The NEUT Generator: Status and Plans

Luke Pickering
25/08/23
NuFact 2023 – Seoul

NEUT Developers: Y. Hayato, C. Wret, C. Bronner, S. Abe + many contributors

Science and Technology Facilities Council

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THE ROYAL SOCIETY

What Is NEUT?

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

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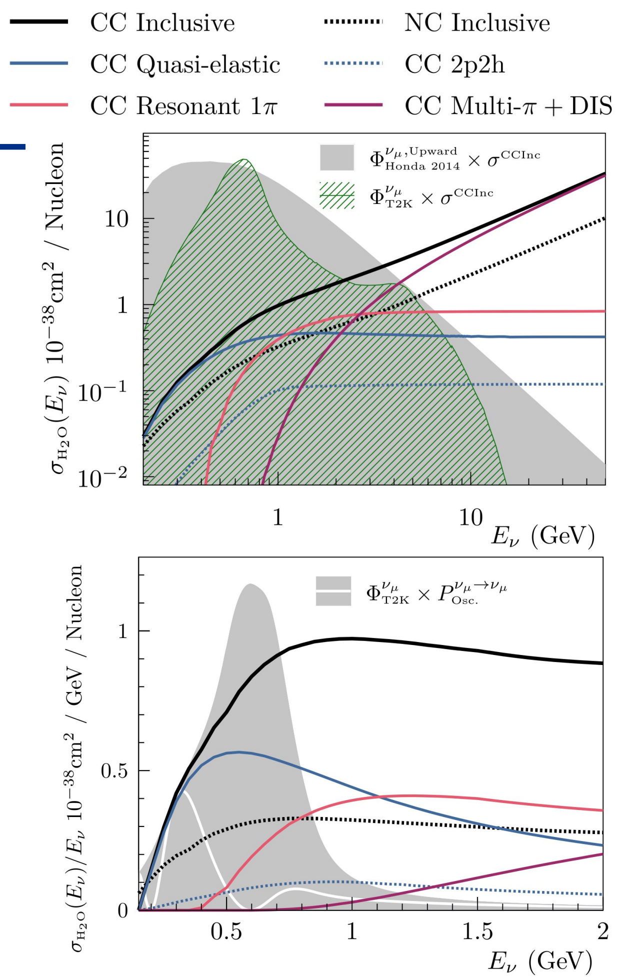
- Maintained 'in house' for use on T2K and SK:
  - Development targets the needs of the long baseline oscillation and cross-section programmes
    - Sub-to-few GeV energy region
    - Hydrocarbon and water targets



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- 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 code has historically not been public, but is available upon request.

