moved to modern CERNLIB 2023.
  - Working implementation of HepMC3-based event format.
  - Working conversion tools for ***neutvect*** to ***NuHepMC3***.

- **Planning open source NEUT6 under the GPL.**
  - New code developments largely being written in NEUT6.
  - Minor updates from NEUT5.7 planning to be merged before future release.
  - Work is underway to reevaluate the model using extensive data comparisons (p-A, π-A, ν-A, e-A).

Guess the Fortran!

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necrosin.F
SUBROUTINE NECROSIN
```

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necrosin.F
SUBROUTINE NECROSIN
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```
INELASTIC PI-0 / NUCLEON SCATTERING, OBTAINED
BY LINE FITTING THE DATA GIVEN IN THE PAPER
BY REIN AND SEGHAL.
```

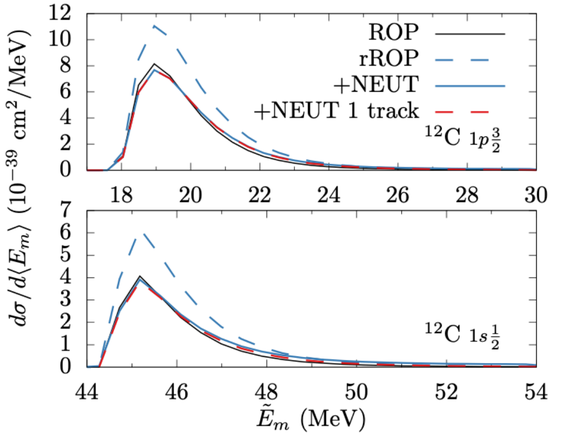
NEUT : RMF MODELS

- First implementation of a macroscopic model based on a Relativistic Mean Field optical models into NEUT
  - Jake McKean, Raul González-Jiménez, Minoo Kabirnezhad

Neutrino-nucleon Operator

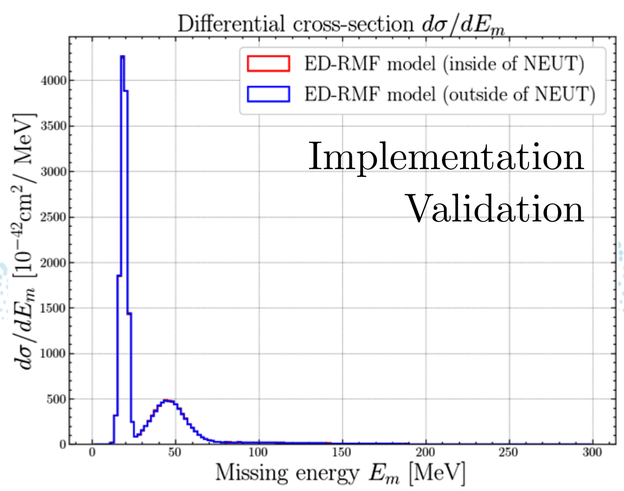
$$J^{\mu} \propto \int d\mathbf{p}\ \bar{\Psi}_{Scattered}\ \mathcal{O}^{\mu}\ \Psi_{Bound}$$

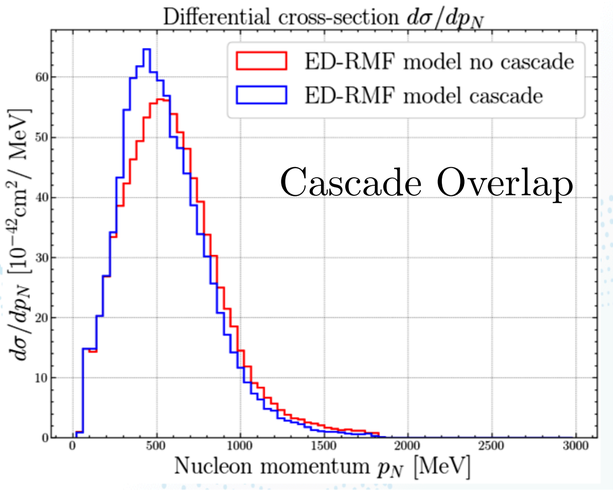
Hadronic Current | Scattering Potential | Bound State Wavefunction



Nikolakopoulos, Alexis, et al. "Benchmarking intranuclear cascade models for neutrino scattering with relativistic optical potentials." Physical Review C 105.5 (2022): 054603.

- Potential for new theory-motivated systematic uncertainty studies in NEUT.
- Possible consideration of alternative operators for different processes.
  - E.g. future extensions to the MK model operator for inelastic pion production.

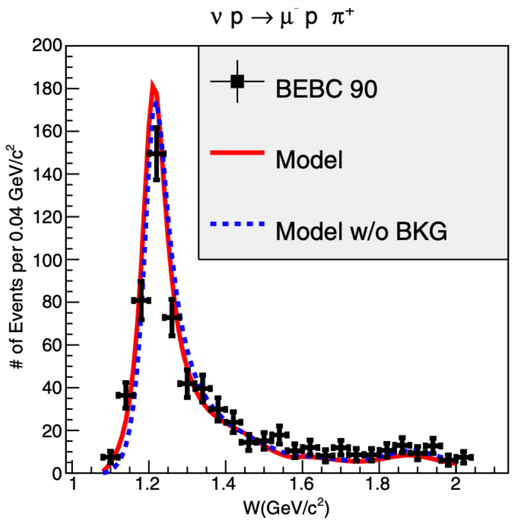




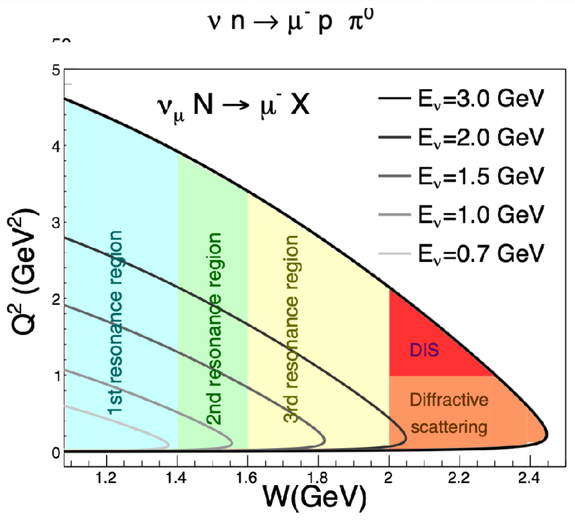
Jake McKean. "First results from a relativistic mean field theory implemented in the NEUT neutrino interaction event generator." IOP Joint APP, HEPP and NP Annual Conference 2024

NEUT : Pion Model Updates

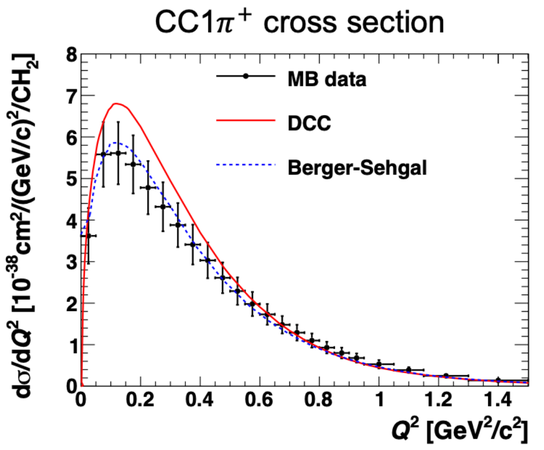
- Alternative Pion Models a key development focus at the moment on NEUT.
- **MK2018 implementation:**
  - Key improvement: Non-resonant channels contribute coherently
  - Hoping a significantly improved model is on the way*, using updated tables. (Minoo, Clarence)
- **DCC 1π [PRD 92, 074024 (2015)]:**
  - State-of-the-art 1π model
  - Inclusive predictions implemented as a model option (Seisho Abe, Yoshinari Hayato)
  - Recent updates to allow e-A scattering with QE, and DCC-1PI model!



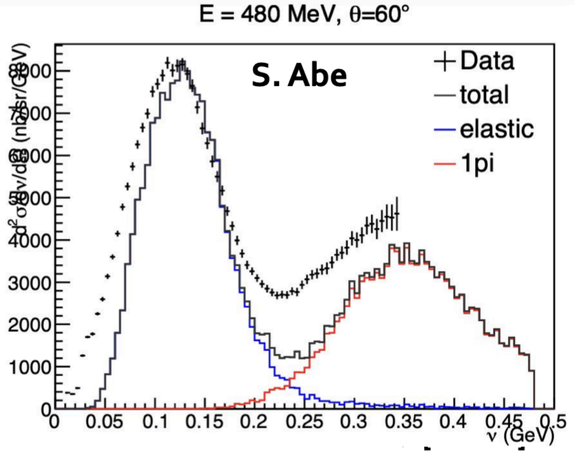
MK 2018 Model
Phys. Rev. D 97, 013002 (2018)



*MK 2024 Model**
arXiv:2409.02890



Yamauchi et al.
PoS TAUP2023 (2024)



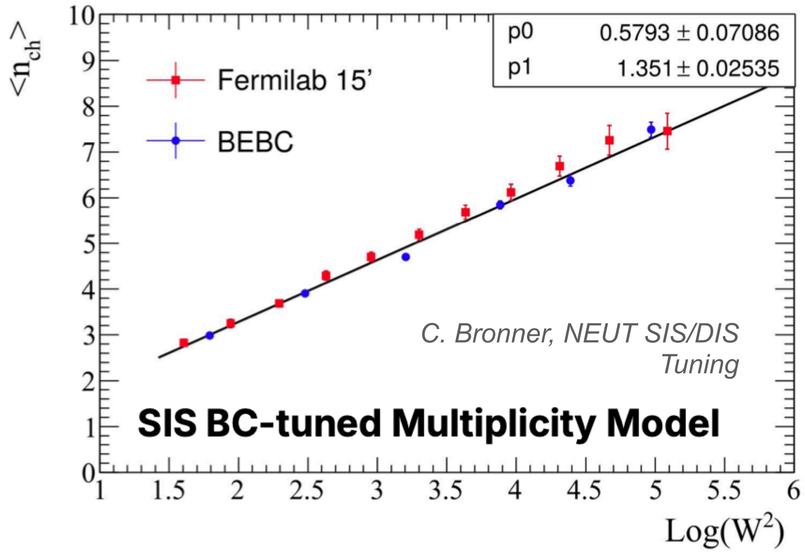
NEUT Updated eA Scattering - S. Abe

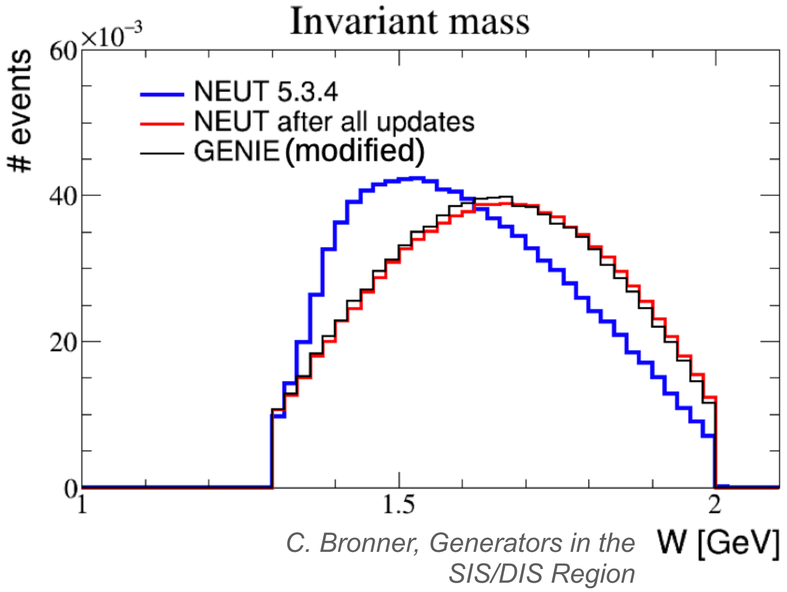
NEUT : SIS/DIS

- Like many generators, NEUT uses Pythia in the deep inelastic scattering regime.
  - GRV98 with Bodek Yang low Q2 corr. and improved tuning and uncertainties from 2021 Bodek/Yang/Xu structure functions (C. Bronner)
  - Relies on Pythia/JETSET 5.72 fragmentation

- SIS: W $<$ 2
  - Must produce >= 2 pions to remove double-counting with SPP Processes
  - Custom charged-hadron multiplicity model with multiple options: Legacy, BC-tuned, AGKY
- DIS: W $>$ 2
  - Full Pythia event generation

- Reweighting systematics allow variation of particle normalisations, and multiplicities.



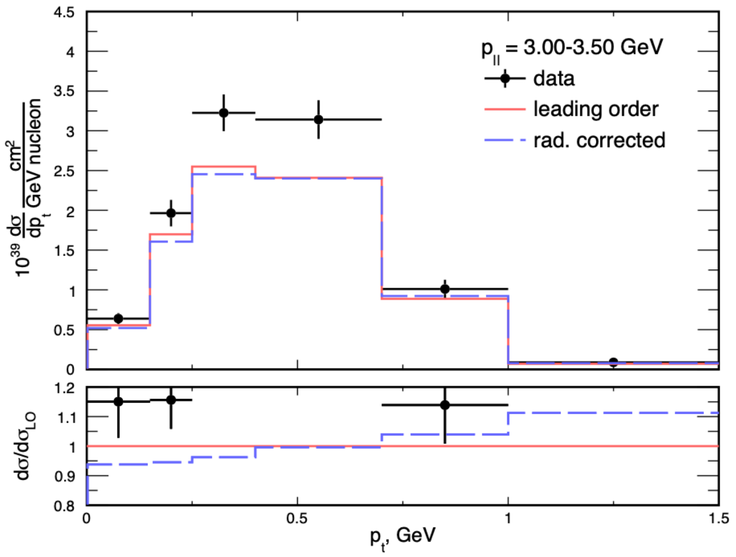


FUTURE - NEUT

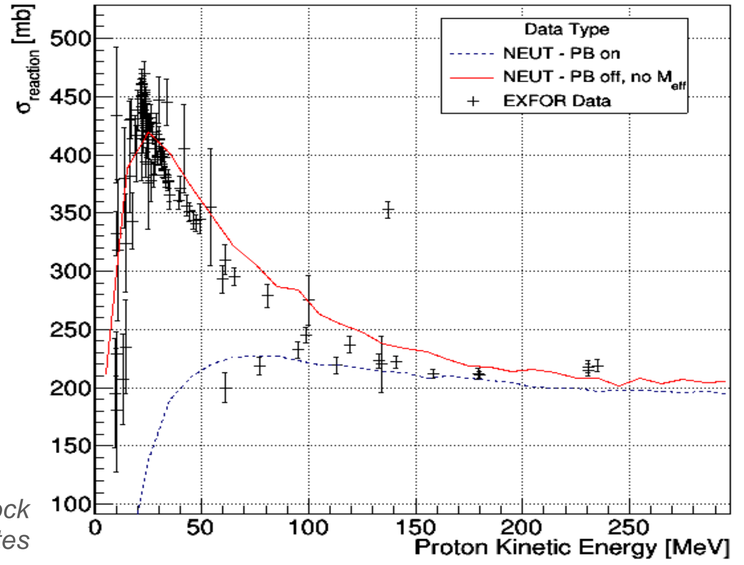
- Focus of R&D on NEUT is now turned towards updated hadronic predictions and systematic uncertainties to support future analyses with the ND280 Upgrade.
  - ED-RMF Models for 1p1h
  - New 2p2h Reweighting Dials
  - Nucleon FSI Reweighting for NEUT
  - INCL Cascade Interface
  - Updated comparisons to e-A Scattering
  - Updated nu-A Radiative Correction Implementations
  - Alternative Pion FSI Reweighting Schemes
  - Uncertainties on pion production mechanisms.
- Looking at potential for regular NEUT focussed development workshops and would value input from theory community - Get in touch!

