# The NEUT Generator: Status and Plans

Luke Pickering, P. Stowell
for the NEUT developers

16/09/24
NuFact 2024
Argonne

Science and Technology Facilities Council

Supported by URF\R1\211661
THE ROYAL SOCIETY

# What Is NEUT?

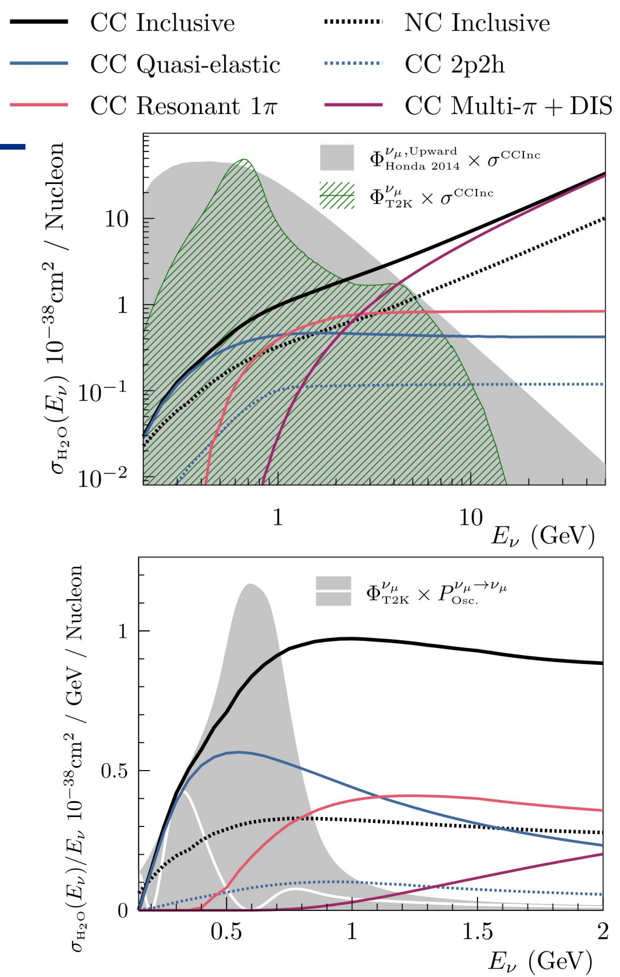
Eur. Phys. J. Spec. Top. 230, 4469–4481 (2021)

- Primarily a Neutrino–Nucleus interaction generator:
  - Simulates primary processes for ~100 MeV to few-TeV neutrinos
  - Interactions with nuclear targets from Hydrogen to Lead
  - Hadron cascade for propagating hadrons out of the nuclear medium

# What Is NEUT?

*Eur. Phys. J. Spec. Top. 230, 4469–4481 (2021)*

- Primarily a Neutrino–Nucleus interaction generator:
  - Simulates primary processes for ~100 MeV to few-TeV neutrinos
  - Interactions with nuclear targets from Hydrogen to Lead
  - Hadron cascade for propagating hadrons out of the nuclear medium
- Maintained 'in house' for use on T2K and SK:
  - Development targets the needs of the long baseline oscillation and cross-section programmes
    - Sub-to-few GeV energy region
    - Hydrocarbon and water targets



# History

- Originally developed to predict neutrino-induced background rate for Kamiokande nucleon decay measurements.

```
*************************************************************************
*        ---------------------
         SUBROUTINE RNAZI(C,S)
*        ---------------------
*
*        (Purpose)
*          Give cosine and sine of random direction
*
*        (Input)
*          NONE
*
*        (Output)
*          C       : COSINE OF RANDOM DIRECTION
*          S       : SINE OF RANDOM DIRECTION
*
*        (Creation Date and Author)
*          1978.09.08 ; S.Yamada, A.Sato
*          1995.02.03 ; K. KANEYUKI  FOR S.K.
*                       RANAZI -> RNAZI
*
*************************************************************************
```

# History

- Originally developed to predict neutrino-induced background rate for Kamiokande nucleon decay measurements.

```
*************************************************************************
*     ---------------------
      SUBROUTINE RNAZI(C,S)
*     ---------------------
*
*     (Purpose)
*       Give cosine and sine of random direction
*
*     (Input)
*       NONE
*
*     (Output)
*       C       : COSINE OF RANDOM DIRECTION
*       S       : SINE OF RANDOM DIRECTION
*
*     (Creation Date and Author)
*       1978.09.08 ; S.Yamada, A.Sato
*       1995.02.03 ; K. KANEYUKI  FOR S.K.
*                    RANAZI -> RNAZI
*
*************************************************************************
```

# History

- Originally developed to predict neutrino-induced background rate for Kamiokande nucleon decay measurements.
- Has since been used for all SK and T2K long baseline oscillation results and the majority of T2K cross-section measurements.
  - Including Nobel and Breakthrough prize-winning measurements!
- The source has historically not been public, but is available upon request.

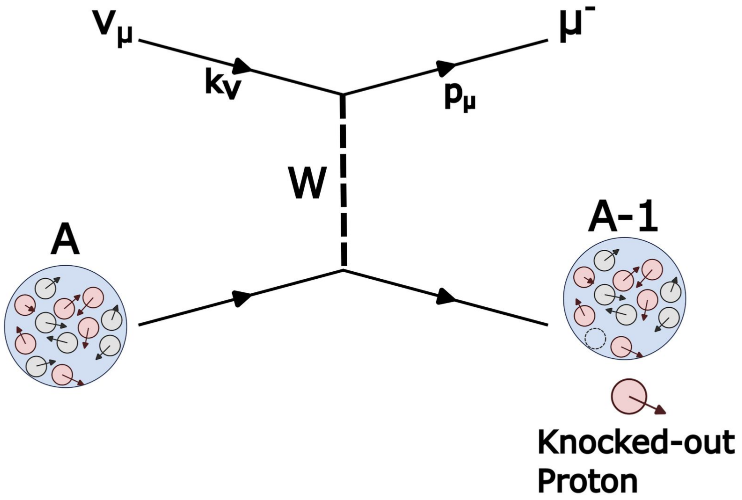
```
************************************************************************
*     ---------------------
      SUBROUTINE RNAZI(C,S)
*     ---------------------
*
*     (Purpose)
*       Give cosine and sine of random direction
*
*     (Input)
*       NONE
*
*     (Output)
*       C       : COSINE OF RANDOM DIRECTION
*       S       : SINE OF RANDOM DIRECTION
*
*     (Creation Date and Author)
```

```
*     (Creation Date and Author)
*       1983.??.?? ; M.NAKAHATA
*       1987.08.?? ; N.SATO     FOR TAU
*       1988.08.31 ; T.KAJITA   DATA UPDATE
*       1988.09.05 ; T.KAJITA   R1314 IS ADDED
*       1988.09.10 ; T.KAJITA   DX/DY WAS CHANGED BY THAT OF N.SATO'S
*                               WHICH INCLUDE LEPTON MASS TERM AND SMALL
*                               TERMS
*       1988.10.05 ; T.KAJITA   SIGMA(NC)/SIGMA(CC) RATIOS AT HIGH ENERGIES
*                               J.E.KIM ET AL., REV.MOD.PHYS.53(1981)211
*       1989.07.21 ; K.KANEYUKI NEU-TAU C.C. CROSS SECTION WAS UPDATED SAME
*                                AS NEU-E,NEU-MU
*                                NEU-TAU N.C. CROSS SECTION =>
*                                SAME AS NEU-E,NEU-MU
*       1998.03.02 ; M.Shiozawa  invariant mass threshold was changed due
*                                 to new improved Rein-Sehgal model.
*       1998.09.?? ; J.Kameda    New Calculation based on New Structure
*                                function GRV94 DIS
*                                Consider Nu_tau cross section
*       2006.08.04 ; G.Mitsuka   Cross section is culculated after loading
*                                cross section table
*       2007.11.05 ; G.Mitsuka   support target nucleus besides 160
*       2007.11.10 ; T.Tanaka    add upmu mode
*       2007.12.05 ; G.Mitsuka   Maximum neutrno energy is extended to 100TeV
*                                even if not upmu mode
*       2008.11.17 ; R.Tacik     calculate inump and inumpn for each event
*       2016.03.03 ; C.Bronner   Put back the possibility to use a given input proton fraction
*                                inump and inumpn are computed from number of nucleons only if
*                                the input fraction is <0 or >1
*       2020.12.02 ; C.Bronner   Cross-section for new BY model
*
```

# Model Components

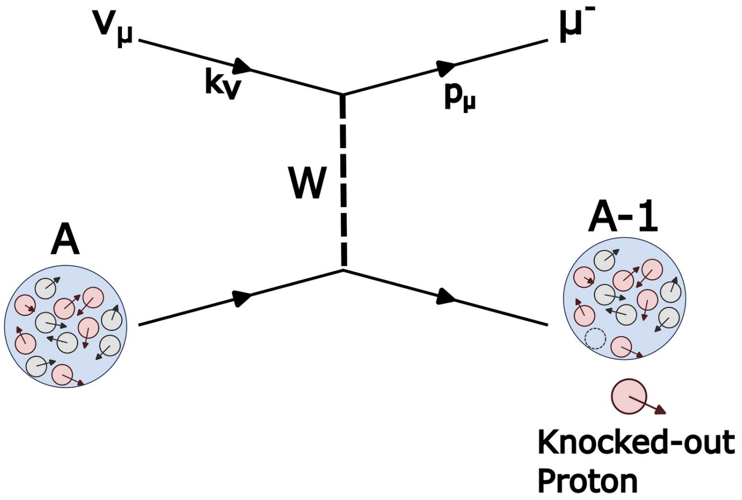
# Anatomy of A Neutrino Interaction

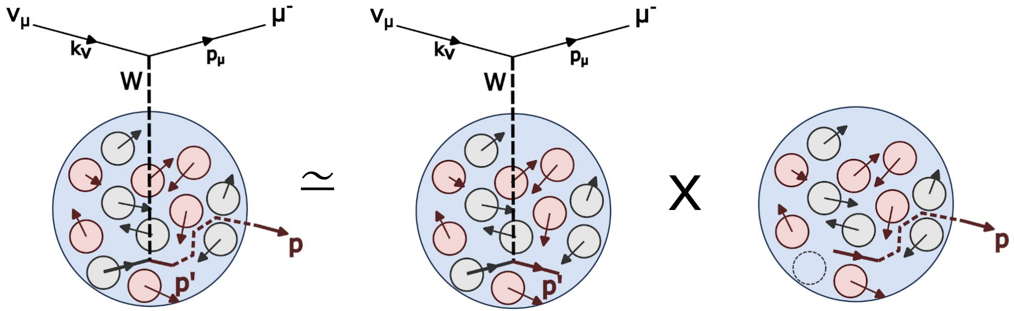
- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable



# Anatomy of A Neutrino Interaction

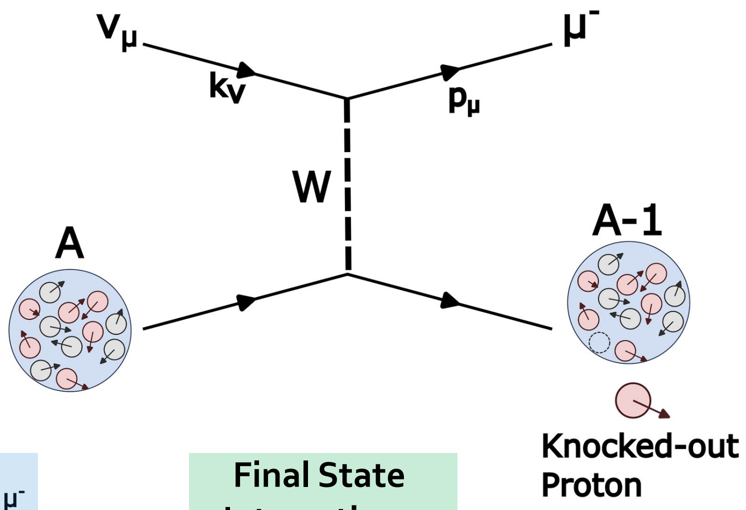
- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable
- Factorisation to the *rescue*!