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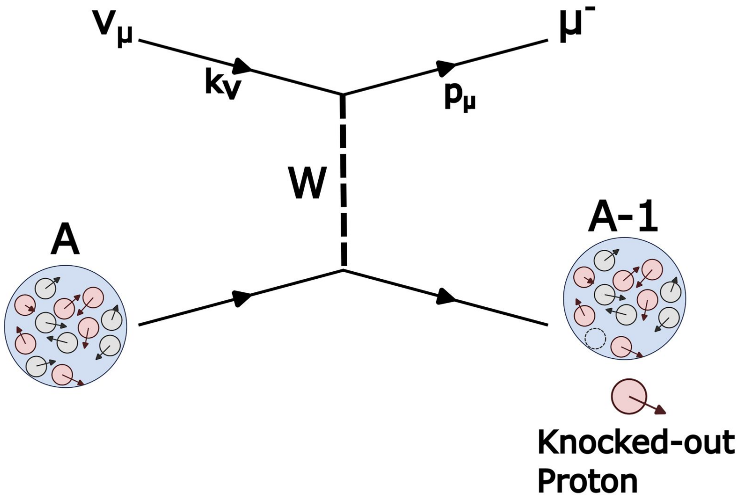
```
*     (Creation Date and Author)
*       1983.??.??  M.NAKAHATA
*       1987.08.??  N.SATO     FOR TAU
*       1988.08.31  T.KAJITA   DATA UPDATE
*       1988.09.06  T.KAJITA   R1314 IS ADDED
*       1988.09.19  T.KAJITA   DX/DY WAS CHANGED BY THAT OF N.SATO'S
*                              WHICH 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 16O
*       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
*       2016.03.08  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



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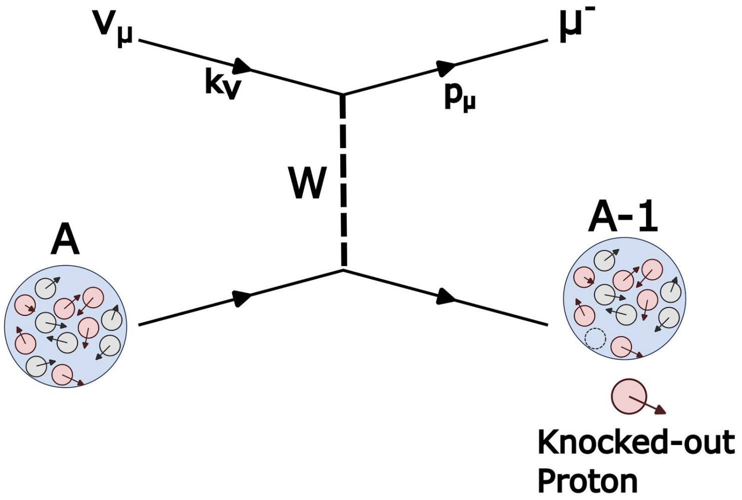