MINERvA ME CCQE-Like
NEUT Radiative Corrections

O. Tomalak et Al.
Phys.Rev.D 106, 9, 093006 (2022)



T. Peacock
NEUT Nucleon FSI Updates



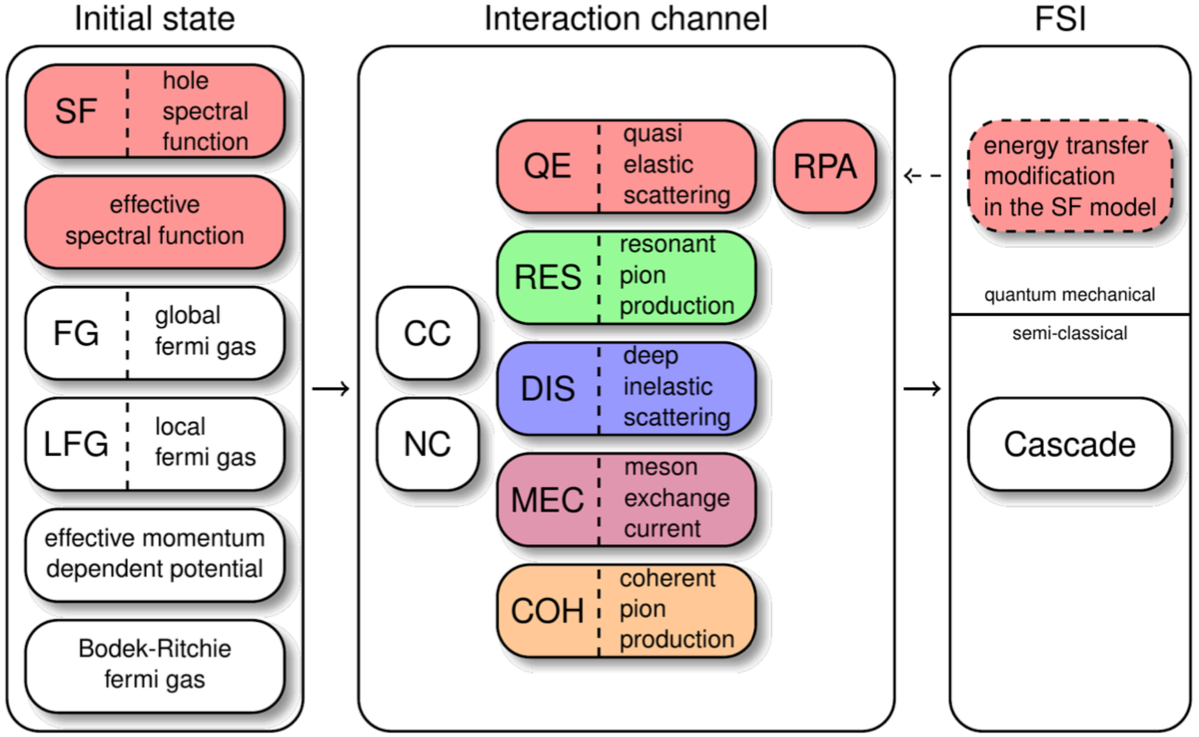
NuWro

- Neutrino interaction generator developed by Wroclaw theory group.

- Collection of different spectral functions, 2p2h, and resonant interaction models.
- Intranuclear cascade model.

- v21.09.00 Physics Highlights
  - Phenomenological 2p2h model.
  - Hyperon production and their FSI.
  - Neutrino scattering of atomic electrons.
  - Validated QE electron scattering.

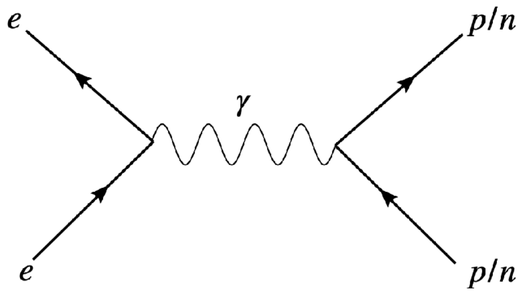
"In MC simulations we are like god, we control all the particles" - Jan Sobczyk (2016)



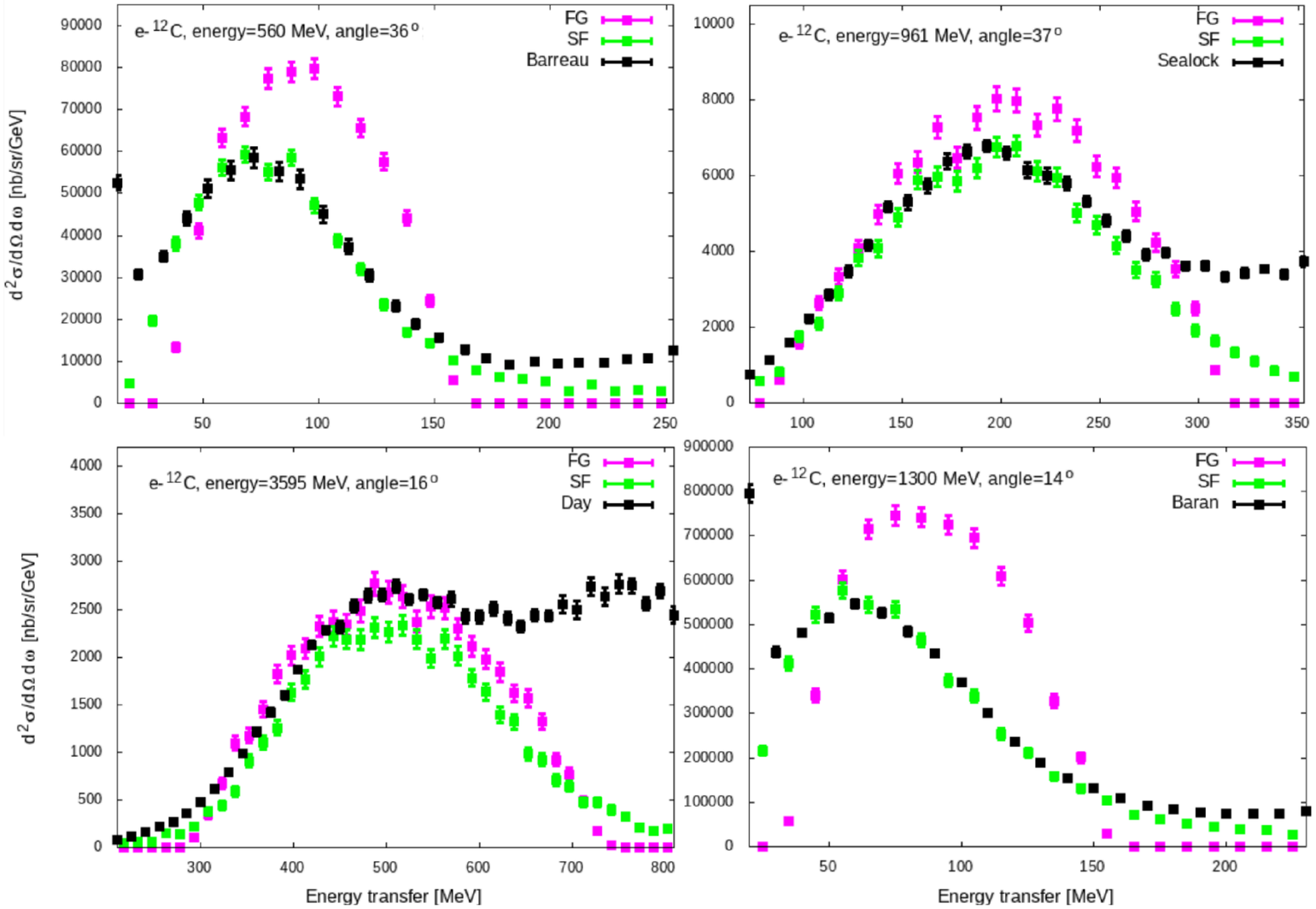
NuWro : eWro

Hemant Prasad, NuFACT 2024

- Electron scattering interface added to make joint comparisons to data for a given nuclear model.
- Only QE interactions are currently possible to simulate.



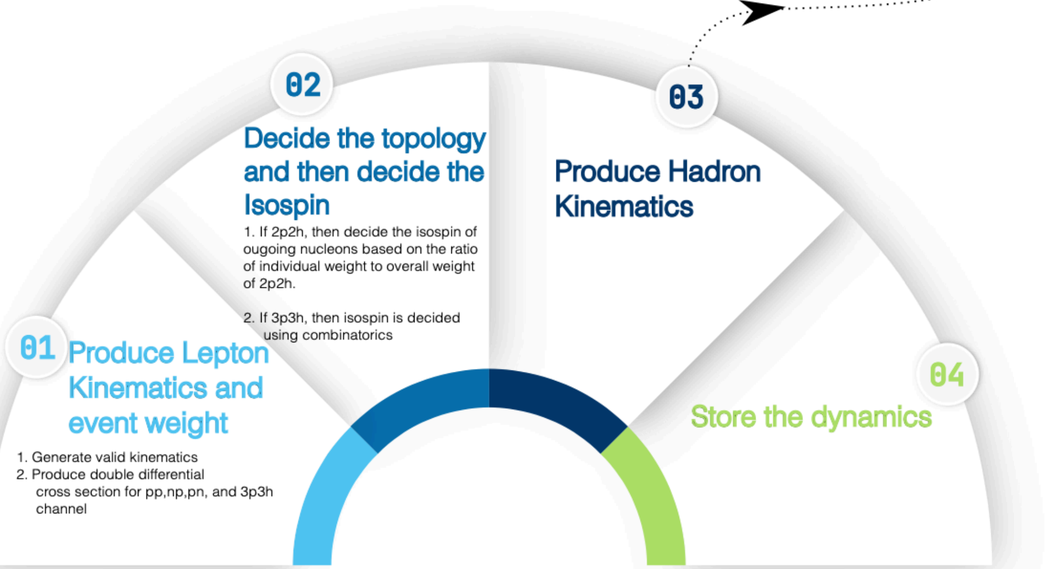
- Simple Fermi-gas performs worse at low momentum transfer as expected.

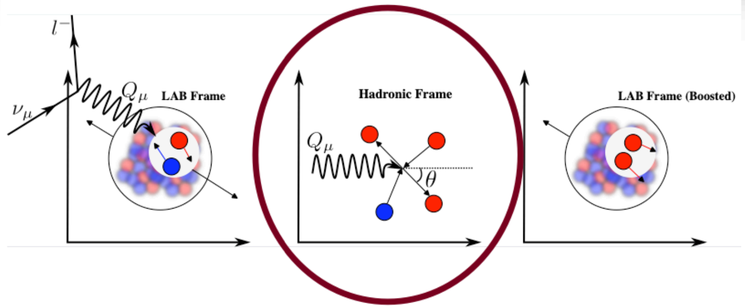


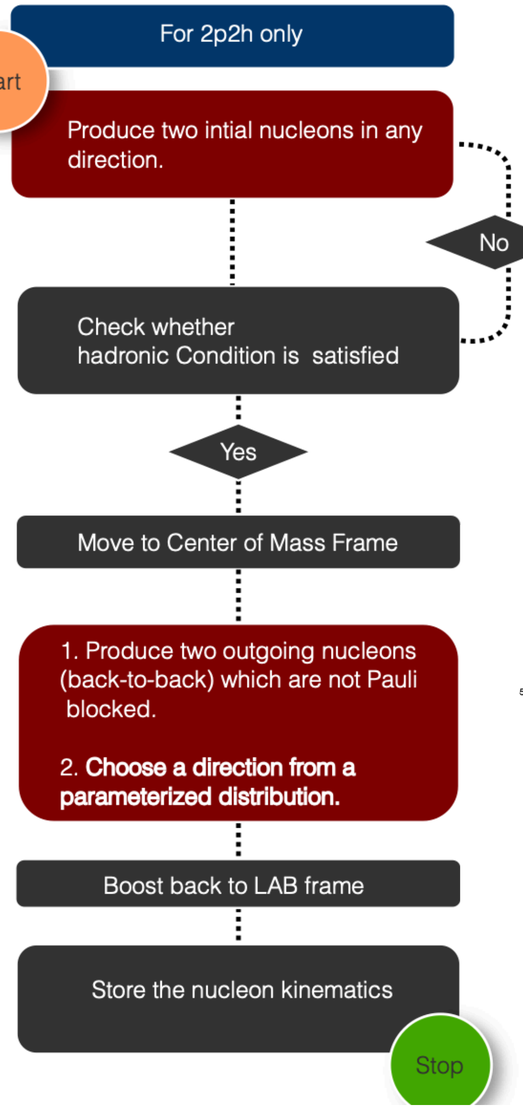
NuWro : Updated 2p2h Model

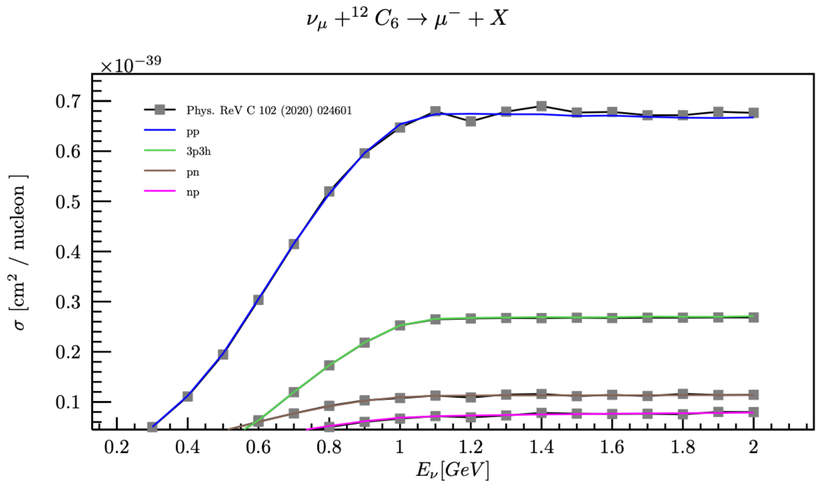
Nuwro v24.xx.?