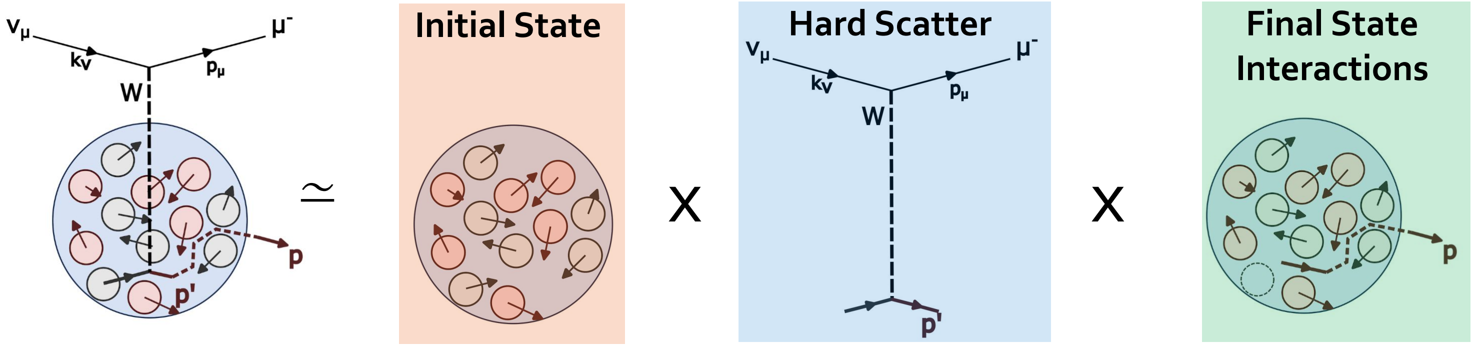


# Anatomy of A Neutrino Interaction

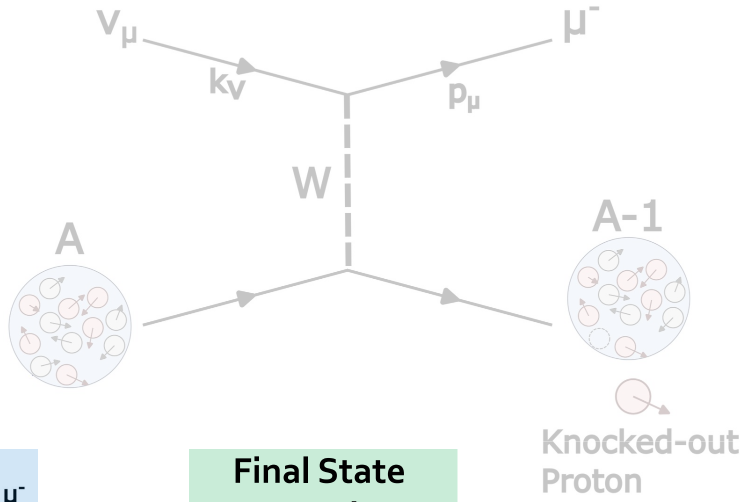
- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable
- Factorisation to the *rescue* **again**!



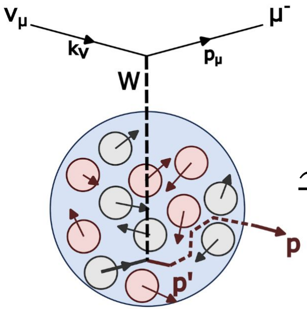



# Anatomy of A Neutrino Interaction

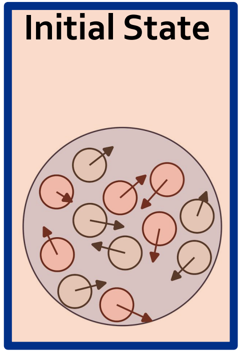
- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable



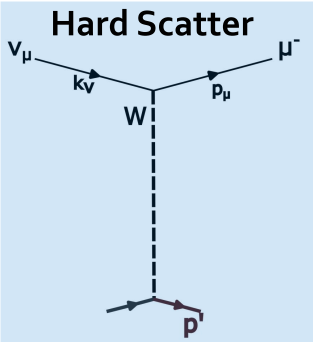

- Factorisation to the *rescue* **again**!



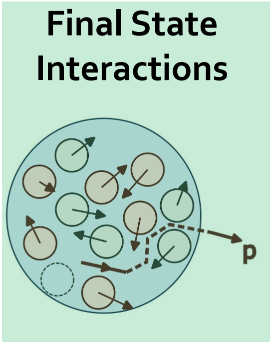

≃




X




X

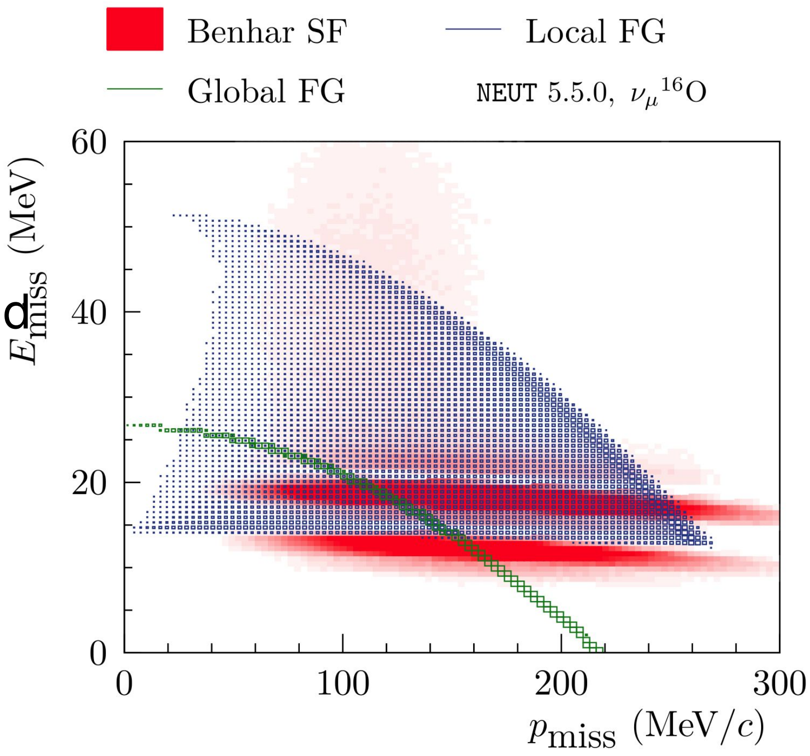


# The Initial State

- The details of the initial state are critical for predicting few-GeV interactions correctly
  - Bound nucleons are in Fermi motion
  - Struck nucleons are off mass shell

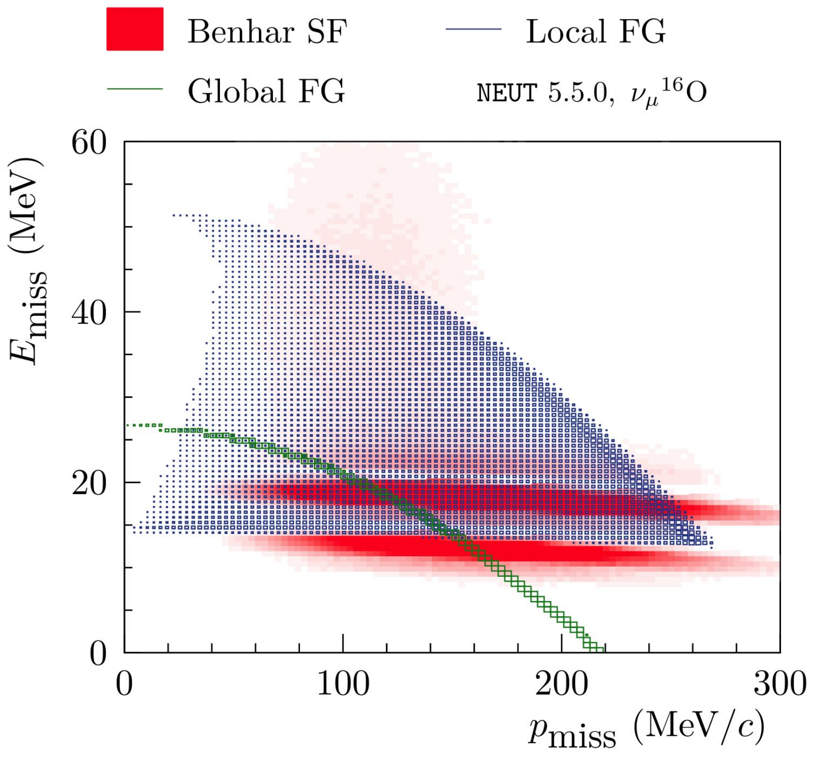
# The Initial State

- The details of the initial state are critical for predicting few-GeV interactions correctly
  - Bound nucleons are in Fermi motion
  - Struck nucleons are off mass shell
- Usually characterised by Spectral Functions tuned to predict observed 'missing energy and momentum' in electron scattering.



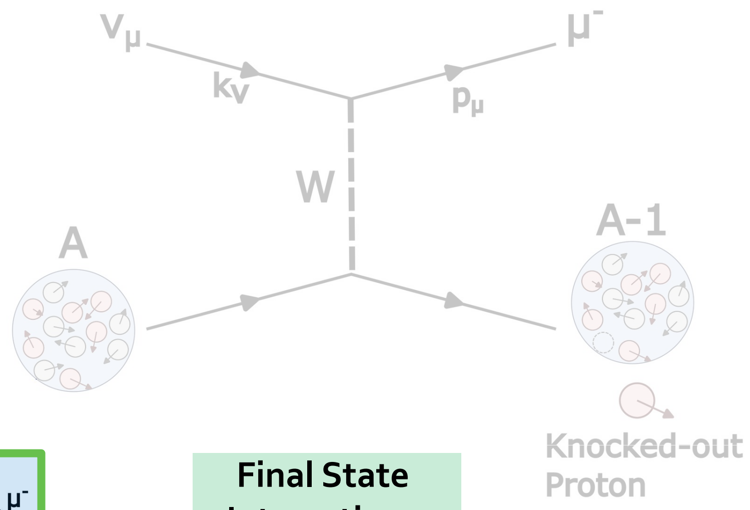
# The Initial State

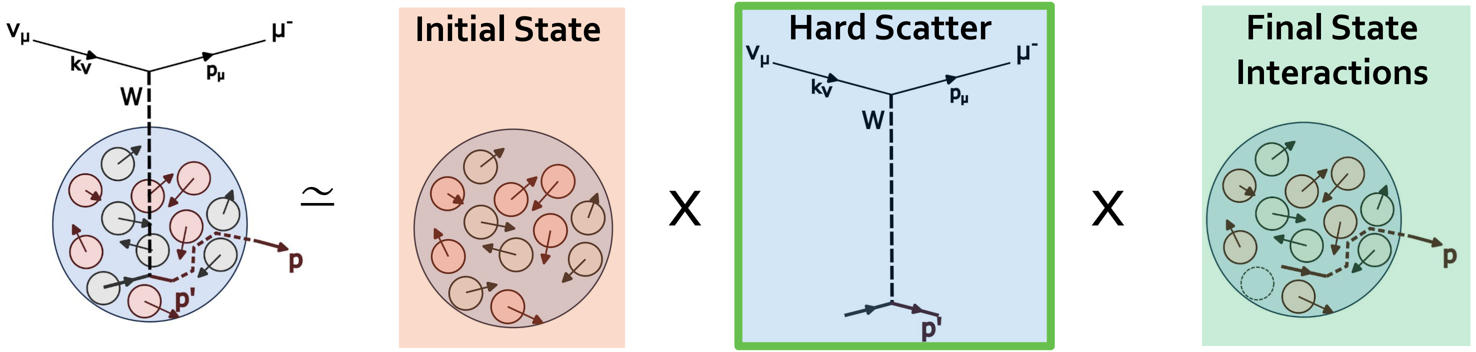
- The details of the initial state are critical for predicting few-GeV interactions correctly
  - Bound nucleons are in Fermi motion
  - Struck nucleons are off mass shell
- Usually characterised by Spectral Functions tuned to predict observed 'missing energy a momentum' in electron scattering.
- NEUT can simulate interactions with FG nuclear models on a wide range of target nuclei
- NEUT can also use the Benhar SF for Quasi Elastic interactions with C12, O16, and Fe56



# Anatomy of A Neutrino Interaction

- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable
- Factorisation to the *rescue* **again**!