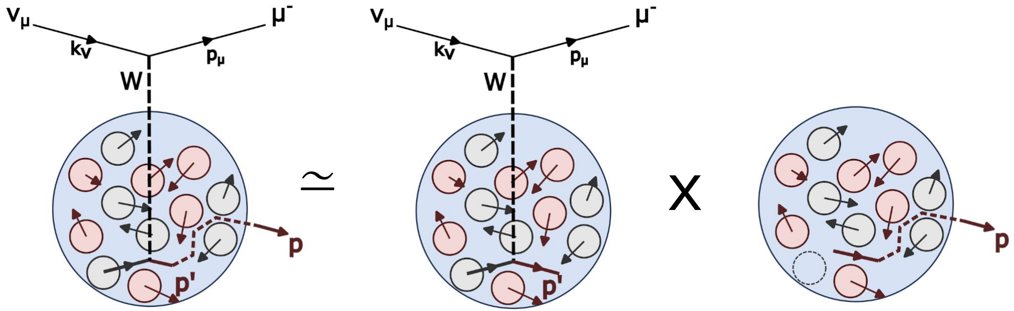

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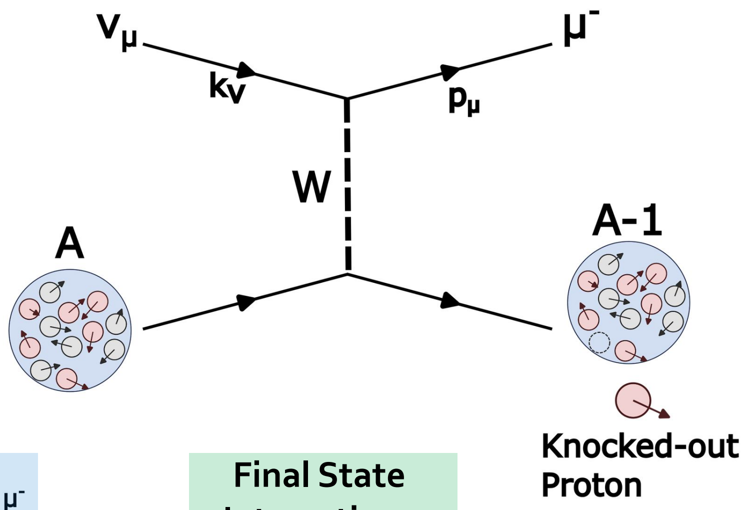

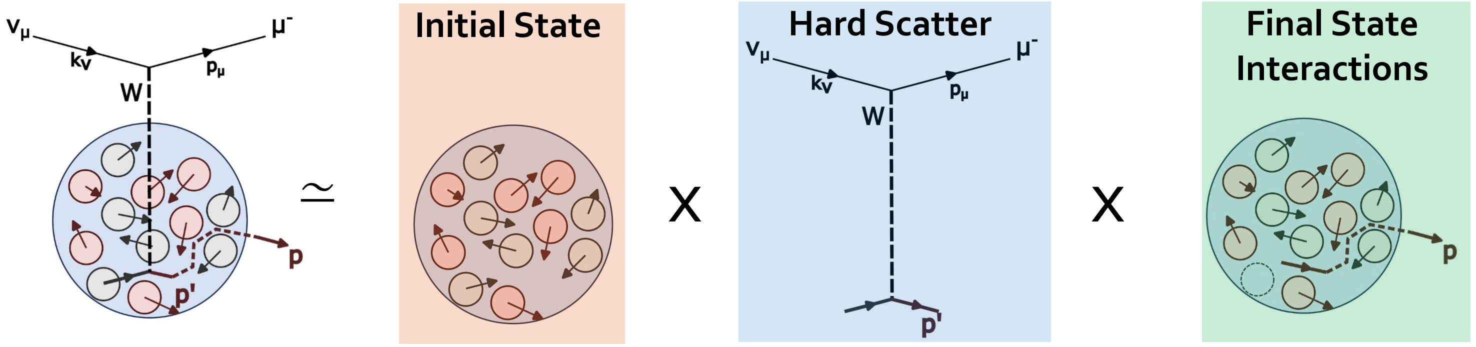

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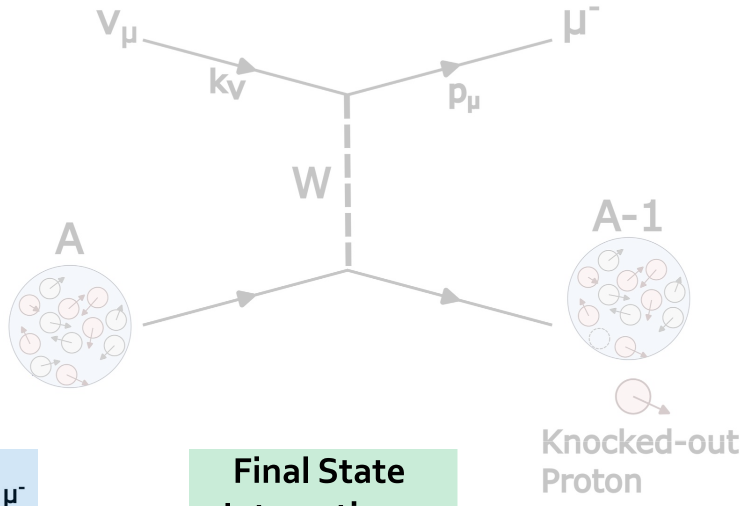

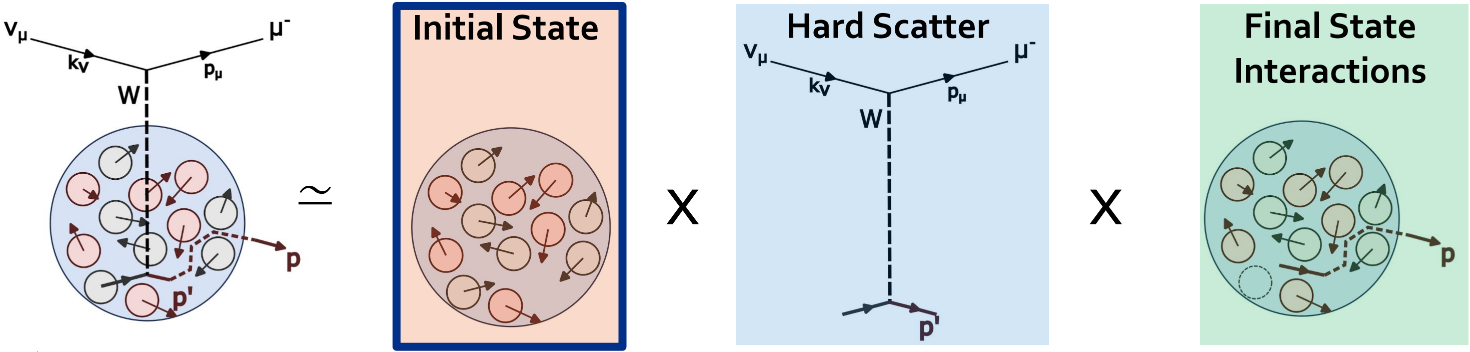

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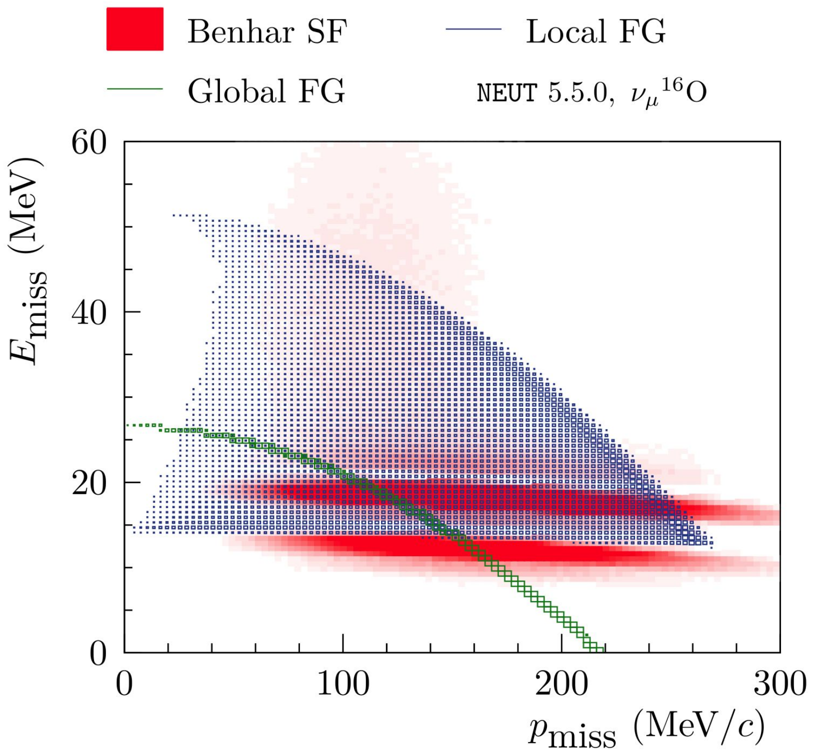

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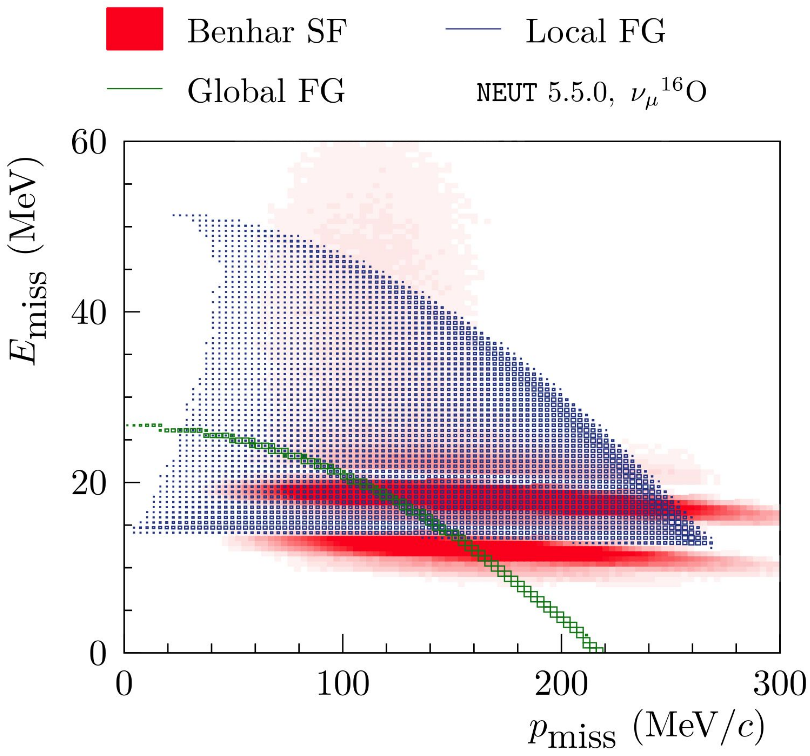
- NEUT can simulate interactions with FG nuclear models on a wide range of target nuclei
- NEUT can also use the Benhar SF for Quasi Elastic interactions with C12, O16, and Fe56