New MEC scheme and Hadronic Model

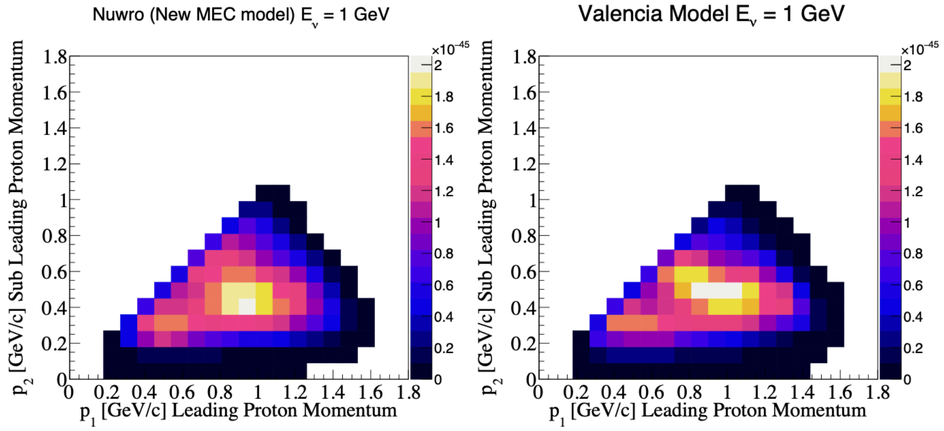








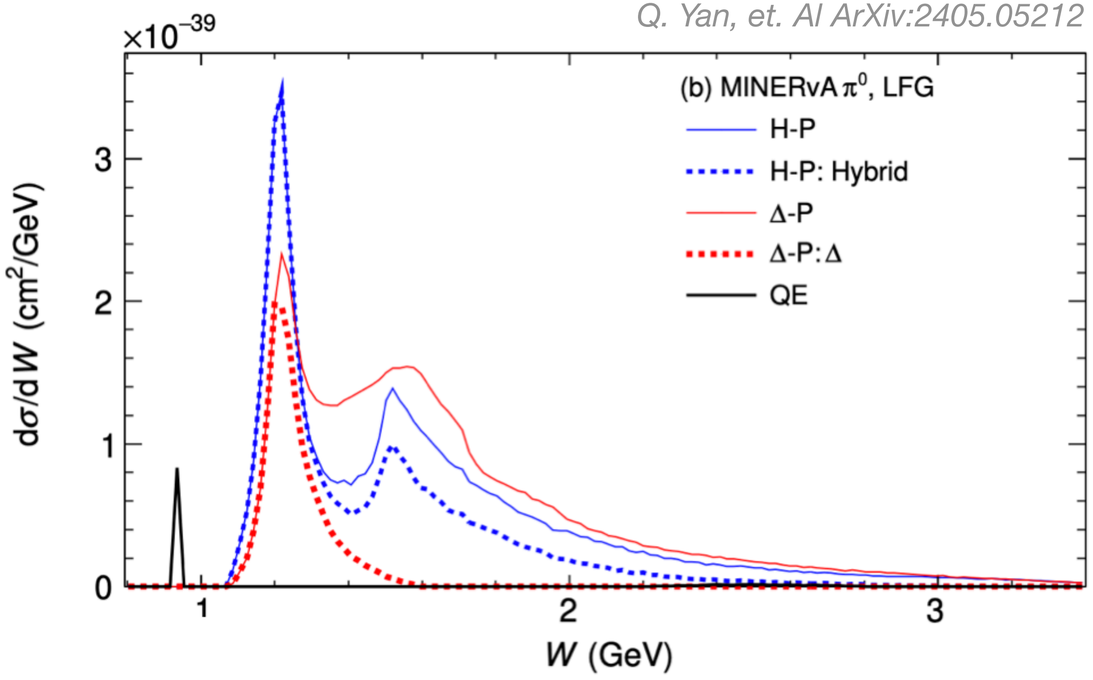
2p2h and 2p2h Model
J. Sobczyk et Al. Phys. Rev. C 102, 024601 (2020)



NuWro : Hybrid Pion Model

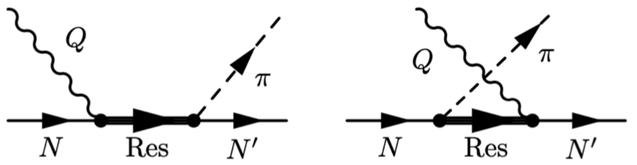
- Recent implementation of "Hybrid Model" from Ghent Group
- Contribution from resonances P33(1232)(Δ), D13(1520), S11(1535), P11(1440) low-energy background, and high energy background.

GHENT Hybrid Model In NuWro
Q. Yan, et. Al ArXiv:2405.05212



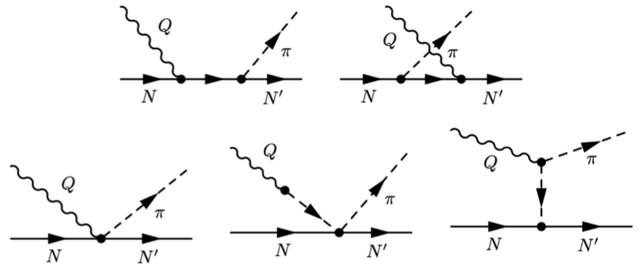
Resonances

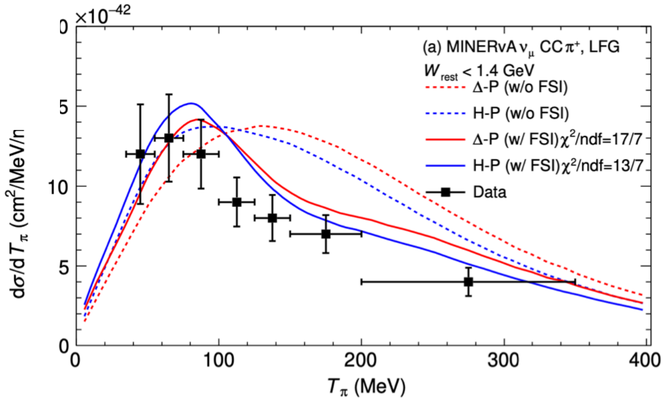
$P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535)$

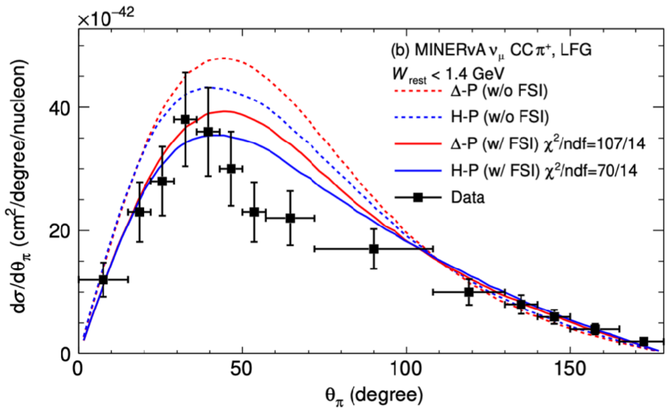


based on [PRD 76 033005, PRD 87 113009, PRD 93 014016]

ChPT background



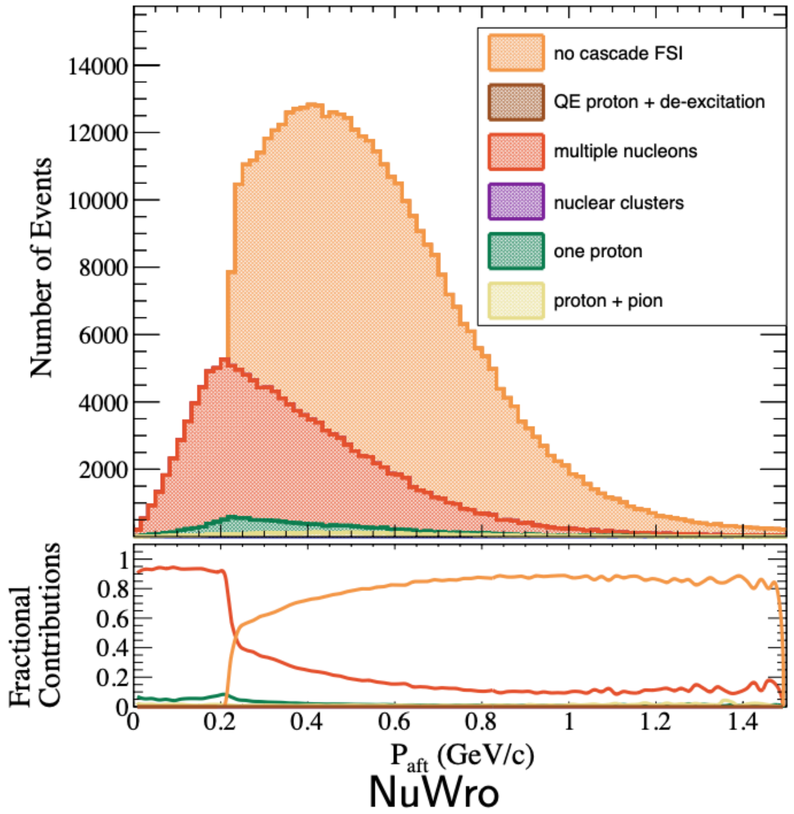


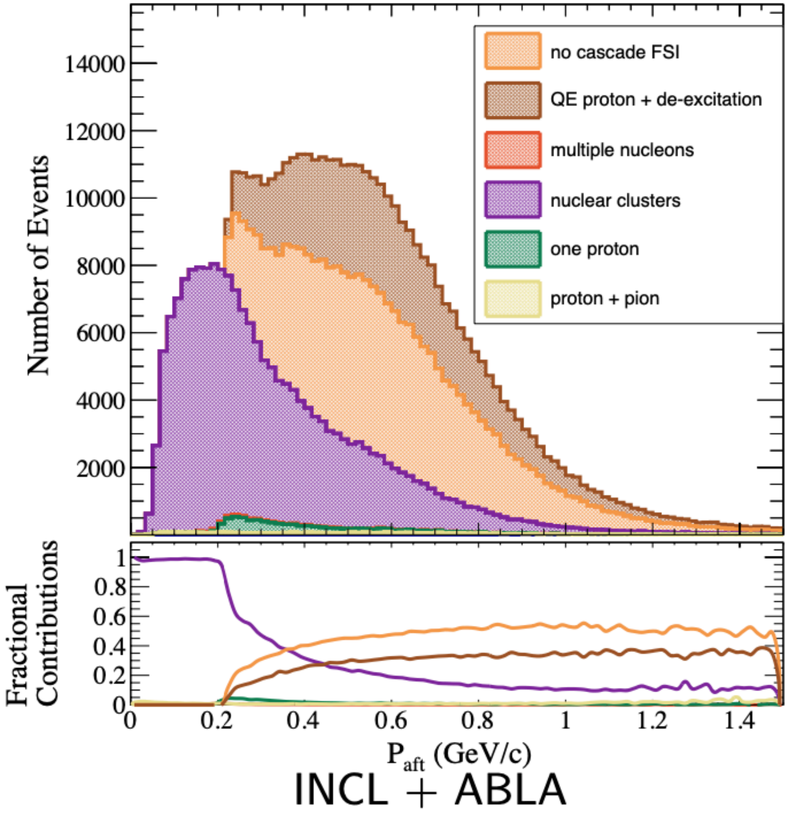


NuWro : FSI INCL Comparisons

- Work on NuWro FSI comparisons by Anna Ershova, using NuWro primary vertices as inputs to INCL model to compare effect of FSI models.
- Complicated by the need to try and correlate initial nucleon momentum between the models.

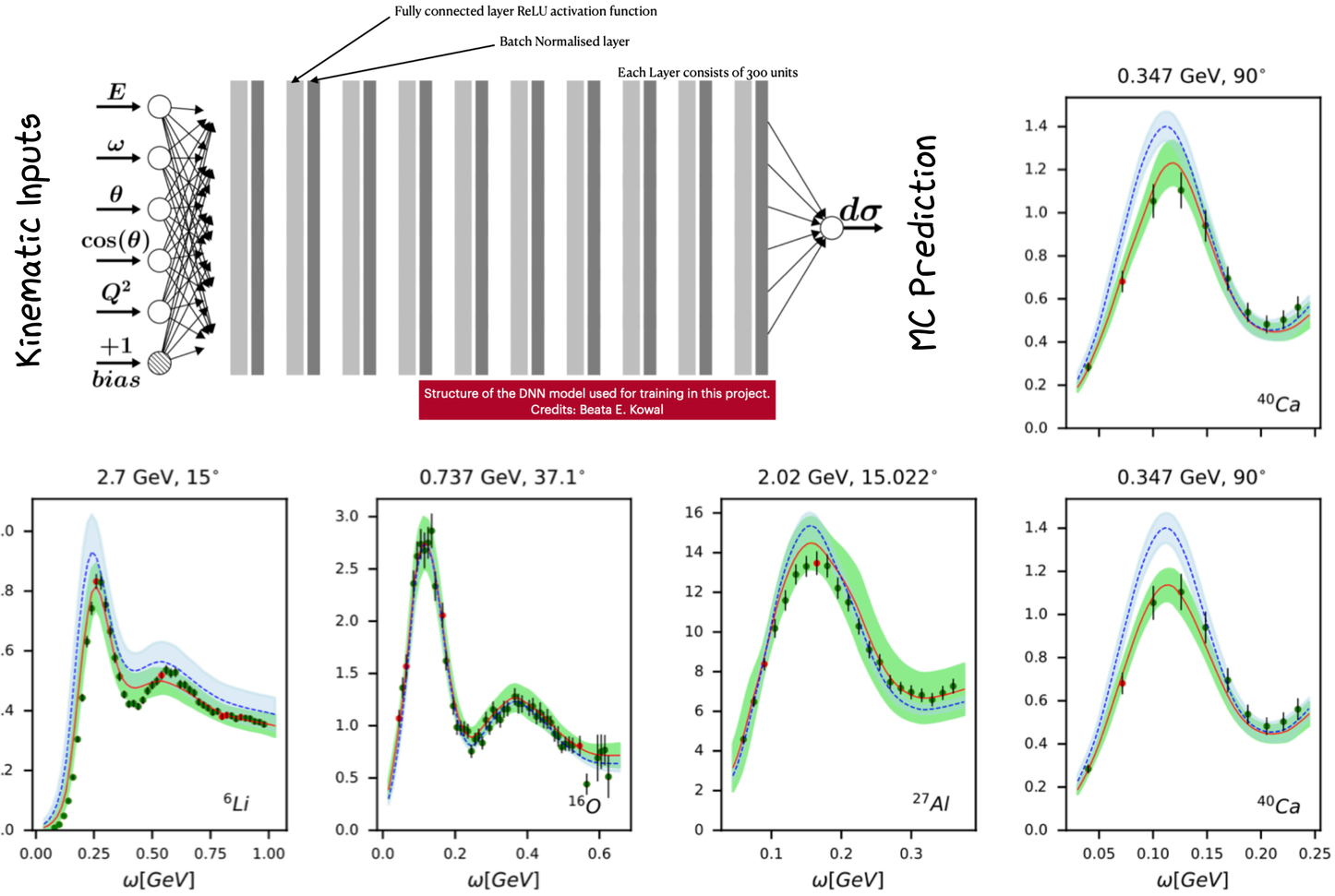
Study of final-state interactions of protons in neutrino-nucleus scattering with INCL and NuWro cascade models
A. Ershova et. Al.
Phys. Rev. D 106, 032009