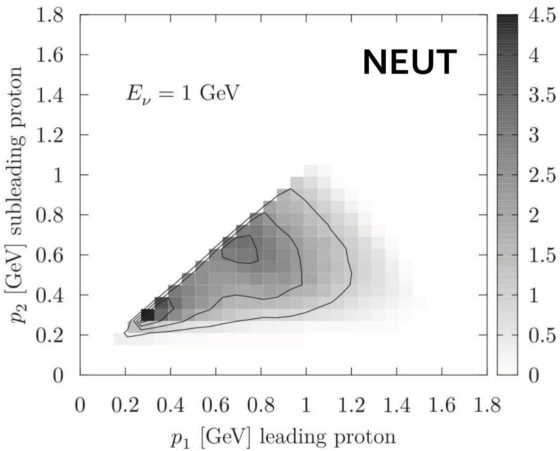
# 0Pi

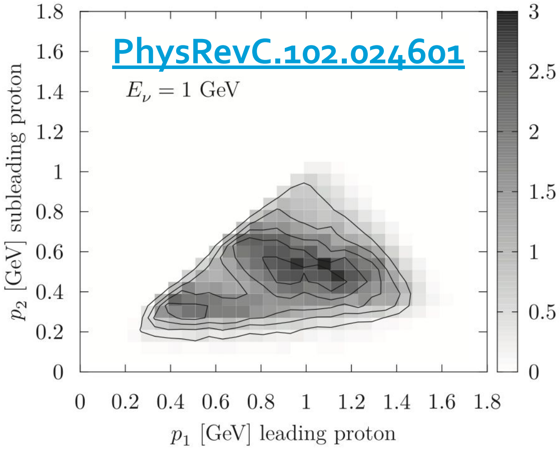
- Inclusive CCQE Models:
  - Smith-Moniz RFG w/Llewellyn Smith cross-section & kinematics
  - Benhar *et al.* SF w/Llewellyn Smith cross-section & kinematics
  - Nieves *et al.* 1p1h (Valencia) w/Bourguille *et al.* removal energy
  - Nucleon Form Factors:
    - Vector: Dipole, BBA05, BBBA07
    - Axial: Dipole, 3-component, Z-expansion

# 0Pi

- Inclusive CCQE Models:
  - Smith-Moniz RFG w/Llewellyn Smith cross-section & kinematics
  - Benhar *et al.* SF w/Llewellyn Smith cross-section & kinematics
  - Nieves *et al.* 1p1h (Valencia) w/Bourguille *et al.* removal energy
  - Nucleon Form Factors:
    - Vector: Dipole, BBA05, BBBA07
    - Axial: Dipole, 3-component, Z-expansion

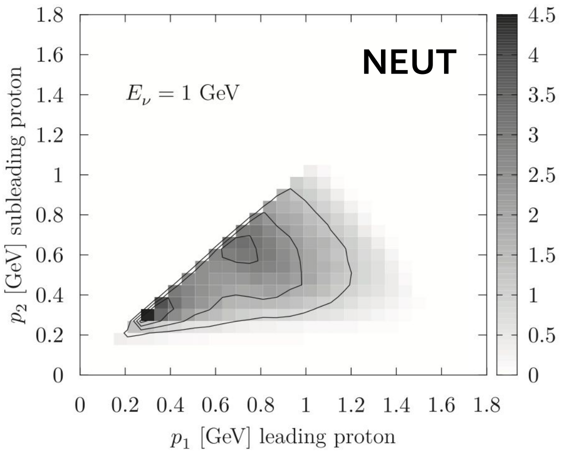
- Inclusive 2p2h Model: Nieves *et al.* 2p2h (Valencia)
  - w/egalitarian hadron kinematics model and Bourguille *et al.* removal energy
  - Breaks second factorisation as interaction is inherently multi-body

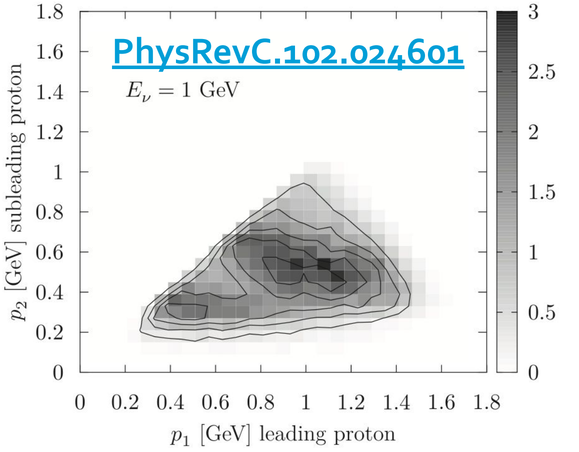


# 0Pi

- Inclusive CCQE Models:
  - Smith-Moniz RFG w/Llewellyn Smith cross-section & kinematics
  - Benhar *et al.* SF w/Llewellyn Smith cross-section & kinematics
  - Nieves *et al.* 1p1h (Valencia) w/Bourguille *et al.* removal energy
  - Nucleon Form Factors:
    - Vector: Dipole, BBA05, BBBA07
    - Axial: Dipole, 3-component, Z-expansion
- Inclusive 2p2h Model: Nieves *et al.* 2p2h (Valencia)
  - w/egalitarian hadron kinematics model and Bourguille *et al.* removal energy
  - Breaks second factorisation as interaction is inherently multi-body
- 2010's NEUT development focussed on 0Pi channels
  - Significant improvements needed for HK/DUNE



# Single Pion Production

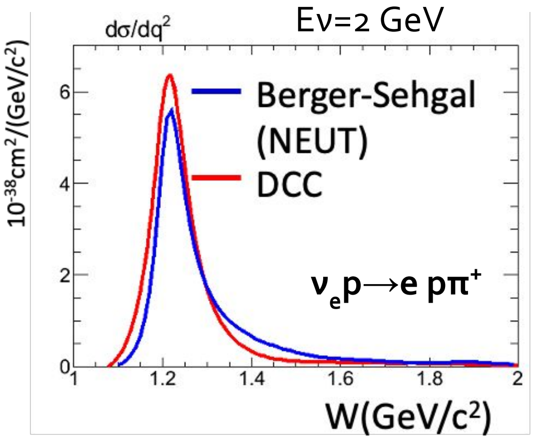
- Rein-Sehgal model: w/Berger-Sehgal lepton mass effects
  - All RS resonances contribute coherently
  - Graczyk–Sobczyk form factors
  - Isospin ½ non-resonant background included incoherently
  - Single Etas, Omegas, and Gamma production is also implemented

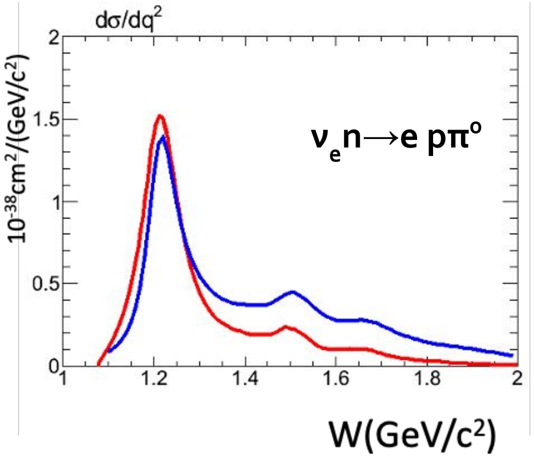
# Single Pion Production

- Rein-Sehgal model: w/Berger-Sehgal lepton mass effects
  - All RS resonances contribute coherently
  - Graczyk–Sobczyk form factors
  - Isospin ½ non-resonant background included incoherently
  - Single Etas, Omegas, and Gamma production is also implemented
- MK2018 implementation:
  - **Key improvement:** Non-resonant channels contribute coherently
  - Significantly improved model on the way, watch this space!

# Single Pion Production

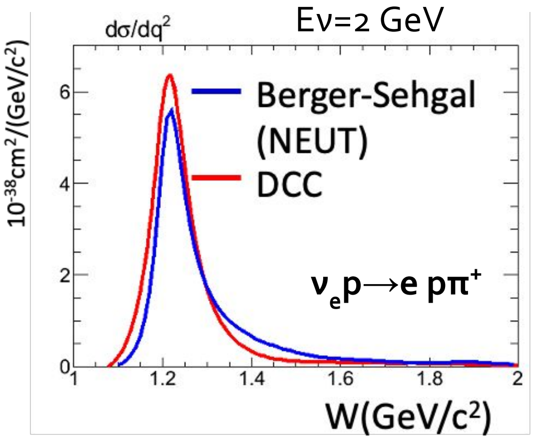
- Rein-Sehgal model: w/Berger-Sehgal lepton mass effects
  - All RS resonances contribute coherently
  - Graczyk–Sobczyk form factors
  - Isospin ½ non-resonant background included incoherently
  - Single Etas, Omegas, and Gamma production is also implemented
- MK2018 implementation:
  - **Key improvement:** Non-resonant channels contribute coherently
  - Significantly improved model on the way, watch this space!
- DCC 1Pi [PRD 92, 074024 (2015)]:
  - State-of-the-art 1Pi model
  - Inclusive predictions implemented in NEUT

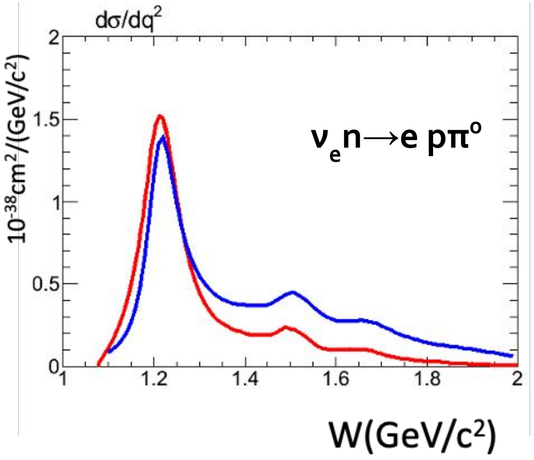


# Single Pion Production

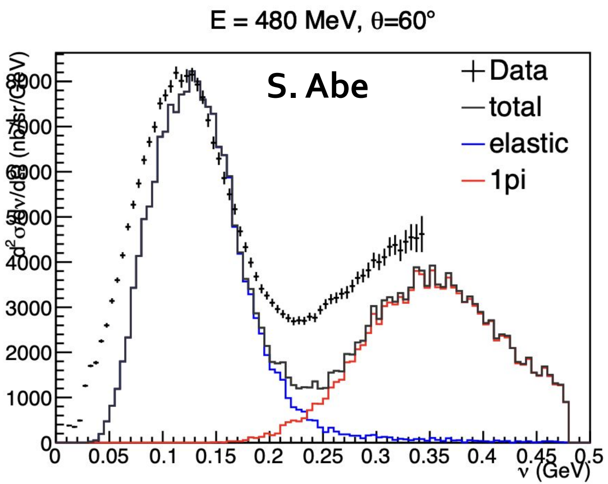
- Rein-Sehgal model: w/Berger-Sehgal lepton mass effects
  - All RS resonances contribute coherently
  - Graczyk–Sobczyk form factors
  - Isospin ½ non-resonant background included incoherently
  - Single Etas, Omegas, and Gamma production is also implemented
- MK2018 implementation:
  - **Key improvement:** Non-resonant channels contribute coherently
  - Significantly improved model on the way, watch this space!
- DCC 1Pi [PRD 92, 074024 (2015)]:
  - State-of-the-art 1Pi model
  - Inclusive predictions implemented in NEUT
- Coherent 1Pi: Rein-Sehgal and **Berger-Sehgal**
- Diffractive 1Pi: Rein Model