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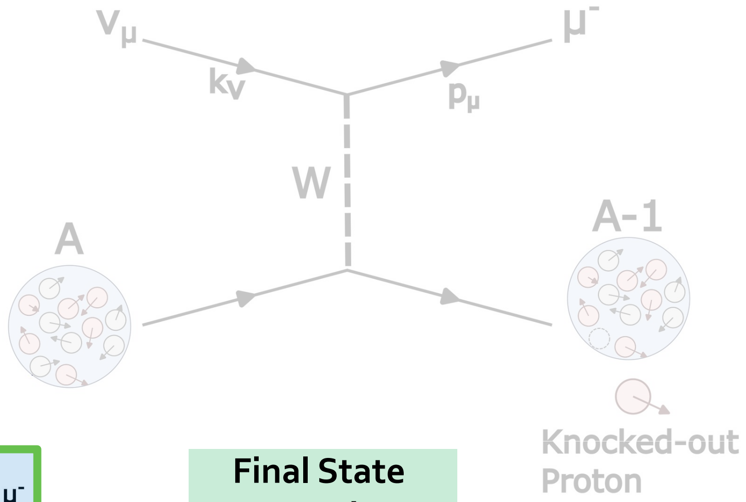

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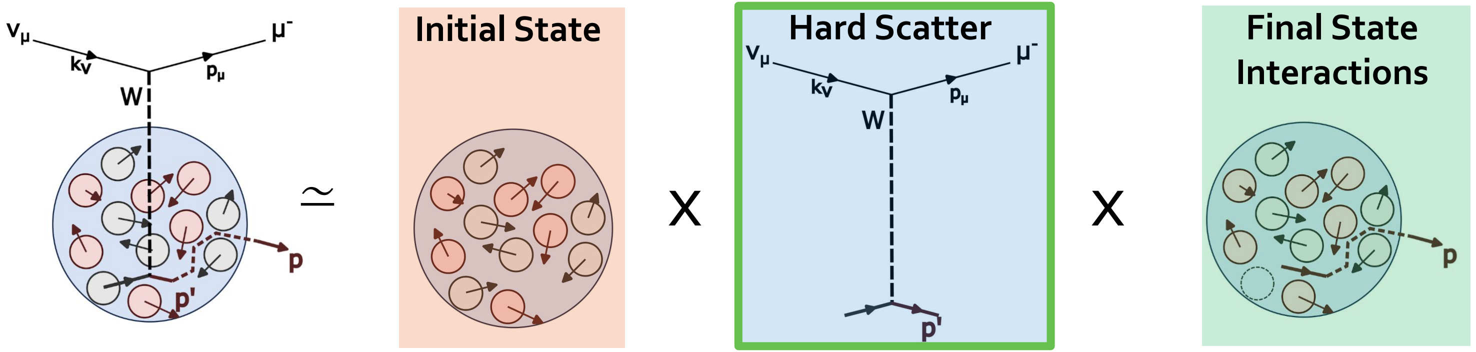

0Pi

- 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
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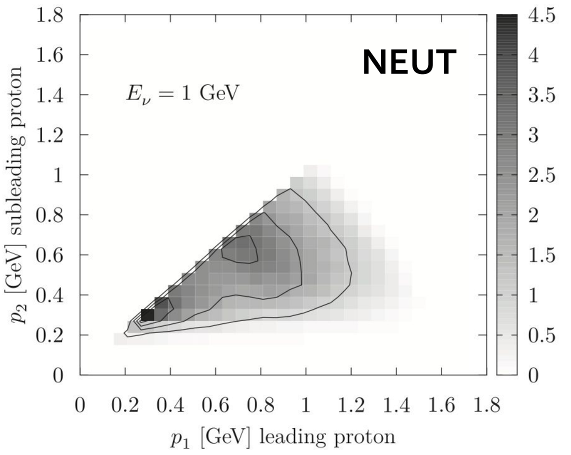

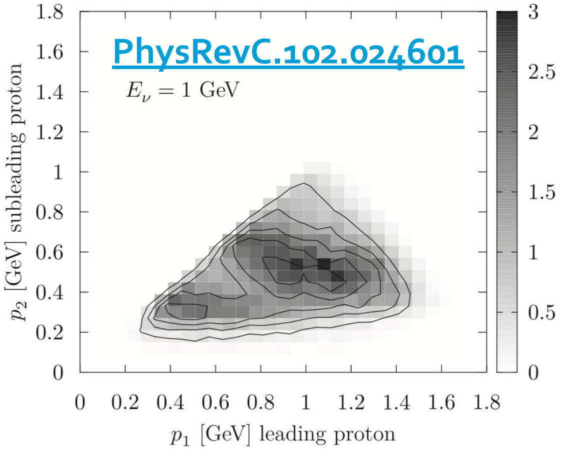

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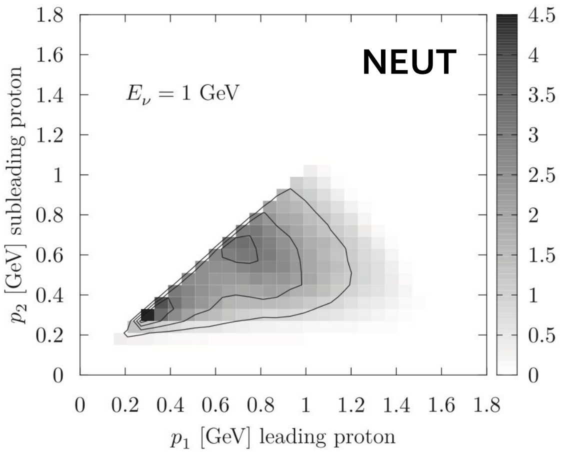
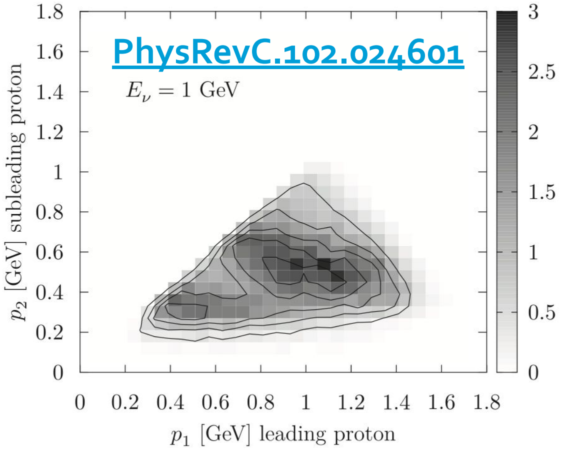
  - Significant improvements needed for HK/DUNE





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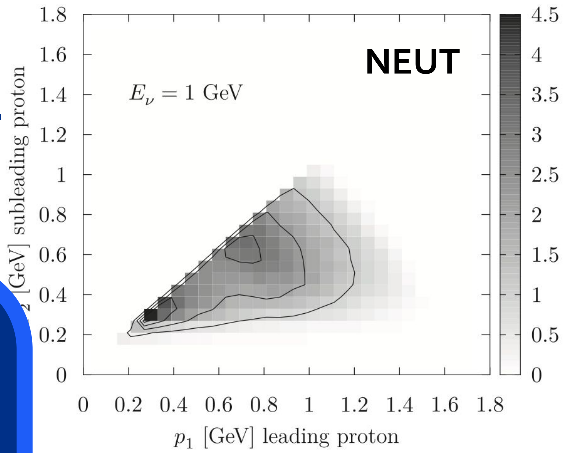
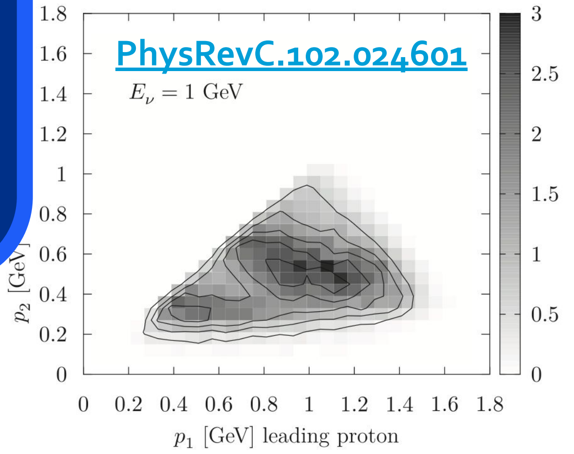
Keep your ears on for [Jake's talk] up next for more NEUT 0pi work!