NuWro : ML Updates

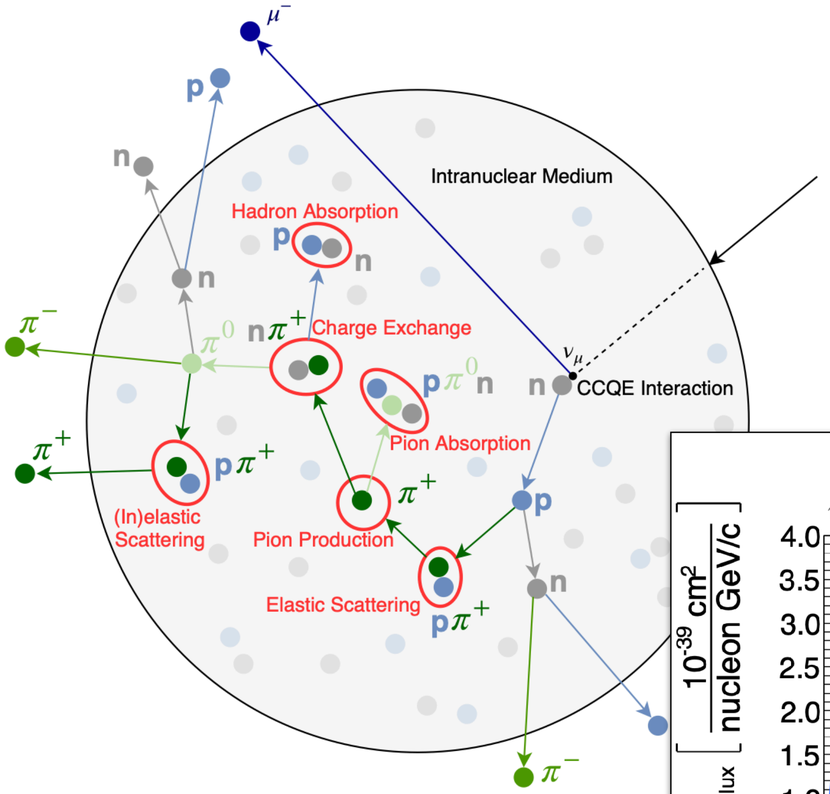
- Modelling deep neutral networks (DNN) and training over experimental datasets.
- Emphasis on parameterisations of electron-scattering cross section, independent from nuclear model.
- The aim is to test pre-trained DNN model from electron-carbon scattering data on datasets from lithium to iron.
- Effective at propagating systematic uncertainties from model inputs to MC prediction.

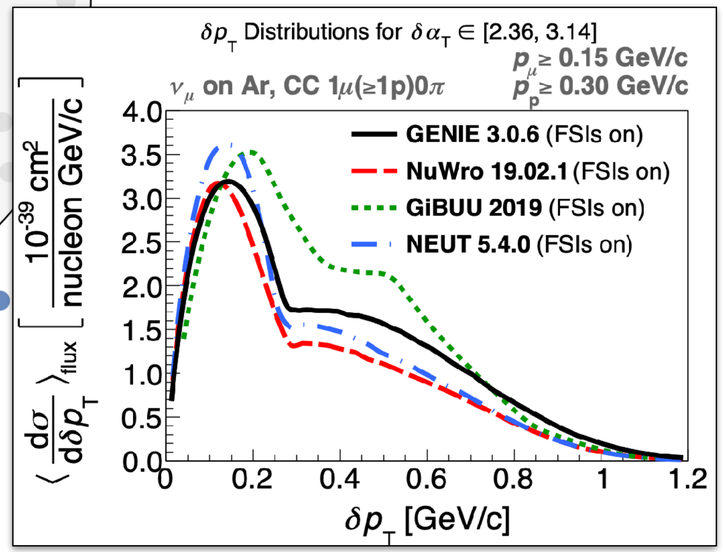


Beata E. Kowal, Krzysztof M. Graczyk et. al. Phys.Rev. C 110 (2024) 025501

GiBUU

- The GiBUU Project (Giessen Boltzmann-Uehling-Uhlenbeck), authored by the Giessen group:
  - Offers a unified theoretical and simulation framework for particle-nucleus interactions, spanning energies from MeV to TeV
  - Based on first-principles interactions.
  - Propagates particles from the initial interaction using a transport model (the BUU equation).
- Recent implementation of photon interactions for eA scattering data comparisons.

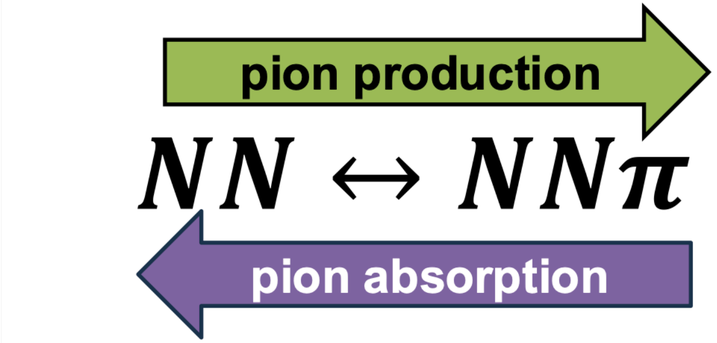




Comparing generator predictions of transverse kinematic imbalance in neutrino-argon scattering
Lars Bathe-Peters, Steven Gardiner, Roxanne GuenetteFERMILAB-PUB-22-007-SCD

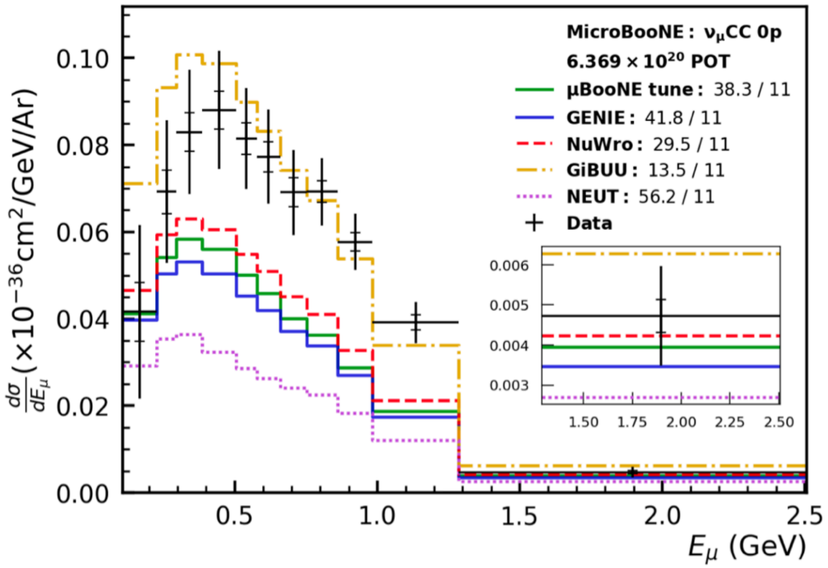
GiBUU : Transport Model

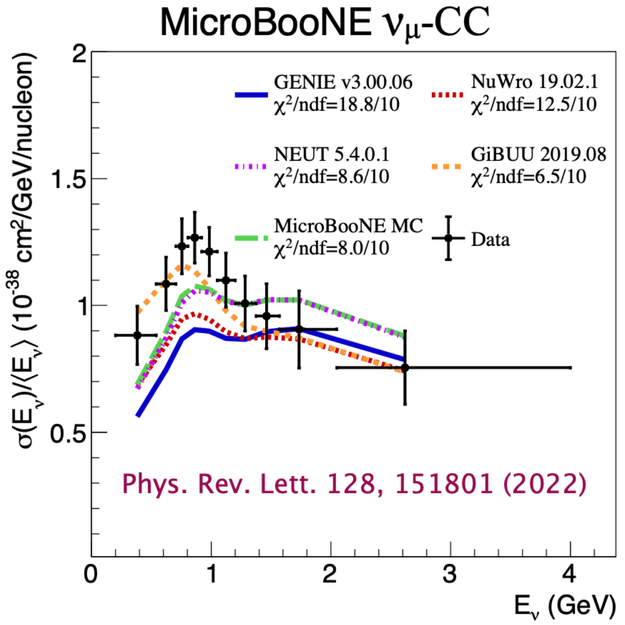
- Implements FSI with a quantum-kinetic transport model.
  - Allows for a precise treatment of nuclear effects.
  - Nuclear binding potential is consistent between the ISI and FSI.
    Interaction rates respect time-reversal: ie. pion absorption/production from the same model.
  - Inputs to the model are the cross sections and potentials for each particle species.



$$|\mathcal{M}_{N_a N_b \to N_A N_B \pi}(s)| = |\mathcal{M}_{N_A N_B \pi \to\ N_a N_b}(s)|$$

Phys. Rev. D 110, 013006 (2024)

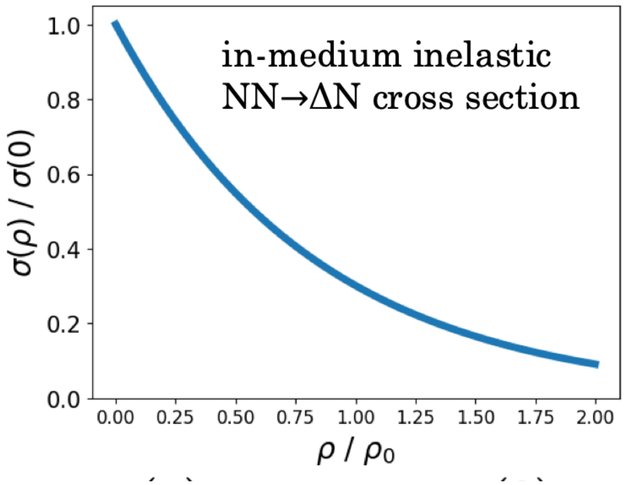


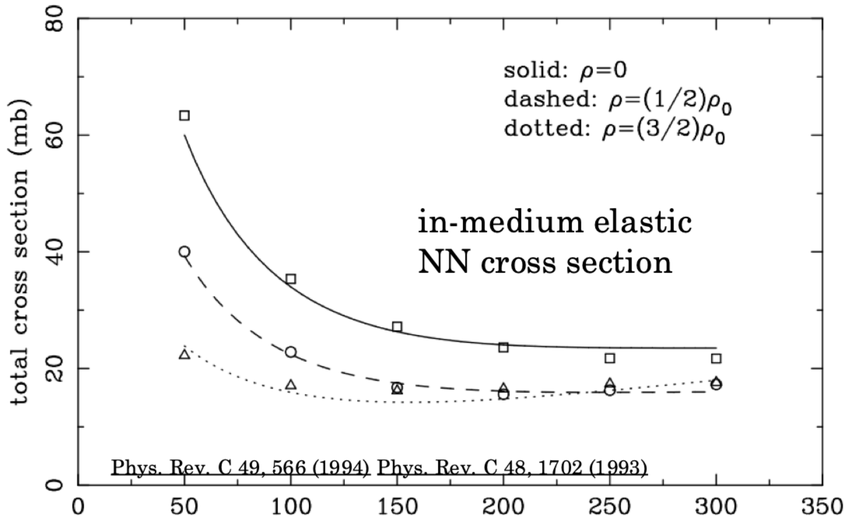


GiBUU : In-medium Corrections

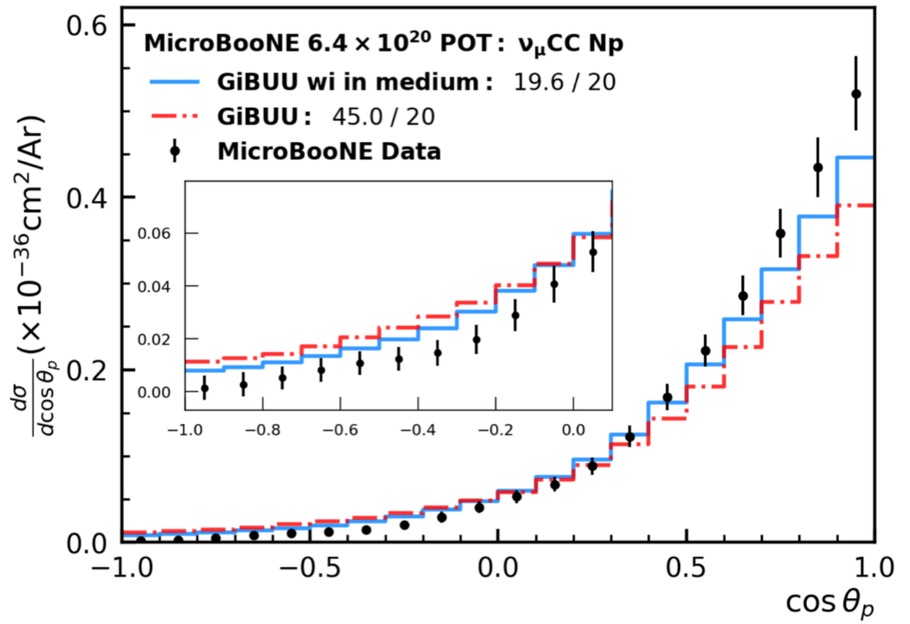
- Degree free nucleon-nucleon cross sections are modified within the nucleus is an open question.
  - The in-medium cross sections may be very different than the vacuum ones.

- Theoretical investigation suggest a lowering of NN cross sections below resonance excitations.
- Mostly investigated in the context of heavy-ion collisions.