# Electron Scattering

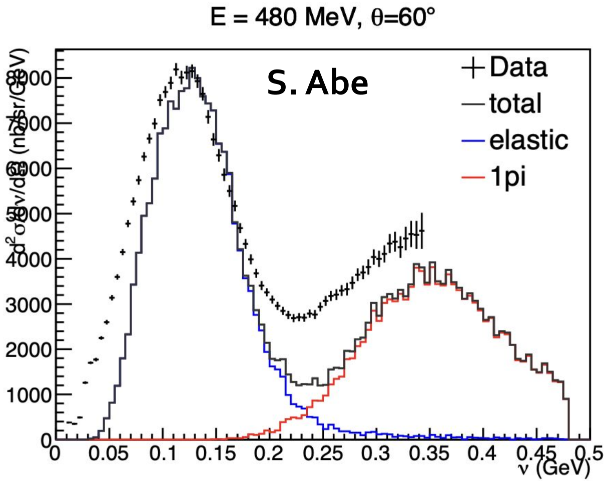
- Recent ability to run an e-like mode in NEUT
- QE channel based on Benhar et al. SF + NCQE
- **NEW!** 1pi predicted by DCC [PRD 92, 074024]

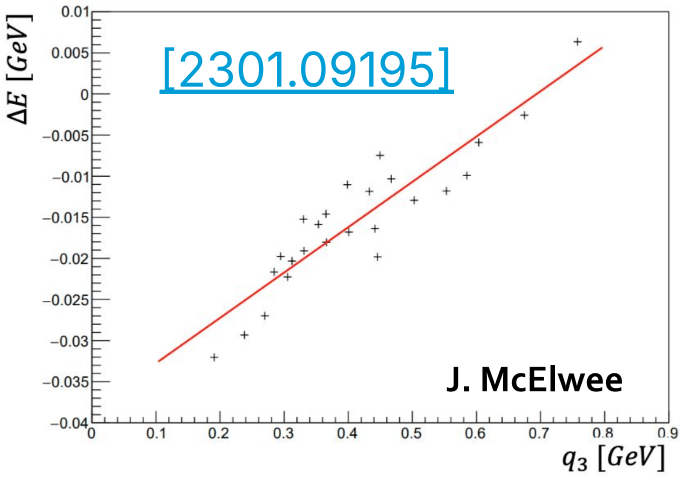


# Electron Scattering

- Recent ability to run an e-like mode in NEUT
- QE channel based on Benhar et al. SF + NCQE
- **NEW!** 1pi predicted by DCC [PRD 92, 074024]

- Can be used to benchmark nuclear response implementation:
  - As expected from earlier work, the QE peak position is not correctly predicted by factorized SF implementation.
  - Shift of predicted to measured QE peak position shows clear dependence on interaction kinematics...
  - The second factorisation is wrong again.
  - But, observed shift ~matches predictions from RMF!

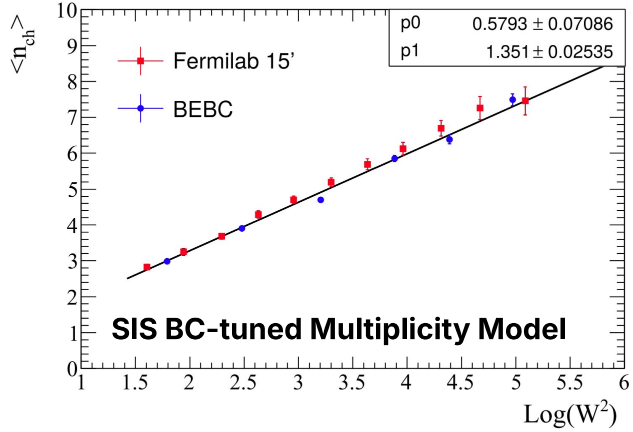


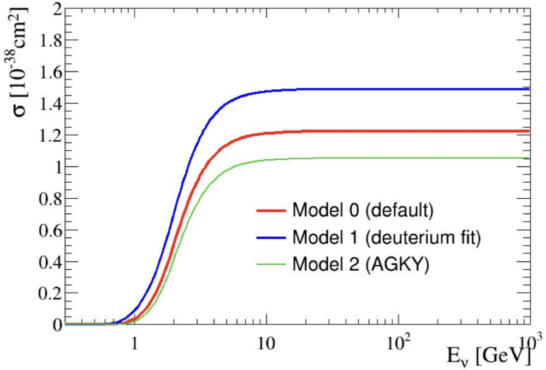



# Shallow & Deep Inelastic Scattering

NEUT SIS+DIS Model:

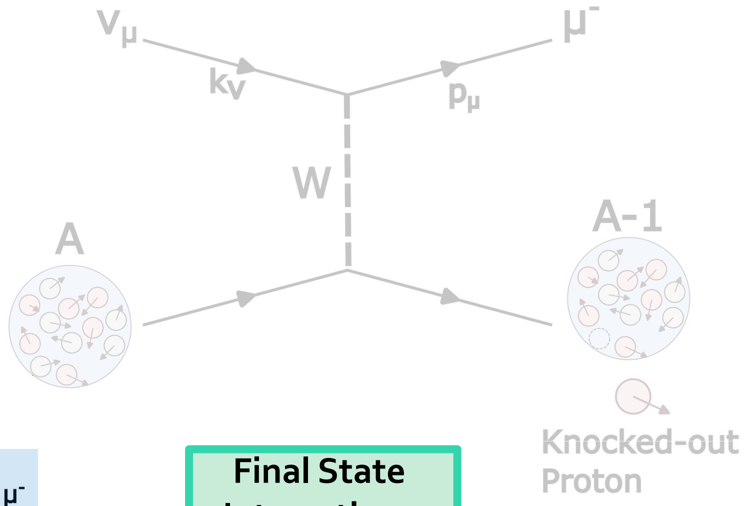
- GRV98 with Bodek Yang low Q2 modifications
  - Updated to 2108.09240v2 with improved tuning and new uncertainty estimation
  - Many new model improvements/fixes, C Bronner
- Pythia/JETSET 5.72 fragmentation
- SIS: W < 2
  - Must produce >= 2 pions to remove double-counting with SPP Processes
  - Custom charged-hadron multiplicity model with multiple options: **Legacy**, **BC-tuned**, **AGKY**
- DIS: W > 2
  - Full Pythia event generation



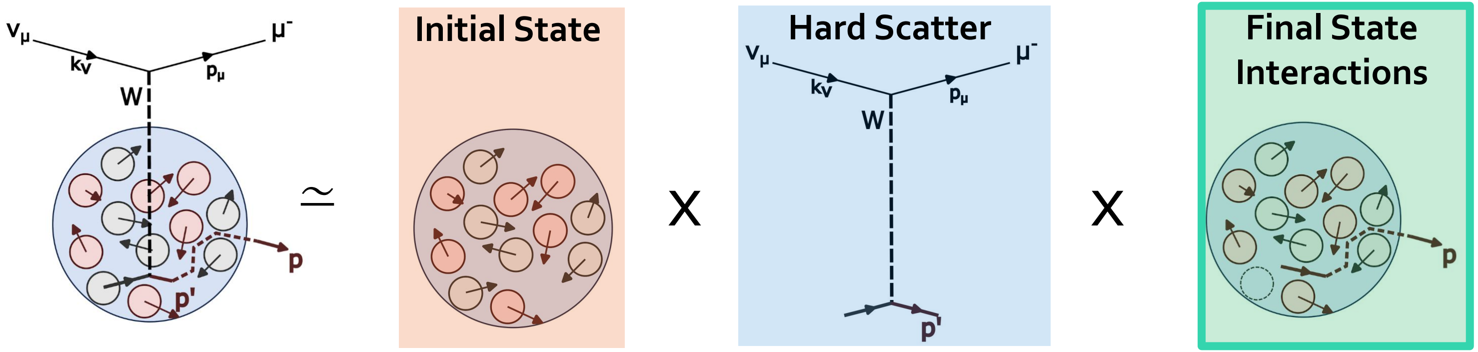



# Anatomy of A Neutrino Interaction

- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable




- Factorisation to the *rescue* **again**!

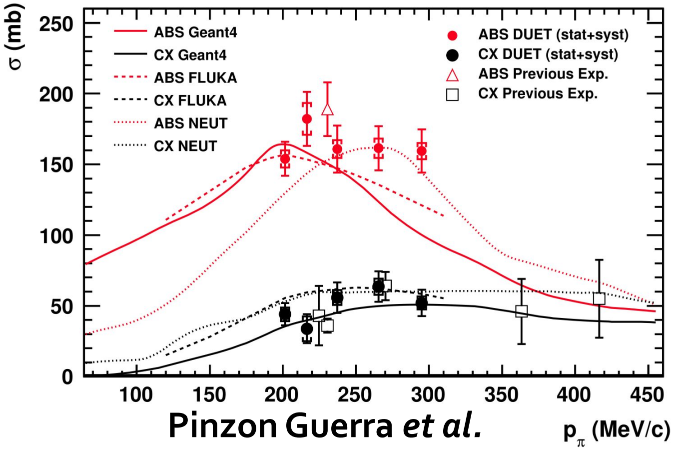


# Cascade

- Hadrons produced in the Hard Scatter must be transported out of the nuclear medium before being considered *observable.*
    - Hadron kinematics, particle species, and multiplicity can change through interactions

# Cascade

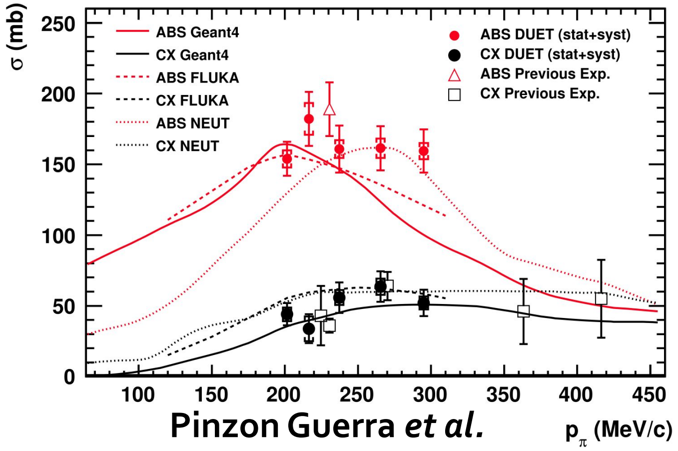
- Hadrons produced in the Hard Scatter must be transported out of the nuclear medium before being considered *observable.*
  - Hadron kinematics, particle species, and multiplicity can chang through interactions
- In NEUT, hadrons are stepped out the nucleus via a semi-classical Metropolis cascade which implements interactions of nucleons, pions, kaons, etas, and omegas
  - Pion processes: Quasi-Elastic, Charge-exchange, Absorption, or pion production tuned to a variety of thin-target data




Pinzon Guerra *et al.*

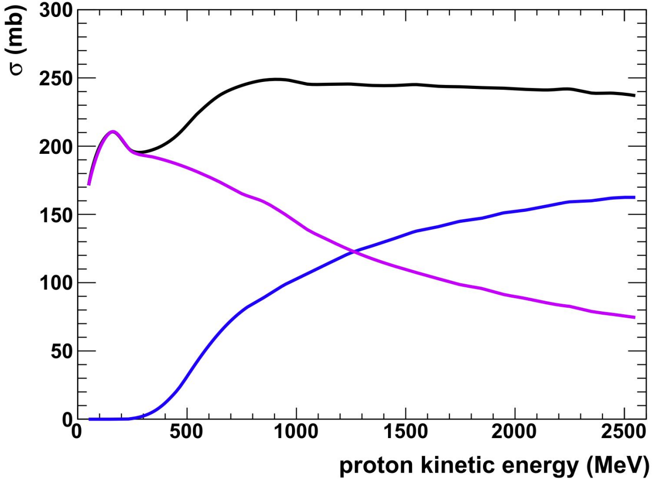
# Cascade

- Hadrons produced in the Hard Scatter must be transported out of the nuclear medium before being considered *observable.*
  - Hadron kinematics, particle species, and multiplicity can chang through interactions
- In NEUT, hadrons are stepped out the nucleus via a semi-classical Metropolis cascade which implements interactions of nucleons, pions, kaons, etas, and omegas
  - Pion processes: Quasi-Elastic, Charge-exchange, Absorption, or pion production tuned to a variety of thin-target data
  - The nucleon cascade follows Bertini *et al*. for MECC-7
- Woods-Saxon nucleon density with LFG spectral function