Electron Scattering

- New capability to run an e-like mode in NEUT
- Based on NCQE cross-section:
  - modified form factors and couplings
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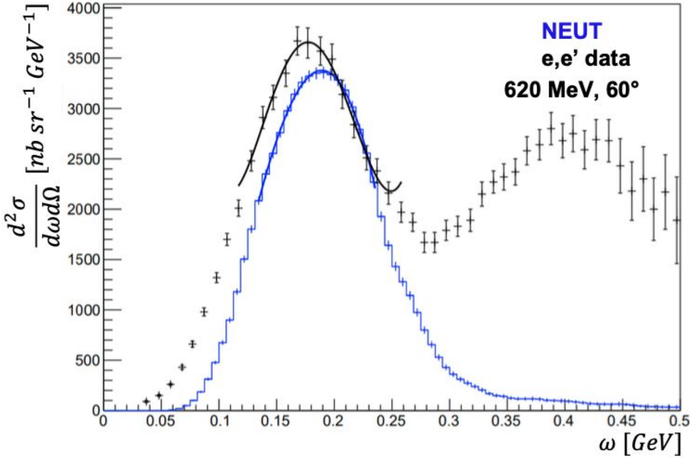

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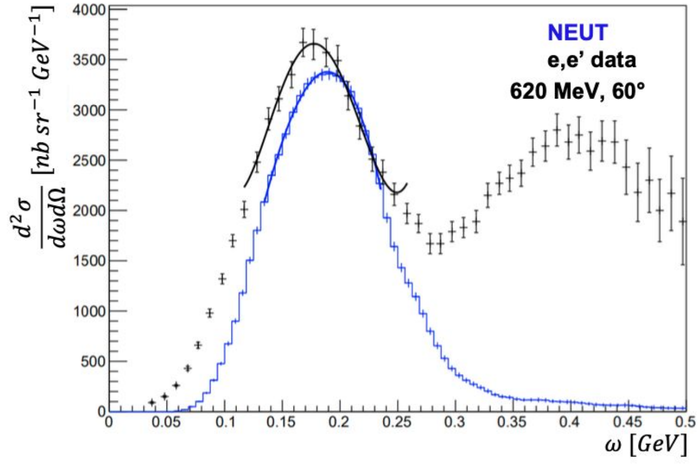
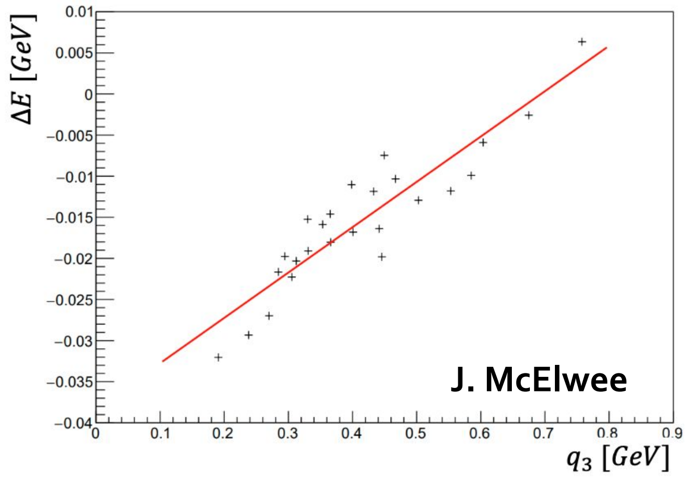
- Can be used to benchmark nuclear response implementation:
  - As expected from earlier work, the QE peak position is not correctly predicted by factorized SF implementation.
  - Shift of predicted to measured QE peak position shows clear dependence on interaction kinematics...