Ben Bogart, In-medium changes of nucleon cross sections tested in neutrino-induced reactions, NuFact 2024

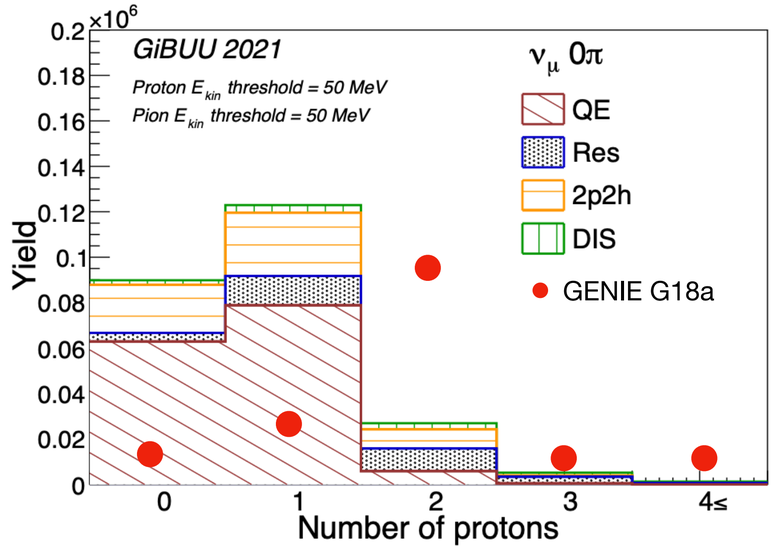


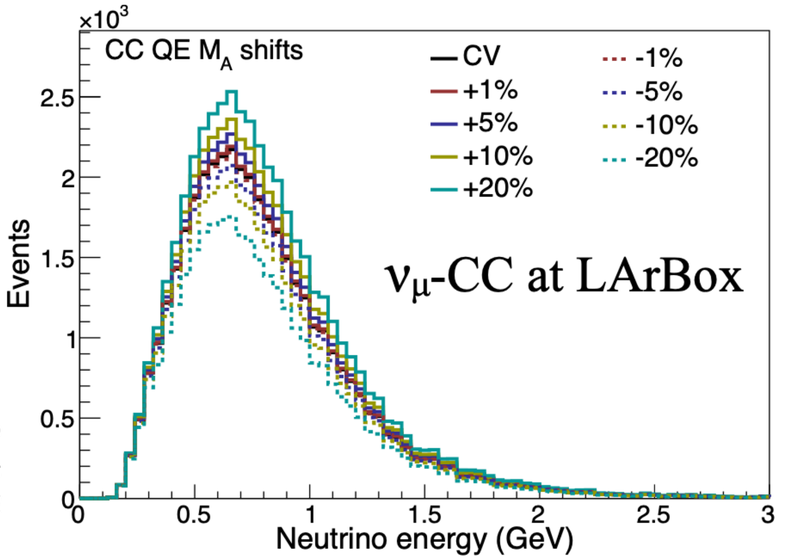
B. Bogard, et. Al. Phys. Rev. C 110, 044001 (2024)

GiBUU : @ DUNE

- Ongoing work to fully implement the GiBUU for DUNE software framework and associate uncertainties.

- Event Ensemble Method to propagate systematic variations within theoretical uncertainties in GiBUU.
  1. Generate a large library of GiBUU-generated events with associated parameter fluctuations.
  2. Use GENIE's geometry and flux drivers to produce output events in a GENIE-compatible format for DUNE software.
  3. Apply a cross-section weighting technique with an acceptance-reject method to select and place events.

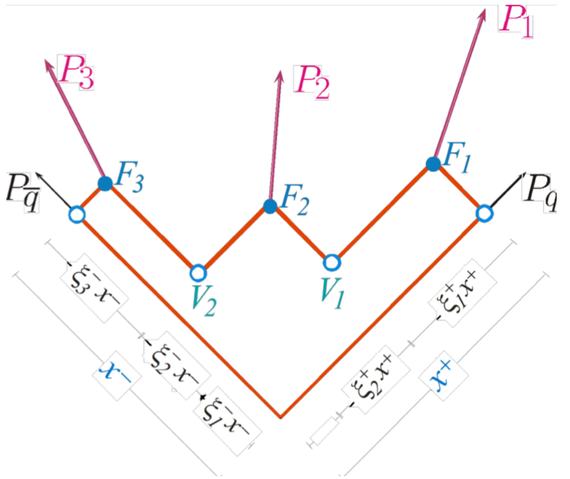




Leo Aliaga, A GiBUU-Based Monte Carlo Simulation for Neutrino Experiments NuFACT 2024

GiBUU : @ FASER

- FASER experiment - potential to understand hadronization in neutrino interactions.
- The higher the hadron‘s energy the larger the formation time
- Only linear dependence on time fits data over wide kinematical range!

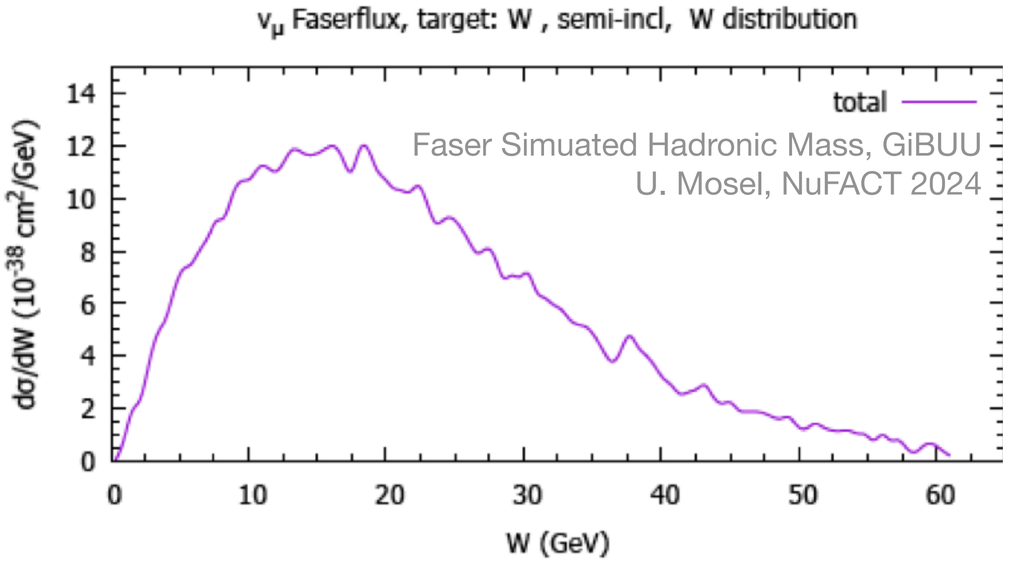


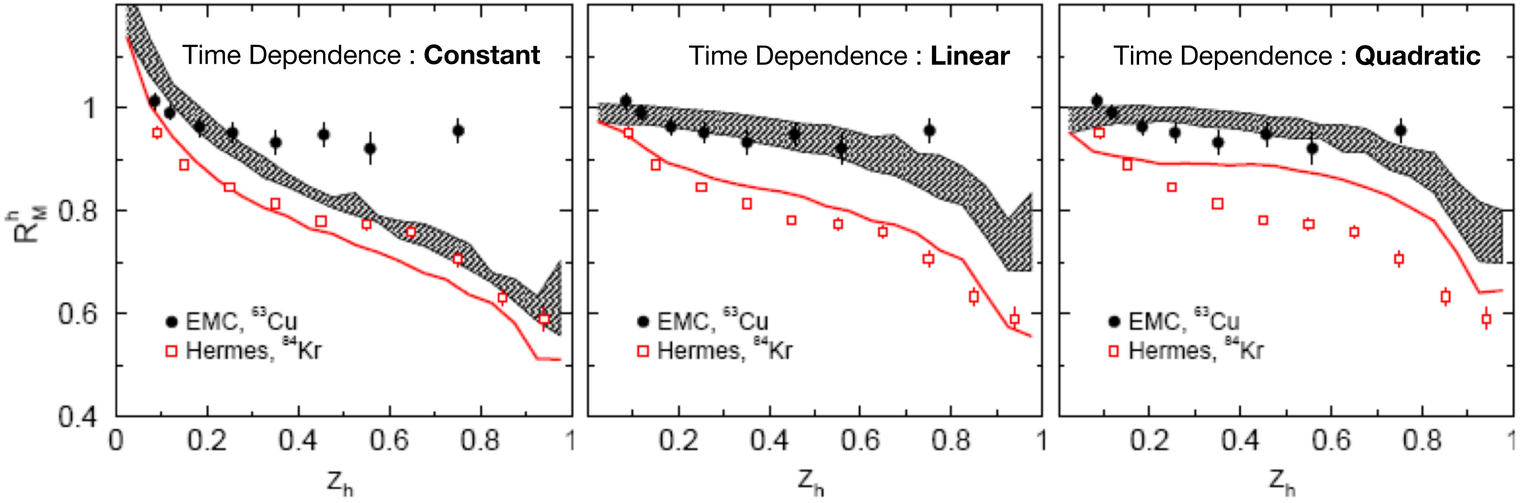
$$R_M^h(\nu, Q^2, z_h, p_T^2, \ldots) = \frac{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_A}{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_D}$$

Nucleus

Deuterium

Hadronization and Color Transparency, MDPI Physics 4 (2022) 2, 440-450

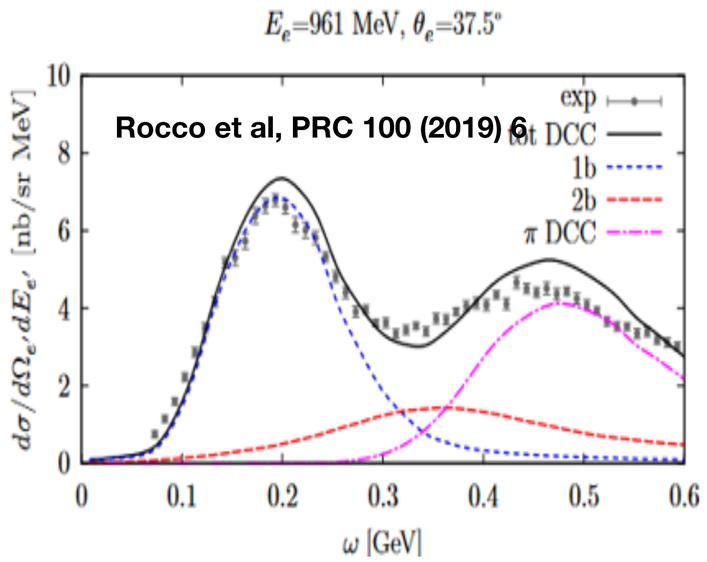


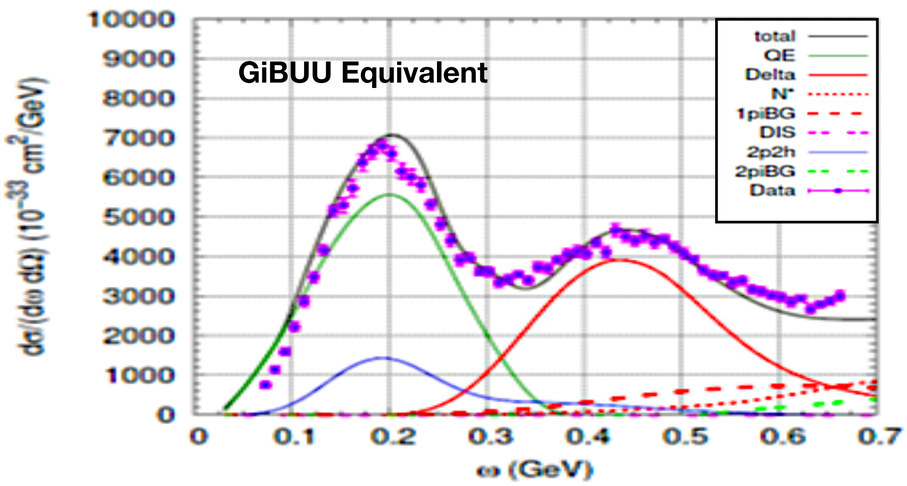


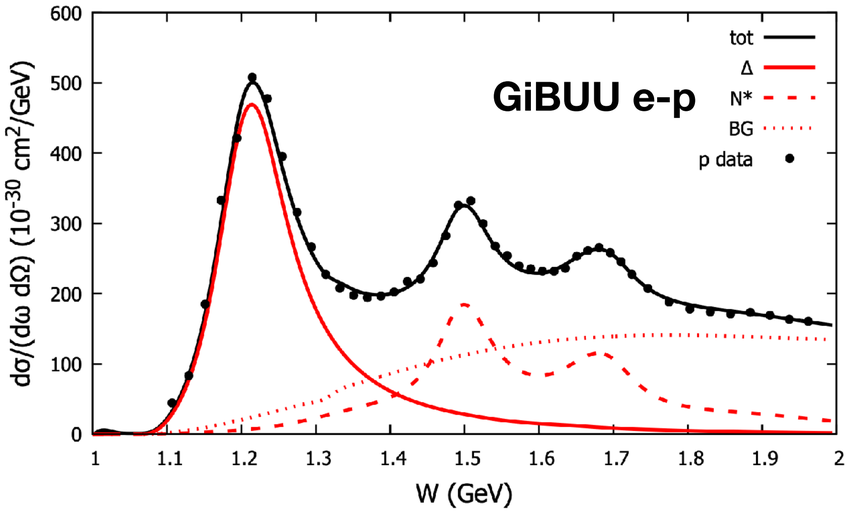
Hadronization time dependence fits, GiBUU. U. Mosel, NuFACT2024

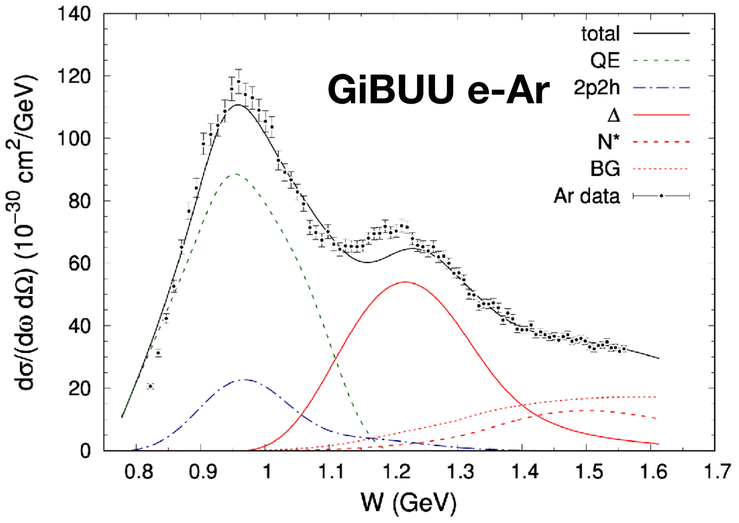
GiBUU e-A Scattering

- GiBUU capable of eA scattering simulations for QE, resonance excitations and DIS
- Recent comparisons show capable of recreating data over broad kinematic range.
- Recent updates include handling of real photons correctly (expected 2024/25 release)









Lepton-induced reactions on nuclei in a wide kinematical regime, U. Mosel, K. Gallmeister, arXiv:2308.16161

Achilles: A CHIcagoLand Lepton Event Simulator

Project Goals:

- Theory driven
- Leverage experiences from LHC event generators
- Develop modular neutrino event generator
- Provide automated BSM calculations for neutrino experiments
- Evaluate theory uncertainties
- Appropriately handle correlations within events

Isaacson, Jay, Lovato, Machado, Rocco [2007.15570],
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378],

Primary Interaction

- Electroweak currents from nuclear theory:

$$J^{\mu}(q) = \sum_{i} j_{i}^{\mu}(q) + \sum_{i<j} j_{ij}^{\mu}(q) + \cdots$$

- Impulse Approximation with SF:

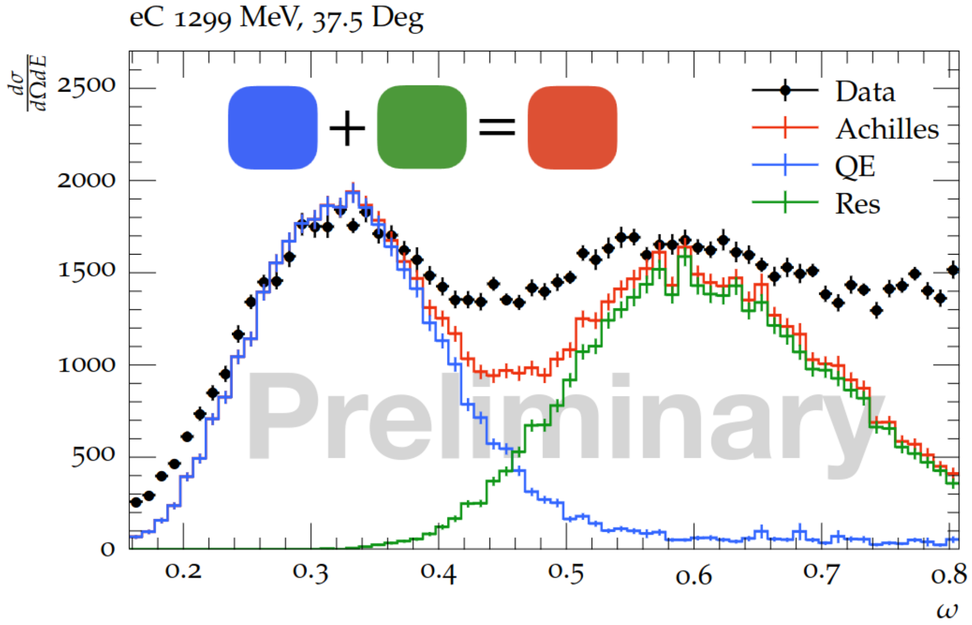
$$|\Psi_f\rangle = |\vec{p}\rangle \otimes |\Psi_f^{A-1}\rangle$$

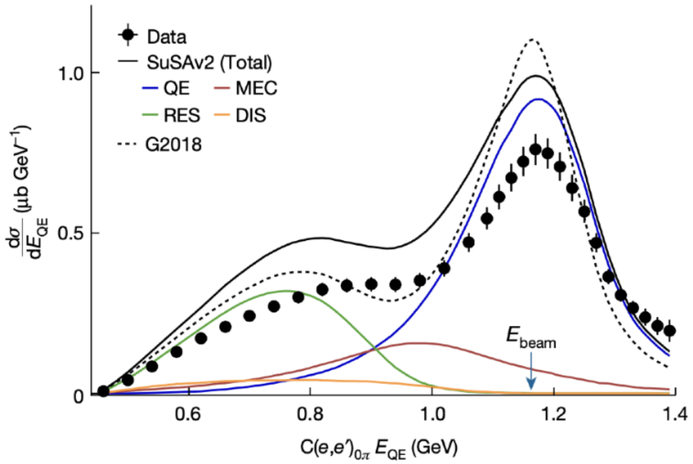
- Express in terms of leptonic and hadronic currents interferences come for free

$$\mathcal{V} = \sum_{i} L_{\mu}^{(i)} W^{\mu(i)}$$

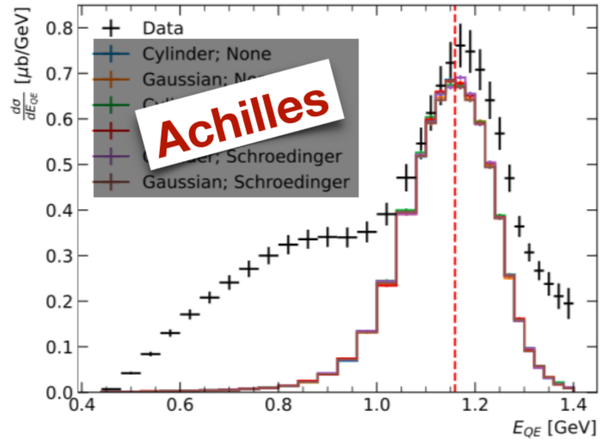
- Have Quasielastic, Resonance (DCC model), One-body-two-body interference implemented

- Important to validate against electron scattering data using same framework (i.e. same code)





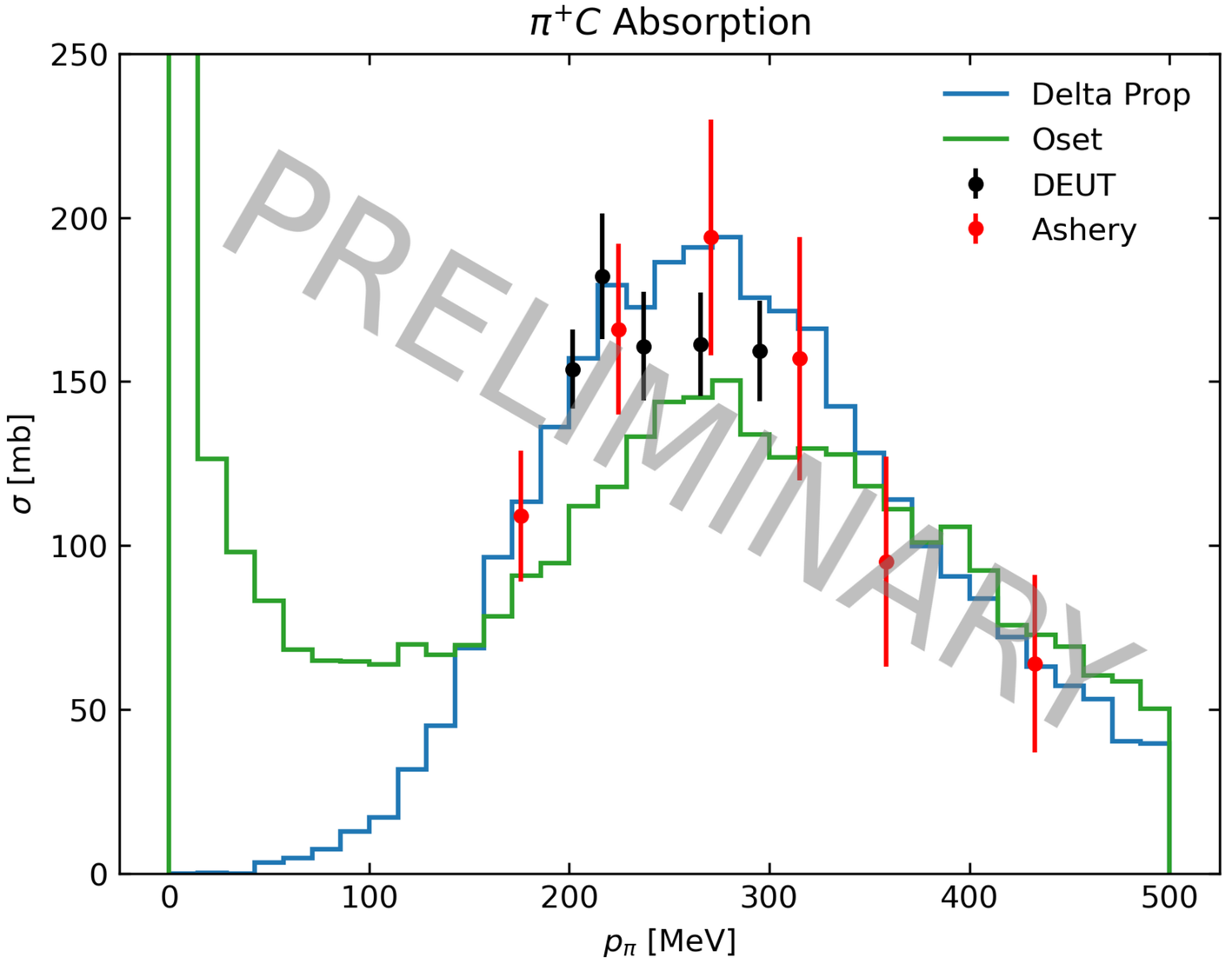
Nature 599 (2021) 7886, 565-570



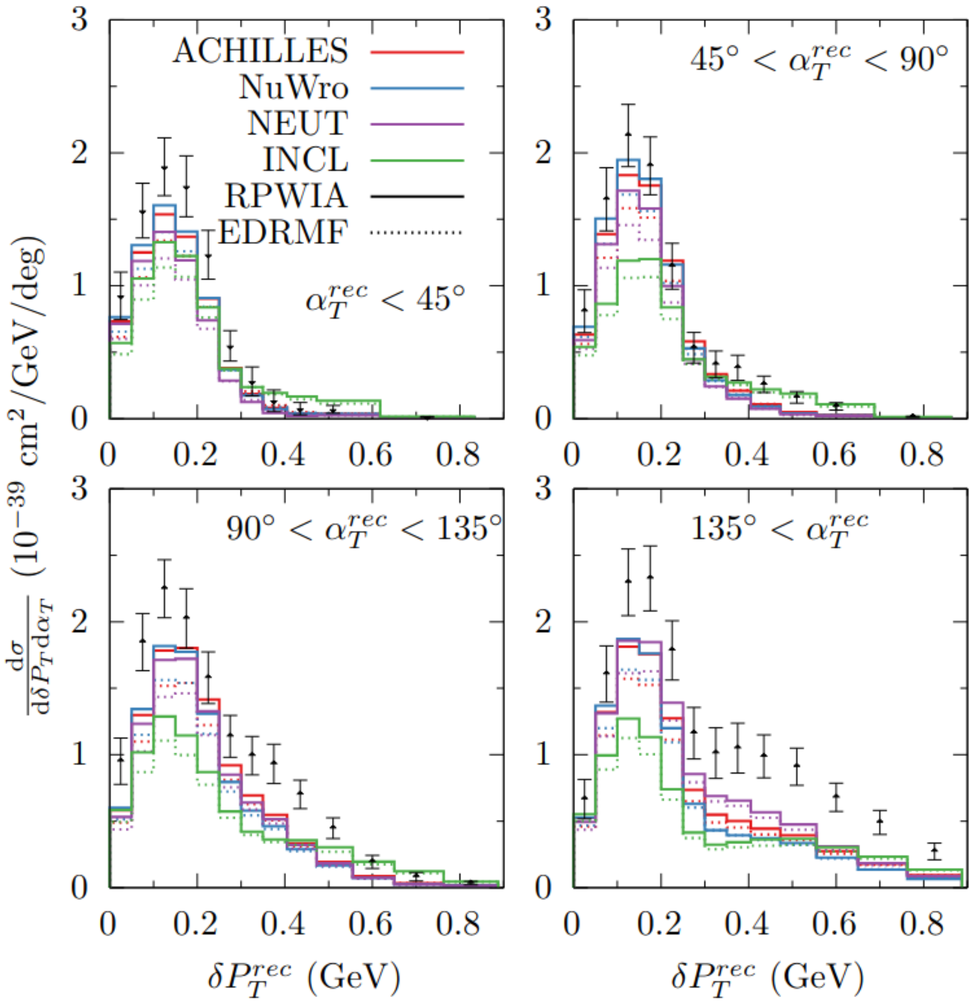
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378]

Intranuclear Cascade: Pions

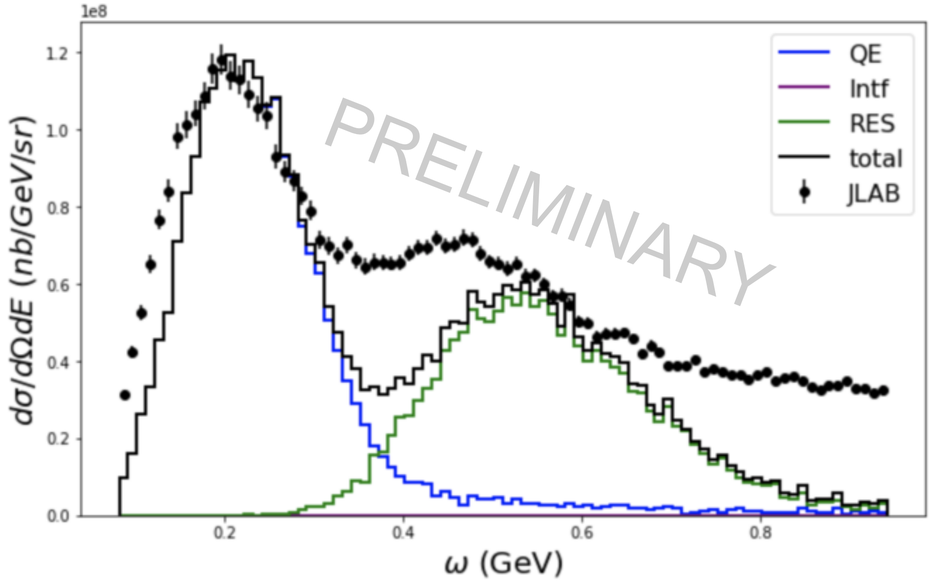
- Multiple approaches to estimate model uncertainty:
  a. Propagate Deltas through the cascade based on single pion-exchange
     Nuclear Phys. A 459 (1986) 503-524
  b. One-step absorption probability based on Oset
     Nuclear Phys. A 484 (1988) 557-592
     With the DCC octet meson-baryon interactions, including hyperons
     Phys. Rev. C 88, 035209
- Propagating Delta approach does not contain any in-medium modifications yet, currently only has Delta(1232) resonance, and missing background channel: $\pi NN \rightarrow NN$
- Oset model includes both 2-nucleon and 3-nucleon absorption rate, but kinematics only two body final state