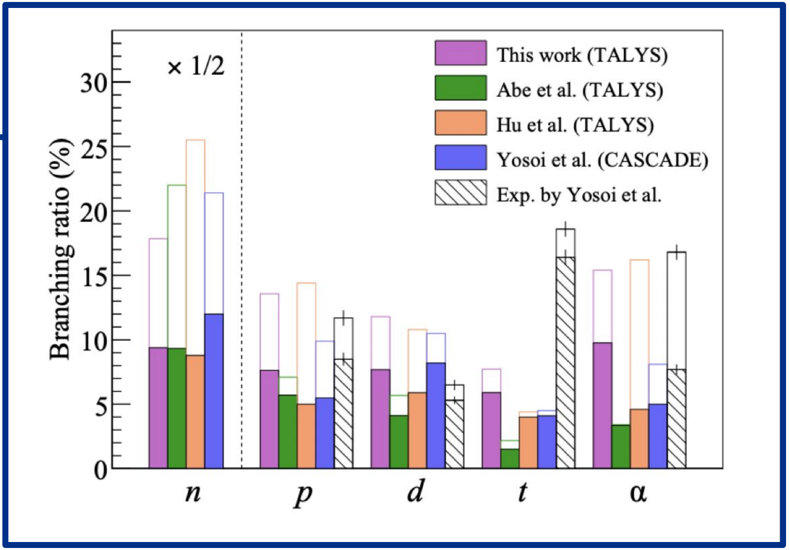

**Pinzon Guerra *et al.***

Proton-Carbon cross-sections



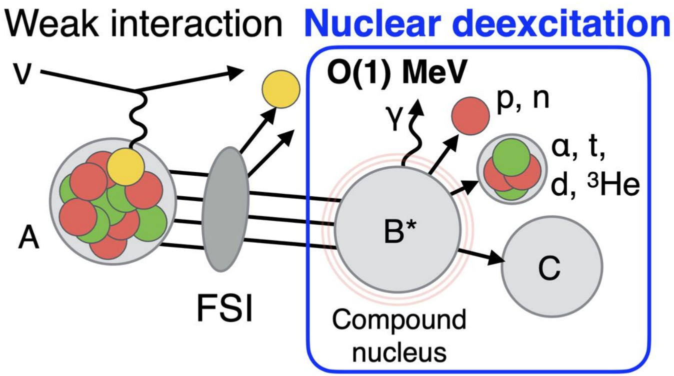
# Nuclear De-excitation

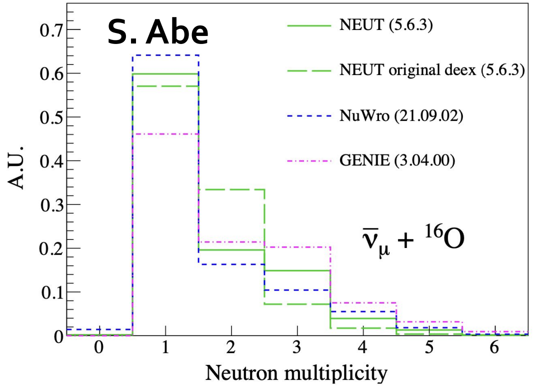
- Interaction can leave nucleus in an excited state which subsequently decays to emit secondary nucleons/gammas.




- NEUT models this only for oxygen targets.

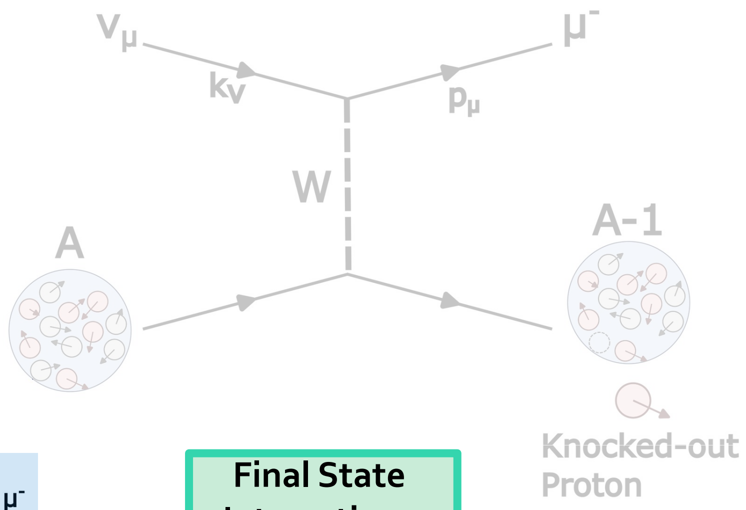
- Recent Work by S. Abe to implement TALYS based NucDeEx model as an alternative option in NEUT



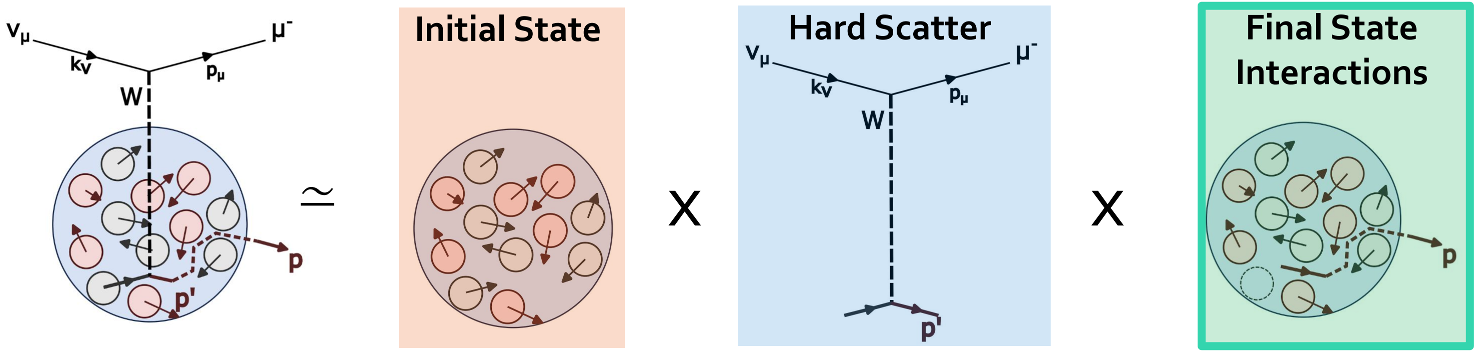



# Anatomy of A Neutrino Interaction

- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
    - But solving the neutrino–nucleus quantum many-body problem fully is intractable

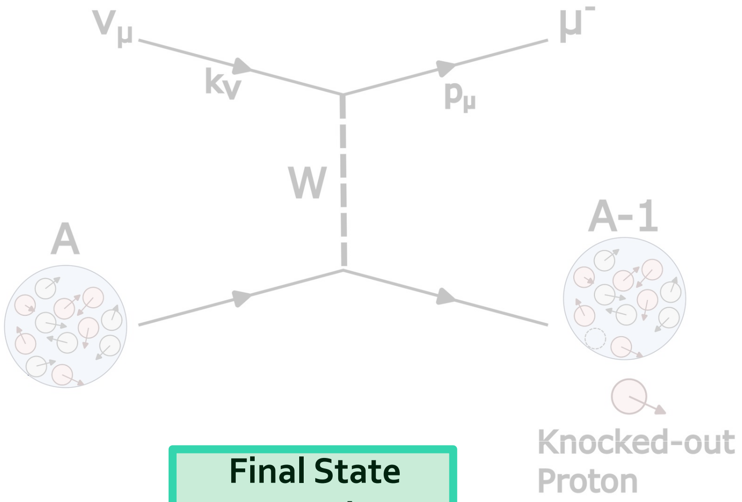


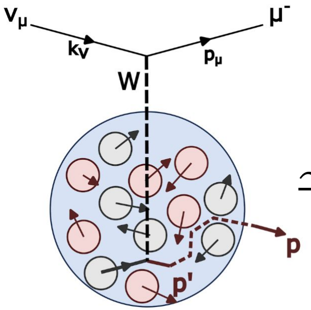

- Factorisation to the *rescue* **again**!



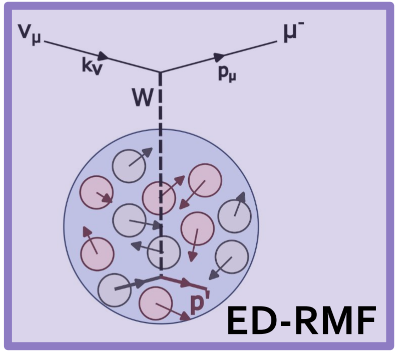
# Anatomy of A Neutrino Interaction

- In the few GeV region, nuclear effects have a significant impact on cross-section predictions
  - But solving the neutrino–nucleus quantum many-body problem fully is intractable
- ~~Factorisation to the *rescue* **again**!~~

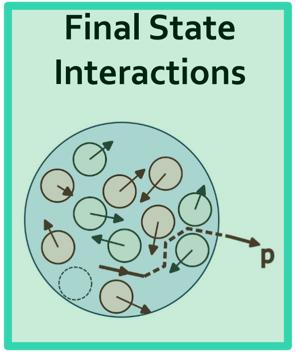



$\simeq$




X



# Relativistic Mean Field

- First implementation of a macroscopic model based on a Relativistic Mean Field optical models into NEUT:
  - Jake McKean, Raul González-Jiménez, Minoo Kabirnezhad
- Potential for new theory-motivated systematic uncertainty studies in NEUT.
- Possible consideration of alternative operators for different processes.
  - *E.g.* Kabirnezhad inelastic pion production model operator.

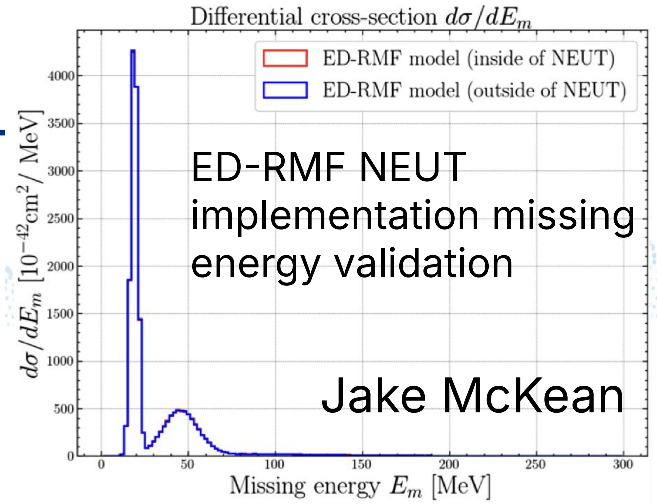
$$J^{\mu} \propto \int d\mathbf{p}\ \bar{\Psi}_{Scattered}\ \mathcal{O}^{\mu}\ \Psi_{Bound}$$