  - The second factorisation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





Single Pion Production

- Rein-Sehgal model: w/Berger-Sehgal lepton mass effects
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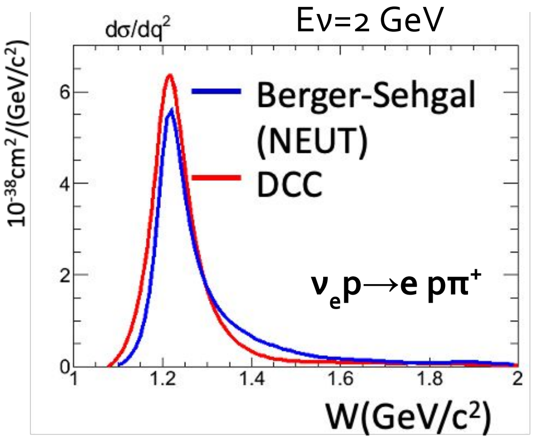
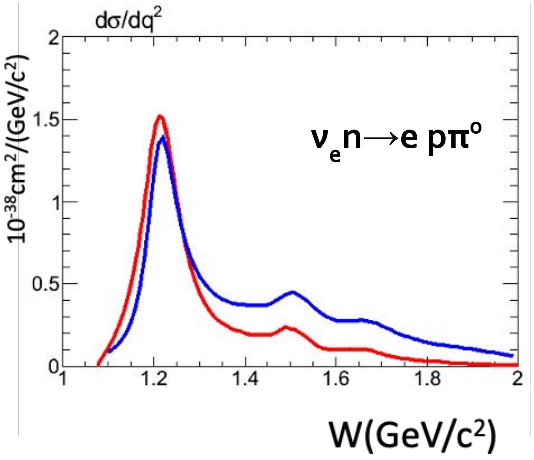
  - State-of-the-art 1Pi model
  - Inclusive predictions implemented in NEUT





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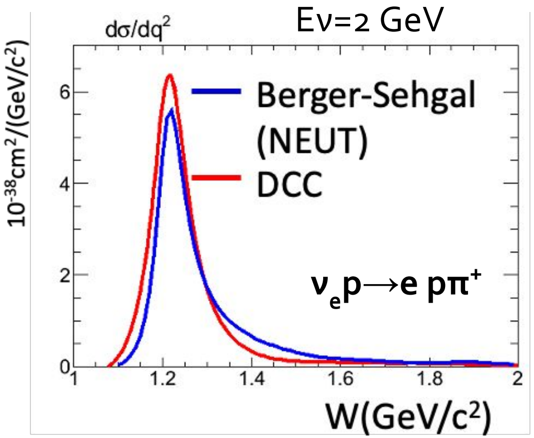
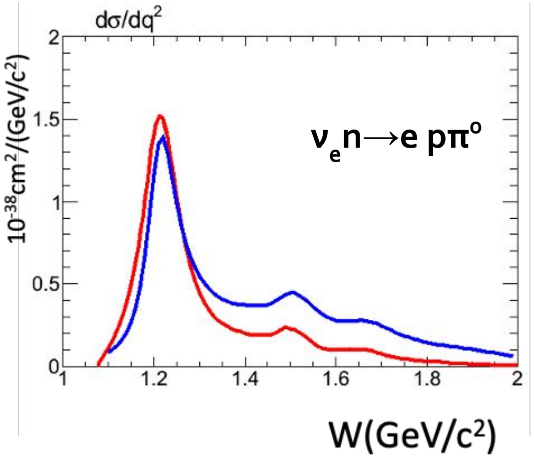
- Coherent 1Pi: Rein-Sehgal and **Berger-Sehgal**
- Diffractive 1Pi: Rein Model

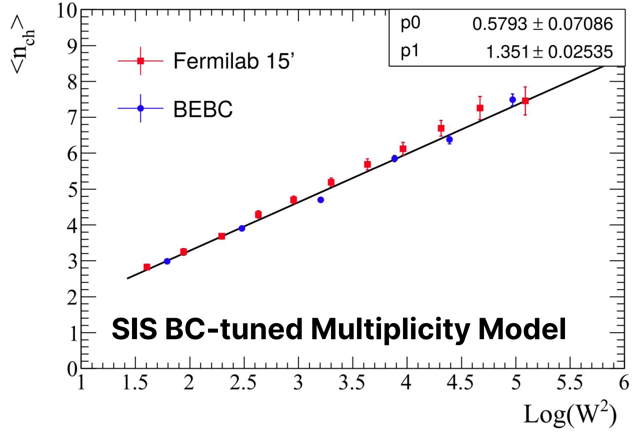


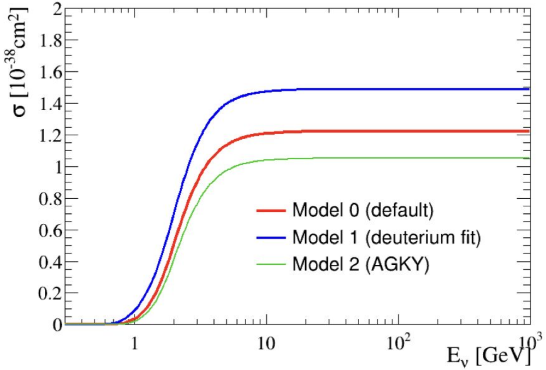


Shallow & Deep Inelastic Scattering

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





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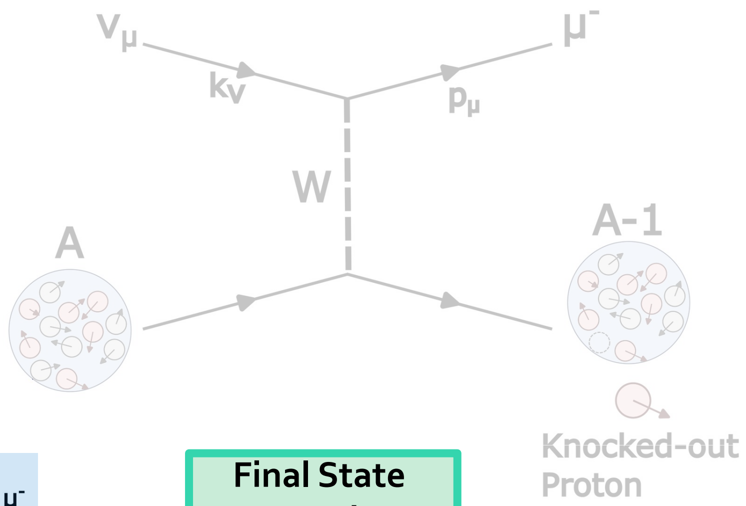

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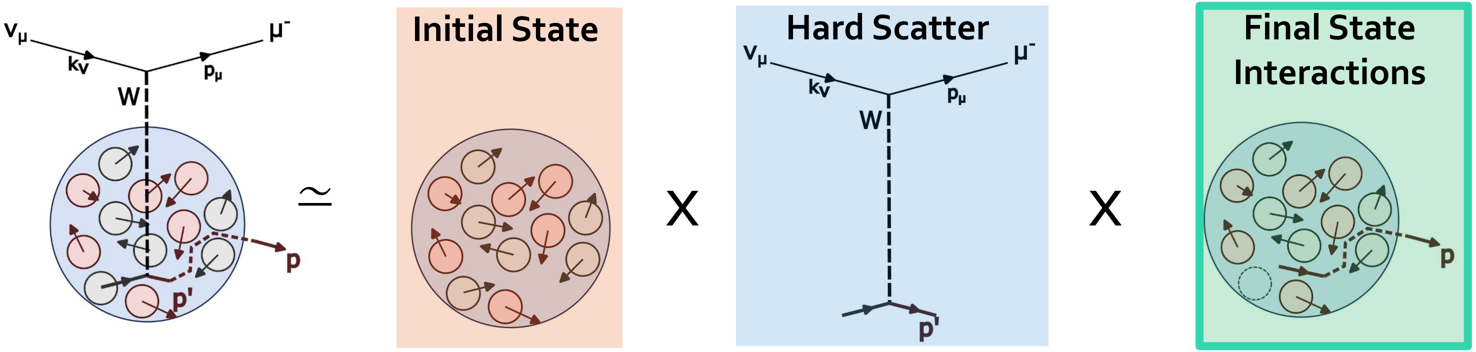

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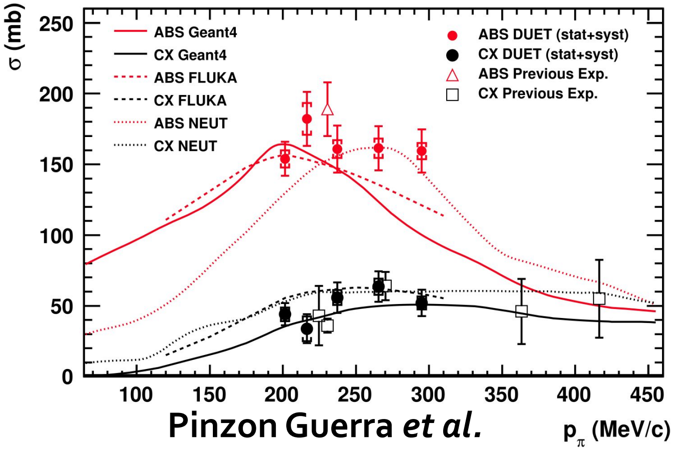
    - Pion processes: Quasi-Elastic, Charge-exchange, Absorption, or pion production tuned to a variety of thin-target data



Pinzon Guerra *et al.*

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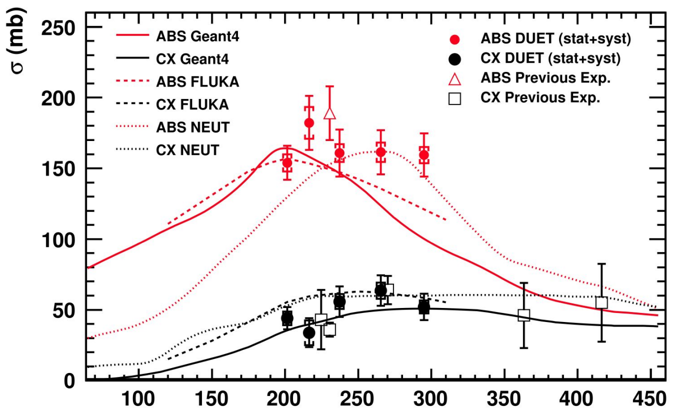
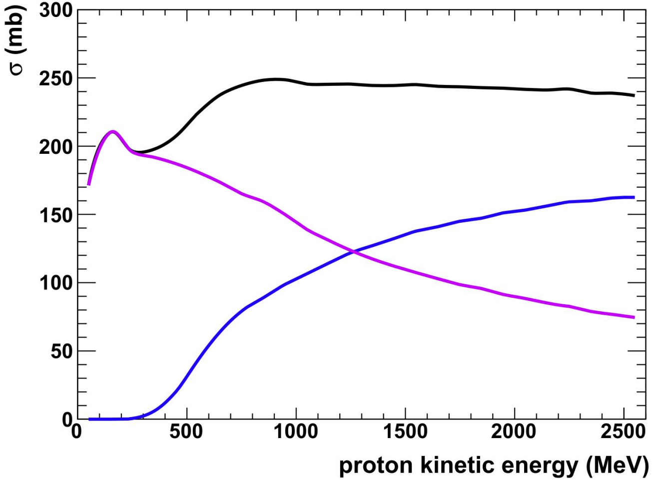
  - Pion processes: Quasi-Elastic, Charge-exchange, Absorption, o pion production tuned to a variety of thin-target data
  - The nucleon cascade follows Bertini *et al.* for MECC-7