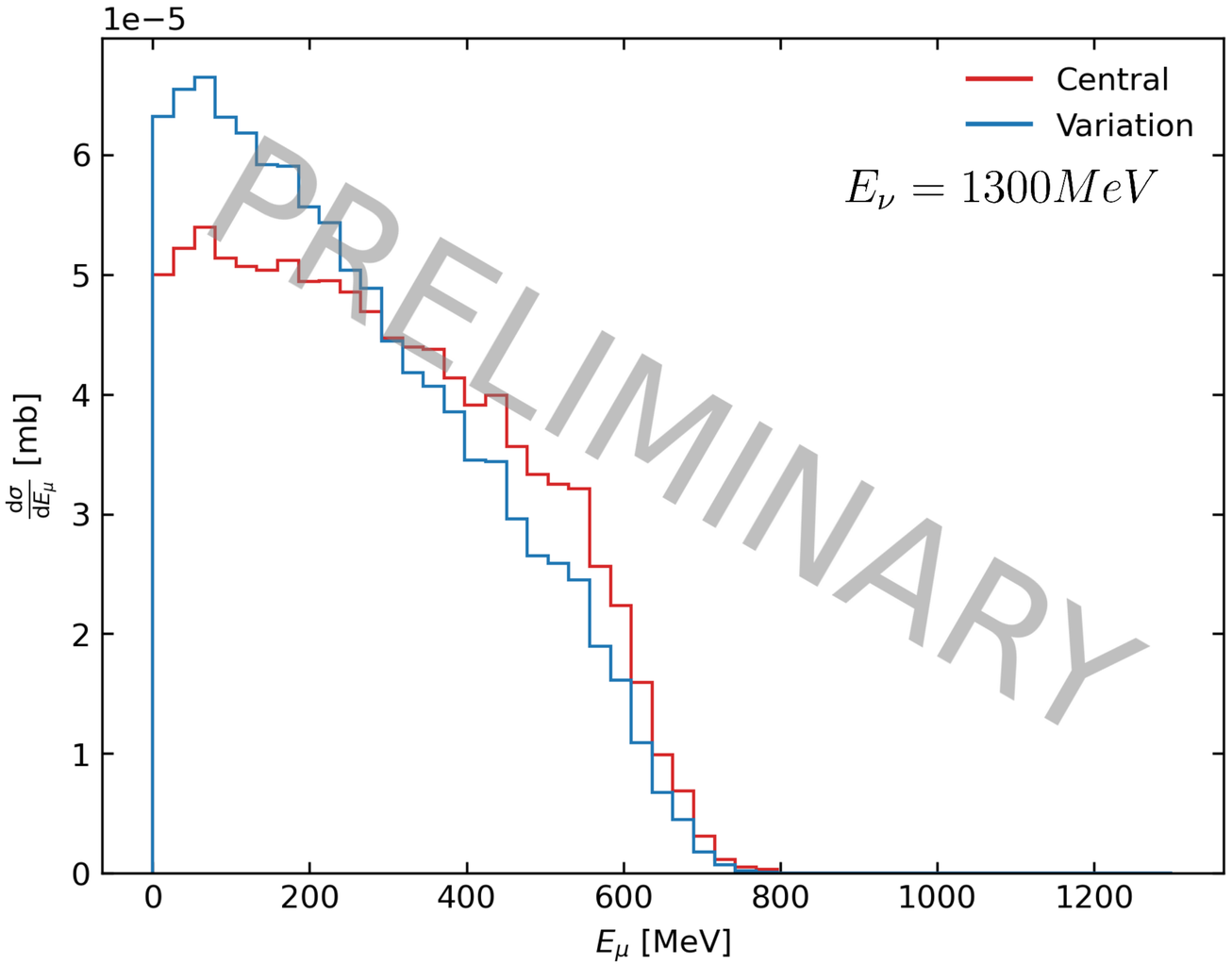
Including Argon



- Spectral function and nuclear configurations obtained from Woods-Saxon single-particle orbitals A. Nikolakopoulos, [Isaacson], et. al. [2406.09244]
- Still missing mean-field spectral function to obtain interference contribution (available soon)

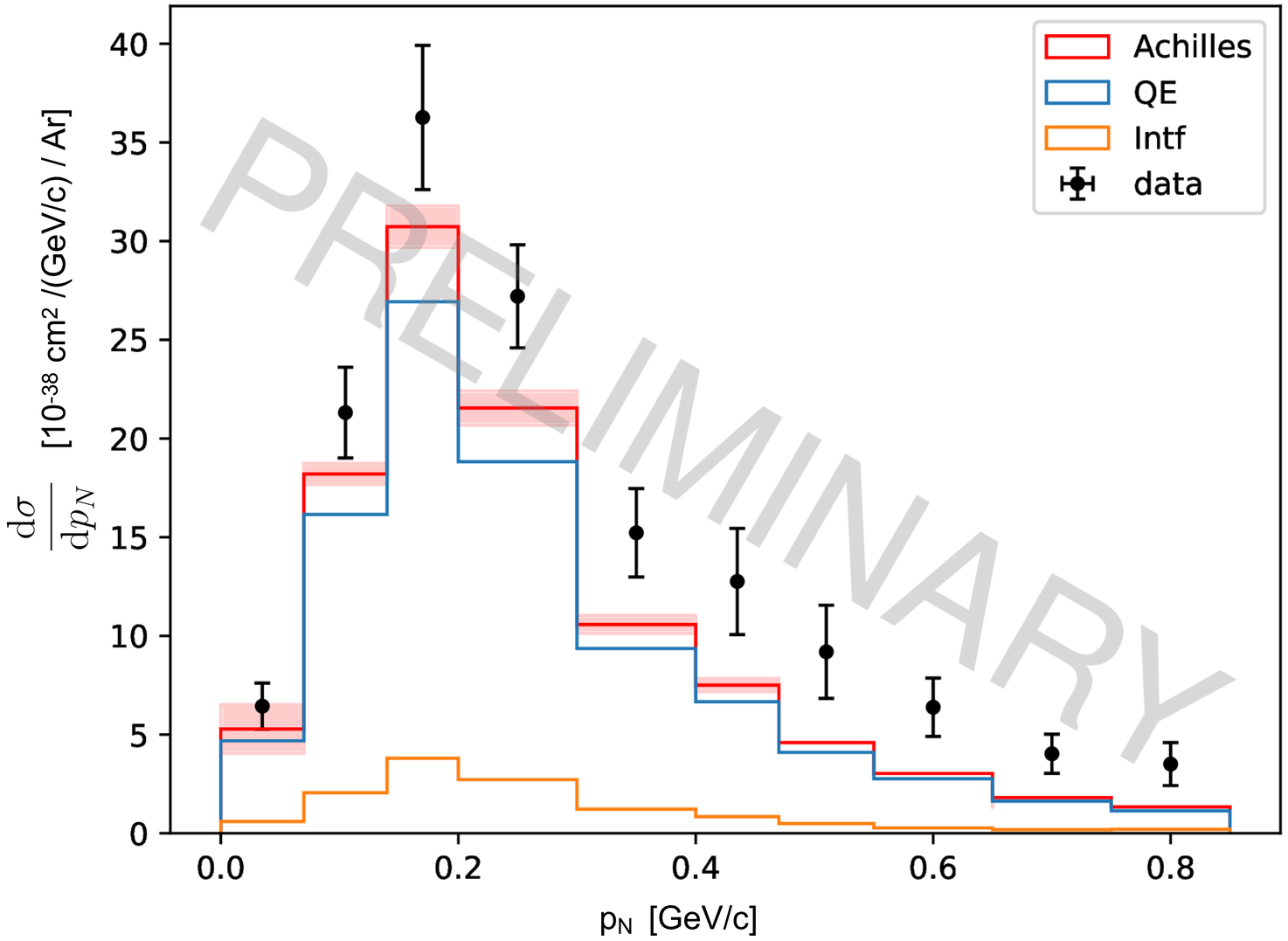


On-the-Fly Variations (in progress)



- Calculate variation of physics parameter at run time (ex. Changing form factors, spectral functions, etc.)
- Output a vector of alternative weights for each event
- Quick estimate of uncertainties without needing multiple runs
- Only evaluate for accepted event
- Single sample through detector simulation
- Based off of developments for the LHC [1606.08753]

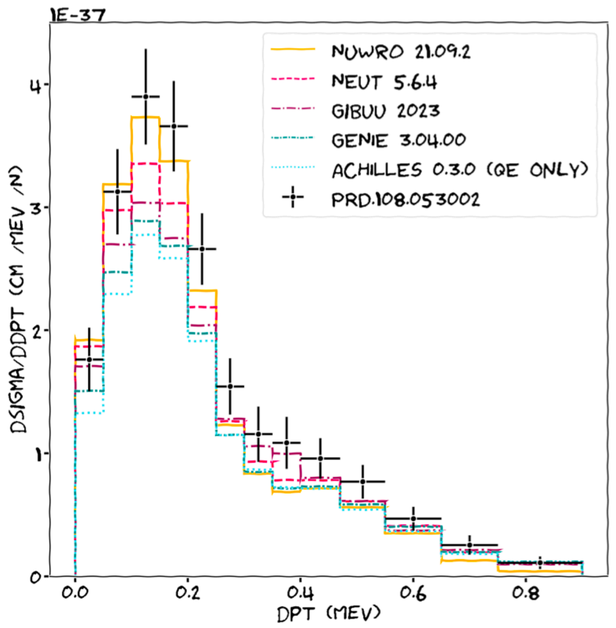
Automatic Data Comparison with Nuisance v3 (in progress)



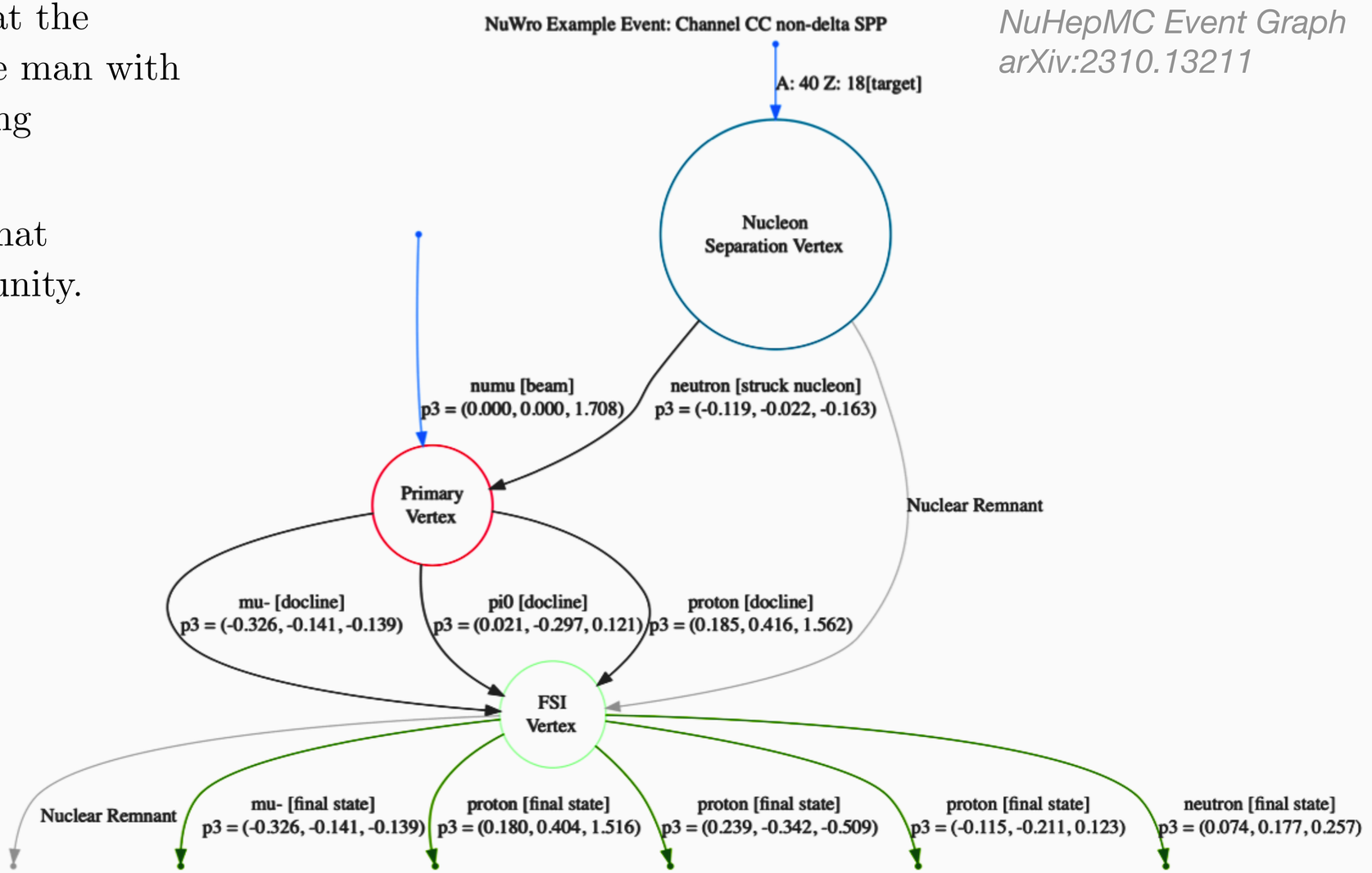
- Automatically download analysis, data, flux, etc. from HepData
- Launch Achilles with required setup automatically
- Appropriately handle correlated uncertainties
- Data from MicroBooNE experiment [2310.06082]

Common Formats : NuHepMC

- Common event formats adopted at the generator level cut out the middle man with NUISANCE flattrees for processing generator outputs.
- NuHepMC built on HepMC3 format maintained by the collider community.