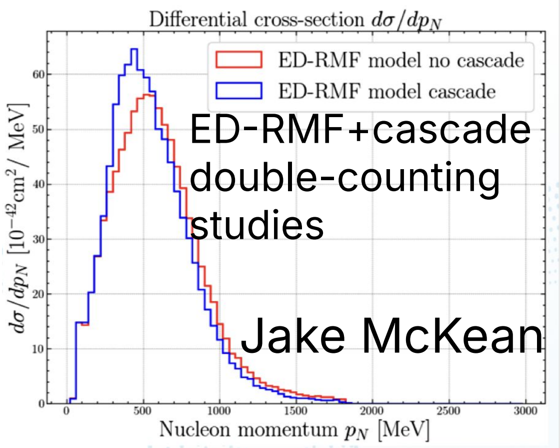
Neutrino-nucleon Operator

Hadronic Current

Scattering Potential

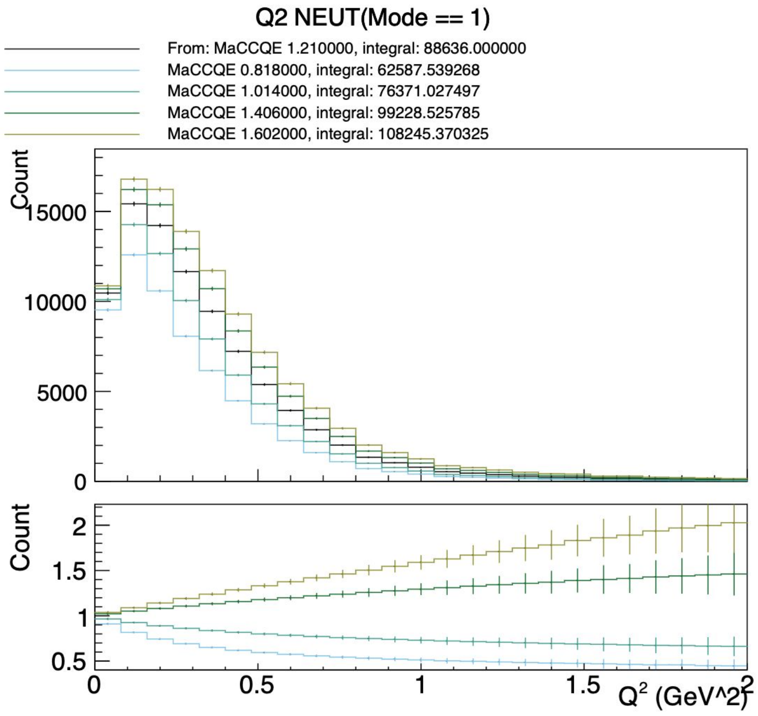
Bound State Wavefunction



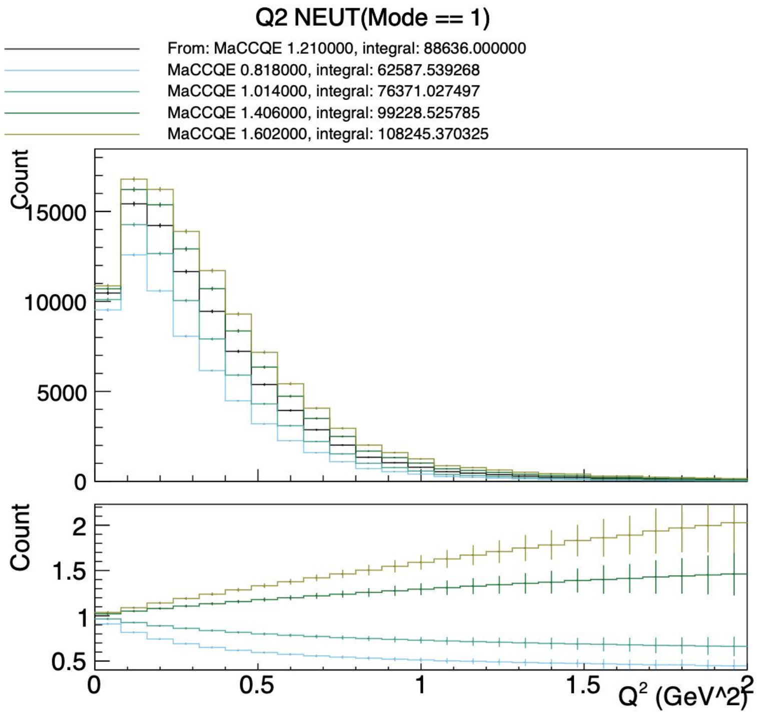
# NEUT Systematics Tools

- NEUT ReWeight:
  - Calculate the relative probability of an already-generated event under some model variation
  - A critical tool for uncertainty propagation:
    - doesn't work for all model variations – complement with approximate techniques
  - Implemented for QE and Res1Pi form factors
  - Implemented for Pion and Nucleon cascade for modest variations of in-medium scattering probabilities



# NEUT Systematics Tools

- NEUT ReWeight:
  - Calculate the relative probability of an already-generated event under some model variation
  - A critical tool for uncertainty propagation:
    - doesn't work for all model variations – complement with approximate techniques
  - Implemented for QE and Res1Pi form factors
  - Implemented for Pion and Nucleon cascade for modest variations of in-medium scattering probabilities




- GEANT interface:
  - Can use the NEUT hadron transport model as an inelastic model in GEANT4
  - Enables correlation of Final State Interaction (intra-nuclear) and Secondary Interaction (in-detector) models

# Known Limitations

- Nuclear models are inconsistent between models or steps in the factorisation:
  - Benhar *et al.* SF can be used for CCQE but no other modes
  - LFG used for FSI nuclear description
- Benhar *et al.* SF Pauli blocking uses a simple, RFG-like approach
- Nuclear effects in single pion production are largely ignored
- Nuclear transparency has no effect on inclusive cross-section for SF/FG
  - Studies ongoing into possible double counting for spectral distortion of the outgoing proton when using ED-RMF & Metropolis semi-classical cascade
- Between us... there are others

> based on the density and momentum predictions from an LFG model. Such an inconsistent model is sometimes affectionately referred to as a Franken-model, after the fictional scientist and his Gothic horror implementation. For single meson production, nuclear effects

# Recent and Future Plans

# NuHepMC: A Common Event Format

- Implementing HepMC3-based event format proposed as a common neutrino generator format: NuHepMC [arXiv:2310.13211]
  - Formats are only one (very small) piece of the puzzle: Common APIs, community interaction uncertainty, flux, and geometry tooling is going to be the next technical step.
  - Then we can work on doing the hard work interpreting neutrino scattering data together
- NuHepMC is a set of minimal extra metadata beyond the particles involved in an event to facilitate automated prediction.
  - Generator implementations are expected to store additional metadata for reweighting, configuration passthrough, etc...
  - Implementations/converters for NEUT, GENIE, NuWro, Achilles, GiBUU, NUISANCE
- HepMC3 is a event format description used by LHC generators:
  - Particle graph + arbitrary metadata
  - Many on-disk formats and official and unofficial analysis tools

# neut-quickstart

- Repository: https://github.com/neut-devel/neut-quickstart
- Image: https://hub.docker.com/repository/docker/picker24/neut580_quickstart
- Initially to service a request from IceCube for simple access to NEUT
    - May be useful for other people who want to make NEUT predictions
    - Can use github issues/feature requests for feedback
- Comes with helper script to generate events in NuHepMC/HepMC3 format from a simple CLI

# neut-quickstart

- Repository: https://github.com/neut-devel/neut-quickstart
- Image: https://hub.docker.com/repository/docker/picker24/neut580_quickstart
- Initially to service a request from IceCube for simple access to NEUT
  - May be useful for other people who want to make NEUT predictions
  - Can use github issues/feature requests for feedback
- Comes with helper script to generate events in NuHepMC/HepMC3 format from a simple CLI

```
[neut580_quickstart:neuttalks $ neut-quickstart -n 1000000 -f flux.root,flux_numu -t H2O -o neut.H2O.flat.hepmc3
[OPT]: Processing/Generating 1000000 NEUT events.
[OPT]: Generating events with the a flux distribution according to flux.root,flux_numu
[OPT]: Generating events on: H2O
[OPT]: Writing final output to neut.H2O.flat.hepmc3
[NEUT] Running in /tmp/neut-quickstart/4936
[INFO]: Reading from neutvect.root
[INFO]: Reading flux information from flux.root:flux_numu
[INFO]: Not mono-energetic, so cannot infer FATX from first event.
[INFO]: Calculated FATX from input file file as: 0.0112455 pb/Nucleon
Converting 1000000/1000000
```

# neut-quickstart

- Repository: https://github.com/neut-devel/neut-quickstart
- Image: https://hub.docker.com/repository/docker/picker24/neut580_quickstart
- Initially to service a request from IceCube for simple access to NEUT
  - May be useful for other people who want to make NEUT predictions
  - Can use github issues/feature requests for feedback
- Comes with helper script to generate events in NuHepMC/HepMC3 format from a simple CLI

```
[neut580_quickstart:neuttalks $ neut-quickstart -n 1000000 -f flux.root,flux_numu -t H2O -o neut.H2O.flat.hepmc3
[OPT]: Processing/Generating 1000000 NEUT events.
[OPT]: Generating events with the a flux distribution according to flux.root,flux_numu
[OPT]: Generating events on: H2O
[OPT]: Writing final output to neut.H2O.flat.hepmc3
[NEUT] Running in /tmp/neut-quickstart/4936
[INFO]: Reading from neutvect.root
[INFO]: Reading flux information from flux.root:flux_numu
[INFO]: Not mono-energetic, so cannot infer FATX from first event.
[INFO]: Calculated FATX from input file file as: 0.0112455 pb/Nucleon
Converting 1000000/1000000
```

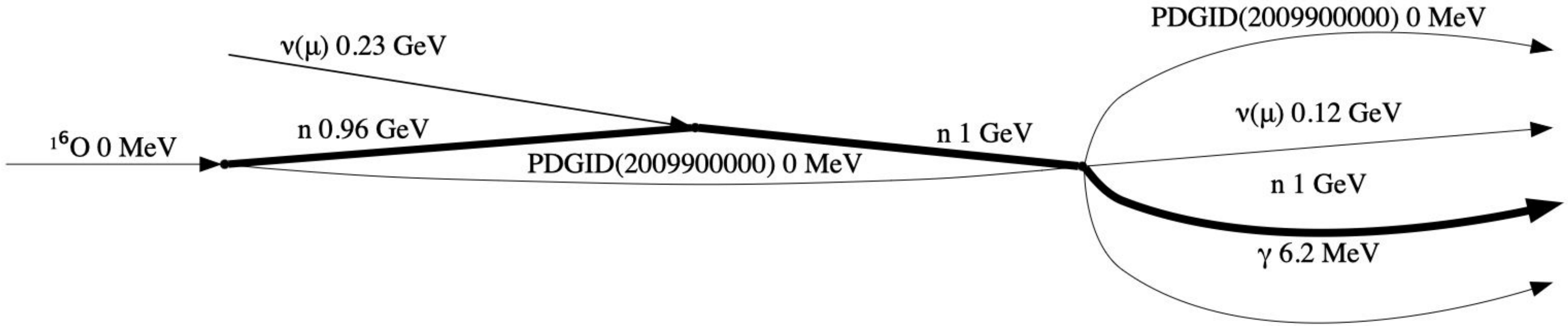
# neut-quickstart + pyhepmc

```
[ ]: !pip3 install pyhepmc
```

```
[2]: import pyhepmc
```

```
[3]: with pyhepmc.open("neut.H2O.flat.hepmc3") as f:
         event = f.read()
     event
```

[3]:



# neut-quickstart + pyhepmc

```
[4]: CCQE_pmu = []
     num_events = 0
     with pyhepmc.open("neut.H2O.flat.hepmc3") as f:
         for ev in f:
             num_events += 1
             if ev.attributes["signal_process_id"].astype(int) != 200: #is true CCQE
                 continue
             for p in ev.particles:
                 if p.status != 1:
                     continue
                 if p.pid == 13:
                     CCQE_pmu.append(p.momentum.p3mod())

     FluxAveragedTotalCrossSection = ev.run_info.attributes["NuHepMC.FluxAveragedTotalCrossSection"] \
             .astype(float)
```

```
[5]: print(f"{FluxAveragedTotalCrossSection:.4} pb/Nucleon")
```