- Woods-Saxon nucleon density with LFG spectral function



Pinzon Guerra *et al.*

Proton-Carbon cross-sections



Tools Worth Mentioning

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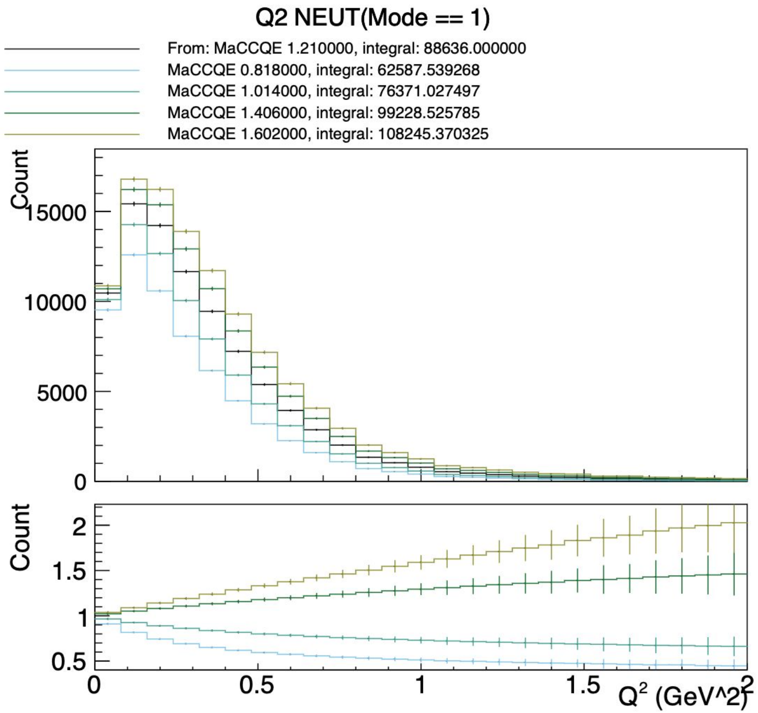
  - Calculate the relative probability of an already-generated event under some model variation
  - A critical tool for uncertainty propagation, but doesn't work for all model variations – complement with approximate techniques
  - Implemented for QE and Res1Pi form factors
  - Implemented for Pion and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



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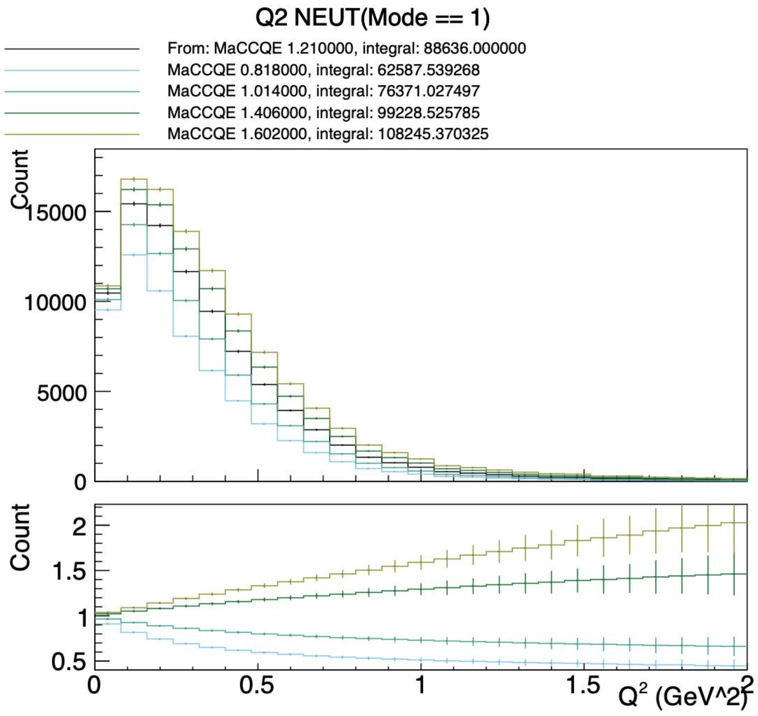
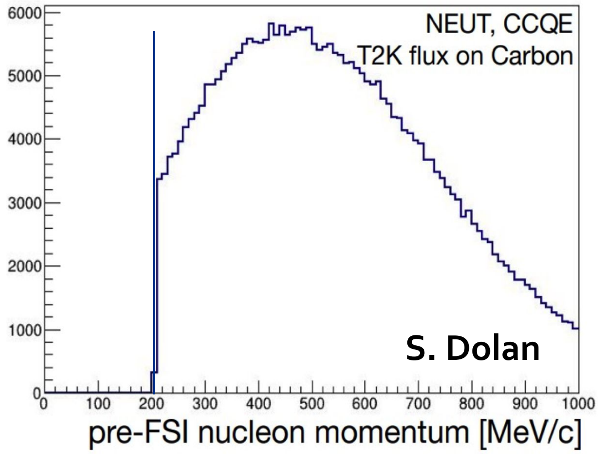


- GEANT interface:
  - Can use the NEUT hadron transport model as an inelastic model in GEANT4
  - Enables correlation of Final State Interaction (intra-nuclear) and Secondary Interaction (in-detector) models

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 simple, RFG-like approach
- Nuclear effects in single pion production are largely ignored
- Nuclear transparency has no effect on inclusive cross-section
- 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

Plans

Future: NEUT 6

- Development has begun on NEUT6 - Targeted at HK and final T2K analyses:
  - Significant reorganization of code-base
  - Improved, modern build system
  - Removed dependence on an external CERNLIB2005
  - New TOML-based configuration file
  - Modern C/Fortran interop
  - Automatic C/Fortran interface generation for model integration
- Aim is to release NEUT6 as open source under the GPL before the end of 2023
  - Will also release the final NEUT5 series release as open source
- Hope to produce comprehensive data-model comparisons alongside NEUT6 release

Future: Common Event Format

- Implementing HepMC3-based event format proposed as a common neutrino generator format: NuHepMC
  - See white-paper motivating this work here: https://arxiv.org/abs/2008.06566
  - Formats are only one (small) piece of the puzzle: Common APIs, community flux and geometry tooling

- NuHepMC is a proposed set of agreed-upon minimal metadata beyond the true vector of particles involved in the event.
  - Generator implementations are expected to store additional metadata
  - First draft nearly ready, will be put on arxiv to solicit feedback
  - Working implementations in NEUT, GENIE, NuWro, Achilles, NUISANCE

- HepMC3 is a event format description used by LHC generators:
  - Particle stack + arbitrary metadata
  - Many on-disk formats and official and unofficial analysis tools

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 effective corrections.

Summary

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  - 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 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
  - Implementing community interfaces and formats
  - Updating dependencies and procedures to modern standards (where possible)