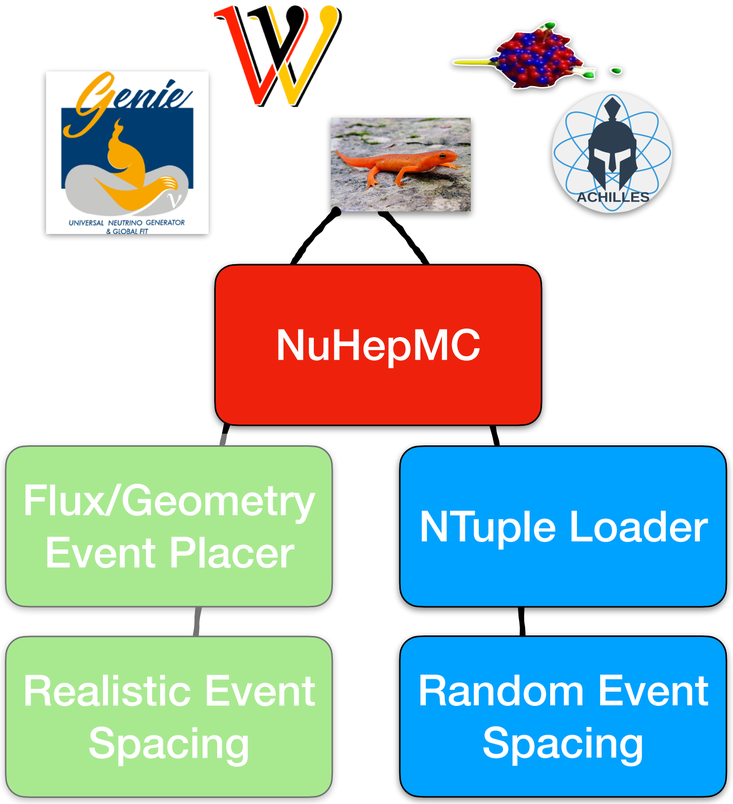


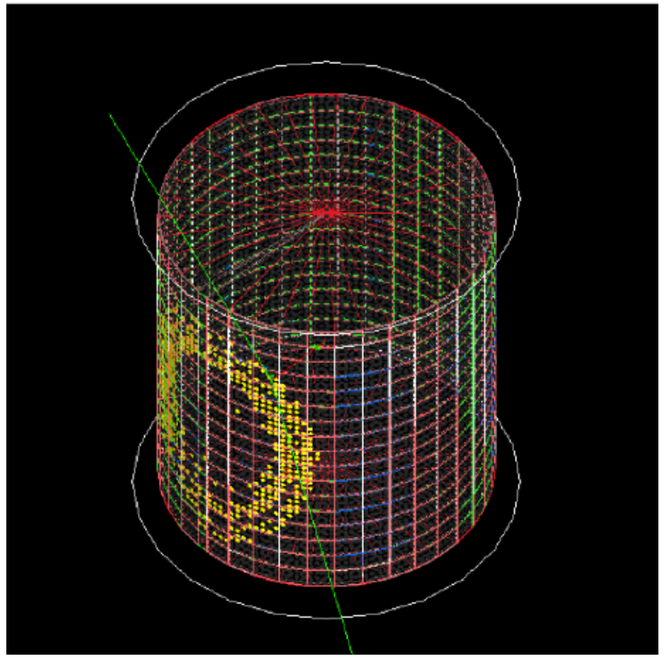
NuHepMC Event Graph
arXiv:2310.13211



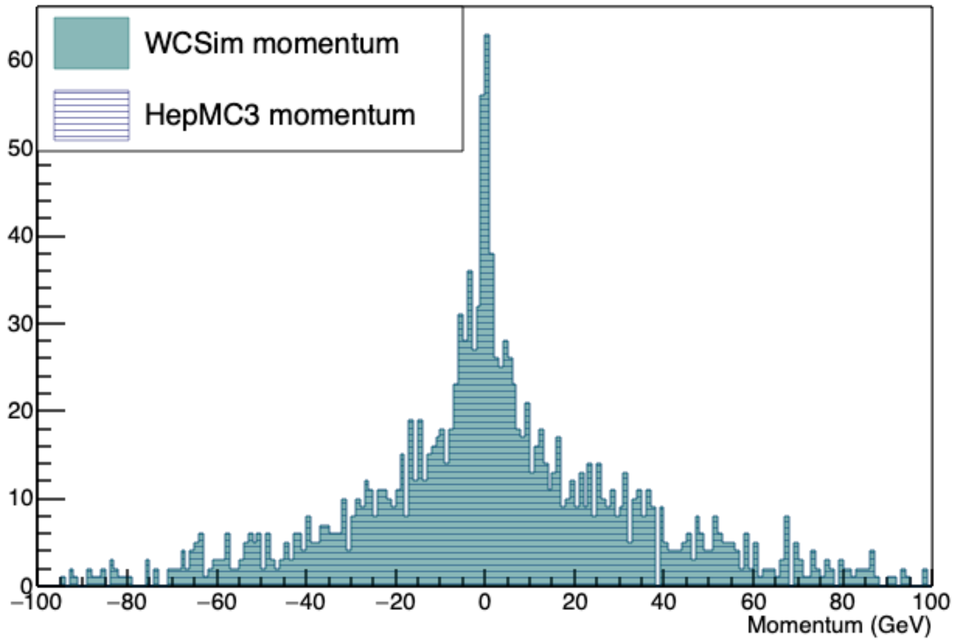
Common Formats : GEANT4 Interfaces

- Harmonised event format means direct experimental ntuple generation significantly quicker.
- Potential for custom events (direct from theory?) to be used to look at detector response.
- G4 tuple reader recently setup for HK and tested with NEUT inputs.





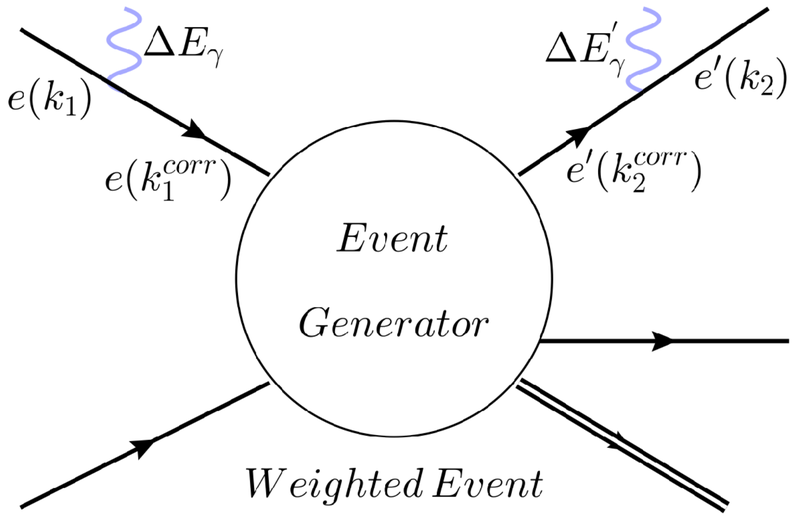
WCSim - HK Geant4 Tool

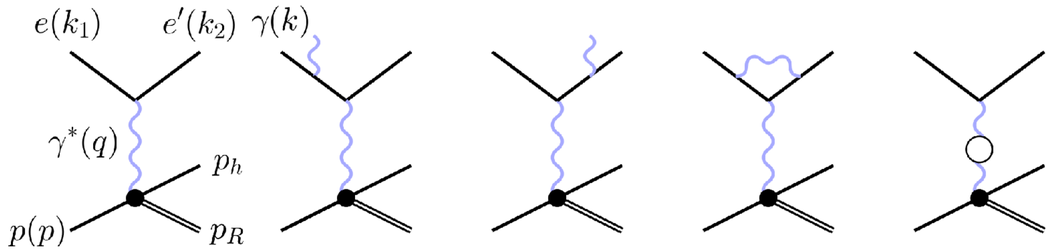


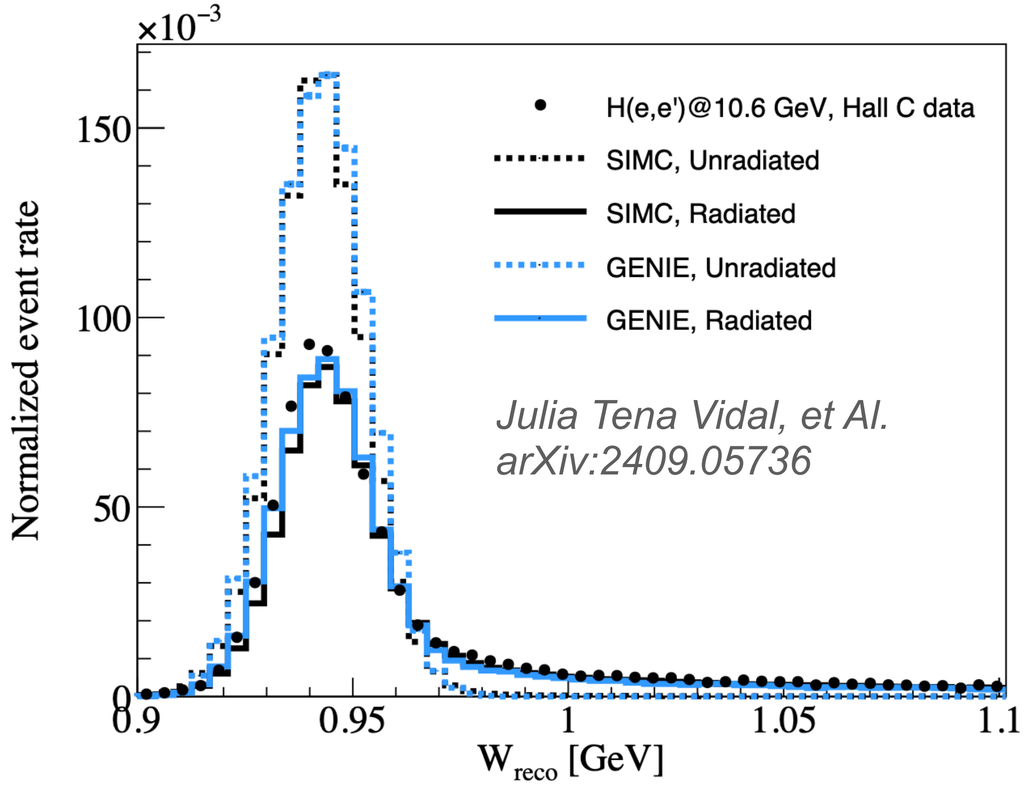
WCSim HepMC3 Loader Validation - J. Fannon

Common Formats : Model Extensions

- Recent work by Julia for eA scattering a good example of common event formats allowing generator agnostic model extensions.
- Universal implementation of radiative effects in neutrino event generators for e-A scattering applied to NuHepMC event

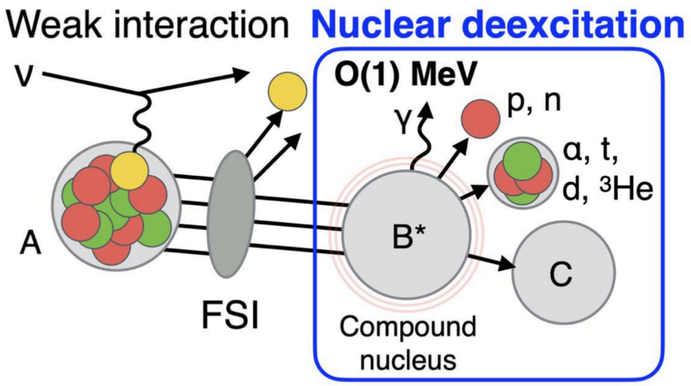


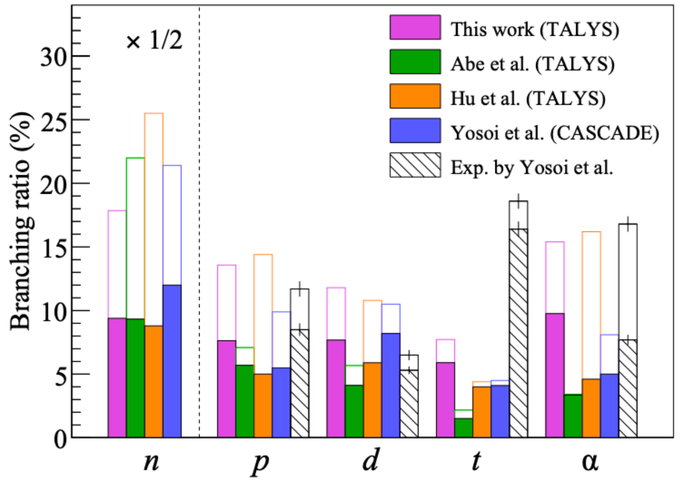


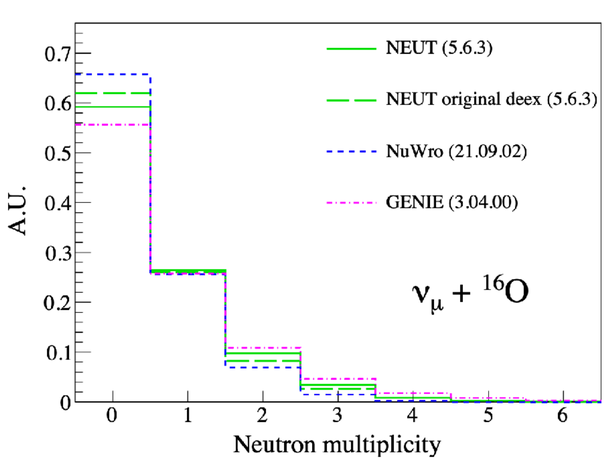


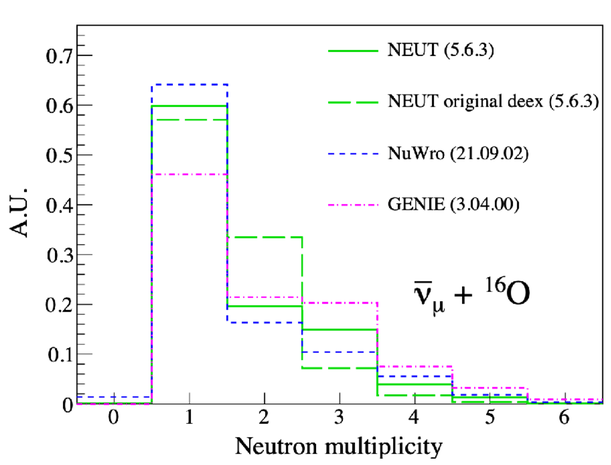
Common Formats : TALYS NucDeEx MODEL

- Neutrino interactions can leave residual nucleus in an excited state which subsequently decays to emit secondary nucleons/gamma rays.
- NEUT models this only for oxygen and nitrogen targets.
- Recent Work by Seisho Abe to implement TALYS based NucDeEx model as an alternative option in NEUT (modular generator agnostic design).









Abe, Seisho. "Nuclear deexcitation simulator for neutrino interactions and nucleon decays of C 12 and O 16 based on TALYS." Physical Review D 109.3 (2024): 036009.

MISSING PIECES OF THE JIGSAW

- Lots of new generator improvements available to support future neutrino physics programs.

- Still several key questions on the generator side
  - **What latest theory models do we consider a priority?** (new pion models, theory motivated hadronic distributions, FSI implementations?)
  - **Do we handle systematics of our current models correctly?** (e.g. Axial Form Factors)
  - **Can we further streamline model implementations on the generator side?** Do we need better standardised templates with automated validation tools?
  - **Can standardised events formats support other model implementations?** Building on prior work on radiative or de-excitation corrections. E.g. Could some externally factorised FSI approaches use NuHepMC as a 'seed' for a cascade?

WANT TO
~~PLAY A GAME~~
IMPLEMENT A MODEL?

GENIE

Luis Alvarez-Ruso (IFIC), Costas Andreopoulos (Liverpool), Adi Ashkenazi (Tel Aviv),
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Vladyslav Syrotenko (Tufts), Julia Tena Vidal (Tel Aviv), Jeremy Wolcott (Tufts), Qiyu Yan (UCAS, Warwick)

(The GENIE Collaboration)

NEUT

NEUT has been actively developed by the SK and T2K collaborations for several decades.

We really need an author list!

And a logo!

N - Newt

NuWro

Founder: Jan T. Sobczyk ~ 2004
• Inspired from Danka Kiełczewska.

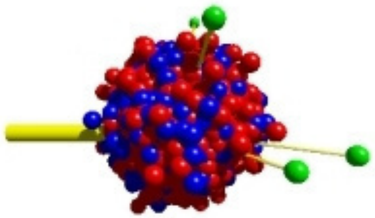
A structure of the code was constructed by Cezary Juszczak.
A major part of NuWro physics models were added by previous PhD students
• Jarosław Nowak
• Tomasz Golan
• Kajetan Niewczas

Important contributions from
• Krzysztof Graczyk
• Artur Ankowski
• Chris Thorpe
• Dmitry Zhuridov
• Jakub Żmuda

Some technical additions by
Luke Pickering and Patrick Stowell.

New additions
• Beata Kowal (PostDoc.)
• Luis Bonilla (PostDoc.)
• Rwik Dharmapal Banerjee (PhD)
• Hemant Prasad (PhD)

GiBUU



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- Dipl.-Phys. Ivan Lappo-Danilevski
- Dr. Tina Leitner
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- Dr. Janus Weil

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- Dr. Alexander Hombach
- Dr. Jürgen Lehr
- Dr. Pascal Mühlich
- Dr. Stefan Teis
- Dr. Markus Wagner

Achilles: A CHIcagoLand Lepton Event Simulator

Core Authors








Undergraduates




ACHILLES

Fermilab