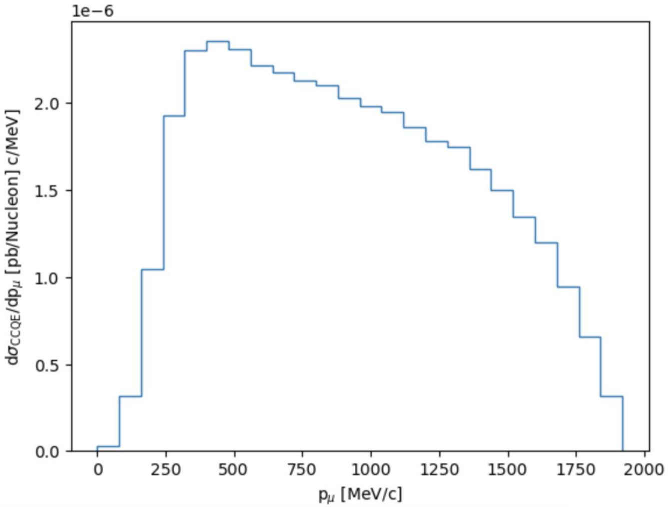
```
0.01125 pb/Nucleon
```

# neut-quickstart + pyhepmc

[6]:
```python
import matplotlib.pyplot as plt
import numpy as np

pmu_max = 2000.0; nbins = 25; bin_width = pmu_max/float(nbins)
(counts, bins) = np.histogram(CCQE_pmu, bins=[i*bin_width for i in range(nbins)])

plt.hist(bins[:-1], bins,
         weights=(FluxAveragedTotalCrossSection/(bin_width*float(num_events)))*counts, histtype="step")
plt.xlabel(r"p$_\mu$ [MeV/c]")
plt.ylabel(r"d$\sigma_\mathrm{CCQE}$/dp$_\mu$ [pb/Nucleon] c/MeV]")
plt.show()
```



# Future: NEUT 6

- Development ongoing on NEUT6 - Targeted at HK and final T2K analyses:
  - Significant reorganization of code-base
  - Improved, modern build system
  - Removed dependence on an external CERNLIB
  - New TOML-based configuration file
  - Modern C/Fortran interop
  - Automatic C/Fortran interface generation for model integration
- ED-RMF implementation and new hadron cascade studies are being done in NEUT 6
- Aim is to release NEUT6 as open source under the GPL before the end of ~~2023~~ 2024
  - Will also release the final NEUT5 series release as open source
- Hope to produce comprehensive data-model comparisons for NEUT6 release

# The NEUT Generator: Status and Plans

Luke Pickering~~, P. Stowell~~
~~for the NEUT developers~~
16/09/24
NuFact 2024
Argonne

UKRI
Science and Technology Facilities Council
Supported by URF\R1\211661
THE ROYAL SOCIETY

# Questions

# Questions

1) How can we have more theory-based uncertainties, in particular for neutrino oscillation studies?
2) How can we incorporate state-of-the-art nuclear models, providing information on the hadrons, in generators?

- Clearly communicate what parts of the prediction are most important for your experiment/measurements
- Meet model-builders *at least* half way:
  - Well defined/documented interfaces
  - Generator developers need to *outreach* to model-builders groups
  - Push for state-of-the-art models to be used in data analysis once implemented
- **Make citing the models used by your generator easy!**

# Questions

```
A NuHepMC.Citations.Generator.DOI 10.1016/j.nima.2009.12.009 10.1140/epjs/s11734-021-00295-7
A NuHepMC.Citations.Process[100].DOI 10.1103/PhysRevD.79.053003
A NuHepMC.Citations.Process[150].DOI 10.1103/PhysRevD.79.053003
A NuHepMC.Citations.Process[200].DOI 10.1016/0370-1573(72)90010-5
A NuHepMC.Citations.Process[250].DOI 10.1103/PhysRevD.19.779 10.1103/PhysRevD.35.785
A NuHepMC.Citations.Process[400].DOI 10.1103/PhysRevD.76.113004
A NuHepMC.Citations.Process[450].DOI 10.1103/PhysRevD.76.113004
A NuHepMC.Citations.Process[600].DOI 10.1103/PhysRevD.50.3085 10.1103/PhysRevD.65.033002
A NuHepMC.Citations.Process[650].DOI 10.1103/PhysRevD.65.033002
A NuHepMC.Citations.Process[701].DOI 10.1016/0550-3213(87)90131-3
A NuHepMC.Citations.Process[703].DOI 10.1088/0954-3899/29/11/013
A NuHepMC.Conventions E.C.1 E.C.2 E.C.4 E.C.5 G.C.1 G.C.4 G.C.6 G.S.2 P.C.1
```

your experiment/measurements

- Meet model-builders *at least* half way:
  - Well defined/documented interfaces
  - Generator developers need to *outreach* to model-builders groups
  - Push for state-of-the-art models to be used in data analysis once implemented
- **Make citing the models used by your generator easy!**

```
~ > HEPReference/NuHepMCParse myevents.hepmc3 citations.bib
```

# Questions

```
16 A NuHepMC.Citations.Generator.DOI 10.1016
17 A NuHepMC.Citations.Process[100].DOI 10.1
18 A NuHepMC.Citations.Process[150].DOI 10.1
19 A NuHepMC.Citations.Process[200].DOI 10.1
20 A NuHepMC.Citations.Process[250].DOI 10.1
21 A NuHepMC.Citations.Process[400].DOI 10.1
22 A NuHepMC.Citations.Process[450].DOI 10.1
23 A NuHepMC.Citations.Process[600].DOI 10.1
24 A NuHepMC.Citations.Process[650].DOI 10.1
25 A NuHepMC.Citations.Process[701].DOI 10.1
26 A NuHepMC.Citations.Process[703].DOI 10.1
27 A NuHepMC.Conventions E.C.1 E.C.2 E.C.4 E
```

citations.bib

```
    title = "{PCAC and coherent pion production by low energy neutrinos}",
    eprint = "0812.2653",
    archivePrefix = "arXiv",
    primaryClass = "hep-ph",
    doi = "10.1103/PhysRevD.79.053003",
    journal = "Phys. Rev. D",
    volume = "79",
    pages = "053003",
    year = "2009"
}
@article{Berger:2008xs,
    author = "Berger, Ch. and Sehgal, L. M.",
    title = "{PCAC and coherent pion production by low energy neutrinos}",
    eprint = "0812.2653",
    archivePrefix = "arXiv",
    primaryClass = "hep-ph",
    doi = "10.1103/PhysRevD.79.053003",
    journal = "Phys. Rev. D",
    volume = "79",
    pages = "053003",
    year = "2009"
}
@article{LlewellynSmith:1971uhs,
    author = "Llewellyn Smith, C. H.",
    title = "{Neutrino Reactions at Accelerator Energies}",
    reportNumber = "SLAC-PUB-0958",
    doi = "10.1016/0370-1573(72)90010-5",
    journal = "Phys. Rept.",
    volume = "3",
    pages = "261--379",
    year = "1972"
}
```

your experiment/measureme

- Meet model-builders *at leas*
  - Well defined/documented inter
  - Generator developers need to
  - Push for state-of-the-art mode
- **Make citing the models use**

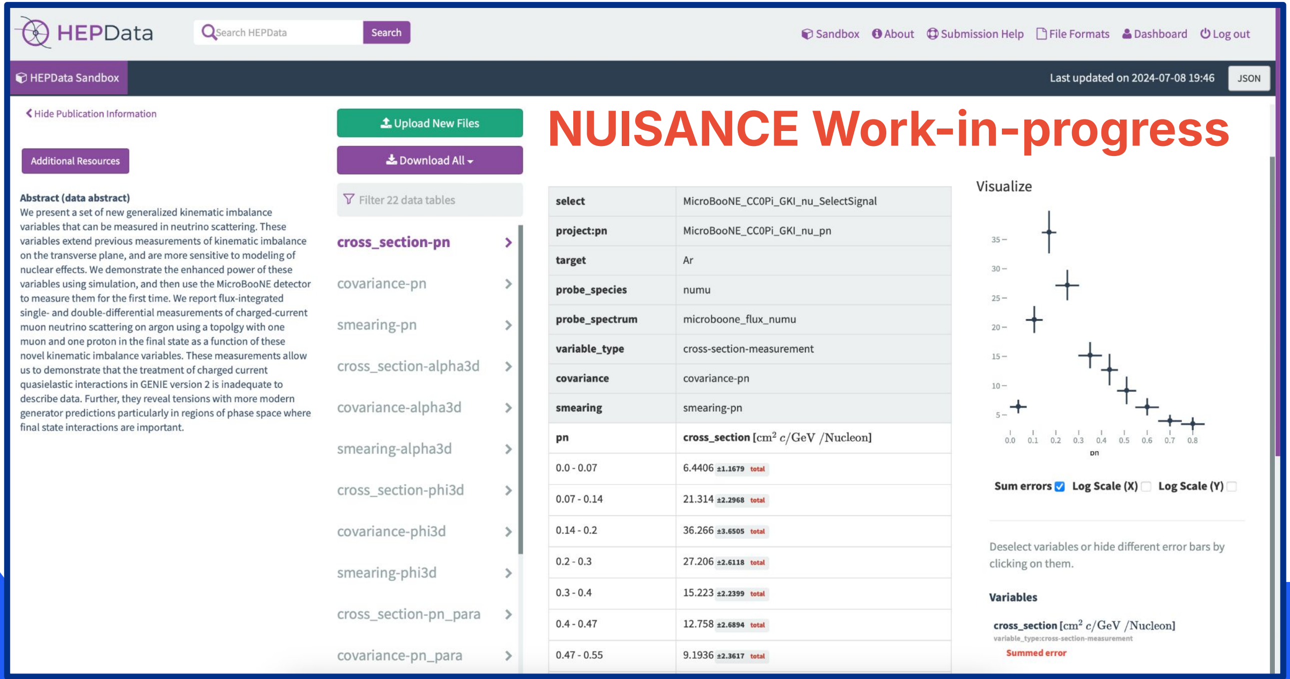
# Questions

3) How to use the wealth of experimental measurements already available and expected in the coming years to solve key issues in neutrino scatterings?

- Community tools and interfaces, built and maintained by experimenters, generator developers, and model-builders
- Open, automated data-comparison tools...

# Questions

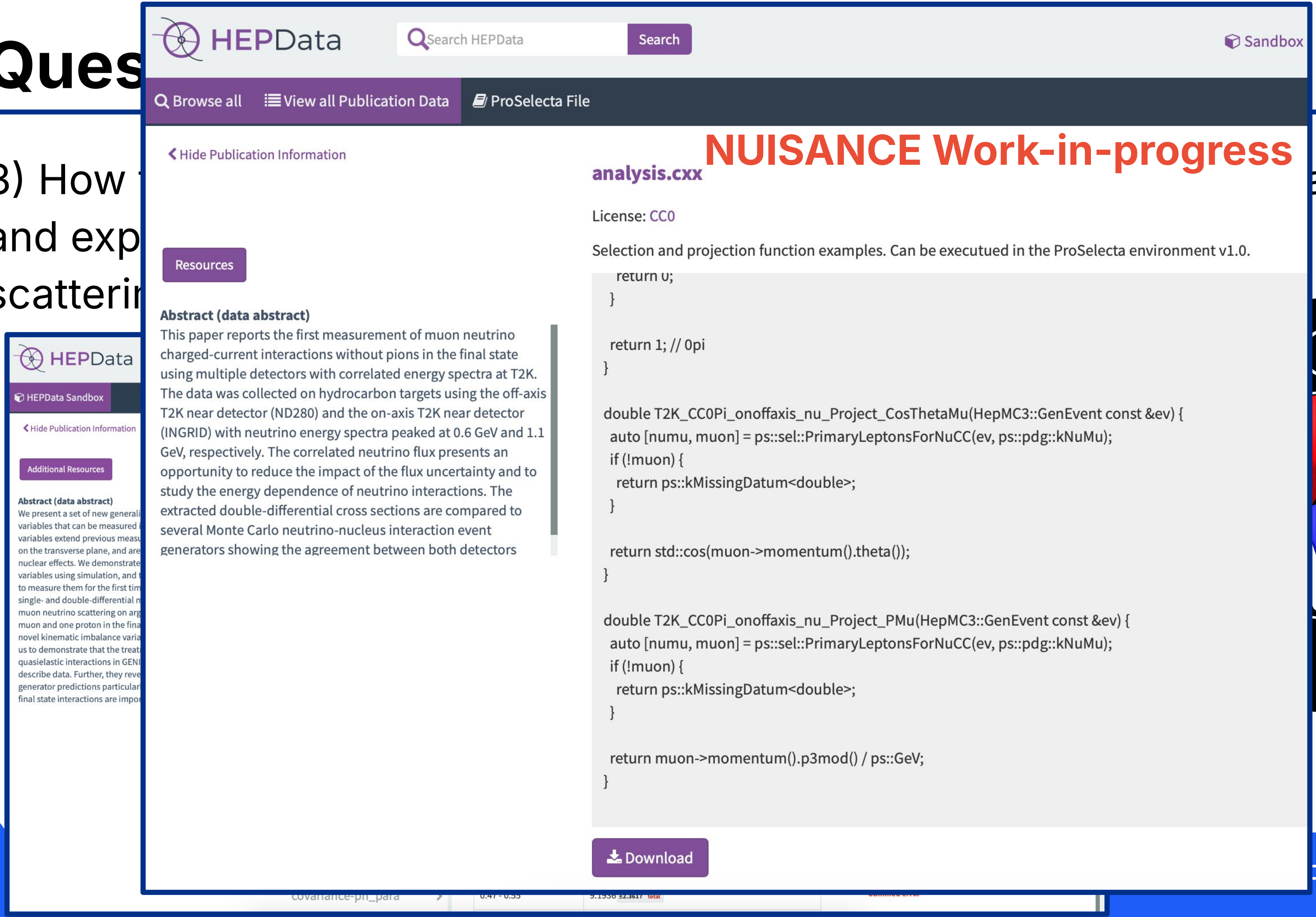
3) How to use the wealth of experimental measurements already available and expected in the coming years to solve key issues in neutrino scatterings?




b

# Ques

3) How ... ailable and exp... scatteri...


HEPData

Search HEPData Search

Sandbox

Browse all View all Publication Data ProSelecta File

NUISANCE Work-in-progress

Hide Publication Information

Resources

**Abstract (data abstract)**

This paper reports the first measurement of muon neutrino charged-current interactions without pions in the final state using multiple detectors with correlated energy spectra at T2K. The data was collected on hydrocarbon targets using the off-axis T2K near detector (ND280) and the on-axis T2K near detector (INGRID) with neutrino energy spectra peaked at 0.6 GeV and 1.1 GeV, respectively. The correlated neutrino flux presents an opportunity to reduce the impact of the flux uncertainty and to study the energy dependence of neutrino interactions. The extracted double-differential cross sections are compared to several Monte Carlo neutrino-nucleus interaction event generators showing the agreement between both detectors

**analysis.cxx**

License: CC0

Selection and projection function examples. Can be executued in the ProSelecta environment v1.0.

```
    return 0;
  }

  return 1; // 0pi
}

double T2K_CC0Pi_onoffaxis_nu_Project_CosThetaMu(HepMC3::GenEvent const &ev) {
  auto [numu, muon] = ps::sel::PrimaryLeptonsForNuCC(ev, ps::pdg::kNuMu);
  if (!muon) {
    return ps::kMissingDatum<double>;
  }

  return std::cos(muon->momentum().theta());
}

double T2K_CC0Pi_onoffaxis_nu_Project_PMu(HepMC3::GenEvent const &ev) {
  auto [numu, muon] = ps::sel::PrimaryLeptonsForNuCC(ev, ps::pdg::kNuMu);
  if (!muon) {
    return ps::kMissingDatum<double>;
  }

  return muon->momentum().p3mod() / ps::GeV;
}
```

Download

HEPData

HEPData Sandbox

Hide Publication Information

Additional Resources

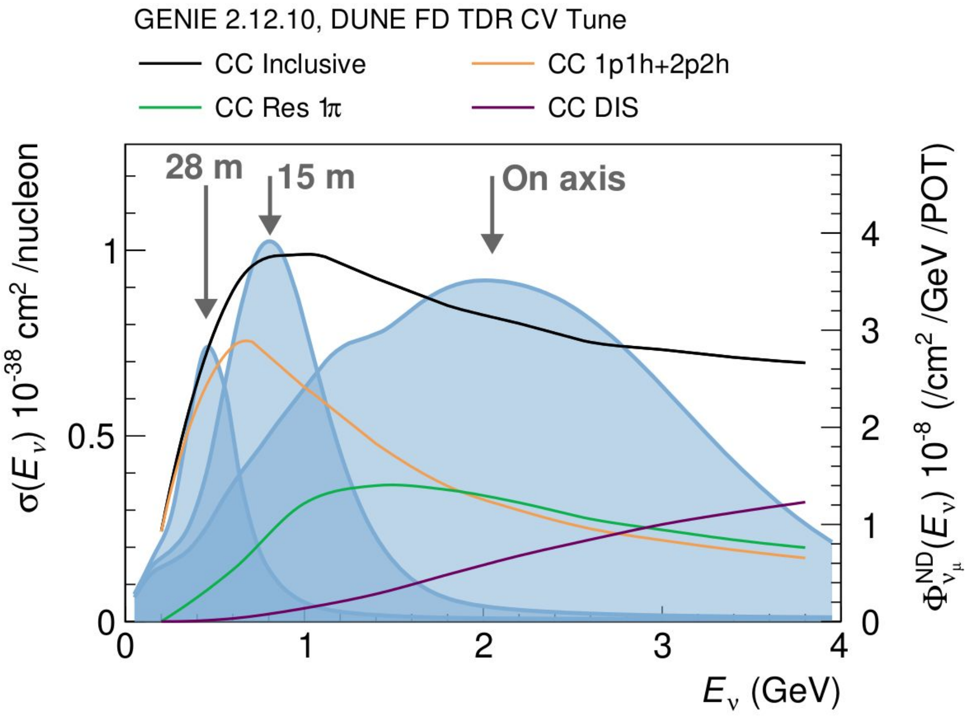
**Abstract (data abstract)**

We present a set of new generali... variables that can be measured i... variables extend previous measu... on the transverse plane, and are... nuclear effects. We demonstrate... variables using simulation, and t... to measure them for the first tim... single- and double-differential m... muon neutrino scattering on arg... muon and one proton in the fina... novel kinematic imbalance varia... us to demonstrate that the treat... quasielastic interactions in GENI... describe data. Further, they reve... generator predictions particular... final state interactions are impor...

# Questions

4) Which kind of experiments are needed to improve the modeling of neutrino-nucleus cross section?

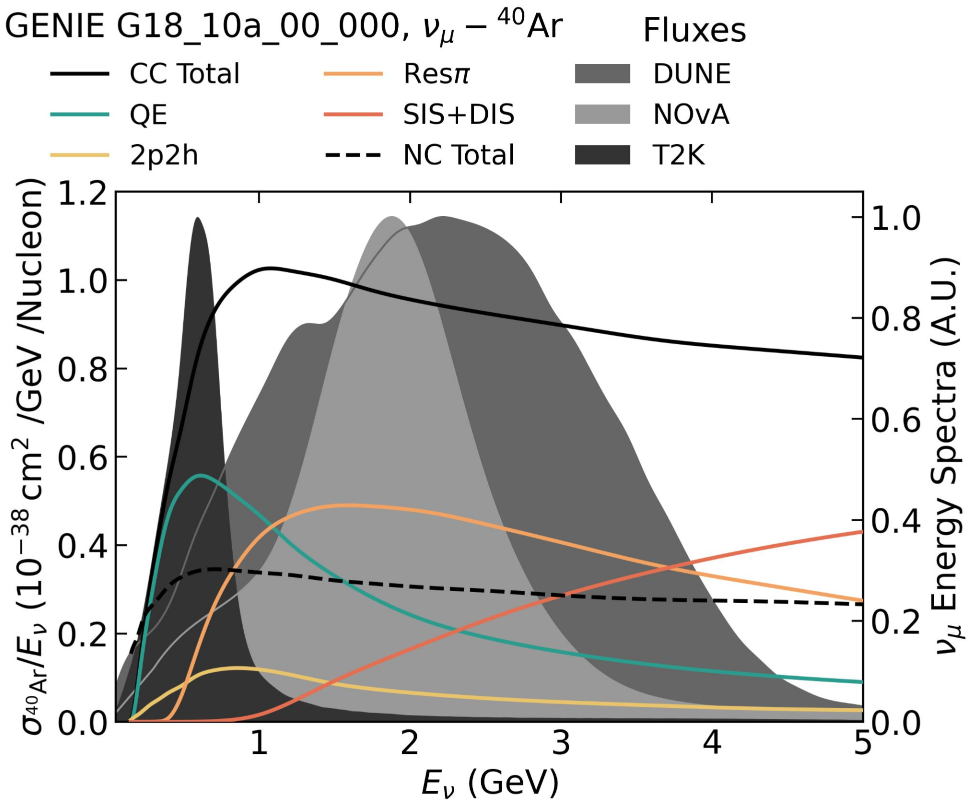
- Mobile near detectors
  - Scan across true energies
  - Ideally magnetised...
- Reduced flux uncertainties
  - Break flux * xs degeneracies
- Low-energy pion/hadron beams...
  - More pion intra- and inter- nuclear transport data at relevant energies



# Questions

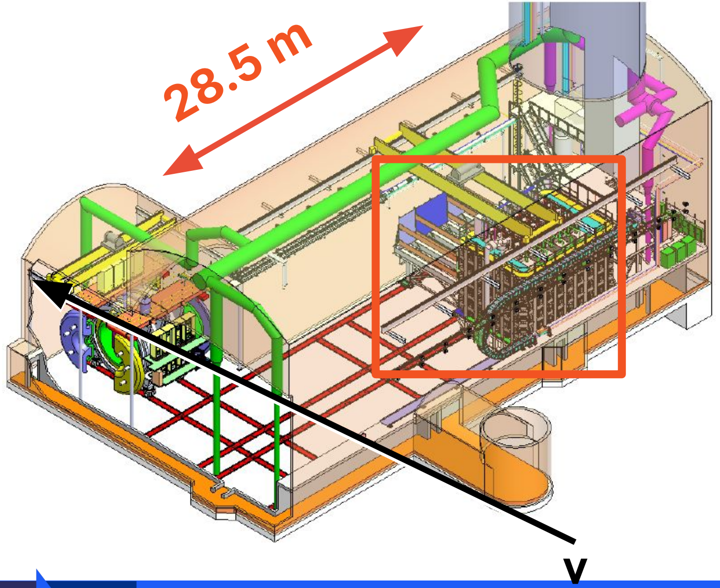
5) What are the main reaction channels and, therefore, identify the main systematic uncertainties in oscillation experiments?

- Depends on the experiment
- But, it's difficult everywhere:
  - Nuclear response
  - Transition region
  - Low W 'DIS'



# Questions

6) Can you highlight the unique experimental capabilities of your detector... and how that relates to important observables?




DUNE PRISM

"And yet it moves"
- Galileo Galilei, 1633

- Make measurements with the same detector in a wide range of peak energies

# Summary

# Summary

- Development targets needs of J-PARC-based neutrino scattering experiments
  - Focus on few-GeV electron, muon, and tau neutrino interactions with $^{1}H$, $^{12}C$, $^{16}O$ targets
- NEUT provides a complete model for interpreting neutrino-scattering data
  - But a step-change in prediction quality is needed for the next generation
- Factorisations are mathematically and computationally necessary, but we know their usages misses important physical effects:
  - Ongoing effort to understand, quantify, and implement more-complete models and effective corrections.
- NEUT has a long, rich history and we want to make sure that it not only survives, but becomes a more useful community tool into the next generation.
  - Effort on opening up the source code and providing user-friendly tools/scripts/examples
  - Implementing and testing community interfaces and formats
  - Updating dependencies and procedures to modern standards (where reasonable)